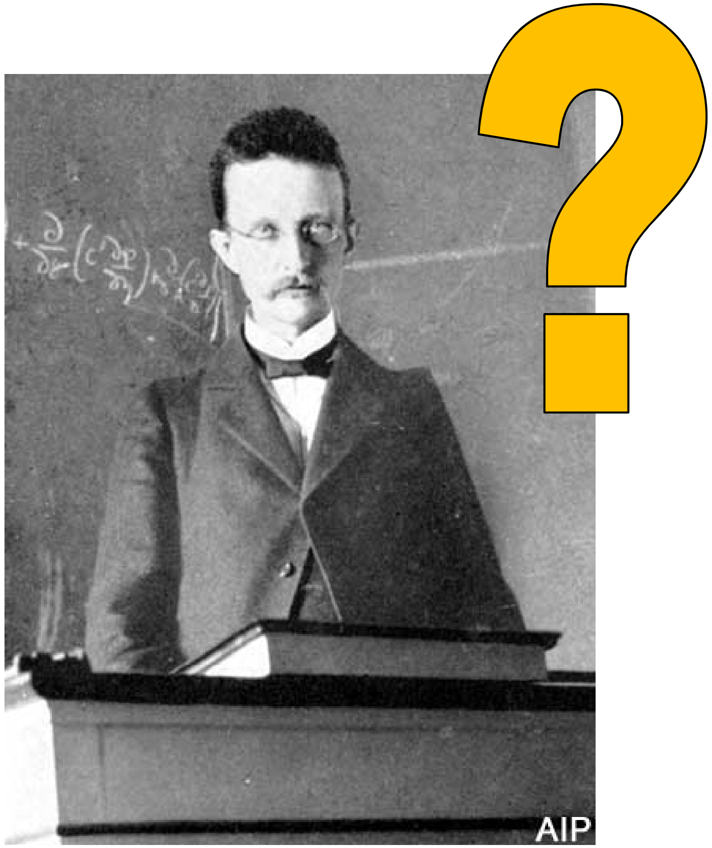

The QUEST of Science

Music or Physics?



Max Planck (1858-1947)

Max Planck asked the expert:

“Physics, that is a fairly nice subject, but you will not be able to find anything fundamentally new in it.
In this science, almost everything has been discovered already and only a few unimportant gaps remain to be filled!"

Phillip Gustav Jolly
(Professor of Physics in Munich)
to Max Planck in 1874

Unimportant Gaps?
Einstein‘s Annum Mirabilis 1905

Annalen der Phvsik. Band 17. Seite 132-148

6. ***Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt; von A. Einstein.***

- Photoeffect, Quantum Mechanics

Annalen der Physik, Band 17, Seite 549-560

5. ***Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen; von A. Einstein.***

- Brownian Motion

Annalen der Physik, Band 17, Seite 891-921

3. ***Zur Elektrodynamik bewegter Körper; von A. Einstein.***

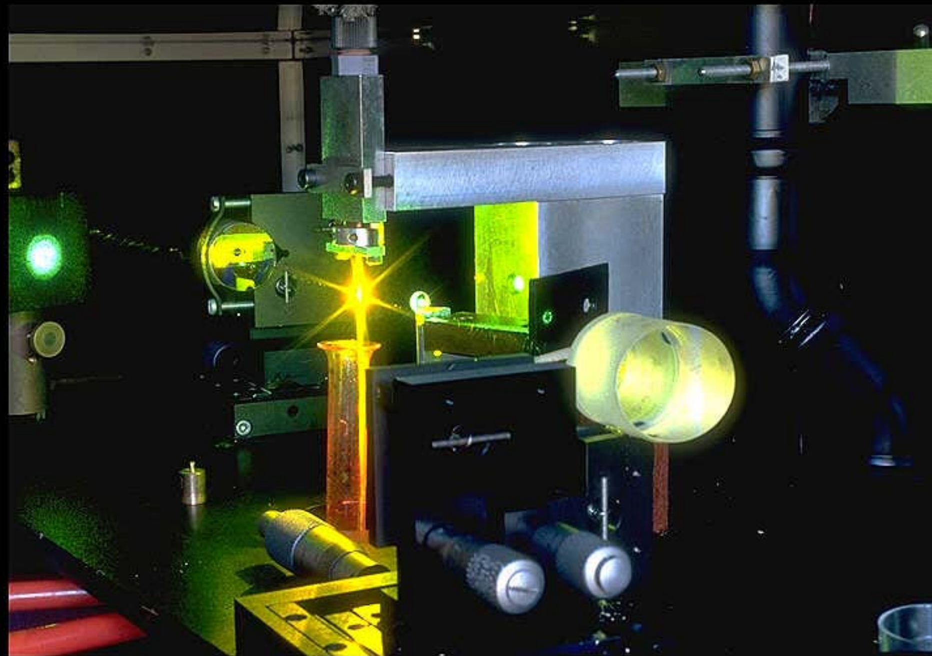
- Special Relativity

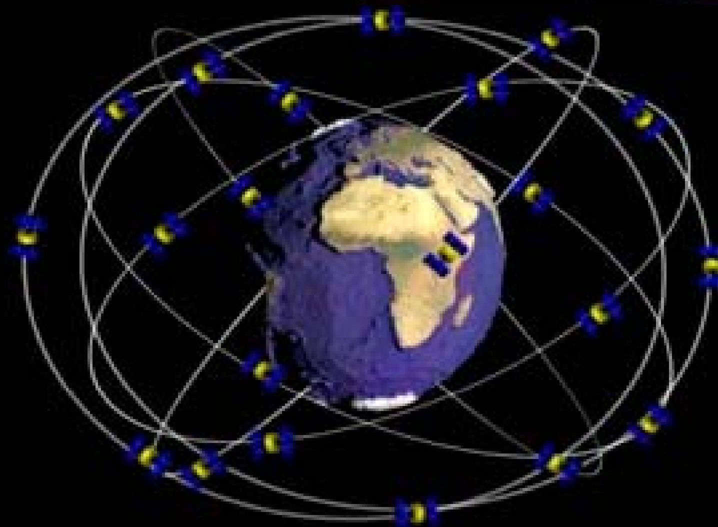
Annalen der Physik, Band 18, Seite 639-641

13. ***Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig? von A. Einstein.***

- Equivalence Principle

Yesterday's Gaps are Today's Tools

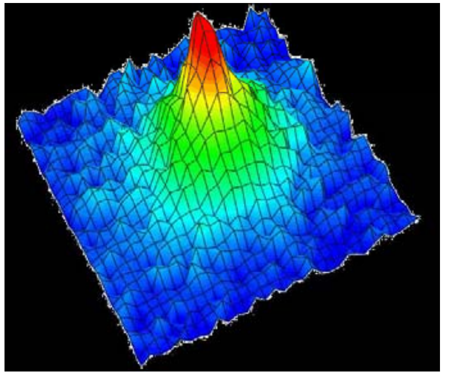


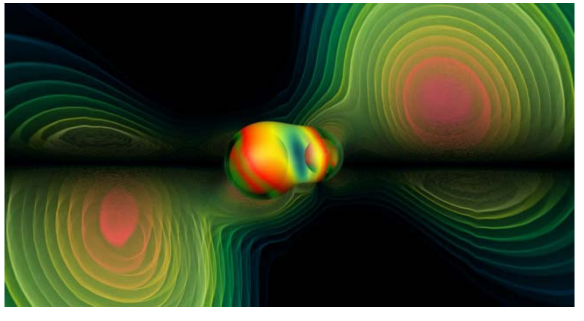


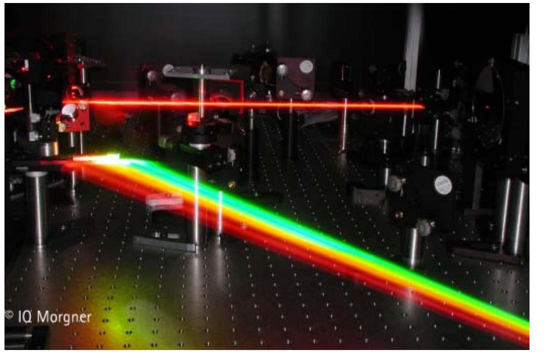

But: The Common Picture
is Still Missing

Cluster of Excellence QUEST

Research at the quantum limit!







Overview

- Motivation
- Introduction of QUEST
- Mission and Structure
- Insight in QUEST's Research
- Some Results *exemplified*

Acronym QUEST:

Centre for Quantum Engineering and Space-Time Research

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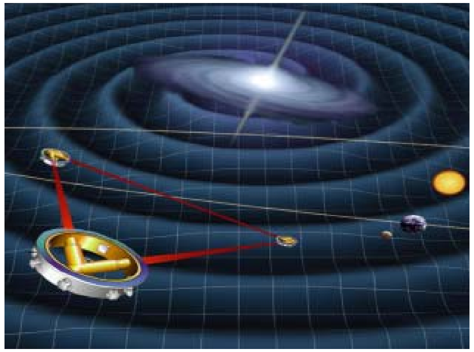
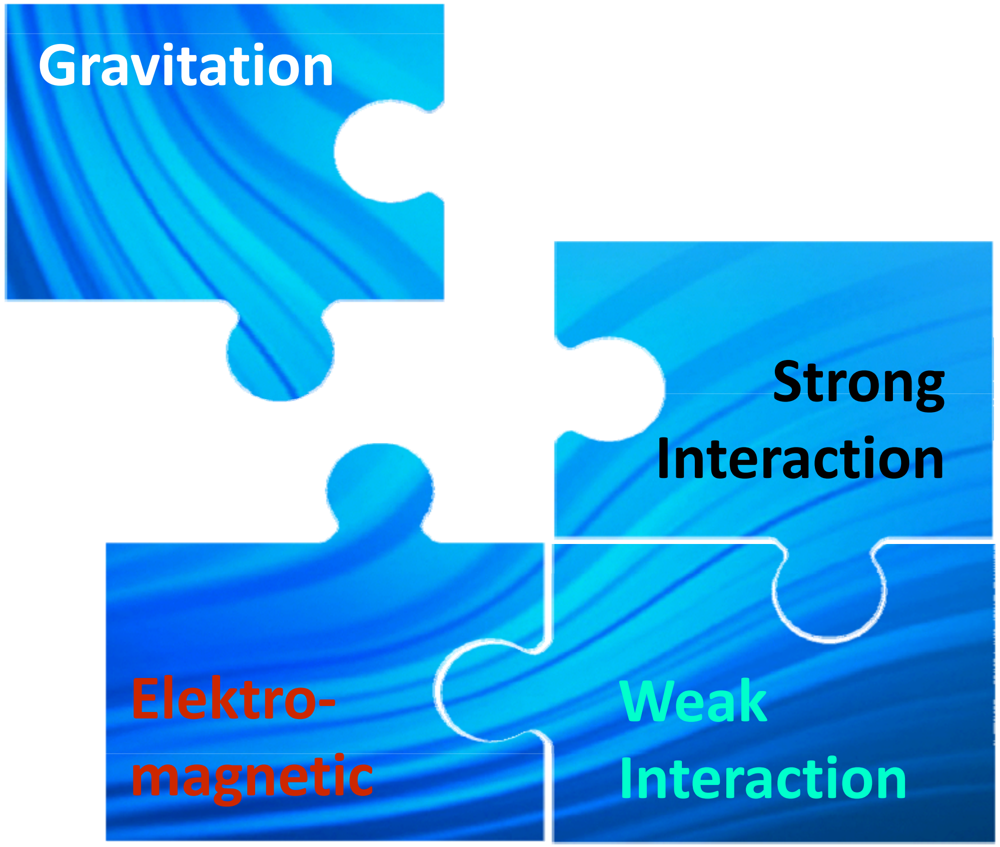


= quest

Quantum-Engineering

Space-Time-Research

Todays Gaps:


Gravitation
Strong
Interaction
Elektro-
magnetic
Weak
Interaction

QUESTs of Today

- Link between die quantum mechanics and gravitation?
- How did "Big Bang" work?
- What is *Dark Matter* and *Energy*?
- What happens inside a Black Hole?
- What is behind quantum physics?
- Can we master Quantum Computing?
- Properties of Gravitational Waves?

More questions anyone can answer immediatley!

Research Quests in QUEST

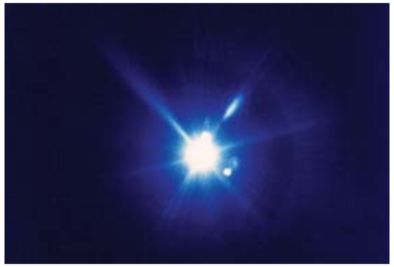
- Understanding the quantum world
  - Nanoscopic quantum world
  - Mesoscopic quantum world
  - Macroscopic quantum to classical world
- Quantum – Gravity?
  - Equivalence principle
  - Constancy of physical constants
- Structure of the universe
  - Preferred frame research
  - Gravitational wave astronomy

Research Routes in QUEST

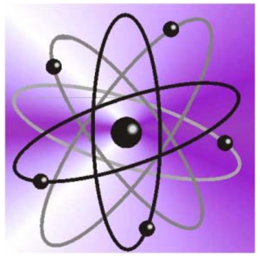
- Strongly correlated systems
  - Macroscopic entanglement
- Matter wave interferometry
  - Atom lasers, gravitational sensors
- Atomic clocks
  - On earth and in space
- Light interferometry beyond all limits
  - Quantum non-demolition and squeezing
- Laser ranging
  - Relativity, geodesy and gravity gradiometry

Engineering at Quantum Level

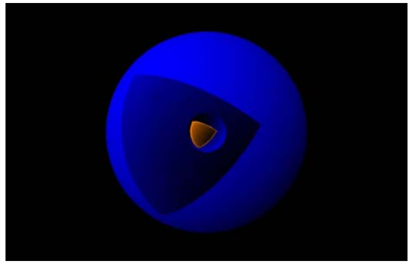
Engineering with …



Photons



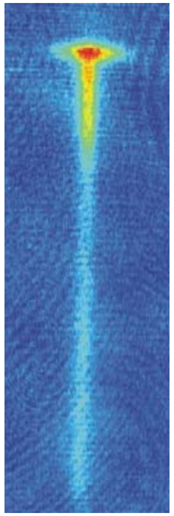
Atoms



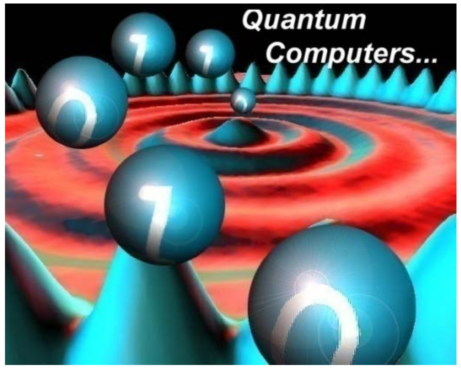
Elektrons

Results …

New States of Light

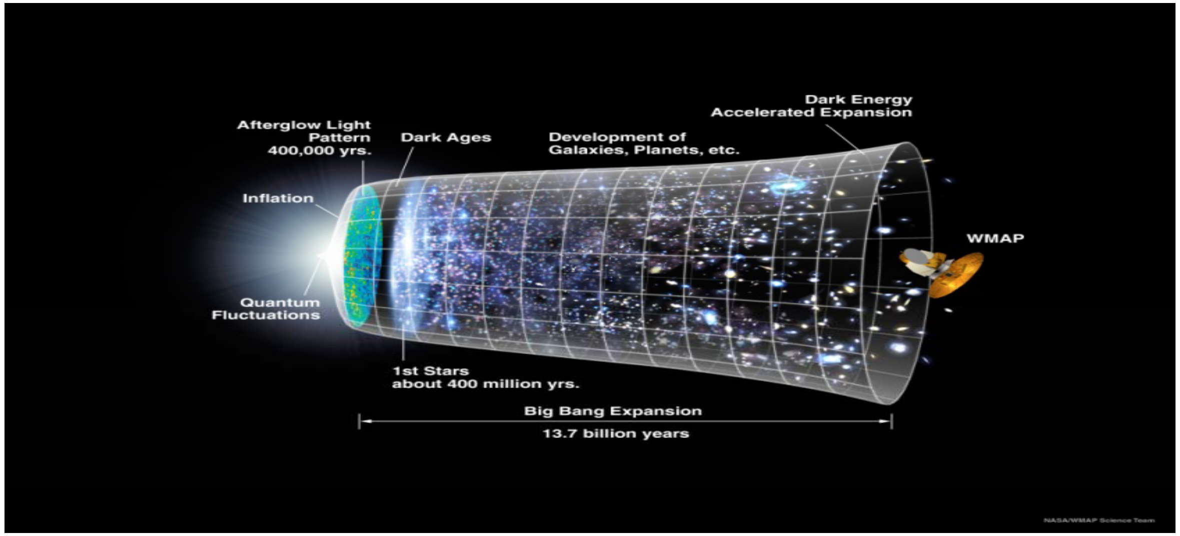


Atom Lasers



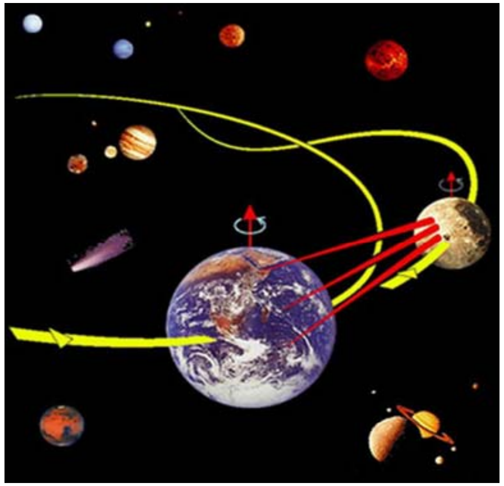
Quantum-Information

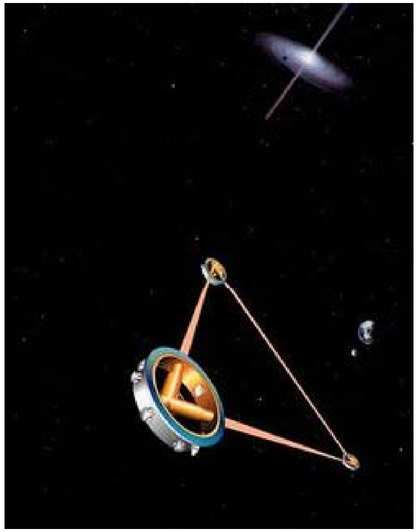
Space-Time-Research?



Cosmology and Quantum-Gravitation

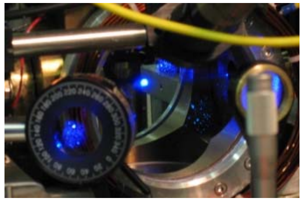
Precision Geodesy



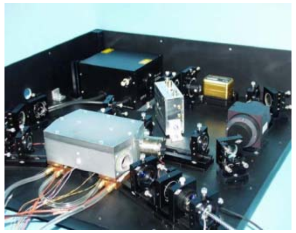


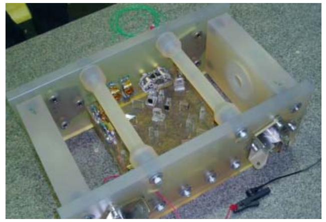
Gravitational Waves

How does QUEST work?



Quantum-
Sensors

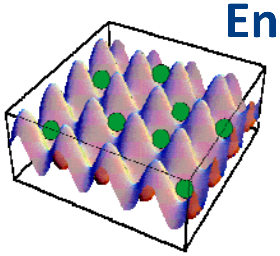


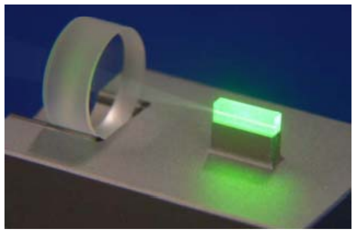


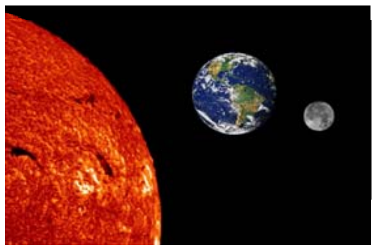
Enabling
Technologies

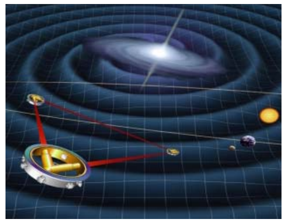
Quantum-
Engineering

Space-Time
Research









Who is QUEST?

Leibniz Universität Hannover

+

PTB

ZARM

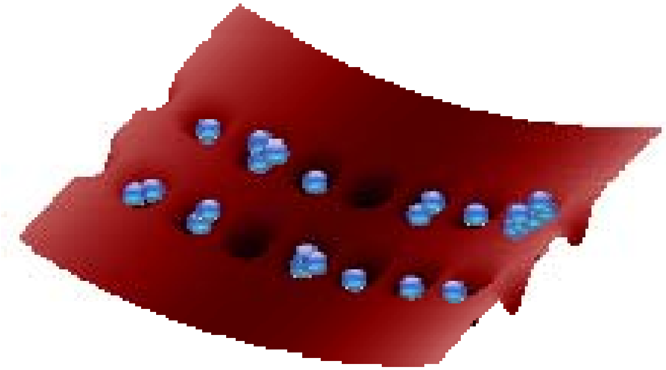
LASER ZENTRUM HANNOVER e.V.

Institutes of Leibniz Universität Hannover

External Partners

Institutes of Leibniz Universität

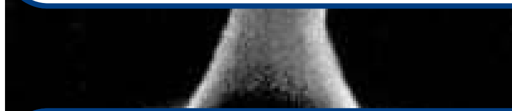
Theoretical Physics



Stringtheory
Gravitation
Quantum Optics

Solid State Physics

Gravitational-physics

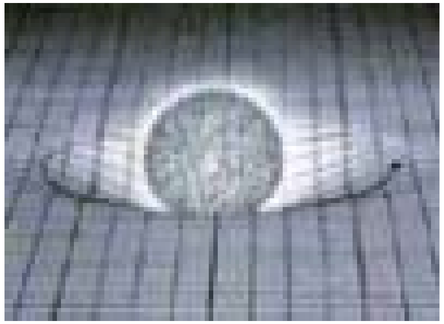


Quantum Optics

Theoretical Physics

External Partners

Centre for Applied Space Technologies and Microgravity (ZARM)



Technology
Space-Time Research

International Networking
Excellent Theory

Task Groups in QUEST (Matrix)

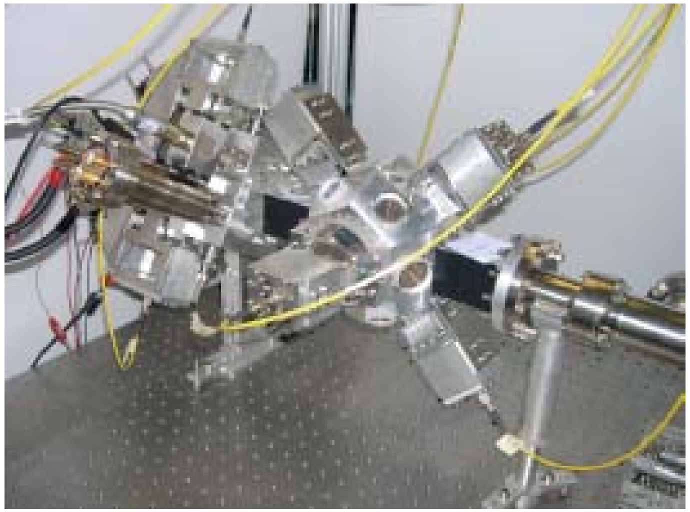
- Task Groups as flexible research units
- Task Groups address multi-area challenges
- Task Groups are "work benches" for new visions

AREA A	AREA B	AREA C	AREA D

- TG 1 Frontiers of Strongly-correlated Systems
- TG 2 Quantum Test of Equivalence Principle
- TG 3 Transportable Ultra-stable Clock
- TG 4 Variations of Fundamental Constants
- TG 5 Third Generation Gravitational Wave Observatories
- TG 6 QND Prototype for a Gravitational Wave Detector
- TG 7 Next Generation Gravity Field Missions

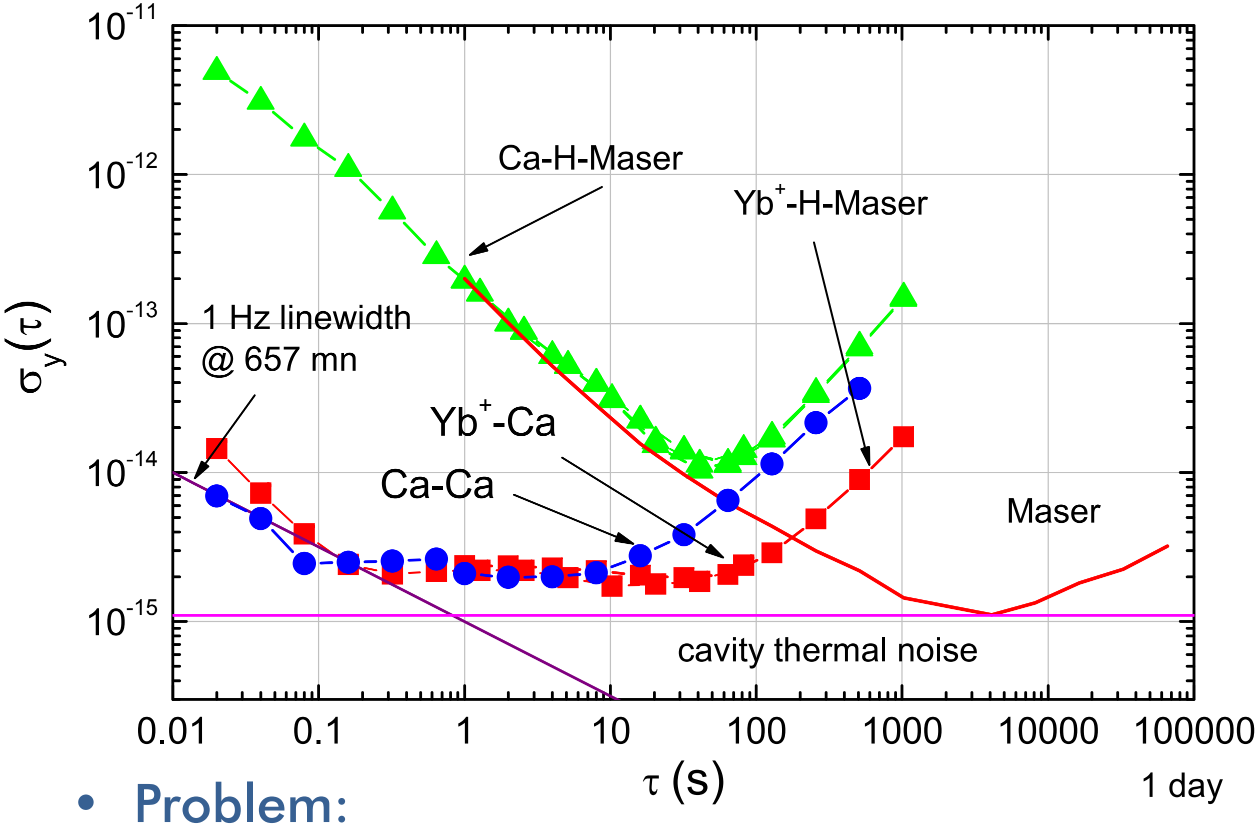
TG 2: Cold Atom Test of the Principle of Equivalence (Caprice)

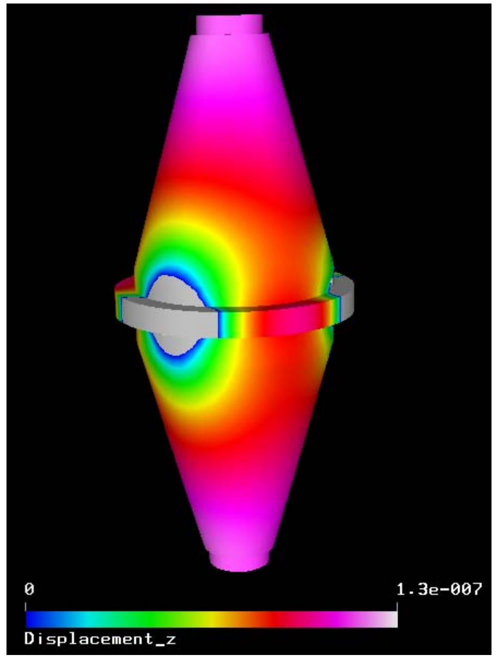
- **All-optical fountain for ultra cold matter**
- **Testing the equivalence principle by using $^{40,41}K$ $^{85,87}Rb$**



www.finaqs.uni-hannover.de

TG 3: Transportable Optical Clock





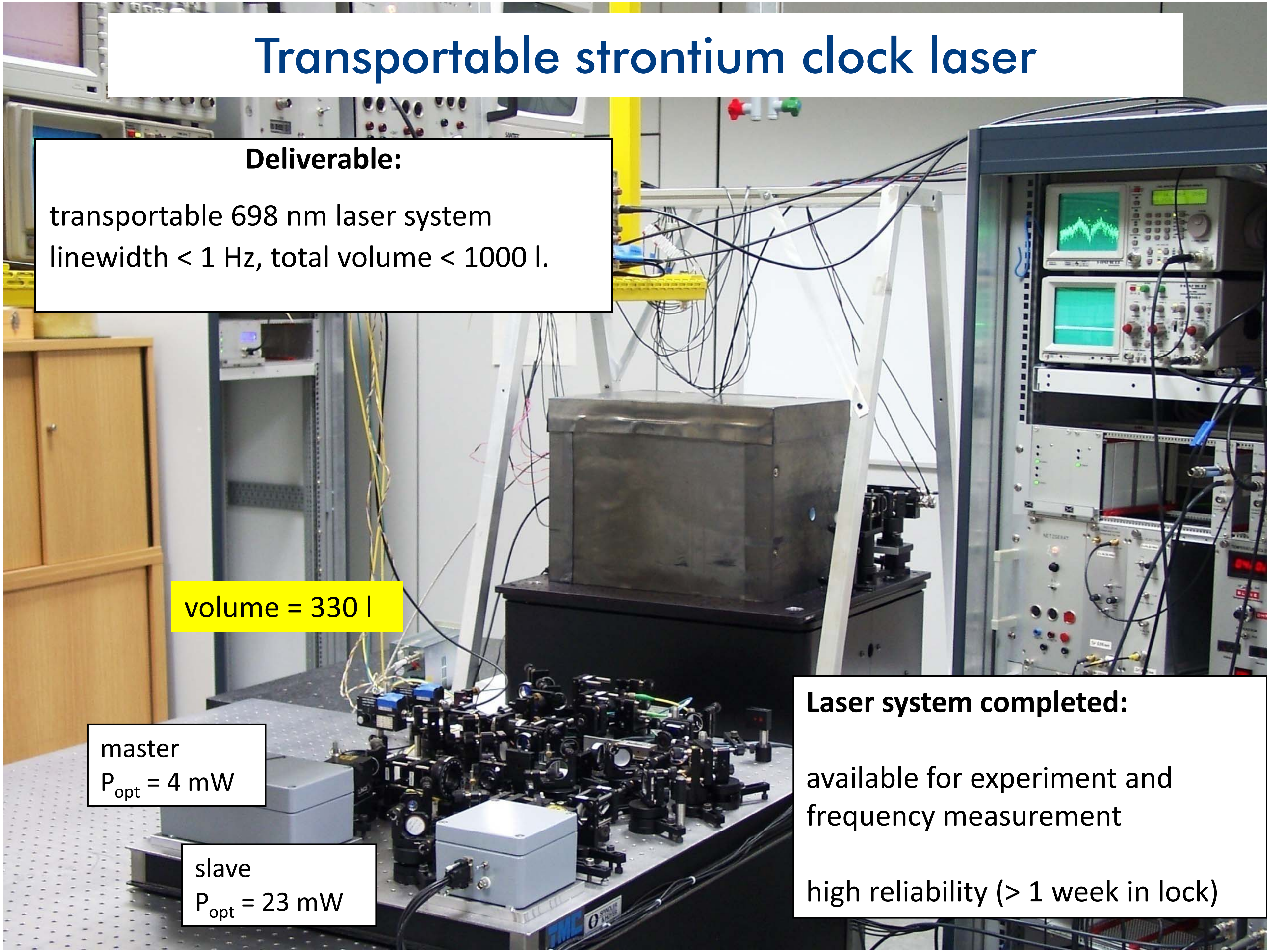
- **Problem:**

Frequency stability of the best lasers is limited by thermal noise in the optical resonator

- **Solution:**

We use a 1.5 μm stabilised to a silicon single crystal resonator (large Q) at 100 K and a fibre comb

Transportable strontium clock laser



Deliverable:

transportable 698 nm laser system
linewidth < 1 Hz, total volume < 1000 l.

volume = 330 l

master
P_{opt} = 4 mW

slave
P_{opt} = 23 mW

Laser system completed:

available for experiment and frequency measurement

high reliability (> 1 week in lock)

Quantum technology

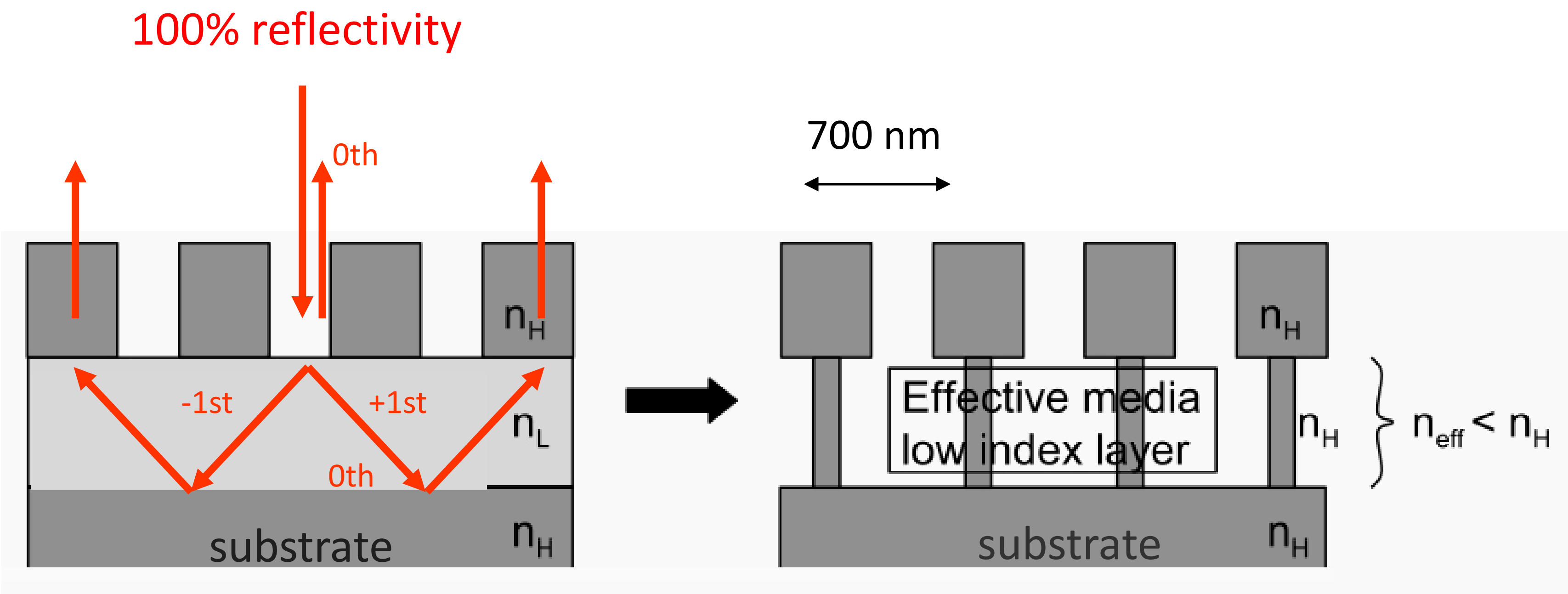
- Demonstration of a high-reflectivity waveguide mirror (a single dielectric coating layer plus a nanostructured surface provides >99% reflectivity)

[[Brückner *et al.*, Opt. Lett.,submitted]

- Proposal für a new light/matter interface: a monolithic high-reflection mirror without any dielectric coating.

[Brückner *et al.*, Opt. Lett., 33, 264 (2008)]

Waveguide Coatings



Monolithic 100% reflection “coating”

[Brückner *et al.*, Opt. Lett., 33, 264 (2008)]

99% reflectivity realized:

[Brückner *et al.*, Opt. Lett.,submitted]

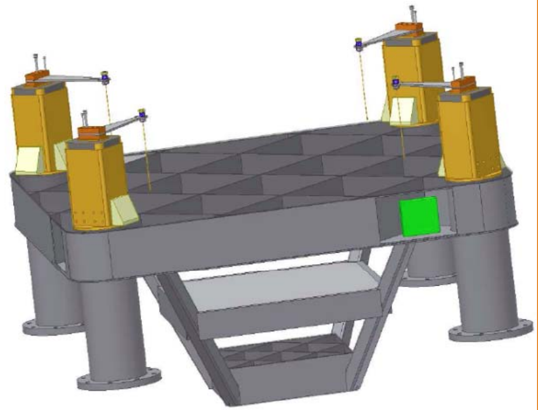
TG 6: QND Detector for a Gravitational Wave Detector

10 m prototype interferometer

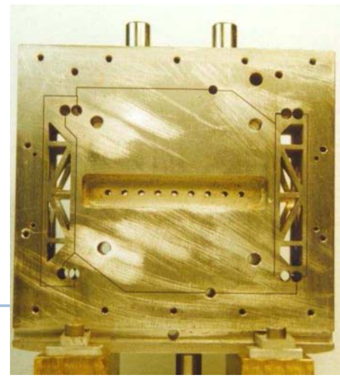
- Infrastructure in prototype hall, including pumps, pump lines, and valves, AC/DC power distribution, network access, seven optical benches, steel work, paint and brick layer work is (almost) completely in place

- Ultra-high vacuum system (Volume ca. 100 m^3, 22 t stainless steel) will be delivered and fully installed in December

- FEA analysis based design of in vacuum suspended optical benches nearing completion



- Monolithic accelerometers choosen as inertial reference sensors; collaboration with VIRGO labs established



For example:

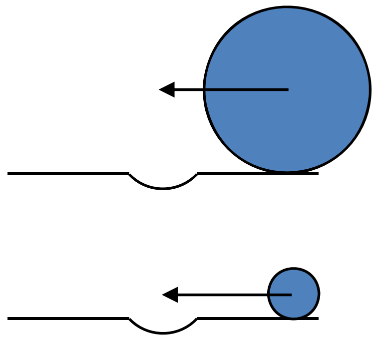
SOME RESULTS

Claus Lämmerzahl, ZARM

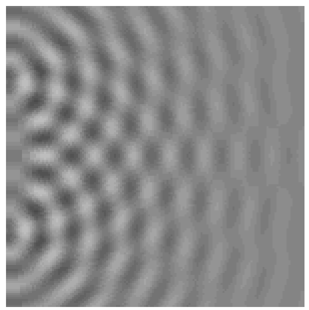
Group „Quantum Gravity Phenomenology“

Quantum gravity phenomenology

- Space-time fluctuations: metrical fluctuations minimally coupled to quantum equations
  - Induce apparent violation of the equivalence principle, testable with atomic interferometry
    (E. Göklü & C. Lämmerzahl, *Class. Quantum Grav.* 25, 105012 (2008))
  - Induce apparent decoherence in atomic systems, but long decoherence time for single particle states
    (H.-P. Breuer, E. Göklü & C. Lämmerzahl, submitted)



Different bodies feel fluctuations differently



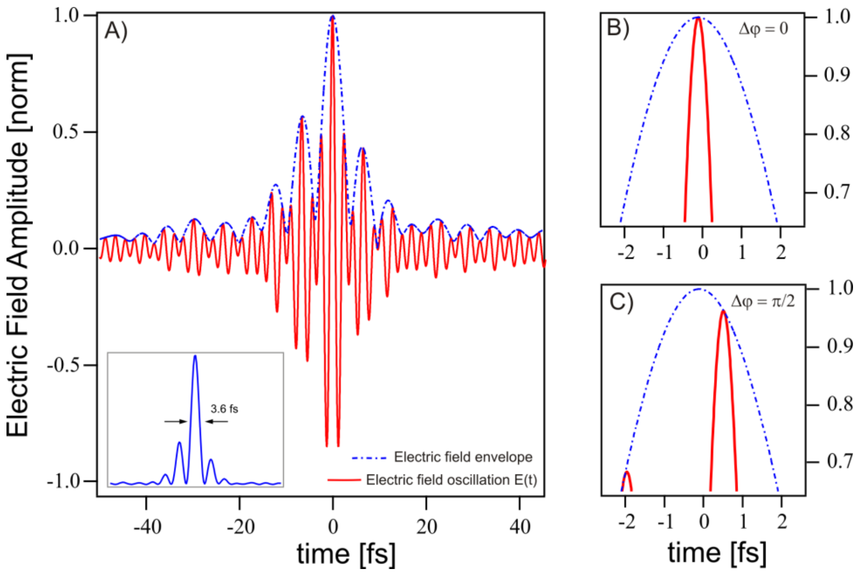
fluctuations lead to decoherence

Uwe Morgner, LUH (IQ)

Group
„Advanced Optical Field Synthesis”
(atto-second-physics)

Few-Cycle Femtosecond Field Synthesizer

- Full control over the electric field of few-cycle laser pulses by:
  - Spectral phase and amplitude
  - Carrier envelope offset phase



- Arbitrary spectral and temporal pulse conditioning:
  - Generation of 3.6-fs-laser pulses
  - field shaping with sub-femtosecond resolution
  - Blanking of wavelength regions, edge-filtering
- Towards as-frequency combs

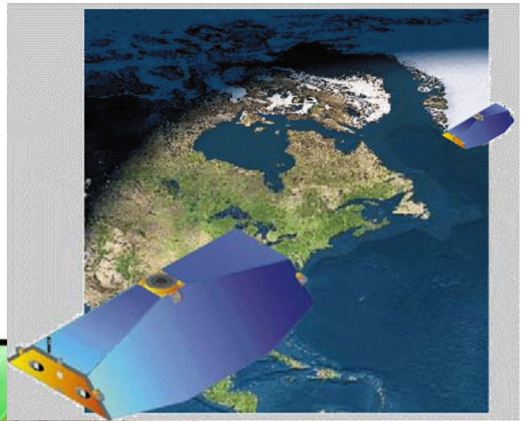
Stefan Rausch, Thomas Binhammer, Anne Harth, Franz X. Kärtner, and Uwe Morgner, „Few-cycle femtosecond field synthesizer," Optics Express, Vol. **16**, No. 22, pp. 17410-17419, (2008).

Jürgen Müller, LUH (ife)

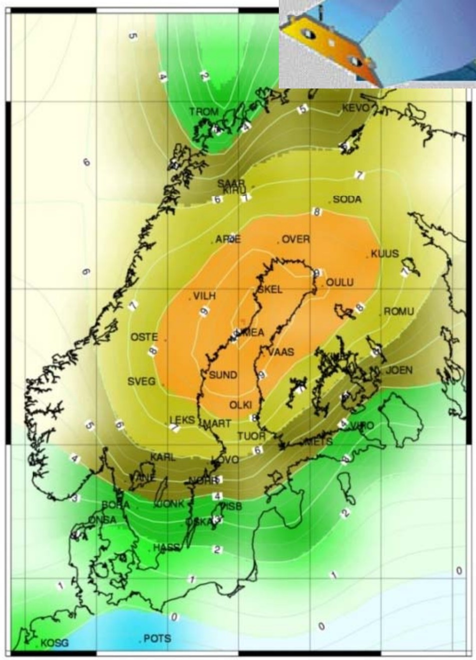
Group
„Precision Geodesy on Earth and in Space“

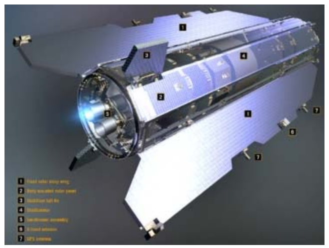
Research Activities in Geodesy

- evaluation of satellite data, preparation of new gravity field satellite missions

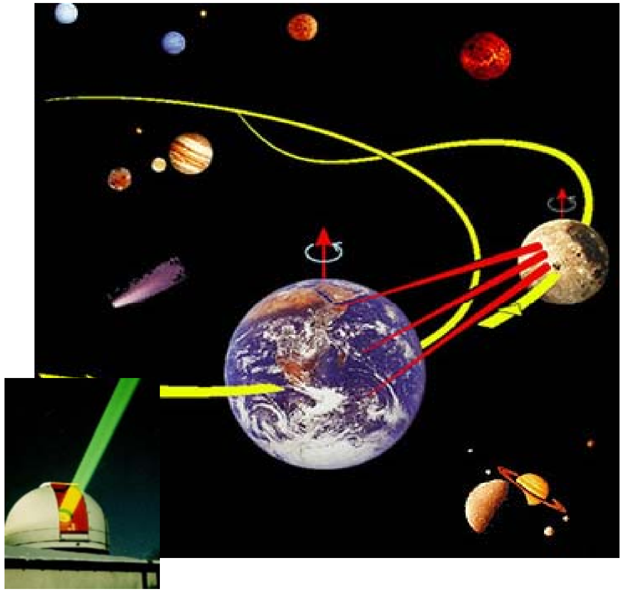


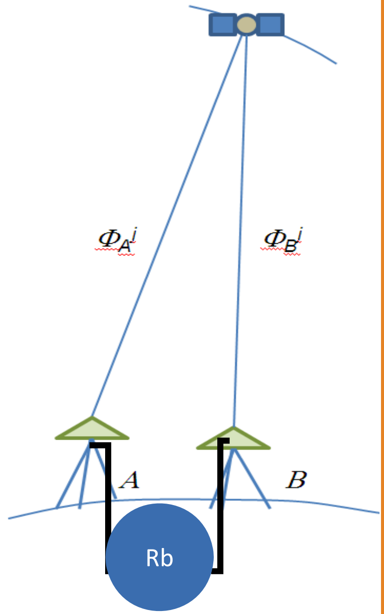
- Earth system research



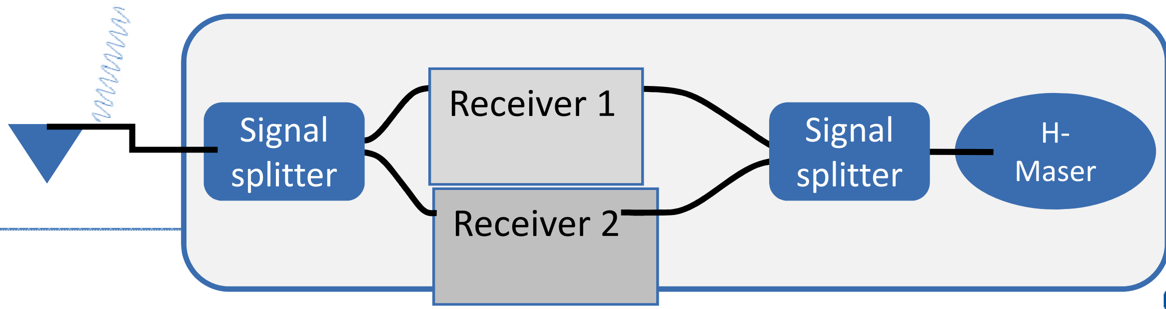


- relativity tests (gravitational constant, equivalence principle, metric) from 38 years of LLR data





- Analysis of clock errors in GNSS



Relativistic Parameters from LLR

- Gravito-magnetic effect in equations of motion via preferred-frame parameter (here, coupled with dynamics within the solar system),

$$\alpha_1 \leq \pm 4 \cdot 10^{-3}$$

(Soffel et al., 2008, Phys.Rev.D, 78)

- Strong Equivalence Principle, new limit for Nordtvedt parameter

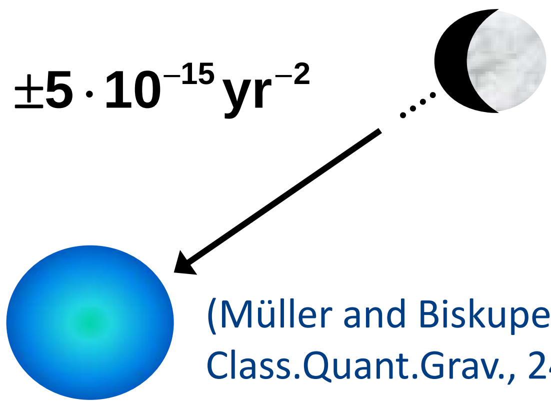
$$\eta \leq \pm 7 \cdot 10^{-4}$$

- Secular and quadratic variation of the gravitational constant

$$G = G_0 \left(1 + \frac{\dot{G}}{G} \Delta t + \frac{1}{2} \frac{\ddot{G}}{G} \Delta t^2 \right)$$

$$\frac{\dot{G}}{G} \leq \pm 7 \cdot 10^{-13} \, \mathrm{yr}^{-1}$$

$$\frac{\ddot{G}}{G} \leq \pm 5 \cdot 10^{-15} \, \mathrm{yr}^{-2}$$



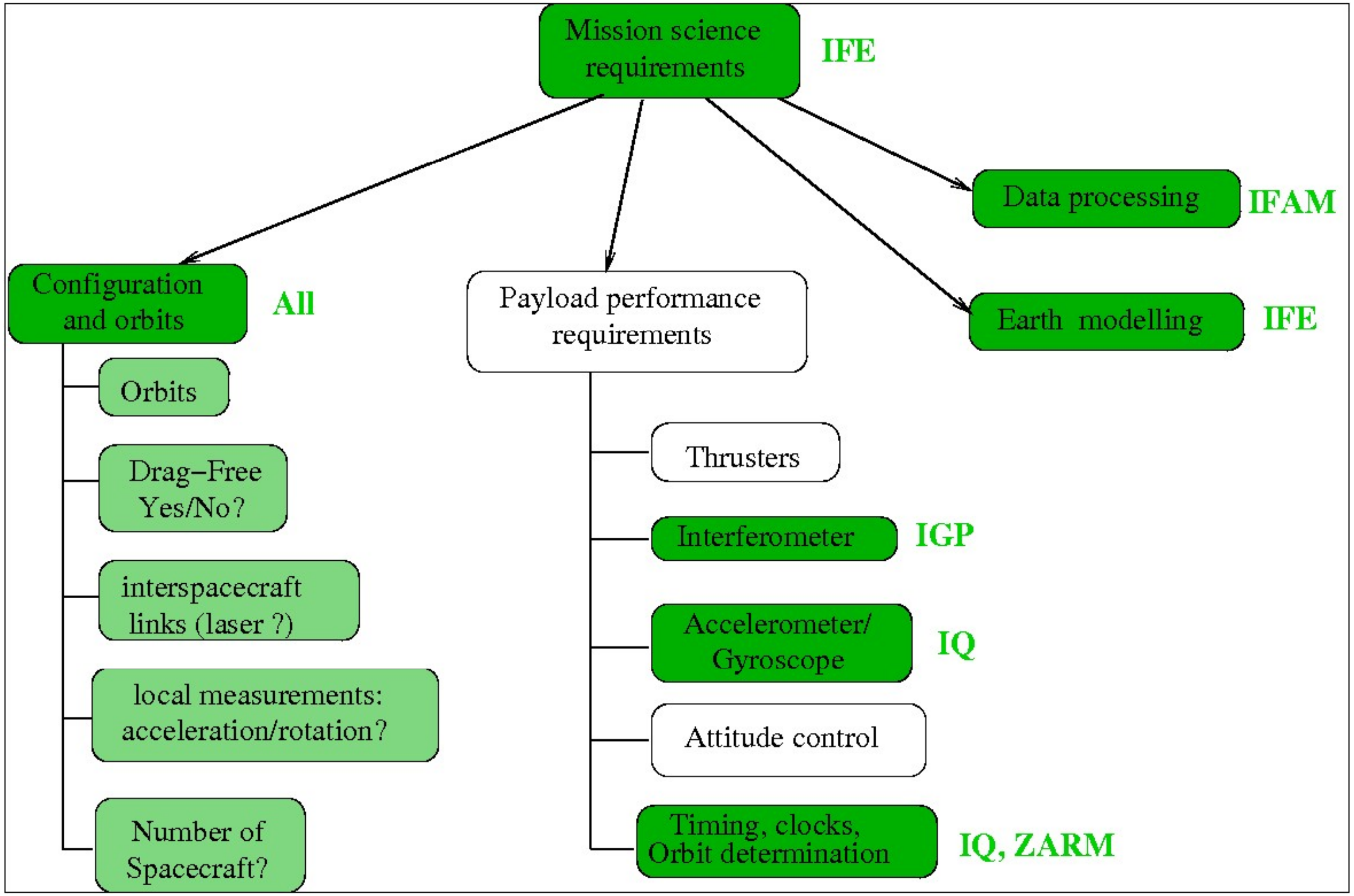
(Müller and Biskupek, 2007, Class.Quant.Grav., 24)

All results confirm Einstein' s theory impressively .

Work in Hannover on gravity field missions

- Aim: follow-on mission for GRACE
- No specific mission plan at this moment
- But: enourmous interest worldwide
- Our aim: investigate and develop central components
- final product: A consistent and complete mission design including data analysis

working approach

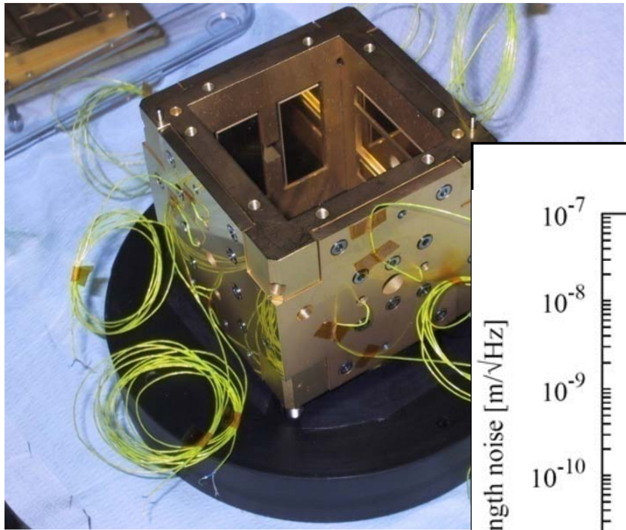


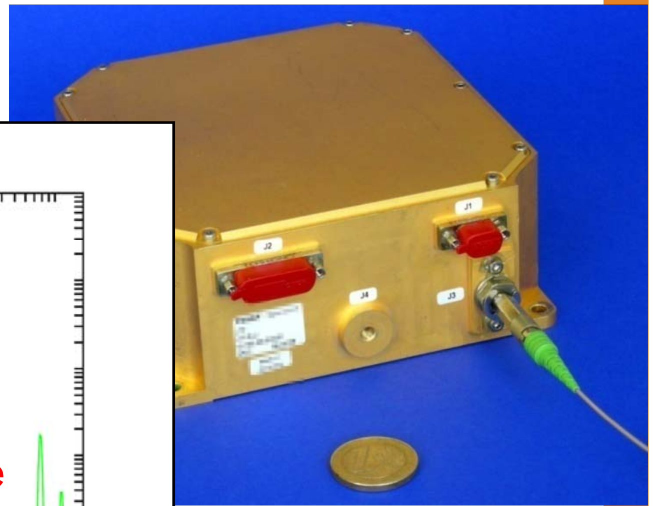
Classical top-down design

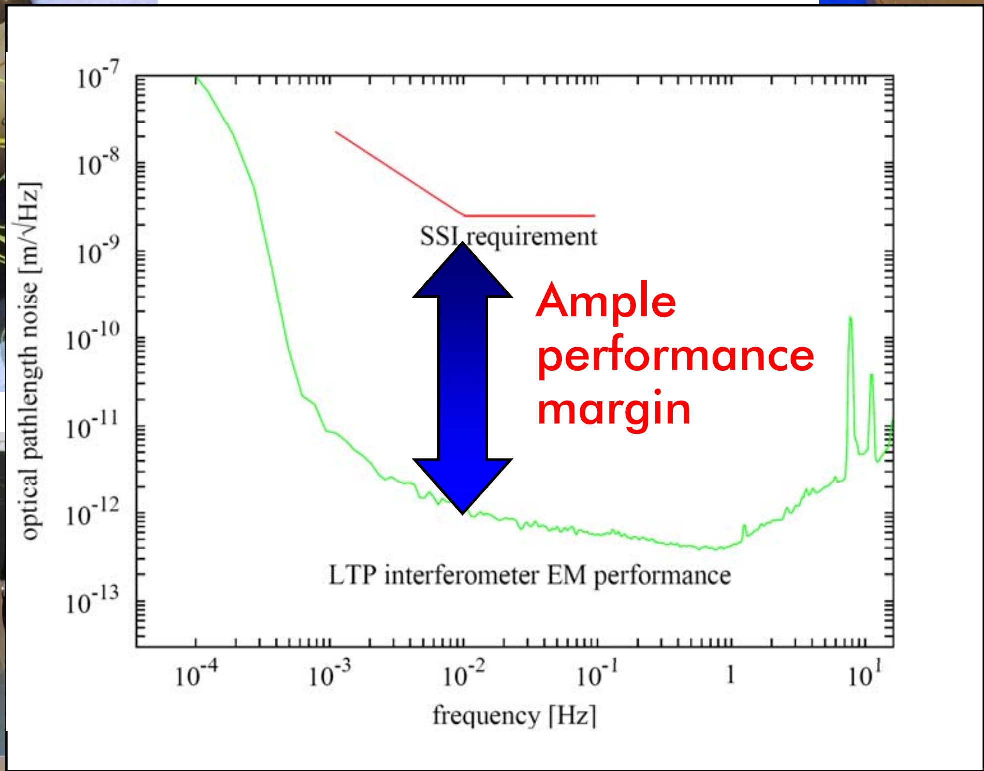
Interferometer technology overlap LISA ↔future geodesy missions

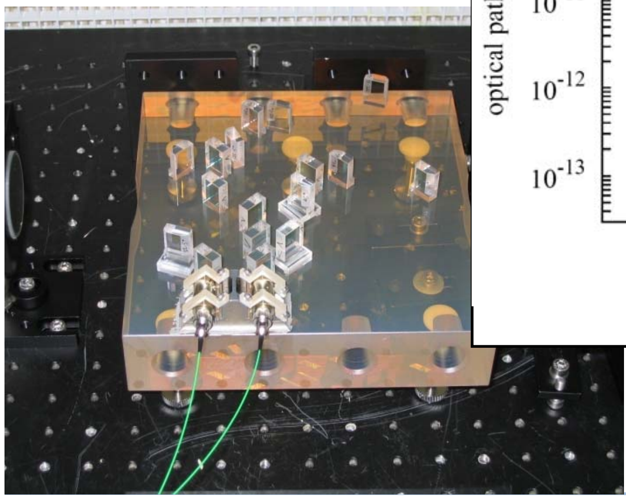
- Heterodyne laser interferometry on long distances with telecsopes
- Same frequency range (mHz)
- Stable optical benches
- Offset phase locking of lasers
- Phase measurement system
- Absolute ranging and clock syncronisation
- Optical sensing of a free floating test mass
- Data transfer on the optical link
- Alignment tracking and autonomous acquisition

Large overlap in technologies





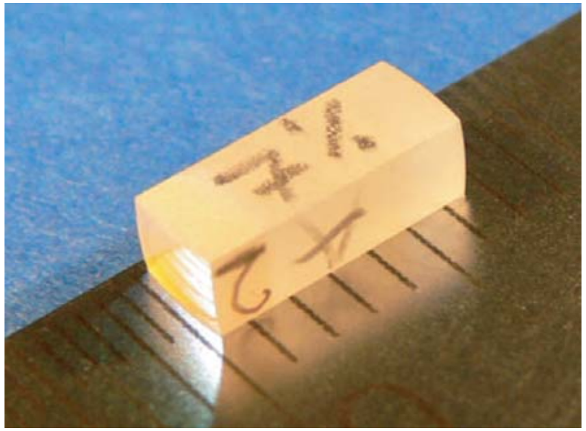




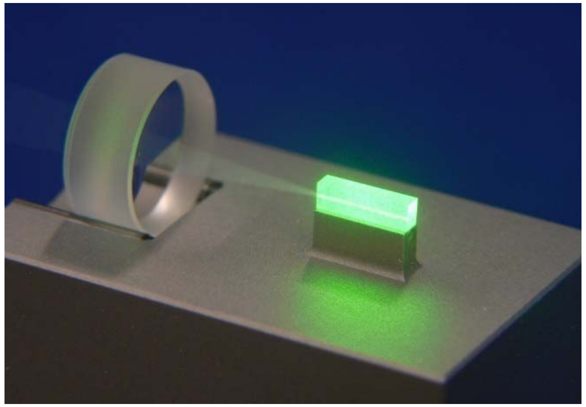
Roman Schnabel, LUH (IGP), Karsten Danzmann, LUH(IGP), AEI

Group “Non-Classical Interferometry”

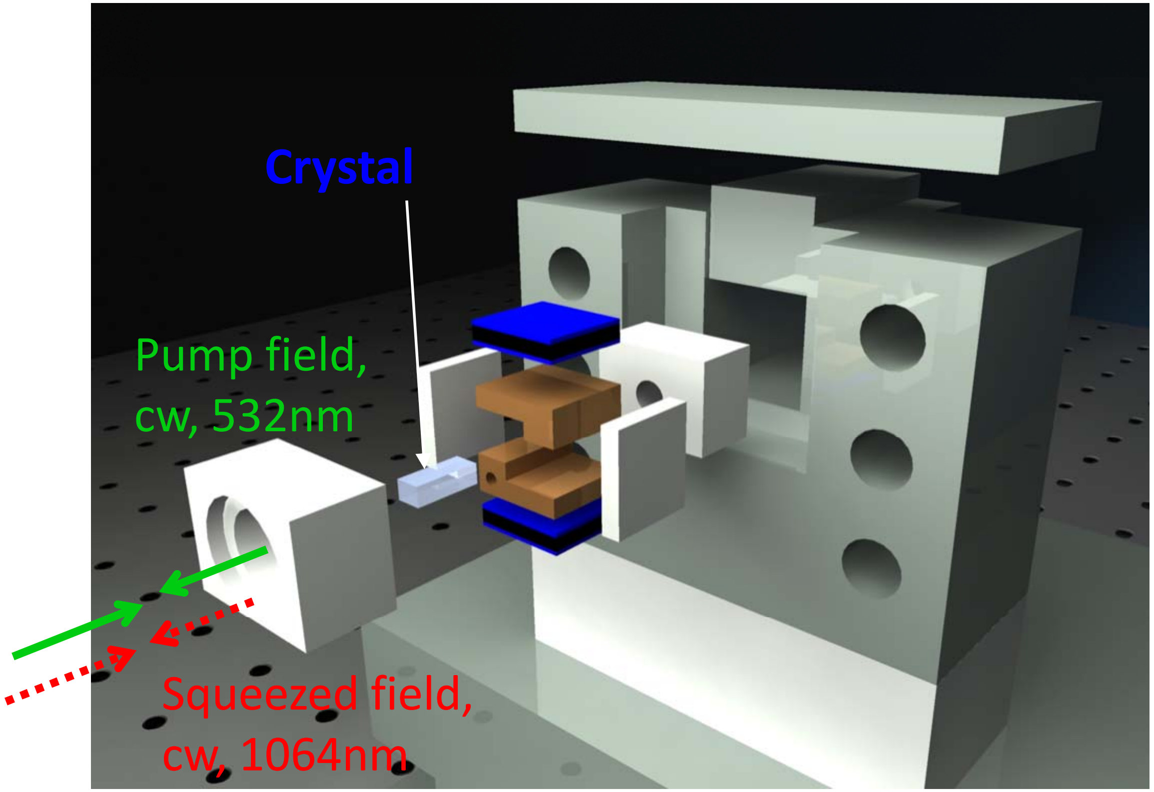
Generation of Squeezed Light



χ_2-nonlinear crystal: $MgO{:}LiNbO_3$

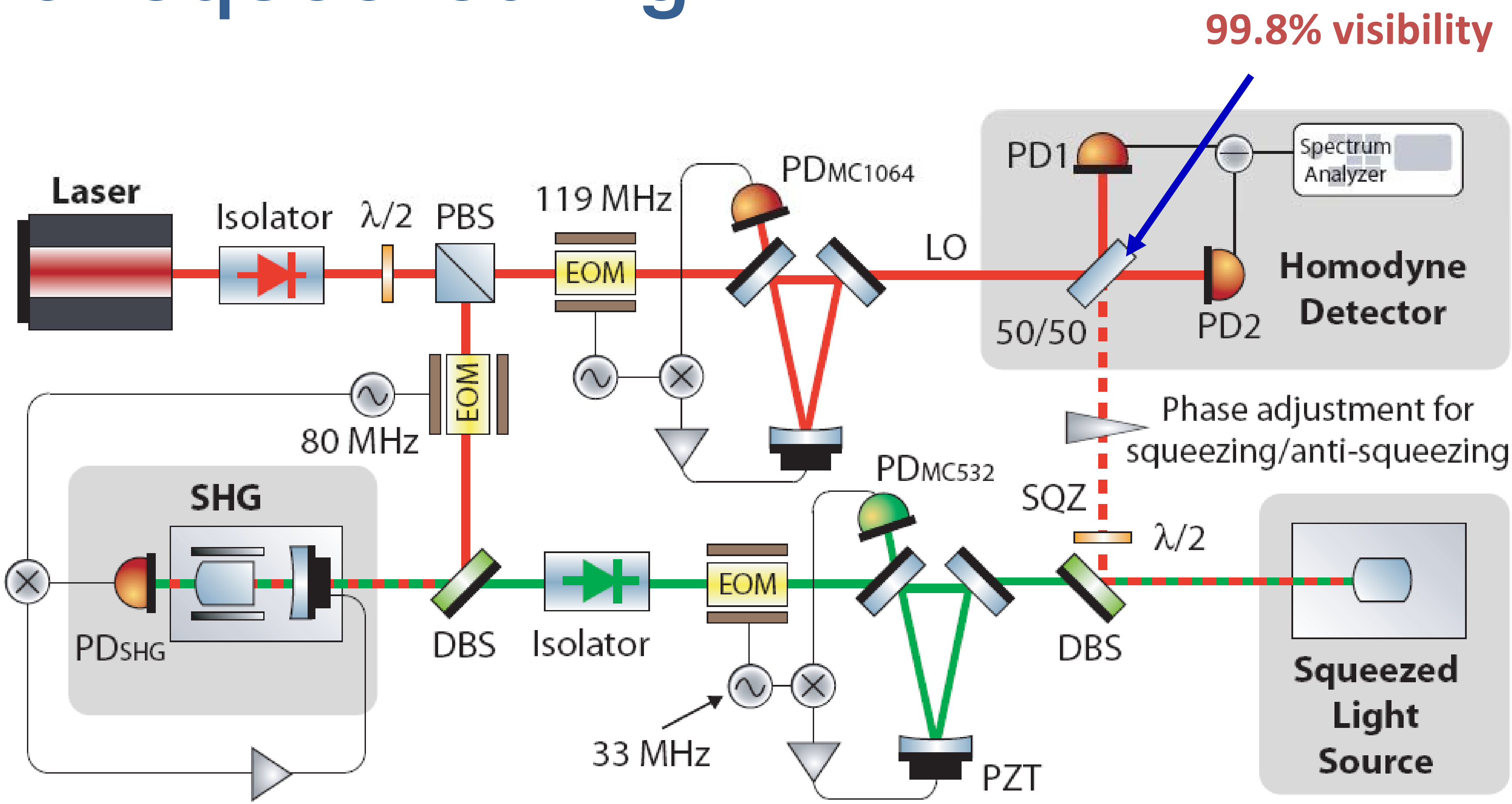


Standing wave cavity

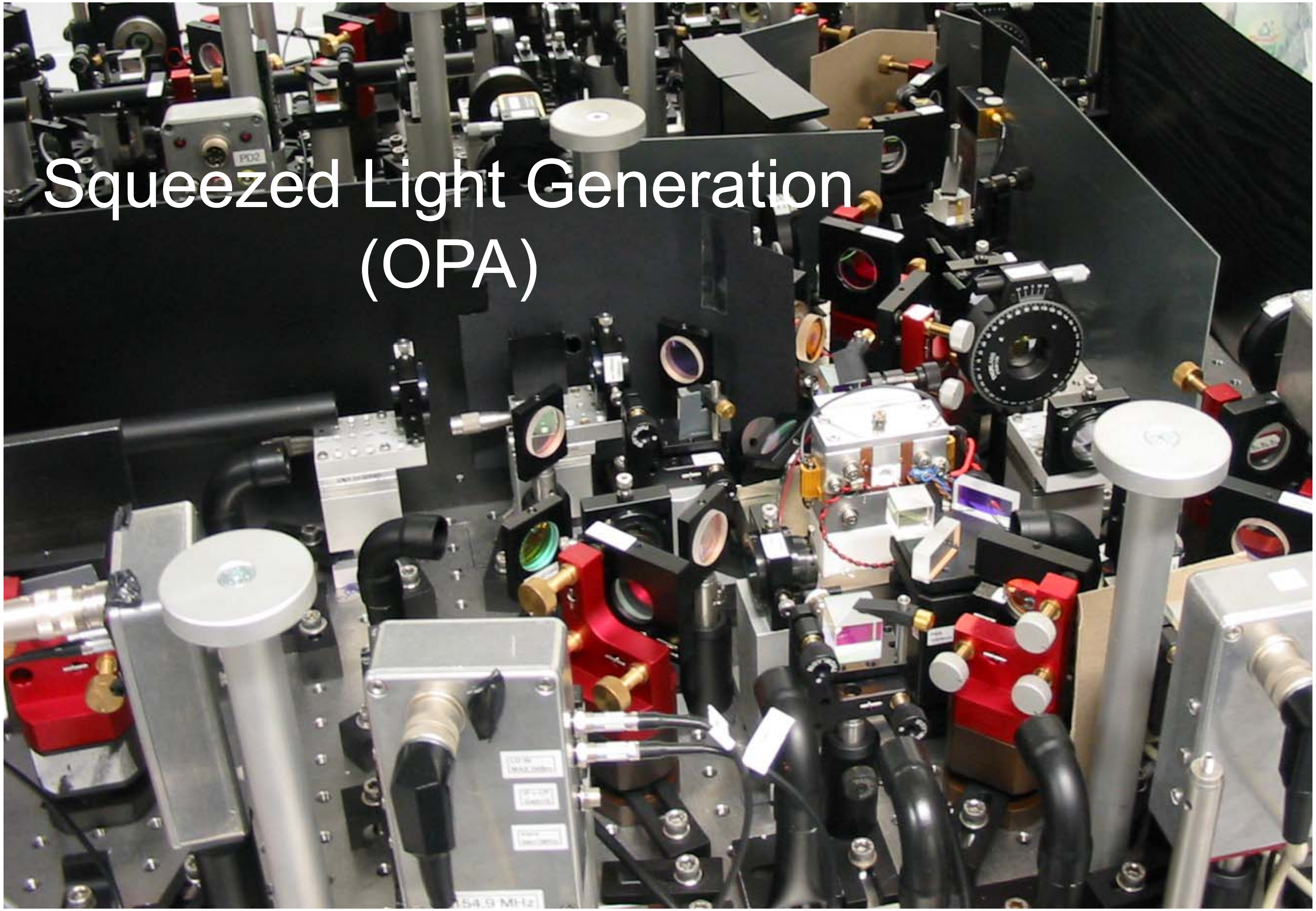


Crystal housing /
Squeezed light source
based on optical parametric amplification (OPA)

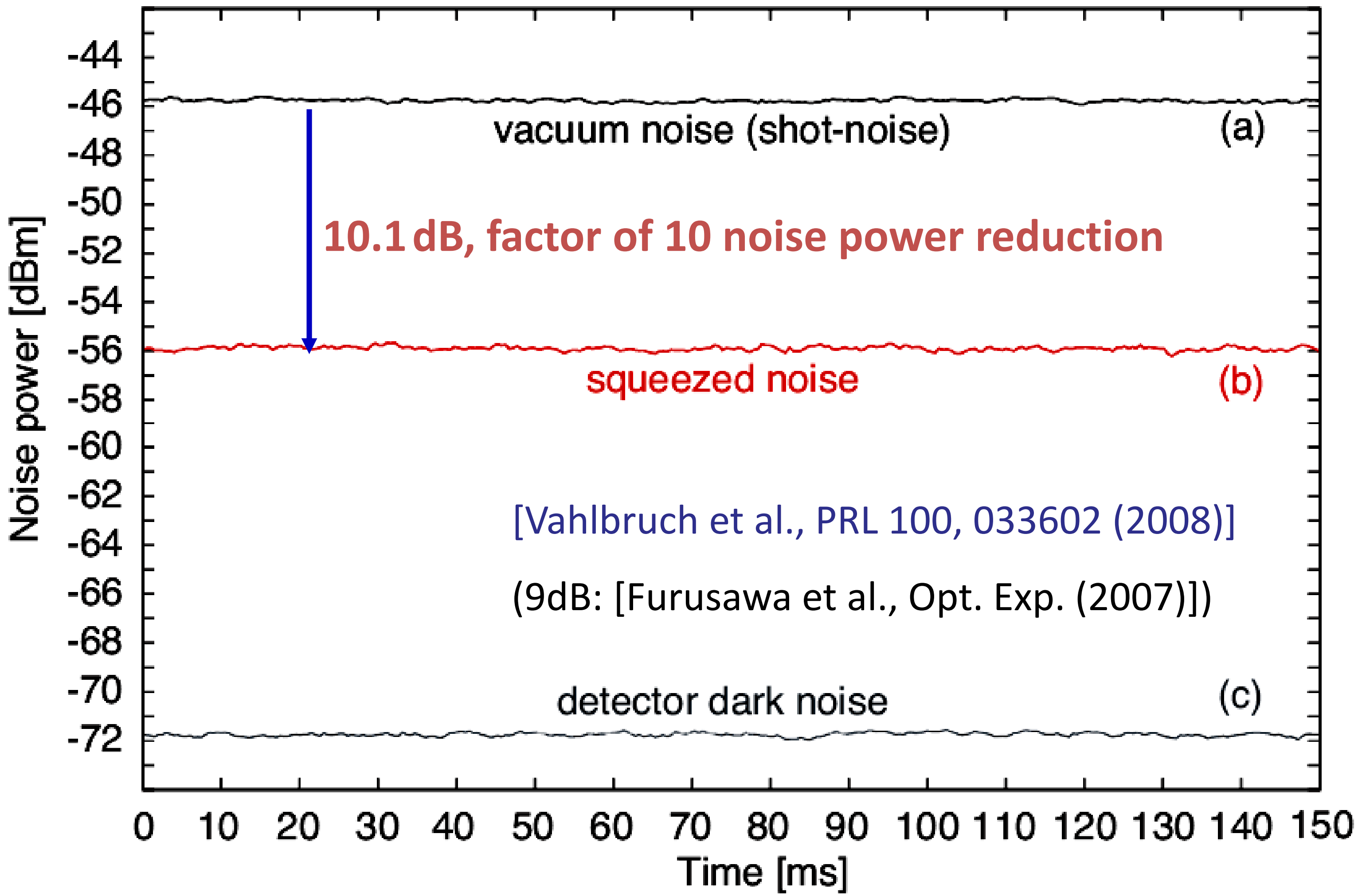
Generation and Observation of Squeezed Light



Squeezed Light Generation (OPA)

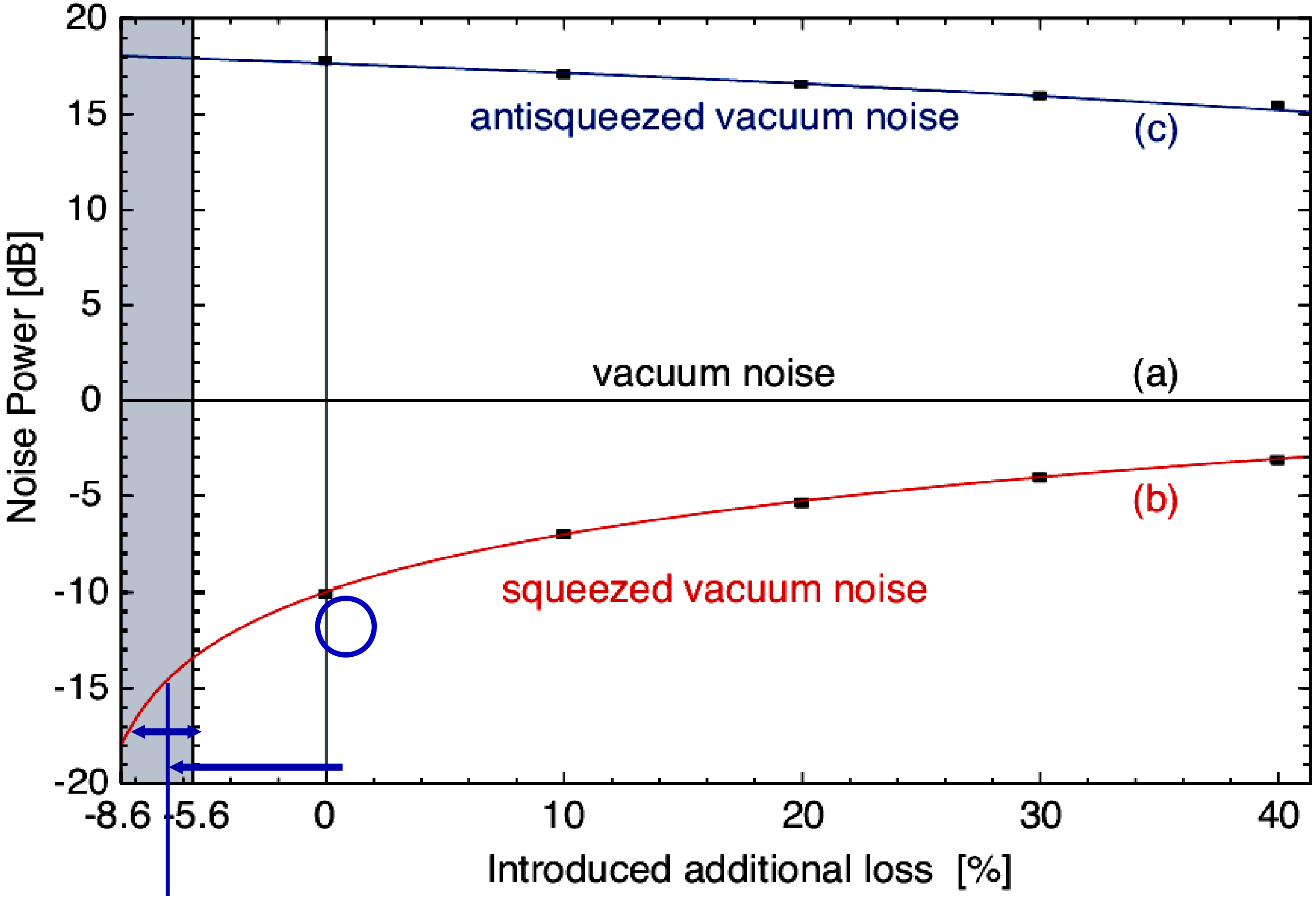


Observation of 10 dB Squeezing



[Vahlbruch et al., PRL 100, 033602 (2008)]

Observation of 10 dB Squeezing



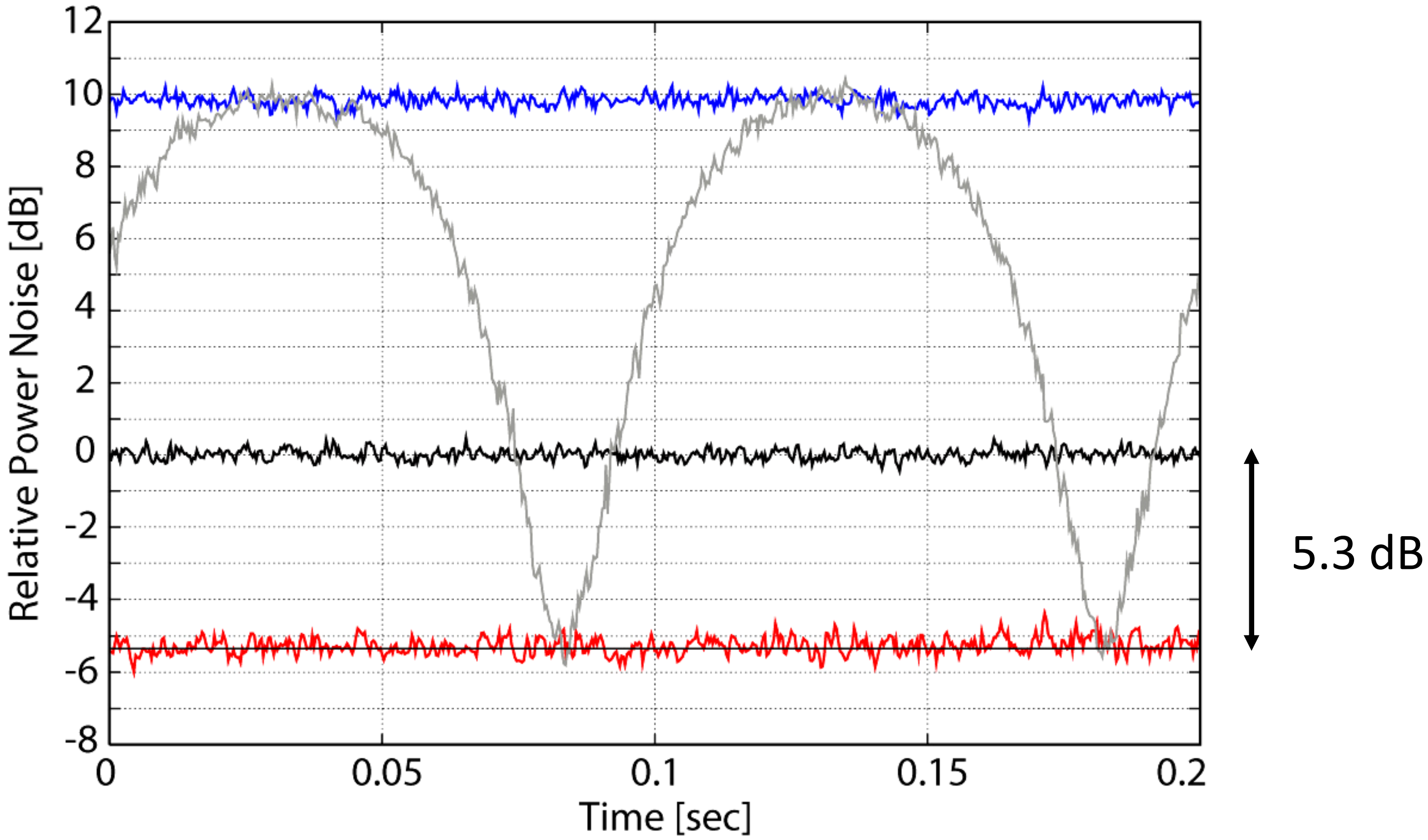
Intrinsic loss (7.1±1.5) %

New developments

- Observation of >5dB squeezing at 1550nm, which might be the wavelength of future GW detectors with silicon mirrors

[Mehmet et al., in preparation for Optics Letters (2008)]

Squeezing at 1550nm



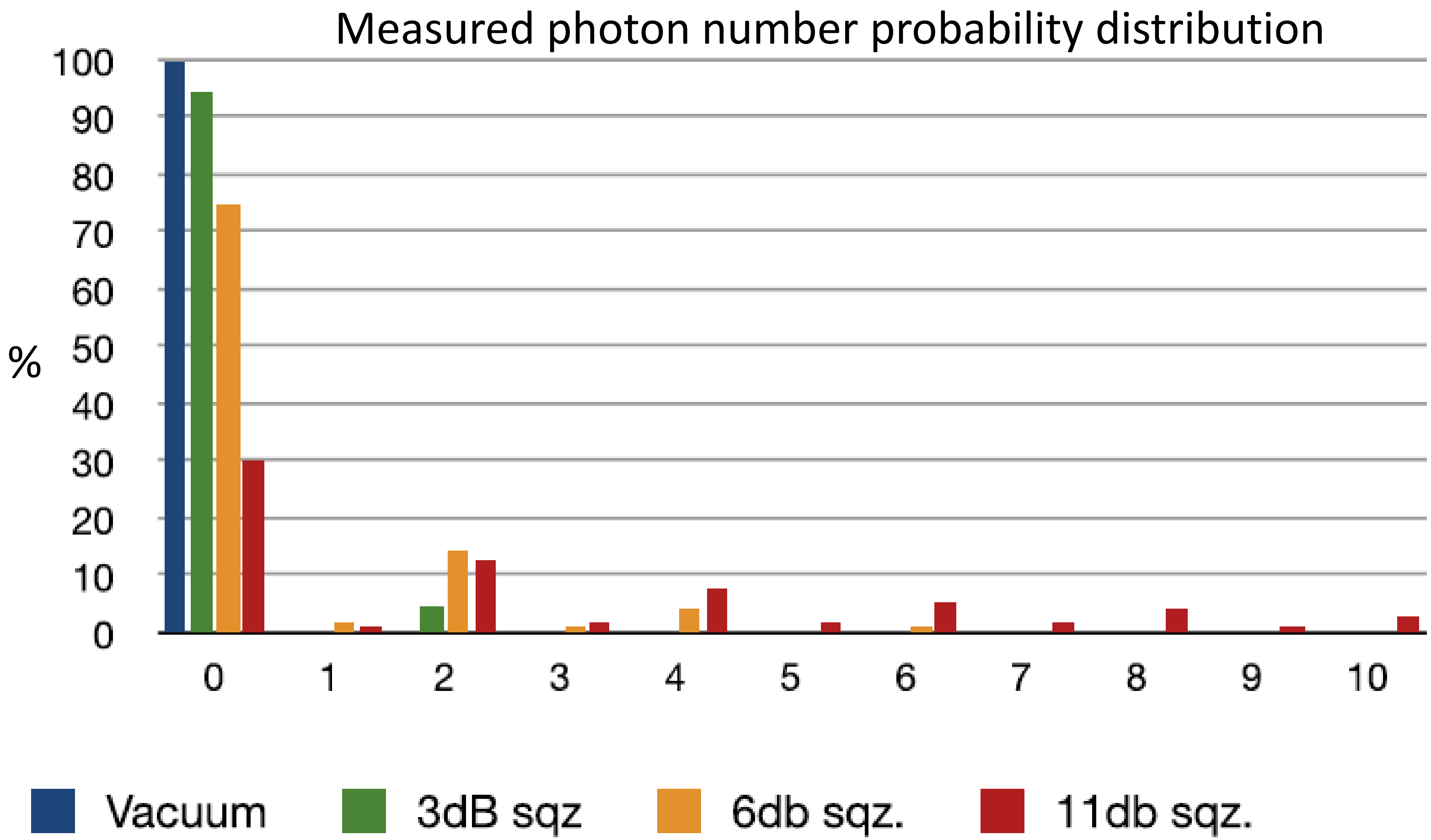
Noise powers of anti-squeezing, vacuum noise and squeezed noise, as well as for a scanned quadrature angle

Latest Results

- First observations of 11dB squeezing and strong photon number oscillations.

[Mehmet et al., in preparation for Nat. Photonics (2008)]

Squeezing in the Photon Picture



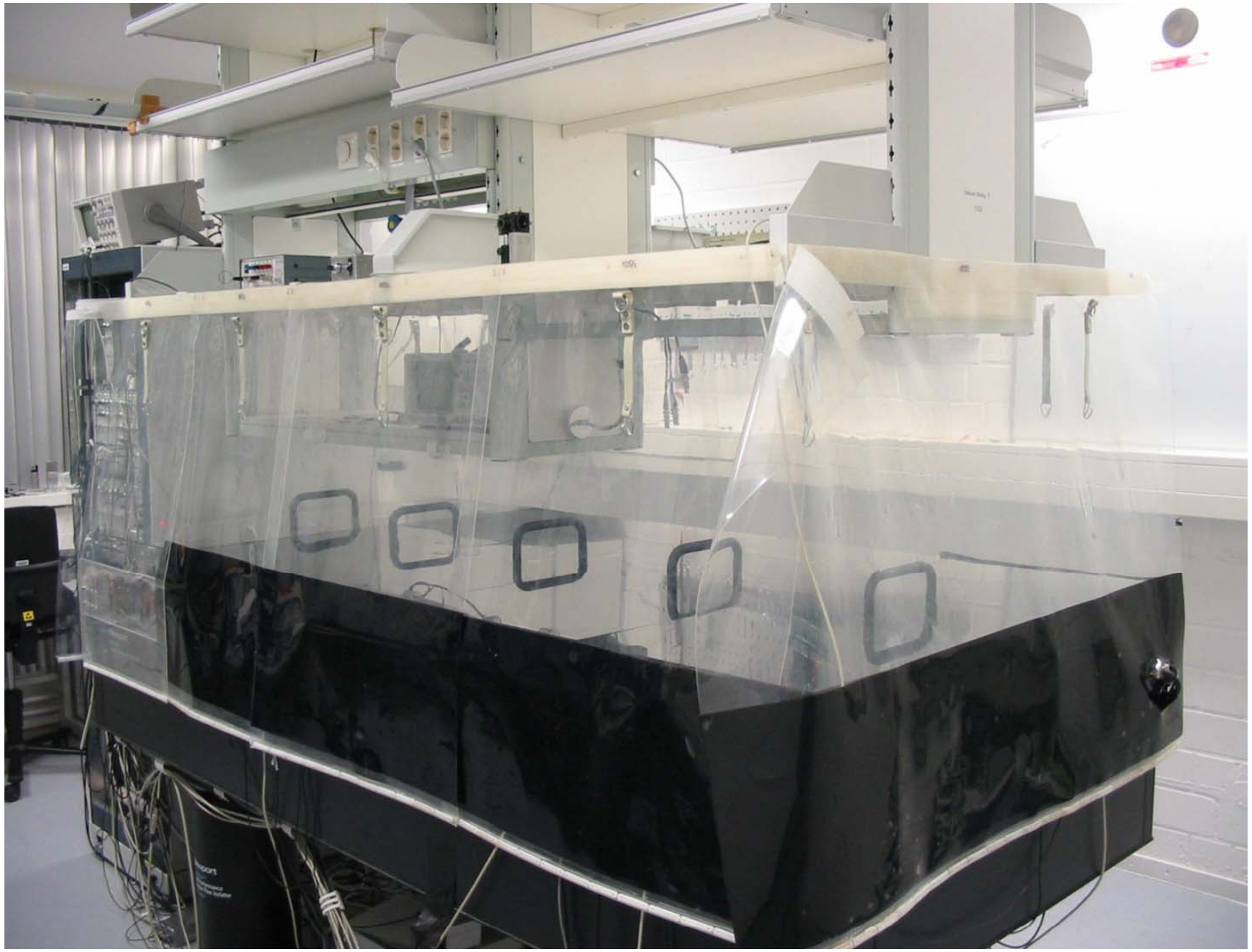
Applications

- Observation of squeezing at audio-band Fourier frequencies

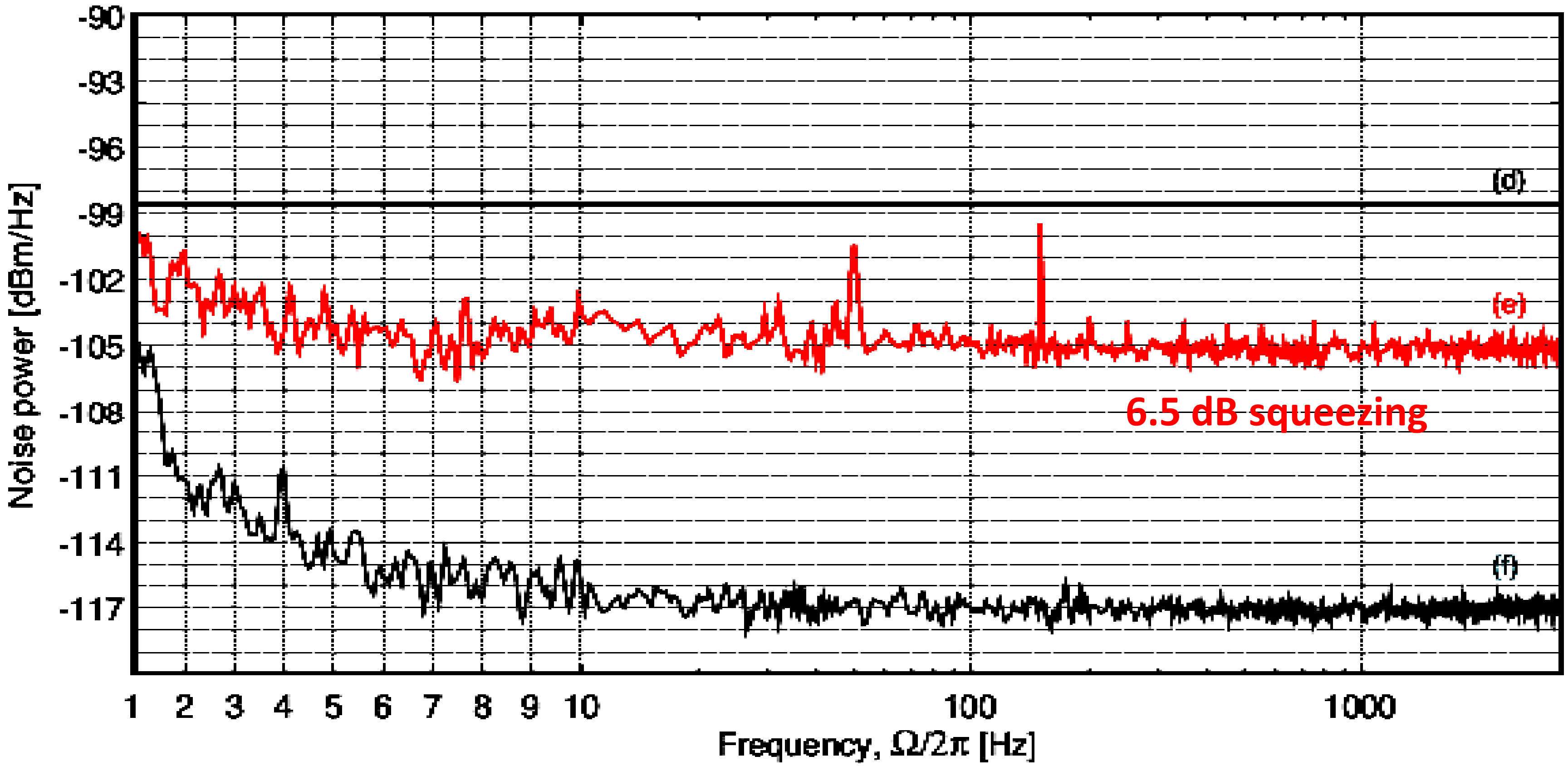
[Vahlbruch et al., New J. Phys. **9**, 371 (2007)]

Photographs show protection against scattered and frequency shifted photons

Squeezed light source for GEO600



Squeezed Light in the Audio-Band



(d) Vacuum noise level, P_{LO}= 464 μW
(e) Squeezed noise, P_{LO}= 464 μW
(f) Electronic dark noise

[H. Vahlbruch *et al.*, New J. Phys. **9**, 371 (2007)]
First audio-band squeezing:
[McKenzie, Phys. Rev. Lett. **93**, 161105(2004)]

Macroscopic Entanglement

- Proposal for the generation of entangled mirrors (entanglement of positions and momenta of centre of masses of two suspended mirrors)

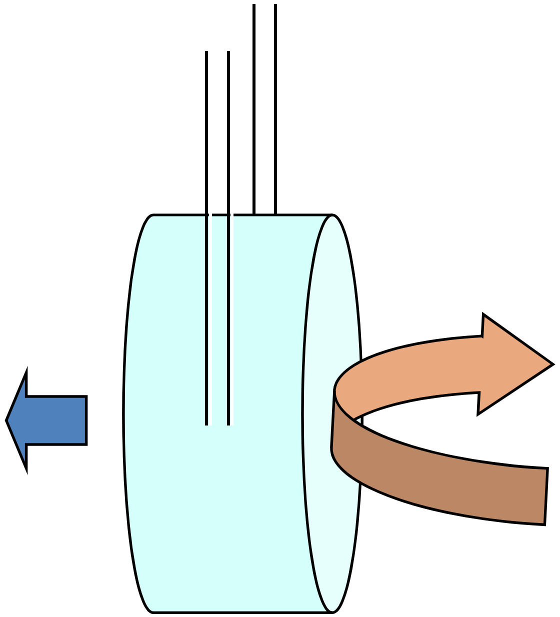
[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, and Chen, PRL 100, 013601 (2008)]

Semi-popular articles:

[Schnabel, Spektrum der Wissenschaft (2008)]

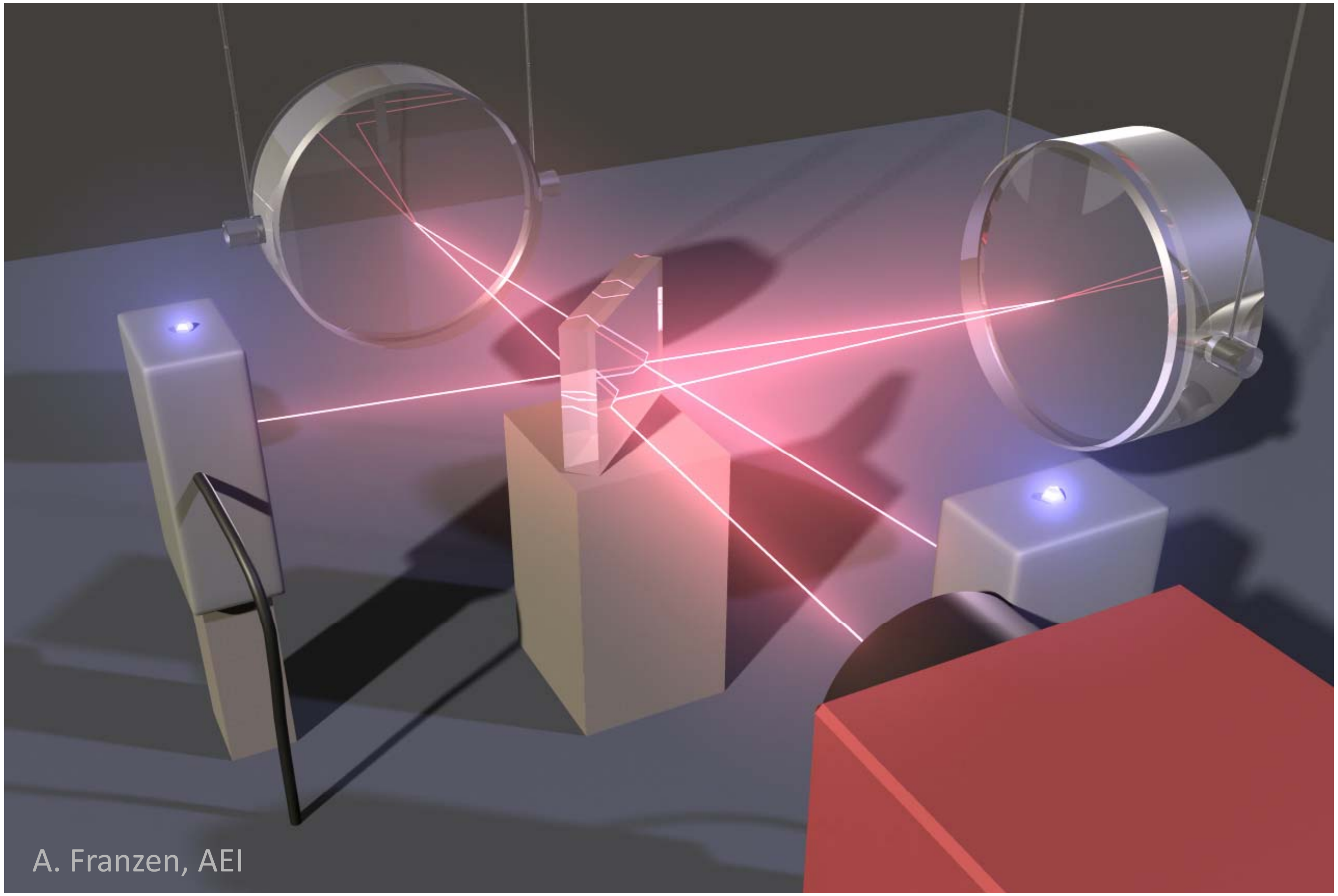
[Schnabel, Müller-Ebhardt, Rehbein, Physik in Unserer Zeit 39, 234 (2008)]

Light / Mirror Quantum Systems



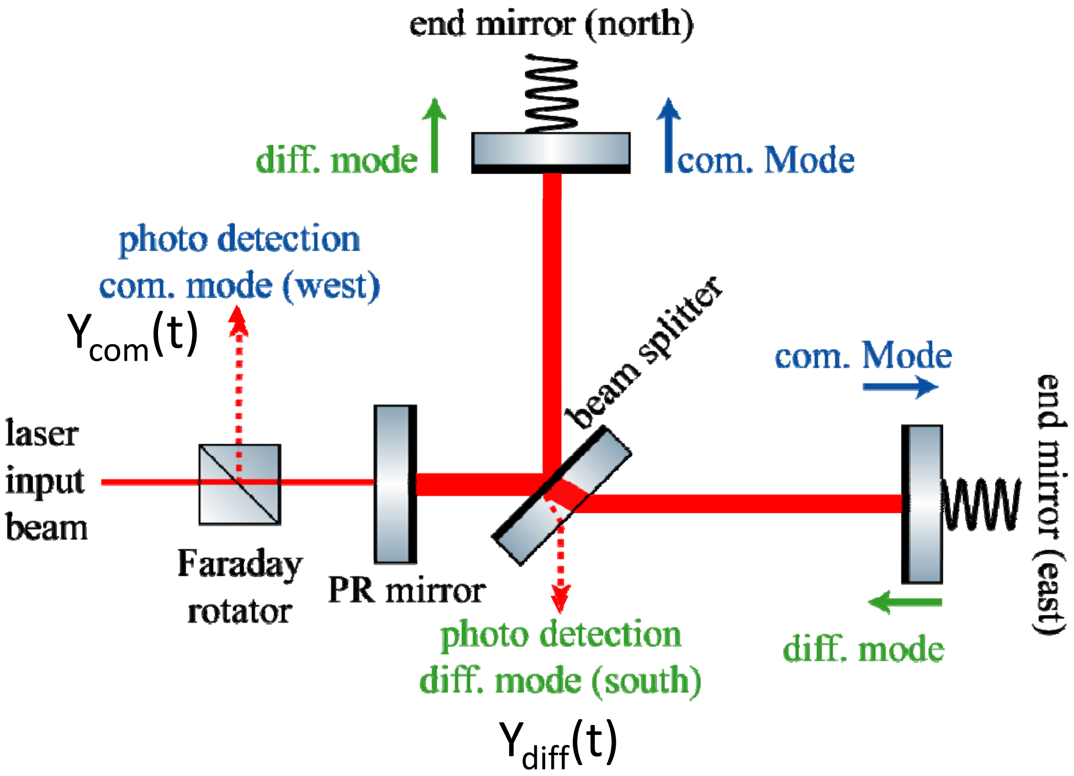
Radiation pressure
coupling of light and mirror

Entangled Mirrors

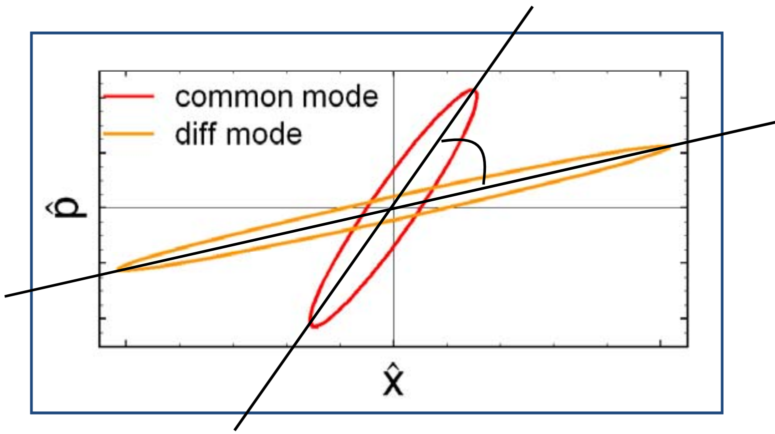


[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, and Chen, PRL 100, 013601 (2008)]

Entangling Test Masses

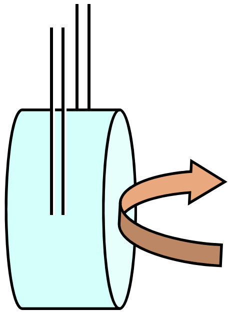


Additional detection of bright port can provide quantum regime for also the common mode.



[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, Chen, PRL 100, 013601 (2008)]

Entangled Mirrors

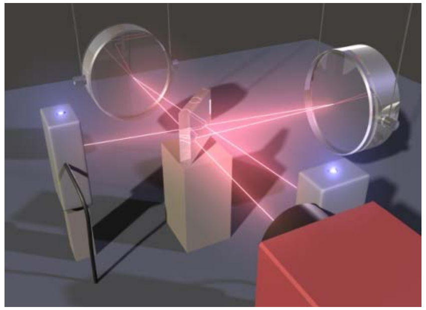


Radiation pressure entangles mirror motion and the light's quadratures

[Vitali *et al.*, Phys. Rev. Lett. 98, 030405 (2007)]

Interference at beam splitter realizes entanglement swapping

[Pirandola *et al.*, Phys. Rev. Lett. 97, 150403 (2006)]



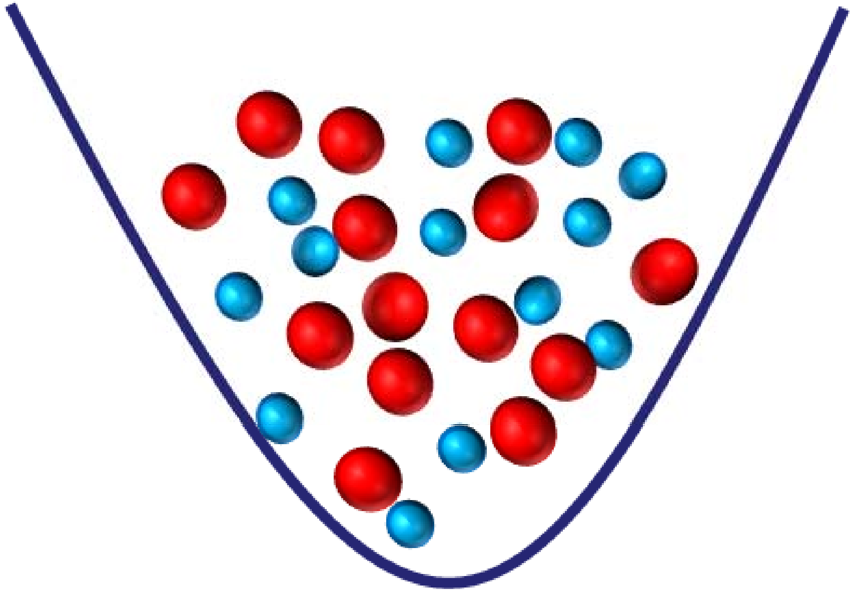
Problem of back-action noise and thermal noise can be solved through conditional states

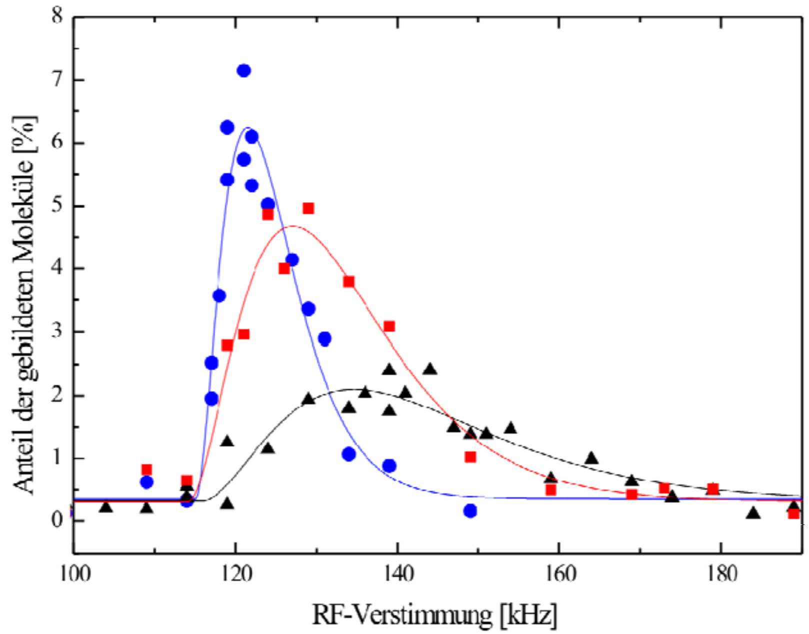
[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, and Chen, Phys. Rev. Lett. 100, 013601 (2008)]

Jan Arlt, Carsten Klempt, W.E., LUH (IQ)

Group "Quantum Engineering with Ultra Cold Gases"

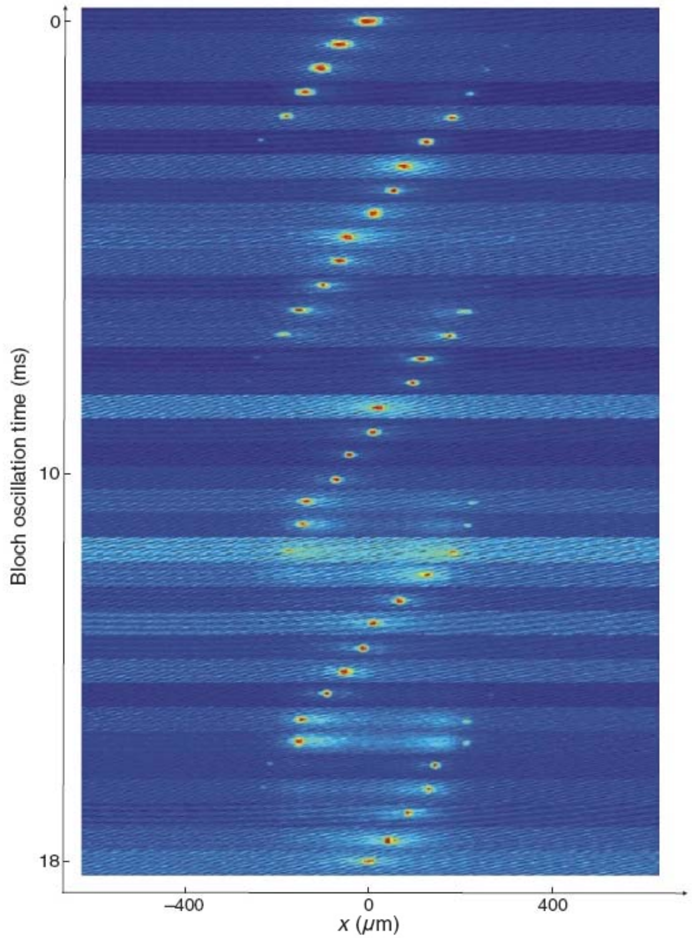
Association of heteronuclear molecules

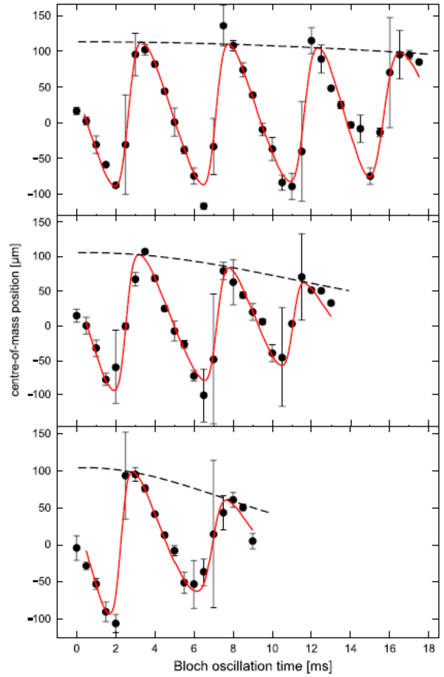




Radio frequency association of heteronuclear Feshbach molecules
C. Klempt, T. Henninger, O. Topic, M. Scherer, L. Kattner, E. Tiemann, W. Ertmer and J. J. Arlt
Accepted in Phys. Rev. A (R)

Damping in disordered systems





Damped Bloch Oscillations of Bose-Einstein Condensates in disordered Potential Gradients

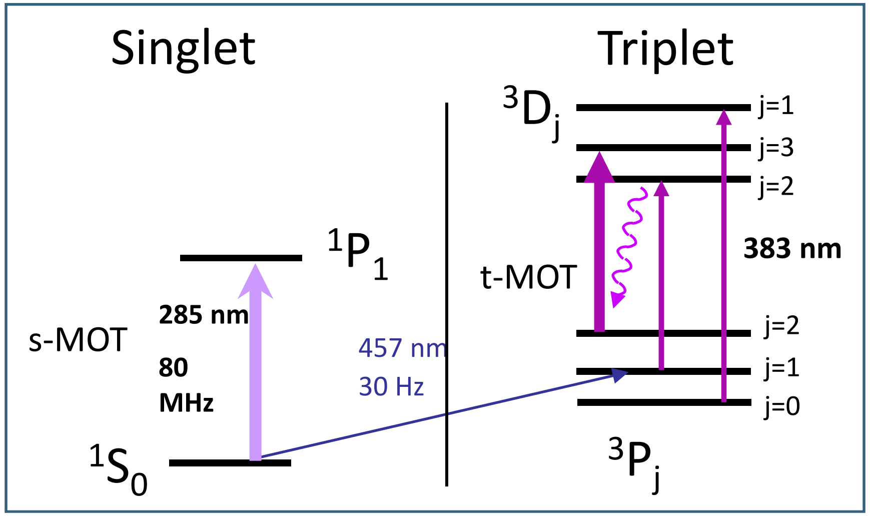
S. Drenkelforth, G. Kleine Büning, J. Will, T. Schulte, N. Murray, W. Ertmer, L. Santos, and J.J. Arlt

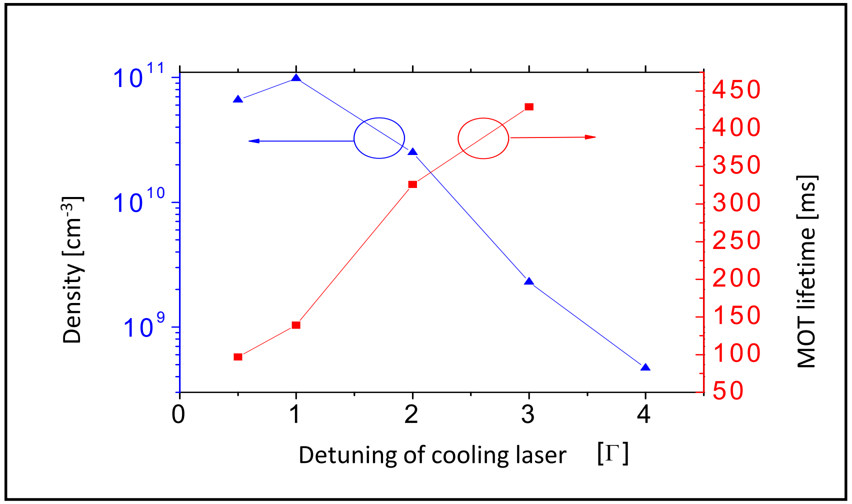
New J. Phys. 10, 045027 (2008).

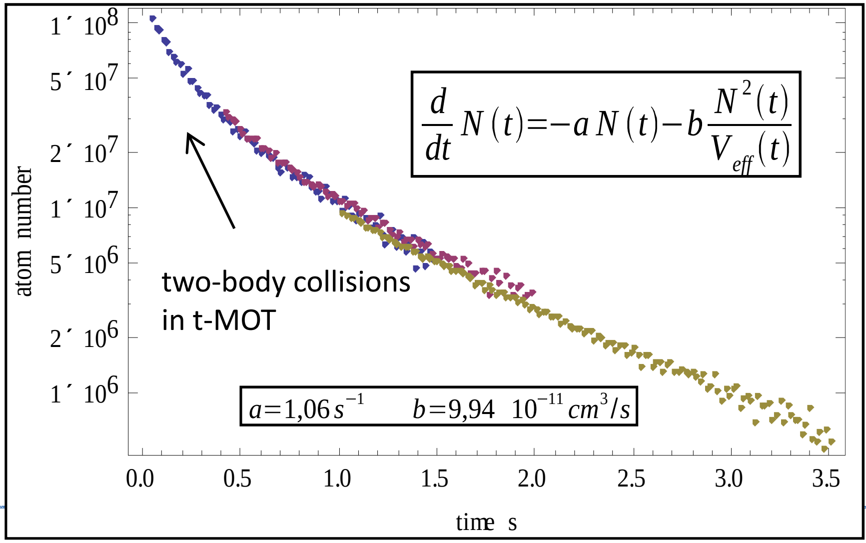
Ernst Rasel, W.E., LUH (IQ)

Group "Atomic Quantum Sensors"

Cooling Metastable Magnesium







s(singlet)-MOT: $^1S_0 \rightarrow {}^1P_1$;10^9 atoms, 3 mK

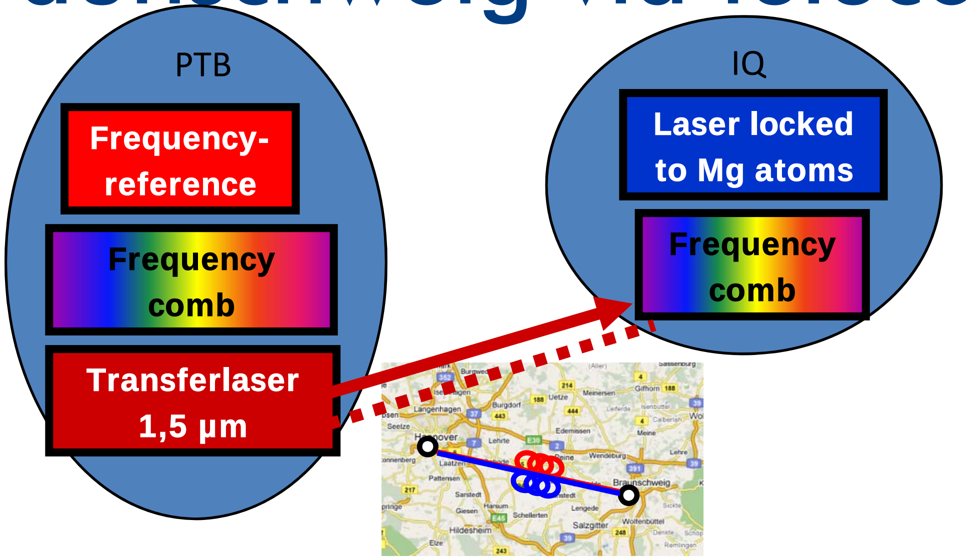
t(triplet)-MOT: $^3P_2 \rightarrow {}^3D_3$;2 10^8 atoms, 1 mK

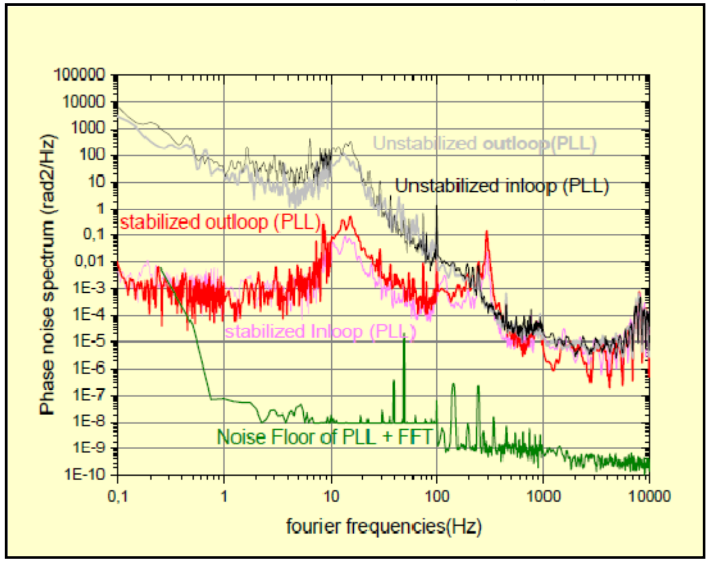
polarisation gradient cooling possible → μK

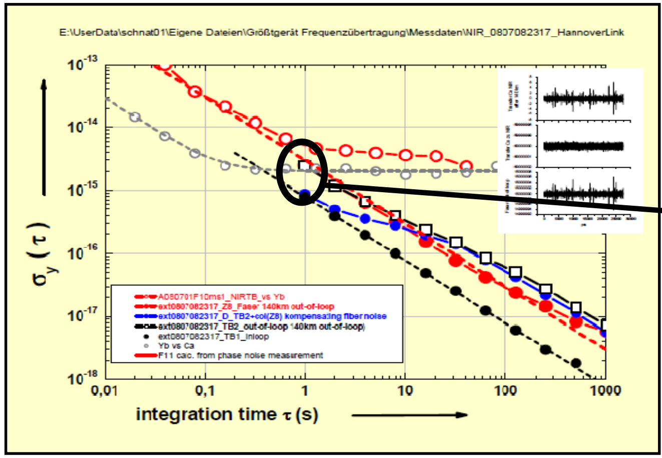
Next steps:

- Optical molasses cooling, dipole trap
- Investigations of collisions

Frequency comparison Hannover-Braunschweig via telecom fiber network







- Servo bandwidth of approx. 200 Hz limited by length of fiber link

- stabilized fiber link shows Allan standard deviation of transferred light of

$$\sigma_y(\tau) = 2.5\text{x}10^{-15}\,\tau^{-1}$$

H. Schnatz, G. Grosche, PTB

L.-S. Ma et al., Opt. Lett. **19** (21), 1777 (1994); G. Grosche et al., CMKK1, Proceed. CLEO 2007

Summery

- Establishment of QUEST as new Research Centre on a very promising track
  - In total 9 new Professorships
    - most positions filled beginning 2009
  - 17 Post-Docs and Junior-Professorships
  - 31 PhD-Positions
- New developments in quantum engineering, space-time research and its applications for fundamental and applied research

Thank you very much for attention