Radiation Pressure Noise Experiment in Hannover

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0.Abstract

Radiation pressure noise measurement

with extremely light

but translucent mechanical oscillator

New topology : Michelson-Sagnac interferometer

Theoretical outlines

Current status of experiment

Future work

Contents

1.Introduction

Interferometric gravitational wave detector

Current : First generation (LIGO,VIRGO,GEO,TAMA,CLIO)

Future : Second generation

(Advanced LIGO and VIRGO, LCGT)

Third generation (Einstein Telescope)

↓

Quantum noise

Shot noise : Phase fluctuation

Radiation pressure noise : Amplitude fluctuation

1. Introduction
Radiation pressure noise (1)

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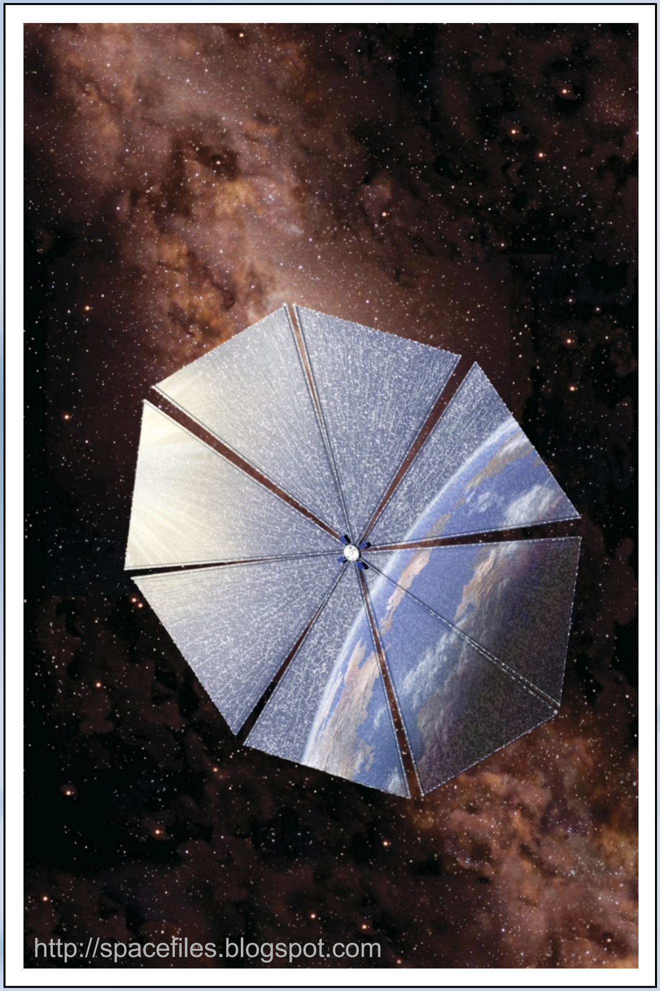
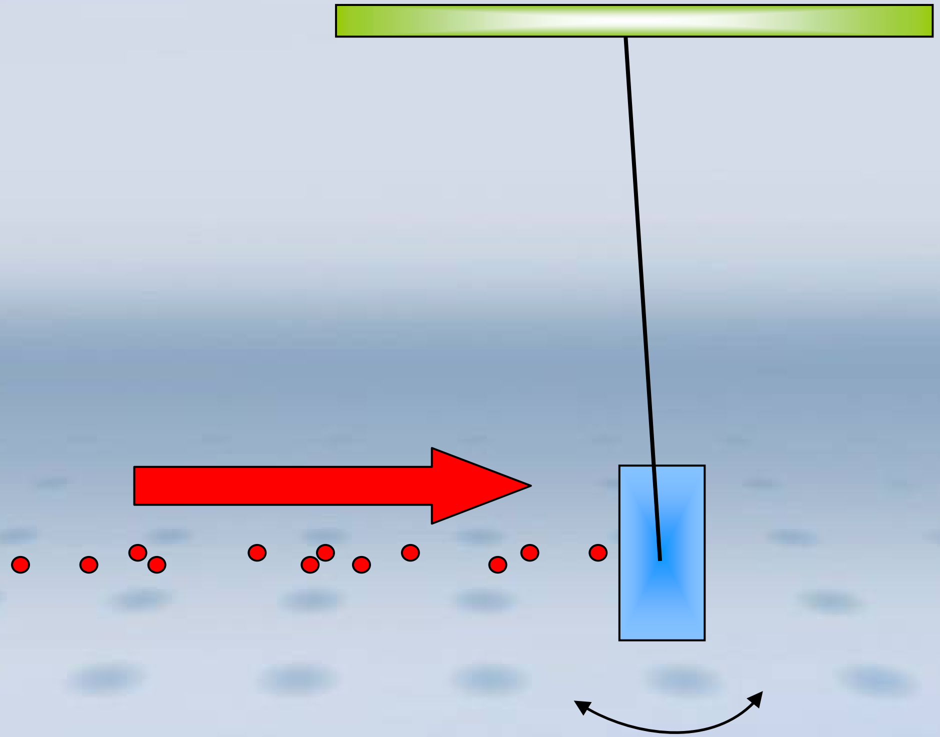




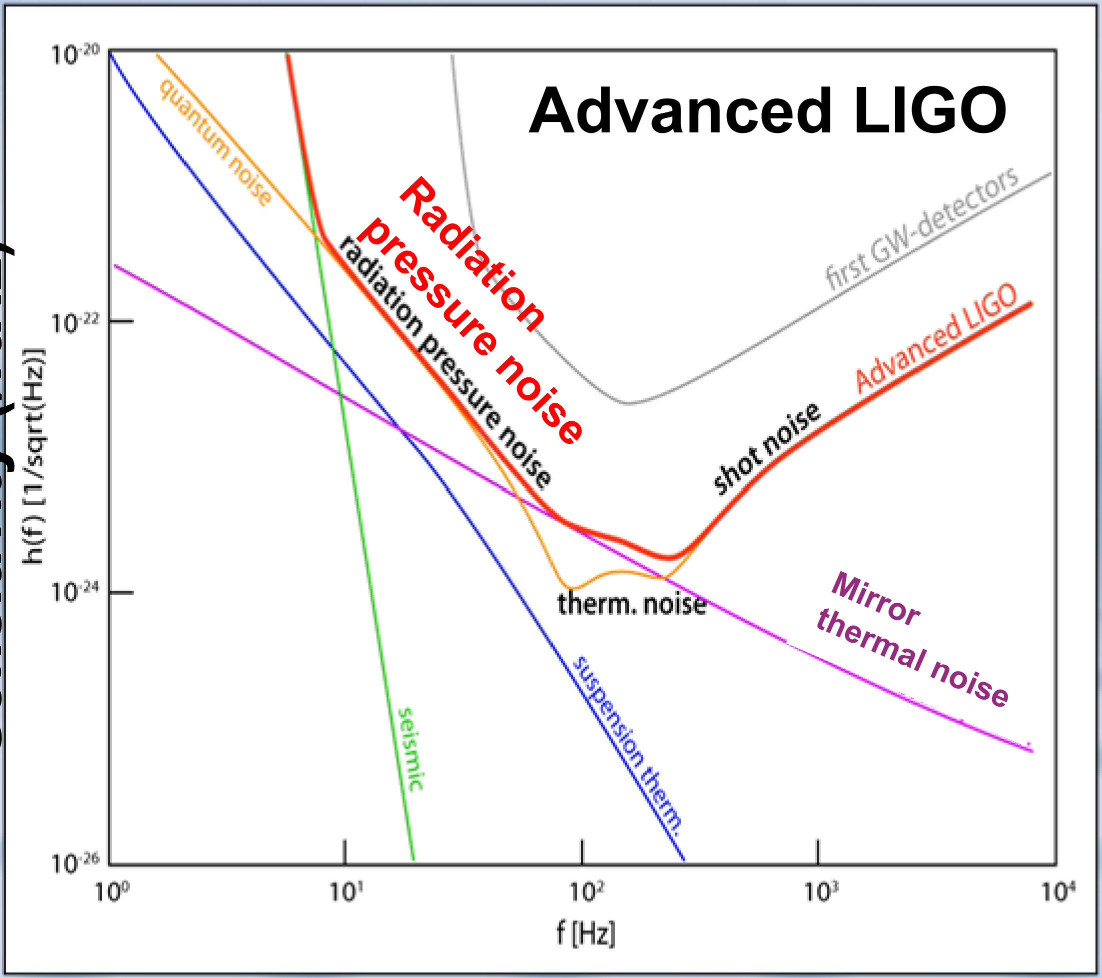
Photons come at random (amplitude fluctuation).

Back action of photon is also at random.

→ Radiation pressure noise

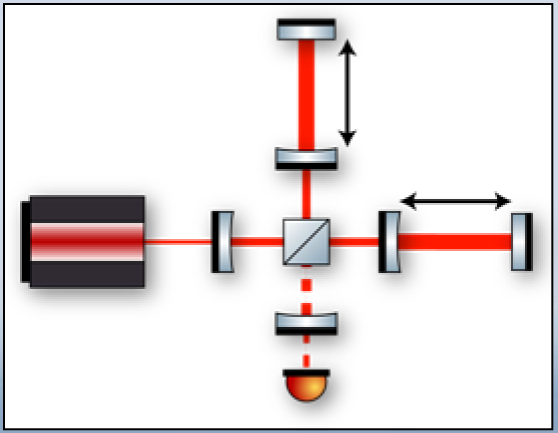
1. Introduction

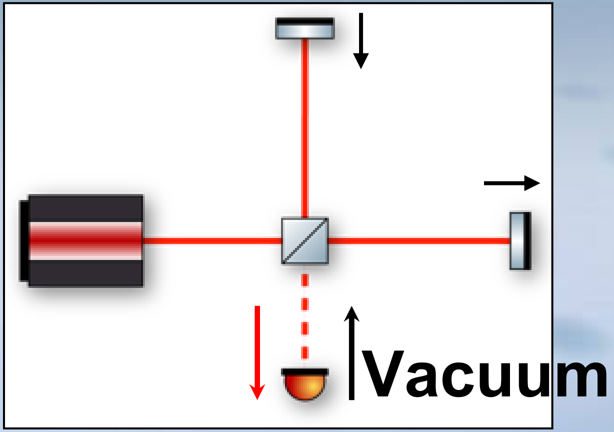
Radiation pressure noise



Sensitivity (/rtHz)

Frequency(Hz)

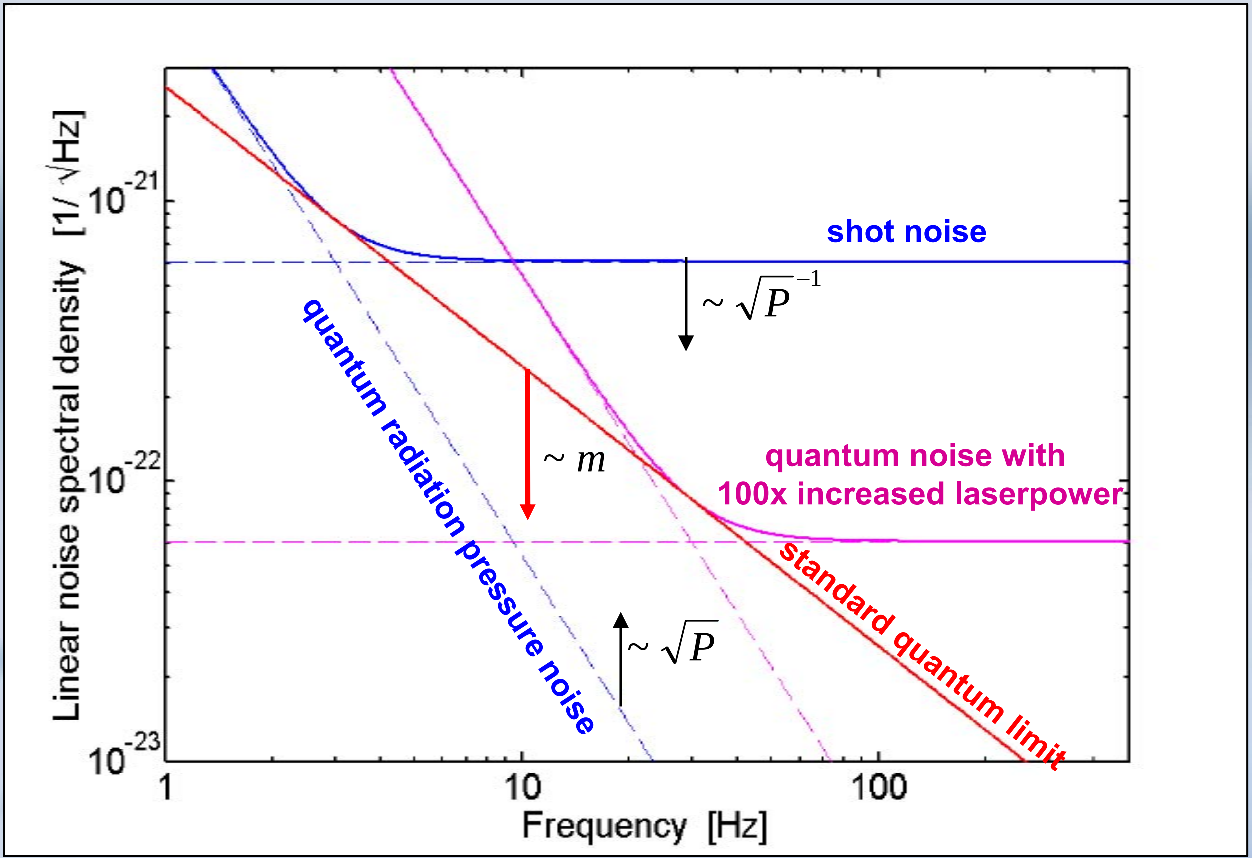




SQL is a fundamental limit for conventional interferometer.

[Standard Quantum Limit (SQL) < Quantum noise]

Nobody observed radiation pressure noise !



Large radiation pressure noise

↓

High laser power
Light mass

1. Introduction

Sizes of oscillators

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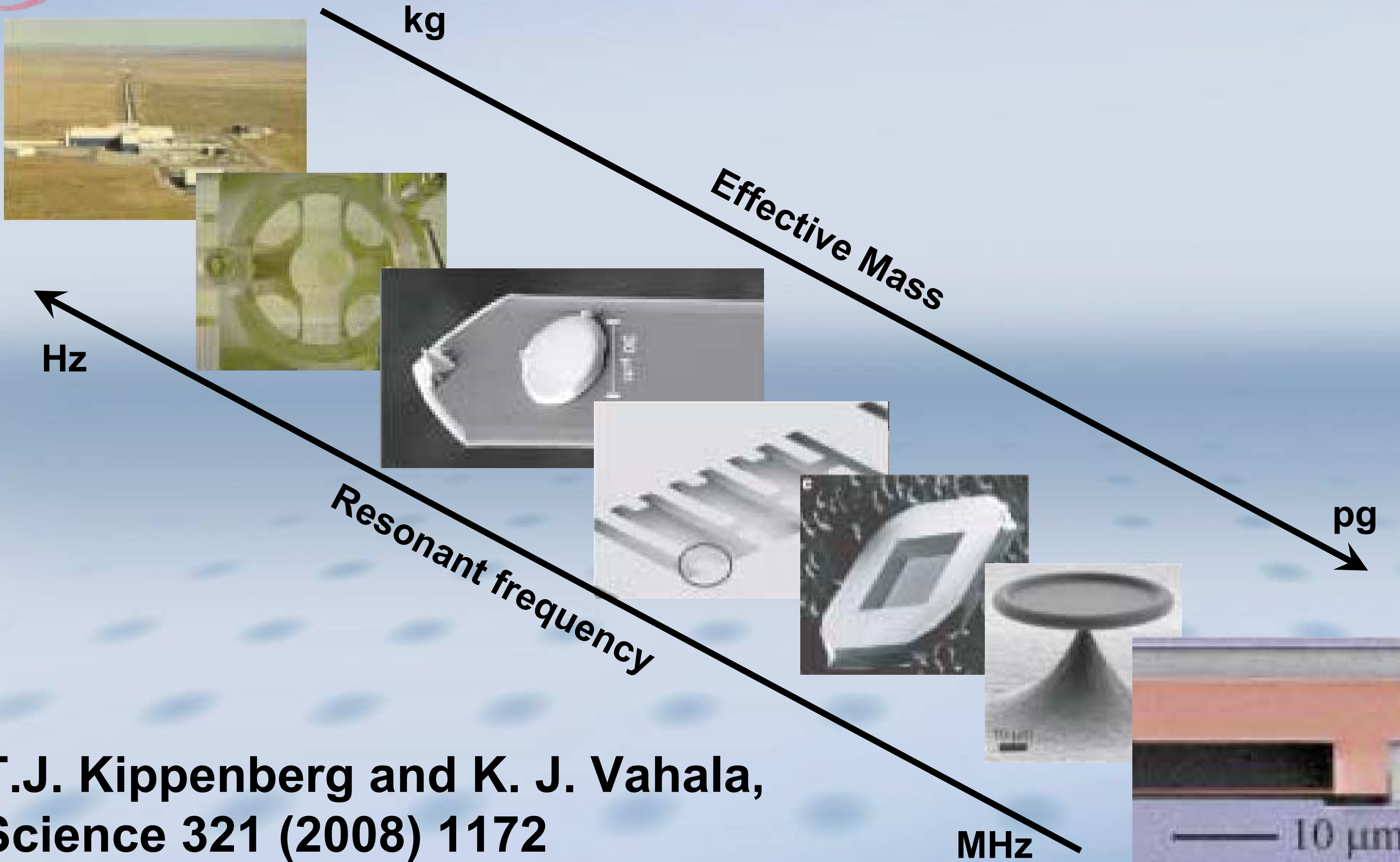
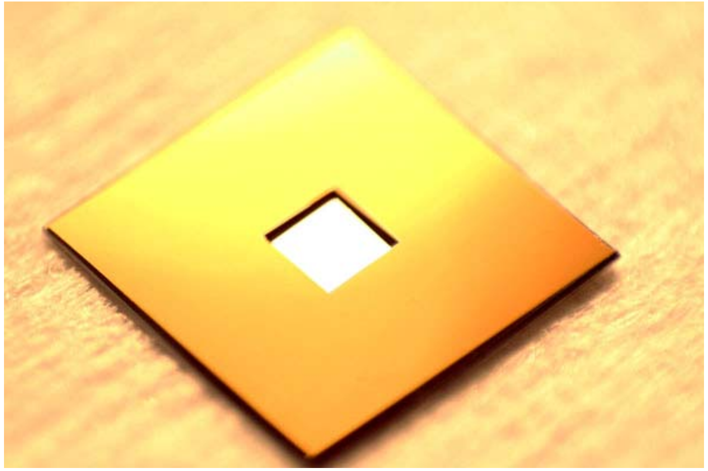


T.J. Kippenberg and K. J. Vahala, Science 321 (2008) 1172

1. Introduction

Membrane (Si_3N_4 in frame)



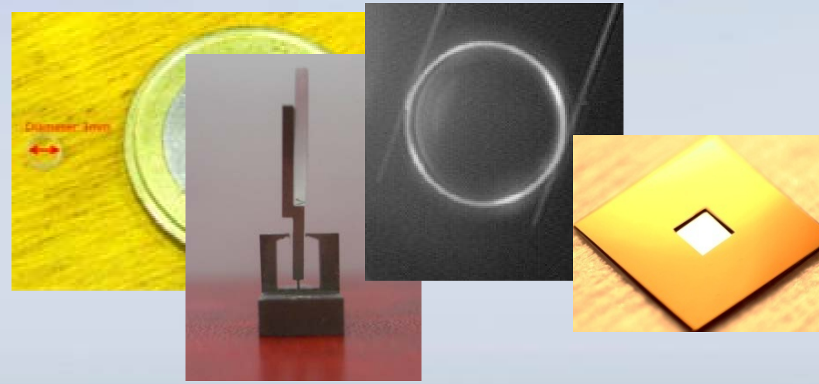
Mechanical properties

frame: $7{,}5^2$ mm² x 200 µm
Area: 1,5 mm x 1,5 mm
Thickness: 75 nm
Effective mass: ~ 100 ng
Resonant frequency: ~ 73 kHz

J.D. Thompson *et al.*, Nature 452 (2008) 72-76.

1. Introduction

compare different approaches

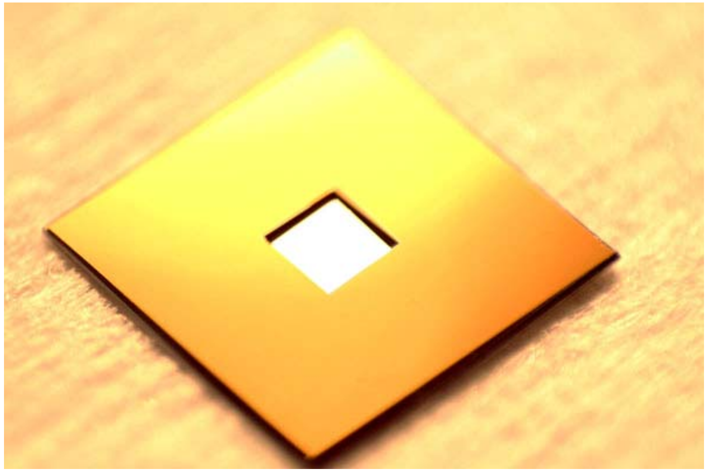


	GEO600	LIGO[3]	Adv. LIGO[3]	Sakata[1]	Goßler[2]	Corbitt[3]	Ours[4]
$m_{eff.}$	1 kg	2,5 kg	10 kg	23 mg	0,5g	1 g	50 ng
P [kW]	10	10	830	1,2	0,003	20	0,06
P/m [kW/kg]	10	4	83	$52*10^3$	6	$20*10^3$	**$1,2*10^9$**
√P/m [√kW/kg]	3	1,3	2,9	48000	110	4500	**$5*10^9$**

[1] N. Mavalvala, Elba conference (2008)
[2] C.M. Mow-Lowry *et al*., Journal of Physics:Congerence Series 32 362-367 (2006)
[3] T. Corbitt, Elba conference (2008)
[4] J.D. Thompson *et al*., Nature 452 72-76 (2008)

1. Introduction

Membrane (Si_3N_4 in frame)



Mechanical properties

frame: $7{,}5^2$ mm² x 200 µm
Area: 1,5 mm x 1,5 mm
Thickness: 75 nm
Effective mass: ~ 100 ng
Resonant frequency: ~ 73 kHz

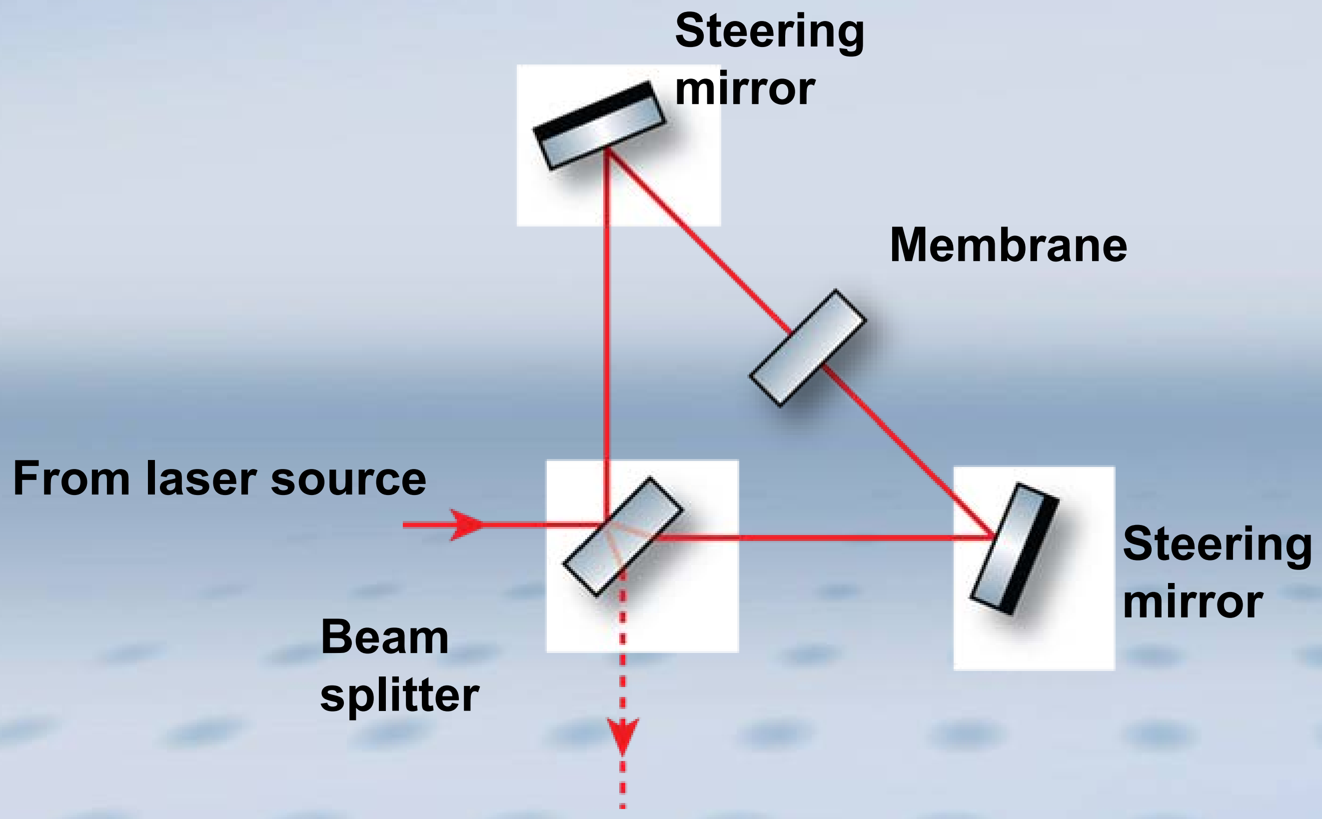
Optical properties

Power Reflectance: ~ 33%
Absorption: ≤ 150 ppm
Flatness: 1 nm?
Micro roughness: 0,2 nm?
Scattering: → 0

J.D. Thompson *et al*.,
Nature 452 (2008) 72-76.

1. Introduction

Michelson-Sagnac interferometer(1)

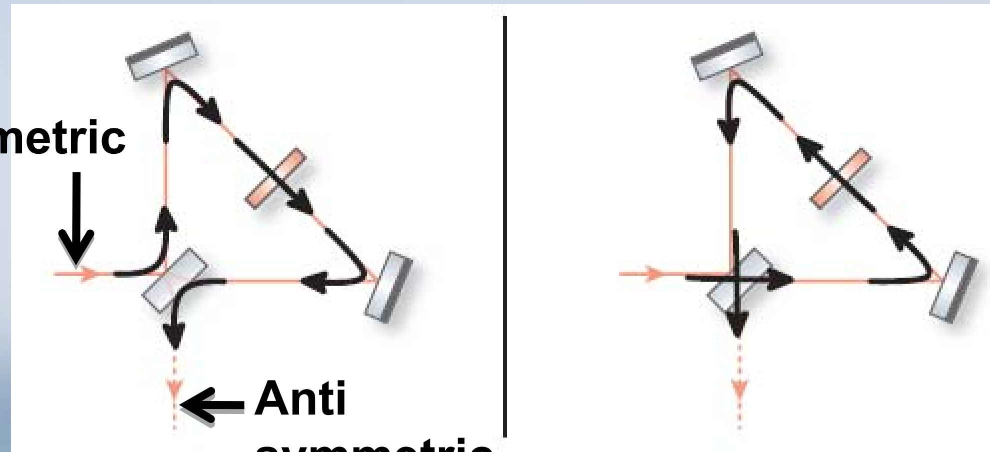


1. Introduction

Michelson-Sagnac interferometer(2)

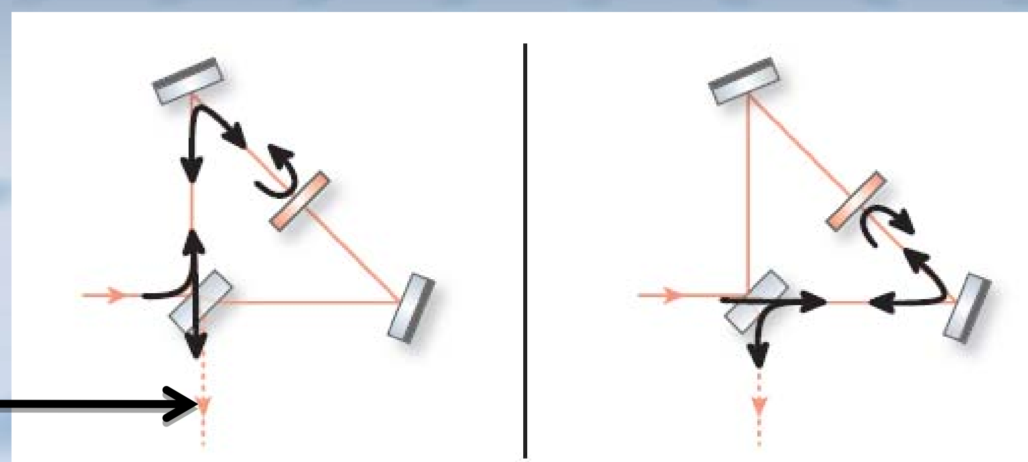
Sagnac mode

Symmetric port



Anti symmetric port (no light of Sagnac mode)

Michelson mode



Membrane position is adjusted to keep this port dark.

1. Introduction

Michelson-Sagnac interferometer(3)

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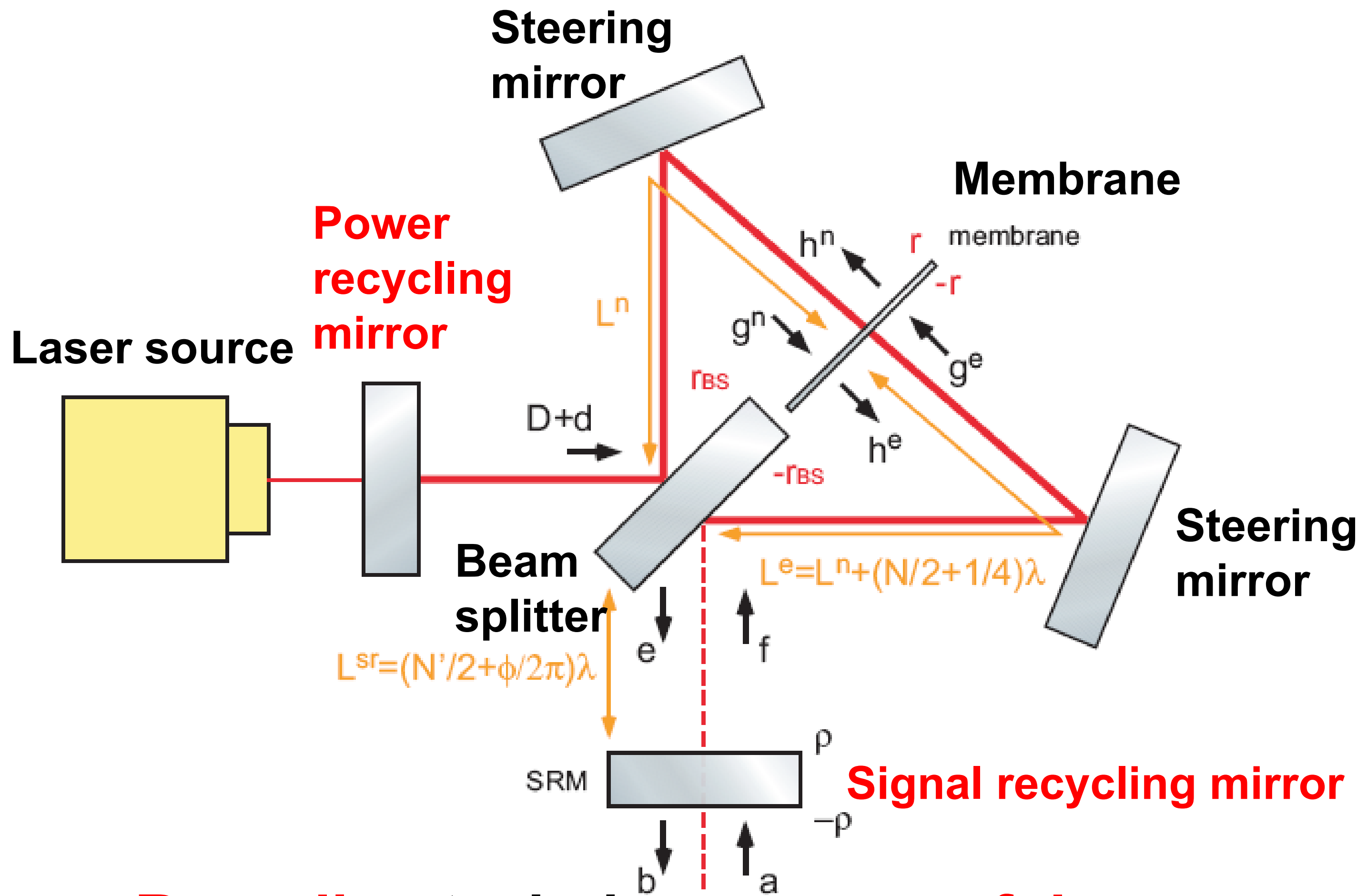


Recycling techniques are useful even if the membrane reflectance is low.

2. Theoretical outlines

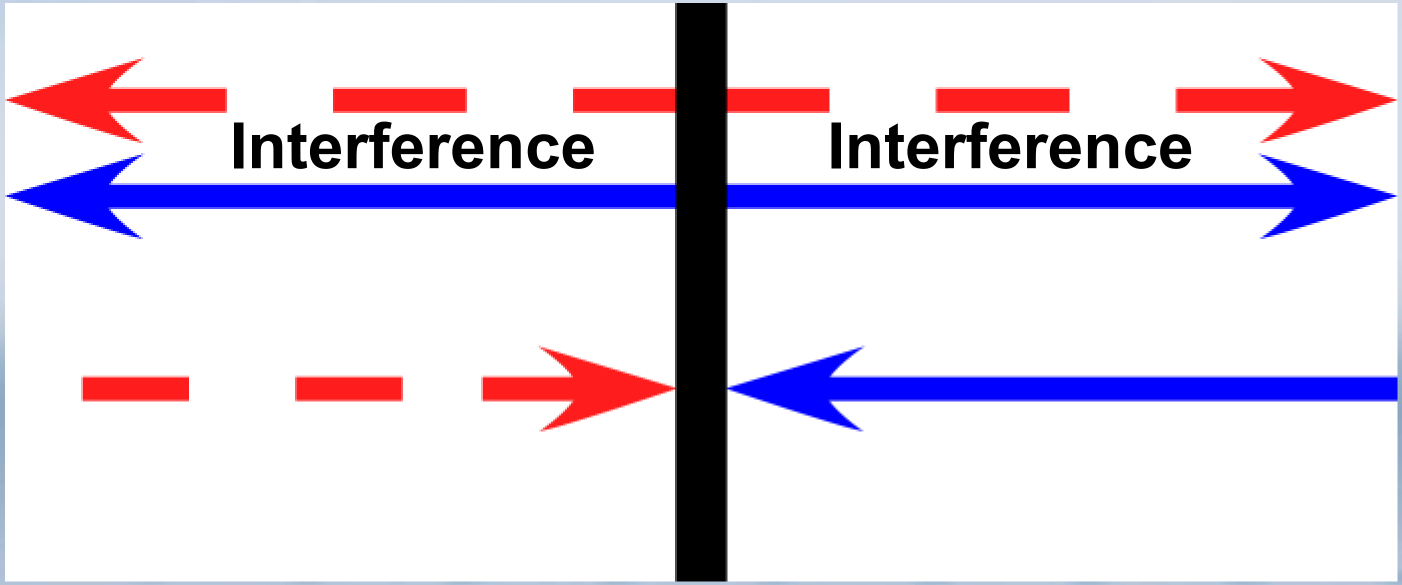
Two differences from simple Michelson

(1)Radiation pressure noise on membrane
(2)Node of Sagnac mode

and goal sensitivity
and standard quantum limit.

2. Theoretical outlines

Radiation pressure noise on membrane



Membrane

Conclusion : Radiation pressure noise is proportional to power reflectance of membrane.

2. Theoretical outlines

Node of Sagnac mode

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Sagnac mode : Clockwise and counterclockwise beams

There is interference between them.

↓

Standing wave

↓

Nodes and anti nodes

Anti symmetric port is dark.

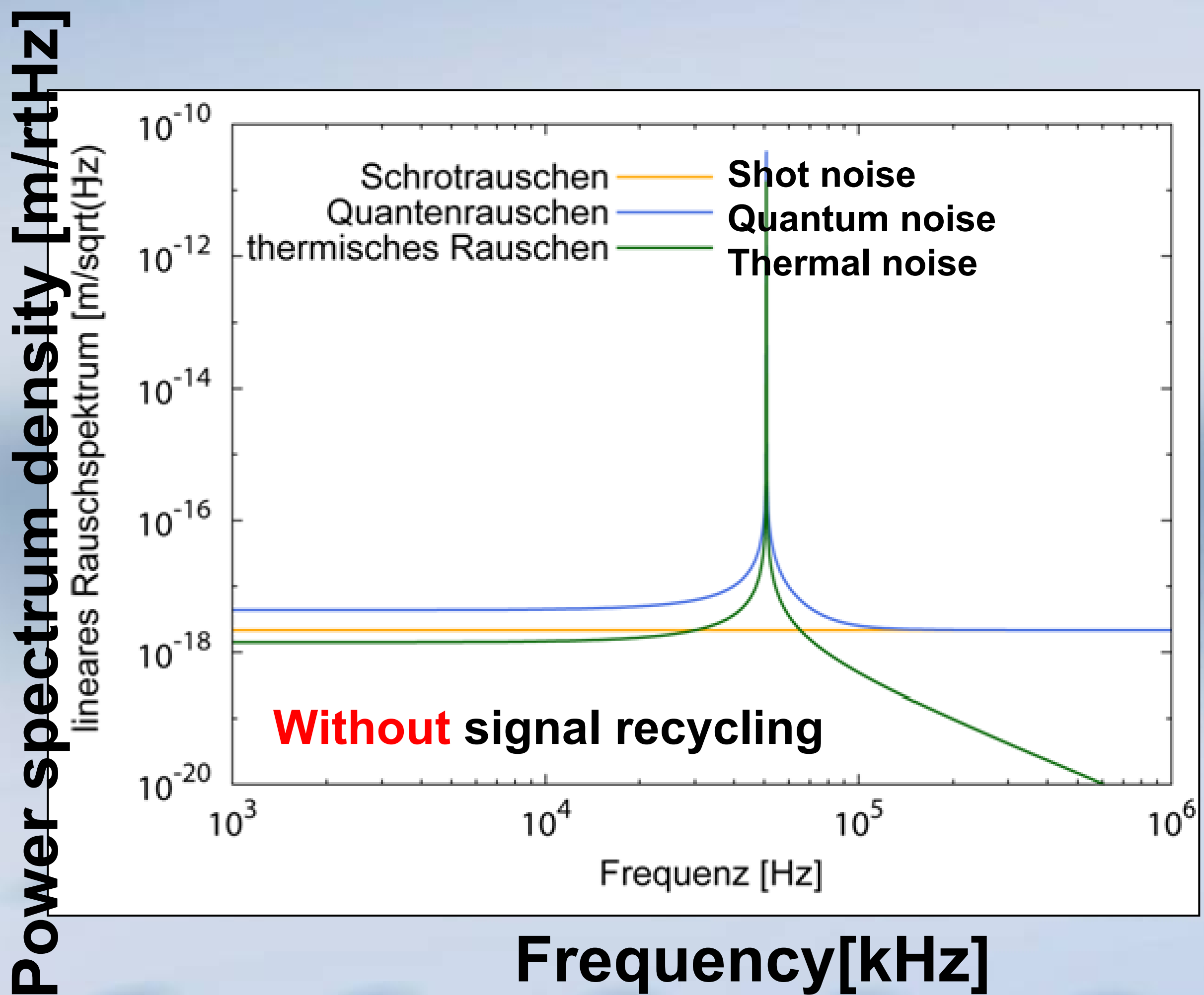
↓

Membrane must be on node or anti-node.

We prefer membrane on node because of absorption.

2. Theoretical outlines

Goal sensitivity



Temperature:	1 K
Q:	10^7
Effective Mass:	125 ng
Power at BS:	400 W
Resonance:	75 kHz

Radiation pressure noise is 2 and 3 times larger than shot noise and thermal noise.

Option
- Signal recycling
  - 99% amplitude reflectance
  - Power at BS : several W

2. Theoretical outlines

Standart Quantum Limit (SQL)

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SQL of Michelson-Sagnac interferometer (one membrane)

$$\sqrt{2\hbar H}$$

SQL of Fabry-Perot Michelson interferometer (four mirrors)

$$\sqrt{8\hbar H}$$

SQL of simple Michelson interferometer (two mirrors)

$$\sqrt{4\hbar H}$$

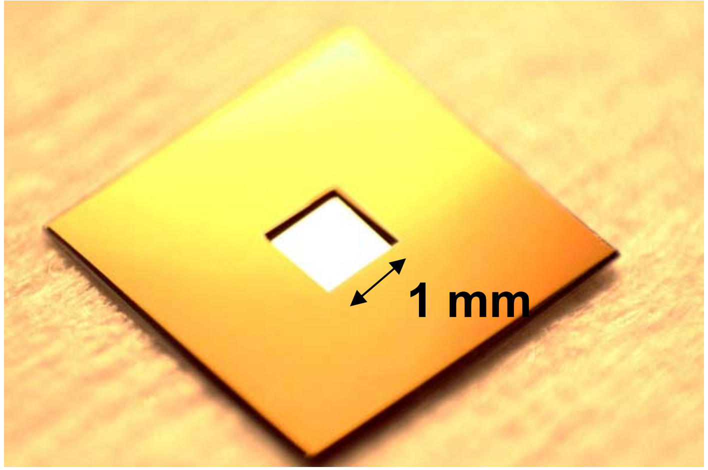
H **: Mechanical responce of one oscillator**

Our conjucture : SQL depends on number of mirrors (*n*).

$$\sqrt{2\hbar n H}$$

3. Current status

Membrane (Si_3N_4 in frame)



Mechanical properties

frame:	7.5^2 mm^2 x 200 µm
Area:	1.5 mm x 1.5 mm
Thickness:	75 nm
Effective mass:	~ 100 ng
Resonant frequency:	~ 73 kHz
Q:	~ 1.3×10^6

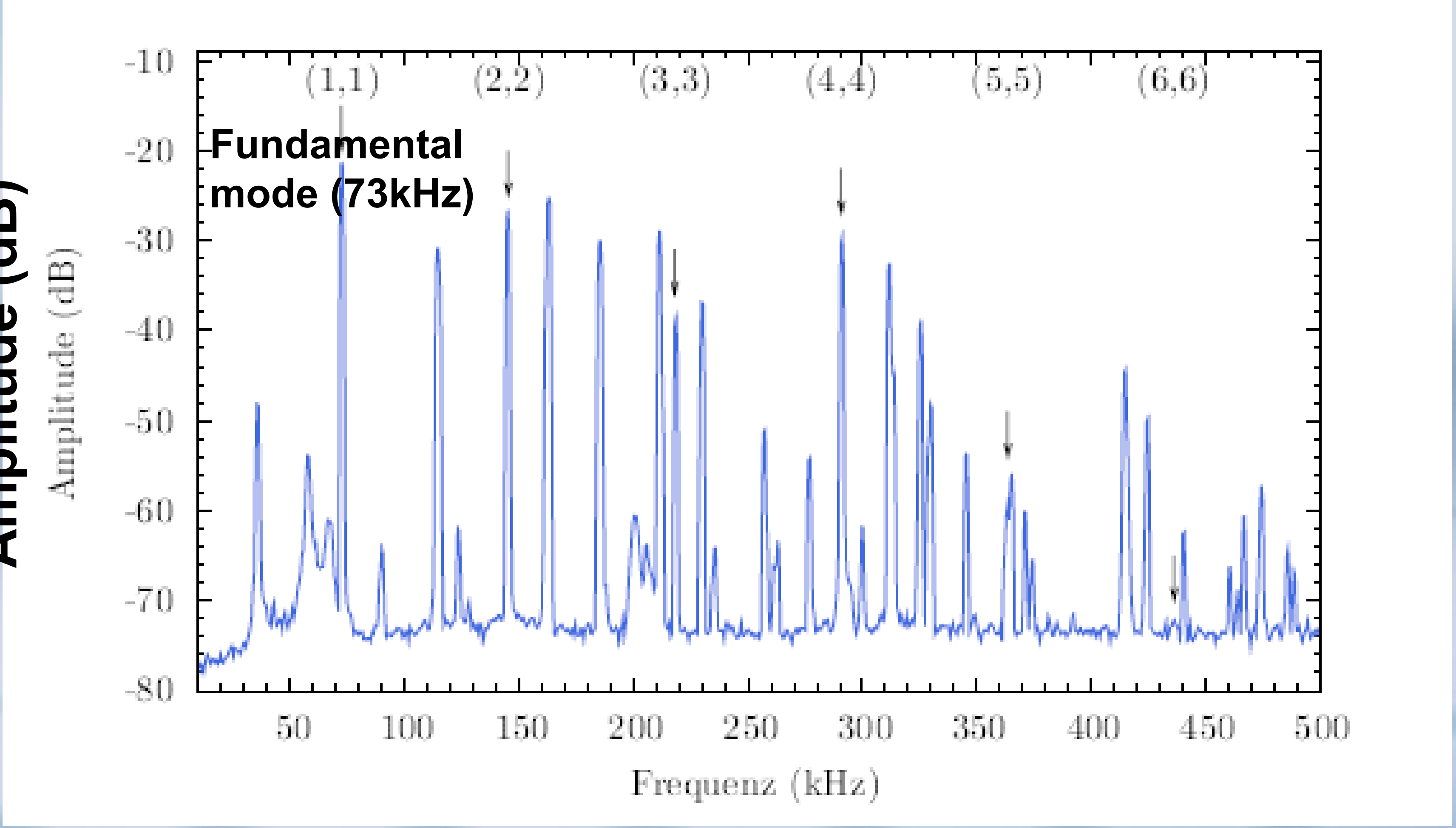
Optical properties

Power reflectance:	~ 33%
Absorption:	≤ 150 ppm
Flatness:	1 nm?
Micro roughness:	0,2 nm?
Scattering:	→ 0

J.D. Thompson *et al*.,
Nature 452 (2008) 72-76.

3. Current status

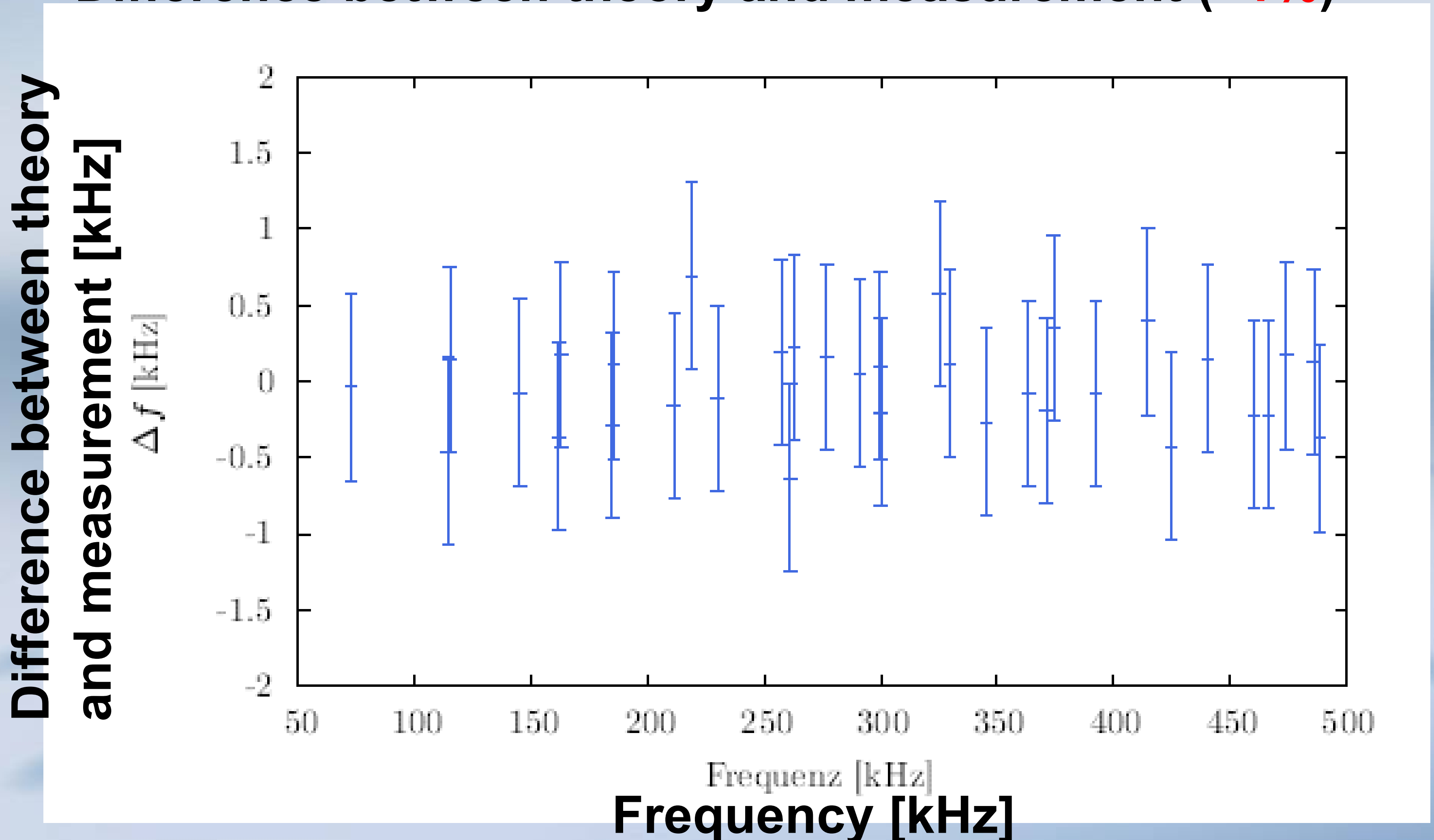
Resonant frequencies of membrane



Amplitude (dB)

Frequency (kHz)

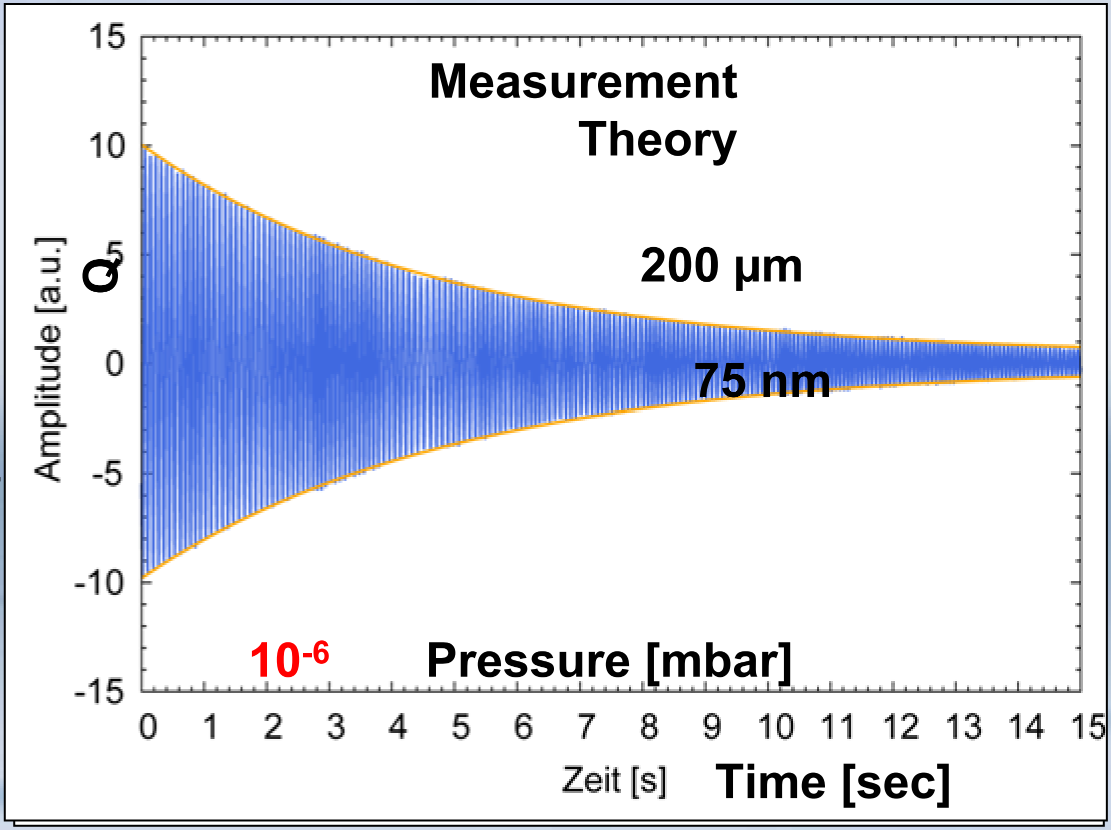
Difference between theory and measurement (~1%)



3. Current status

Q-values of membrane

- Residual gas damping
  → Vacuum (~ 10^{-6} mbar)
- Recoil loss
  → Estimation: Q > 10^7
- Thermoelastic damping
  → Estimation: Q ~ 5 x 10^7
- Bulk loss
  → Unknown
- Loss on surface
  → Unknown

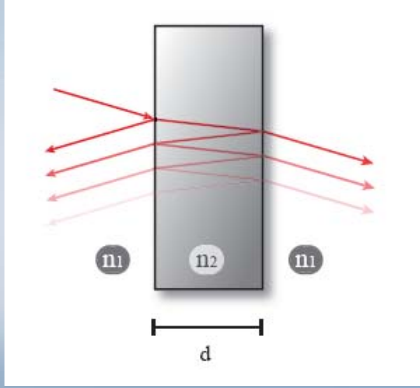


- Our measurement: Q ~ 1.3 x10^6 @ 300 K
- Measurement of other group: Q ~ 1 x10^7 @ 0.3 K

B.M. Zwickl *et al.*, Applied Physics Letters 92(2008)103125.

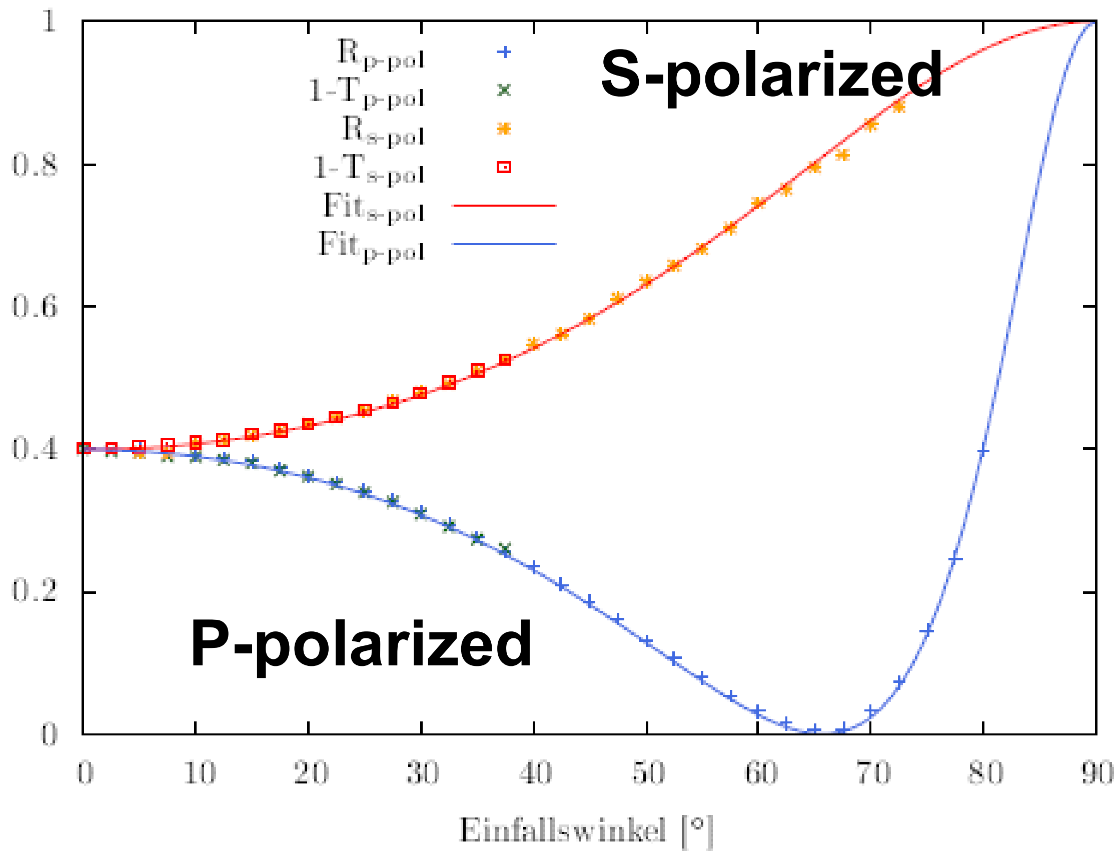
3. Current status

Reflectance of membrane



Membrane as etalon

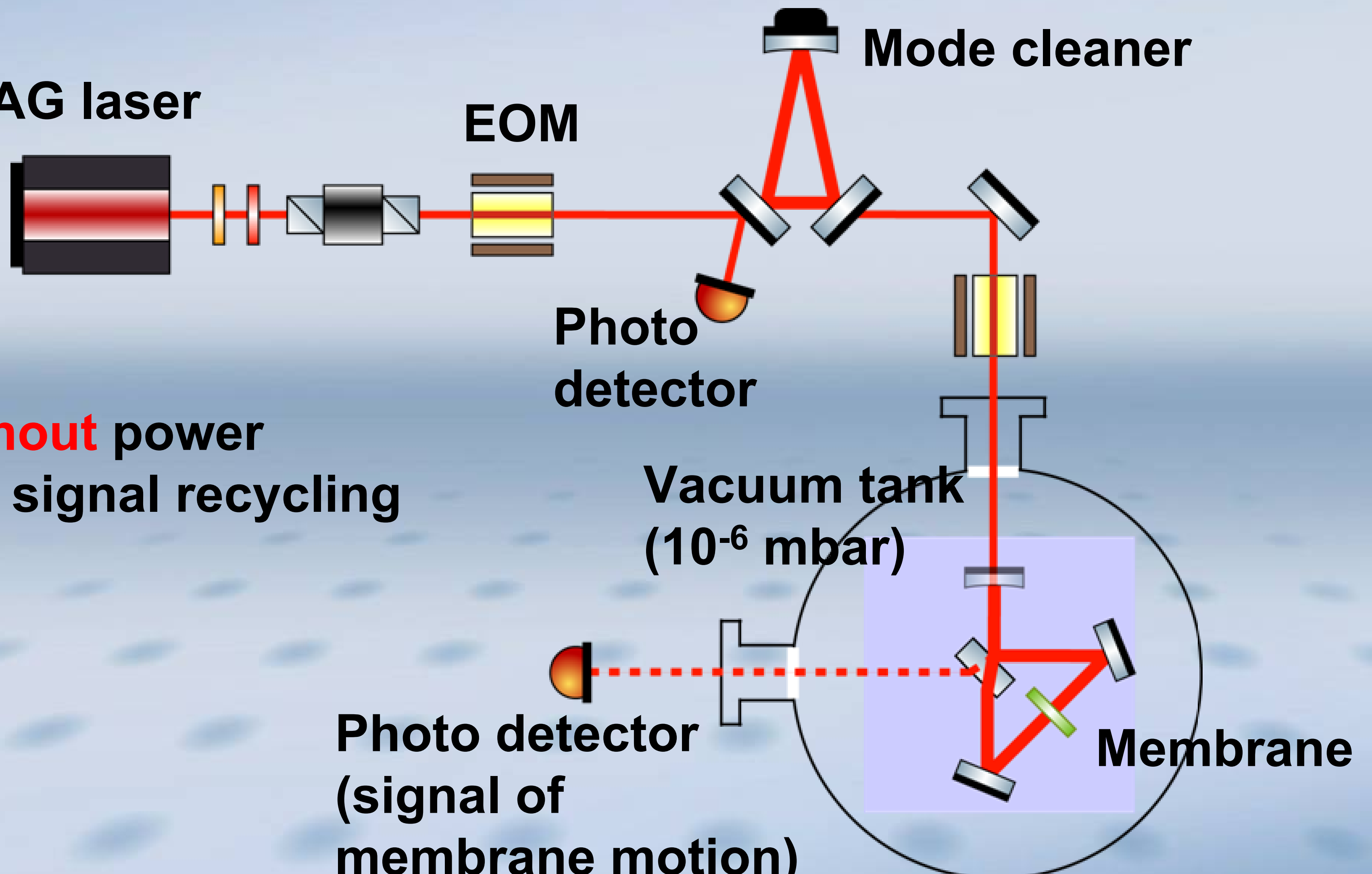
Power reflectivity



Incident angle [degree]

3. Current status

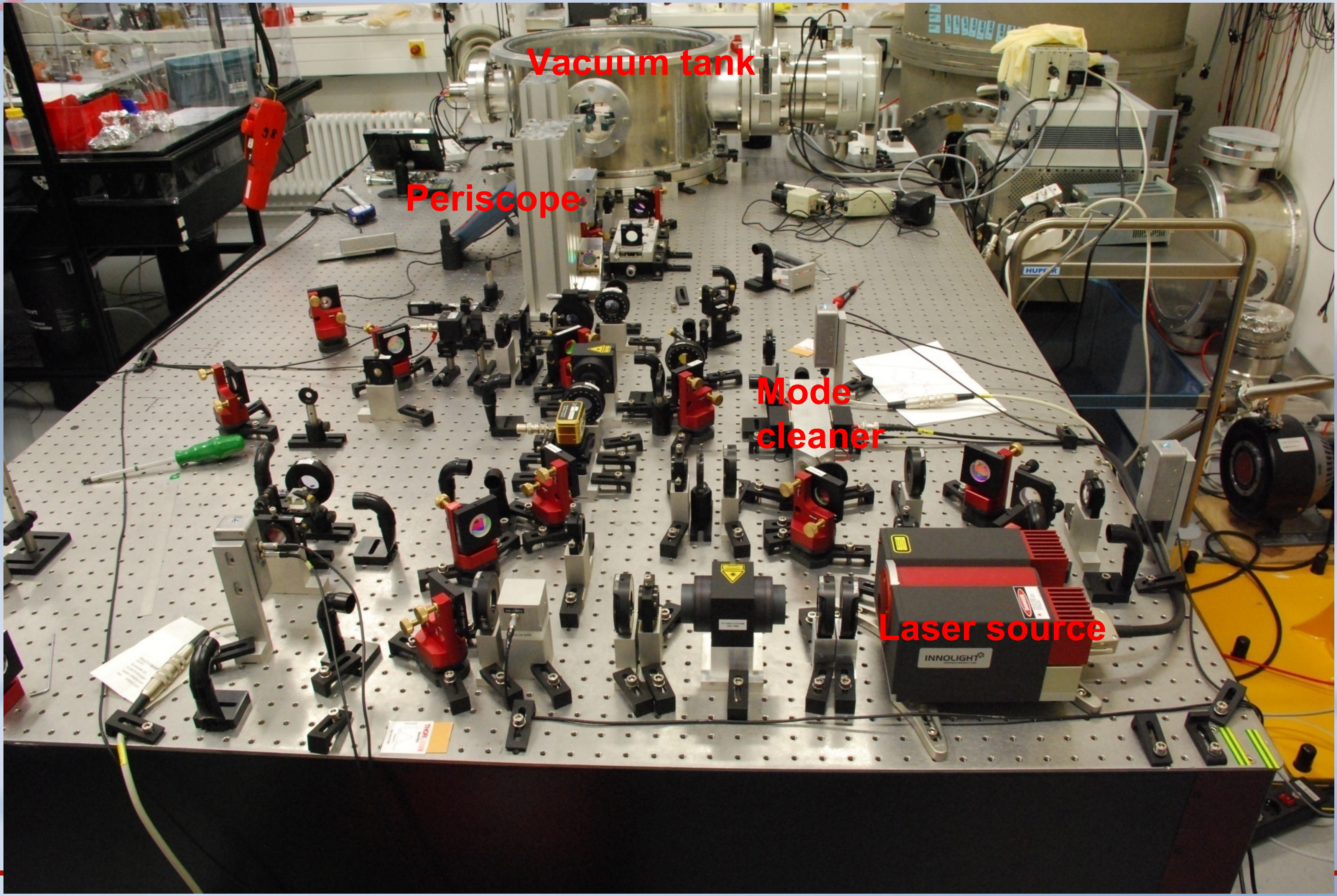
Michelson-Sagnac interferometer



Without power and signal recycling

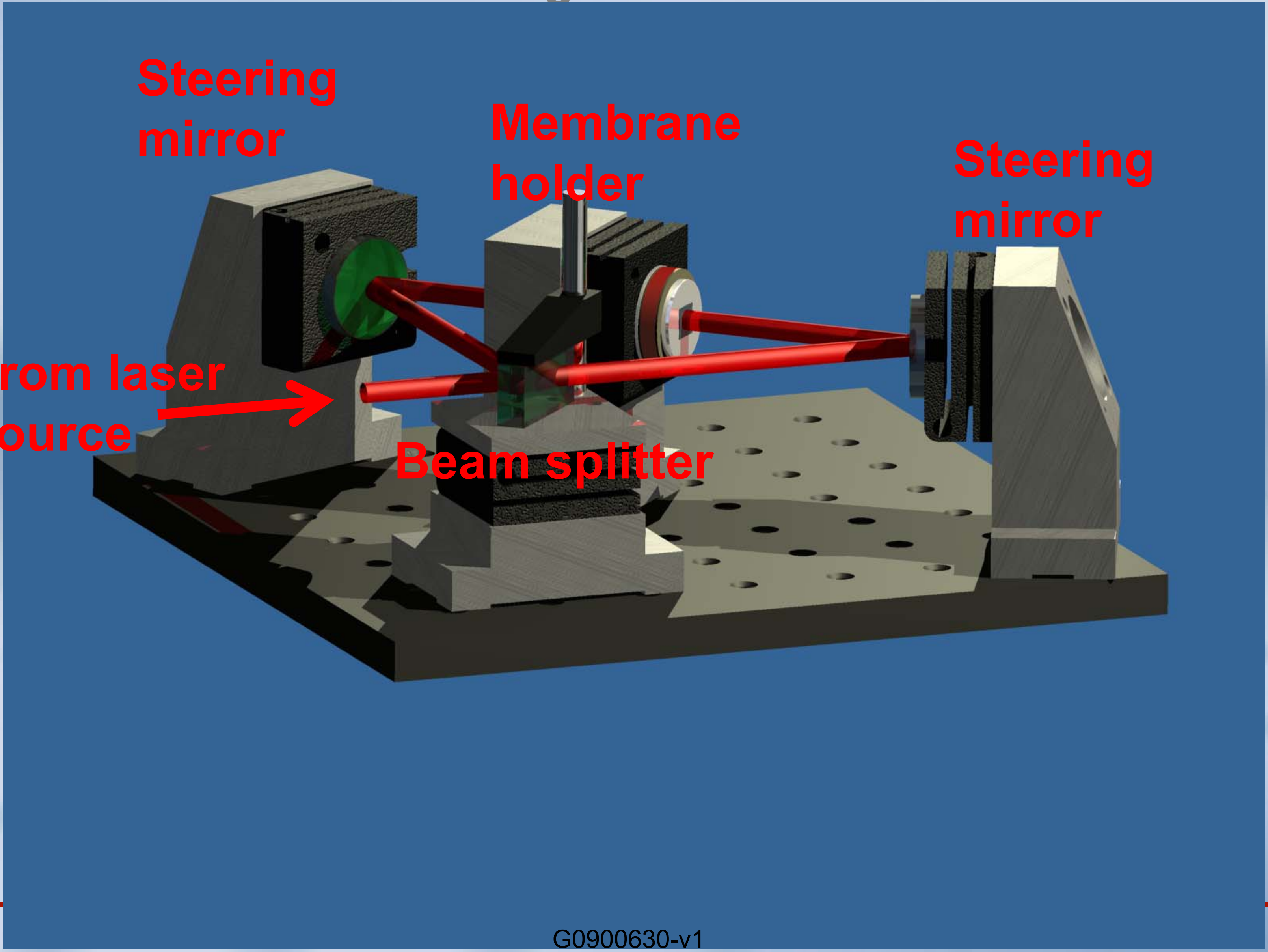
3. Current status

Optical table



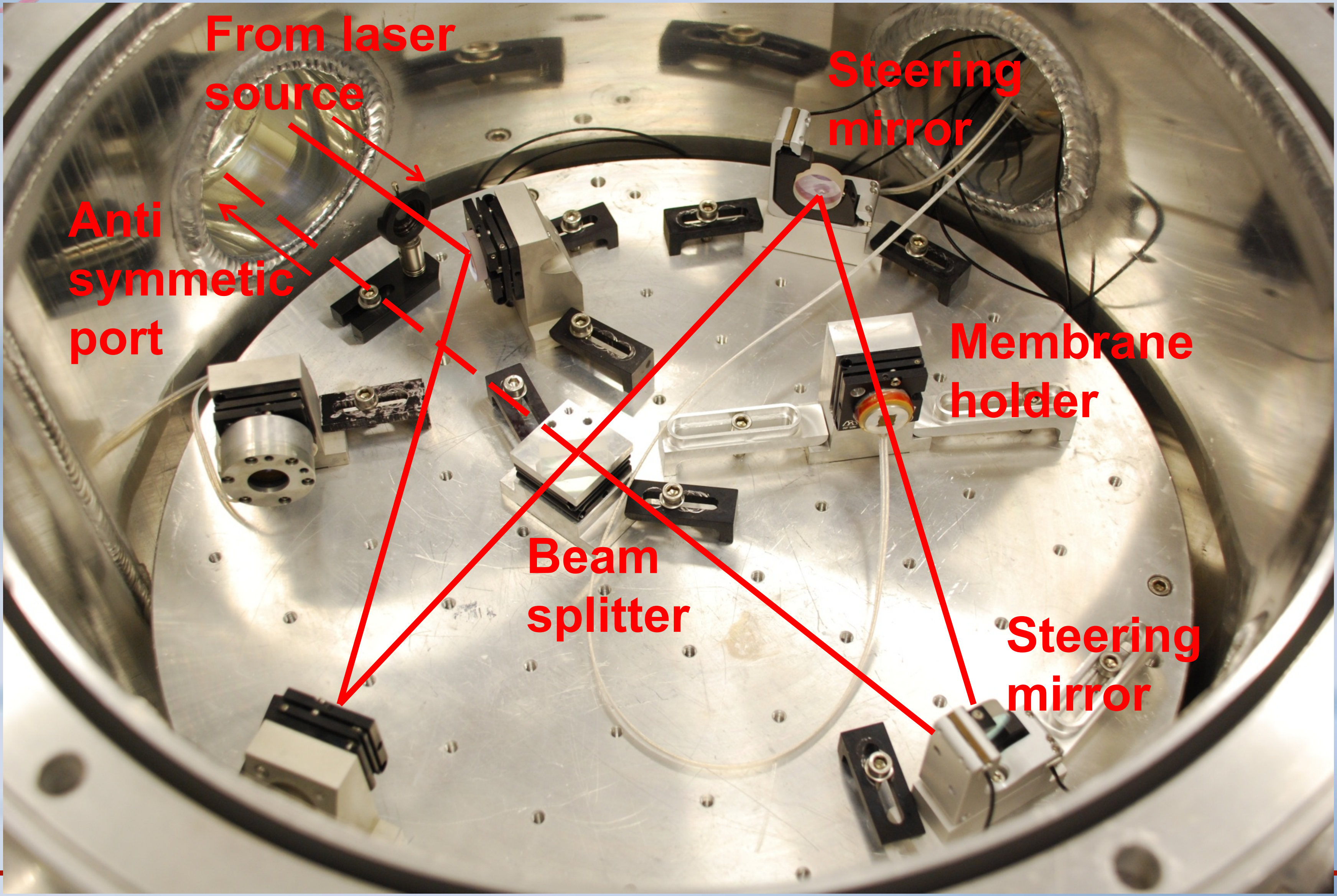
3. Current status

Michelson-Sagnac interferometer



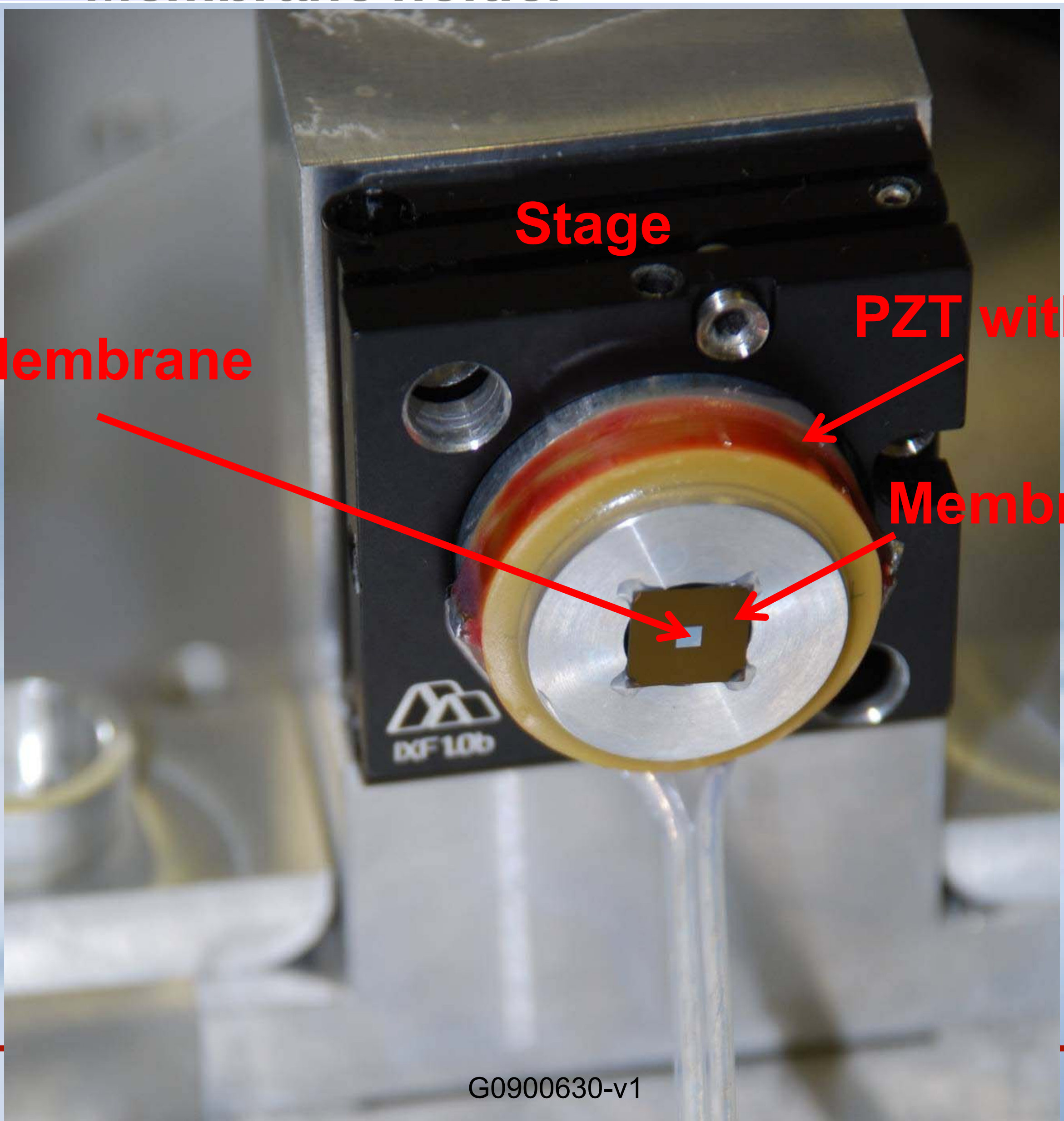
3. Current status

Inside vacuum tank



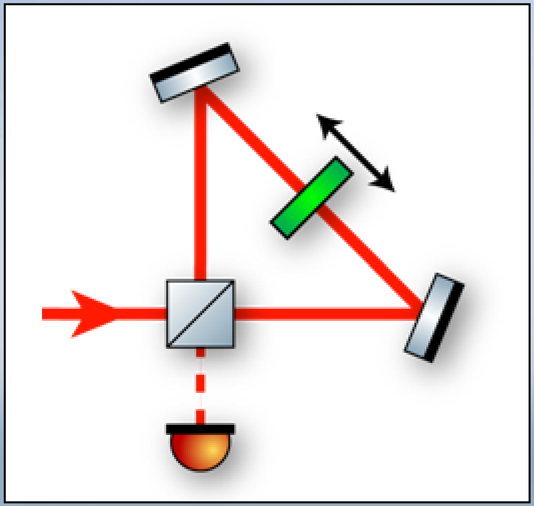
3. Current status

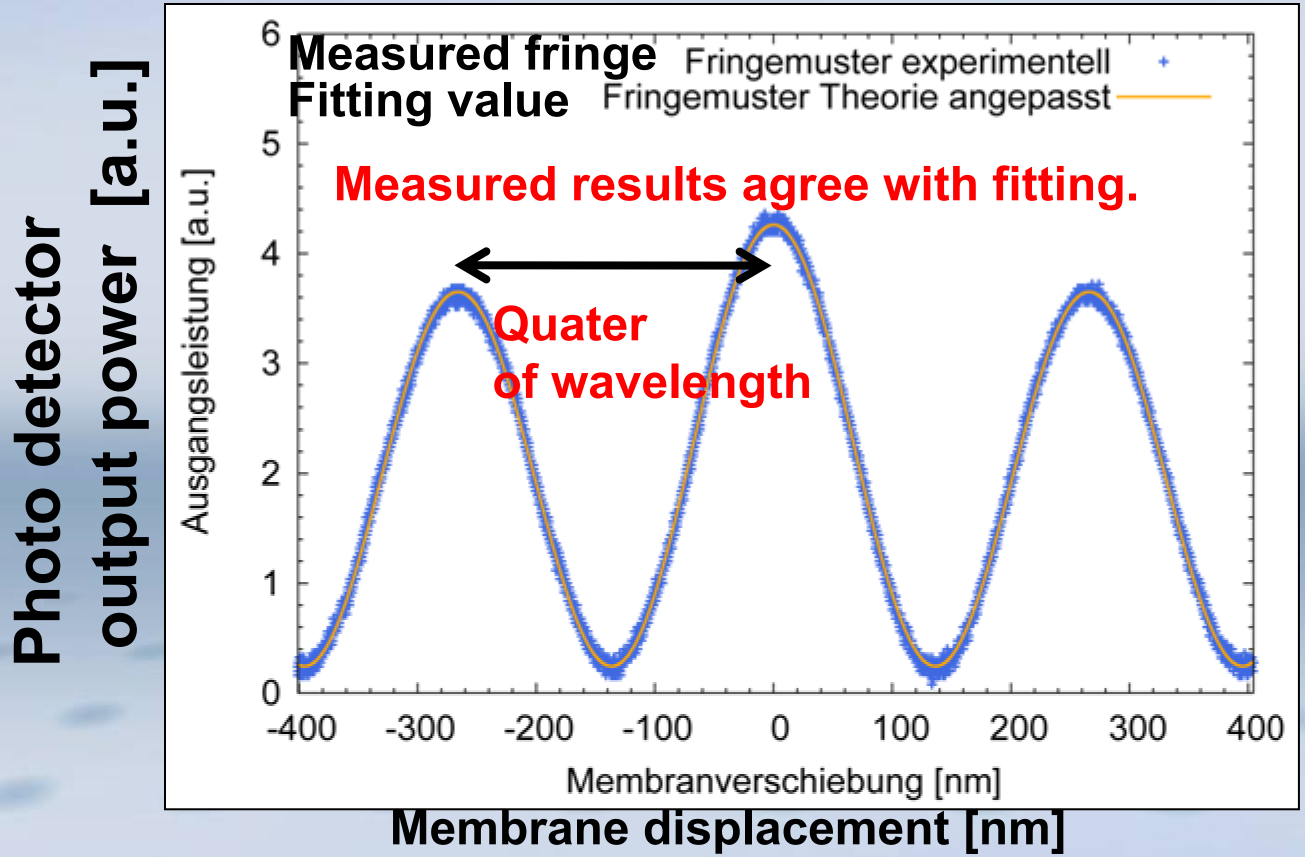
Membrane holder



3. Current status

Calibration

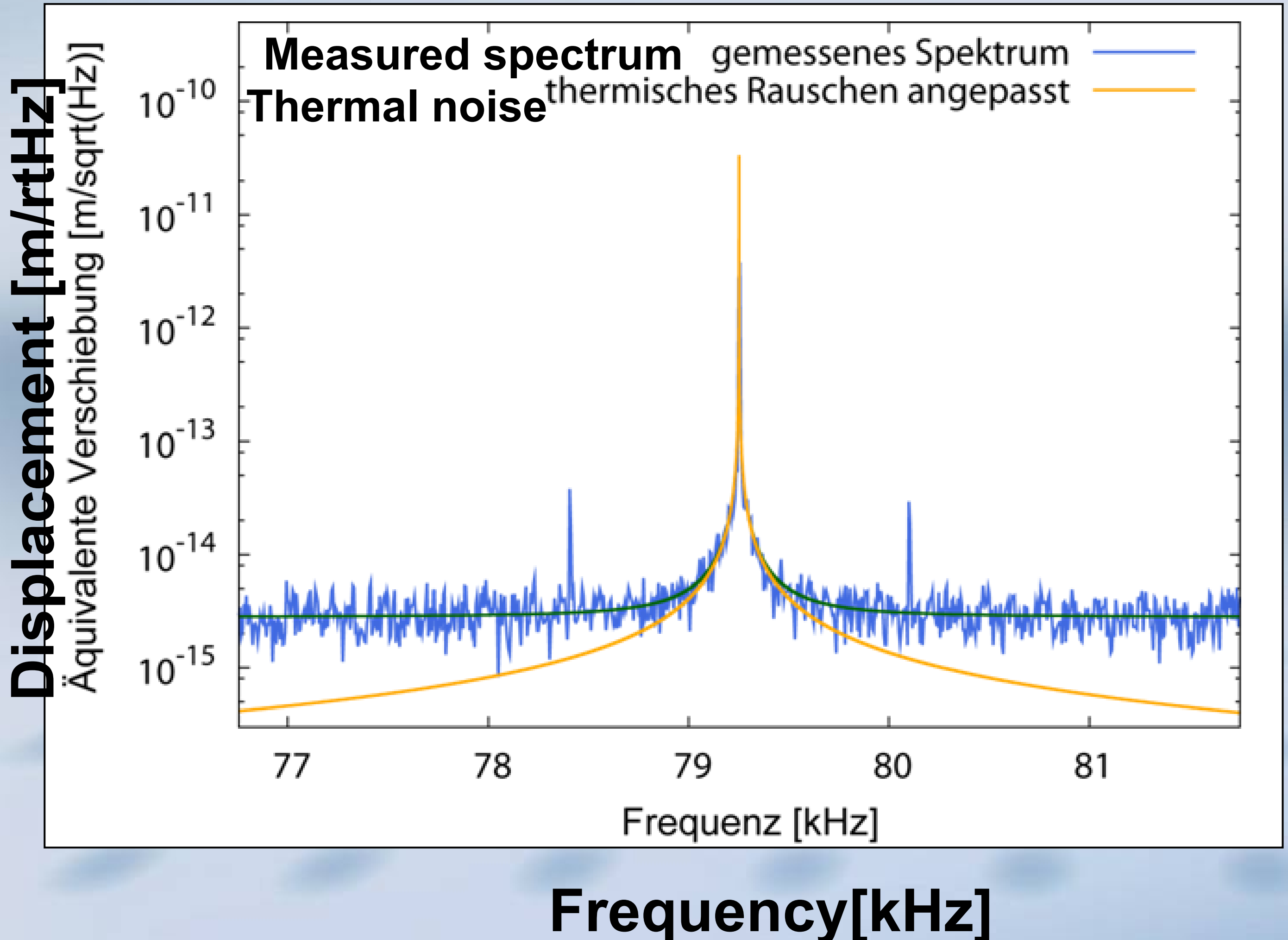




Calibration
(photo detector output vs. displacement of membrane) is possible as like simple Michelson interferometer.

3. Current status

Measured power spectrum



Off resonance : Intensity noise

On resonance : Thermal noise

$3*10^{-15}$ m/rtHz

4. Future work

(1) Reduction of noise

(to observe off resonance thermal noise)

Laser stabilization

Output mode cleaner

(2) Power and signal recycling

(3) Observation of radiation pressure noise

Cryogenic apparatus (about 1K : ^{3}He evacuation)

Suspension

5. Summary

Radiation pressure noise measurement

with extremely light but translucent membrane

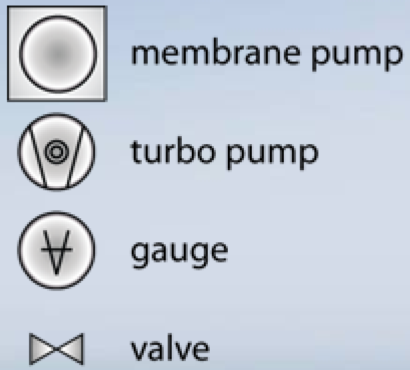
New topology : Michelson-Sagnac interferometer

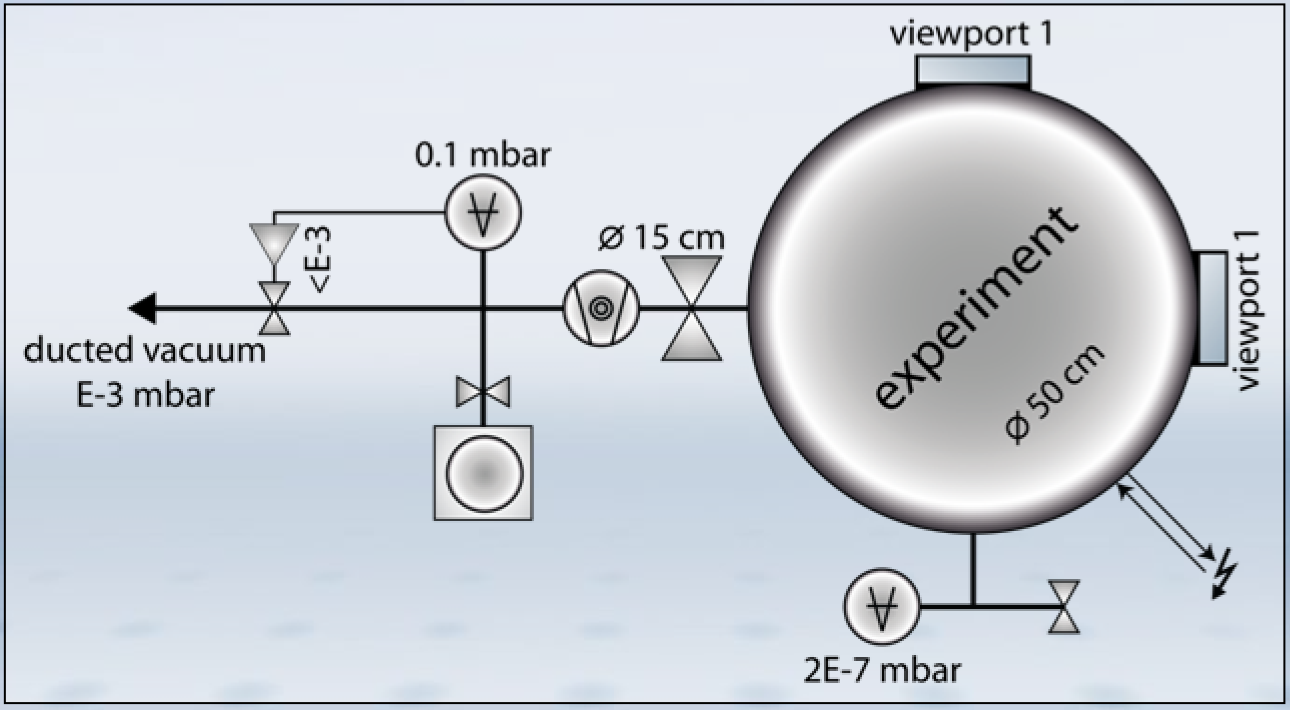
- Theoretical outlines
  - Nodes of Sagnac mode, Goal sensitivity
  - Conjecture about Standard Quantum Limit
- Current status of experiment
  - Mechanical and optical properties of membrane
  - Operation without power and signal recycling
  - Current sensitivity ($3*10^{-15}$ m/rtHz)
- Future work
  - Cryogenic apparatus and so on

Vielen Dank für die Aufmerksamkeit (Thank you for your attention)

vacuum system

to reach < 10^{-6} mbar



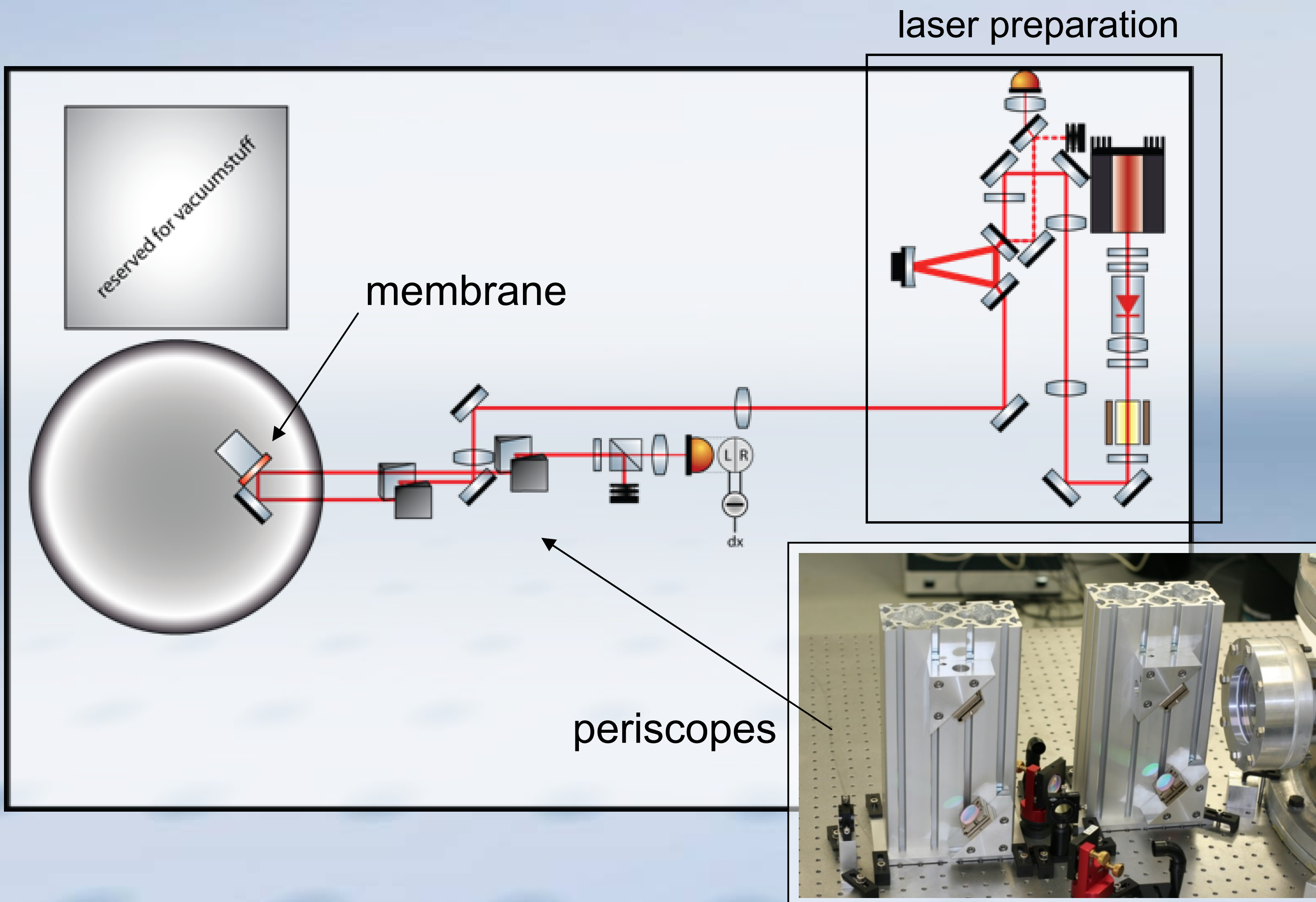


actual pressure in experiment: **$1.5 \cdot 10^{-7}$ mbar**

backing pump pressure: 10^{-1} mbar, not good enough to use ducted vacuum

Q-measurement

actual status of the table

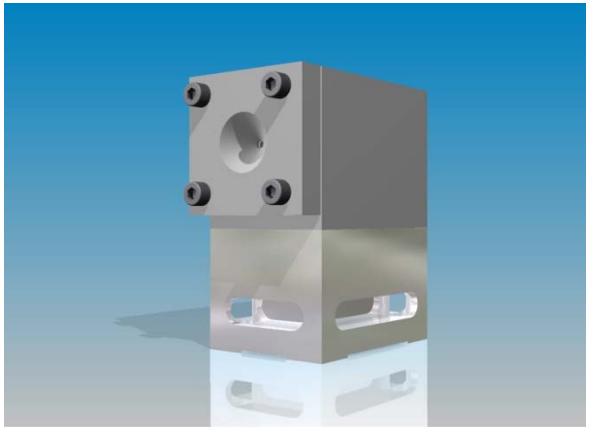


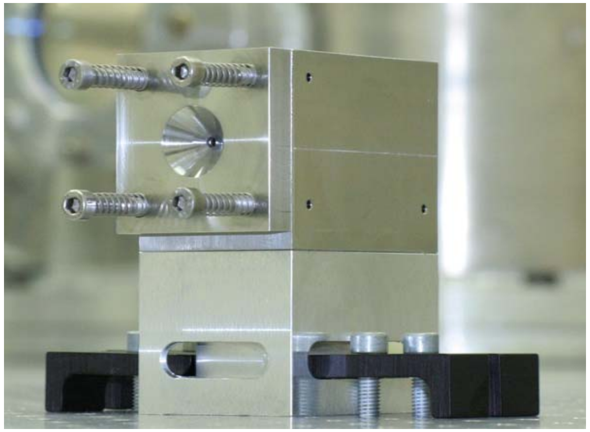
recoil loss

energy transfer to membraneholder limits Q

- many unknown values
- had no verification for Harris results

→ designed very **sturdy mount**





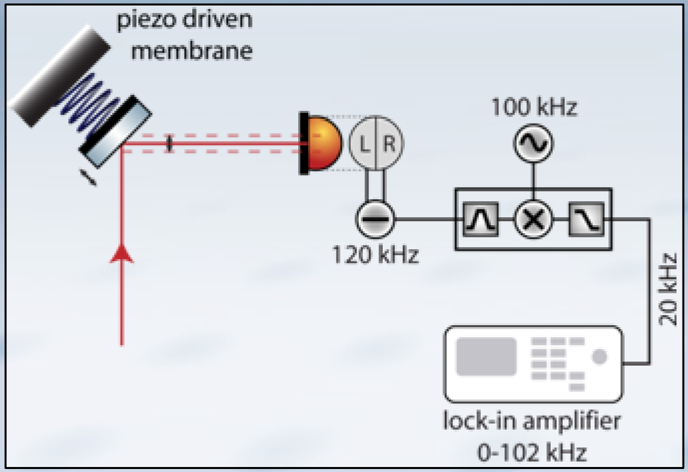
recent results:

$$Q_{osc_{recoil}}^{-1} \approx Q_{osc}^{-1} + Q_{sup}^{-1} \frac{m_{osc}}{m_{sup}} \frac{\omega_{sup}}{\omega_{osc}}$$

it should be sufficient to **conserve Q** of the small frame to be not limited!!!

we will design a smaller mount for further experiment ringdown time:

$$Q = \frac{\text{total contained energy}}{\text{energyloss per period}} = \pi \, \tau \, f_0$$

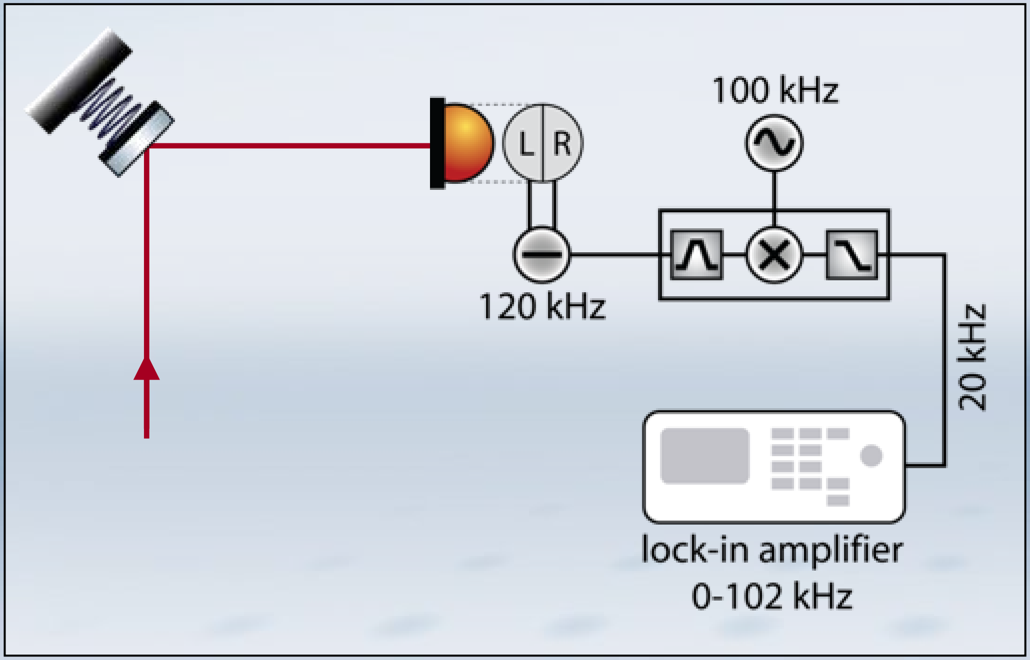


- 10^6 periods per ringdowntime!

→ use **lock in amplifier** (variable filters)

↯ our lock-in amp. is too slow!

→ mixer shifts signal to some kHz



10^6 periods per ringdowntime!

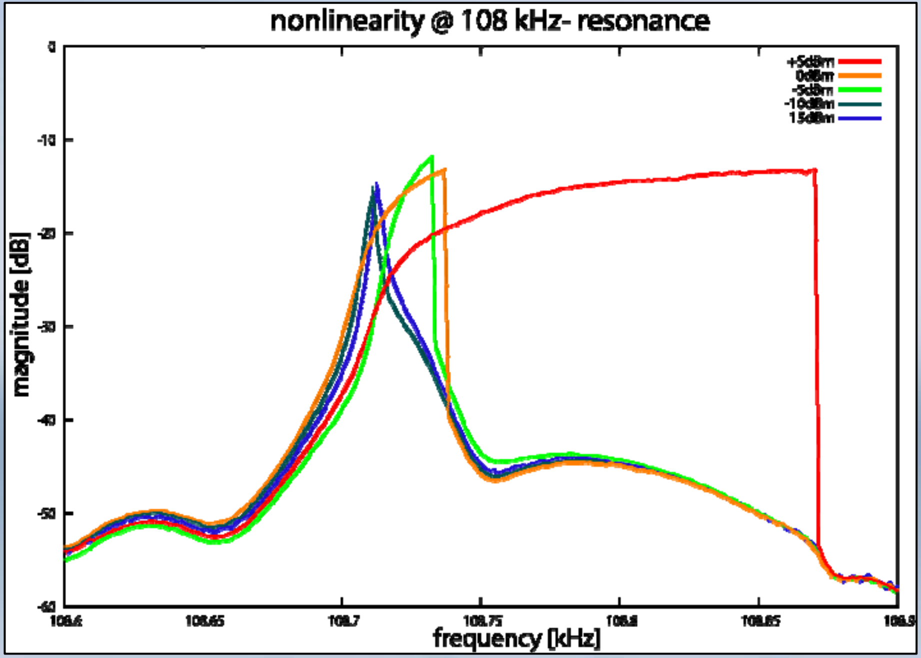
→ mix signal down
(shift to lower freq.)

↯ Lock-in amp. is too slow!

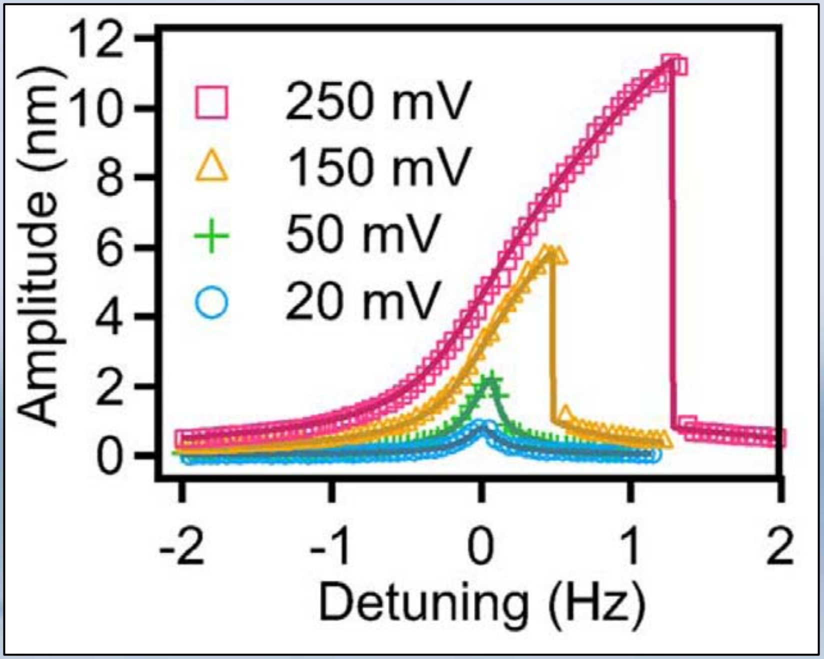
→ second mixer for some kHz

nonlinearity of the oscillation

comparison of our results to Harris`



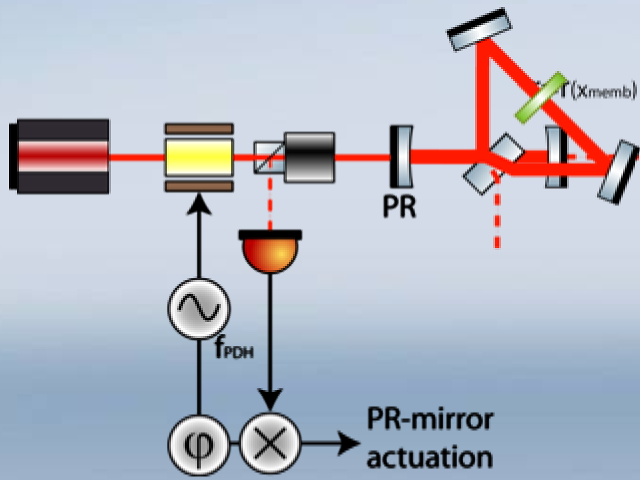
our results

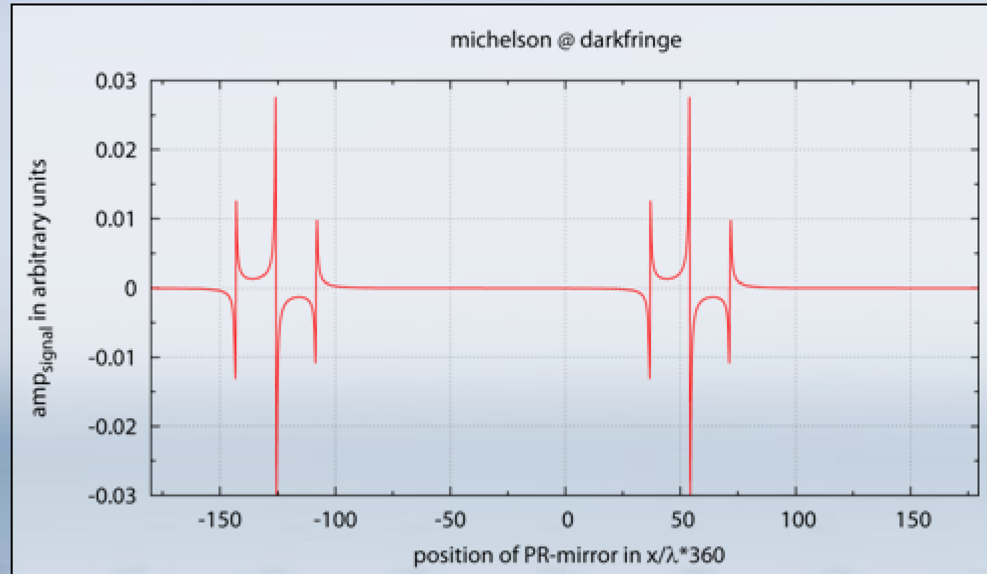


Harris et al. APL **92**, (2008)

locking scheme for PR-cavity

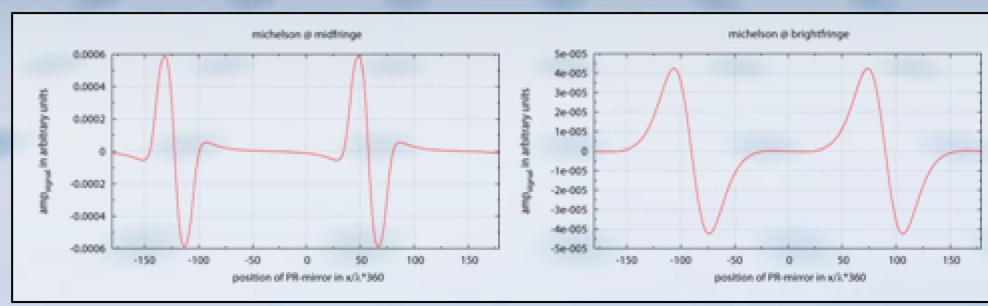
using Pound Drever Hall signal





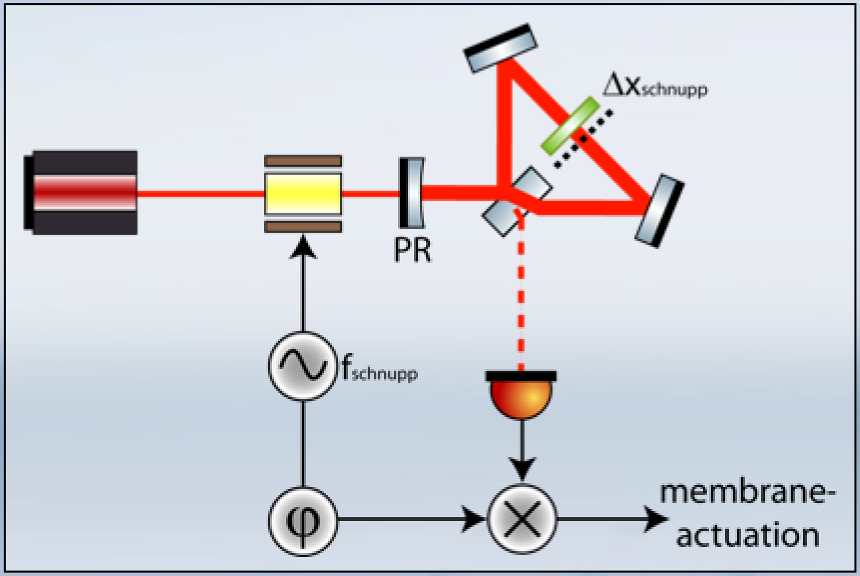
- michelson acts as mirror

- membrane-position dependent reflectivity (and phase)



locking scheme for Michelson interferometer

using Schnupp asymmetry

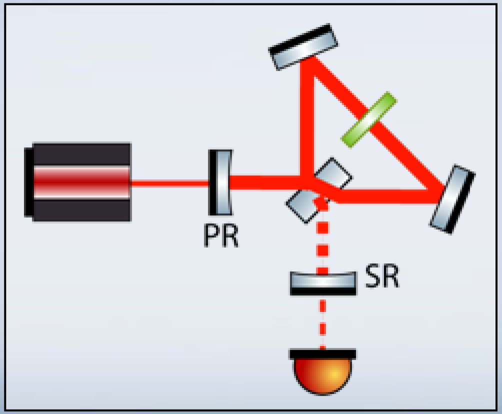


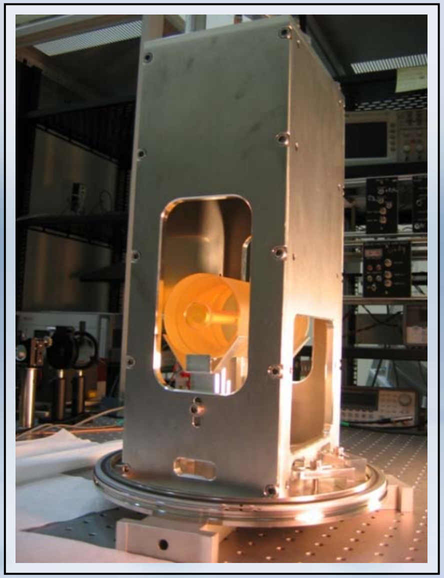
- need different armlength
- IFO reflecting carrier
- IFO partly transmitting sidebands
- errorsignal in transmission

problems:

- need to preserve contrast
- **small asymmety**
- **high modulation frequency**

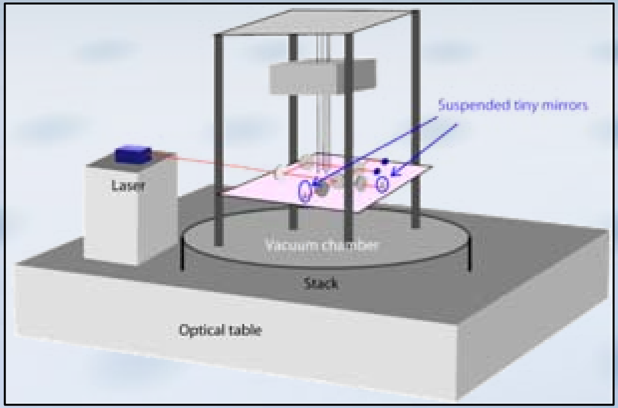
- dual recycling





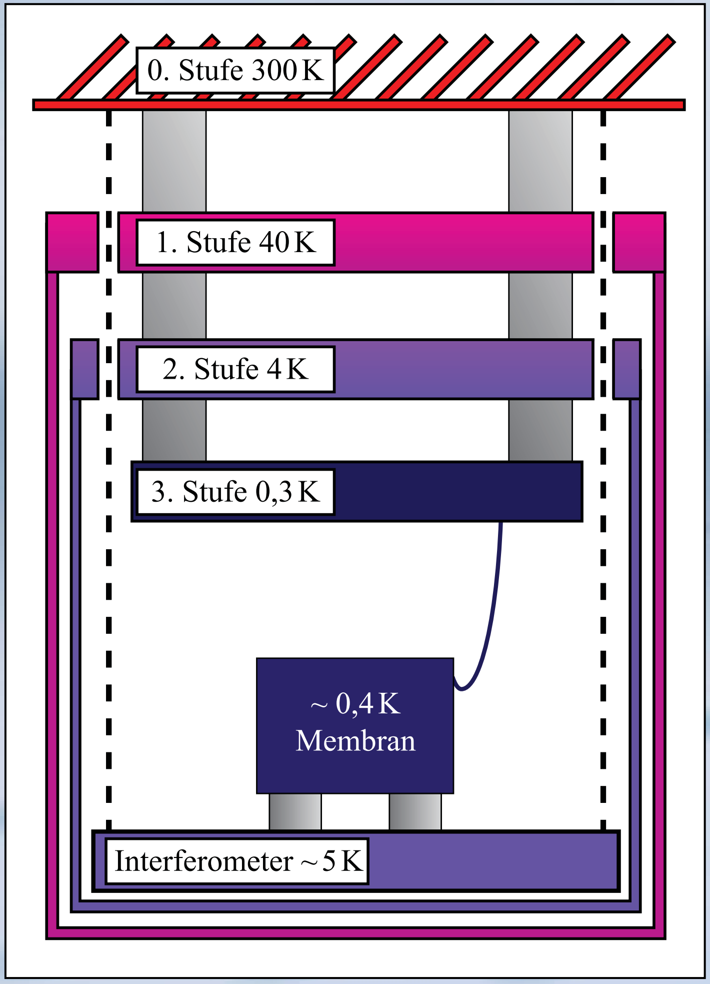
- frequency stabilisation
  with reference cavity

- suspended interferometer
  to isolate from seismic motion
  (like Tokyo- group)



Kryostat

Reduzierung thermischen Rauschens



Thermisches Rauschen erfordert Kühlung

Mehrstufiges Konzept (Zwiebelschalenmodell):

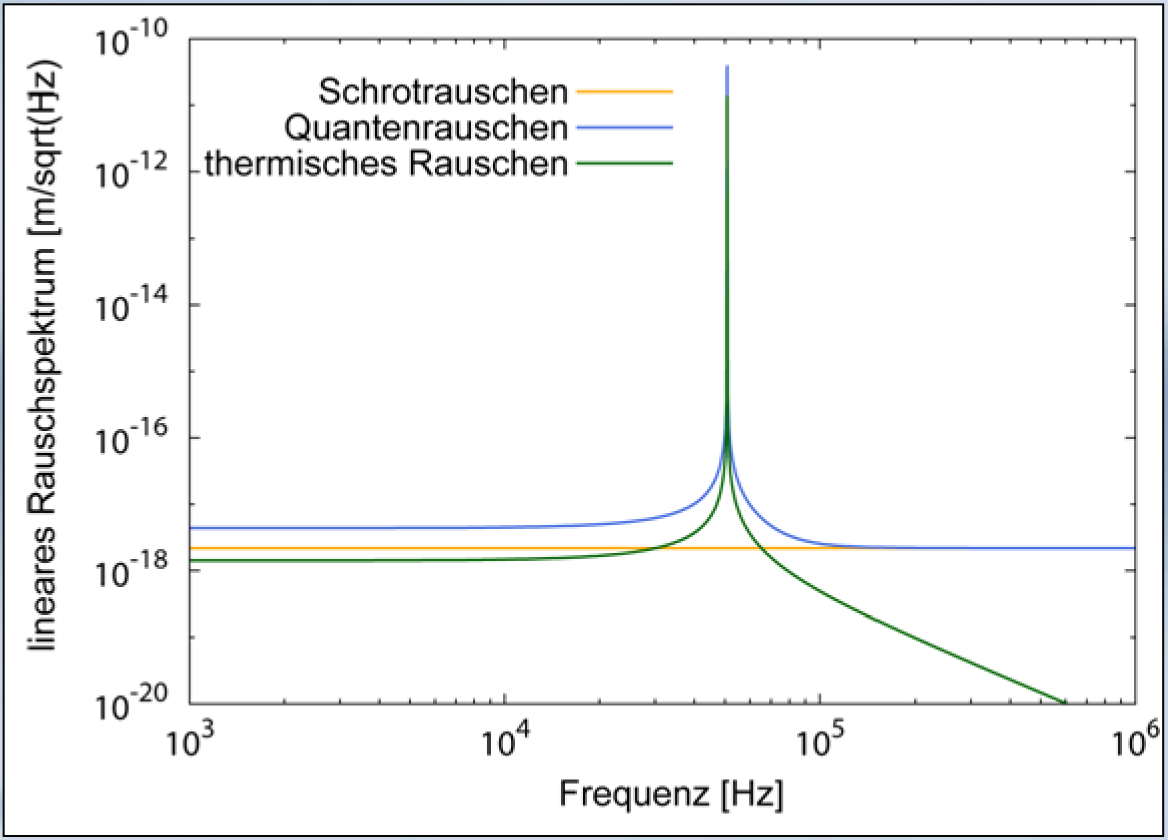
→ Interferometer durch ^{4}He gekühlt

→ Membran darüber hinaus durch ^{3}He gekühlt

Kryostat verursacht „Erschütterungen“

→ Seismische Entkopplung des Interferometers

Erwartete Empfindlichkeit
für kryogene Temperaturen



Temperatur:	1 K
Güte:	10^7
Effektive Masse:	125 ng
Leistung:	400 W
Resonanz:	50 kHz
(optische Feder)	

→ Schrotrauschen: Faktor 2
→ therm. Rauschen: Faktor 3

Weitere Option:
- Signal Recycling
  (nur gegen Schrotrauschen)

Große Überschrift

kleine Überschrift

Text

2. Theoretical outlines

Three differences from simple Michelson

(1)Radiation pressure noise on membrane

(2)Node of Sagnac mode

(3)Optical spring

2. Theoretical outlines

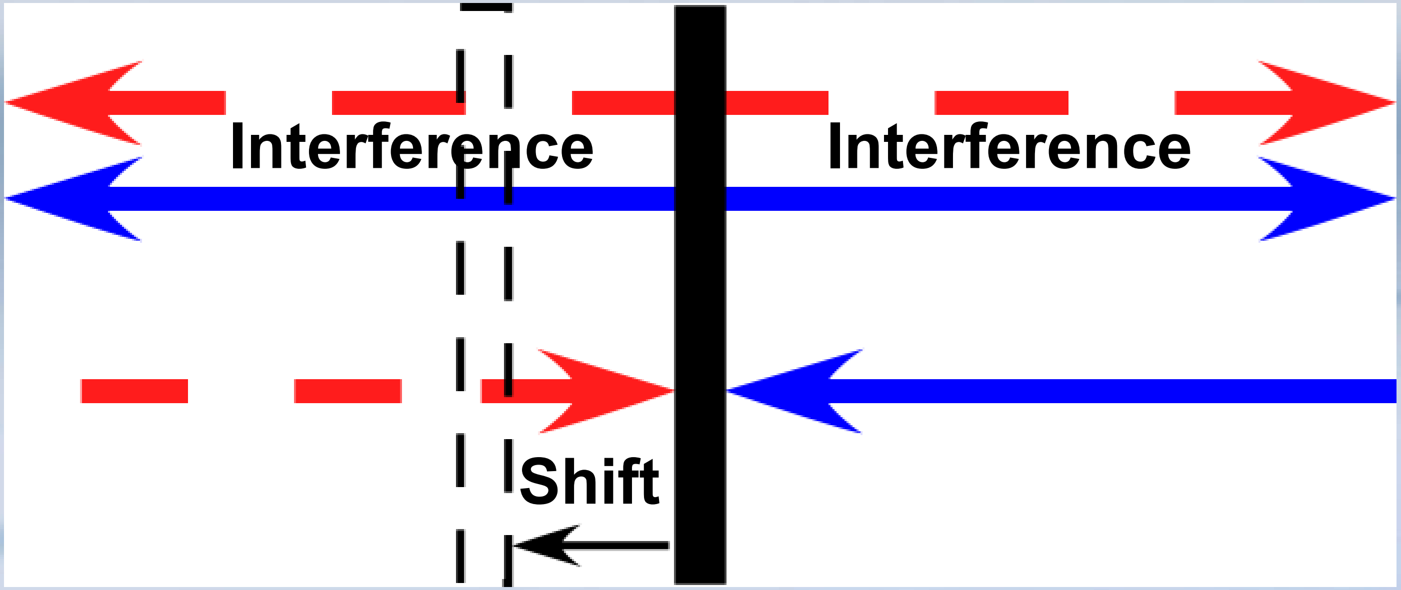
Optical spring (1)

Optical spring (without cavity) : Light acts as spring.

Radiation pressure on membrane depends on its position.

Radiation pressure changes

resonant frequency of membrane.



Membrane

2. Theoretical outlines

Optical spring (2)

Left side of membrane

Right side of membrane

Phase of Michelson mode : Shift

Sign of shift on right side is opposite to that on left side.

Phase of Sagnac mode : No shift

2. Theoretical outlines

Optical spring (3)

Left side of membrane

Right side of membrane

Interference: Constructive (larger power) on right side

Destructive (smaller power) on left side

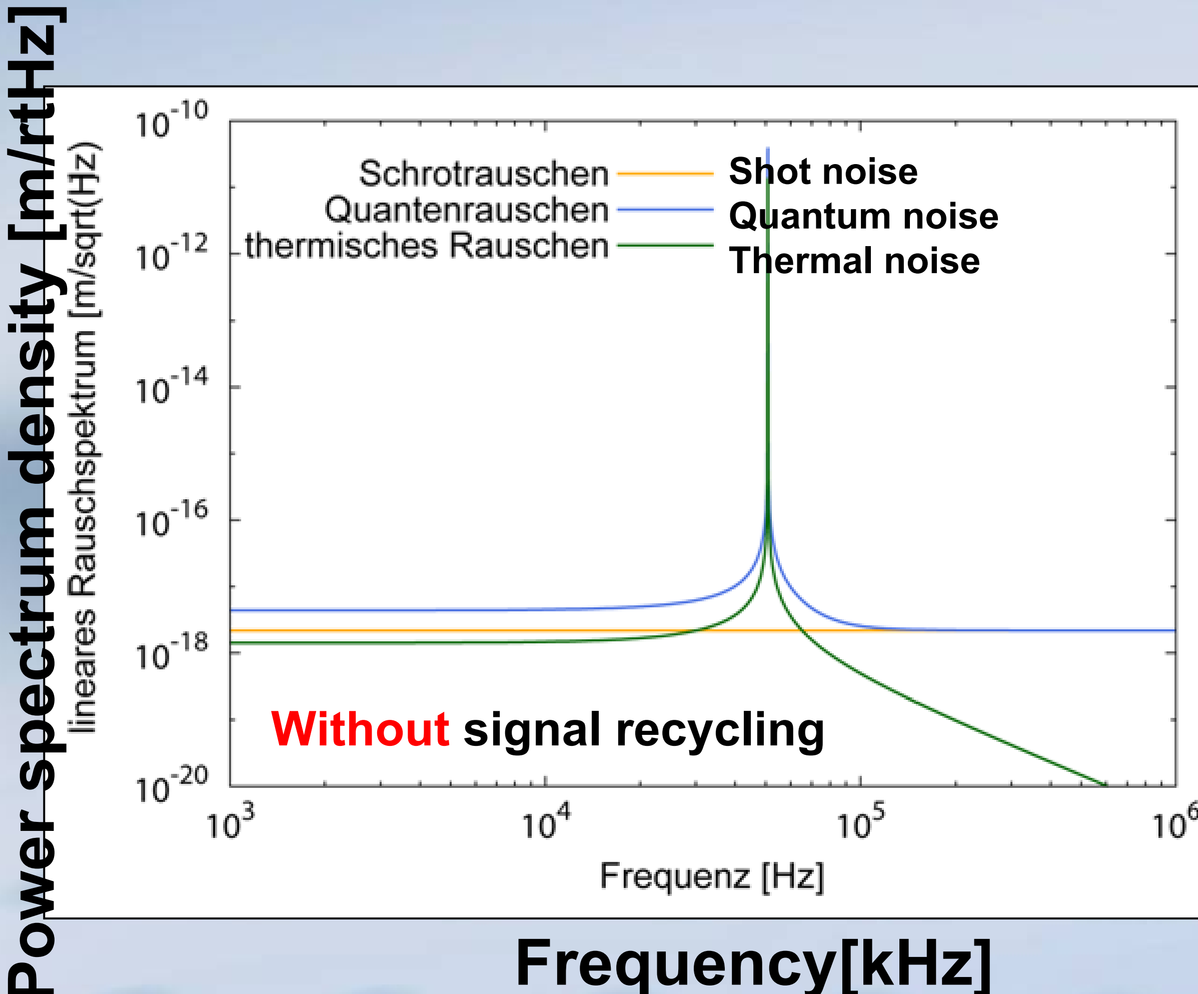
→ Radiation pressure on right side becomes larger.

(Optical spring effect)

2. Theoretical outlines

Goal sensitivity

Leibniz Universität Hannover



Temperature: 1 K
Q: 10^7
Effective Mass: 125 ng
Power at BS: 400 W
Resonance: 75 kHz
(with optical spring)
Resonance: 50 kHz
(without optical spring)

Shot noise: Factor 2
Thermal noise: Factor 3

Option
- **Signal Recycling**
  - **99% power reflectance**
  - **Power at BS : about 1W**