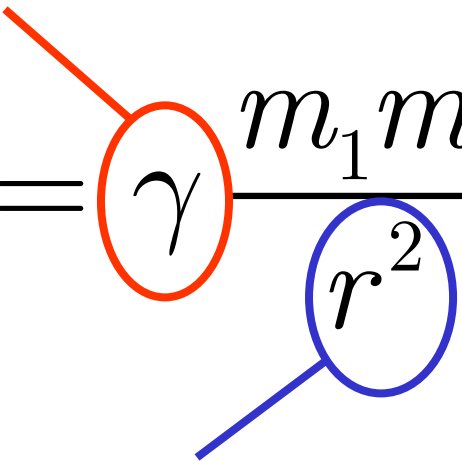


# Präzisionsexperimente zur Untersuchung der Gravitation

Ulrich Schmidt

## Messung der Gravitationskonstanten

$$F_G = \gamma \frac{m_1 m_2}{r^2}$$


Newton's Gravitationsgesetz

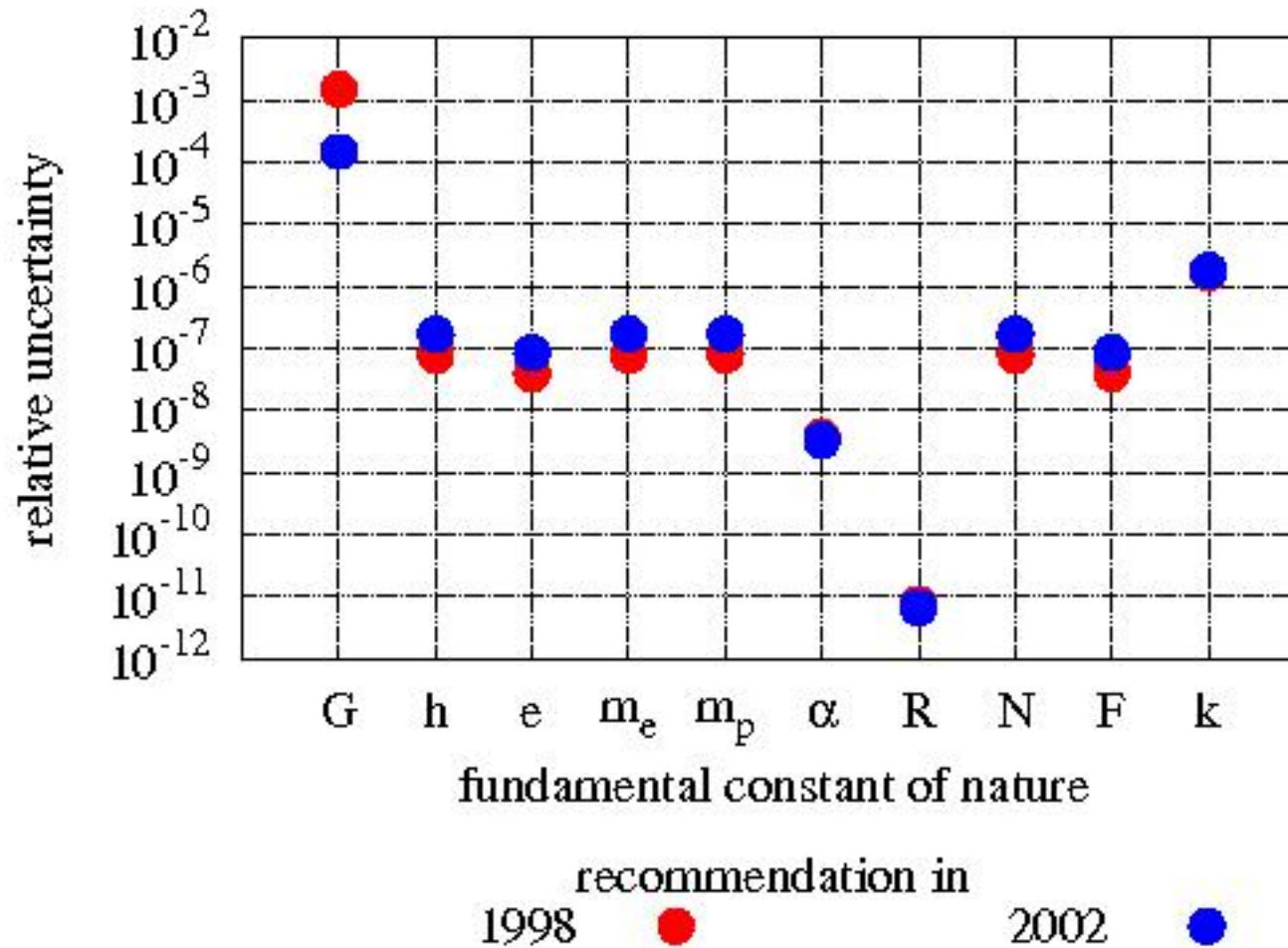
$$m_{schwere} = m_{tr\u00e4ge}$$



Universalit\u00e4t  
des freien Falls

Äquivalenzprinzip (Einstein)

# Messung der Gravitationskonstanten

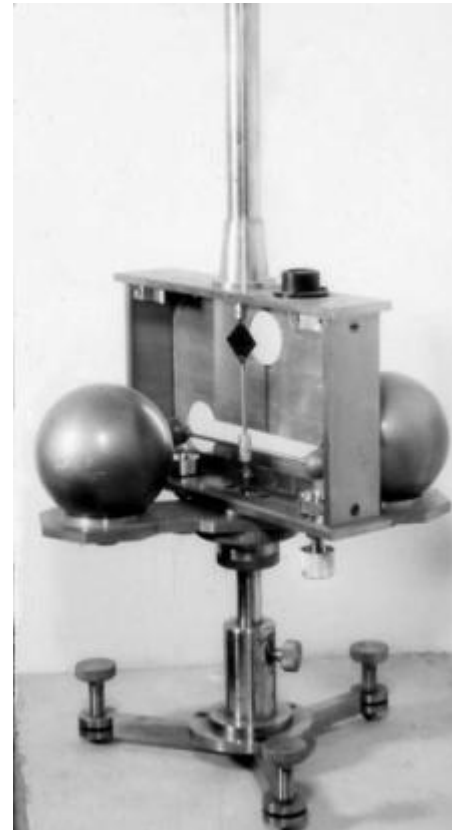


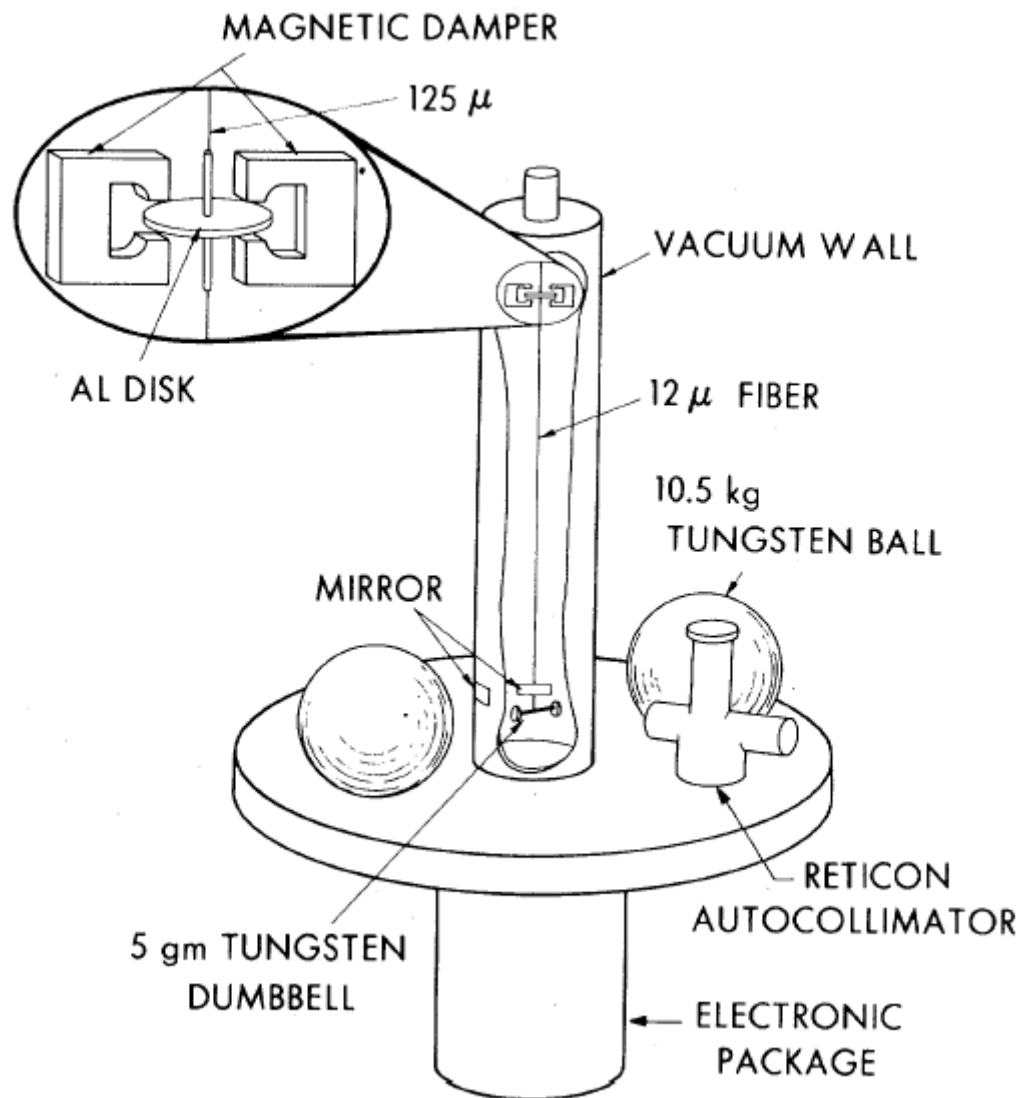
$$F_G = \gamma \frac{m_1 m_2}{r^2}$$

$$F_C = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$$

Für zwei Protonen

$$\left| \frac{F_G}{F_C} \right| \approx 10^{-38}$$





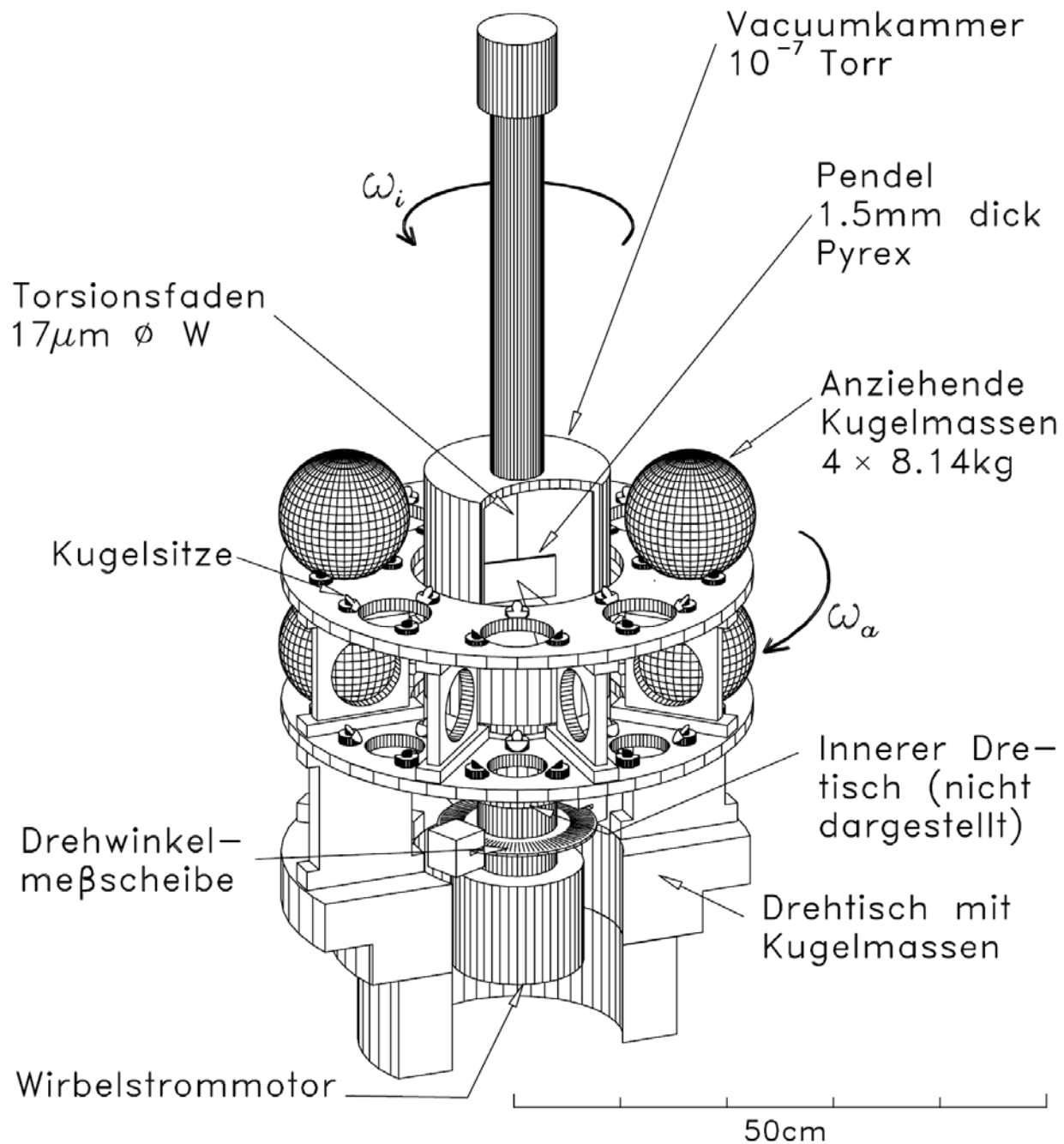
Experiment von G. G. Luther und W. R. Towler

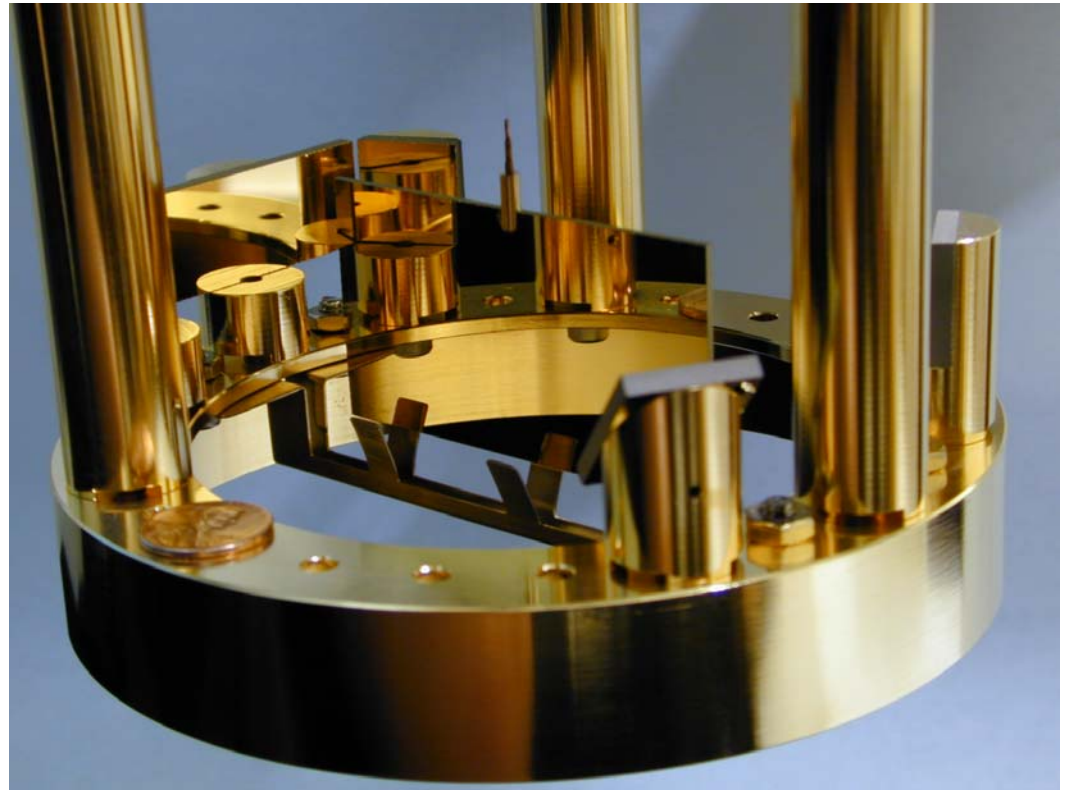
Quellmassen (Attraktor)  
 rotieren gleichförmig um  
 Pendel =>  
 periodisches Signal,  
 Fourieranalyse erlaubt  
 extreme  
 Rauschunterdrückung

Limitierende Faktoren:

-Massenverteilung des  
 Pendels (Dumbbell)  
 nicht genau genug  
 bekannt

-Nichtlinearität der  
 Rückstellkraft  
 (Kuroda-Effekt)





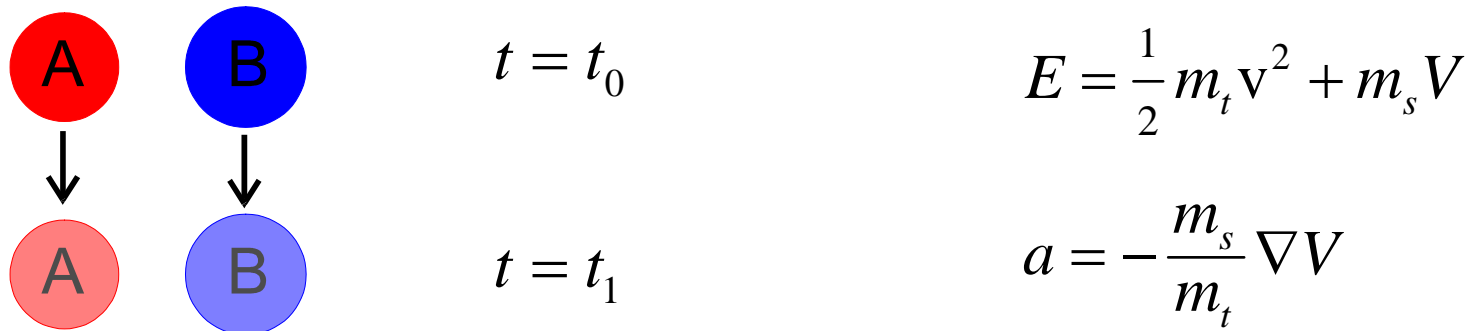
$$\gamma = (6.674215 \pm 0.000092) \cdot 10^{11} \frac{\text{m}^3}{\text{kg} \cdot \text{s}^2}$$

Äquivalenzprinzip:  $m_{träge} = m_{schwere}$

**Äquivalenzprinzip  $\Leftrightarrow$  Universalität des freien Falls**

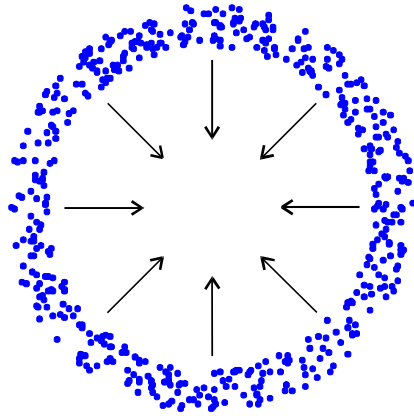
### Schwaches Äquivalenzprinzip

Laborexperiment: freier Fall, punktförmige Masse



Eötvösfaktor:  $\eta = \frac{a_A - a_B}{(a_A + a_B)/2} = \frac{\Delta a}{\bar{a}}$

Schwaches Äquivalenzprinzip:  $m_t = m_s \Leftrightarrow \eta_{SchwachesAP} = 0$



Gravitationsenergie  
wird frei  
⇒



Selbstenergie  $\hat{=}$  Massendefekt

Selbstenergie für homogene Kugel:

$$E_G = -\frac{3Gm^2}{5R} = -\frac{4\pi G\rho}{5} R^2 m$$

$$E_{G_{Erde}} = -4.6 \times 10^{-10} m_{Erde} c^2$$

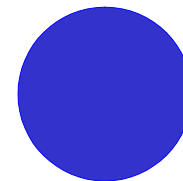
$$E_{G_{Mond}} = -0.2 \times 10^{-10} m_{Mond} c^2$$

**Starkes Äquivalenzprinzip:**

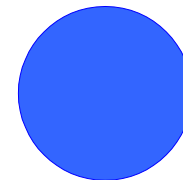
Äquivalenzprinzip gilt auch für  
gravitative Bindungsenergie

**A**

**B**



$t = t_0$



$t = t_1$

Verletzung des Schwachen Äquivalenzprinzips  $\Rightarrow$  Fünfte Kraft

Beispiel: Quintessenz; Kosmonfeld koppelt unterschiedlich an Neutron und Proton, Vorhersage:  $\eta \approx 10^{-14}$

Reichweite der fünften Kraft endlich falls Austauscheteilchen nicht masselos  
 $\Rightarrow$  Abstand zur Gravitationsquelle kann eine Rolle spielen.

Verletzung des Starken Äquivalenzprinzips

$\Leftrightarrow$  Allgemeine Relativitätstheorie nicht gültig

(Vermutung; C.M.Will: *The Confrontation between General Relativity and Experiment* )

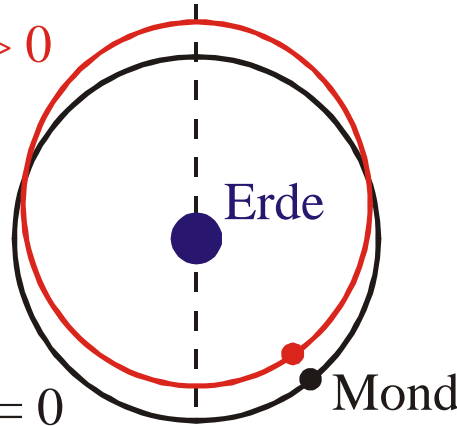
# Test des Starke Äquivalenzprinzips:

## Freier Fall von Erde und Mond zur Sonne

### Nordvedteffekt

$$\eta_{LLR} = \frac{\Delta a_{LLR}}{a_S} = \frac{a_{Erde} - a_{Mond}}{a_S}$$

$$\eta_{LLR} > 0$$



$$\eta_{LLR} = 0$$

$$\eta_{LLR_{max}} = \frac{-E_{G_{Erde}}}{m_{Erde} c^2} = -4.6 \cdot 10^{-10}$$

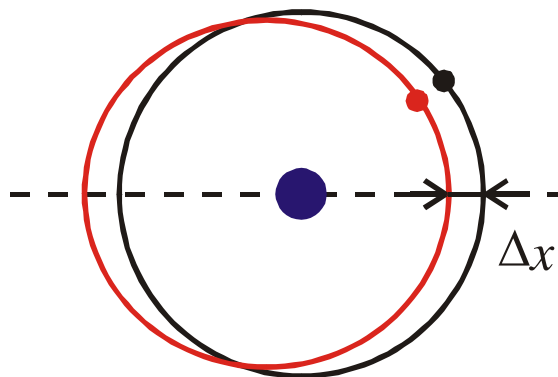
$$\Rightarrow \Delta x_{max.} = 12m$$

Williams *et al.* (2000):

$$\eta_{LLR} = (1 \pm 2) \cdot 10^{-13}$$

Müller *et al.* (1997):

$$\eta_{LLR} = (3.6 \pm 4.0) \cdot 10^{-13}$$



$$\Delta x$$

Sonne

$$\Rightarrow \Delta x \leq 8 \text{ mm}$$

$$\eta_{LLR} = \frac{\Delta a_{LLR}}{a_S} = \frac{a_{Erde} - a_{Mond}}{a_S} = \frac{\Delta a_G - \Delta a_{Material}}{a_S}$$

## Schwaches Äquivalenzprinzip

Galileo Galilei (Pisa 1589) Fallgesetzte (Genauigkeit ?)

Newton (Philosophiä naturalis Principiä 1687)

$$\eta \leq 1 \cdot 10^{-3}$$

Schwebung zwischen zwei Pendeln gleicher Länge, aber unterschiedlicher Zusammensetzung

$$m_t l \ddot{\varphi} + m_s g \sin \varphi = 0 \quad \Rightarrow \quad T = 2\pi \sqrt{\frac{l}{g}} \sqrt{\frac{m_t}{m_s}}$$

Bessel (ca.1820 ?)  $\eta \leq 1.7 \cdot 10^{-5}$

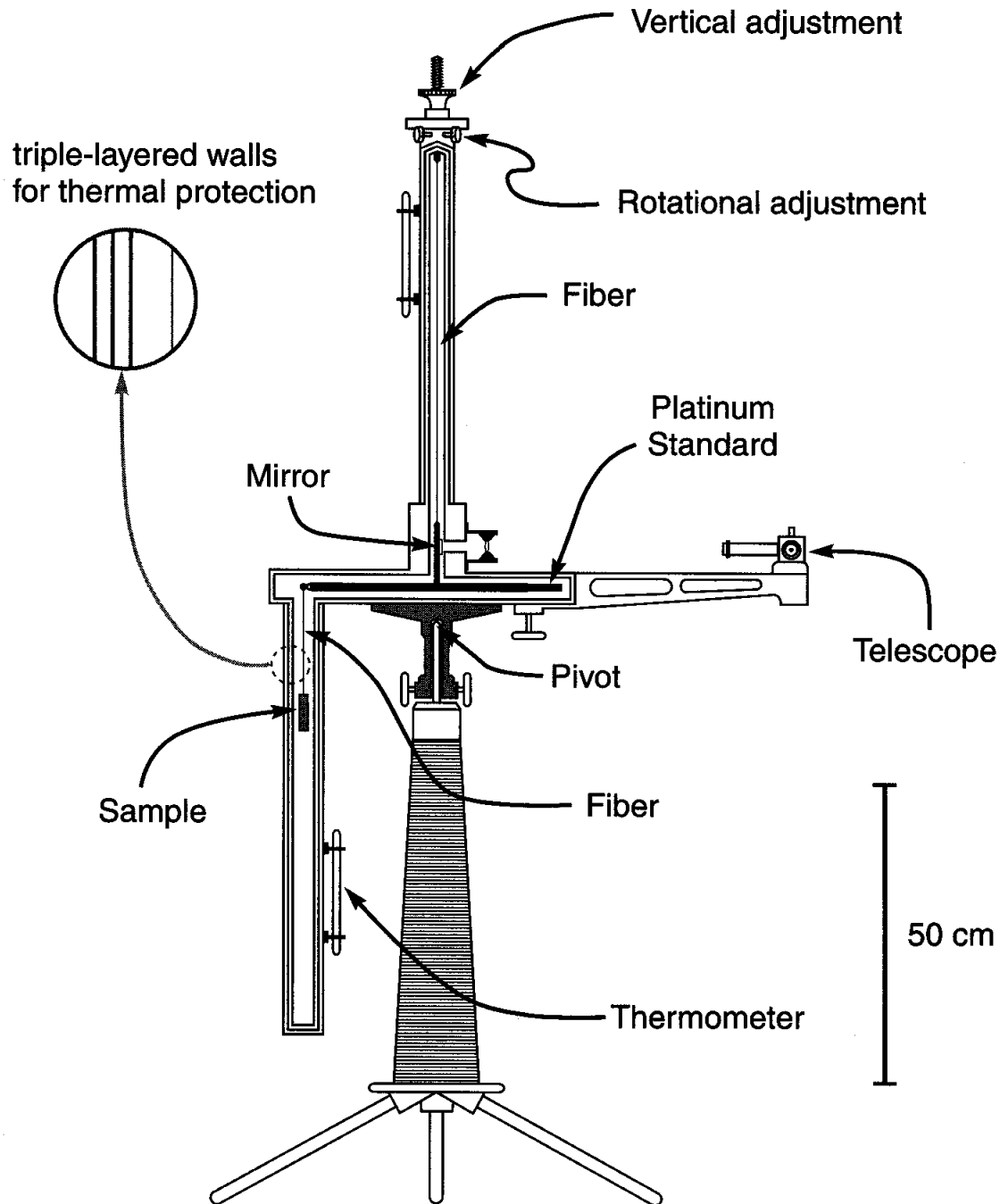


Figure 4.6: Single-arm torsion balance used by Eötvös, Pekár, and Fekete.

## Eötvösh

verbesserte Drehwaage

(1889)  $\eta \leq 5 \cdot 10^{-8}$

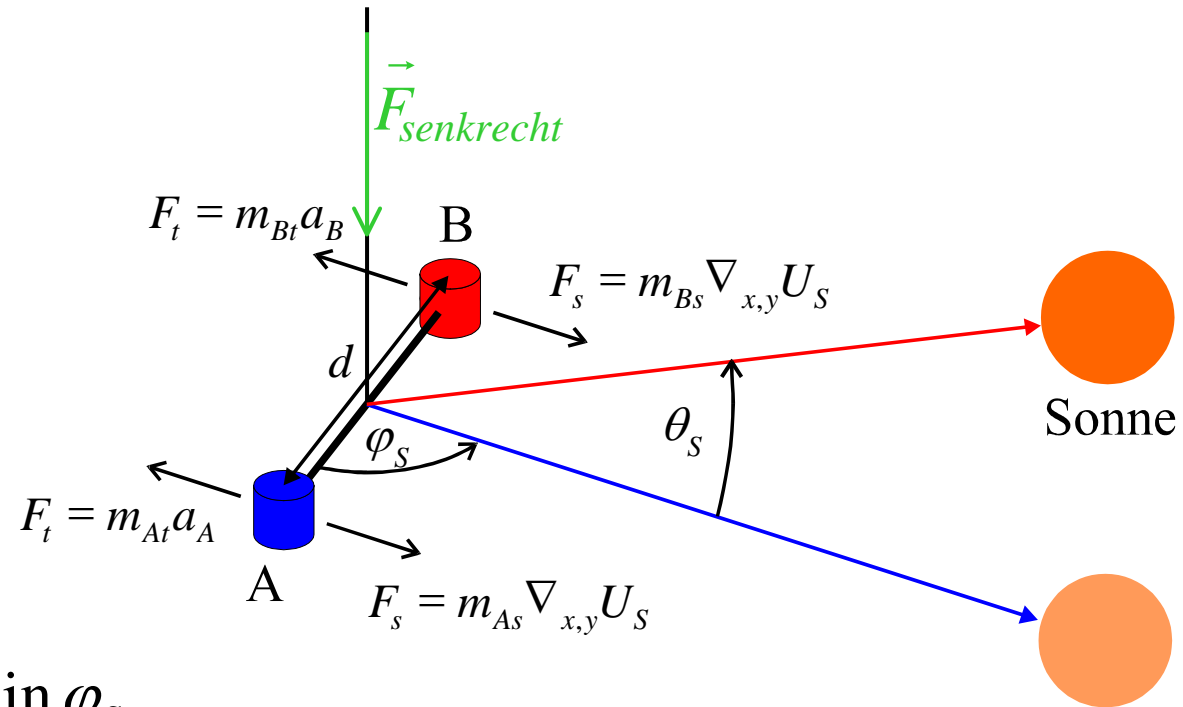
Material:

Platin, Kupfer, Wismut,  
Messing, Glas...

1922; Eötvös, Pekár  
und Fekete : um mehr  
als eine GröÙeordnung  
verbesserte Ergebnisse

Sonne als  
Gravitationsquelle

$$(a_S = 6.04 \cdot 10^{-4} g)$$



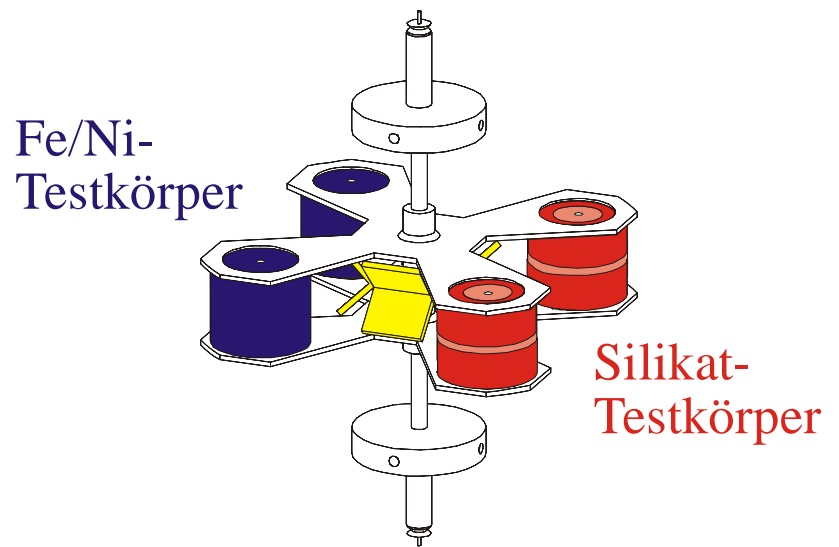
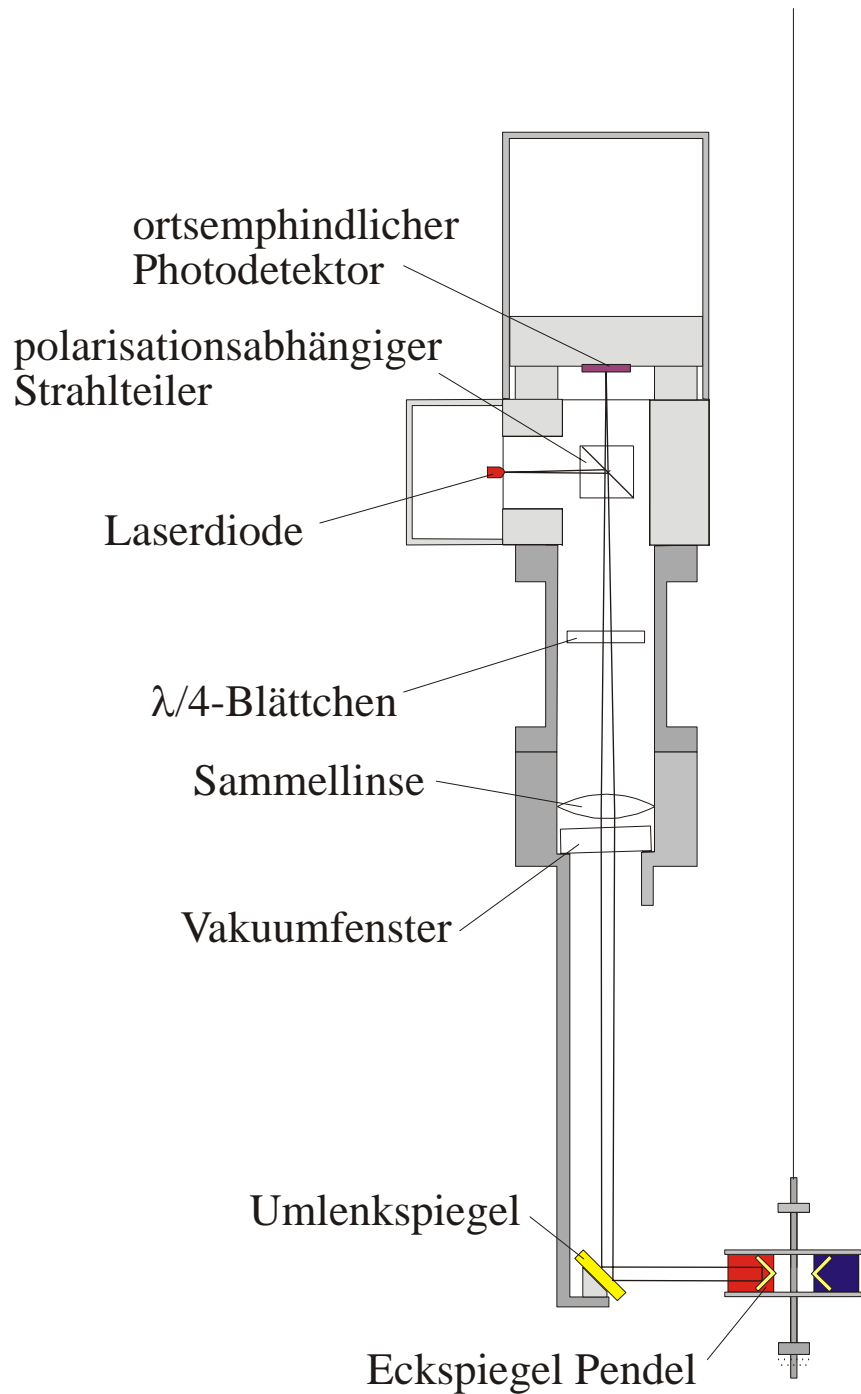
$$D = (F_A d_A - F_B d_B) \sin \varphi_S$$

$$\text{Schwerpunktsbedingung} \Rightarrow D = (a_A - a_B) \frac{m_A m_B}{m_A + m_B} d \sin \varphi_S \cos \theta_S$$

Roll, Krotov und Dicke (1964; Al-Au):  $\eta \leq (1.3 \pm 1.0) \cdot 10^{-11}$

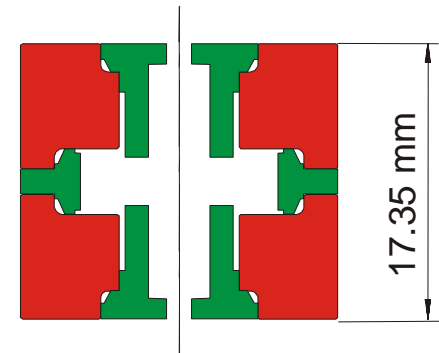
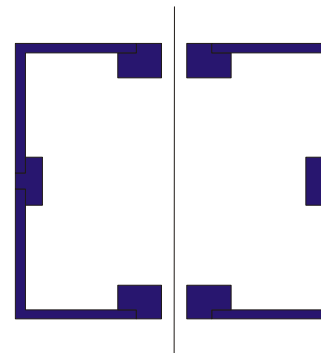
Braginsky und Panov (1971; Al-Pt):  $\eta \leq (-0.3 \pm 0.9) \cdot 10^{-12}$

Ziel Eöt-Wash-Gruppe:  $\eta_{\text{Erde-Mond}} \leq 5 \cdot 10^{-13}$



Fe/Ni-Testkörper  
(Zylinder)

Silikat-Testkörper  
(Zylinder)

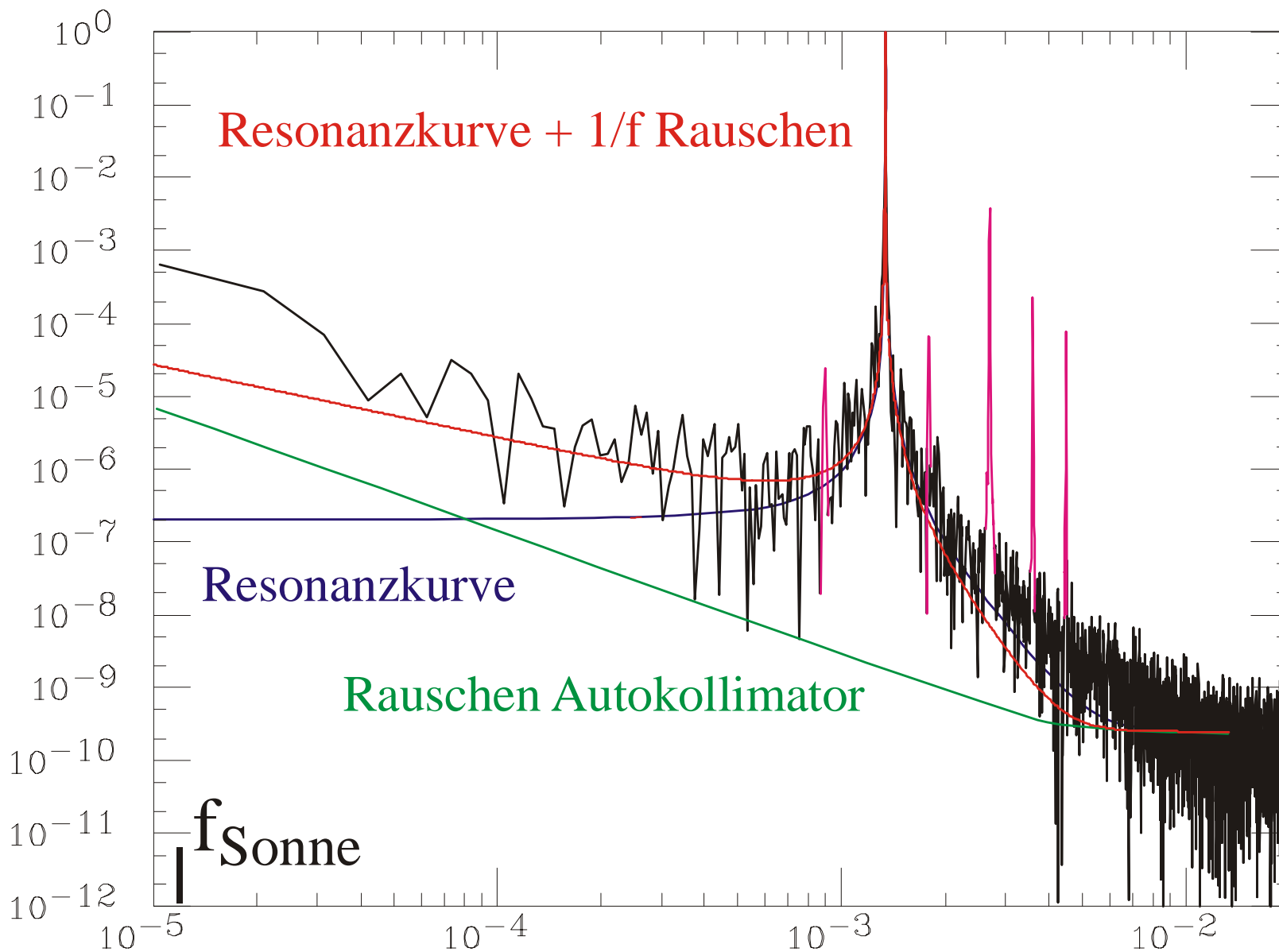


■ AISI 304  
Stainless Steel

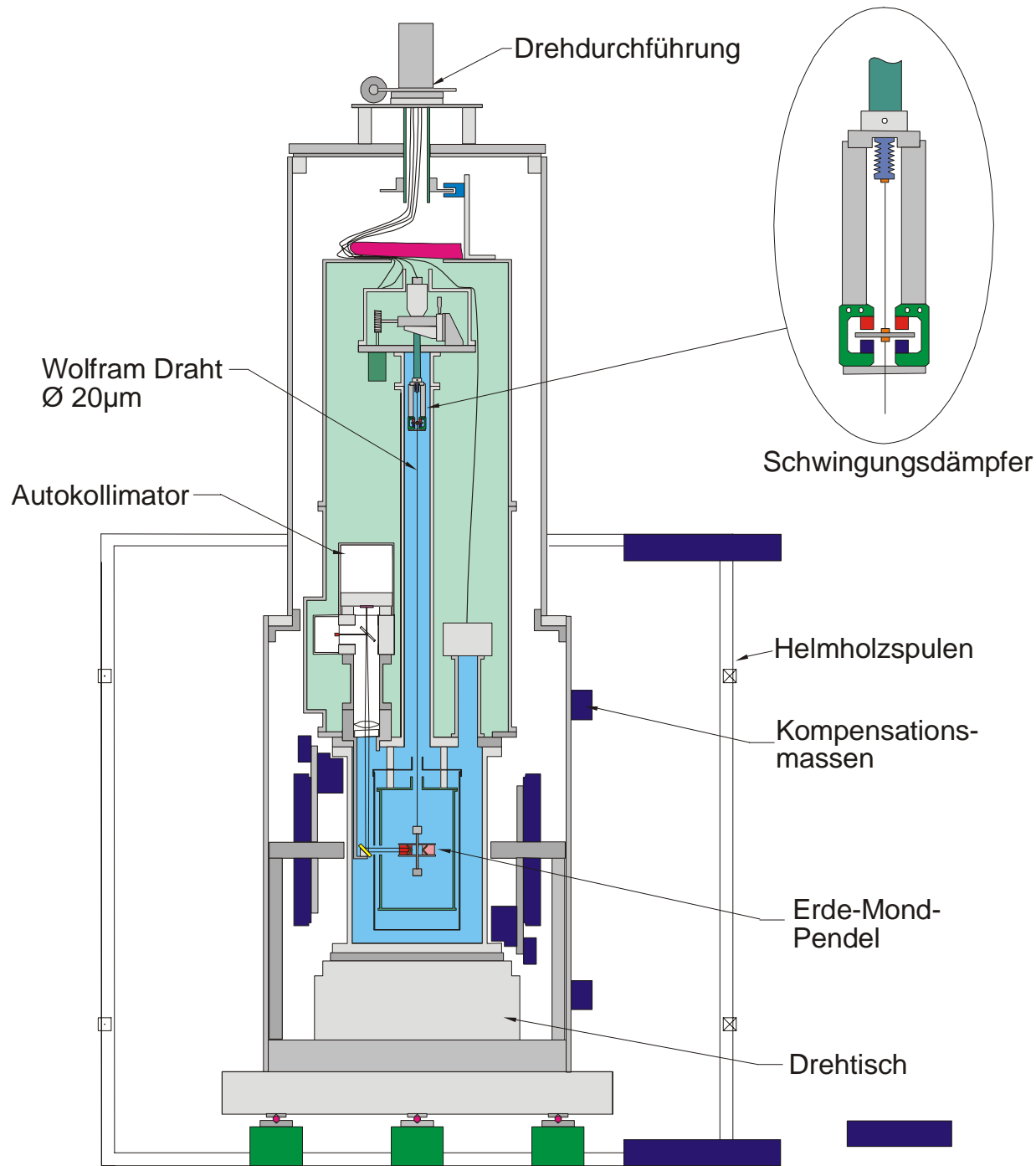
■ AZ16A-F Magnesium Alloy  
■ Fused Quartz

Masse eines Testkörpers: 10.04 g

Leistungsdichte  $\vartheta^2$  [mrad<sup>2</sup> s]

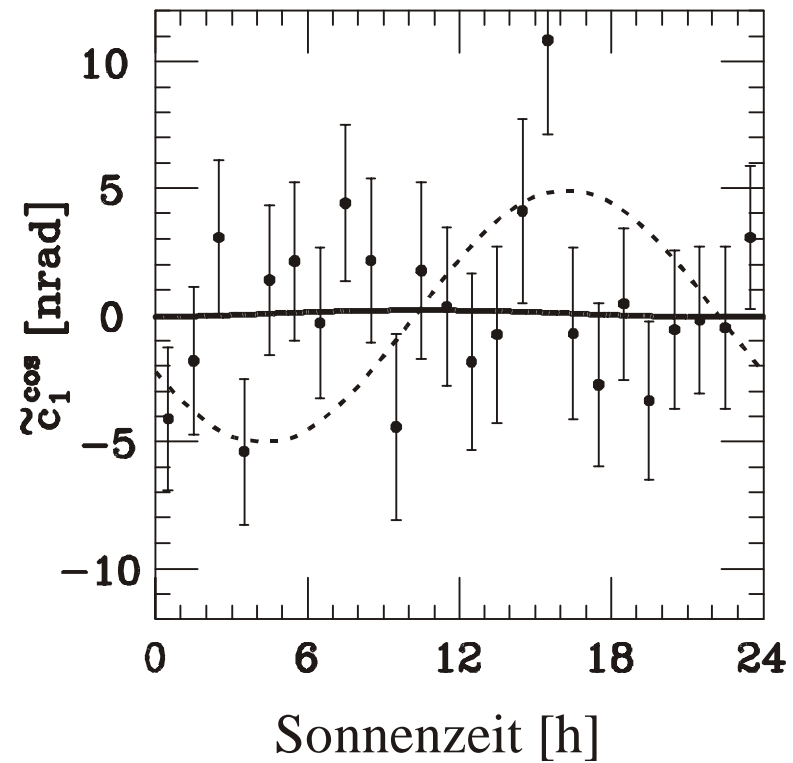
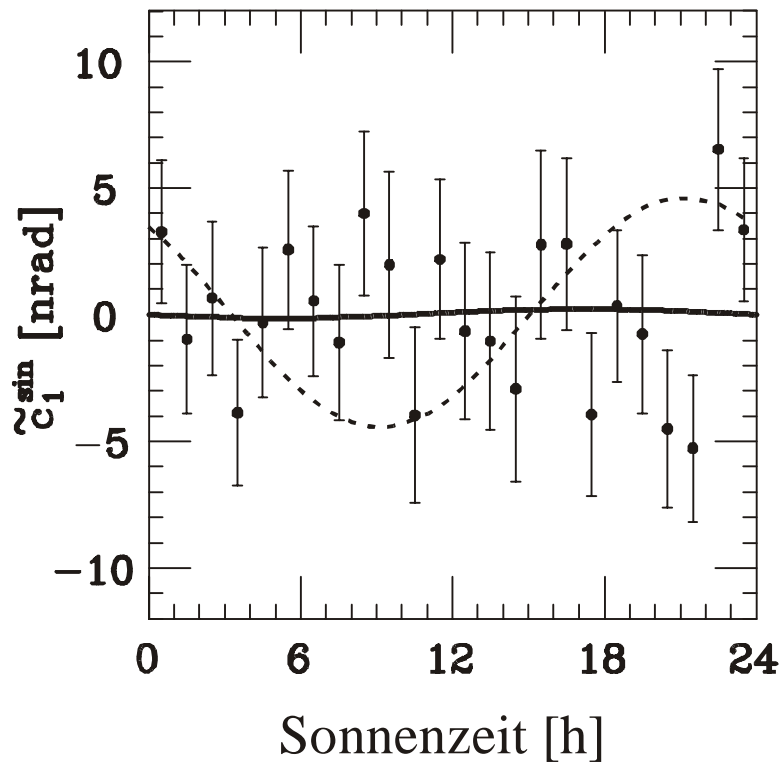
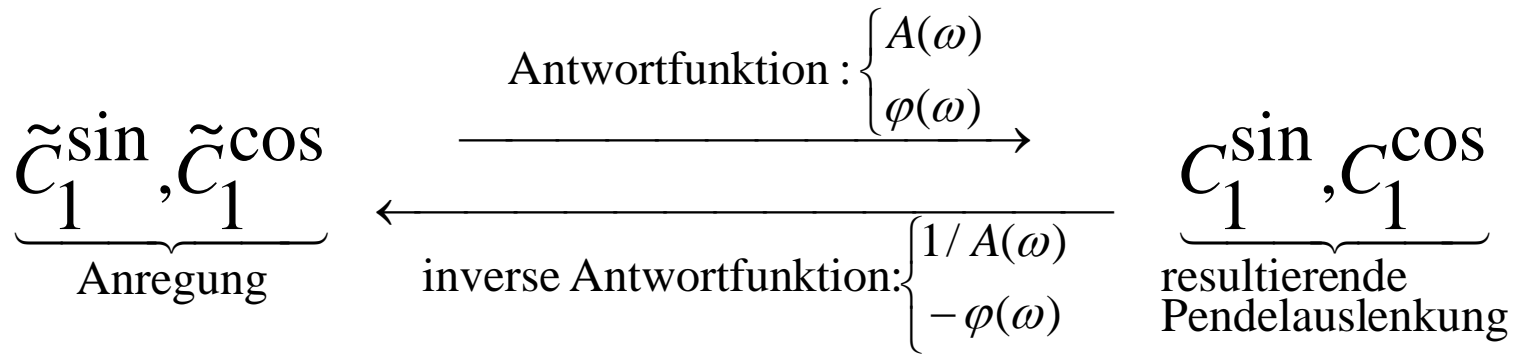


Frequenz [Hz]



## Anforderungen:

- Magnetfeld an der Pendelposition  $< 10\text{nT}$
- Temperaturänderung im inneren Teil  $< 100\ \mu\text{K}$
- tägliche Komponente (sonnenstandskorreliert) der Temperaturänderung  $< 5\ \mu\text{K}$
- Gleichlaufschwankungen des Drehtisches  $\Delta\omega/\omega < 10^{-6}$
- ....



gestrichelte Linie entspricht  $\eta_{EM}$  von  $20 \cdot 10^{-13}$

$$\eta_{EM} = (1.0 \pm 1.4 \pm 0.2) \cdot 10^{-13}$$

## Lunar Laser Ranging

Williams *et.al.* (2000) :

$$\eta_{LLR} = (1 \pm 2) \cdot 10^{-13}$$

Müller *et.al.* (1997) :

$$\eta_{LLR} = (3.6 \pm 4.0) \cdot 10^{-13}$$

$$\Rightarrow \eta_{St\ddot{A}P} = (-2.0 \pm 2.4) \cdot 10^{-13}$$

$$\eta_{Gravitation} = \frac{|\eta_{S\ddot{A}P}|}{4.4 \cdot 10^{-10}} \leq 1.0 \cdot 10^{-3}$$

$$\frac{\Delta a_{Testk\ddot{o}rper}}{a_{Milchstra\ddot{b}e}} = (1.7 \pm 1.5 \pm 0.3) \cdot 10^{-5}$$

„Fünfte Kraft“ der dunklen Materie in unserer  
Milchstraße  $< 10^{-4} \times$  Gravitationskraft

# Newton's Gravitationsgesetz

Gravitationsfeld einer Punktmasse:  $g(r) = G \frac{m}{r^2}$

$g(r) \propto \frac{1}{r^2}$  folgt aus Gauß'schem Satz in 3  
Raumdimensionen und Quellfreiheit  
( $\operatorname{div} g = 0$ ) des Raumes

Anzahl der Raumdimensionen:  $n$

$$g(r) \propto \frac{1}{r^{n-1}}$$

Newton's gravity potential:

$$V(r) = -G \frac{m}{r}$$

Deviation from the Newtonian gravity potential:

=> Additional Yukawa potential

$$V(r) = -G \frac{m}{r} (1 + \alpha e^{-r/\lambda})$$

$\alpha$  : Coupling constant (relative to  $G$ )

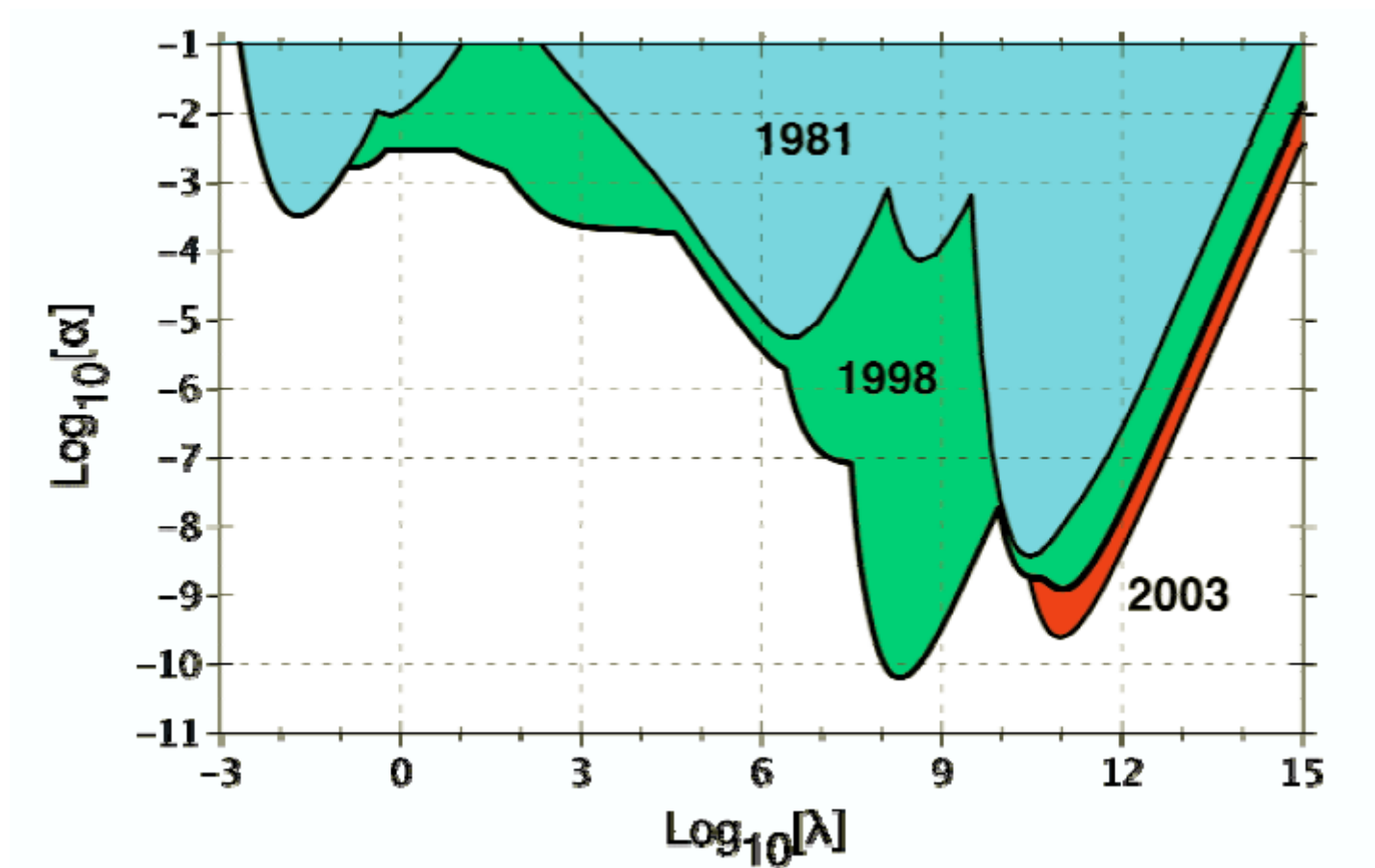
$\lambda$  : Range

find no deviation from Newtonian physics :

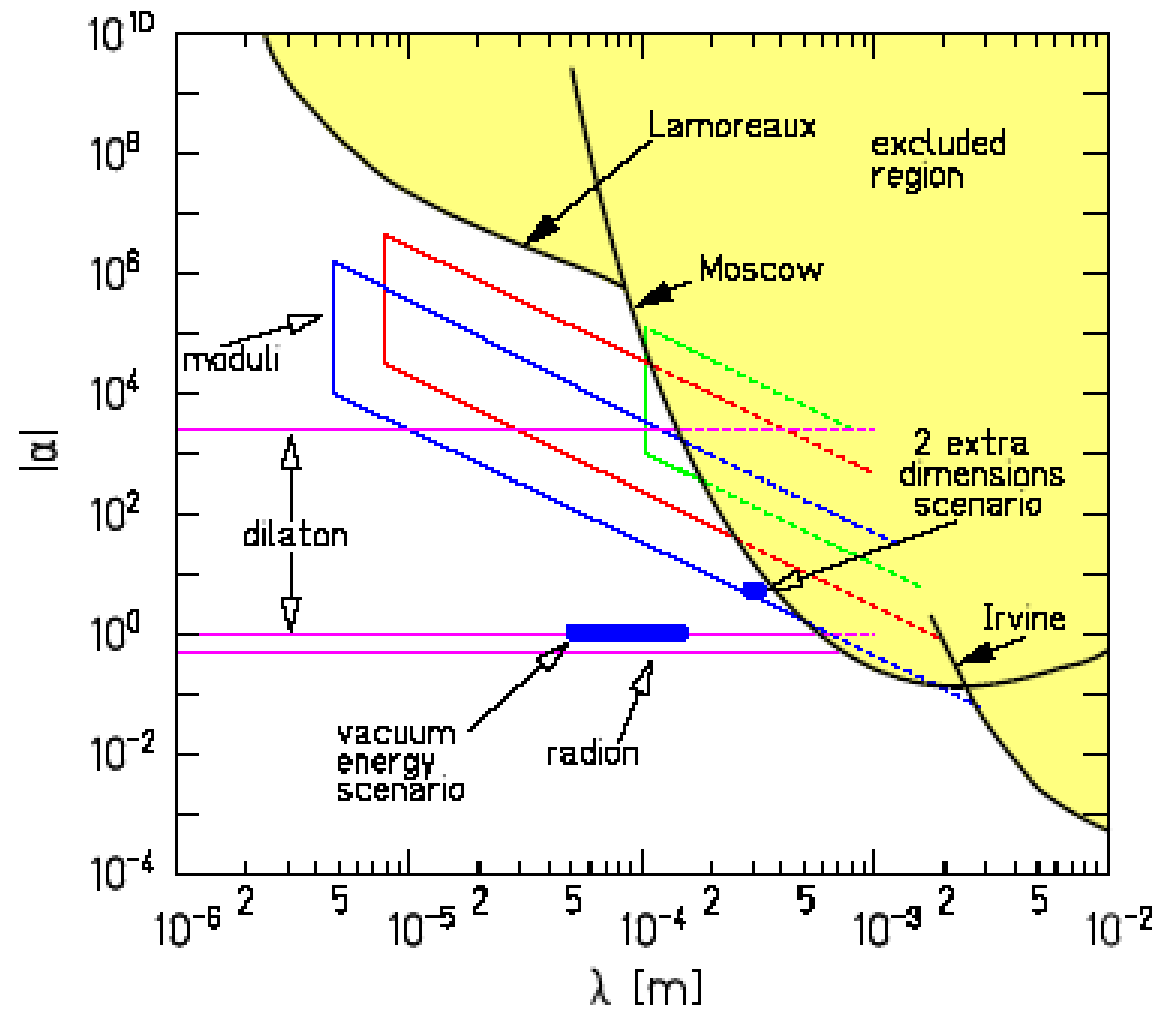
=> Exclude region of the a-l-plain

# Limits on Extra Dimensions and New Forces:

## Long-Range Limits



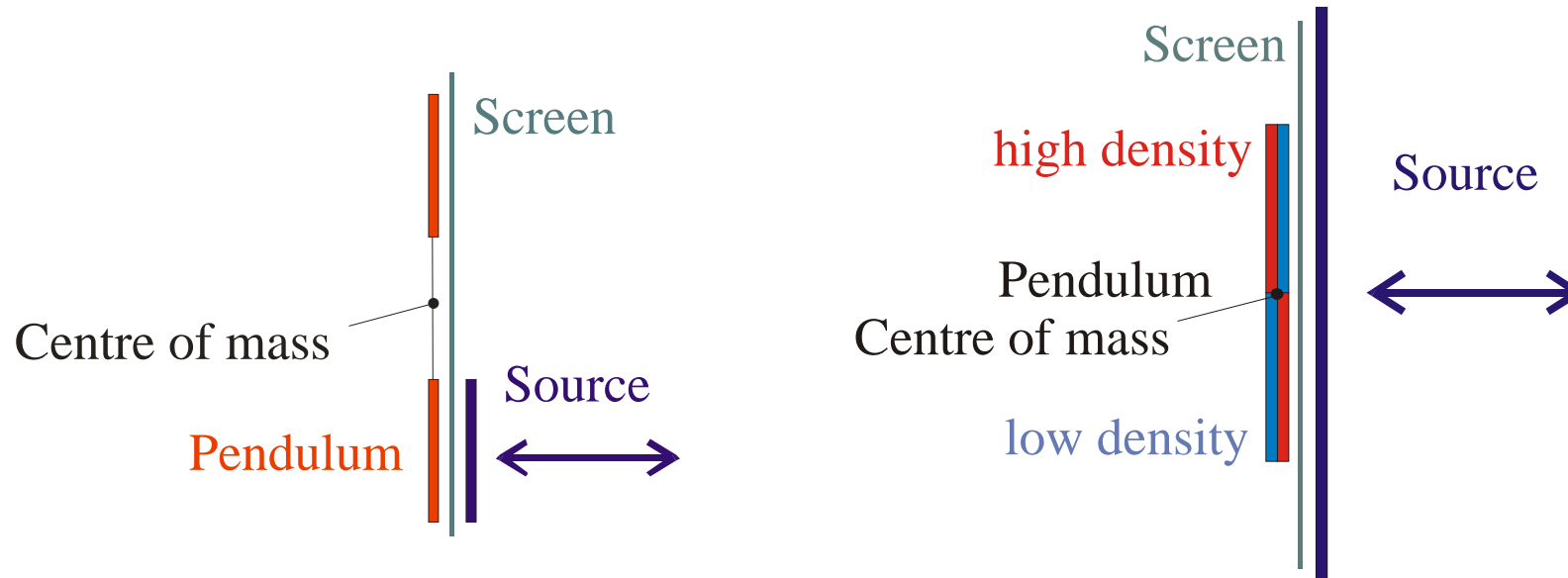
Reference: Coy, Fischbach, Hellings, Standish & Talmadge (2003)



95% confidence upper limits on a short-range Yukawa violation of the gravitational ISL as of 1999

## Measurement of a short range gravitational force

- sufficient mass of pendulum and source has to be close to each other  
=> flat plate
- patch effect: electrical conductors have a charge pattern on their surfaces  
=> screen

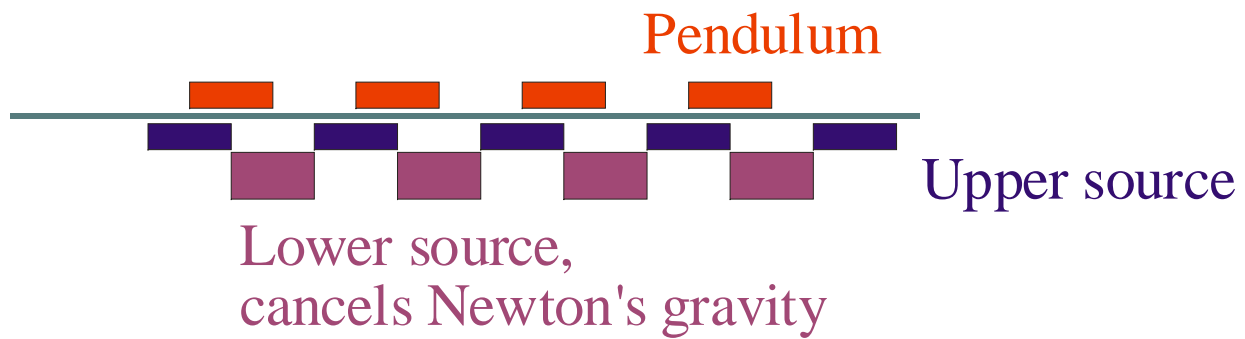
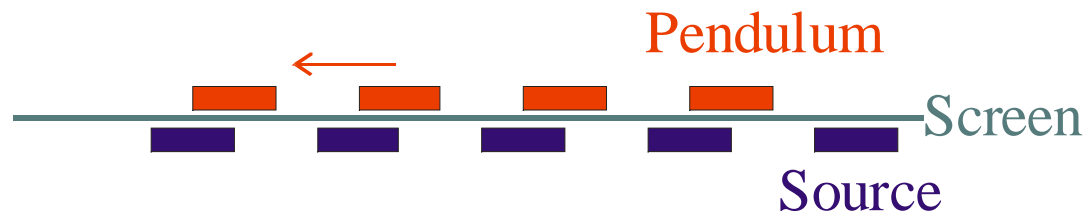
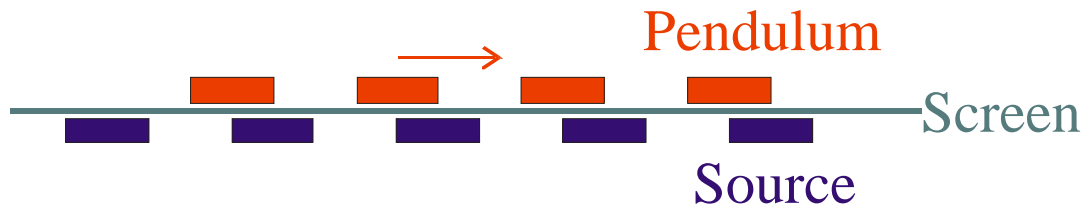


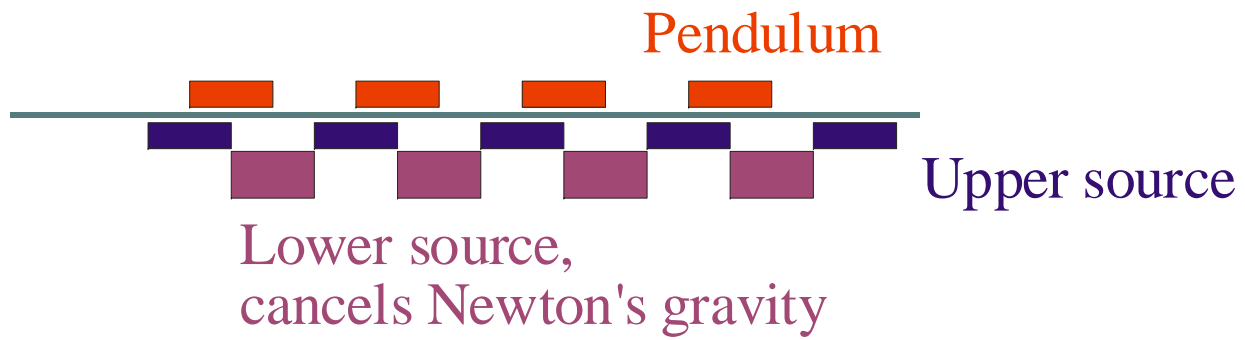
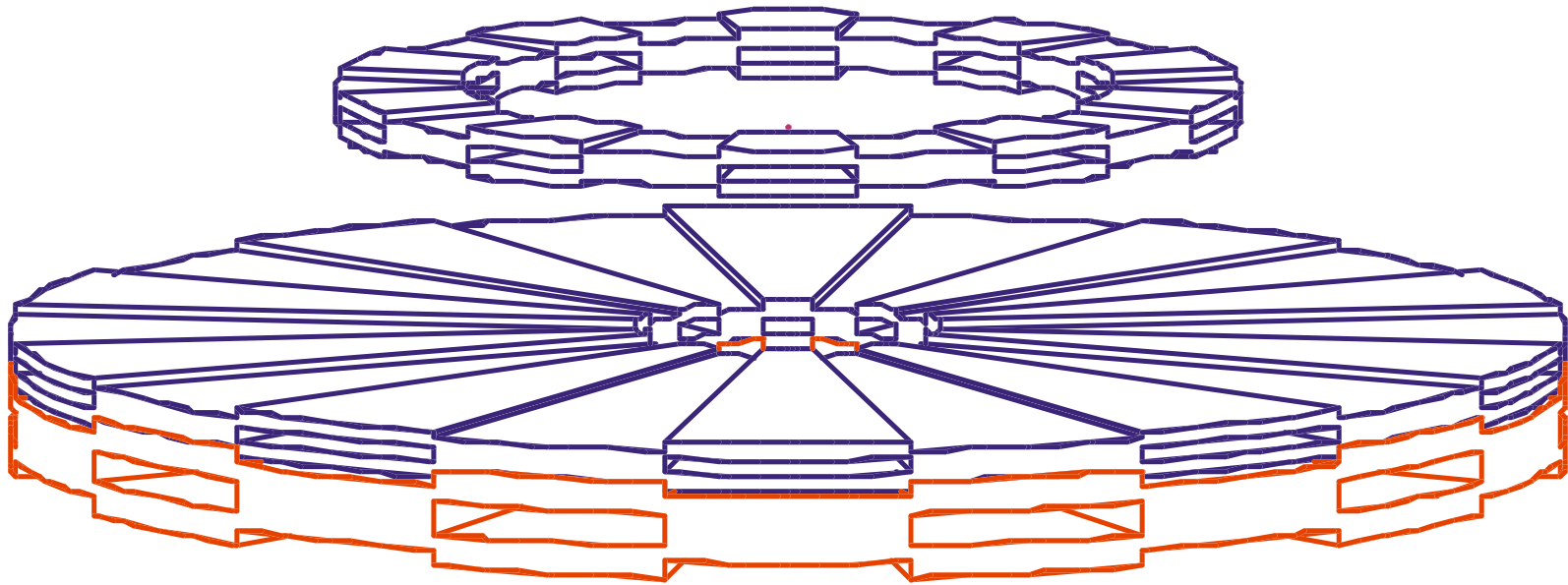
=> short range signal small  
compared to Newton's  
gravity

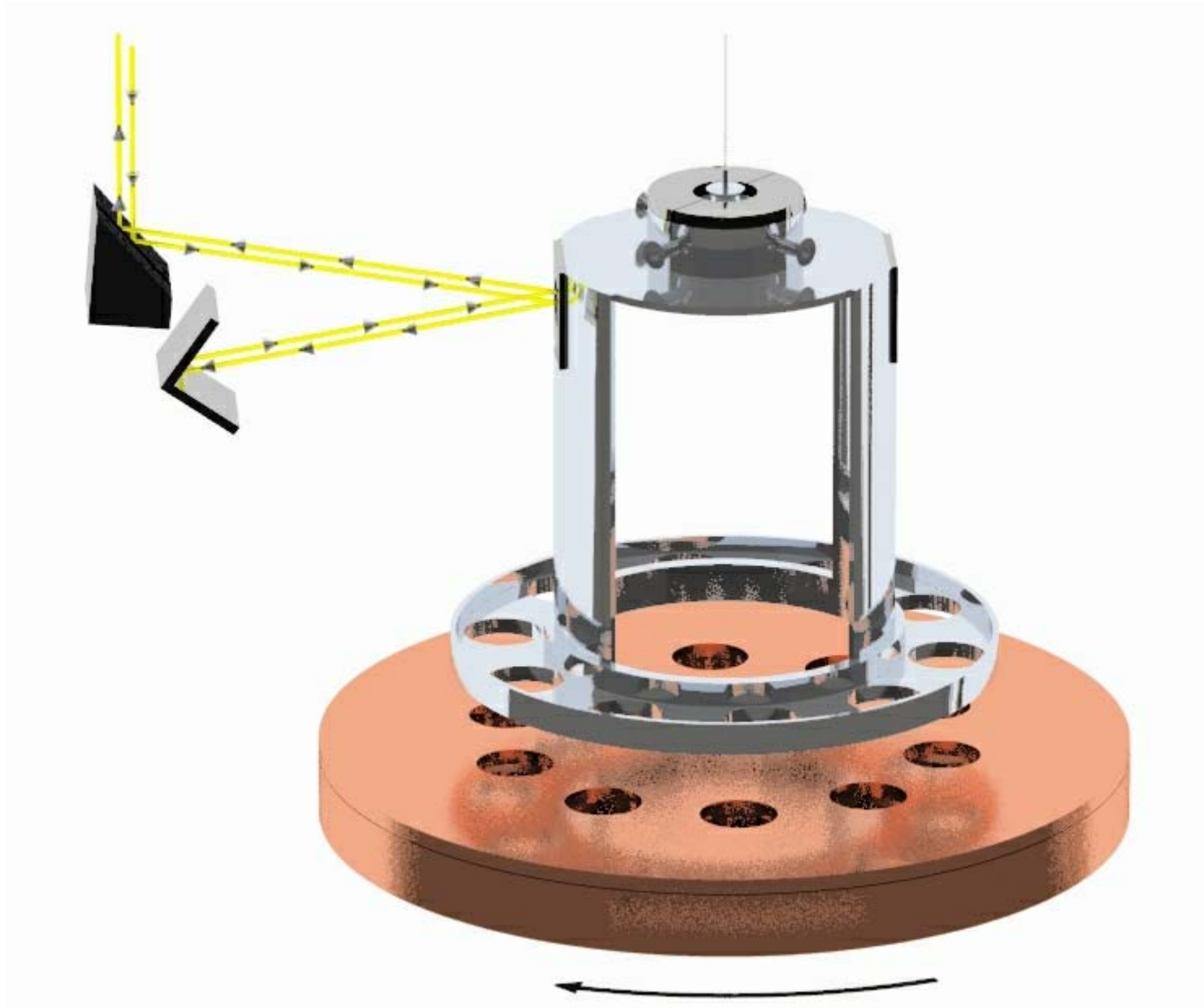
Infinite plate => force from  
Newton's gravity  
independent from distance

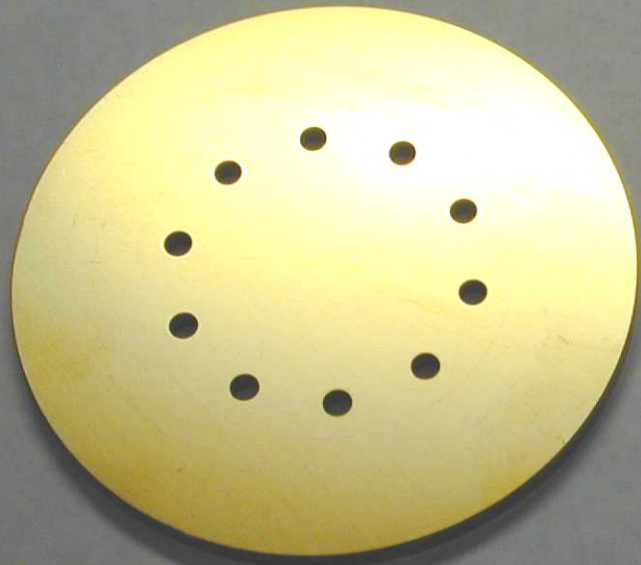
Problem: Frequency of signal = frequency of Source

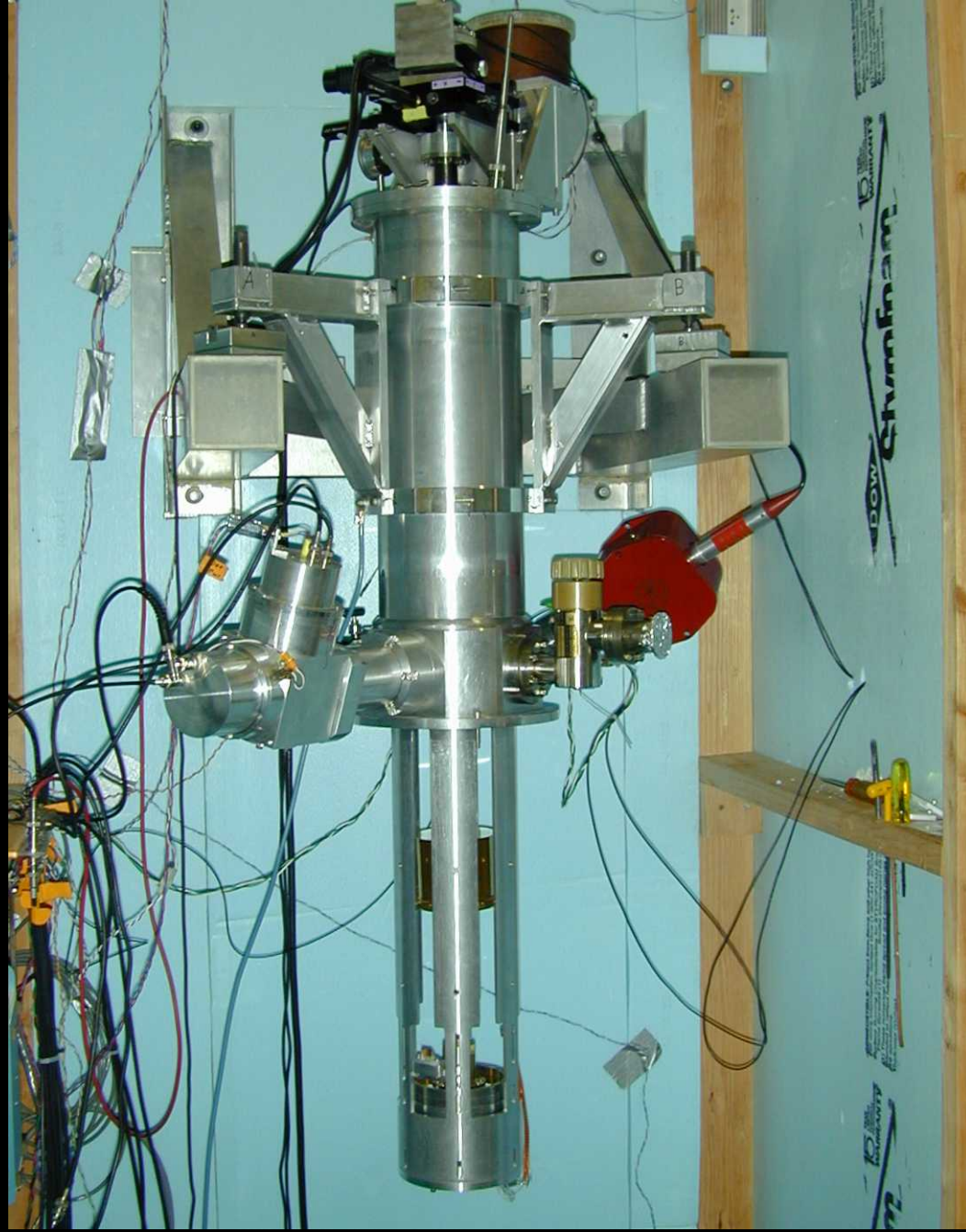
=> Coupling due to vibrations, finite stiffness of apparatus etc.

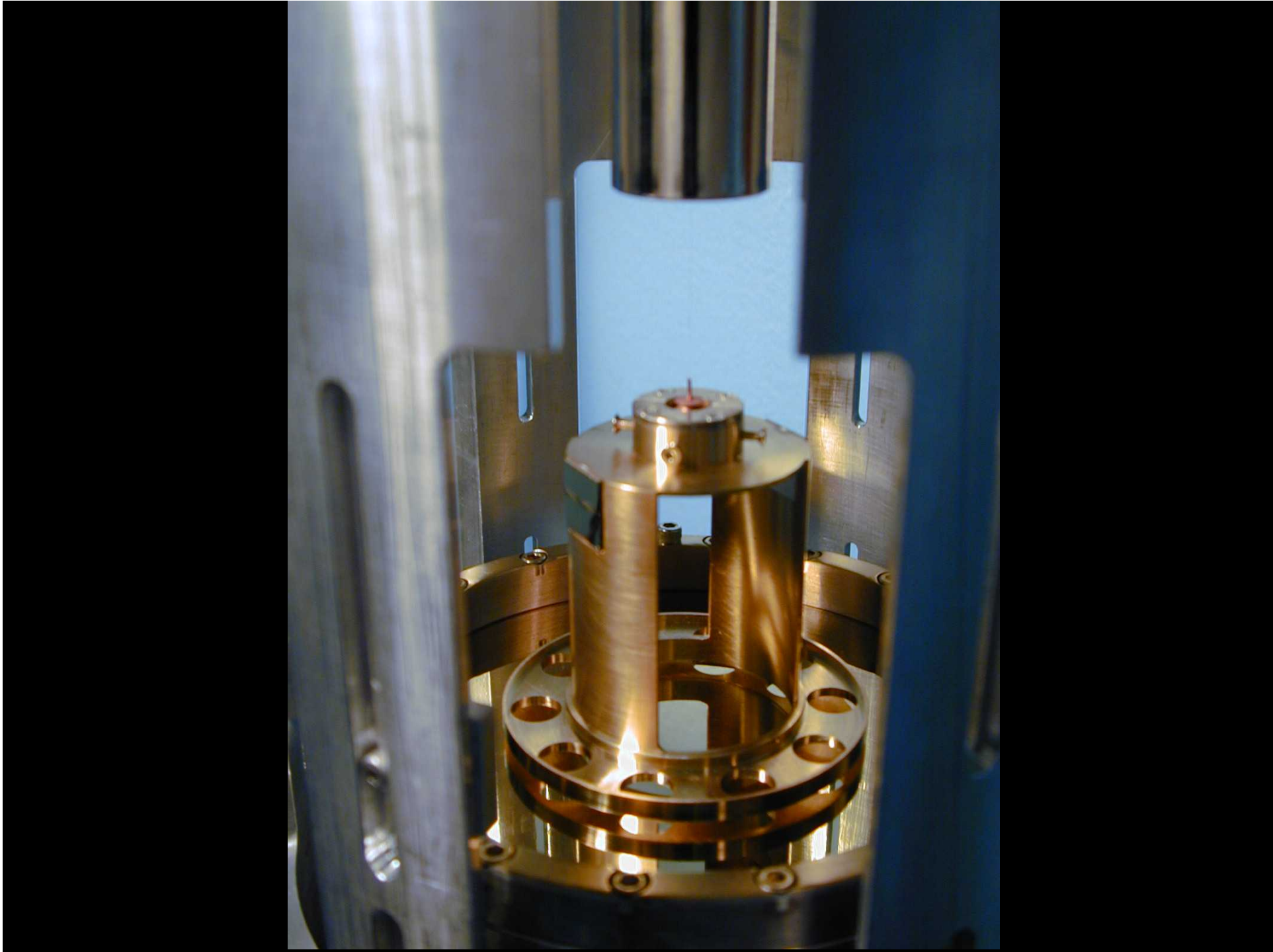


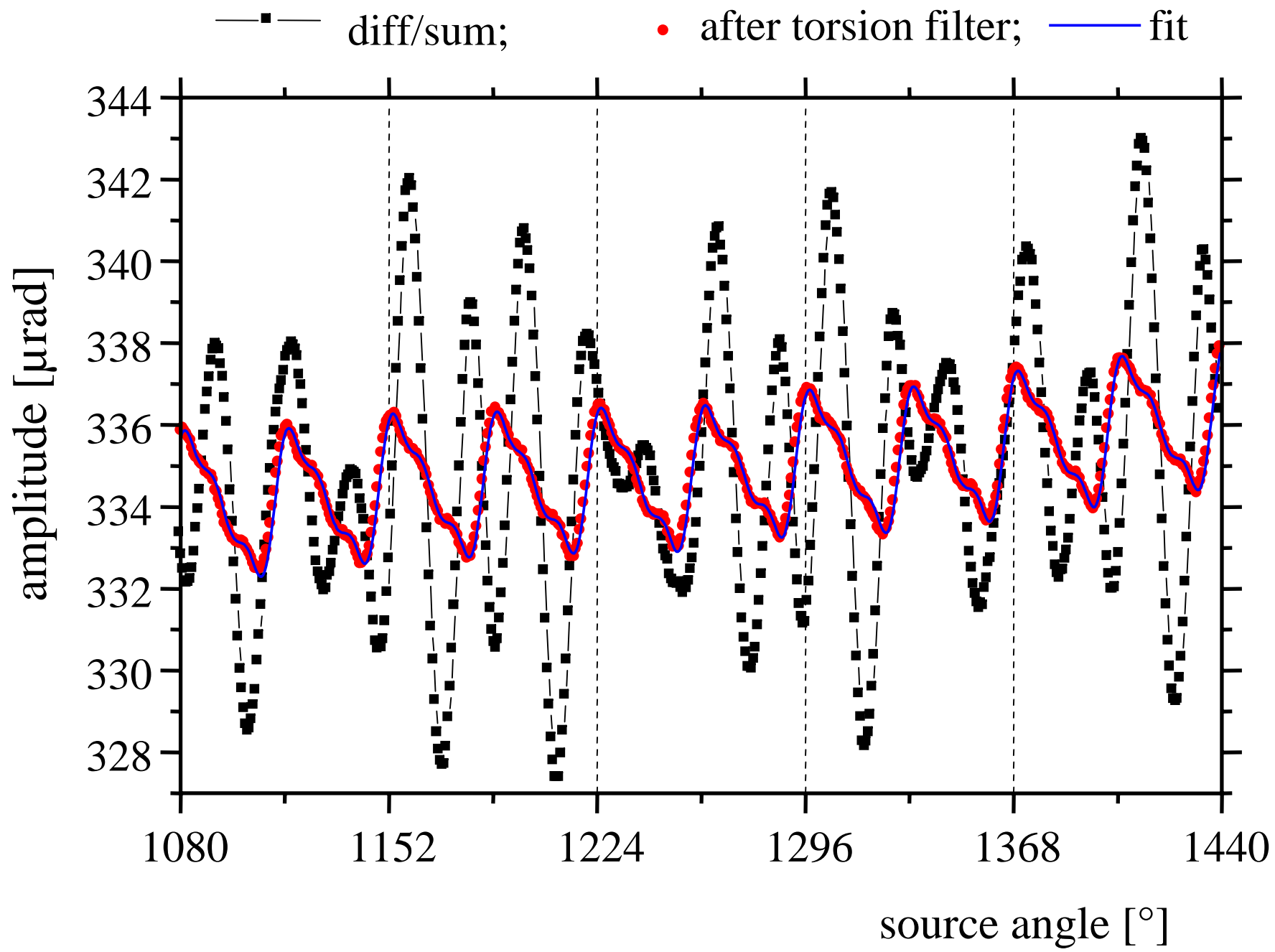


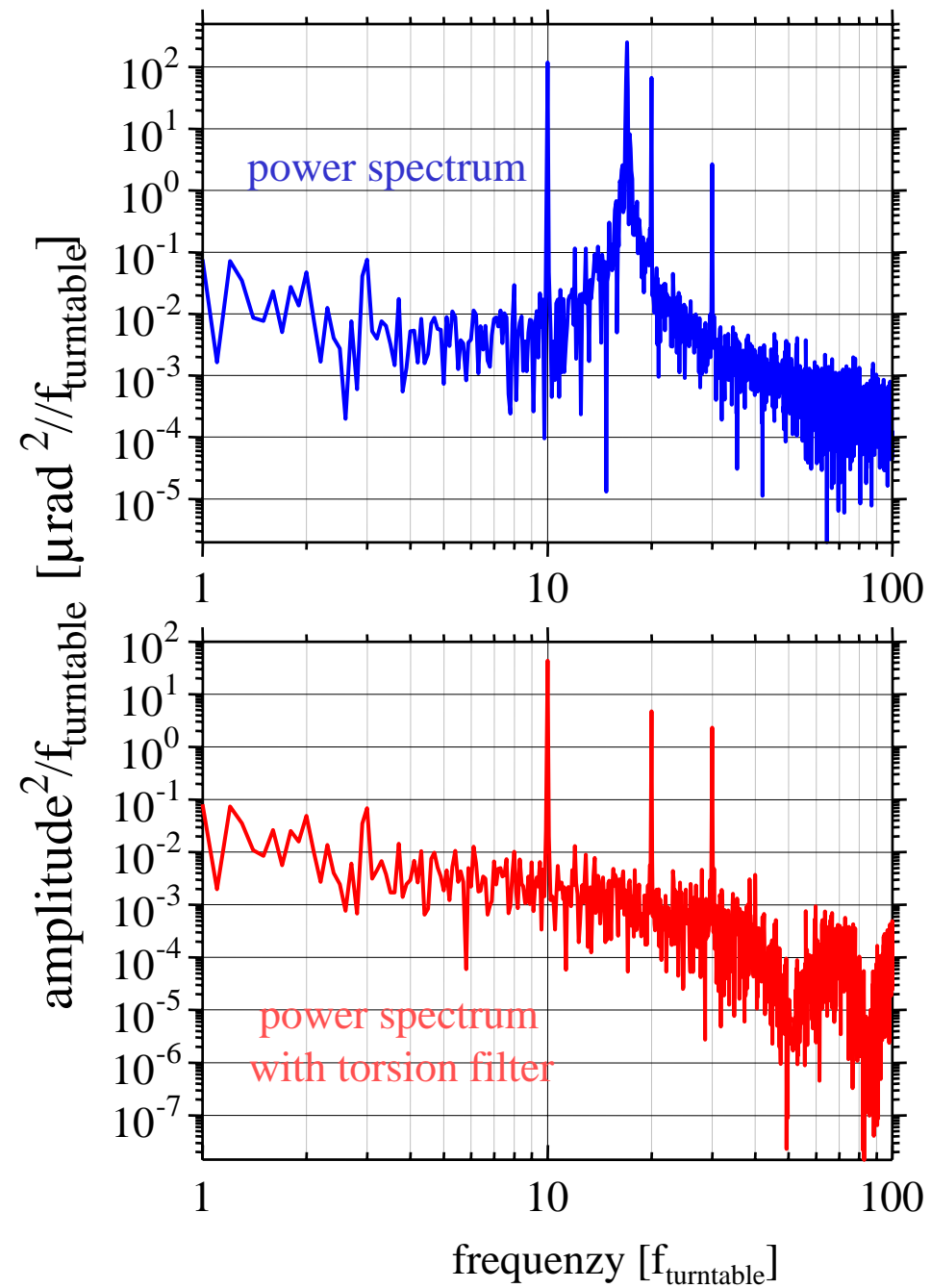


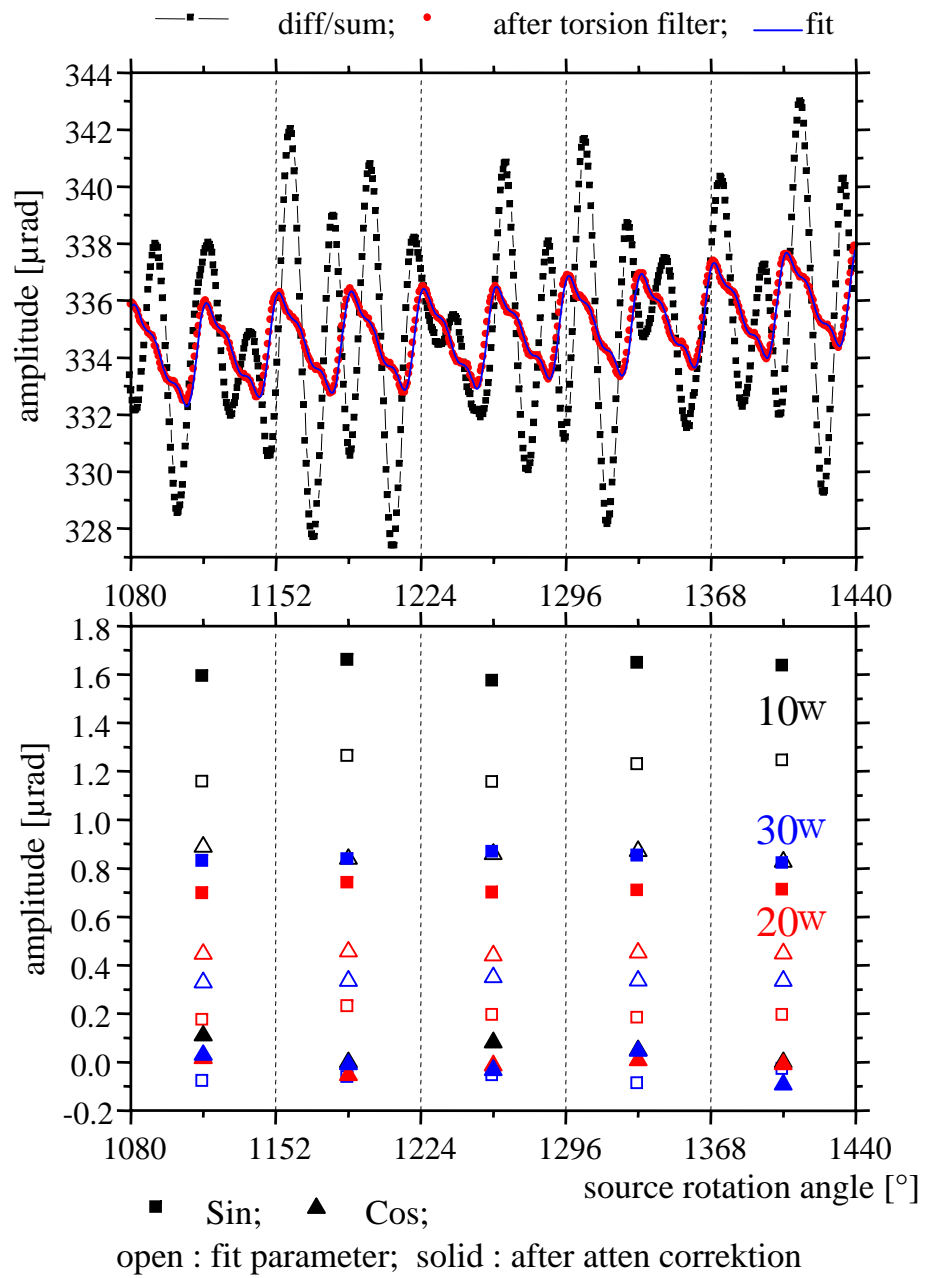


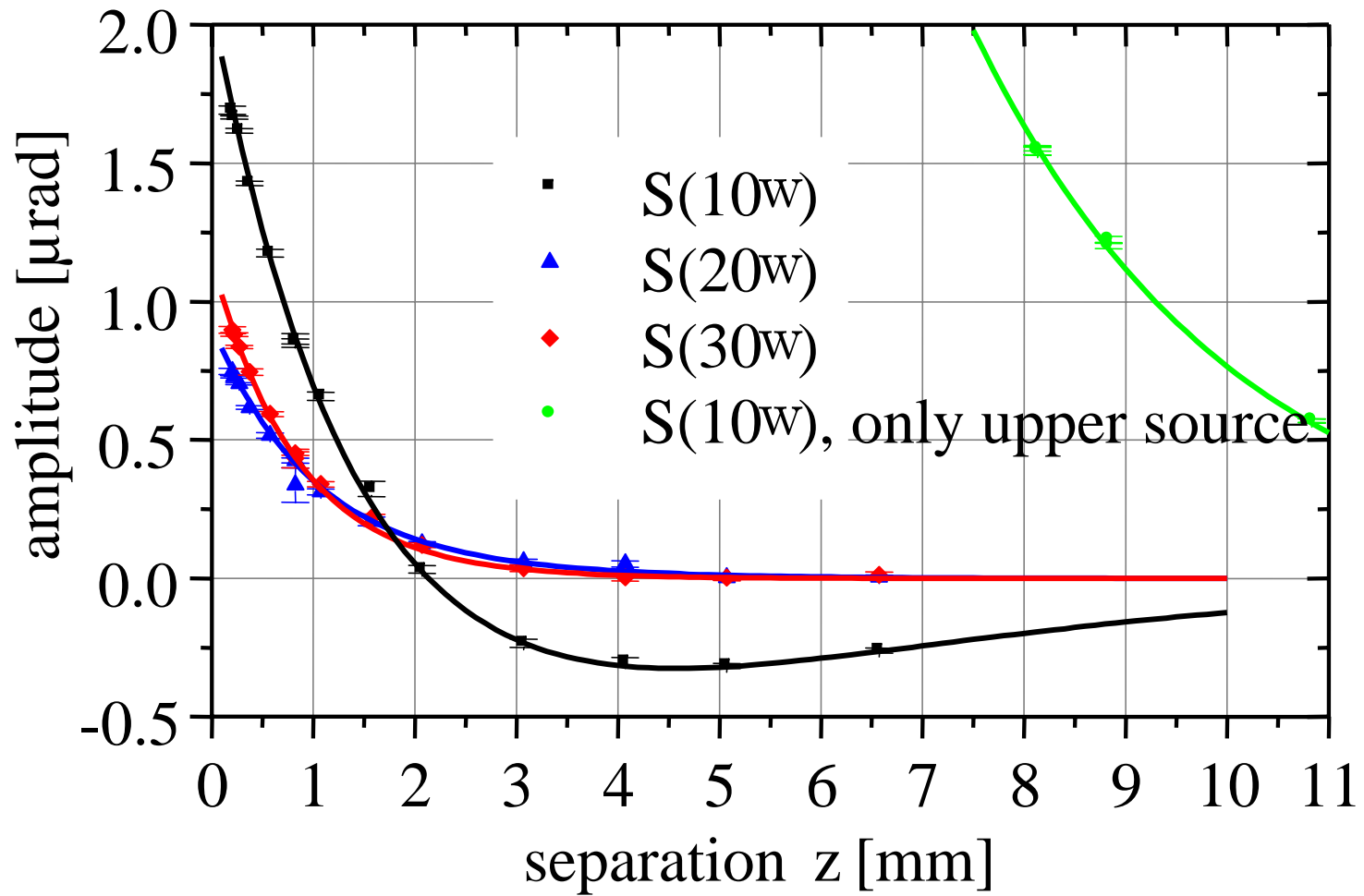




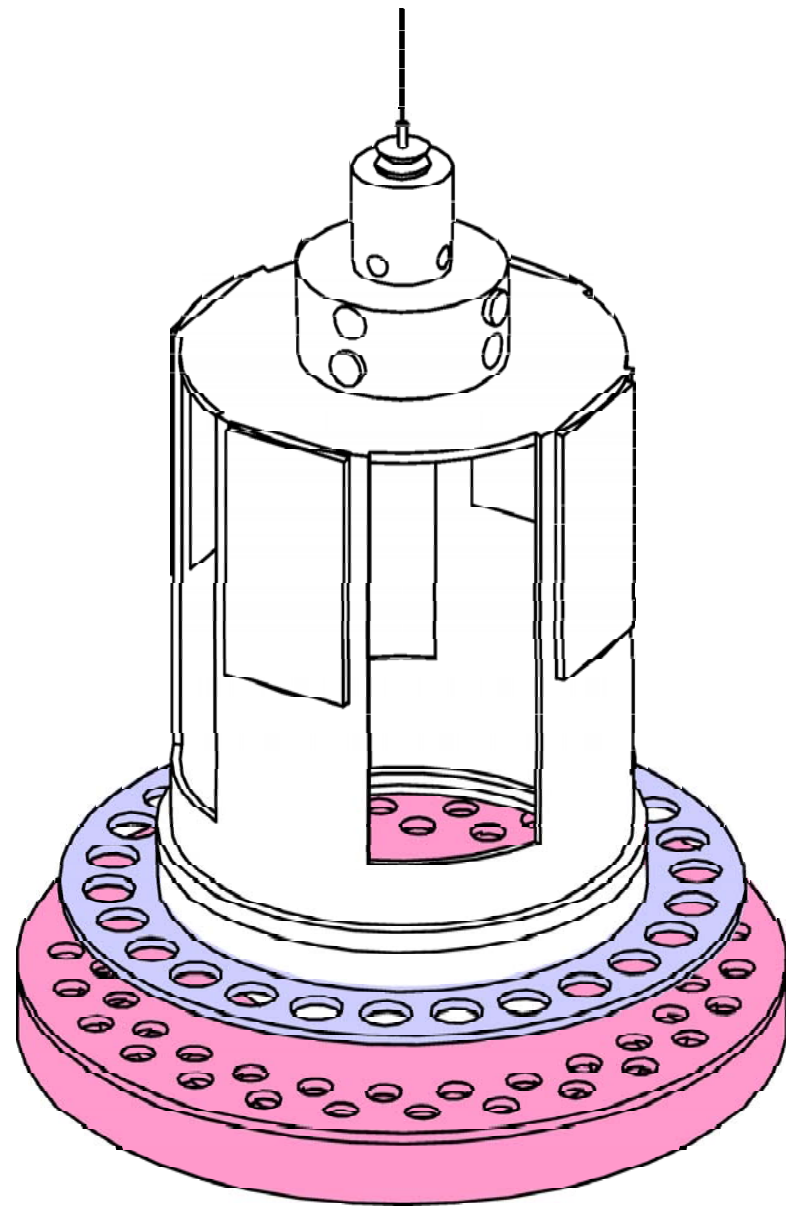


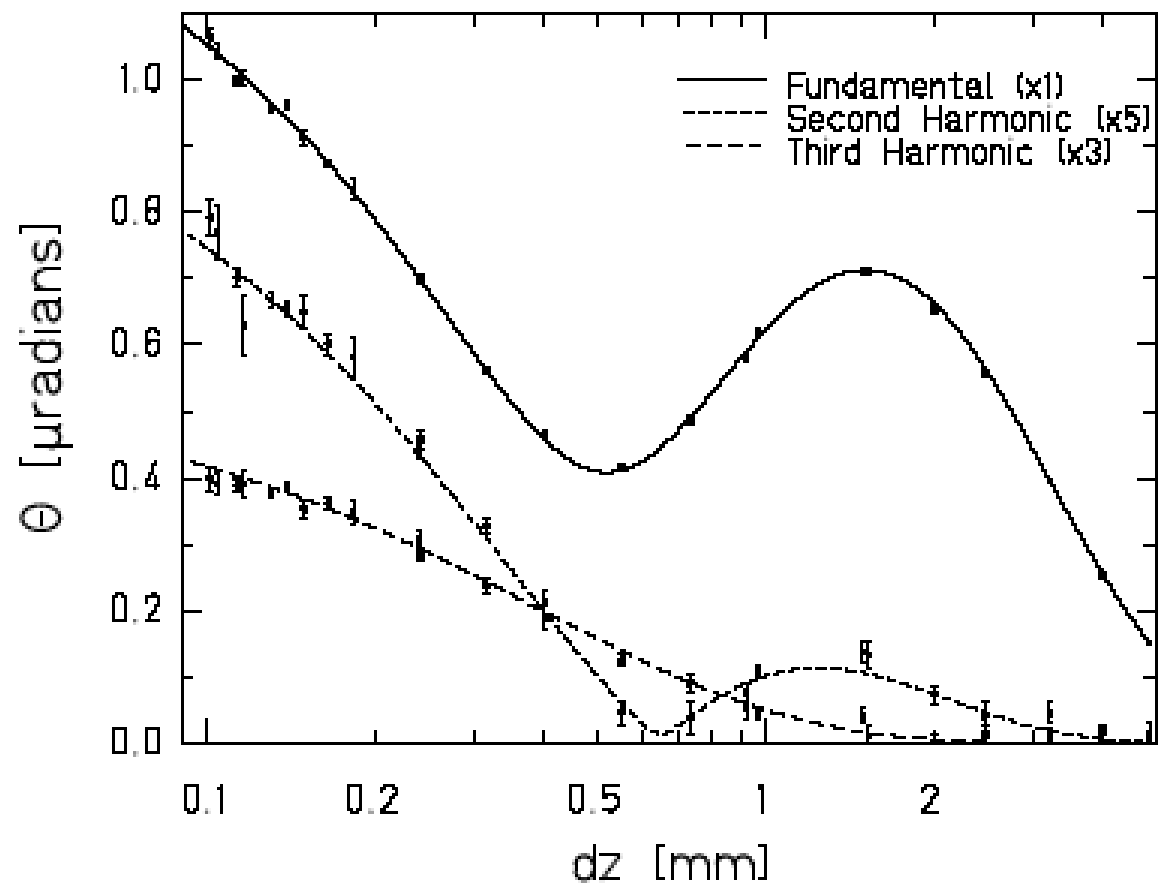
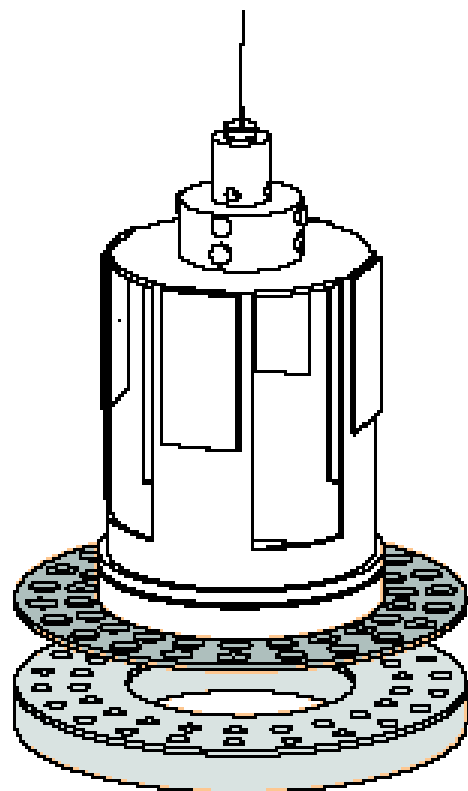


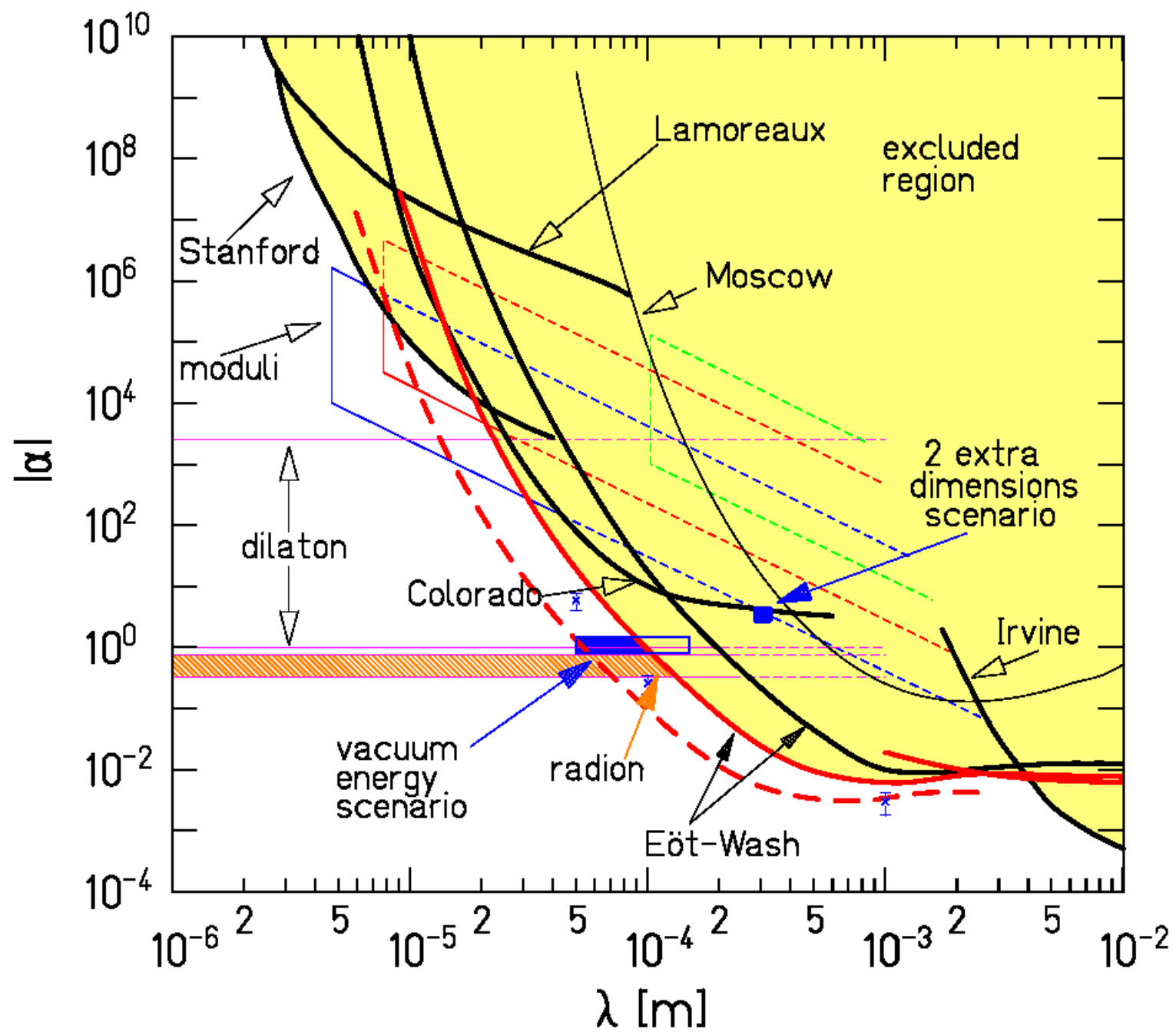


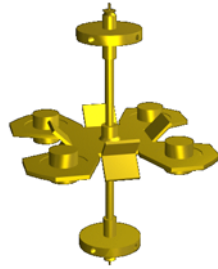
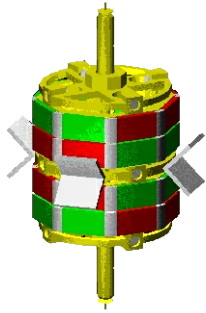












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