Galiano Island 2013

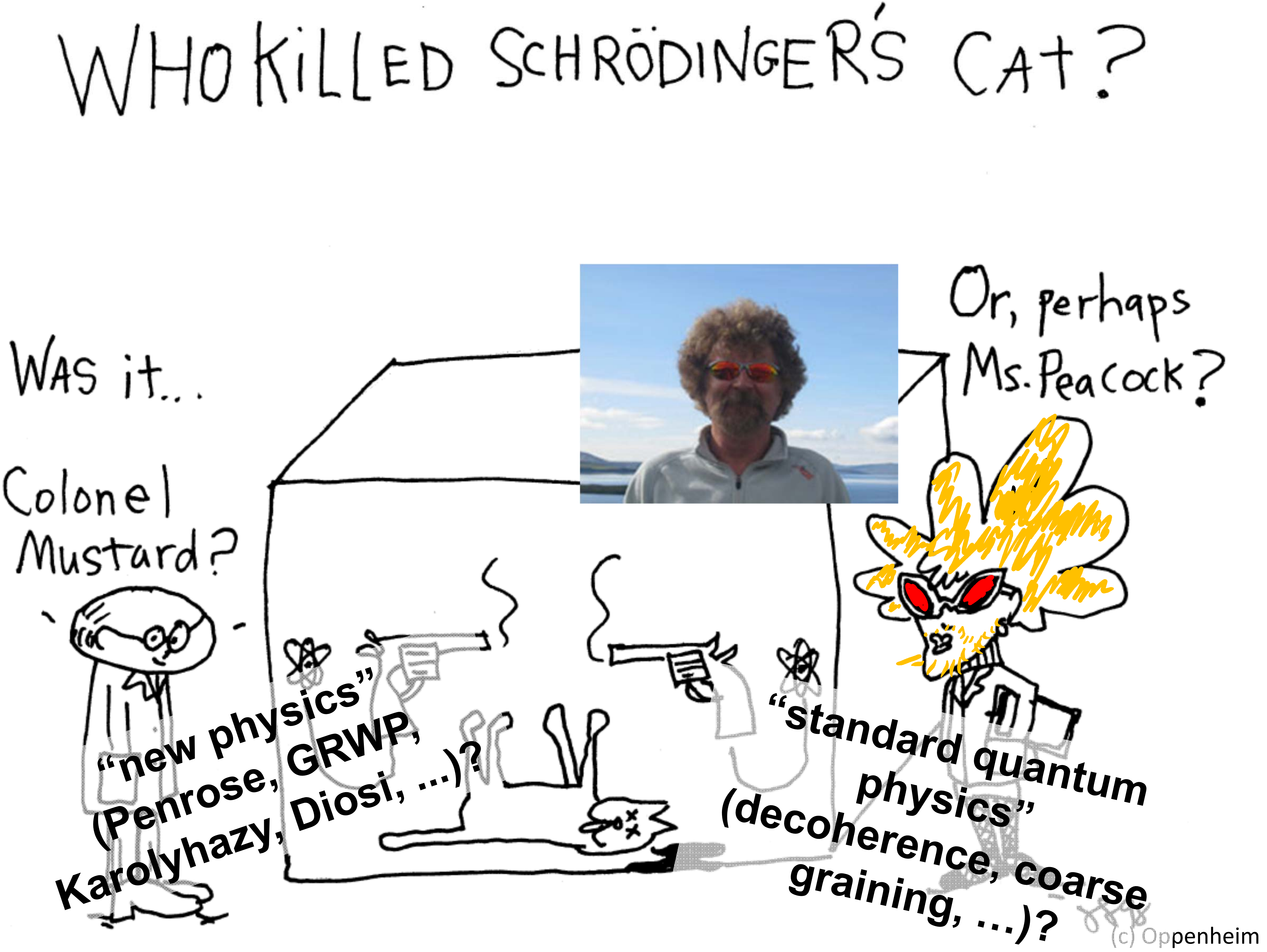
Quantum experiments with massive mechanical resonators: *status, challenges and perspectives*

Markus Aspelmeyer

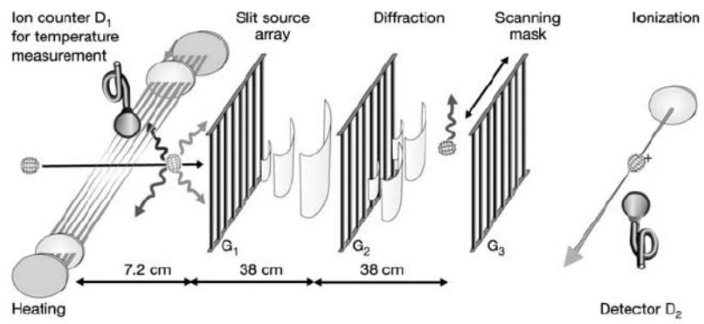
Vienna Center for Quantum Science and Technology (VCQ)

Faculty of Physics

University of Vienna, Austria


WHO KILLED SCHRÖDINGER'S CAT?
WAS it...
Colonel Mustard?
Or, perhaps Ms. Peacock?
"new physics" (Penrose, GRWP, Karolyhazy, Diosi, ...)?
"standard quantum physics" (decoherence, coarse graining, ...)?
(c) Oppenheim

Decoherence in experiments



Nature 427, 711 (2004)

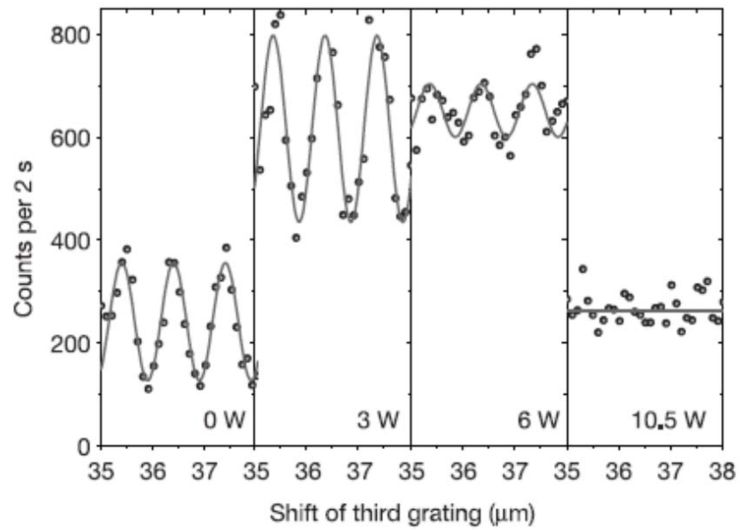
Decoherence of matter waves by thermal emission of radiation

Lucia Hackermüller, Klaus Hornberger, Björn Brezger*, Anton Zeilinger & Markus Arndt

[1]*Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria*

* Present address: Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany

Emergent quantum technologies have led to increasing interest in decoherence—the processes that limit the appearance of quantum effects and turn them into classical phenomena. One important cause of decoherence is the interaction of a quantum system with its environment, which 'entangles' the two and distributes the quantum coherence over so many degrees of



Nature 403, 269 (2000)

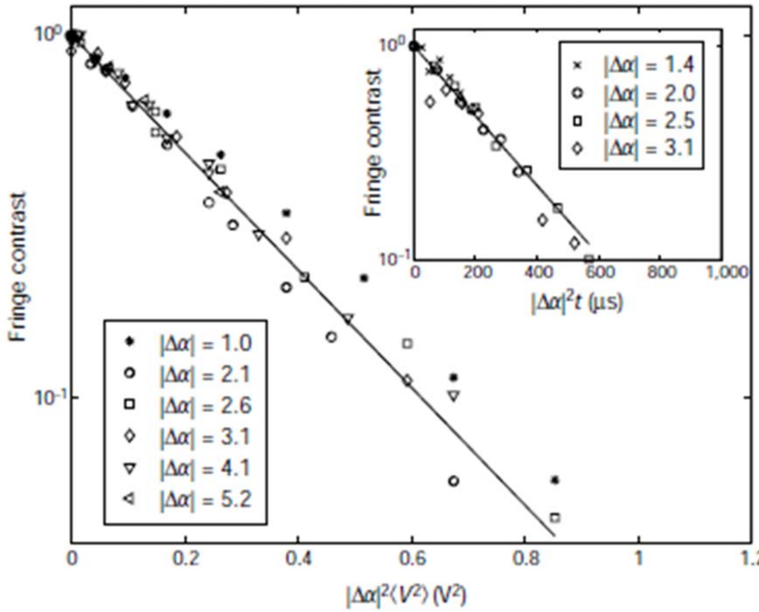
articles

Decoherence of quantum superpositions through coupling to engineered reservoirs

C. J. Myatt*, B. E. King*, Q. A. Turchette, C. A. Sackett, D. Kielpinski, W. M. Itano, C. Monroe & D. J. Wineland

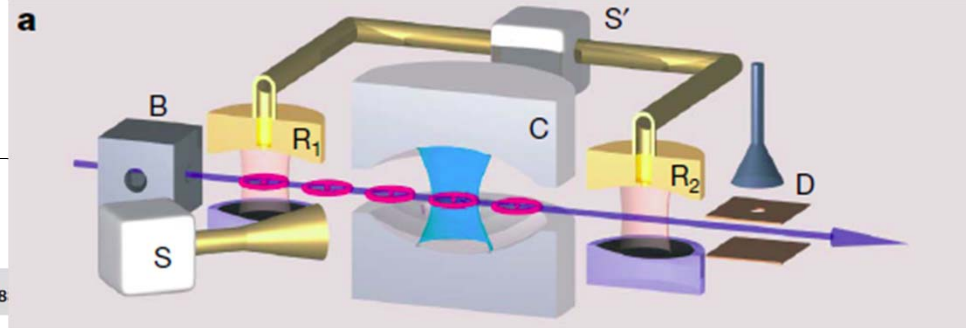
National Institute of Standards and Technology, Div. 847.10, 325 Broadway, Boulder, Colorado 80303, USA

The theory of quantum mechanics applies to closed systems. In such ideal situations, a single atom can, for example, exist simultaneously in a superposition of two different spatial locations. In contrast, real systems always interact with their environment, with the consequence that macroscopic quantum superpositions (as illustrated by the 'Schrödinger's cat' thought-



Decoherence in experiments

Nature 455, 510 (2008)



nature Vol 455|25 September 2008|doi:10.1038/nature0728

LETTERS

Reconstruction of non-classical cavity field states with snapshots of their decoherence

Samuel Deléglise[1], Igor Dotsenko[1,2], Clément Sayrin[1], Julien Bernu[1], Michel Brune[1], Jean-Michel Raimond[1] & Serge Haroche[1,2]

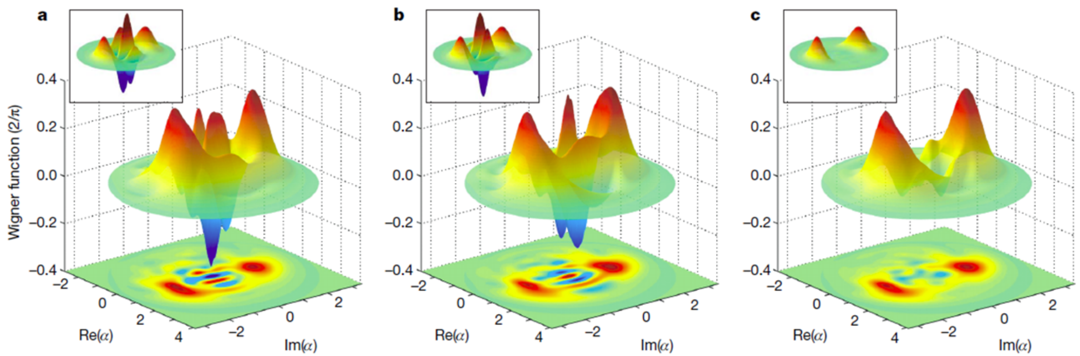


Figure 3 | Reconstructing Schrödinger cat states. **a**, **b**, The Wigner functions (in units of $2/\pi$) of even (**a**) and odd (**b**) Schrödinger cat states with $n_m = 3.5$ and $\chi = 0.37\pi$ are reconstructed, following state preparation. The same detuning ($\delta/2\pi = 51$ kHz) and interferometer phase ($\phi = -\Phi(0,\delta) + \pi$) are used for state preparation and reconstruction. The number of sampling points is ~500, with ~2,000 atoms detected at each point, in 400 realizations. The dimension of the Hilbert space used for reconstruction is 11. The small insets present for comparison the theoretical Wigner functions computed in the case of ideal preparation and detection of the atomic state superpositions. Decoherence during state preparation is taken into account. The maximum theoretical values of the classical components and interference fringes are close to 0.5 and 1, respectively. In the reconstructed states, the quantum interference is smaller, mainly owing to imperfections of the Ramsey interferometer that affect the preparation of the Schrödinger cat state (but not its reconstruction). **c**, Reconstructed Wigner function of the field prepared in C when the state of the preparation atom is not read-out (statistical mixture of two classical fields). Inset, corresponding theoretical Wigner function.

Phys. Rev. Lett. 103, 200404 (2009)

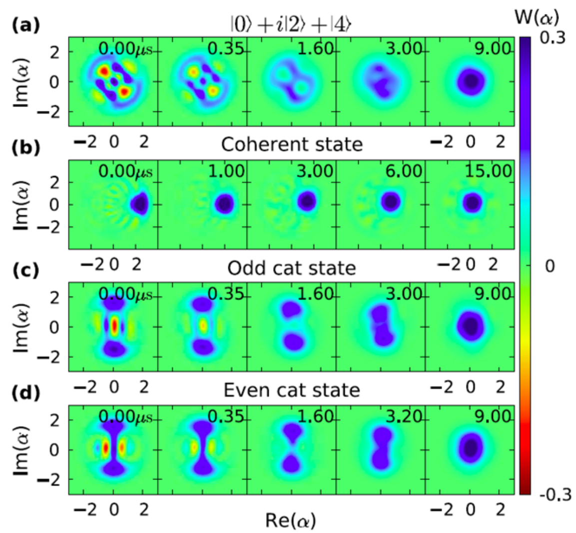
PRL 103, 200404 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

Decoherence Dynamics of Complex Photon States in a Superconducting Circuit

H. Wang, M. Hofheinz, M. Ansmann, R. C. Bialczak, Erik Lucero, M. Neeley, A. D. O'Connell, D. Sank, M. Weides, J. Wenner, A. N. Cleland,* and John M. Martinis†
Department of Physics, University of California, Santa Barbara, California 93106, USA

(Received 29 July 2009; published 13 November 2009)

Quantum states inevitably decay with time into a probabilistic mixture of classical states due to their interaction with the environment and measurement instrumentation. We present the first measurement of the decoherence dynamics of complex photon states in a condensed-matter system. By controllably preparing a number of distinct quantum-superposed photon states in a superconducting microwave resonator, we show that the subsequent decay dynamics can be quantitatively described by taking into account only two distinct decay channels: energy relaxation and pure dephasing. Our ability to prepare specific initial quantum states allows us to measure the evolution of specific elements in the quantum density matrix in a very detailed manner that can be compared with theory.



Schrödinger's Cat: Death due to new physics?

- *Nonlinear extensions of Schrödinger equation*? (Bialinicky-Birula; Shimony)

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r},t) + F(|\psi(\vec{r},t)|^2)\right)\psi(\vec{r},t) = i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t) \qquad F(|\psi|^2) = -\underline{b}\ln(\underline{a}^n|\psi|^2)$$

→**Experimentally falsified** by neutron diffraction

(Gähler, Klein, Zeilinger, PRA 23, 1611 (1981))

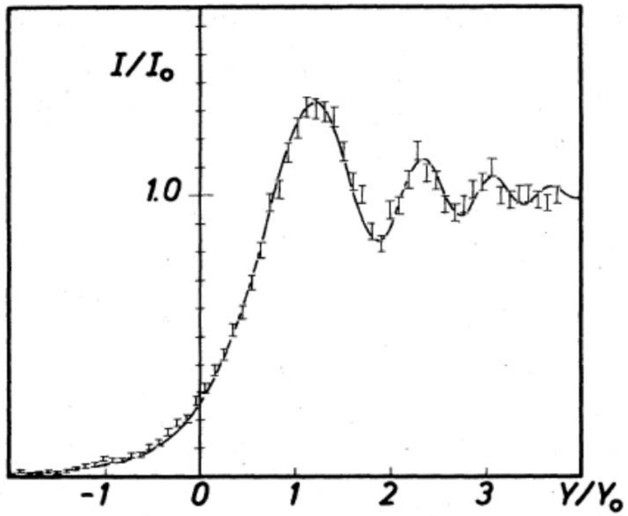


FIG. 3. Measured diffraction pattern of an absorbing straight-edge compared with the curve obtained from standard linear theory.

- *Deviation from Born's rule?*

→**First negative test** via 3-slit interference experiment

(Sinha, Couteau, Jennewein, Laflamme, Weihs, Science 329, 418 (2010))

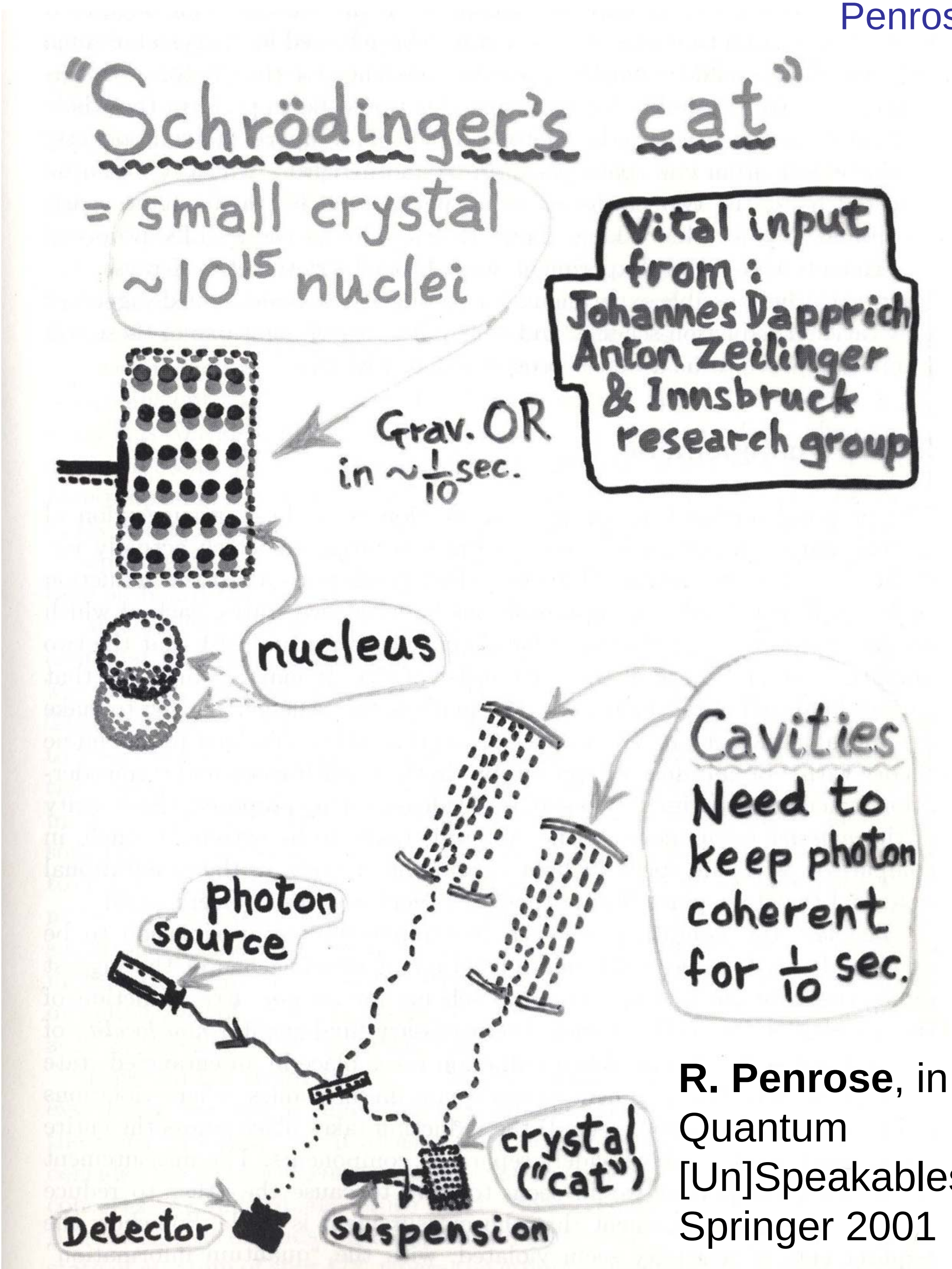
- *„Collapse" via stochastic background field?*

Ghirardi, Rimini, Weber
Pearl
Gisin…

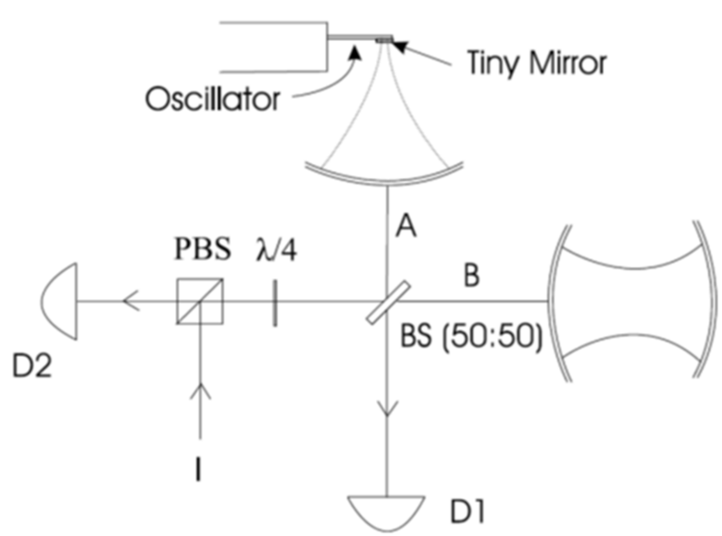
→ Can be tested in principle!

„Collapse“ by gravity?

Karolyhazy (1960s), e.g. Nuovo Cimento 42, 390 (1966)
Diosi (1980s), e.g. J. Phys. A: Math. Gen. 21, 2885 (1988)
Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)



Marshall, Simon, Penrose, Bouwmeester, PRL 91, 130401 (2003)



also: A.D. Armour, M.P. Blencowe, and K. Schwab, PRL 88, 148301 (2002.)

Light-mirror entanglement

Bose, Jacobs, Knight, Phys. Rev. A **56**, 4175 (1997)
Mancini, Manko, P. Tombesi, Phys. Rev. A **55**, 3042 (1997)

Macroscopic quantum coherence

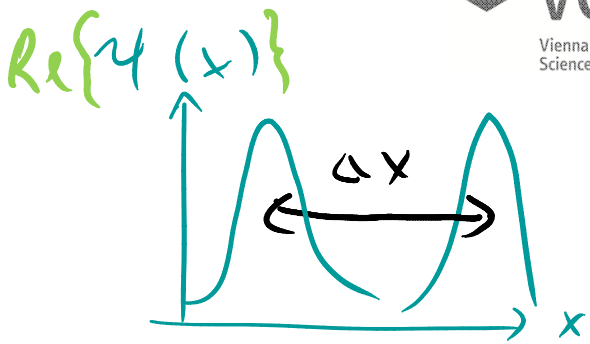
Bouwmeester, Schmiedmayer, Weinfurter, Zeilinger, in: Gravitation and Relativity, IUCAA 1998

R. Penrose, in: Quantum [Un]Speakables, Springer 2001

Decoherence

Joos & Zeh, Caldeira & Leggett, Unruh & Zurek
Paz & Zurek, Hu & Paz & Zhang, Milburn, …

universität wien
VCQ
Vienna Center for Quantum Science and Technology



$$\dot{\rho} = -\frac{\mathrm{i}}{\hbar}[H,\rho] + \mathcal{L}[\rho]$$

Master equation approach

Gas scattering

$$\langle x|\mathcal{L}_g[\rho]|x'\rangle = \begin{cases} -[\Delta x]^2 \Lambda_g \langle x|\rho|x'\rangle, & \Delta x < \frac{\hbar}{m\bar{v}} \\ -\Gamma'_g \langle x|\rho|x'\rangle, & \Delta x > \frac{\hbar}{m\bar{v}}. \end{cases}$$

where

$$\Lambda_g = \frac{3m\bar{v}P\pi R^2}{\hbar^2}$$

$$\Gamma'_g = \frac{\pi R^2 P}{m\bar{v}}$$

See also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)

Penrose model

$$\langle x|\mathcal{L}_g[\rho]|x'\rangle = \begin{cases} -\Lambda_P \Delta x^2 \langle x|\rho|x'\rangle, & \Delta x \ll R \\ \Lambda_P \langle x|\rho|x'\rangle, & \Delta x > R. \end{cases}$$

$$\Lambda_P = \Lambda_D = \frac{20\rho^2 R^3}{\hbar}, \quad \Delta x \ll R$$

$$\Lambda'_P = \frac{20\rho^2 R^5}{\hbar}, \quad \Delta x \geq R.$$

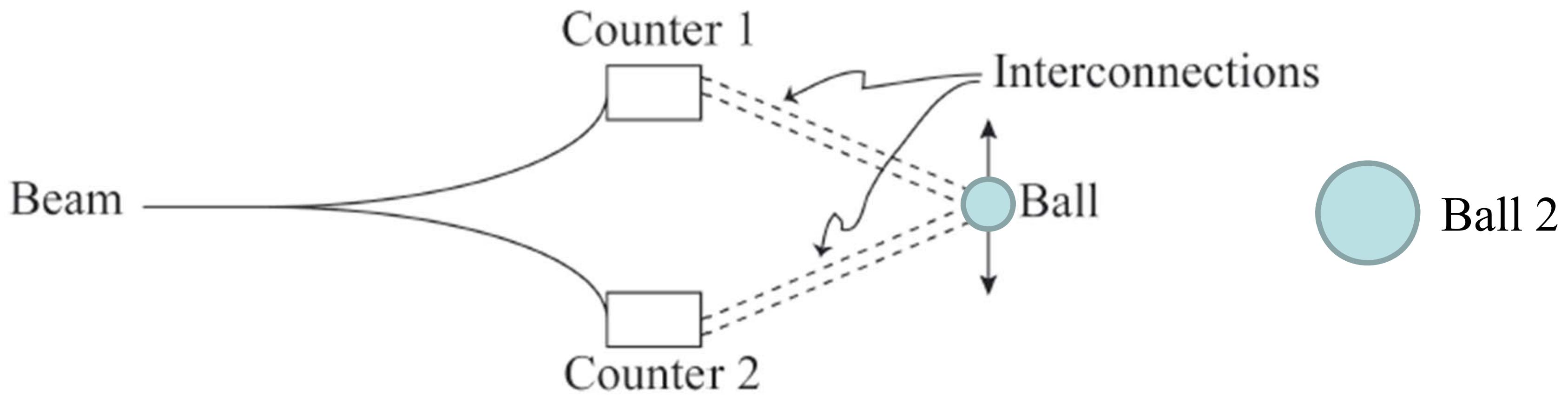
GRWP

$$\Lambda_{\mathrm{CSL}} = m^2 \lambda_0 \alpha f(\sqrt{\alpha}R)/(2m_0^2)$$

$$\alpha^{-1/2} \approx 10^{-7}\ \mathrm{m}$$

$$\lambda_0 \approx 2.2 \times 10^{-17}\ \mathrm{s}^{-1}$$

An ultimate experiment? Entanglement by gravity…



|Ball1_u> + |Ball1_d> → |Ball1_u>|Ball2_u> + |Ball1_d>|Ball2_d>

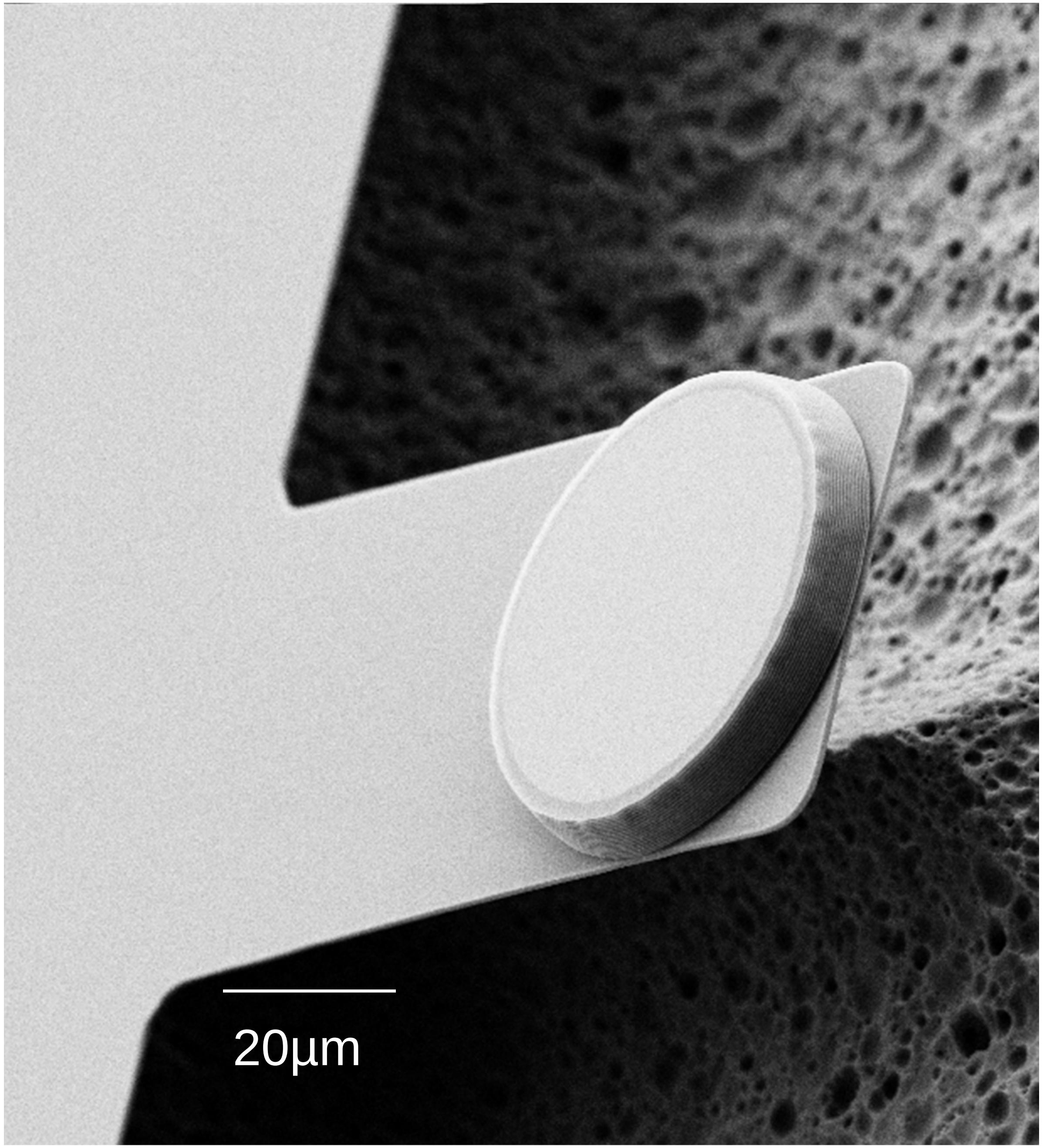
FEYNMAN: "Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There is a *bare* possibility (which I shouldn't mention!) that quantum mechanics fails and becomes classical again when the amplification gets far enough, because of some minimum amplification which you can get across such a chain. But aside from that possibility, if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

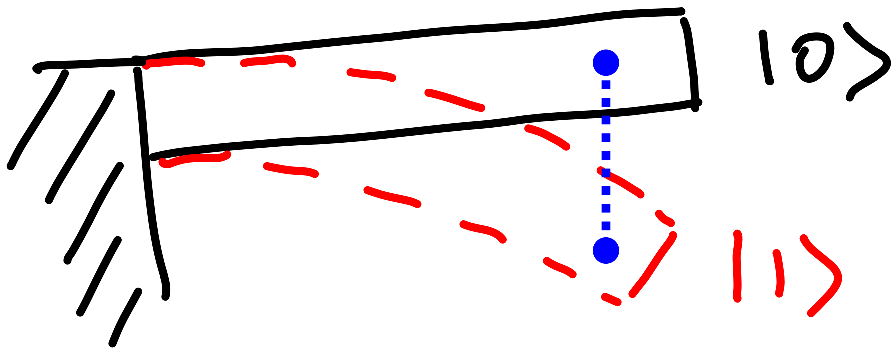
(Chapel Hill Conference 1957)

A mechanical cat? Schrödinger‘s mirrors

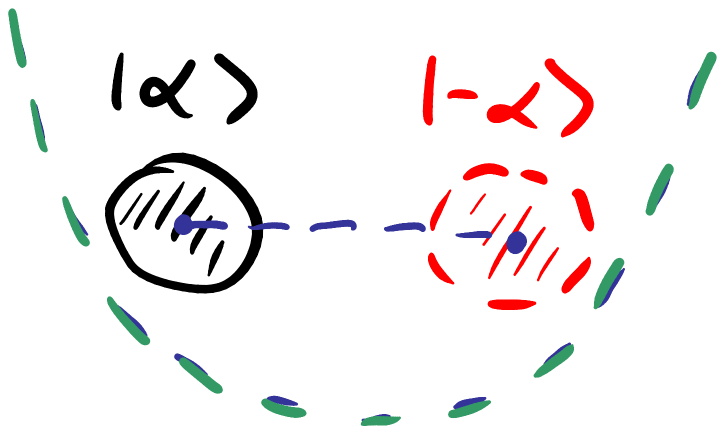
universität wien

VCQ
Vienna Center for Quantum Science and Technology



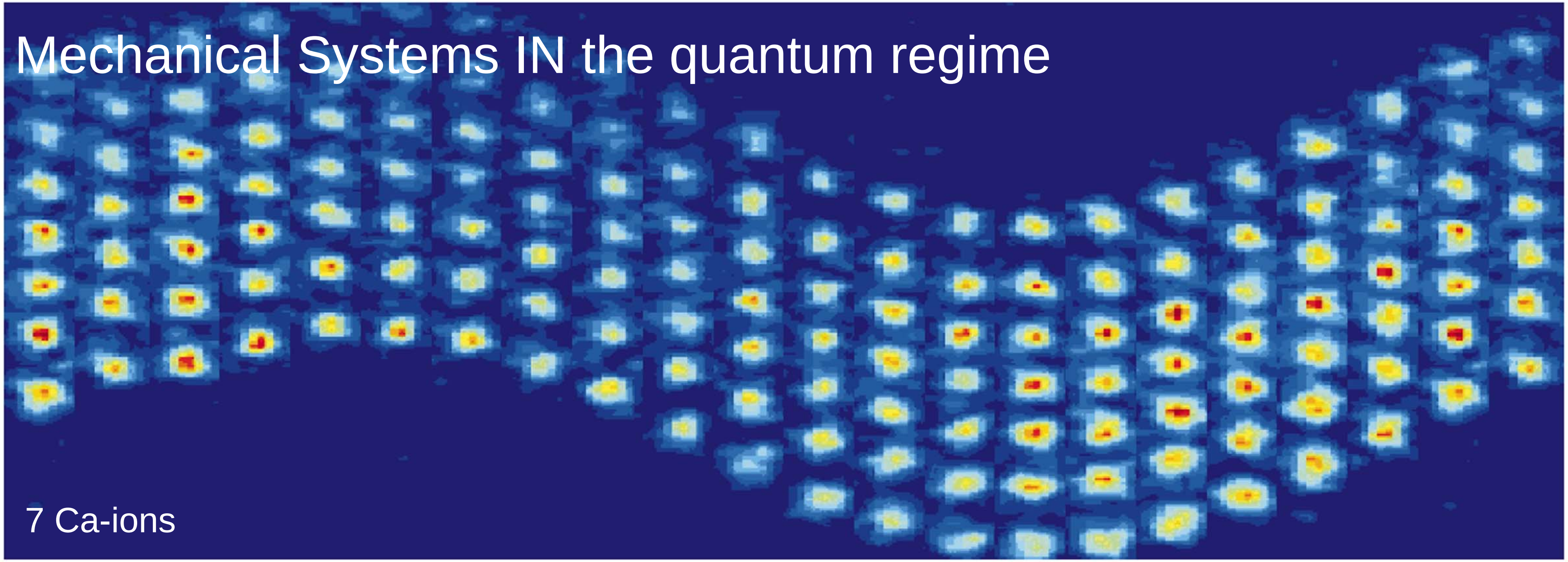


Cantilever

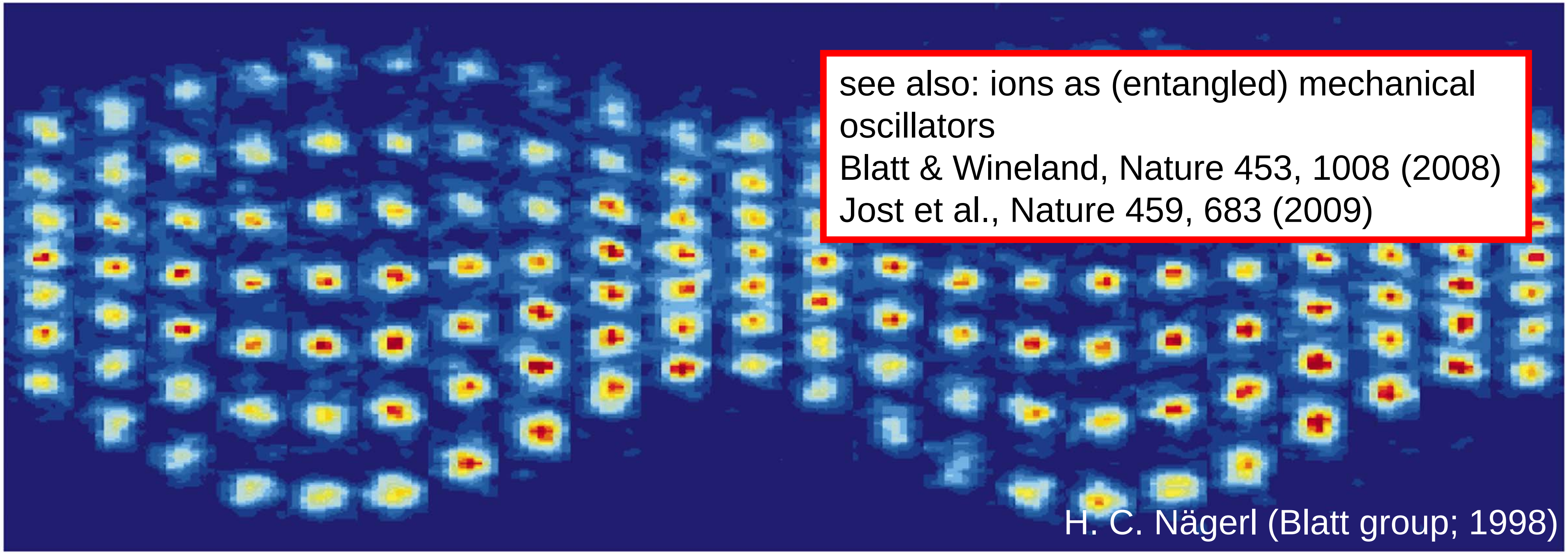


Trapped Particle

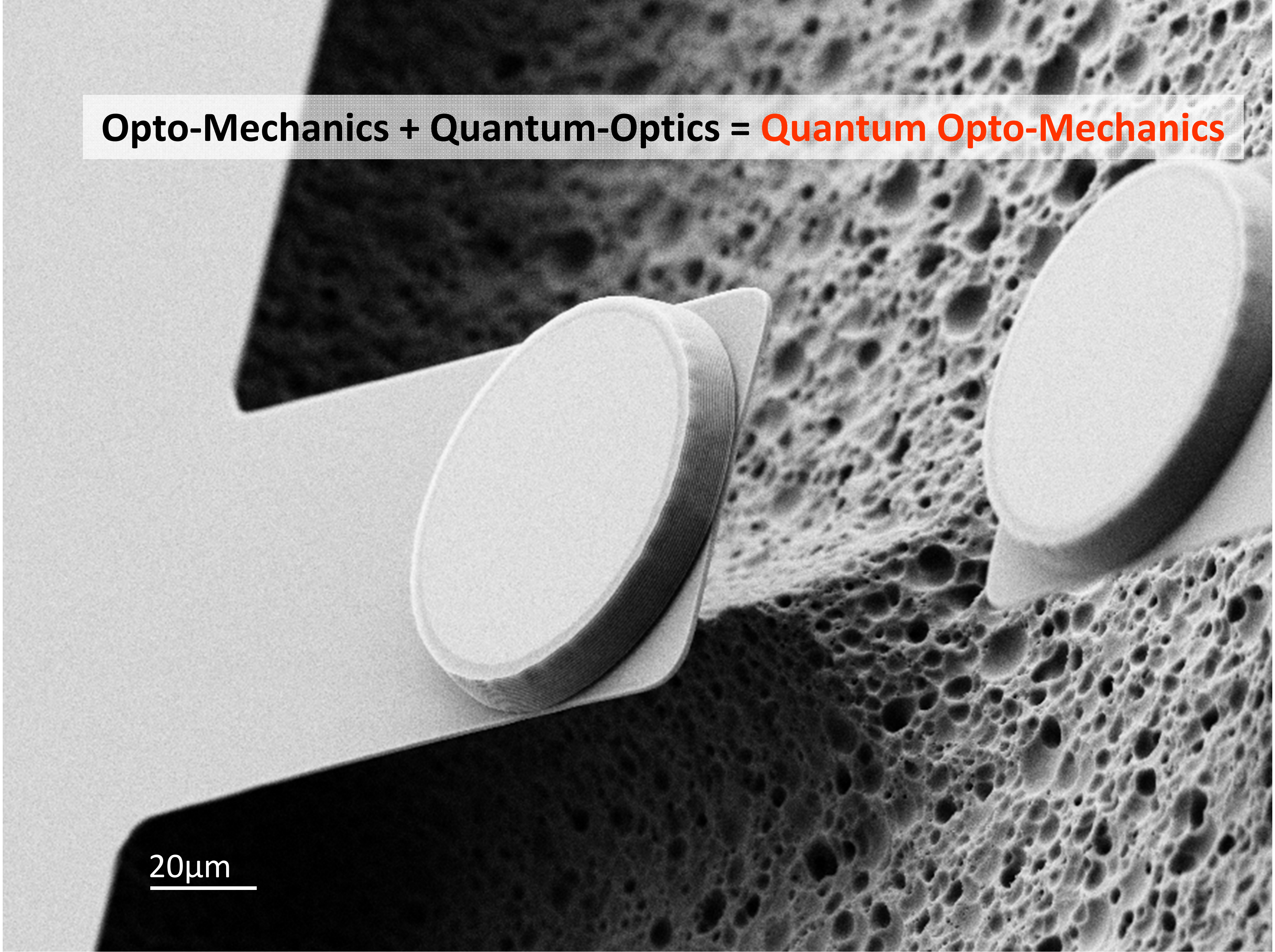
Mechanical Systems IN the quantum regime



Trapped ions: **quantum physics with phonons** (Cirac & Zoller, PRL 74, 4091 (1995))



Opto-Mechanics + Quantum-Optics = Quantum Opto-Mechanics



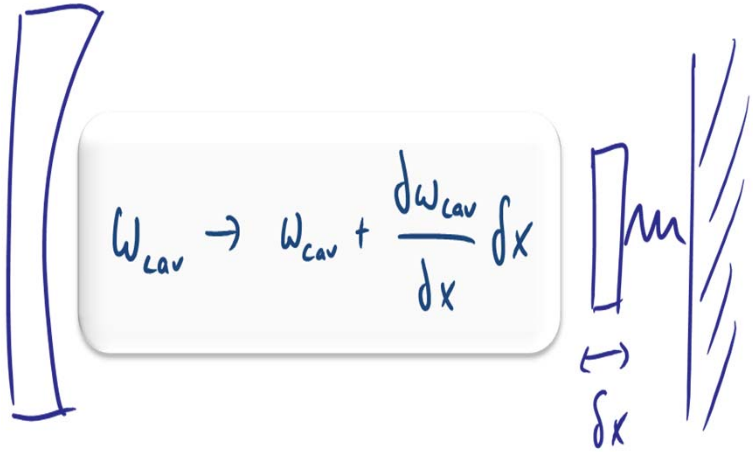
Coupling mechanics to light: Cavity Opto-Mechanics

universität wien
VCQ
Vienna Center for Quantum Science and Technology

Main idea: **Radiation pressure effects** in high-finesse cavities open up a completely new field of **controllable light-matter interaction** from the **nano-** to the **macro**scale.

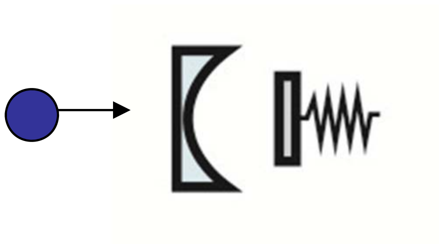
Fundamental interaction:

- Intensity-dependent displacement (optical bistability*)
- Intensity-dependent phase shift (**optical nonlinearity**)
- Retarded forces (modify **mechanical susceptibility**⁺)



$$\omega_{cav} \rightarrow \omega_{cav} + \frac{d\omega_{cav}}{dx}\,\delta x$$

Single-photon coupling



$$H_{int} = \hbar g_0 \hat{n}_c \hat{x}_m$$

g_0: single-phonon cavity frequency shift

Driven optomechanical cavity

$$H_{int} = \hbar g_0 \alpha \hat{x}_c \hat{x}_m$$

$$a \rightarrow \alpha + \bar{a}$$

1967 Braginsky et al.: first proof-of-concept with microwave transducers

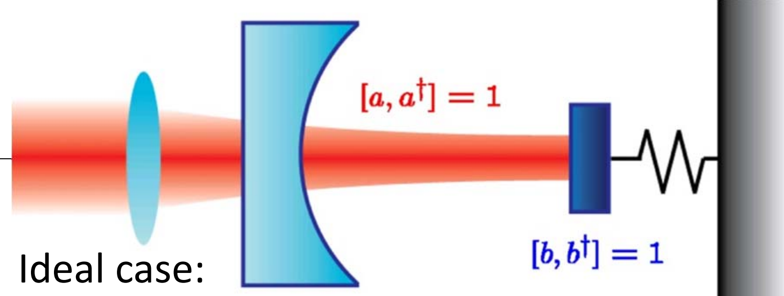
1983 Dorsel/Meystre/Walther: first optical radiation-pressure based instabilities [PRL 51, 1550]

2003 Karrai/Vogel (*optical spring*) [APL 83 1337]
2005 Vahala/Kippenberg (*parametric driving*) [Opt Exp 13, 5293]

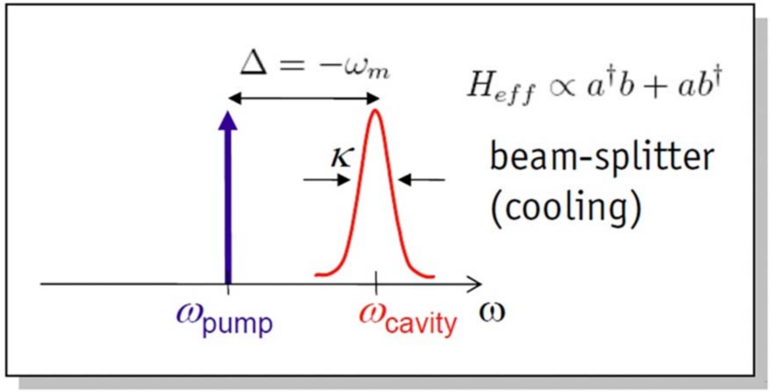
Quantum Opto-Mechanics

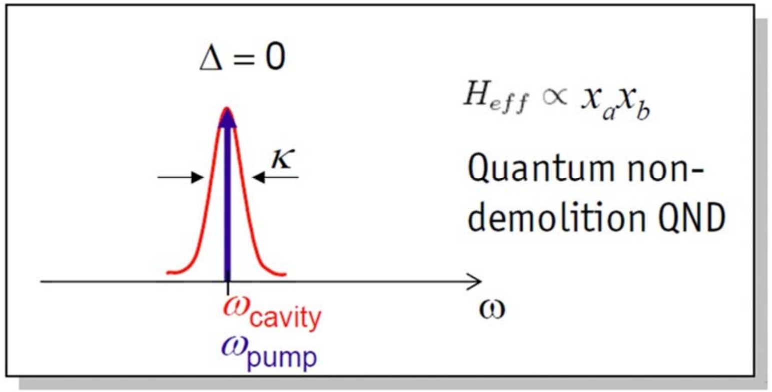
full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states

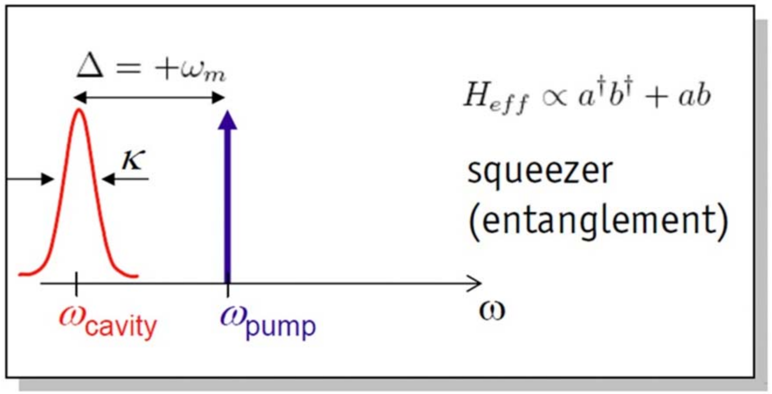
Requires:
Minmum entropy mechanical states
(e.g. ground state)
+
Strong optomechanical coupling
(coupling rate > decoherence rate)
=
$k_B T/\hbar Q \ll \kappa \ll \omega_m, g_0\alpha$



Ideal case:
resolved sideband regime, RWA

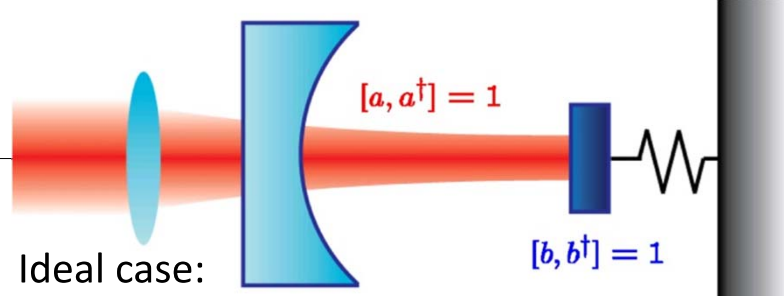






Early ideas:
Zhang, Peng, Braunstein, PRA **68**, 013808 (2003)
Recent review:
Aspelmeyer, Kippenberg, Marquardt, arXiv:1303.0733 (2013)

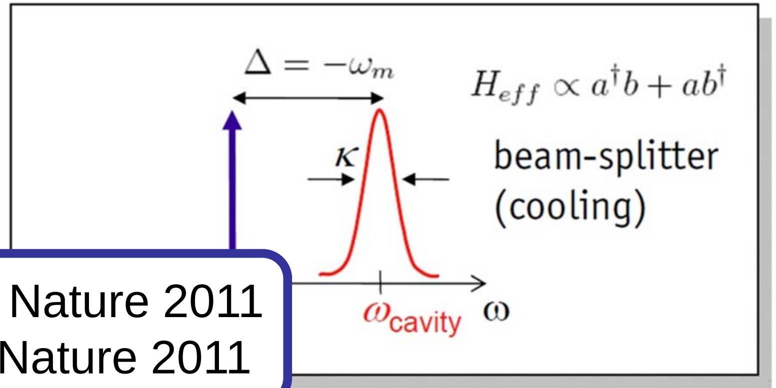
Quantum Opto-Mechanics



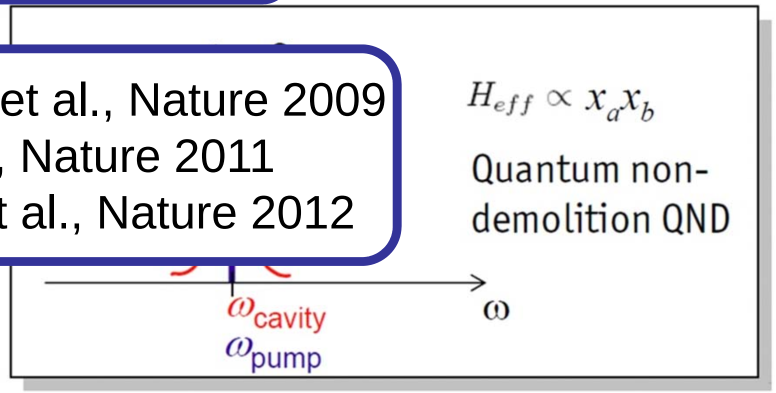
Ideal case:
resolved sideband regime, RWA

full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states

Requires:
Minmum entropy mechanical states
(e.g. ground state)
+
Strong optomechanical coupling
(coupling rate > decoherence rate)
=
$k_B T/\hbar Q \ll \kappa \ll \omega_m, g_0\alpha$

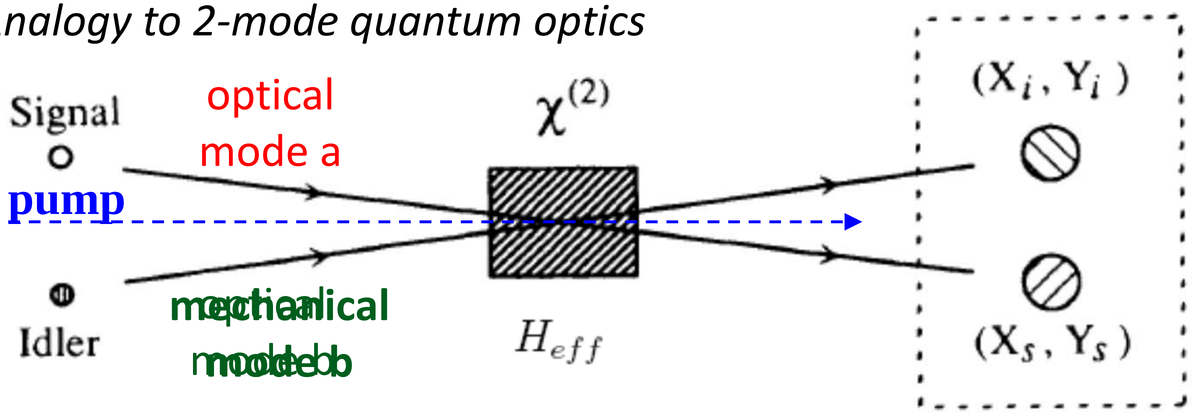


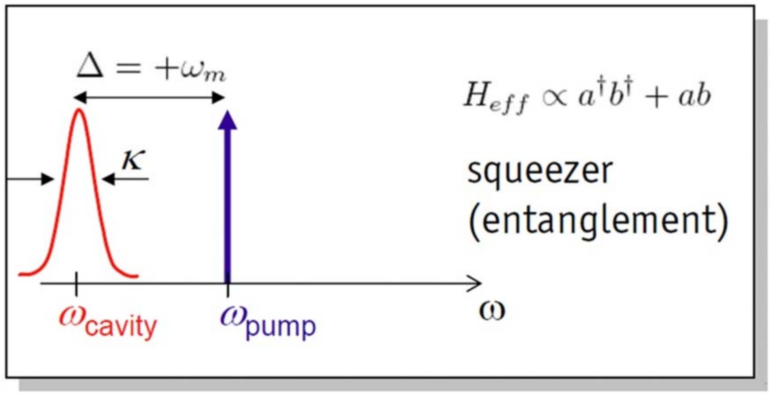
Teufel et al., Nature 2011
Chan et al., Nature 2011



Gröblacher et al., Nature 2009
Teufel et al., Nature 2011
Verhagen et al., Nature 2012

Analogy to 2-mode quantum optics





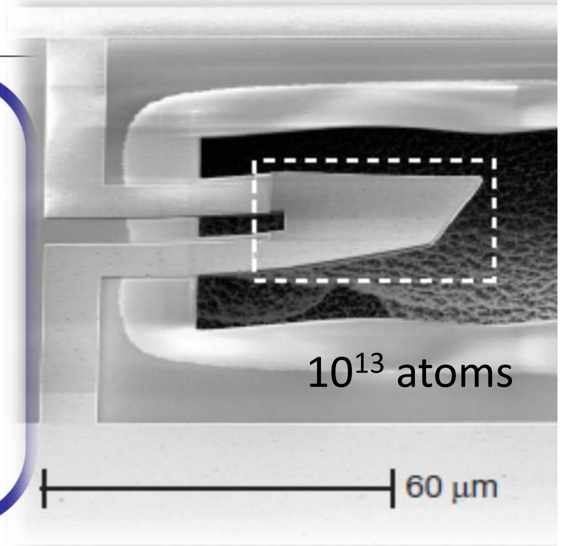
Mechanical Systems IN the quantum regime

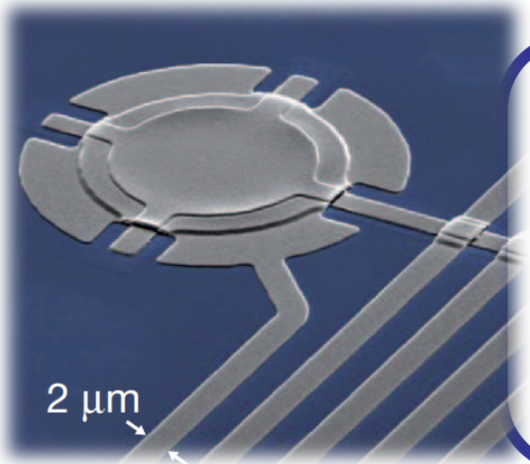
universität wien

Nature **464**, 697-703 (2010)

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]





Nature **475**, 359-363 (2011)

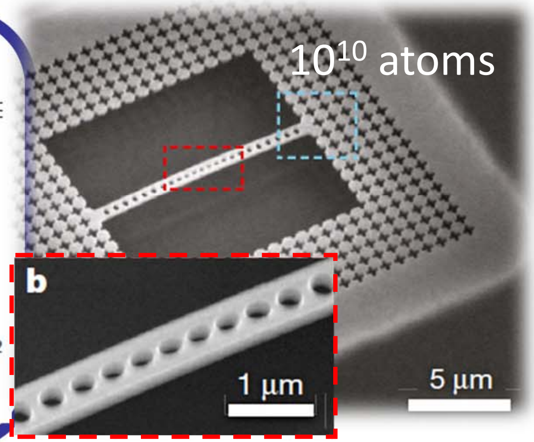
Sideband cooling of micromechanical motion to the quantum ground state

J. D. Teufel[1], T. Donner[2,3], Dale Li[1], J. W. Harlow[2,3], M. S. Allman[1,3], K. Cicak[1], A. J. Sirois[1,3], J. D. Whittaker[1,3], K. W. Lehnert[2,3] & R. W. Simmonds[1]

Nature **478**, 89-92 (2011)

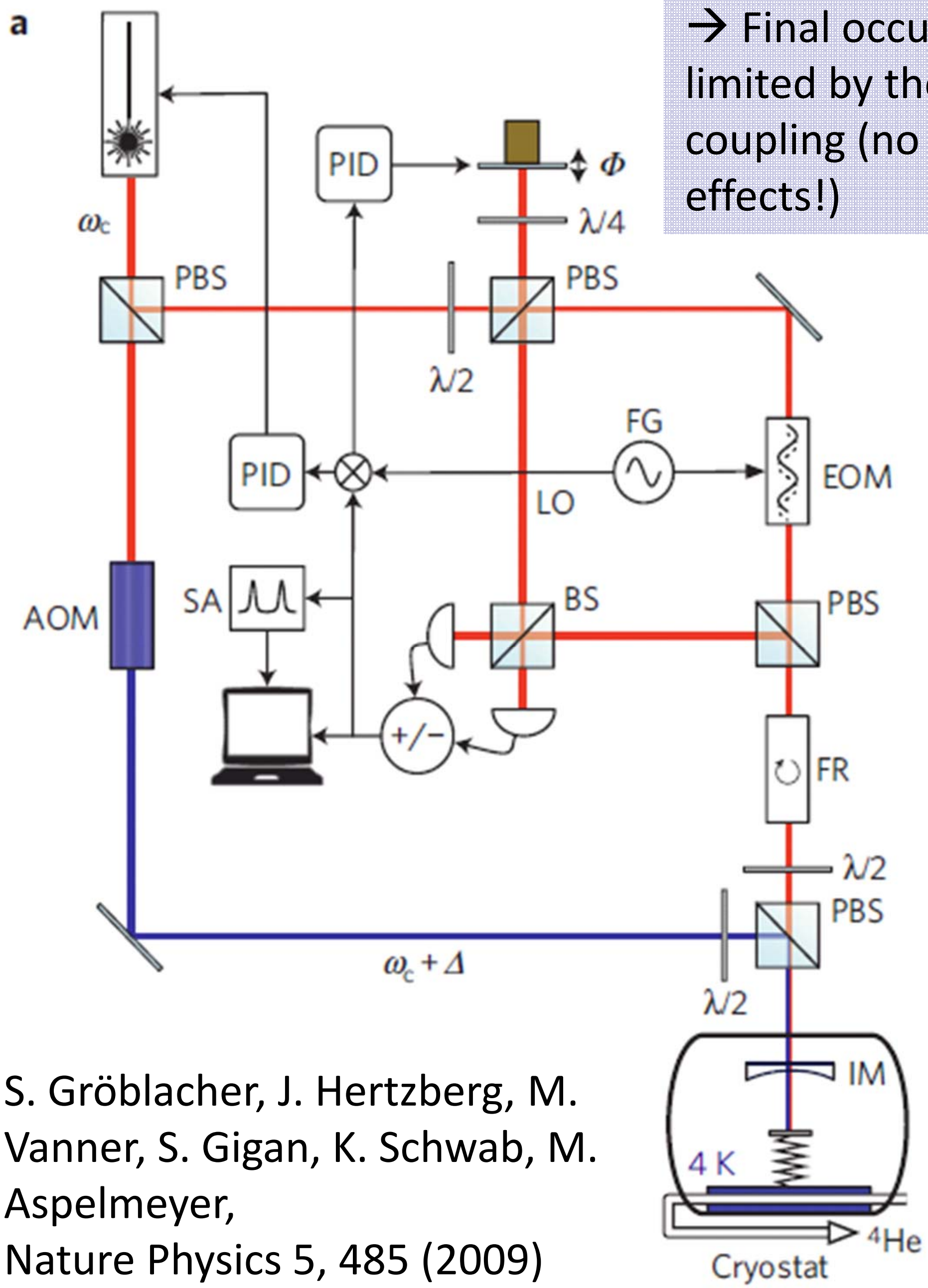
Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan[1], T. P. Mayer Alegre[1]†, Amir H. Safavi-Naeini[1], Jeff T. Hill[1], Alex Krause[1], Simon Gröblacher[1,2], Markus Aspelmeyer[2] & Oskar Painter[1]

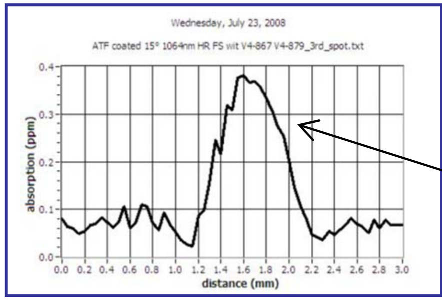


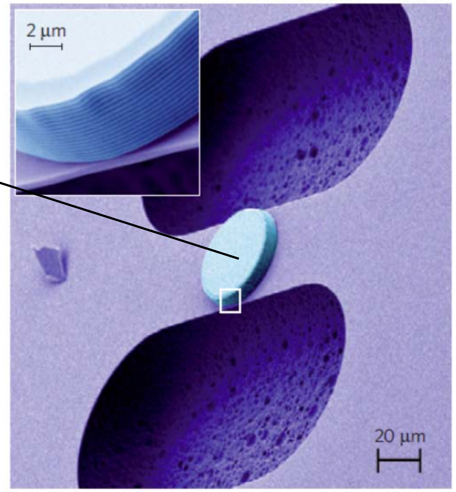
Towards „quantum mechanics“: cryogenic cavities

Nature Physics 5, 485 (2009)

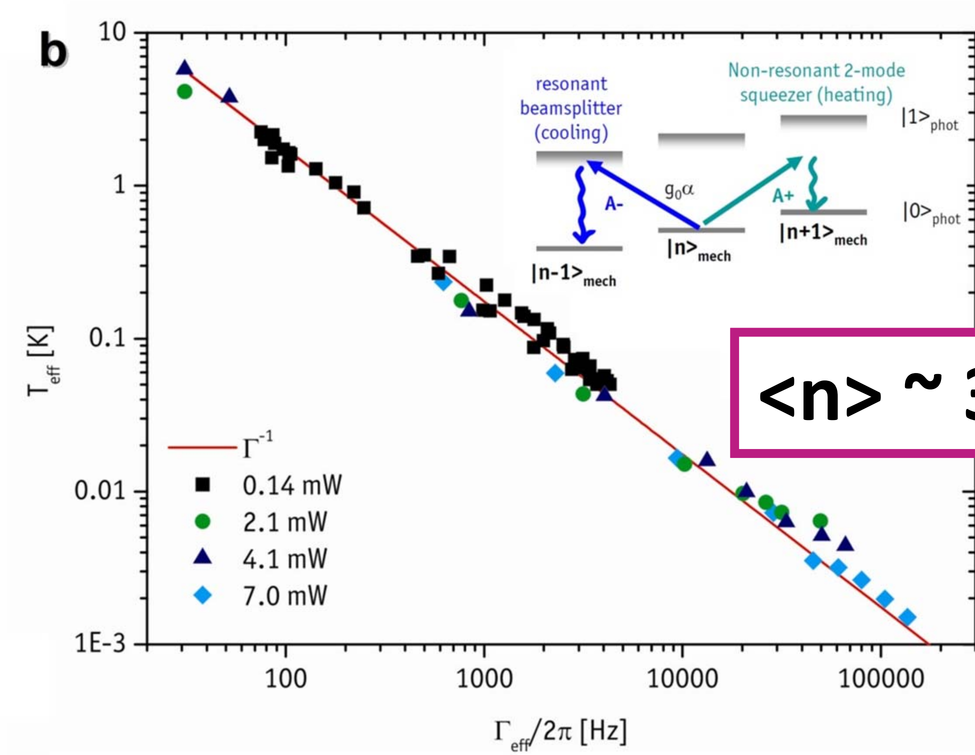


→ Final occupation only limited by thermal coupling (no absorption effects!)





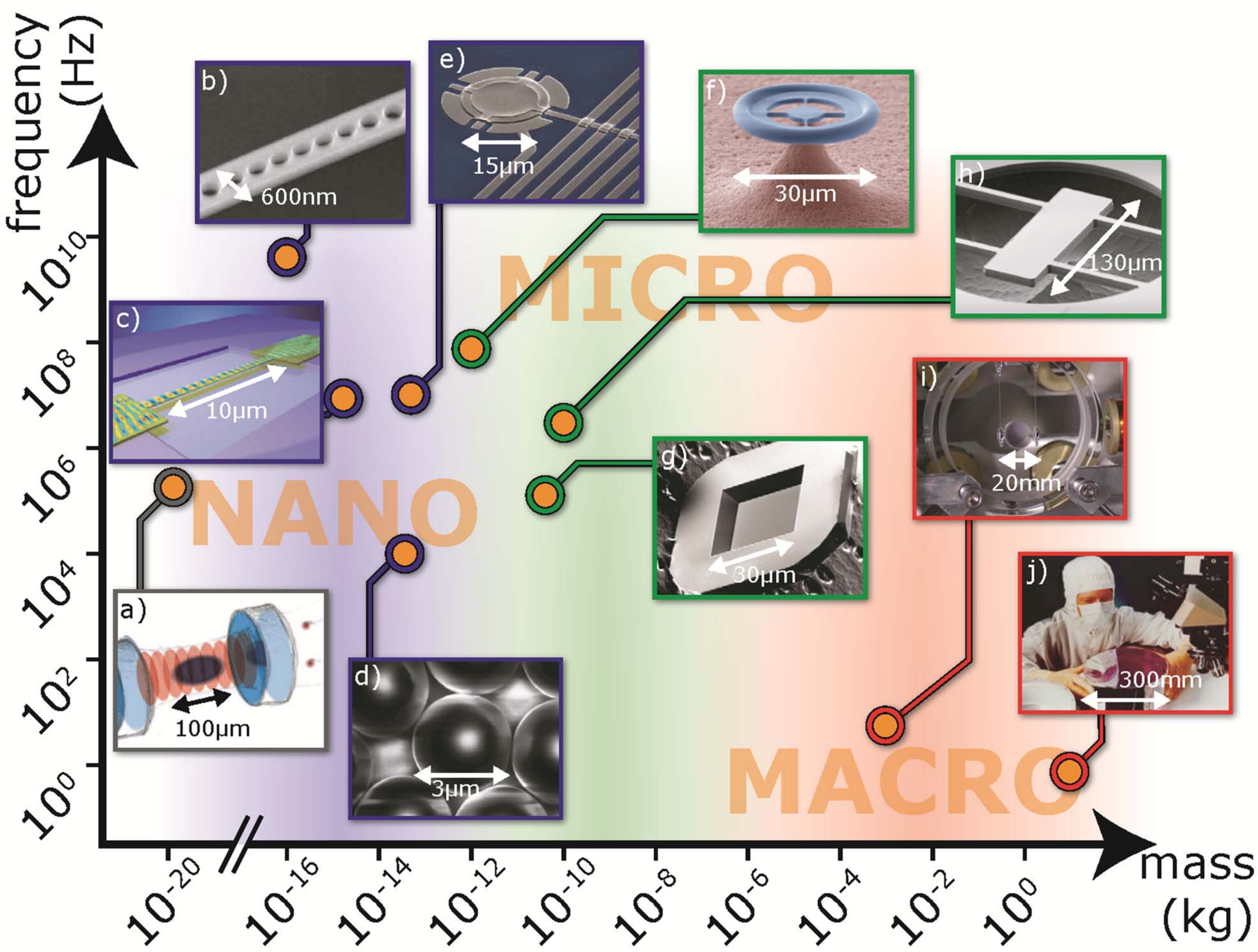
mirror absorption < **0.4ppm**!



<n> ~ 30

S. Gröblacher, J. Hertzberg, M. Vanner, S. Gigan, K. Schwab, M. Aspelmeyer,
Nature Physics 5, 485 (2009)

Opto-mechanical devices (a few examples)

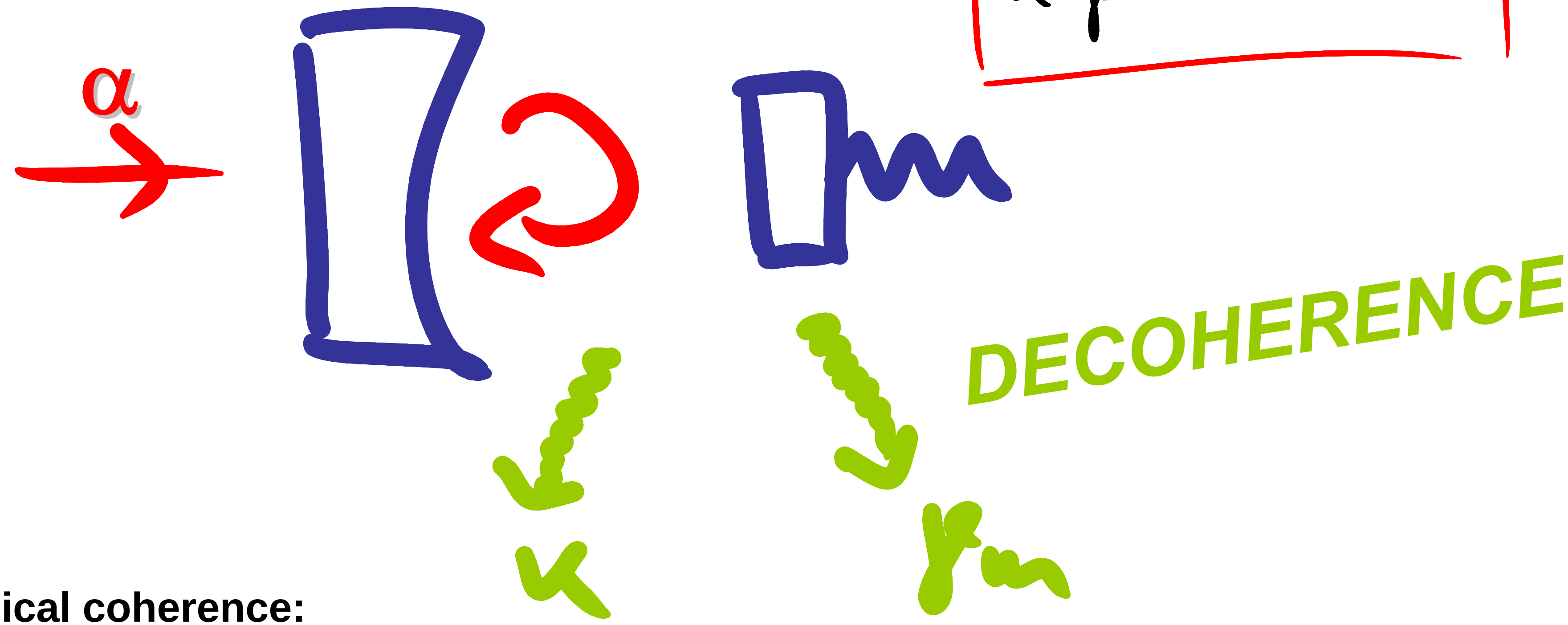


Aspelmeyer, Meystre, Schwab (*Physics Today, July 2012*)

Towards opto-mechanical quantum control...

Ground state cooling:

$$\langle n \rangle_{mech} \ll 1 \quad \text{eq} \quad \Gamma_{therm} \ll \Gamma \quad \text{eq} \quad \boxed{\frac{g^2}{\kappa \gamma} \gg \langle n \rangle_{bath}}$$



Mechanical coherence:

$$\Gamma_{therm} \ll \omega_m = 2\pi f_m \quad \text{eq} \quad \boxed{Q \cdot f_m \gg \frac{1}{2\pi} \cdot \frac{k_B}{\hbar} \cdot T \approx 2 \cdot 10^{10} \cdot T}$$

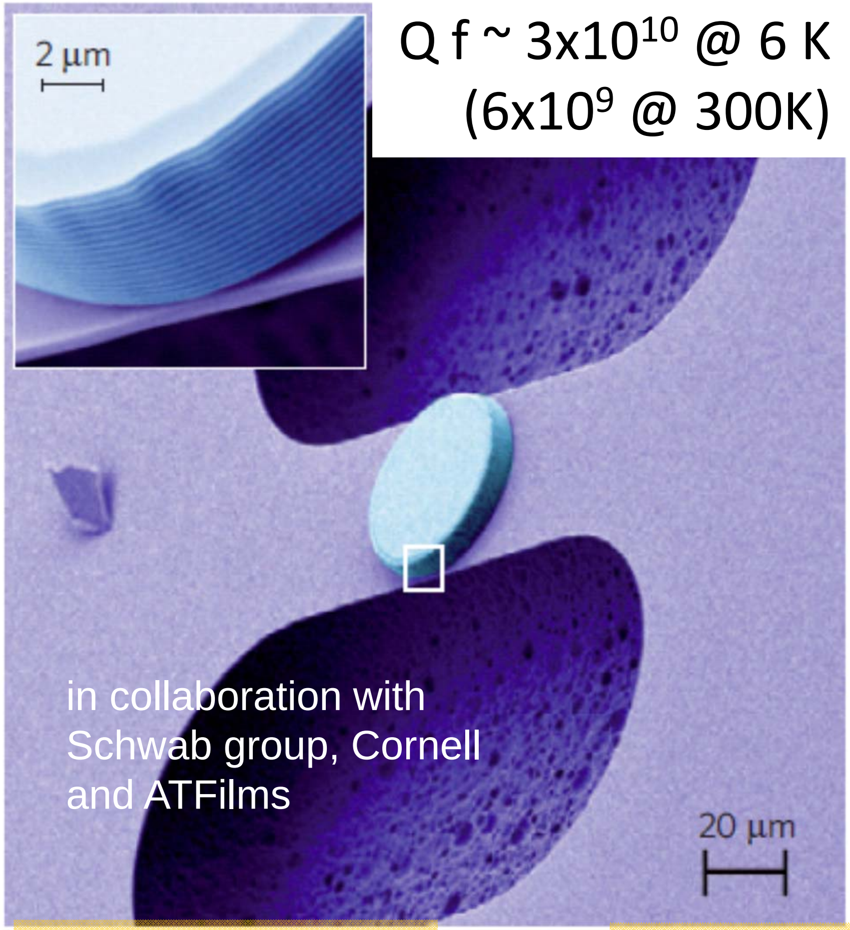
→ **Strong coupling, low temperature, high mechanical and optical quality**

Oh Q, where art thou

Main sources of mechanical dissipation
- internal materials losses (e.g. TLF)
- phonon tunneling loss

• Mirror pad on high-Q (SiN) mechanical substrate

Q f ~ 3x10^{10} @ 6 K (6x10^{9} @ 300K)

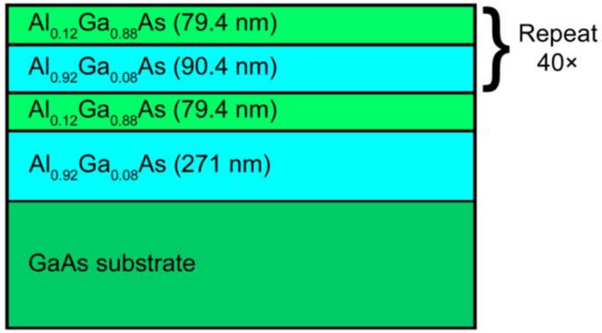


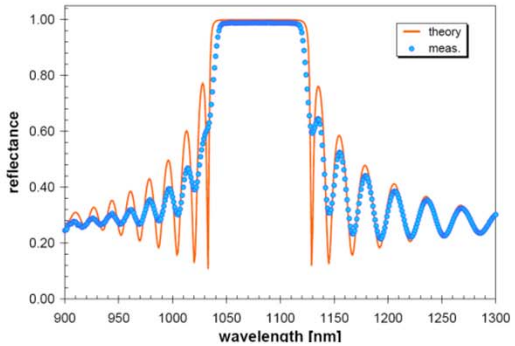
in collaboration with Schwab group, Cornell and ATFilms

Q > 10,000 @ 300 K
R ~ 0.99991

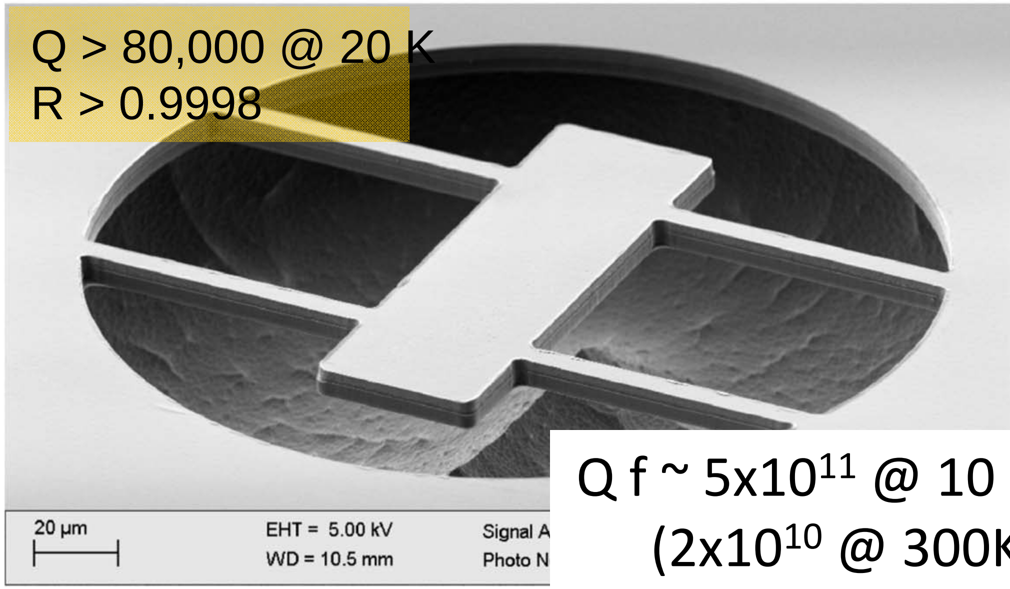
$k/w_m \sim 0.1$

• monocrystalline GaAs/GaAlAs free-standing Bragg mirrors with optimized geometry





Q > 80,000 @ 20 K
R > 0.9998



Q f ~ 5x10^{11} @ 10 K (2x10^{10} @ 300K)

Cole et al., APL 92, 261108 (2008)
Cole et al., Nature Comm. 2, 231 (2011)

Direct observation of a non-Markovian heat bath

universität wien

VCQ Vienna Center for Quantum Science and Technology

- current „**paradigm**“: mechanical Brownian motion is **Markovian**

$$I(\omega) \propto \omega$$

$$S_{xx}^{M}(\omega) = \frac{2k_B T\gamma}{\pi m} \frac{1}{(\omega_m^2 - \omega^2)^2 + \gamma^2\omega^2}$$

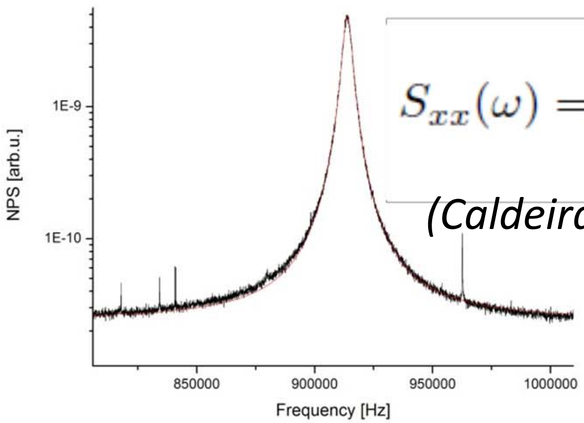
I(ω): spectral density of heat bath (weakly coupled, high T)

- Ludwig, Hammerer, Marquardt, *Phys. Rev. A 82, 012333 (2010):* **non-Markovian environment can strongly influence entanglement** (see also Loss & diVincenzo 2005; Abdi et al. arxiv:1106.0029; Ghobadi et al. arxiv:1106.0788)

- **what is the actual spectral density of the mechanical environment?**
  - Wilson-Rae, *Phys. Rev. B 77, 245418 (2008)*: mode geometry can result in sub-Ohmian spectral densities
  - Can we directly **measure** properties of I(ω)? **Yes!**

$$I(\omega) \propto \omega^k$$

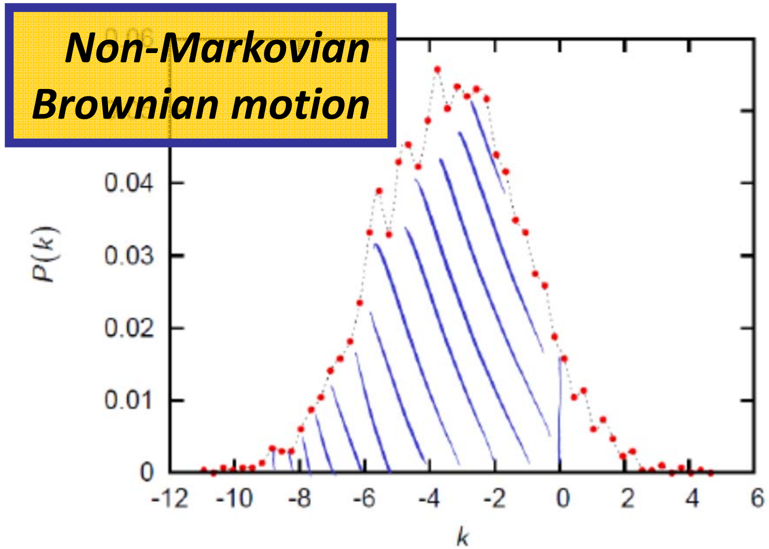
k < 1: sub-Ohm



$$S_{xx}(\omega) = \frac{2k_B T\gamma}{\pi m} \frac{I(\omega)/\omega}{(\omega_m^2 - \omega^2)^2 + \gamma^2\omega^2}$$

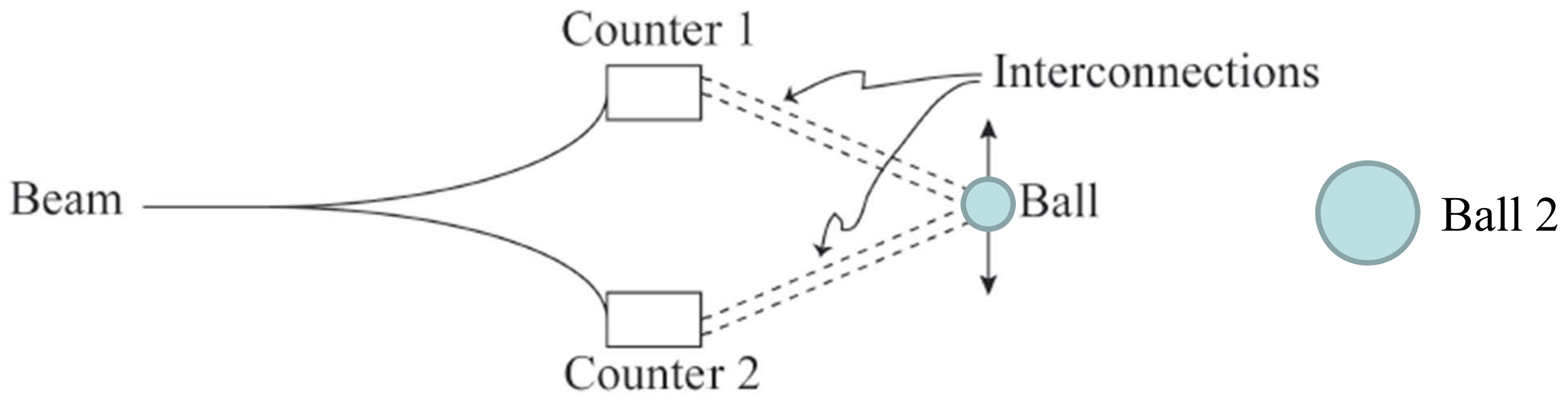
(Caldeira-Leggett)

Non-Markovian Brownian motion



Gröblacher, Prigge, Trubarov, Aspelmeyer, Eisert (in preparation)

An ultimate experiment? Entanglement by gravity…



|Ball1_u> + |Ball1_d> → |Ball1_u>|Ball2_u> + |Ball1_d>|Ball2_d>

FEYNMAN: "Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There is a *bare* possibility (which I shouldn't mention!) that quantum mechanics fails and becomes classical again when the amplification gets far enough, because of some minimum amplification which you can get across such a chain. But aside from that possibility, if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

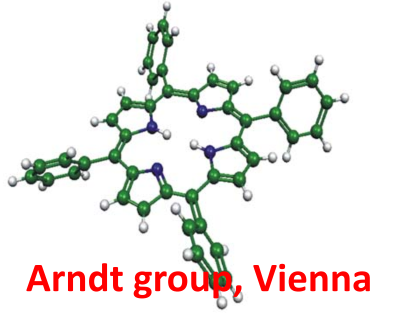
(Chapel Hill Conference 1957)

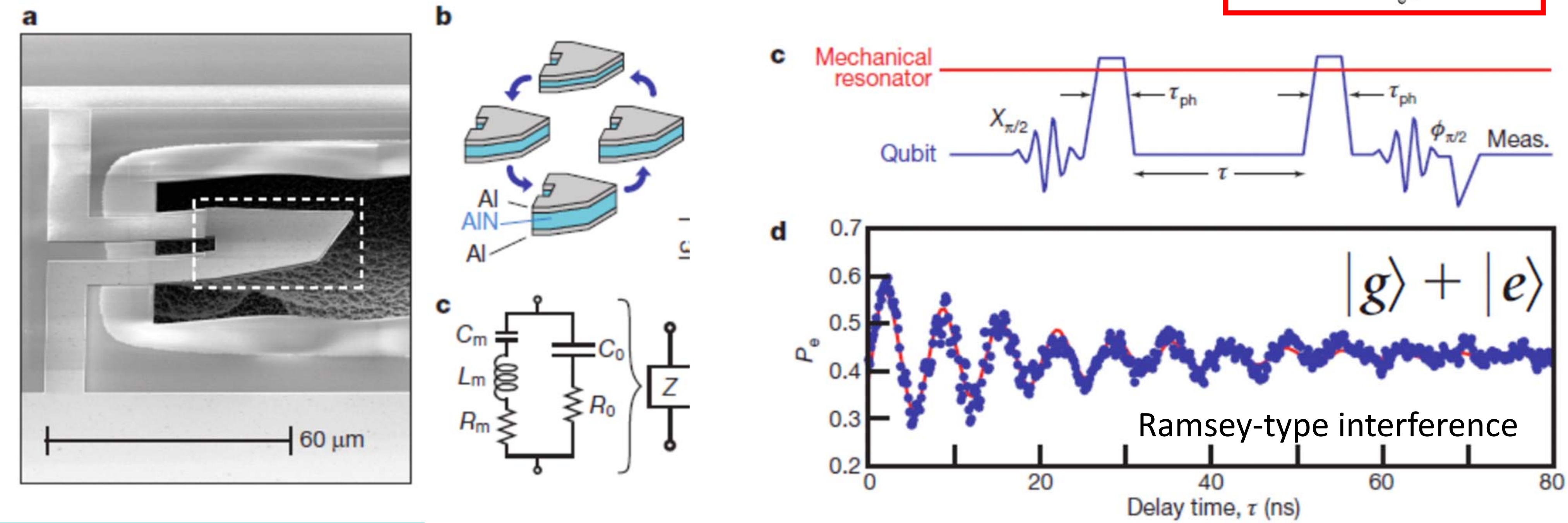
6 GHz thickness oscillation
→ n ~ 0.07 @ 20 mK

ARTICLES

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]





Neutron, 1 „atom"
m ~ 10^{-27} kg = 1 AMU
Δx ~ 1 cm
(~10^{13}x its diameter)

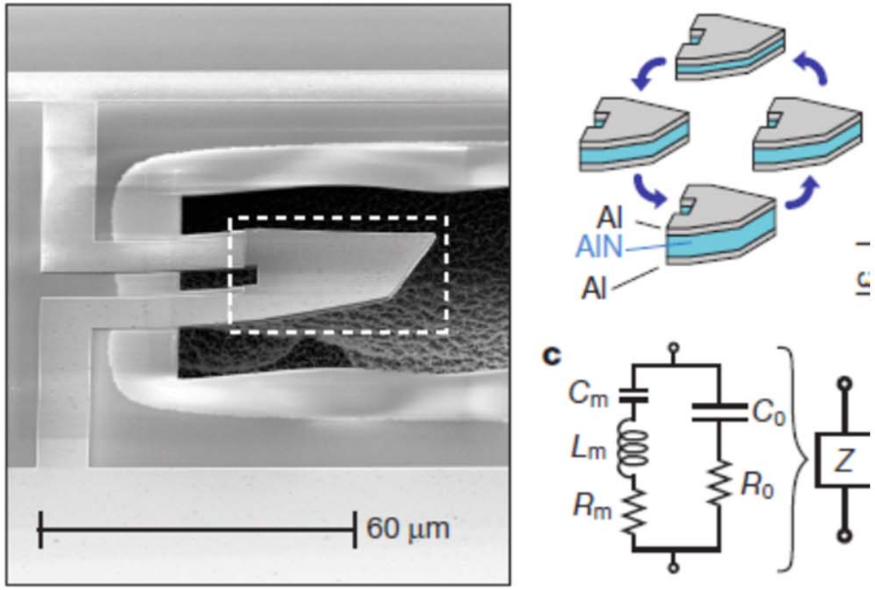
PFNS10: $C_{60}[C_{12}F_{25}]_{10}$,430 atoms
m ~ 10^{-23} kg = 6910 AMU
Δx ~ 100 nm (~50x its diameter)

Micromechanics, 2×10^{13} atoms
m ~ 10^{-12} kg = 7×10^{14} AMU
Δx ~ 10^{-16} m (~10^{-10}x its diameter)

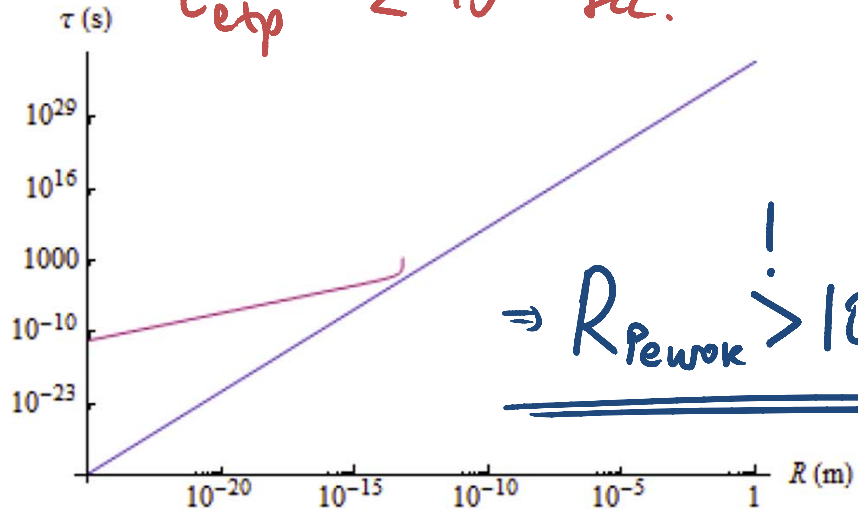
Testing gravitational collapse with „quantum mechanics“

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]

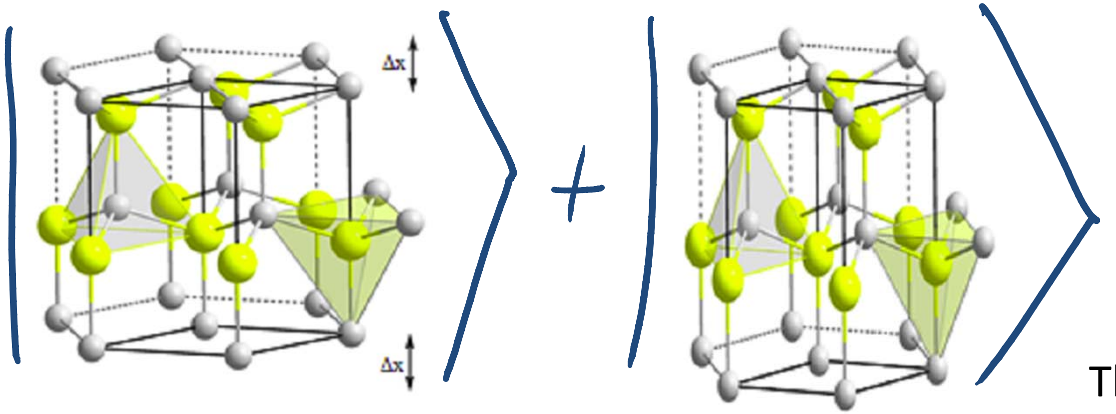


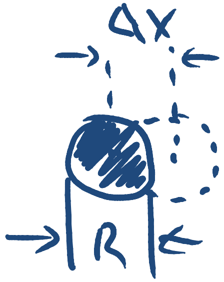
$\tau_{exp} \sim 2 \cdot 10^{-8}$ sec.



$\Rightarrow R_{Penrose} \overset{!}{>} 10^{-21}$ m

Figure 10: Lifetime for $R \gg \Delta x$ and $R \ll \Delta x$





- MASS confined to volume R^3
- SUPERPOSITION ΔX

Thomas Deimel, Philipp Köhler, Igor Pikovski, MA

Towards quantum state preparation of a free particle

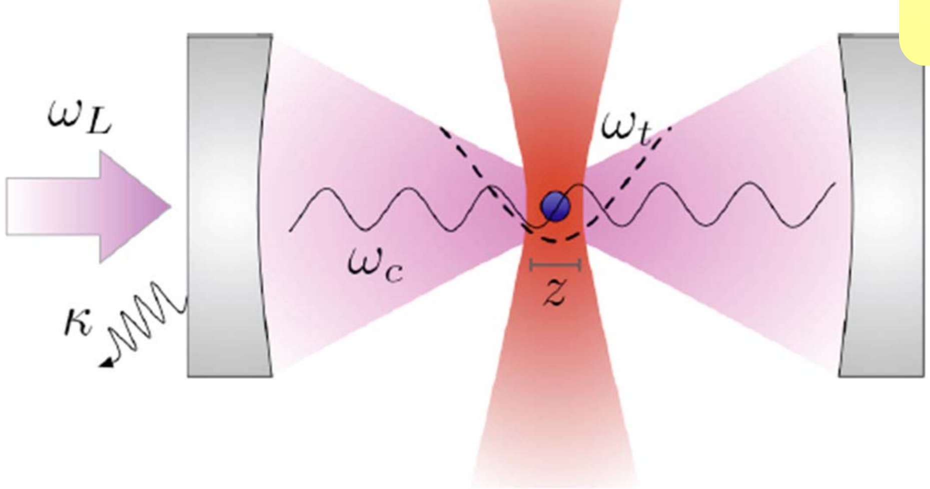
universität wien

VCQ Vienna Center for Quantum Science and Technology

Optically levitated nanospheres

Magnetically levitated spheres

(Romero-Isart et al., 1112.5609
Cirio et al., 1112.5208)



Chang et al., quant-ph 0909.1548 (2009), PNAS 2010
Romero-Isart et al., quant-ph 0909.1469 (2009), NJP 2010
P. F. Barker et al., PRA 2010
early work: Hechenblaikner, Ritsch et al., PRA 58, 3030 (1998)
Vuletic & Chu, PRL 84, 3787 (2000)

→ **Harmonic oscillator in optical potential**
(negligible support loss, high Q)

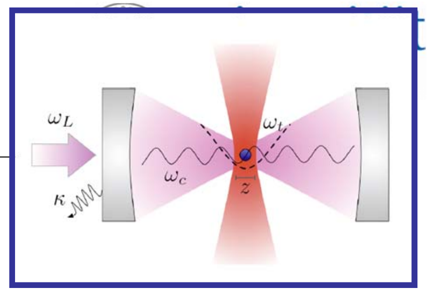
→ **Quantum control via cavity optomechanics**
(laser cooling, state transfer, etc.)

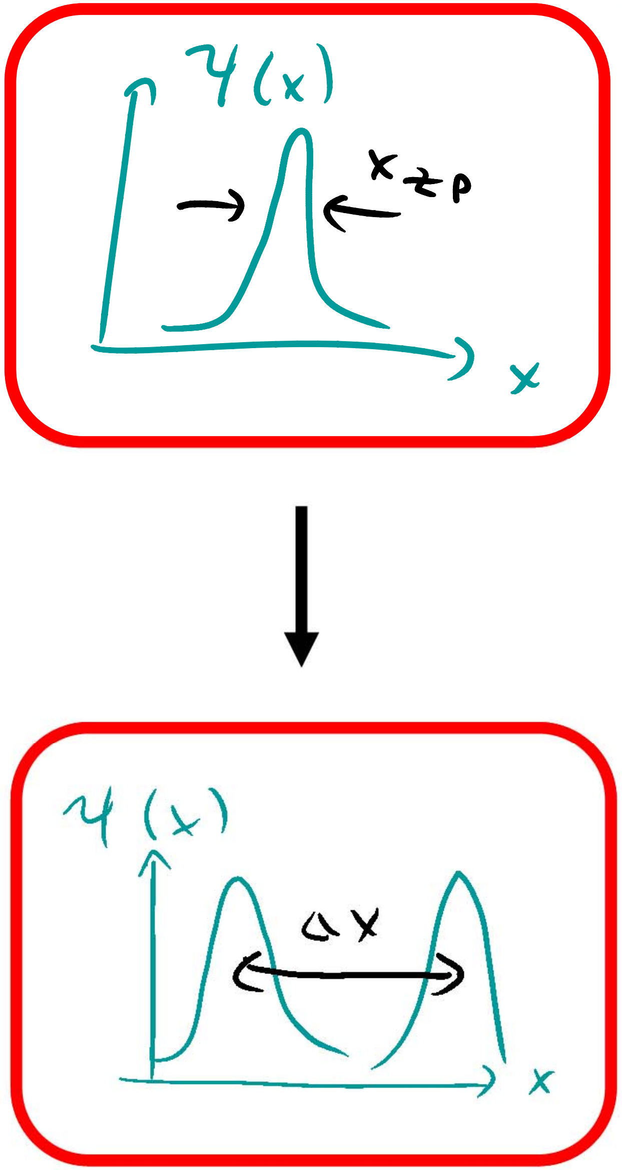
Generation of quantum superposition states

- single-photon quantum state transfer
- quantum state teleportation
- …
- ***free fall . . .***

- Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)
- Khalili, Danilishin, Miao, Müller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

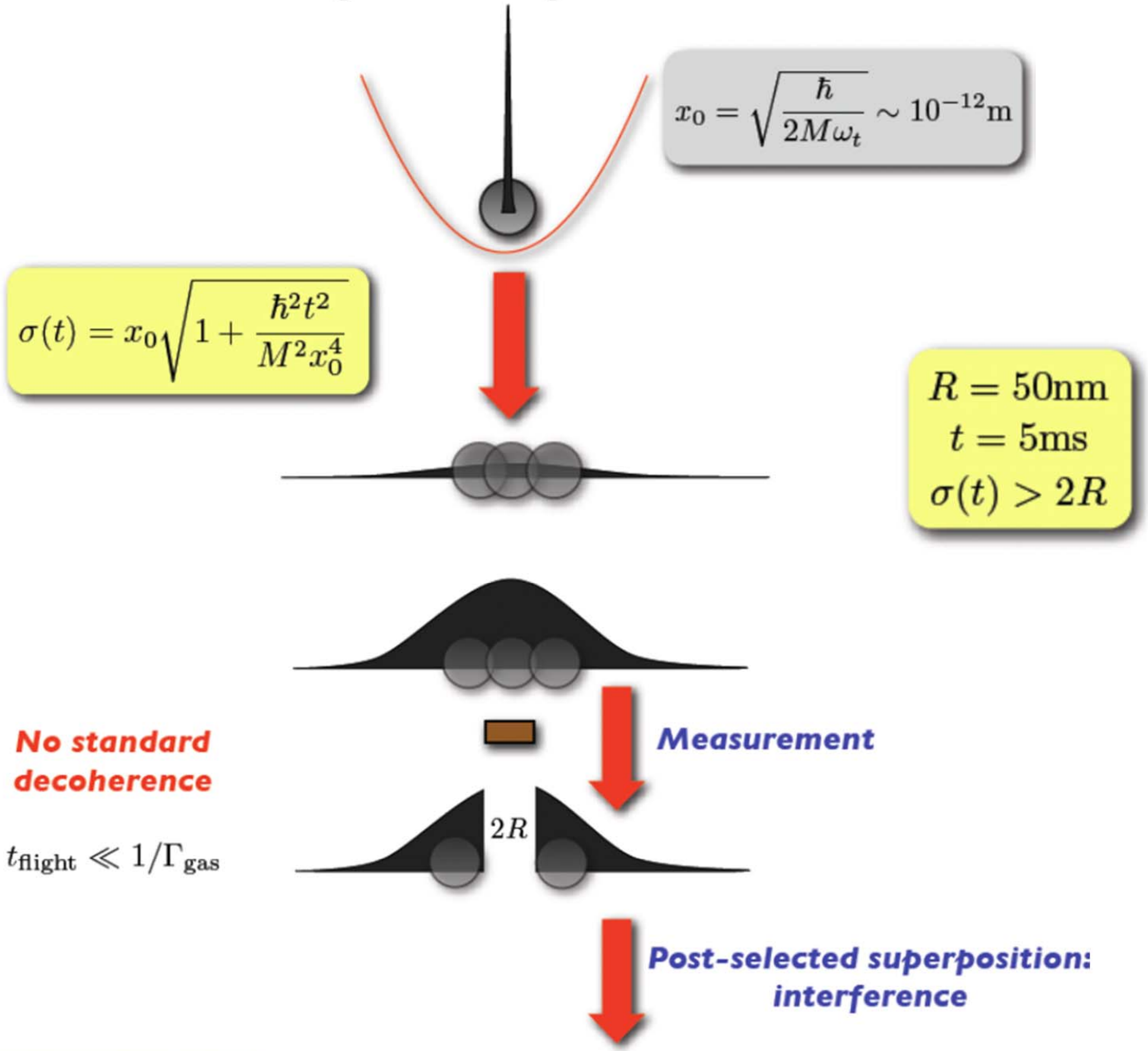
Superposition of macroscopic distinct states via free fall?





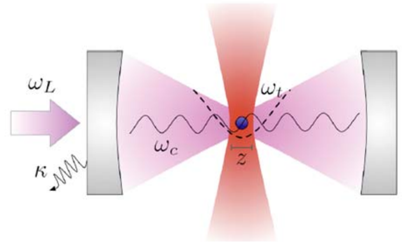
Proposal

- Ground state cooling + time-of-flight

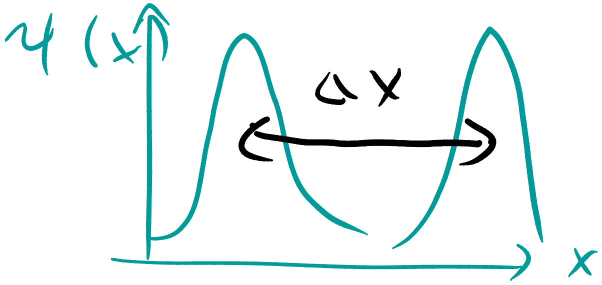


O. Romero-Isart et al., PRL 107, 020405 (2011)

One possible application: test of alternative decoherence models



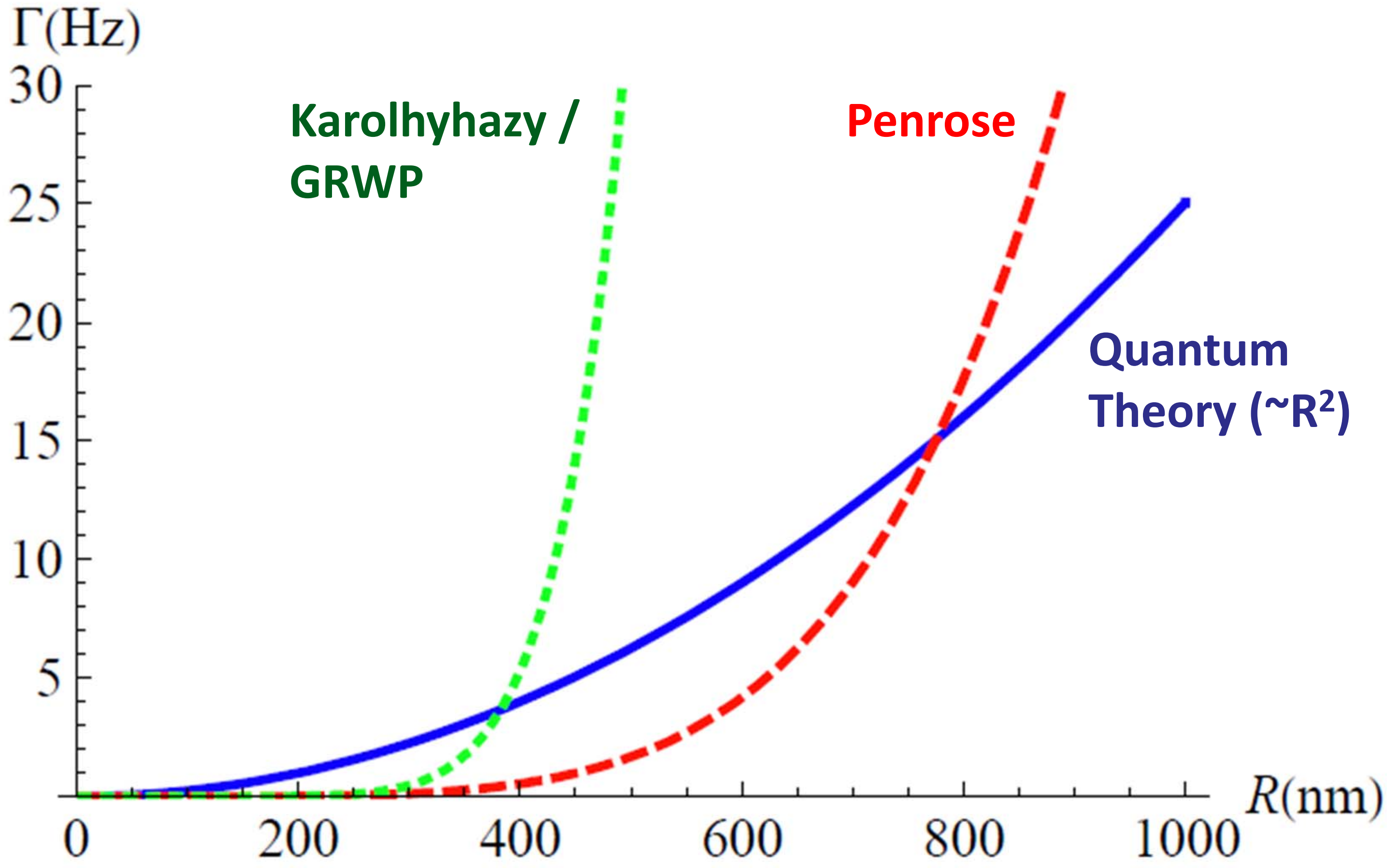
O. Romero-Isart et al., PRL 107, 020405 (2011)



$\Delta x \sim R$

Background gas
$p \sim 10^{-13}$ mbar

(here: no blackbody radiation!)

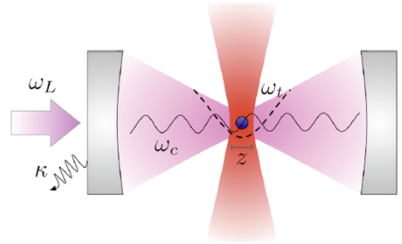


Karolyhazy (1960s), e.g. Nuovo Cimento 42, 390 (1966)
Diosi (1980s), e.g. J. Phys. A: Math. Gen. 21, 2885 (1988)
Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)

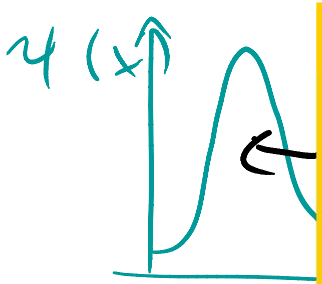
$P \sim 10^{-13}$ mbar, $T \sim 4$K

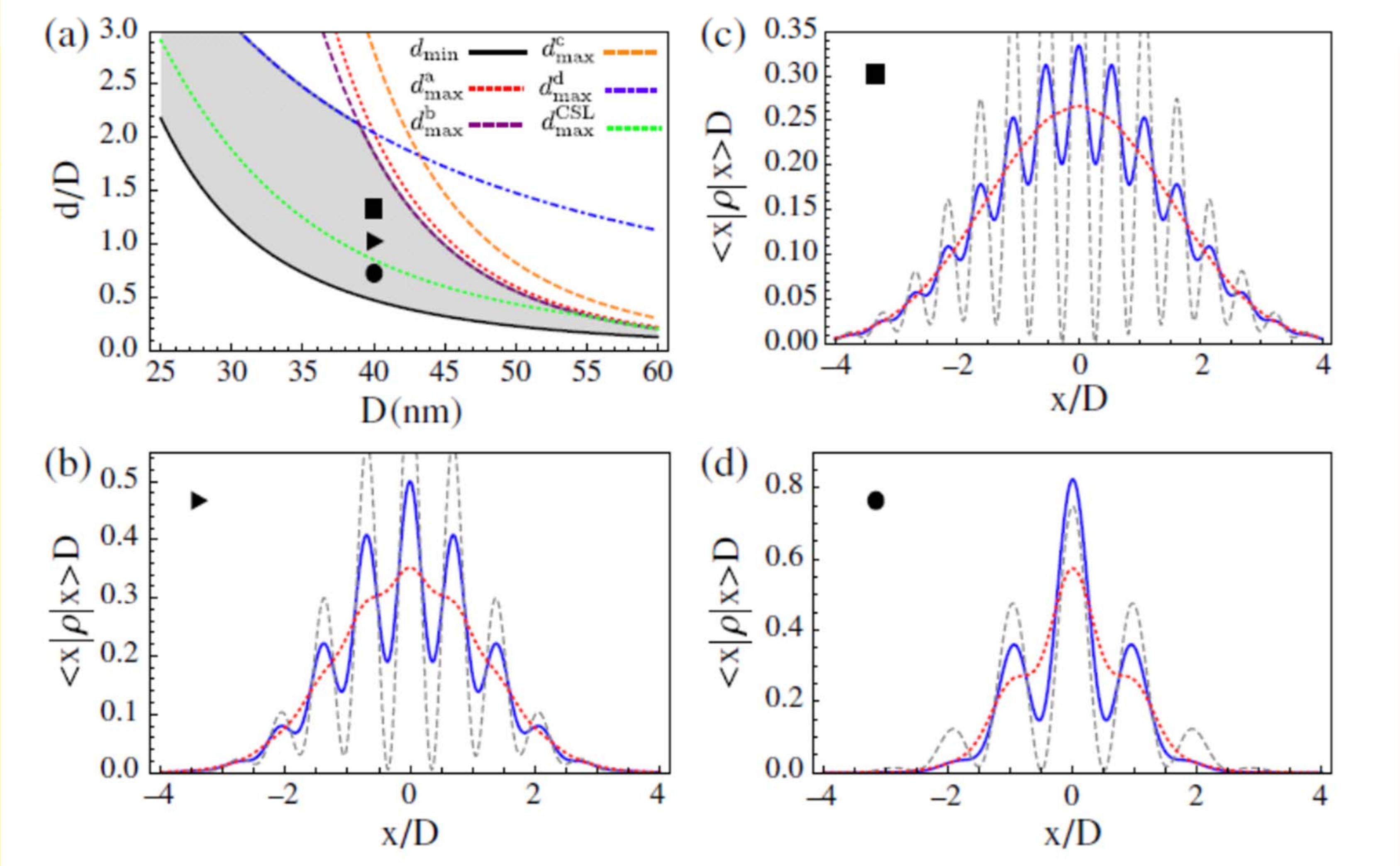
In collaboration with O. Romero-Isart, A. Pflanzer, I. Cirac
see also Romero-Isart, Phys. Rev. A 84, 052121 (2011)

One possible application: test of alternative decoherence models



O. Romero-Isart et al., PRL 107, 020405 (2011)





$\Delta x \sim R$

Backgro

$p \sim 10^{-13}$

(here: n

blackbo

radiatio

n)

Karolyhazy (1960s), e.g. Nuovo Cimento 42, 390 (1966)
Diosi (1980s), e.g. J. Phys. A: Math. Gen. 21, 2885 (1988)
Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)

$P \sim 10^{-13}$ mbar, $T \sim 4$K

In collaboration with O. Romero-Isart, A. Pflanzer, I. Cirac
see also Romero-Isart, Phys. Rev. A 84, 052121 (2011)

Classical gravity: localization of macro-objects

How to incorporate a Newtonian gravity field into quantum framework?

e.g. add **gravitational self-interaction** (Diosi, Penrose)

$$i\hbar\partial_t\Psi(t,\vec{x}) = \left(-\frac{\hbar^2}{2m}\Delta - Gm^2\int\frac{|\Psi(t,\vec{y})|^2}{\|\vec{x}-\vec{y}\|}\,d^3y\right)\Psi(t,\vec{x})$$

Schrödinger-Newton equation (Diosi 1984)

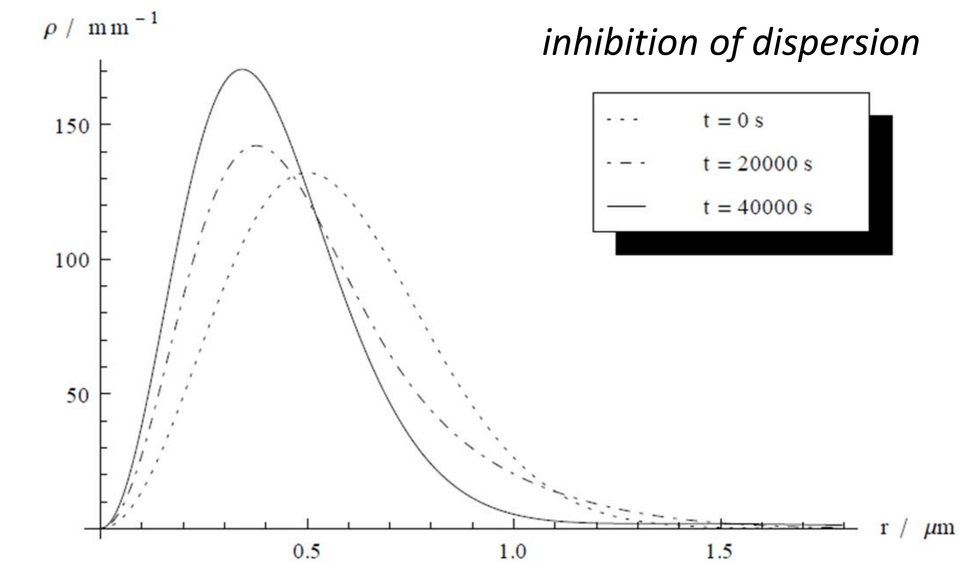


Figure 4: Collapsing wave packet for $m = 7\times10^9$ u. Plotted is the radial probability density $\rho = 4\pi r^2\,|\psi|^2$ against r at three different times.

Giulini & Großardt, arxiv 1105.1921 [gr-qc]
See also Yanbei Chen et al., arxiv 2012

→ **gravitational inhibition of dispersion**
→ gravitationally bound states
→ modified ground state (Gross-Pitaevskii)

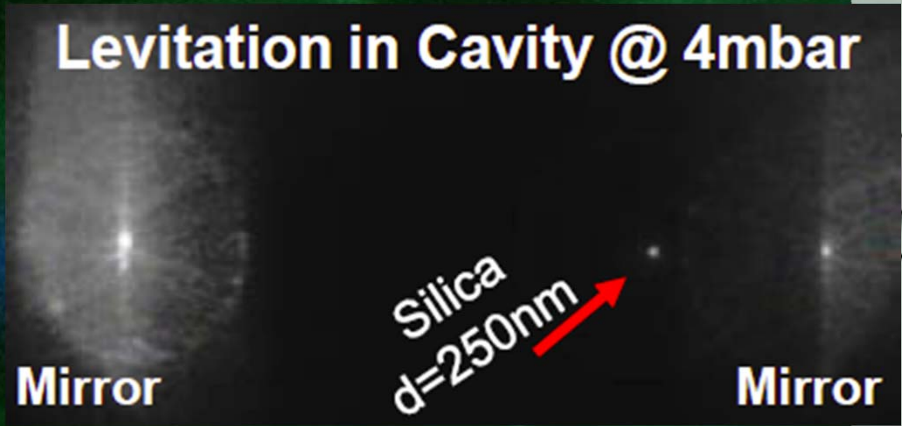
m = 10^{10} amu, σ(0) = 500 nm
→ collapse time t~30,000 sec

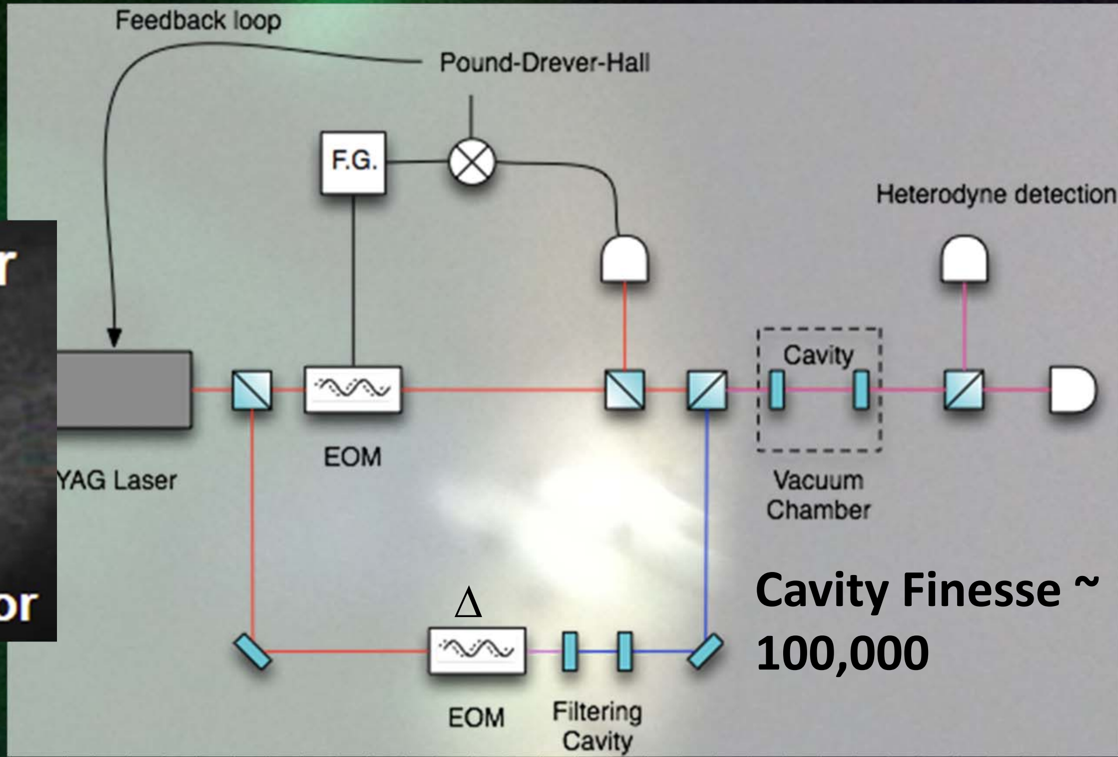
m = **10^{12} amu**, σ(0) = **500 fm**
→ collapse time t~**3×10^{-6} sec**

→ R ~ 400 um , $\omega_m \sim 10^6$ Hz !

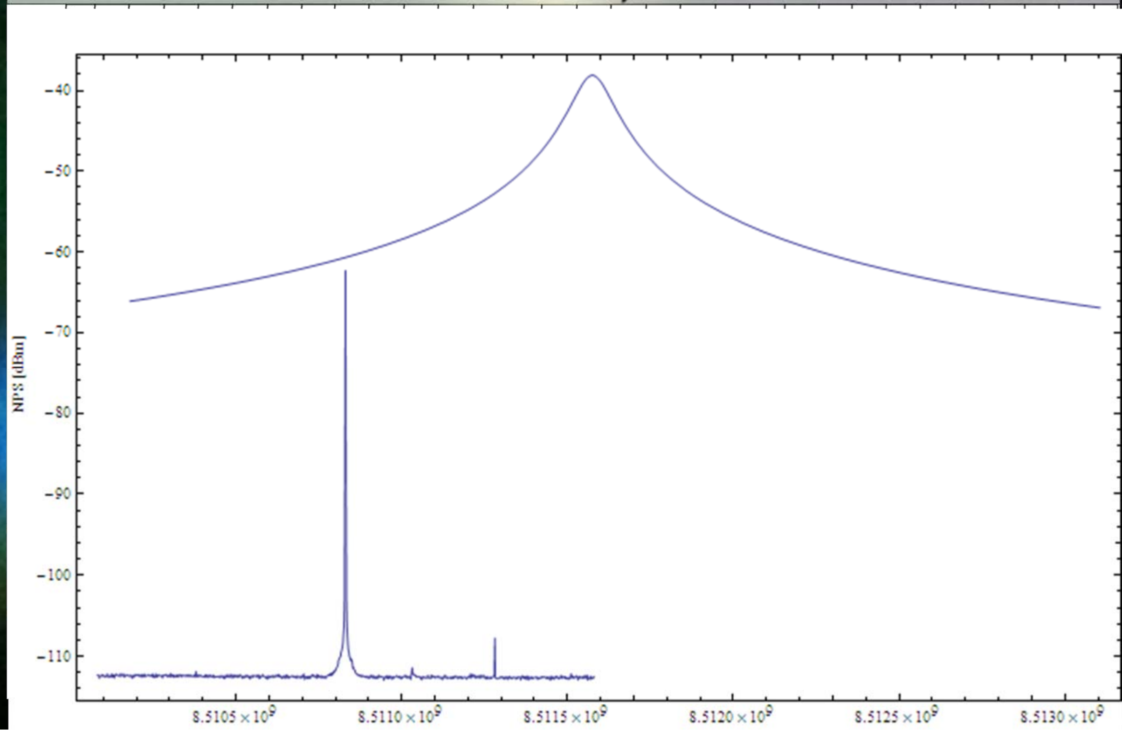
Optically trapped nanospheres as mechanical resonators

Ashkin since 1967
Raizen group, Science 2010
Novotny 2012



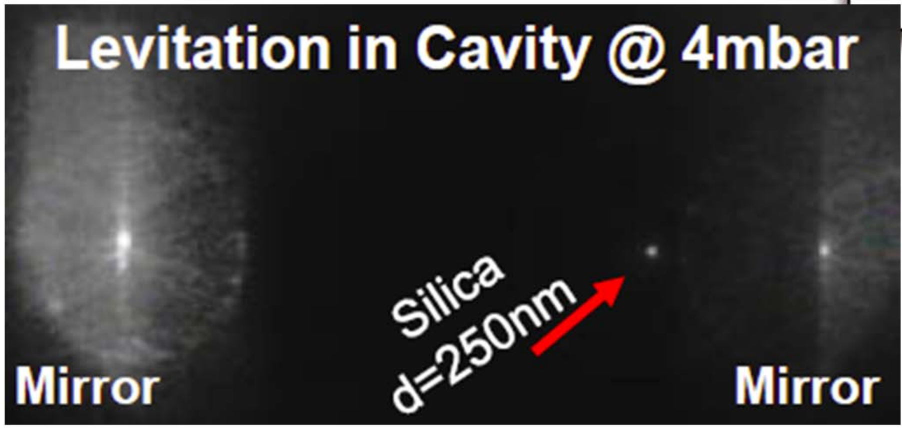


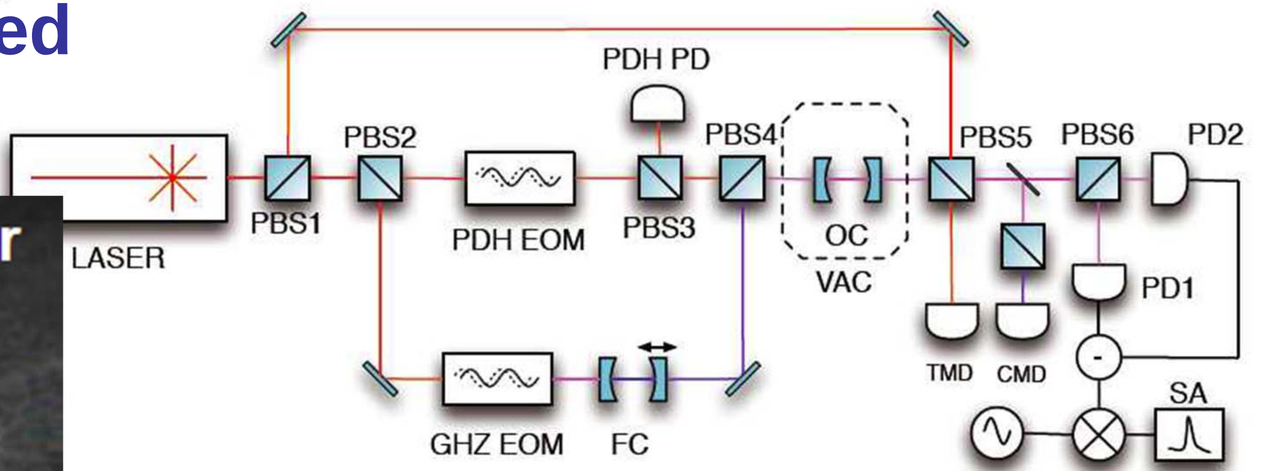
Cavity Finesse ~ 100,000

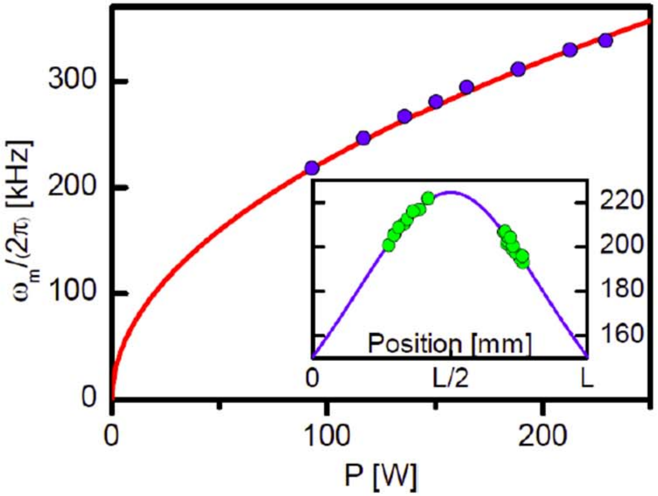


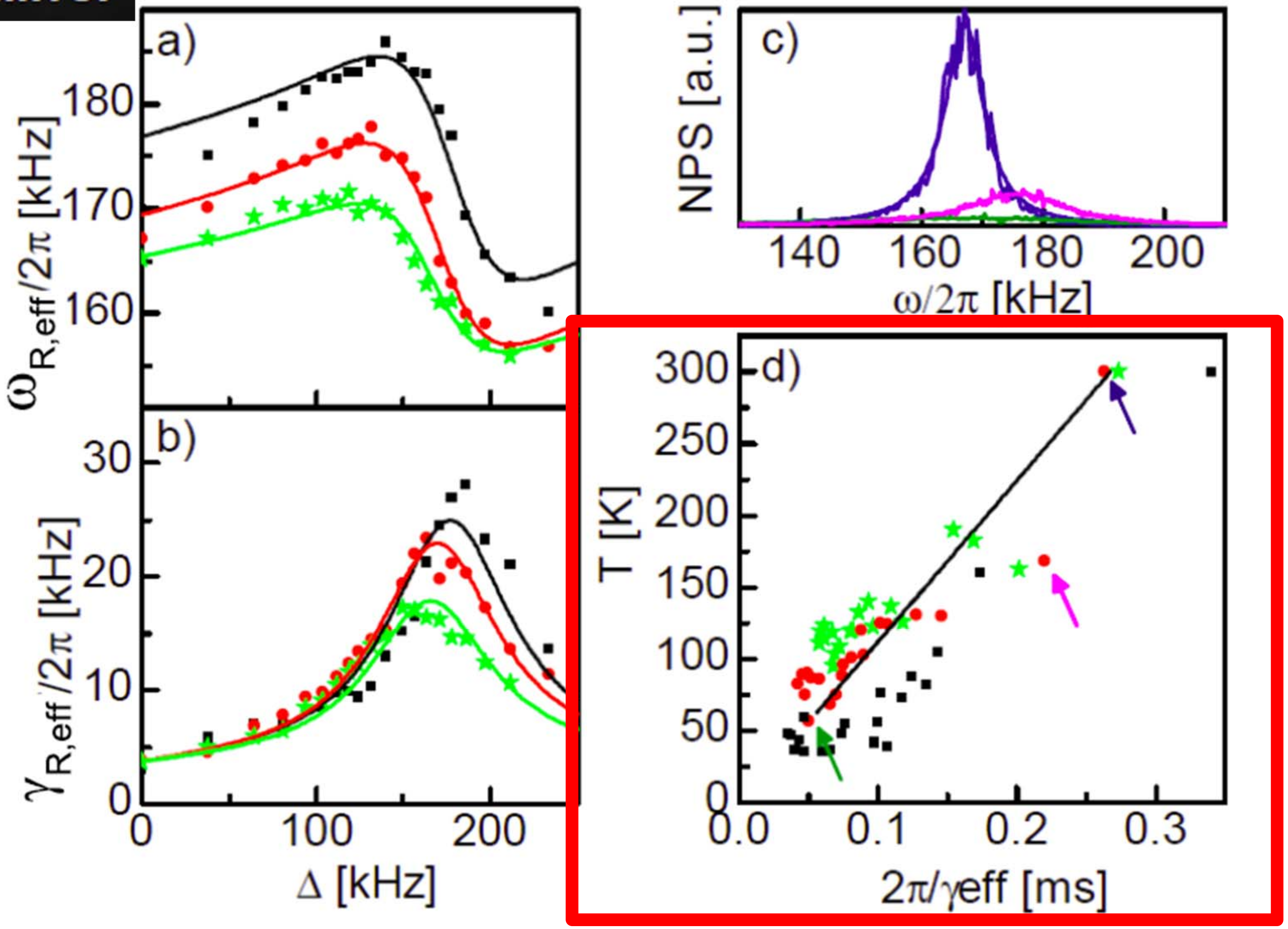
Optical trapping inside a cavity… (R~20nm – 2µm)
Kiesel et al., work in progress

Cavity cooling of a trapped nanosphere



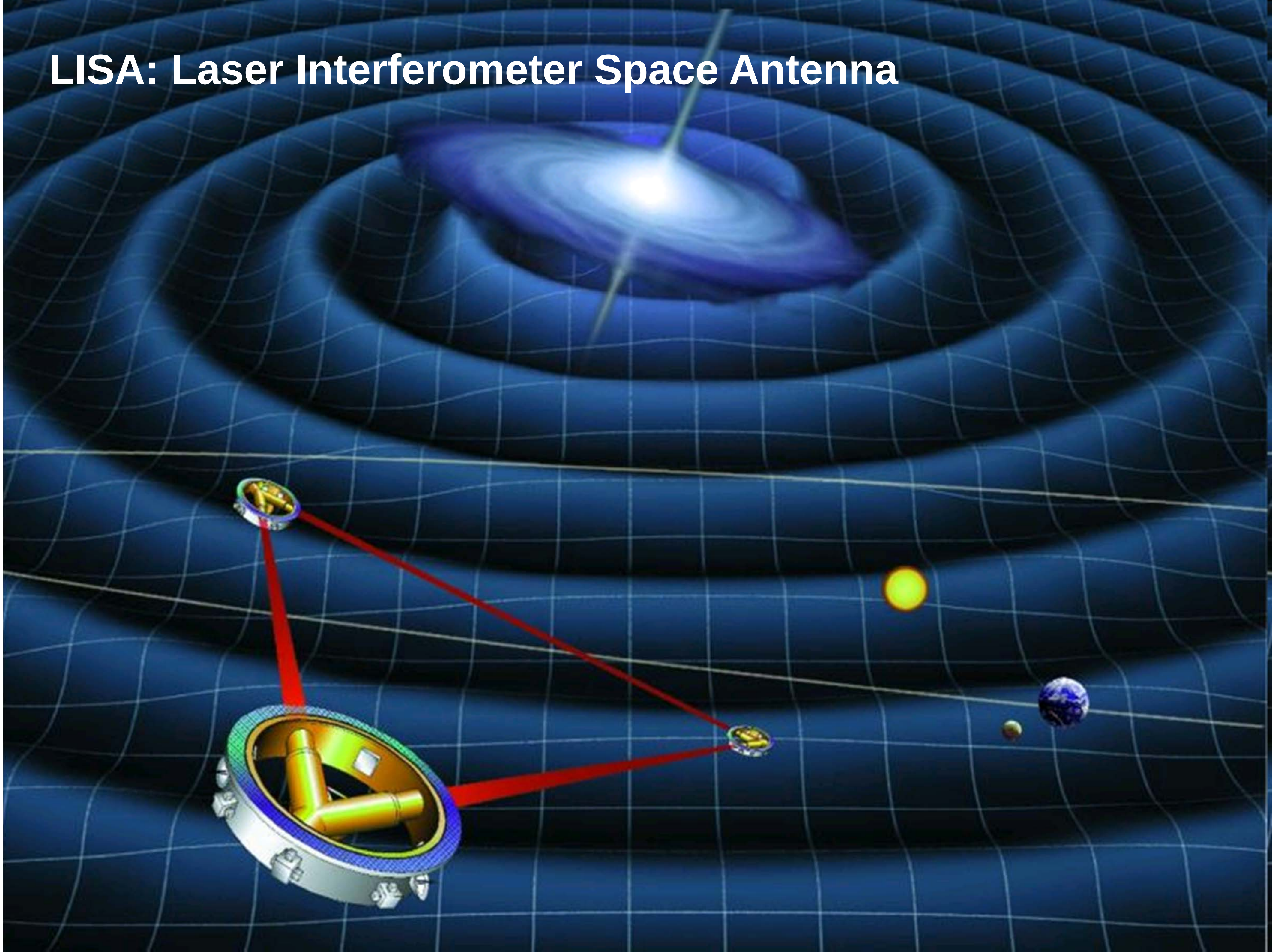






Nikolai Kiesel, Florian Blaser, Uros Delic, David Grass, Rainer Kaltenbaek, Markus Aspelmeyer, arXiv:1304.6679 (2013)

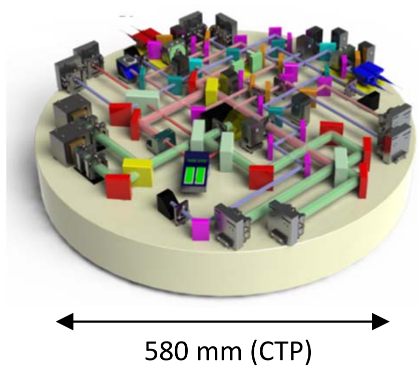
LISA: Laser Interferometer Space Antenna

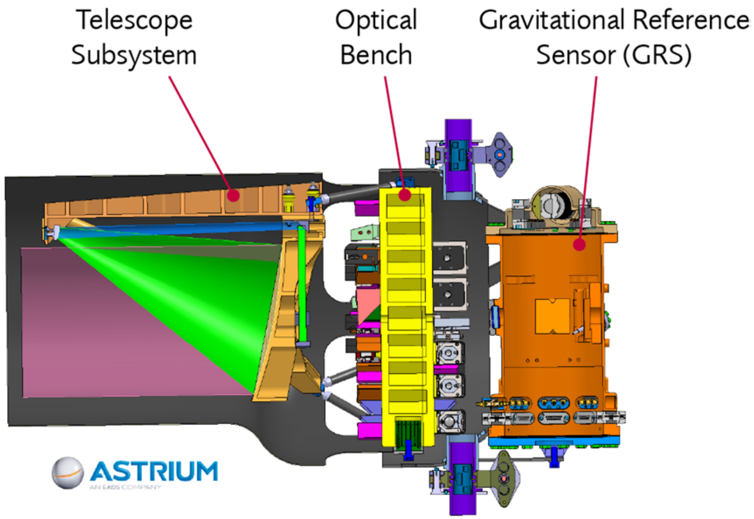


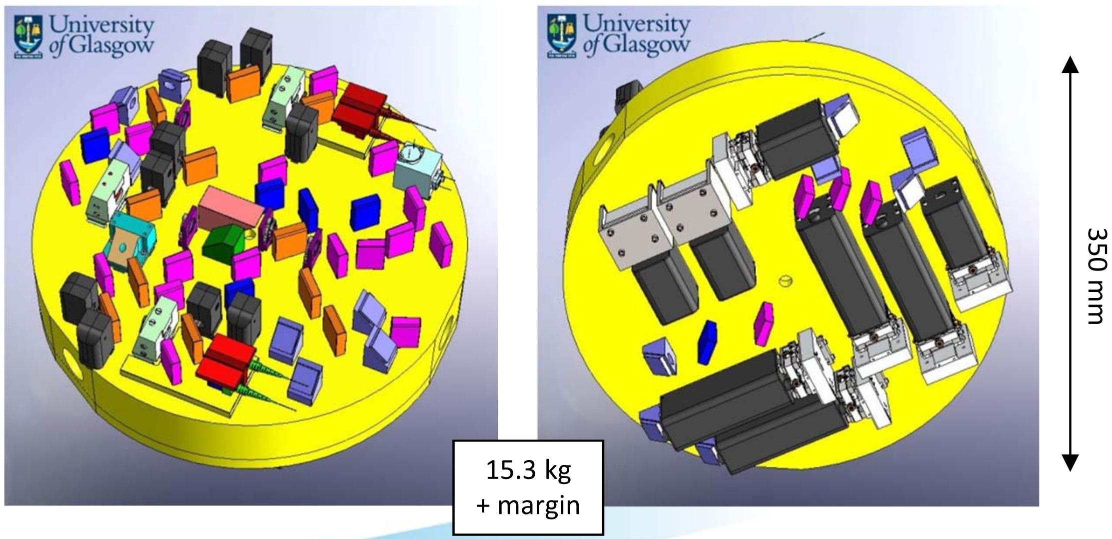
Payload Architecture

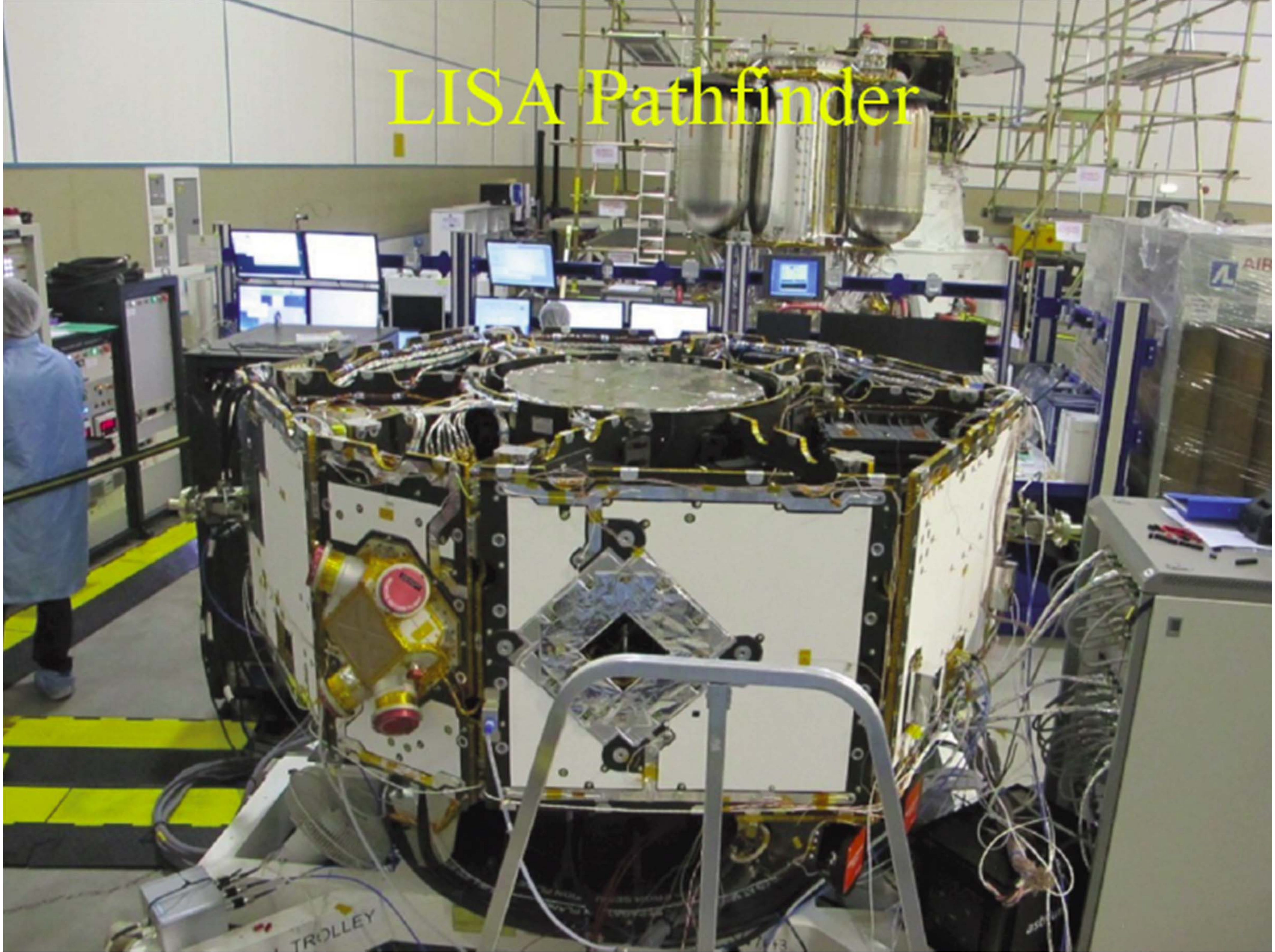
Optical Bench

- As in LMF, OB diameter drives payload and thus s/c *height*
  - Sizing coherent with reduced telescope dimensions is enabled by
    - Removal of PAAM, PAAM Metrology & Optical Truss
    - **Double-sided** OB
  - Basic feasibility demonstrated by very detailed design, employing maximum heritage from LTP and LISA OB CTP



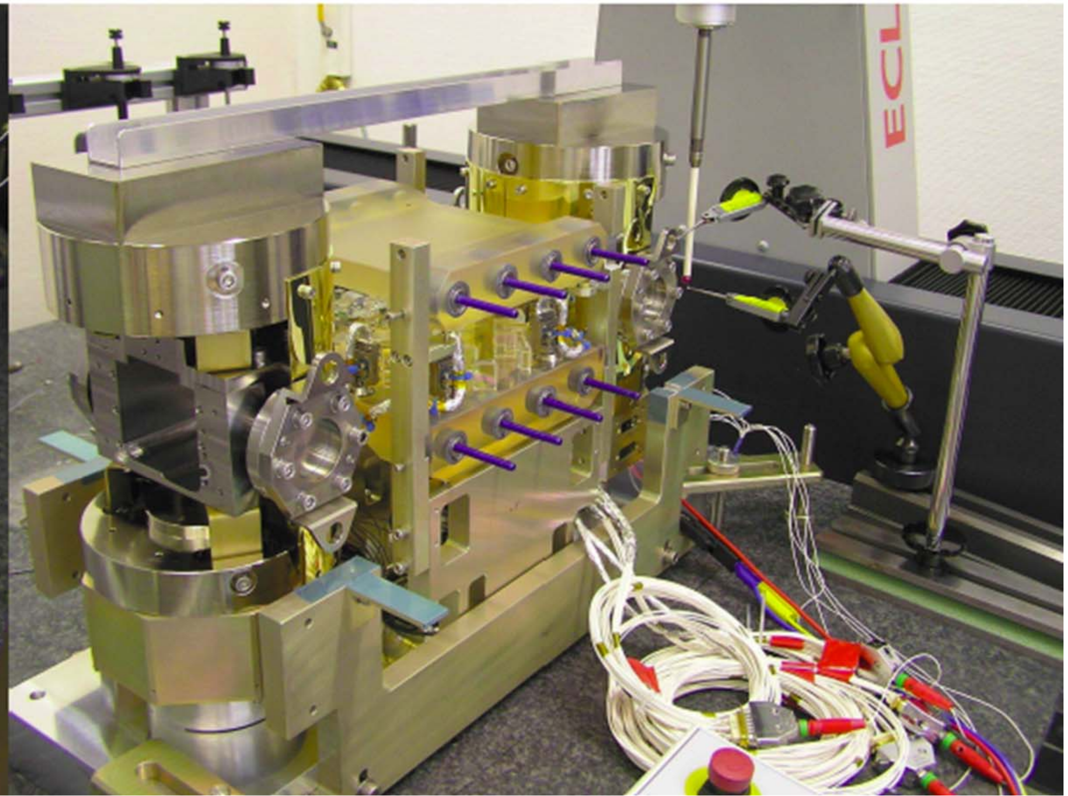





LISA Pathfinder
TROLLEY

The Optical Bench and Structure

- Thermo-optical qualification model of optical bench and structure
- Successfully tested end-to-end for optical performance (see F. Guzman talk)
- Strong candidate for flight

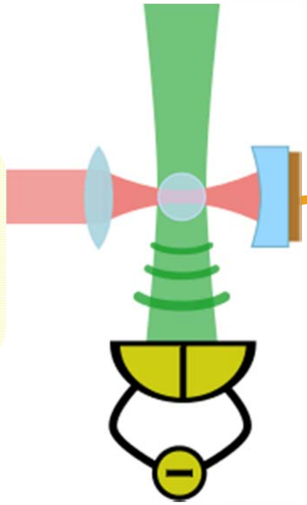
MAQRO: Macroscopic Quantum Resonators for Space

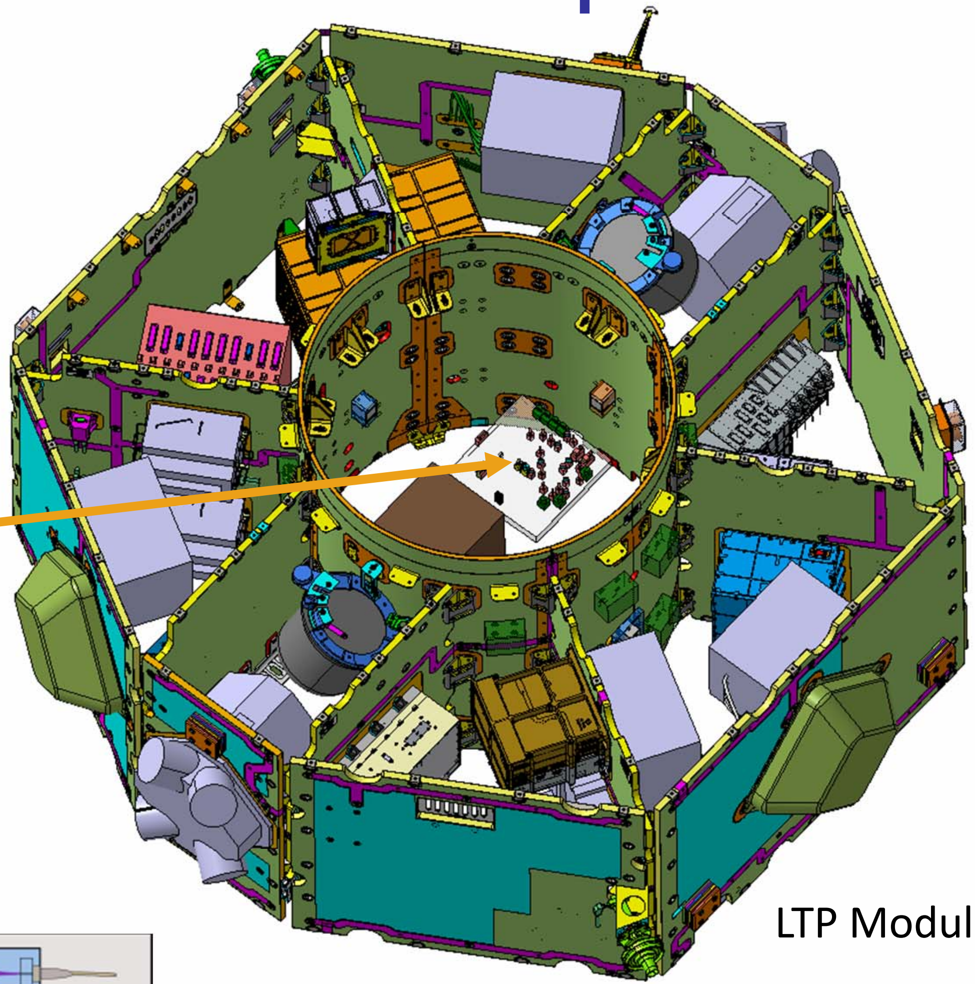
A possible space experiment under extreme conditions (vacuum, temperature):

T_{env} ~ 10 K, background pressure << 10^{-15}mbar, micro-gravity environment

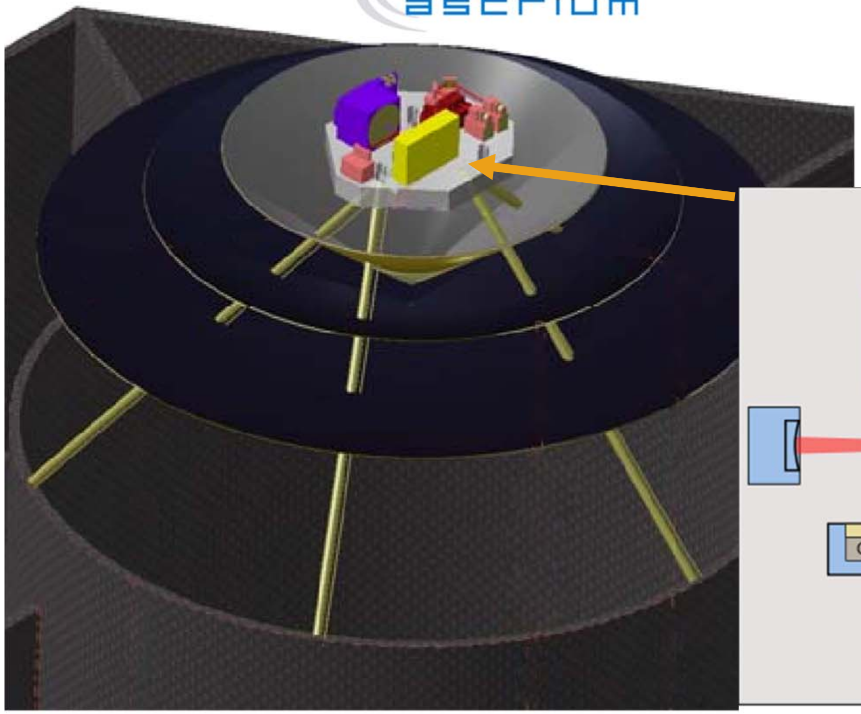
→ Long fall times

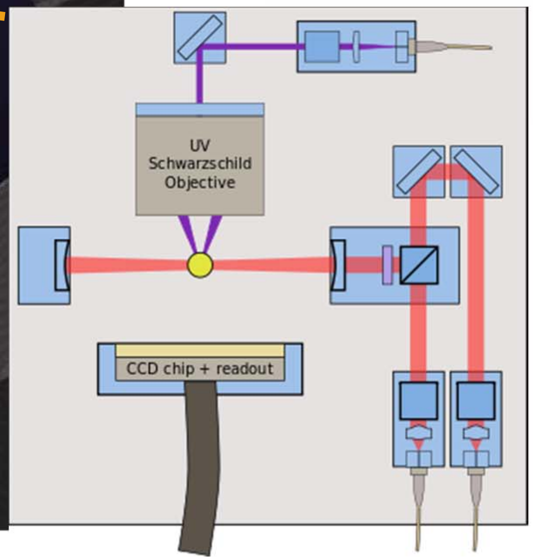
R. Kaltenbaek, Schwab, Aspelmeyer et al., arXiv:1201.4756
in collaboration with EADS ASTRIUM Friedrichshafen





LTP Module





DECIDE

- **macroscopic quantum states** („Schrödinger Cat")
- test quantum theory against macrorealistic models

nature physics

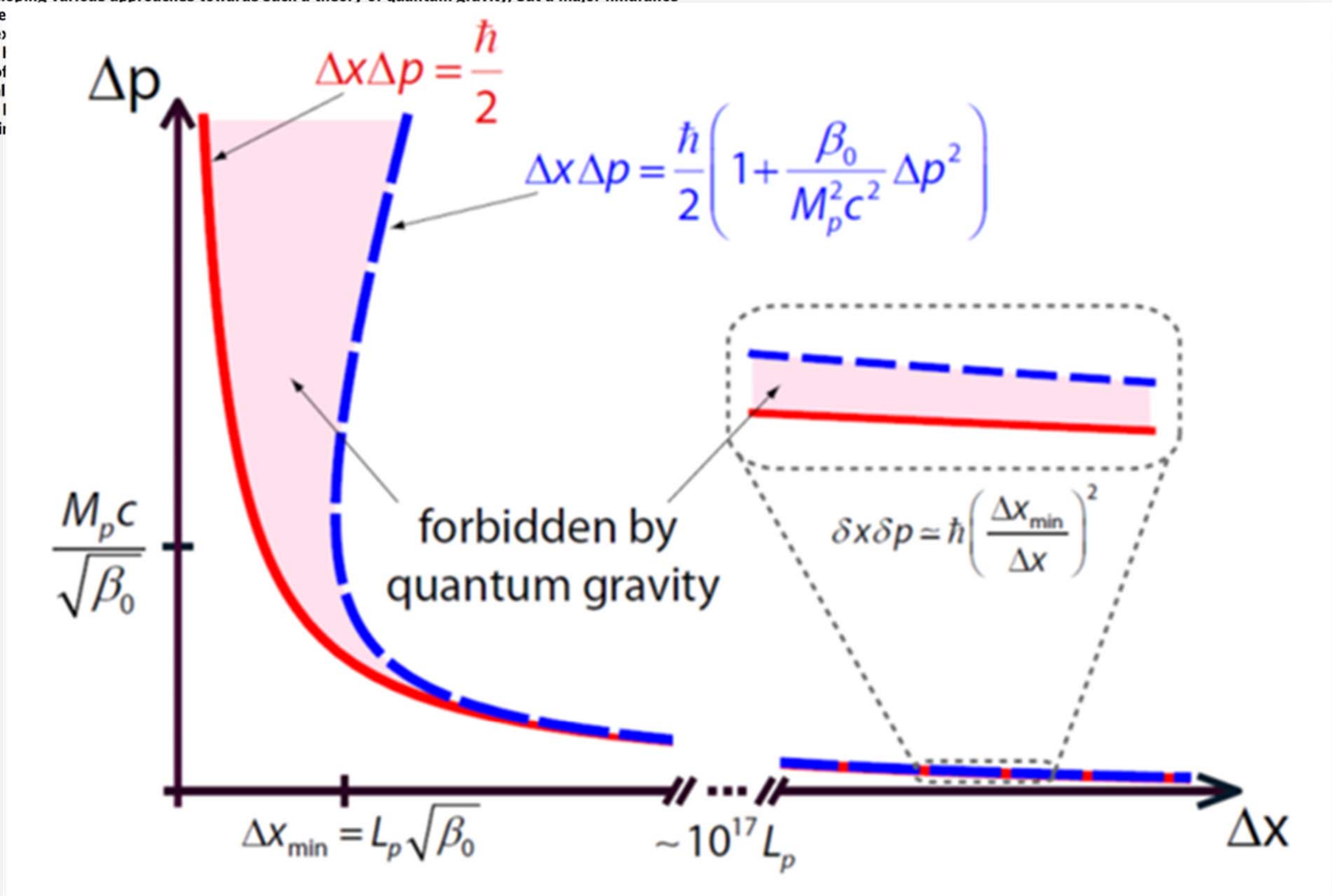
ARTICLES

PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262

Probing Planck-scale physics with quantum optics

Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]

One of the main challenges in physics today is to merge quantum theory and the theory of general relativity into a unified framework. Researchers are developing various approaches towards such a theory of quantum gravity, but a major hindrance is the lack of experimental evide
experimental implications: the ex
Heisenberg uncertainty relation. I
canonical commutation relation of
Our protocol uses quantum optical
commutation relation even at the I
feasible route for table-top experi



Measuring the canonical commutator of a massive system

Idea: **Closed loop** in (mechanical) phase space generates an (optical) **phase** related to the (mechanical) **commutator**

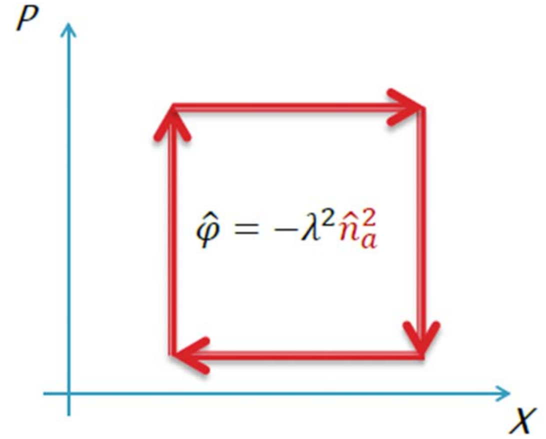
$$\hat{\xi} = e^{i\lambda\hat{n}_a\hat{P}}\, e^{-i\lambda\hat{n}_a\hat{X}}\, e^{-i\lambda\hat{n}_a\hat{P}}\, e^{i\lambda\hat{n}_a\hat{X}}$$
$$= e^{-\lambda^2\hat{n}_a^2[\hat{X},\hat{P}]}$$

By measuring the ancilla one can obtain a measure of the commutator.

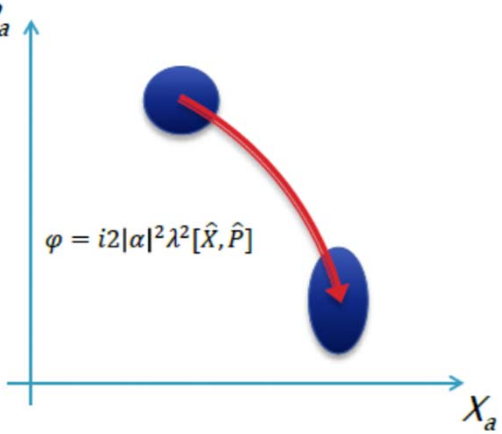
For an initial coherent state:

$$\langle\hat{a}_a\rangle = \langle\alpha|\hat{\xi}^+\hat{a}_a\hat{\xi}|\alpha\rangle$$
$$= \alpha e^{-\lambda^2[\hat{X},\hat{P}]}e^{-|\alpha|^2\left(1-e^{-2\lambda^2[\hat{X},\hat{P}]}\right)}$$
$$\approx \alpha e^{-2|\alpha|^2\lambda^2[\hat{X},\hat{P}]} \qquad (\text{for } \lambda^2[\hat{X},\hat{P}] \ll 1)$$

mechanics



optical ancilla



Phase shift scales with the intensity of the input state.
⇒ Can measure the commutator even for small coupling λ!

Without ancilla: see e.g. ion experiments
Leibfried et al., Nature 422, 427 (2003)

Pikovski et al. Nature Physics (2012); doi:10.1038/nphys2262

Towards tests of quantum gravity predictions?

Different proposals in the literature

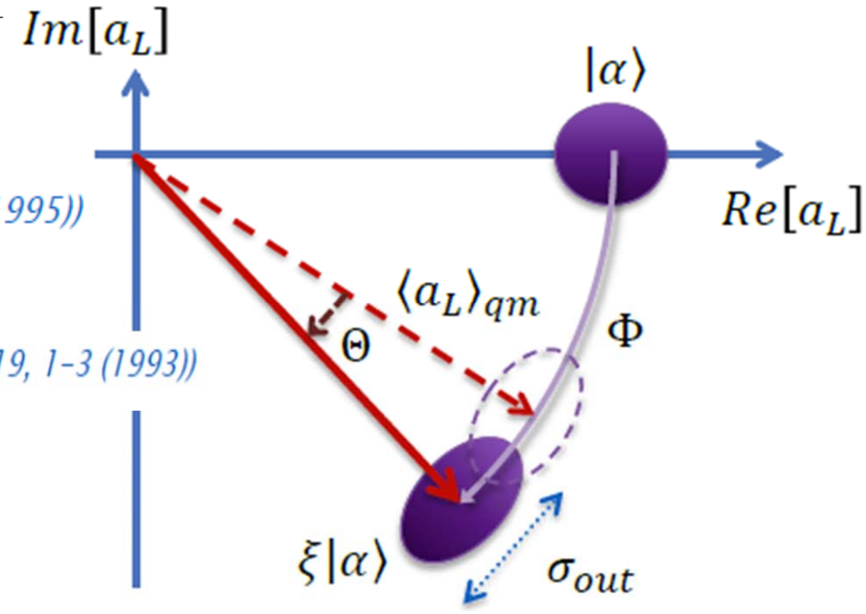
$$[x,p]_{\beta_0} = i\hbar\left(1+\beta_0\left(\frac{p}{M_{Pl}\,c}\right)^2\right)$$

(Kempf et al, PRD, 52, 2 (1995))

$$[x,p]_{\mu_0} = i\hbar\sqrt{1+2\mu_0\frac{(p/c)^2+m^2}{M_{Pl}^2}}$$

(Maggiore, Physics Letters B, 319, 1-3 (1993))

$$[x,p]_{\gamma_0} = i\hbar\left(1-\gamma_0\frac{p}{M_{Pl}\,c}+\gamma_0^2\left(\frac{p}{M_{Pl}\,c}\right)^2\right)$$



$$\langle a_L\rangle \simeq \langle a_L\rangle_{qm}\; e^{-i\Theta}$$

Provides a feasible route to put **experimental upper bounds on possible modifications**

	$[x,p]$	label	Θ
1)	0	classical	-
2)	$i\hbar$	quantum	0
3)	Eq. (2)	β-mod.	$\beta_0\frac{4\hbar\omega_m m}{3(M_{Pl}c)^2}N_P^3\lambda^4\,e^{-i6\lambda^2}$
4)	Eq. (3)	μ-mod.	$\mu_0\frac{2m^2}{M_{Pl}^2}N_P\lambda^2 e^{-i2\lambda^2}$
5)	Eq. (4)	γ-mod.	$\gamma_0\frac{3\sqrt{\hbar m\omega_m}}{2M_{Pl}c}N_P^2\lambda^3\,e^{-i4\lambda^2}$

Current state of the art:

system/ experiment	$\beta_{0,max}$	$\gamma_{0,max}$
Position measurements	10^{24}	10^{24}
Lamb shift in Hydrogen	10^{36}	10^{10}
Electron tunneling	10^{33}	10^{11}

Pikovski et al. Nature Physics (2012); doi:10.1038/nphys2262

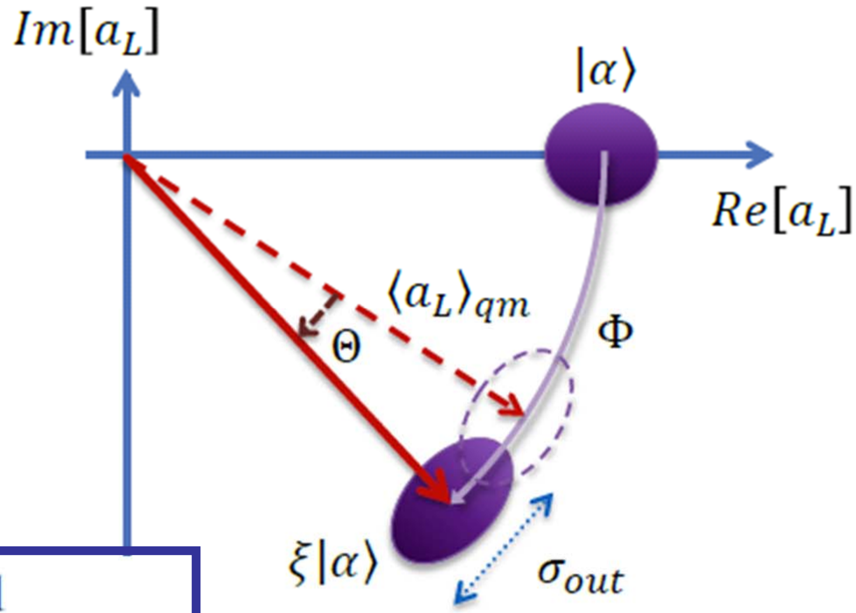
Towards tests of quantum gravity predictions?

Current state of the art:

system/ experiment	$\beta_{0,max}$	$\gamma_{0,max}$
Position measurements	10^{24}	10^{24}
Lamb shift in Hydrogen	10^{36}	10^{10}
Electron tunneling	10^{33}	10^{11}

Estimates for optomechanics scheme:

$[X_m, P_m]$ $\lvert\Theta\rvert$	Eq. 2 $\mu_0 \frac{32\hbar\mathcal{F}^2 m N_P}{M_P^2\lambda_L^2\omega_m}$	Eq. 3 $\gamma_0 \frac{96\hbar^2\mathcal{F}^3 N_P^2}{M_P c\lambda_L^3 m\omega_m}$	Eq. 1 $\beta_0 \frac{1024\hbar^3\mathcal{F}^4 N_P^3}{3M_P^2 c^2\lambda_L^4 m\omega_m}$
$\mathcal{F}$	10^5	2×10^5	5×10^5
m	10^{-11} kg	10^{-11} kg	10^{-6} kg
$\omega_m/2\pi$	10^5 Hz	10^5 Hz	10^5 Hz
λ_L	1064 nm	1064 nm	532 nm
N_p	10^8	5×10^{10}	10^{14}
N_r	1	10^2	10^4
$\delta\langle\Phi\rangle$	10^{-4}	5×10^{-7}	10^{-8}



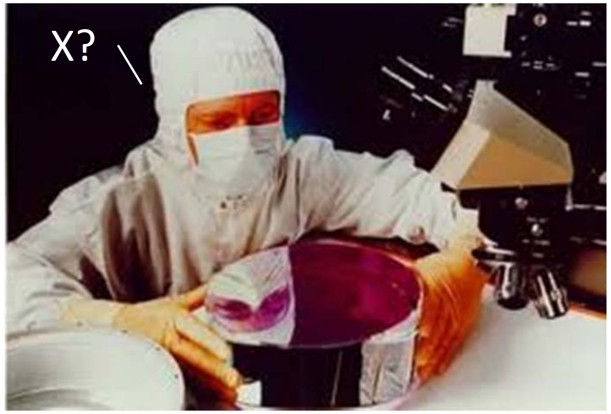
$$\langle a_L\rangle \simeq \langle a_L\rangle_{qm}\, e^{-i\Theta}$$

→ Improvement by more than 20 orders of magnitude compared to existing bounds !

$\delta\mu_0 \sim 1,\ \delta\gamma_0 \sim 1$ and $\delta\beta_0 \sim 1$ → measuring **Planck-scale deformations**

Pikovski et al.
Nature Physics (2012);
doi:10.1038/nphys2262

„How it all began“… beating the standard quantum limit through (quantum) non-demolition



Braginsky: *„Beating the standard quantum limit can be achieved only in one way: design the probe so it sees only the measured observable.“*

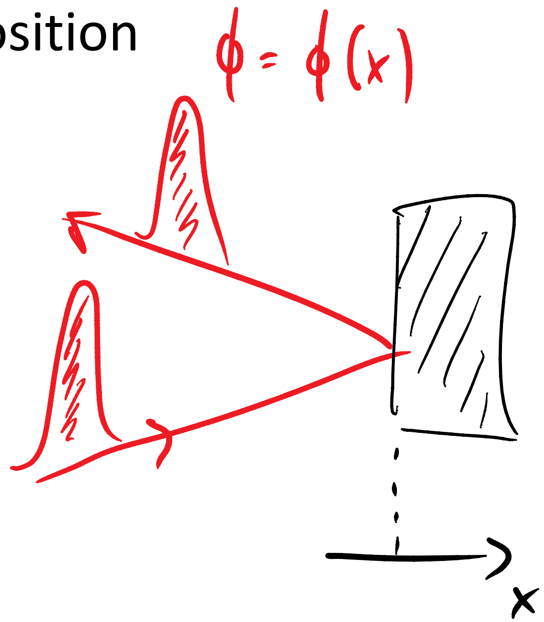
→ **quantum non-demolition (QND)**

Braginsky, Unruh, Thorne, Caves, etc…

How to measure position x to arbitrary accuracy?

- Stroboscopic measurements (periodic interaction), e.g. Schwab et al. (2012)
- **Single shot measurements**

  → Optical phase is correlated with instantaneous position



Pulsed quantum optomechanics

M. R. Vanner[a,1], I. Pikovski[a], G. D. Cole[a], M. S. Kim[b], Č. Brukner[a,c], K. Hammerer[c,d], G. J. Milburn[e], and M. Aspelmeyer[a]

[a]Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria; [b]QOLS (Quantum Optics and Laser Science Group), Blackett Laboratory, Imperial College London, London SW7 2BW, United Kingdom; [c]Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences, A-1090 Vienna and A-6020 Innsbruck, Austria; [d]Institute for Theoretical Physics and Albert Einstein Institute, University of Hannover, Callinstrasse 38, D-30167 Hannover, Germany; and [e]School of Mathematics and Physics, University of Queensland, Saint Lucia 4072, Australia

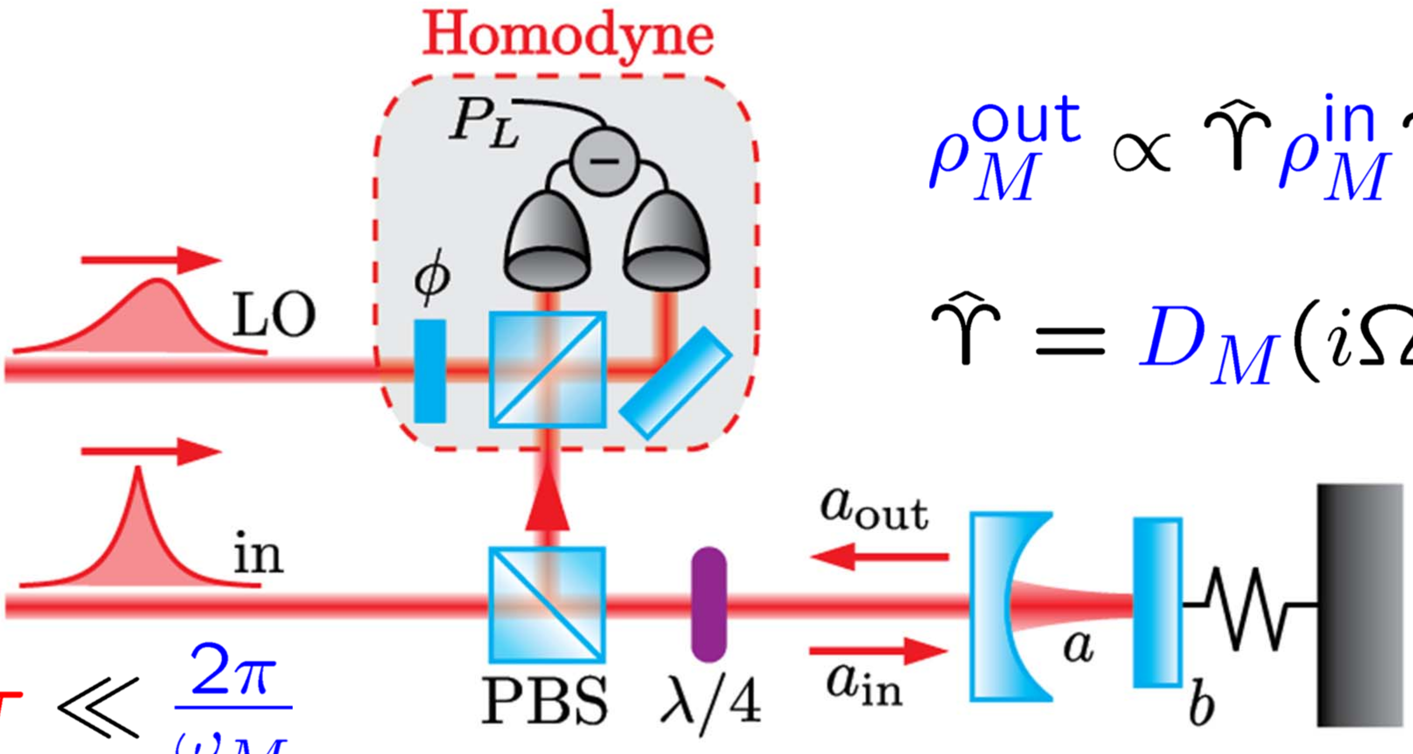
Edited by Mikhail Lukin, Harvard University, Cambridge, MA, and accepted by the Editorial Board July 21, 2011 (received for review April 1, 2011)

Studying mechanical resonators via radiation pressure offers a rich avenue for the exploration of quantum mechanical behavior in a macroscopic regime. However, quantum state preparation and especially quantum state reconstruction of mechanical oscillators remains a significant challenge. Here we propose a scheme to realize quantum state tomography, squeezing, and state purifi-

distribution of phase noise of strong pulses of light at various times throughout a mechanical period. We show that the same experimental tools used for quantum state tomography can also be used for squeezed state preparation and state purification, which thus provides a complete experimental framework. Our scheme does not require "cooling via damping" (11–13) and

PNAS USA 108, 16182 (2011)

Pulsed quantum optomechanics



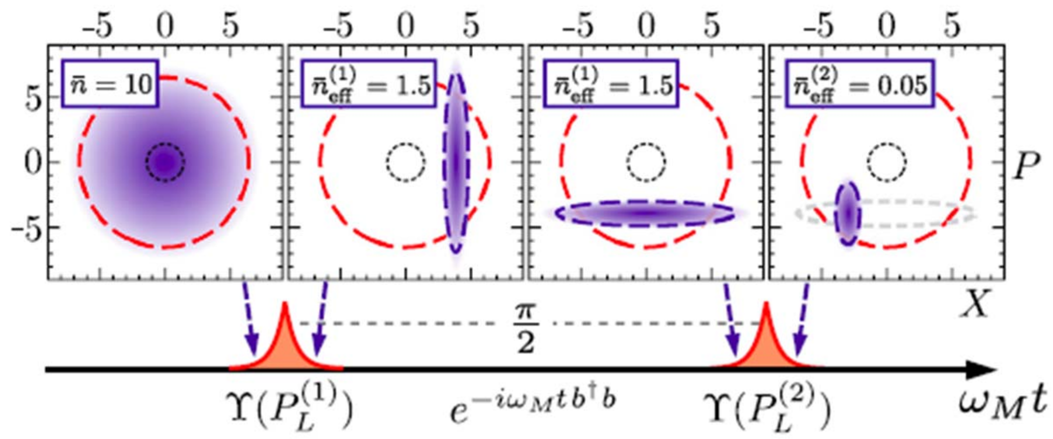
$$\tau \ll \frac{2\pi}{\omega_M}$$

$$\rho_M^{\text{out}} \propto \hat{\Upsilon}\rho_M^{\text{in}}\hat{\Upsilon}^\dagger$$

$$\hat{\Upsilon} = D_M(i\Omega)e^{-\frac{1}{2}(P_L - \chi\hat{X}_M)^2}$$

$$\mathcal{N}_\beta \Upsilon|\beta\rangle = S(r)D(\mu_\beta)|0\rangle$$

→ Squeezing, displacement and cooling of mechanical resonator **through information update!**

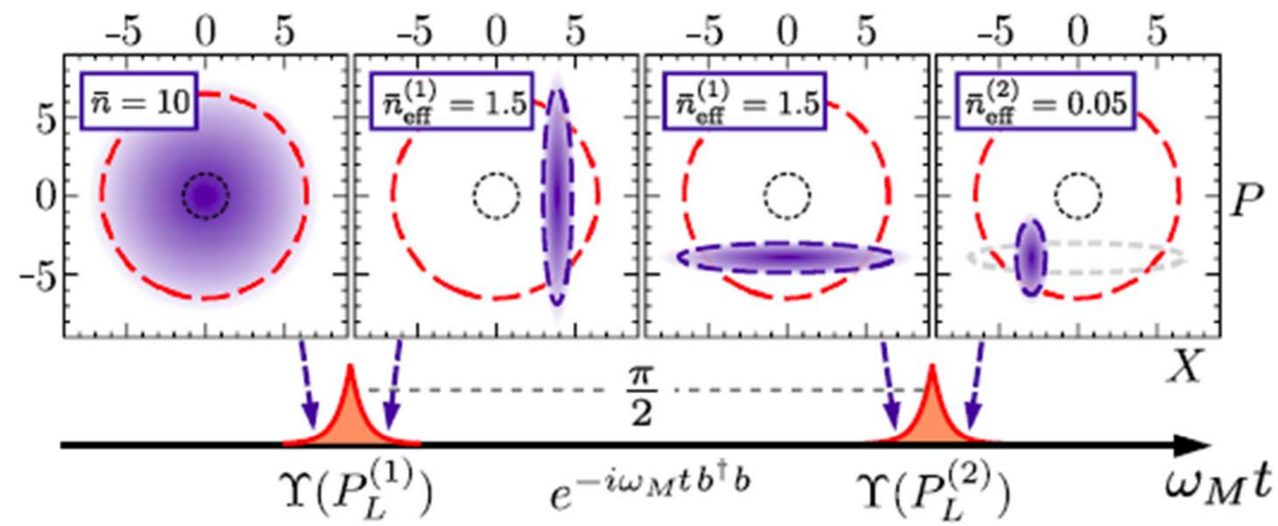


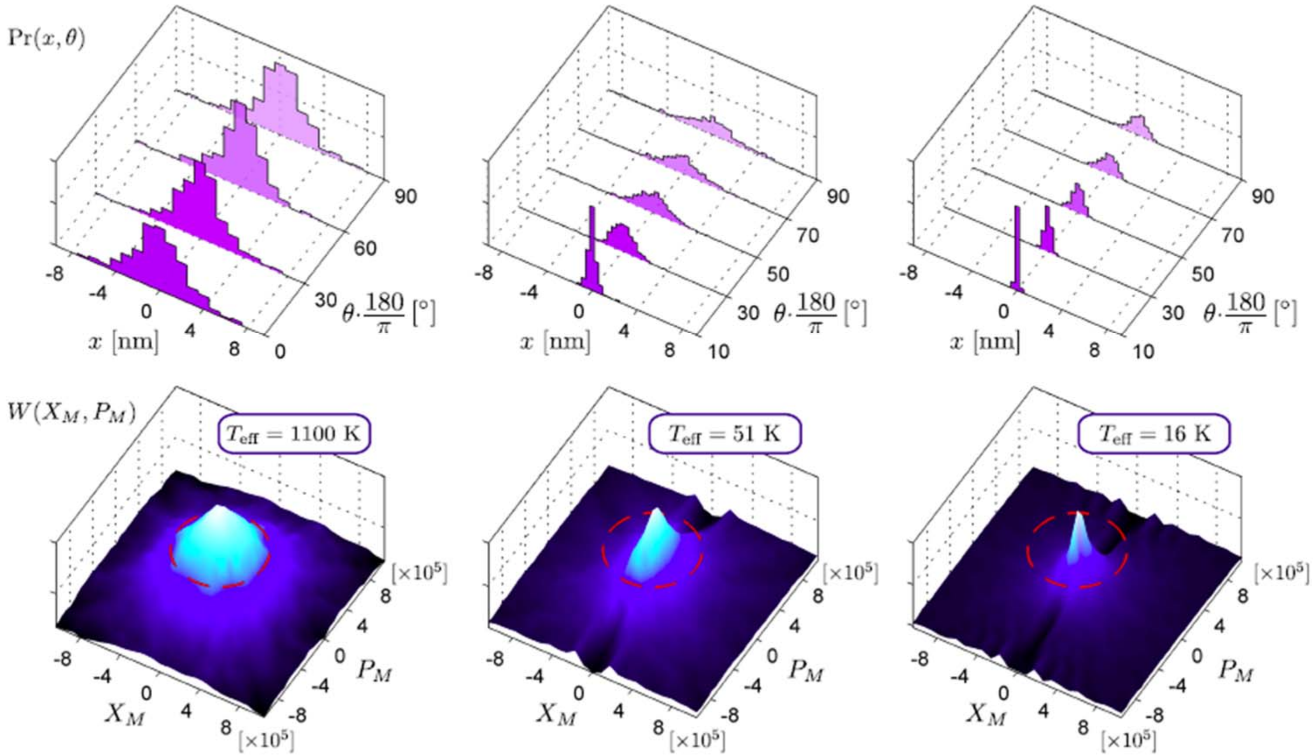
Vanner, Pikovski et al., PNAS 108, 16182 (2011)

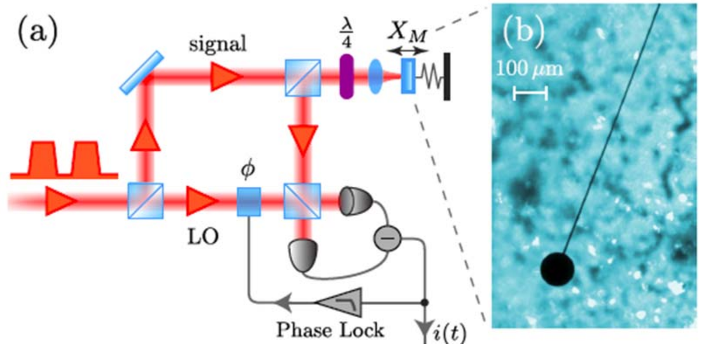
Latest data from the lab…
Cooling-by-measurement and state tomography

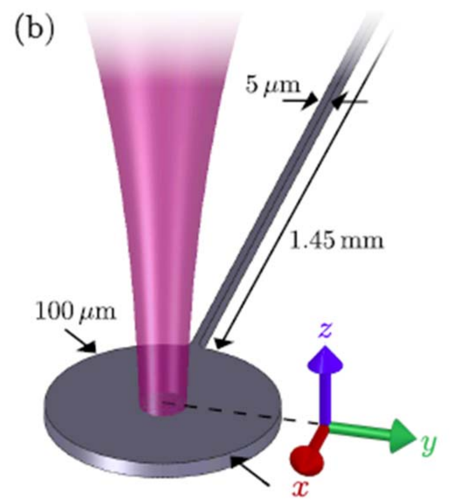
universität wien

VCQ Vienna Center for Quantum Science and Technology









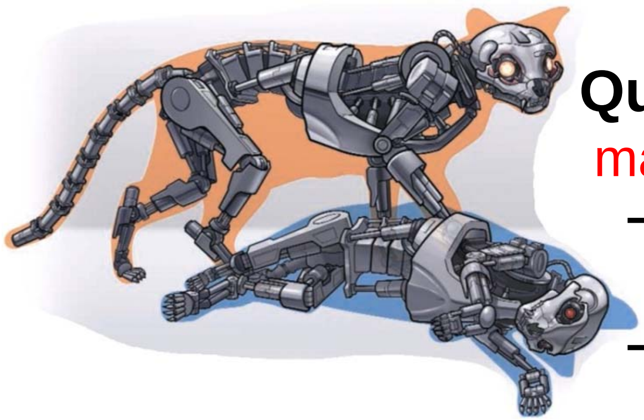
M. Vanner, J. Hofer, G.D. Cole, M. Aspelmeyer, arxiv 1211.7036 (2012)

A new playground: adding „quantum“ to mechanics…

universität wien

VCQ

Vienna Center for Quantum Technology

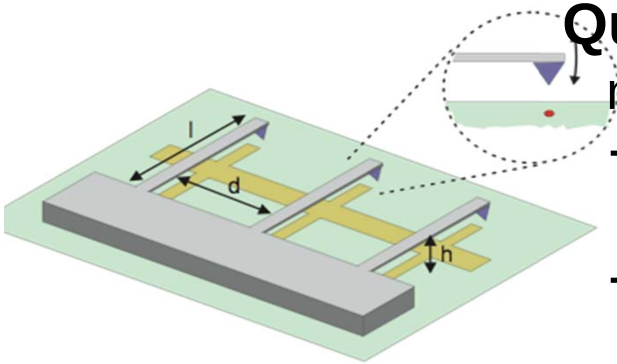


Quantum Foundations

macroscopic quantum physics

→decoherence and the quantum measurement problem

→ quantum physics and gravity

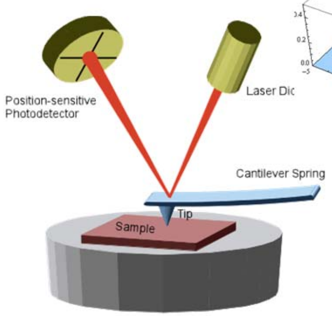


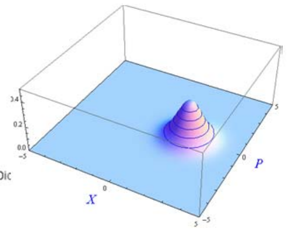
Quantum Information

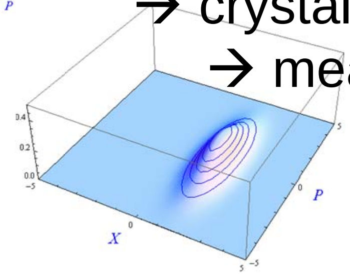
novel on-chip architectures

→ coherent light-matter interfaces (transducers, memories)

→ strong photon-phonon nonlinearities







(Quantum) Measurement

new levels of accuracy

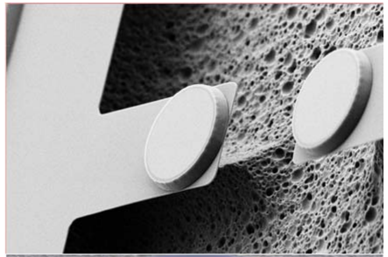
→ crystallline mirrors

→ measurements of G?

g – kg

Hz

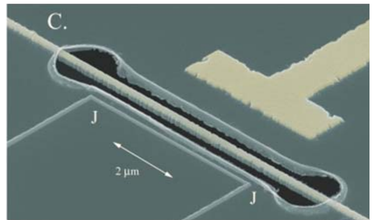
cm



ng -mg

kHz – MHz

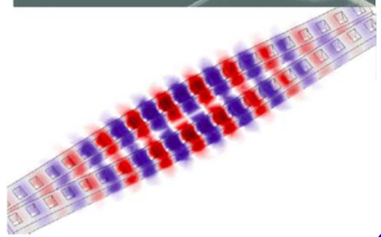
µm



pg -ng

MHz – GHz

nm



Our collaborators and discussion partners include…

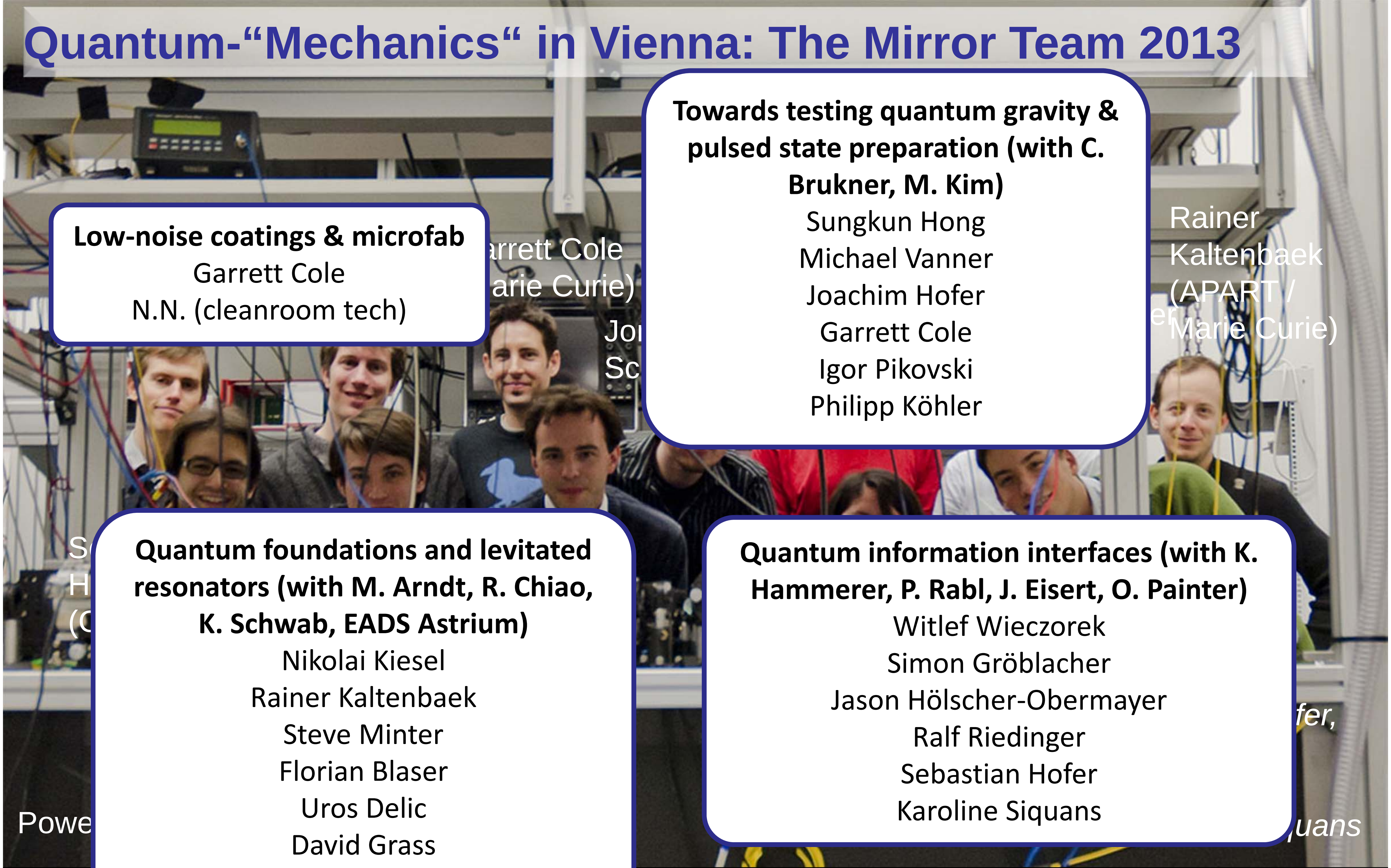
Foundations of quantum physics:
Markus Arndt (Vienna, Austria)
Caslav Brukner (Vienna, Austria)
Raymond Chiao (UC Merced, USA)
Anthony J. Leggett (UIUC, USA)
Anton Zeilinger (Vienna, Austria)

Quantum optical control and quantum information (theory):
Ignacio Cirac (MPQ, Germany)
Jens Eisert (Potsdam, Germany)
Klemens Hammerer (Hannover, Germany)
Myungshik Kim (London, UK)
Gerard Milburn (Queensland, Australia)
Alex Retzker (Ulm, Germany)
Peter Rabl (Innsbruck, Austria)
Helmut Ritsch (Innsbruck, Austria)
Oriol Romero-Isart (MPQ, Germany)
Frank Verstraete (Vienna, Austria)
Peter Zoller (Innsbruck, Austria)

Micro- and nanomechanical fabrication, quantum interfacing and low-loss coatings:
Greg Harry (Caltech, LIGO, USA)
Nergis Mavalvala (MIT, LIGO, USA)
Oskar J. Painter (Caltech, USA)
Achim Peters (HU Berlin, Germany)
Keith Schwab (Caltech, USA)
Ignacio Wilson-Rae (Munich, Germany)
Jun Ye (NIST, USA)

Special thanks to our former group members
Hannes Böhm → EADS, Germany
Sylvain Gigan → ESPCI, France
Mauro Paternostro → QUni Belfast, Ireland
Katharina Gugler → FFG, Austria
Simon Gröblacher → Caltech, USA

Quantum-“Mechanics“ in Vienna: The Mirror Team 2013



Low-noise coatings & microfab
Garrett Cole
N.N. (cleanroom tech)

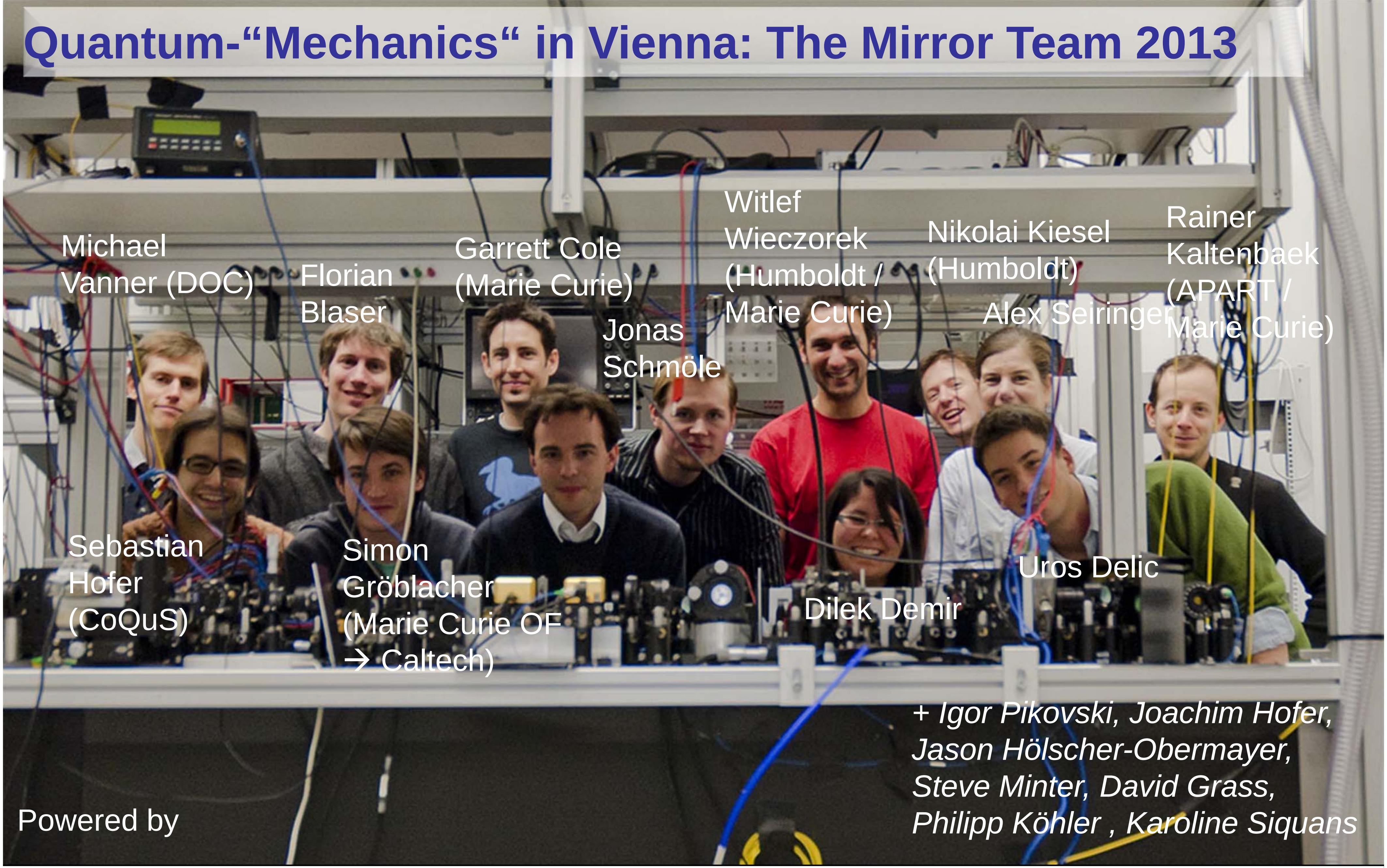
Towards testing quantum gravity & pulsed state preparation (with C. Brukner, M. Kim)
Sungkun Hong
Michael Vanner
Joachim Hofer
Garrett Cole
Igor Pikovski
Philipp Köhler

Quantum foundations and levitated resonators (with M. Arndt, R. Chiao, K. Schwab, EADS Astrium)
Nikolai Kiesel
Rainer Kaltenbaek
Steve Minter
Florian Blaser
Uros Delic
David Grass
Nils Prigge
Jonas Schmöle

Quantum information interfaces (with K. Hammerer, P. Rabl, J. Eisert, O. Painter)
Witlef Wieczorek
Simon Gröblacher
Jason Hölscher-Obermayer
Ralf Riedinger
Sebastian Hofer
Karoline Siquans

Der Wissenschaftsfonds.
SEVENTH FRAMEWORK PROGRAMME
opean esearch Council
fq(x) Foundational Questions Institute
ÖAW Österreichische Akader der Wissenschaften
Alexander von Humboldt Stiftung/Foundation
esa

Quantum-“Mechanics“ in Vienna: The Mirror Team 2013



+ Igor Pikovski, Joachim Hofer, Jason Hölscher-Obermayer, Steve Minter, David Grass, Philipp Köhler , Karoline Siquans

Powered by

FWF Der Wissenschaftsfonds. · SEVENTH FRAMEWORK PROGRAMME · erc European Research Council · fq(x) Foundational Questions Institute · ÖAW Österreichische Akademie der Wissenschaften · Alexander von Humboldt Stiftung/Foundation · esa