Neutrons test Newton's law

GRAVITY AND QUANTUM INTERFERENCE

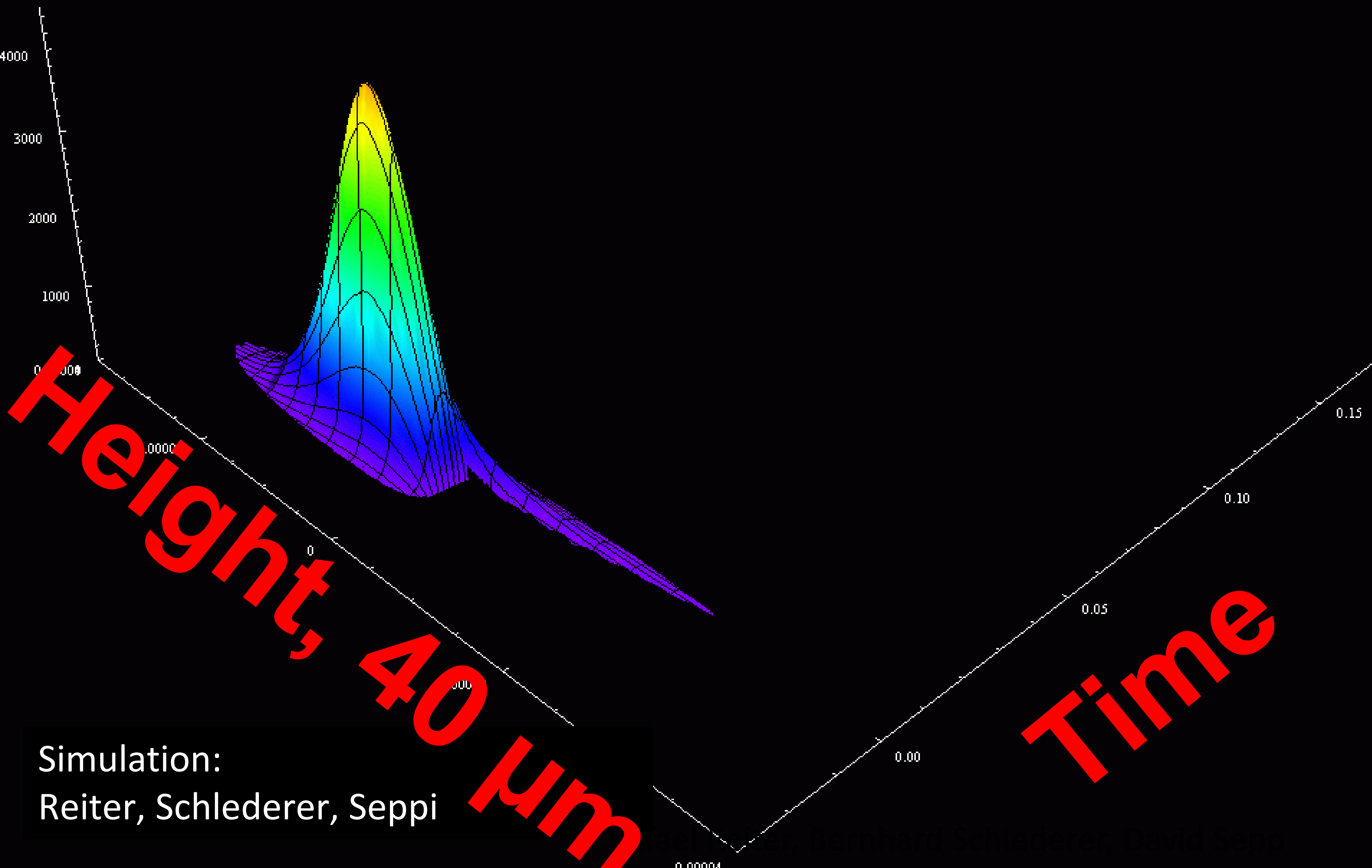
Hartmut Abele

Blaubeuren I, 30 July 2013

TU Wien

Show Case I:

Test of Gravitation at Short Distances with Quantum Interference

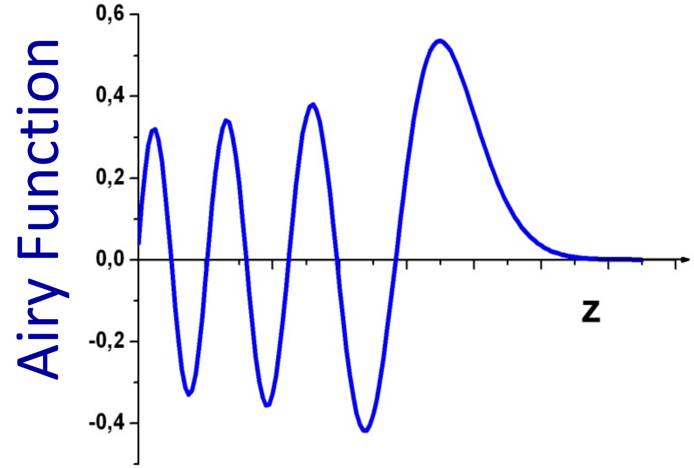


Simulation:
Reiter, Schlederer, Seppi

Schrödinger Equation

$$-\frac{\hbar^2}{2m}\Delta\psi + V(z)\psi = E\psi$$

$$V(z) = mgz \quad \text{for} \quad z \geq 0 \quad \text{and} \quad V(z) = \infty \quad \text{for} \quad z < 0$$



- **Scale with length scale z_0**

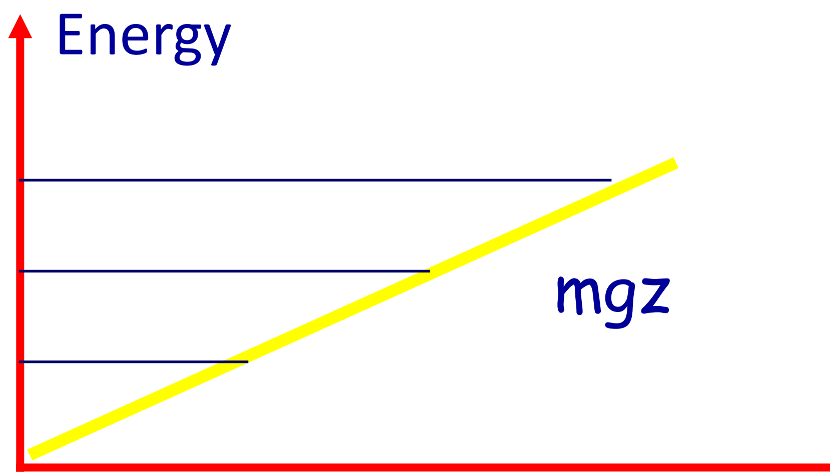
$$\zeta = \frac{z}{z_0}$$

- **Shift**

$$\psi_n(\zeta) = Ai(\zeta - \xi_n)$$

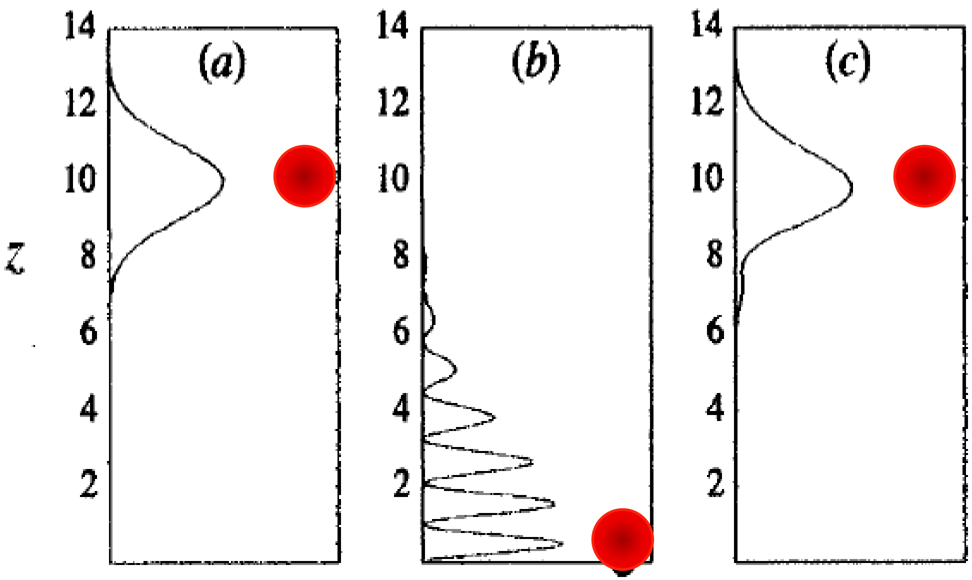
- **Turning Points:**

$$z_1 = 13.7\,\mu\text{m},\ z_2 = 24.1\ \mu\text{m}$$



the dynamics of ultra-cold neutrons in the gravity potential

the free Fall



<u>Quantum interference:</u>

sensitivity to fifth forces

coming from extra dimensions

string theories

(higher dimensional field theories)

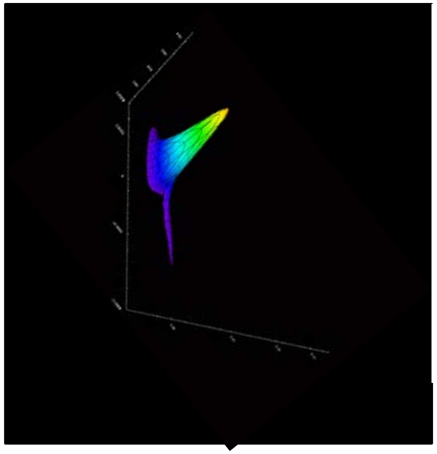
or axion fields *at short distances*

- Theory:

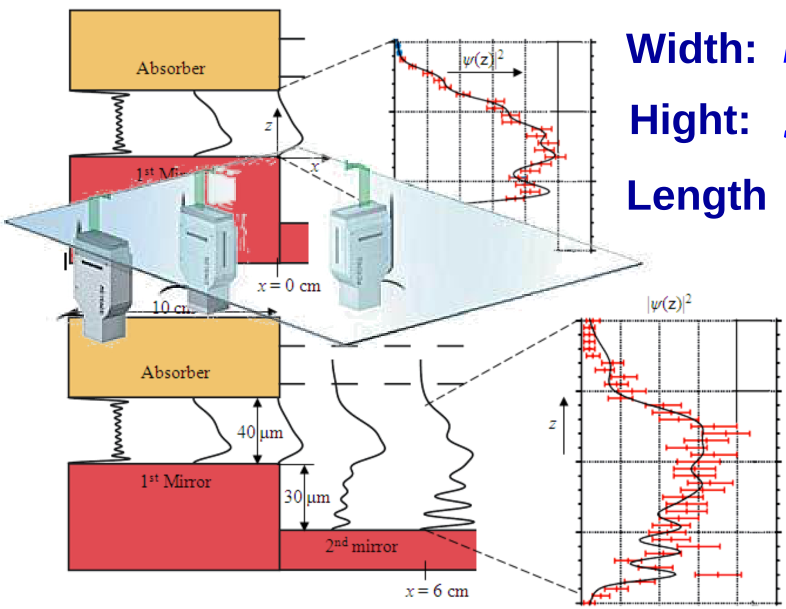
  Kajari et al., Inertial and gravitational mass in quantum mechanics, *Appl. Phys. B* **100**, 43 (2010)
- Julio Gea-Banacloche, Am. J. Phys.(1999)
- H.A. et al., PRD (2010)

qBounce: Neutrons test Newton's Law

the dynamics of ultra-cold neutrons in the gravity potential



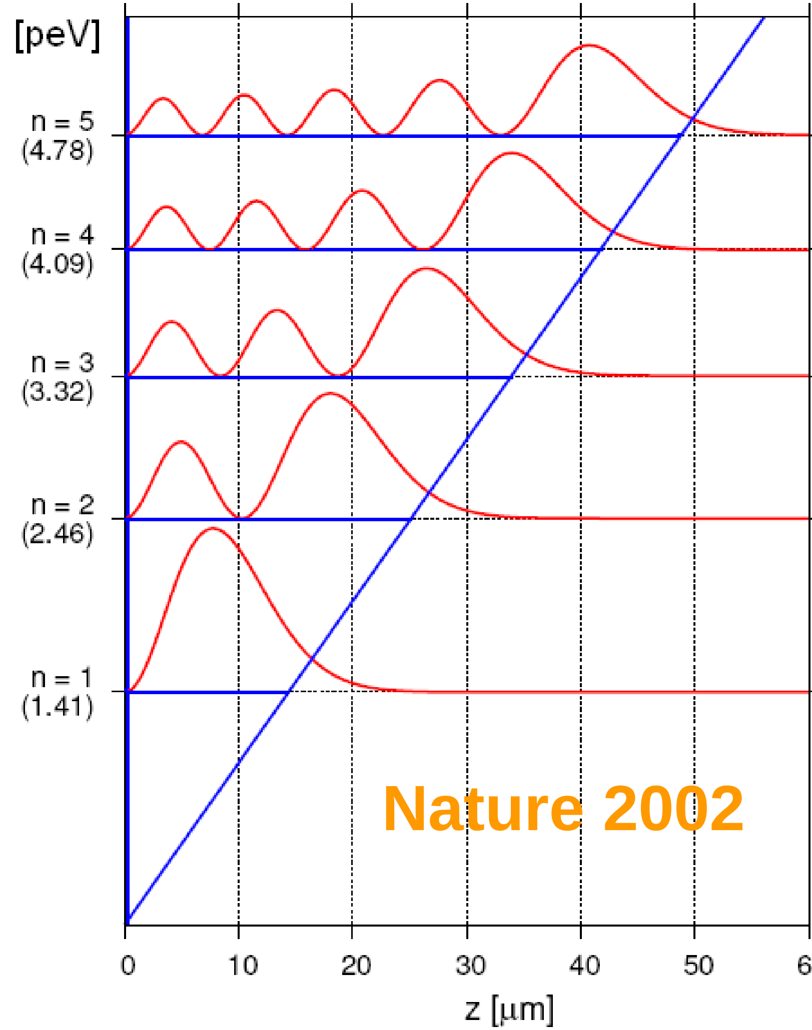
- Bound States
- Discrete energy levels
- Ground state 1.4 peV
- Airy-Functions



Width: $l = 43\mu m$

Hight: $s = 30\mu m$

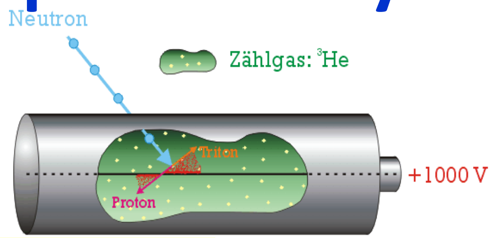
Length $x = 6\ cm$



Abele, H., Jenke, T., Stadler, D., & Geltenbort, P. QuBounce: The dynamics of ultra-cold neutrons falling in the gravity potential of the Earth. *Nucl. Phys.* **A827**, 593c (2009), Fig. from Dubbers

How are Neutrons detected?

- **Convert a neutron into charged particles by a nuclear reaction**

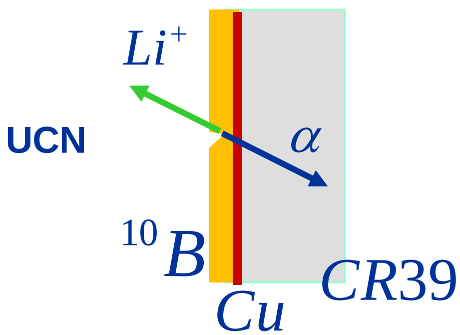


- **Neutron converter**
  - ^{3}He + n → ^{3}H + p + 0.76 MeV   5330 b
  - ^{6}Li + n → ^{3}H + α + 4.49 MeV   940 b
  - ^{157}Gd + n → ^{158}Gd + γ + e^-(29-181 keV)   254000 b
  - ^{10}B + n → ^{7}Li + α + 2.79 MeV (6%)   3838 b
    → ^{7}Li* + α + 2.31 MeV (94%)
    ^{7}Li + γ (0.48 MeV)

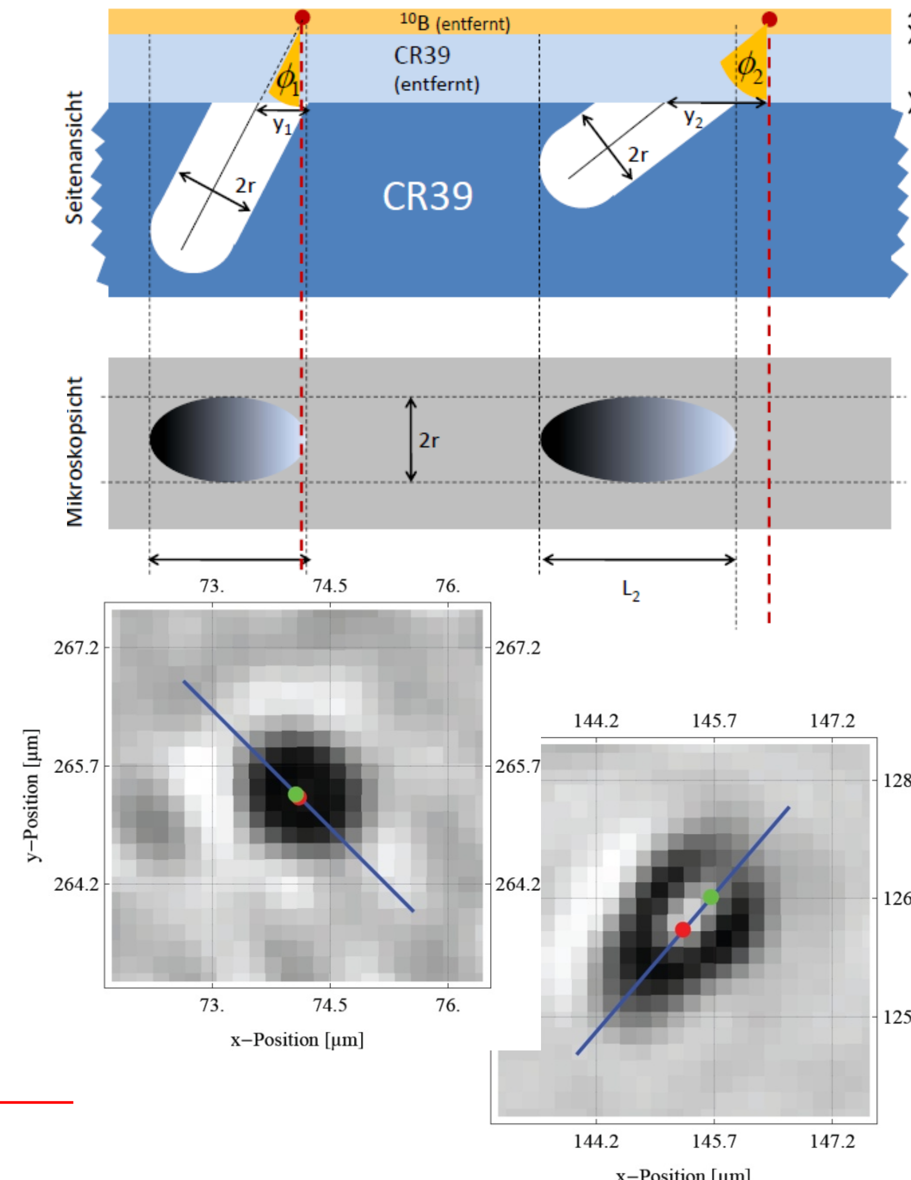
- **Detectors for ionising particles:**
  - Gas detektors
  - Szinitillation detectors
  - Solid state detectors

Courtesy: Dr. Martin Klein, CDT

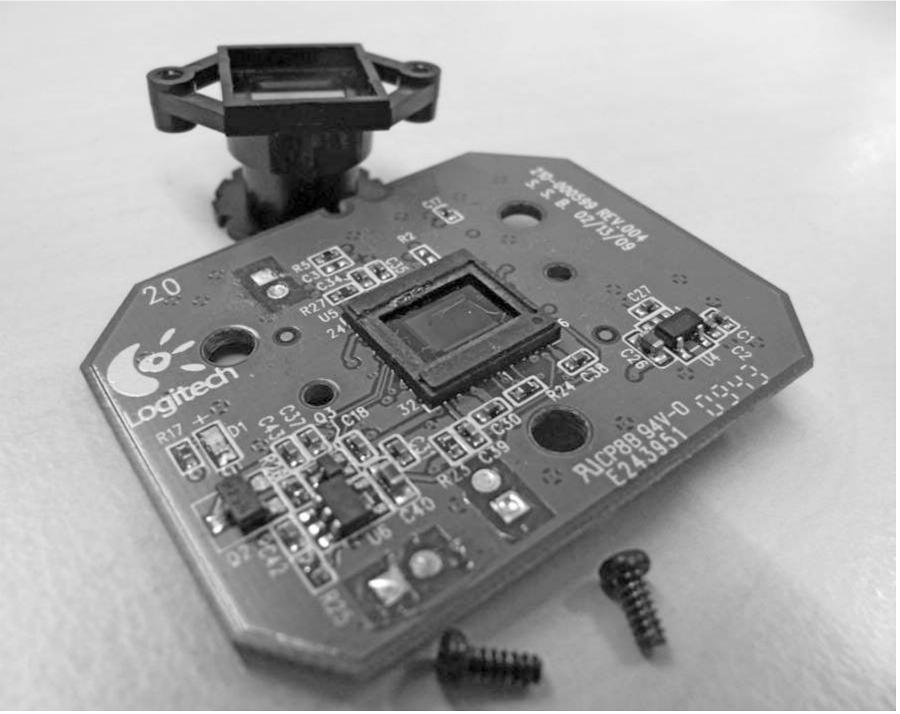
CR39-plastic detector $n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$

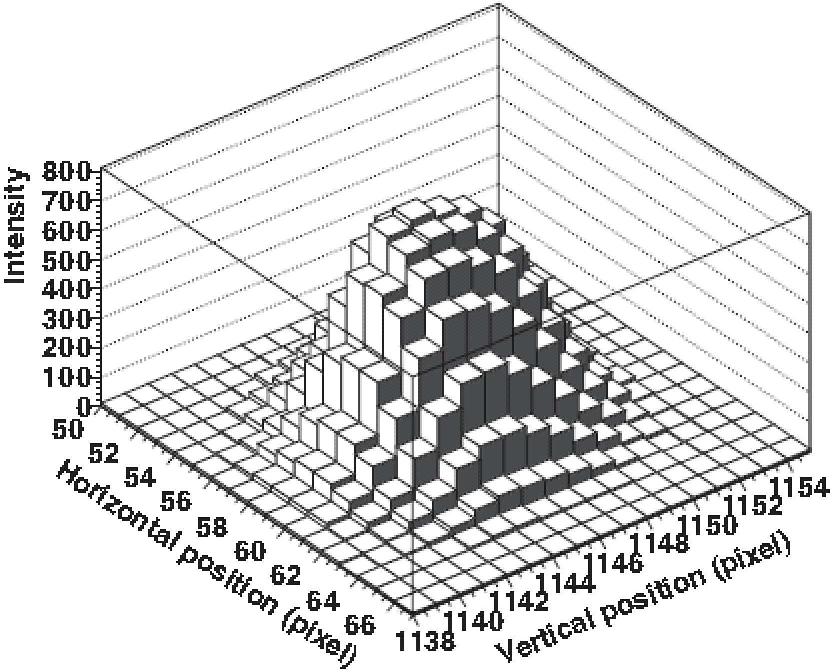


- Spatial resolution: 1.5 µm – 2 µm
- Boron conversion efficiency: 91%
- Detector efficency: ~ 62 %



T. Lauer et al.: CMOS Detectors

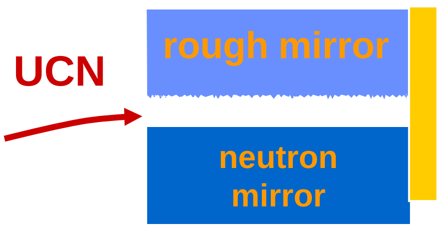


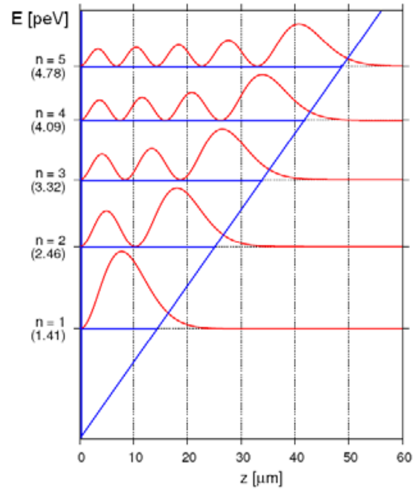


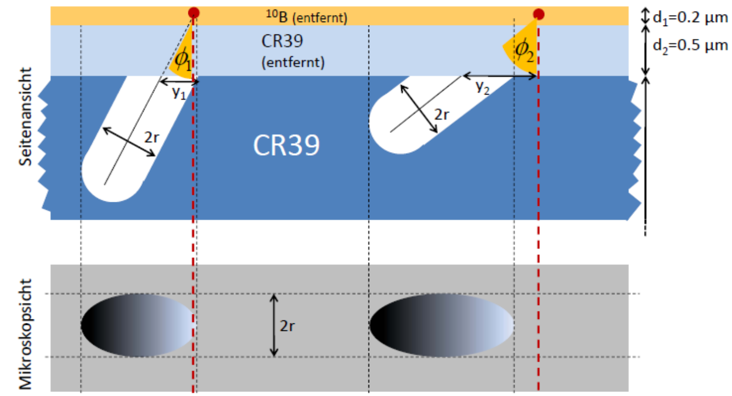
- CMOS Chip coated with B, pixel size ~ 3 µm

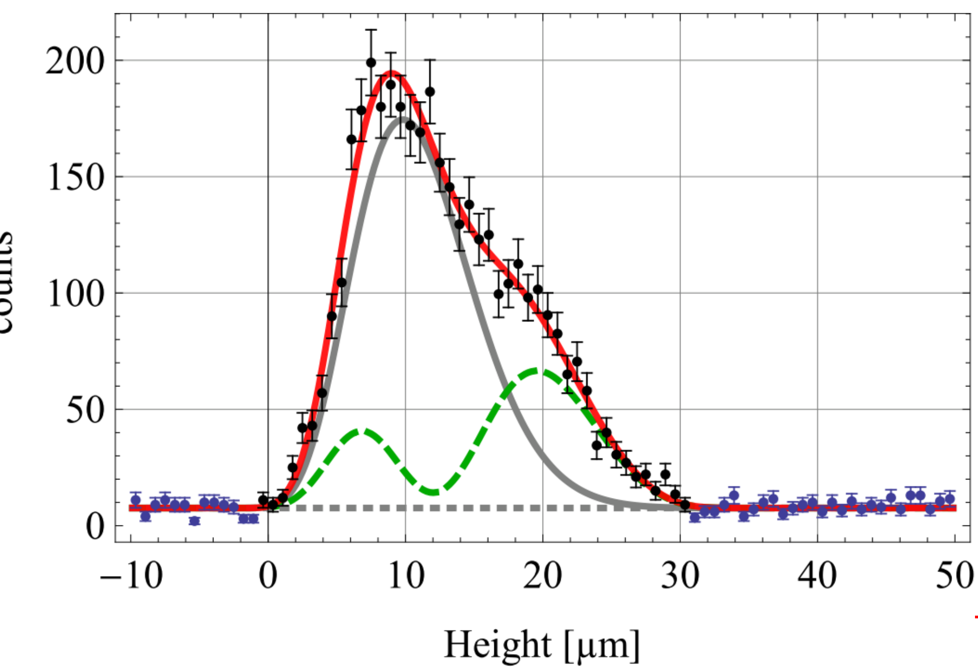
Eur. Phys. J. A (2011) **47**: 150

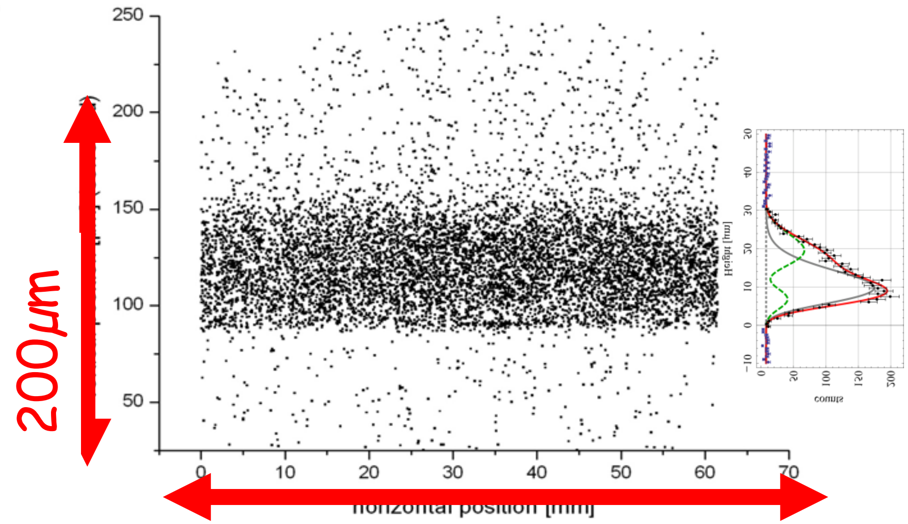
CR39-plastic detector $n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$











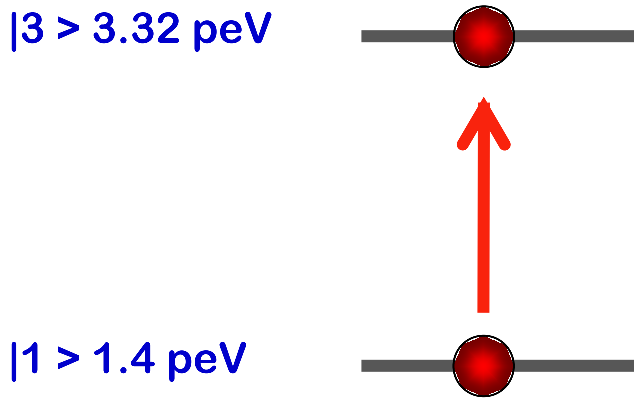
~ 10 cm

Outline II

- *q*Bounce
  - High resolution ~ 1µm
  - Large Area ~ 10 cm
- ucn sources
  - Precision experiments in particle- and astrophysics with cold and ultracold neutrons
- Gravity Resonance Spectroscopy and *q*Bounce
- Limits on dark matter / dark energy particles

Nature Physics, 1 June 2011

Key Technique: Gravity Resonance Spectroscopy



$$\Delta E = h\nu$$

- atomic clocks
- nuclear magnetic resonance spectroscopy
- spin echo technique
- quantum metrology
- gamma resonance spectroscopy

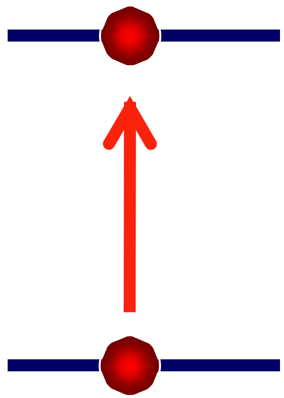
Test Newton‘s law at short distances:

- **String Theories**
- **Dark Matter**
- **Dark Energy**

Rabi-Gravity-Spectroscopy

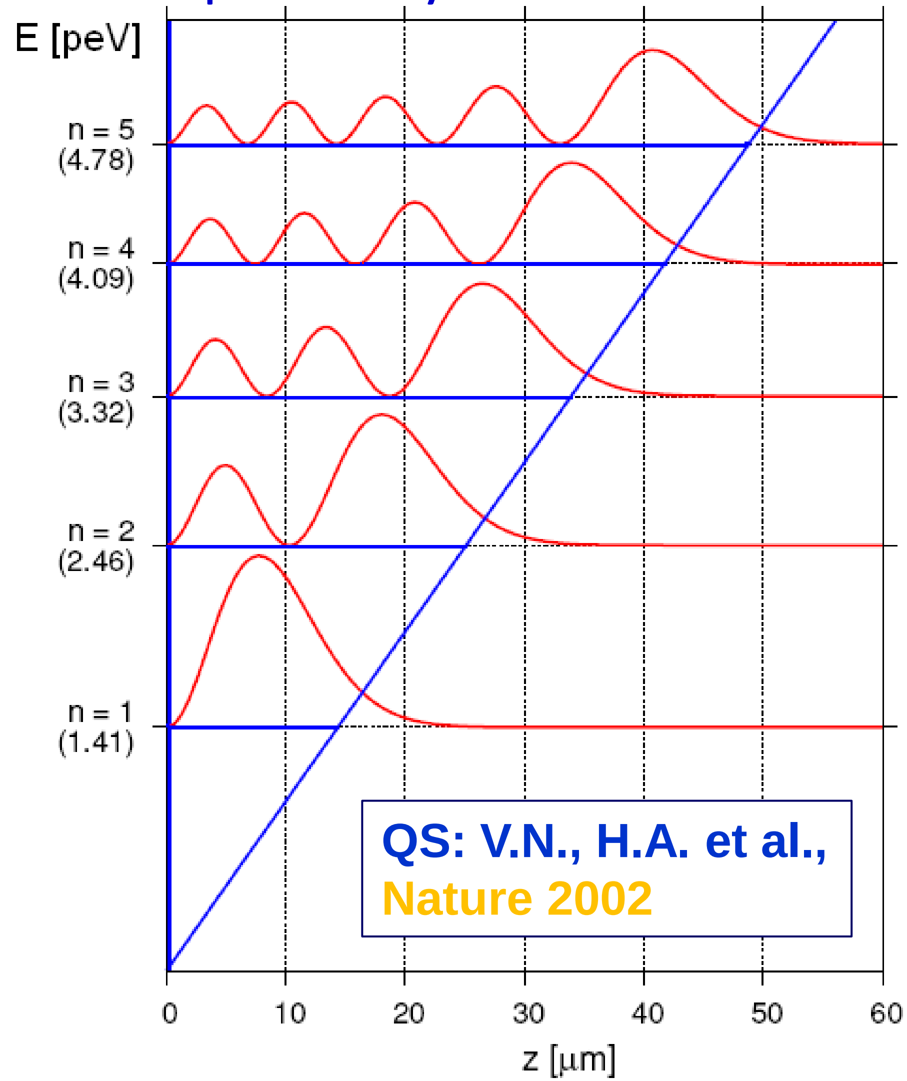
a 2-level system can be considered as a Spin ½ - System

|3 > 3.32 peV



|1 > 1.4 peV

Alternating Magnetic gradient fields



GRS: T.J., H.A. et al., Nature Physics 2011

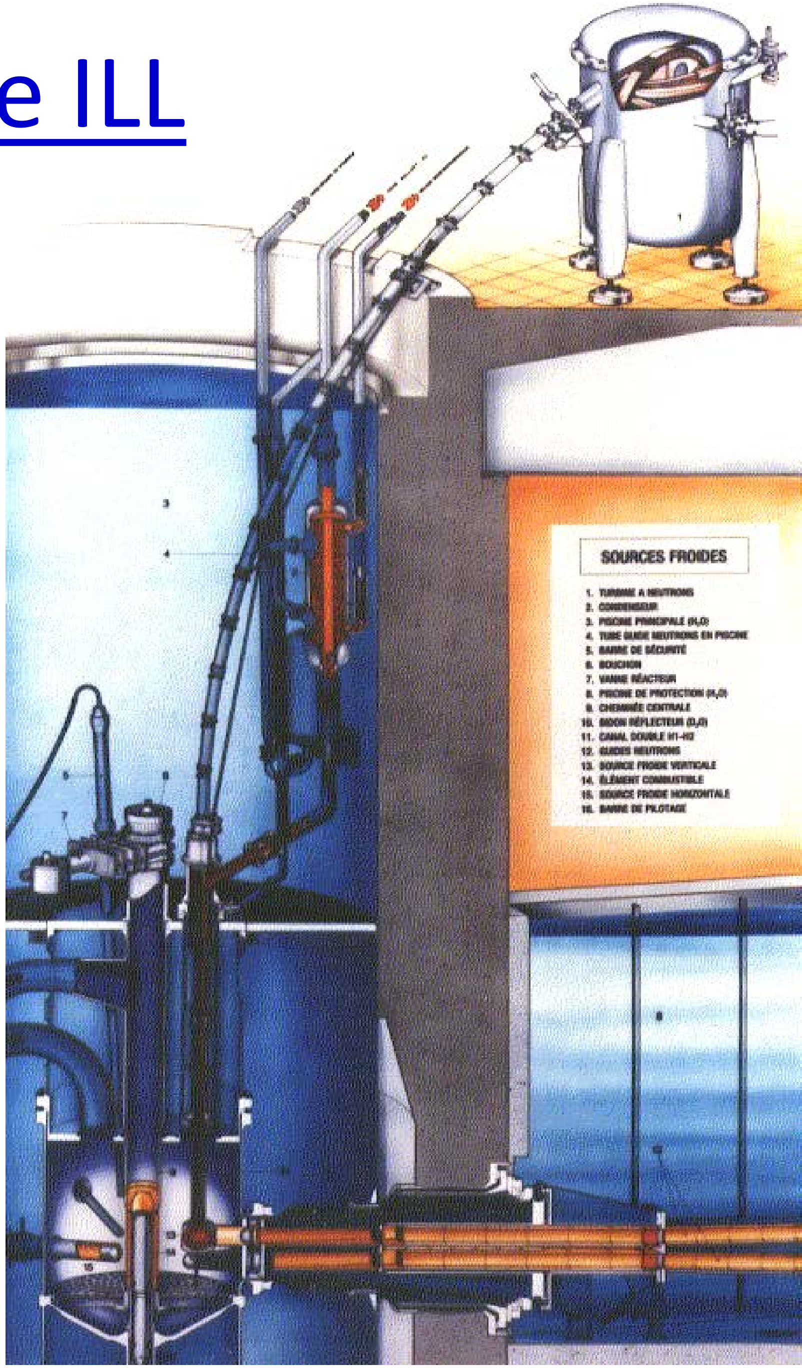

NEUTRONS
FOR SCIENCE
ESRF
INSTITUT
LAUE-LANGEVIN

Neutron Production at the ILL

Fission: 2 MeV

Thermal: 25meV, 300K

Cold: 4 meV, 40K



S-DH

H.A. et al., characterization of a ballistic super mirror guide, NIM A562 407 (2006)

Neutron Production

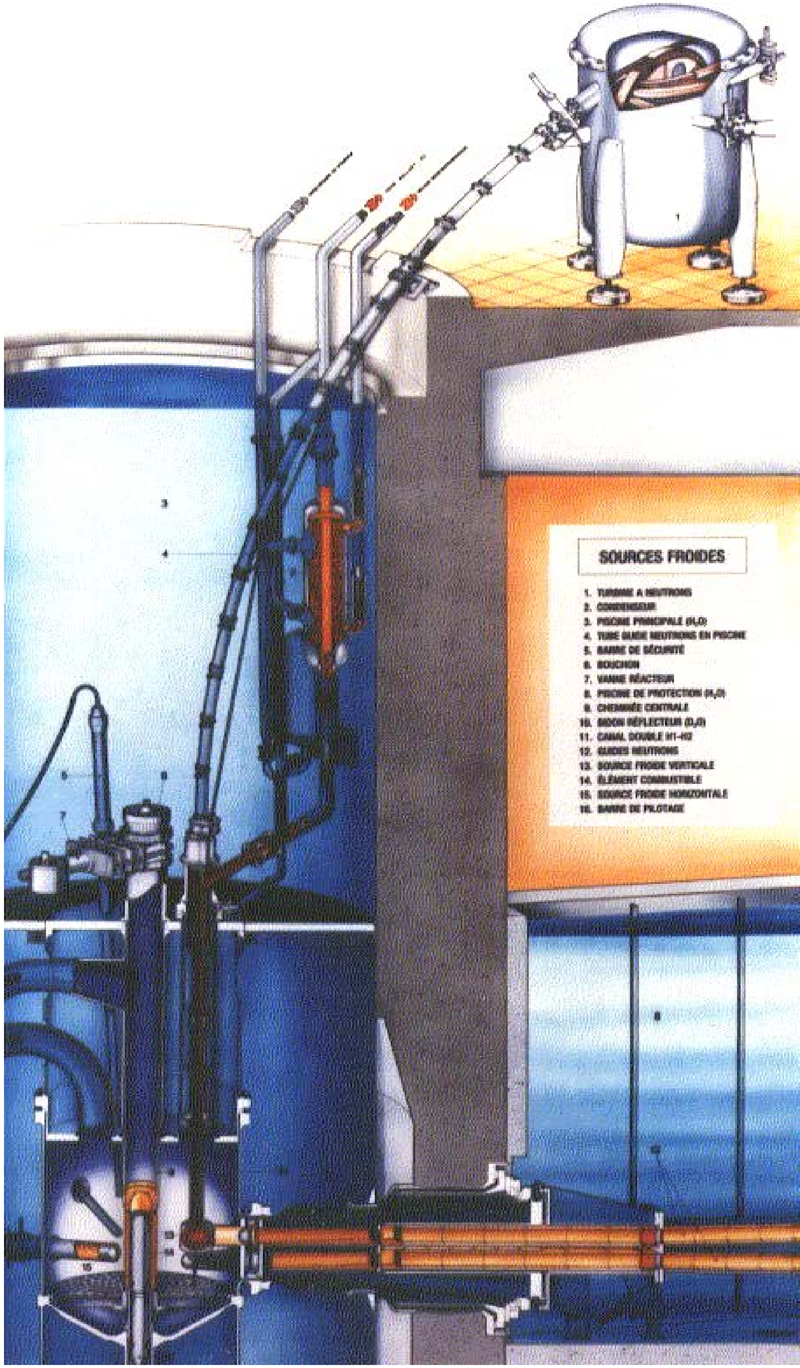
Fission: 2 MeV

Thermal: 25meV, 300K

Cold: 4 meV, 40K

ultra cold: 100 neV, 1mK

Gravity Experiment: 1 pico-eV



Neutron Production

Fission: 2 MeV

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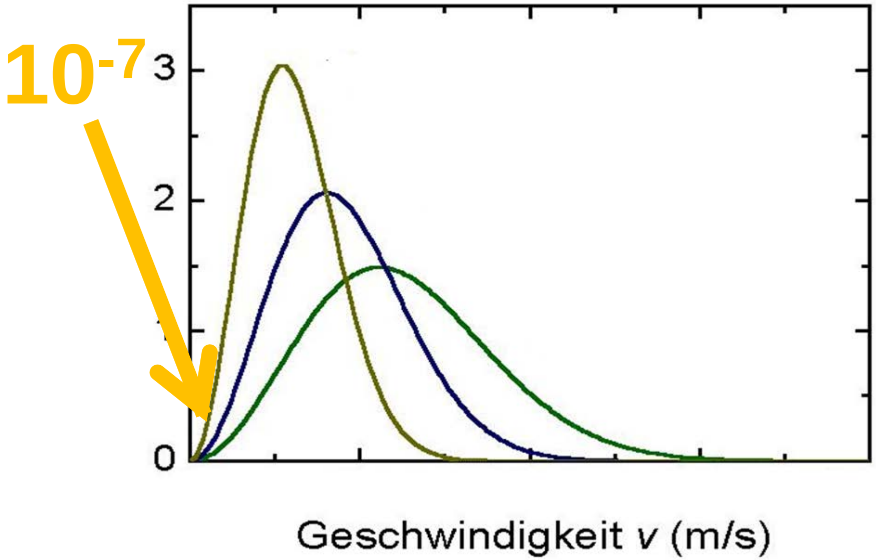
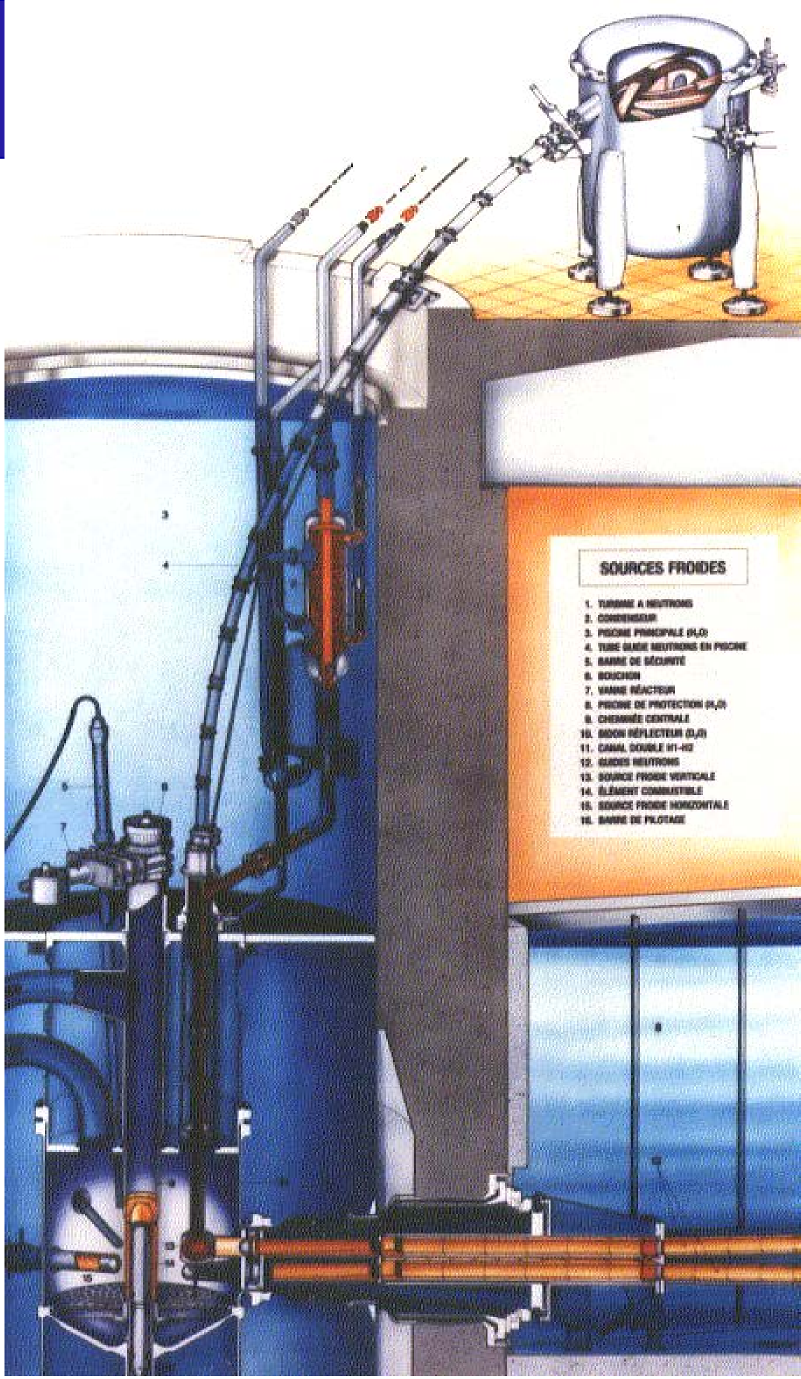
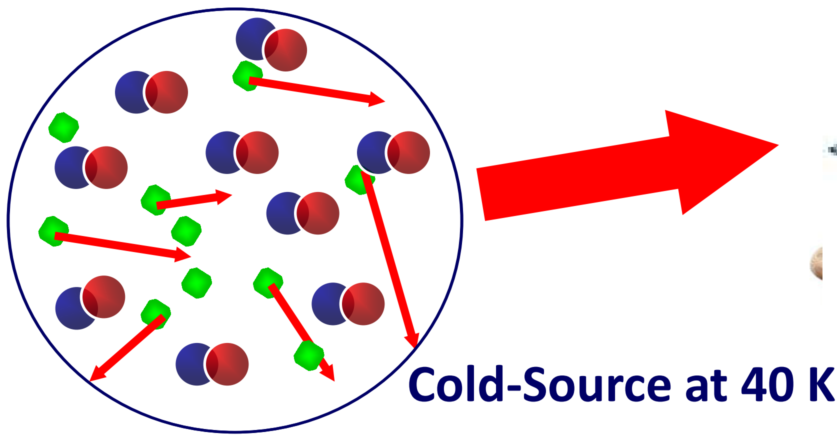
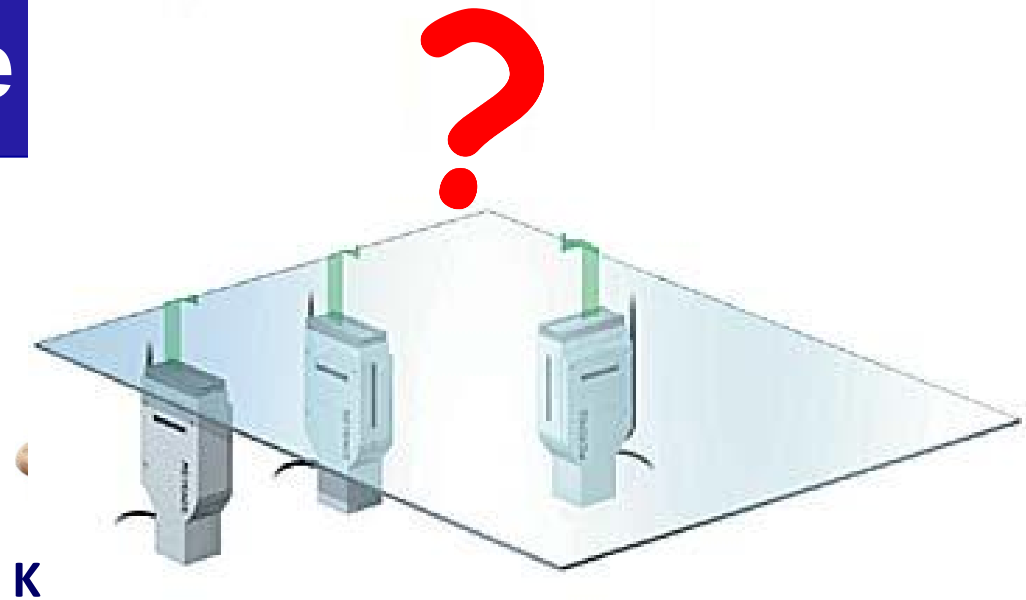




Quantum Bounce





- **System Neutron & Earth**
  - Neutron bound in the gravity potential of the earth
  - <r> = 6 µm
  - Ground state energy of 1.4 peV
  - 1 dim.
  - Schrödinger Equ.
    - Airy Functions

- **Hydrogen Atom**
  - Electron bound in proton potential
  - Bohr radius <r> = 0.1 nm
  - Ground state energy of 13 eV
  - 3 dim.
  - Schrödinger Equ.
    - Legrendre Polynomials

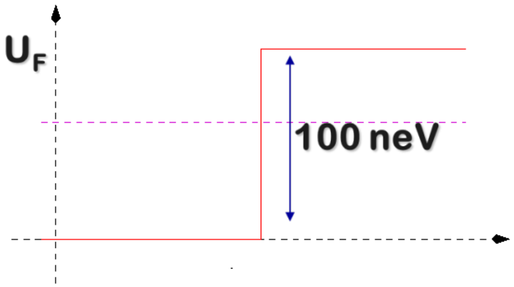
ATOMINSTITUT

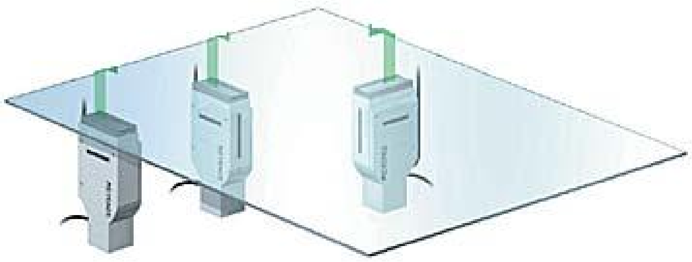
Neutrons test Newton's law
GRAVITY AND QUANTUM INTERFERENCE

Hartmut Abele

Blaubeuren II, 30 July 2013

Tool: Ultra-Cold Neutrons





Strong Interaction: V ~ 100 neV

Kinetic Energy: < 100 neV

3m/s < v < 20m/s

Magnetism, Zeeman splitting : 120 neV/T

Energy in the earth's gravitational field:

E = mgh 100neV/m

Neutron Production

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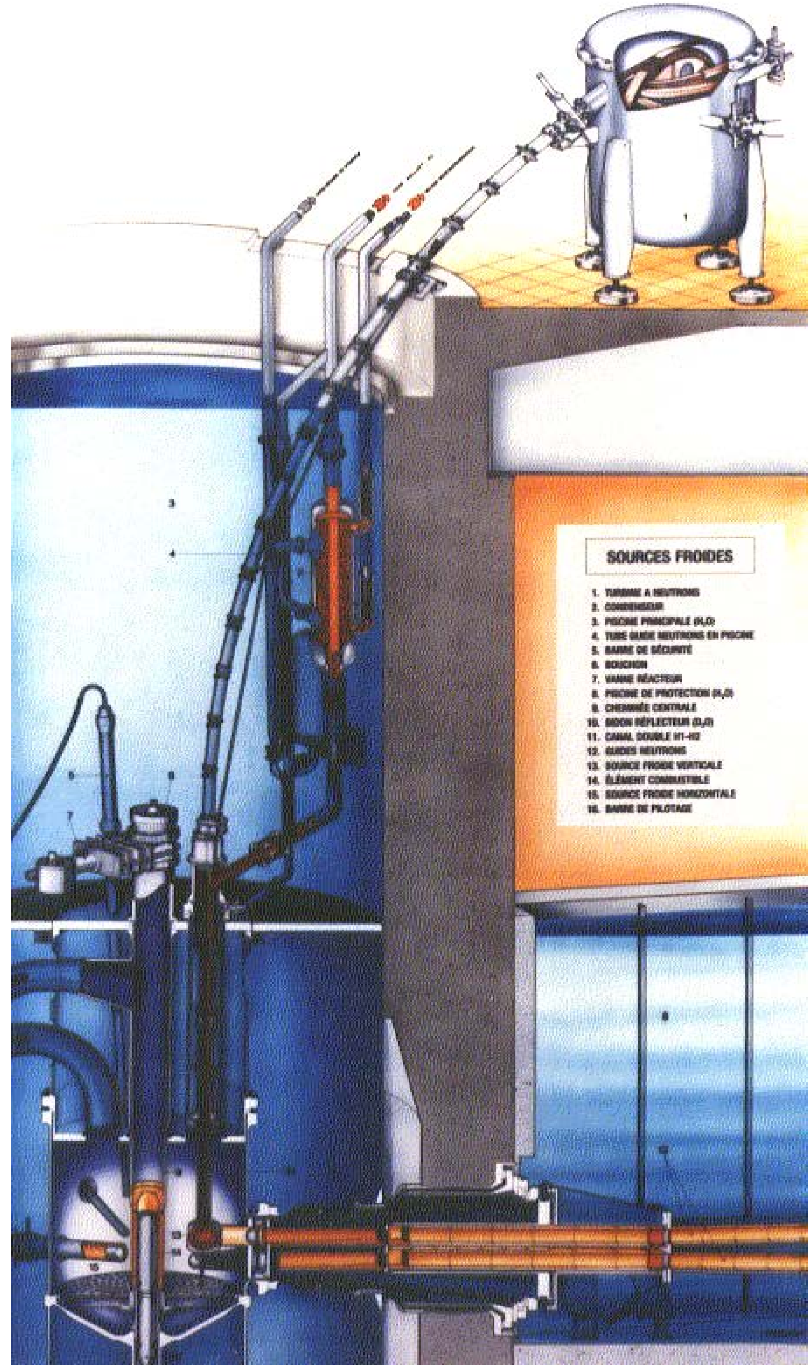
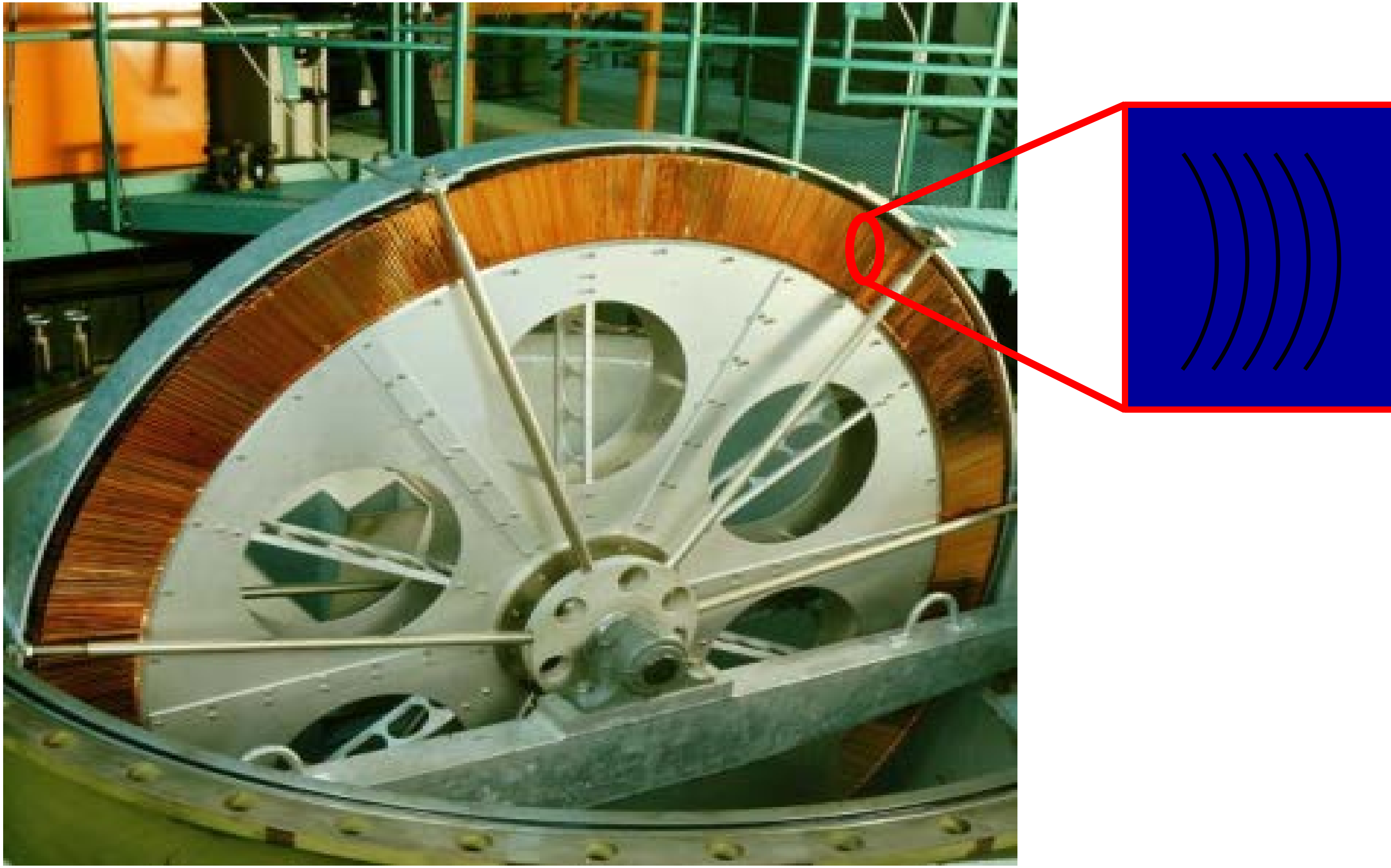
Thermal: 25meV, 300K

Cold: 4 meV, 40K

ultra cold: 100 neV, 1mK

Gravity Experiment: 1 pico-eV





P. Fierlinger

Neutron Production

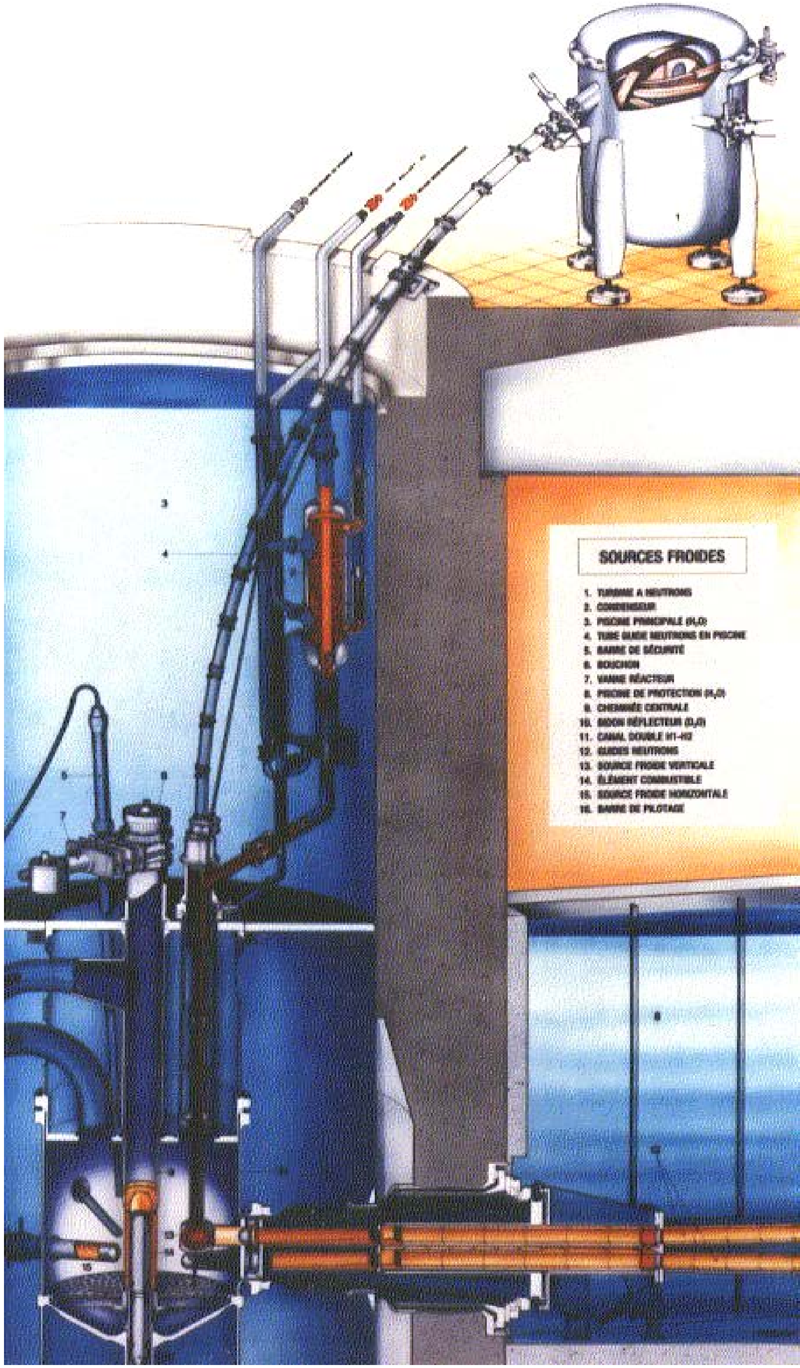
Fission: 2 MeV

Thermal: 25meV, 300K

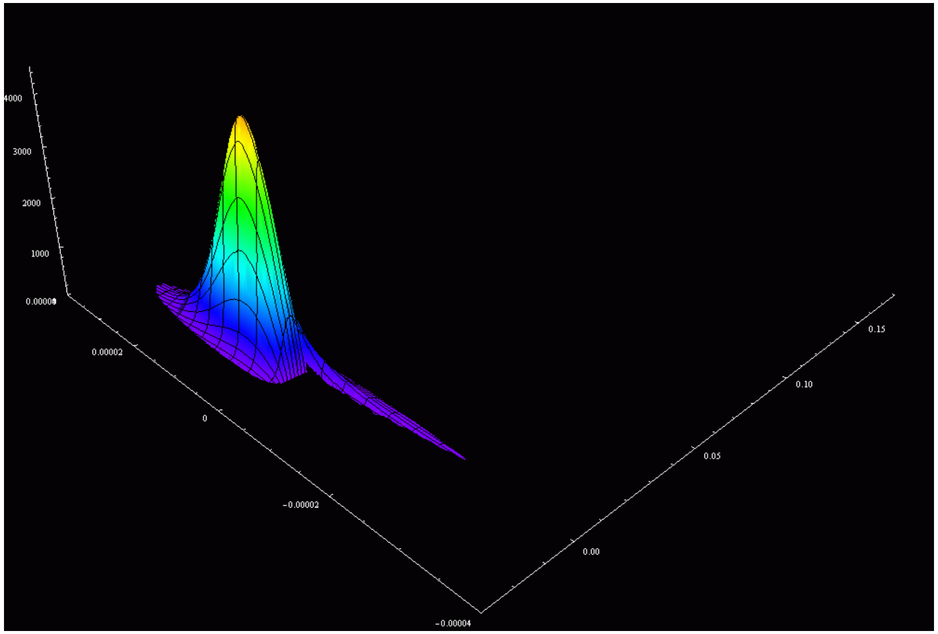
Cold: 4 meV, 40K

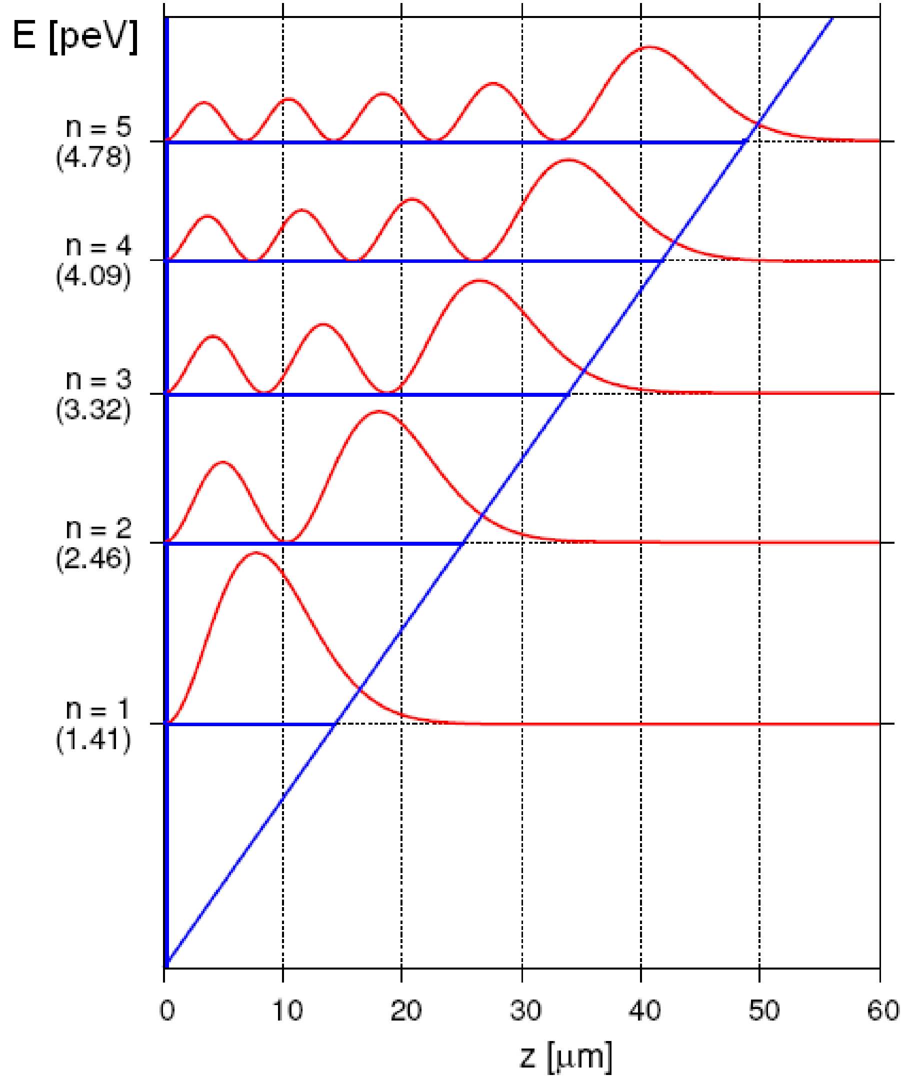
ultra cold: 100 neV, 1mK

Gravity Experiment: 1 pico-eV



Quantum States in the Gravity Potential





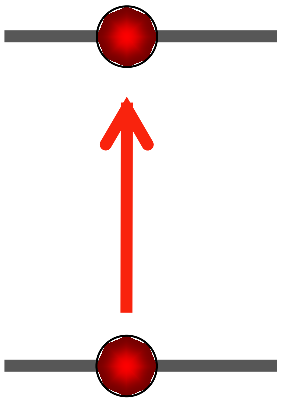
Demonstration of Quantum States
in the Gravity Potential of the Earth
Nesvizhevsky, H.A. et al.
Nature 2002

***q*Bounce, 2009**

Nature Physics, 1 June 2011

Key Technique: Gravity Resonance Spectroscopy

|3 > 3.32 peV



|1 > 1.4 peV

$$\Delta E = h\nu$$

- atomic clocks
- nuclear magnetic resonance spectroscopy
- spin echo technique
- quantum metrology
- gamma resonance spectroscopy

Test Newton‘s law at short distances:

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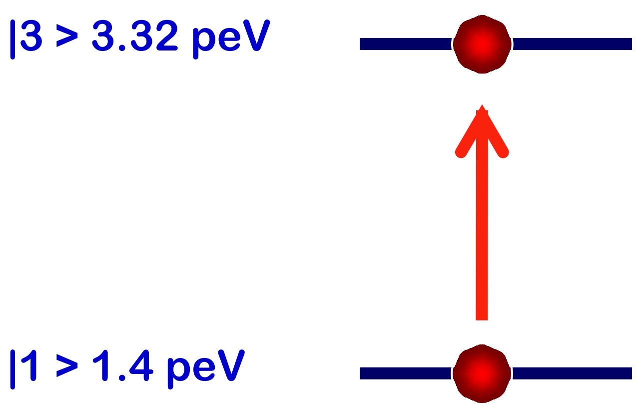
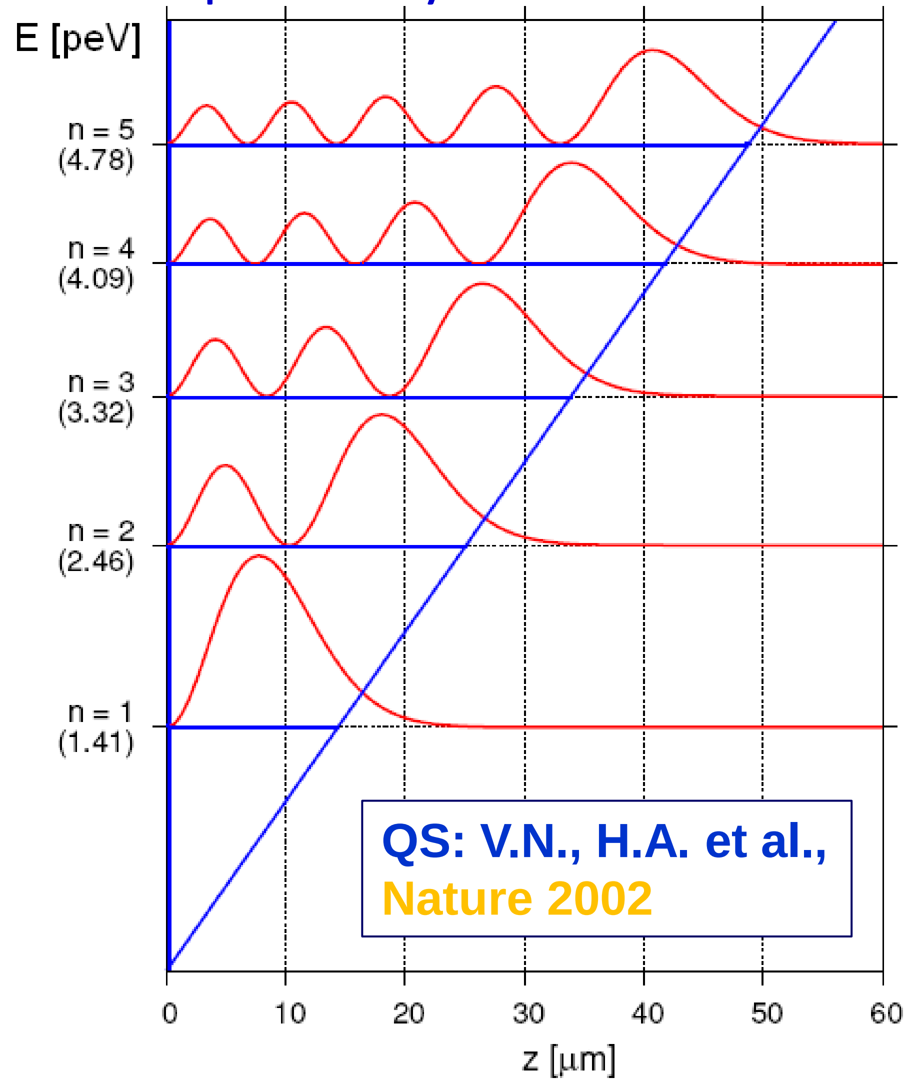
- **Dark Energy**

Rabi-Gravity-Spectroscopy

a 2-level system can be considered as a Spin ½ - System





QS: V.N., H.A. et al., Nature 2002

Alternating Magnetic gradient fields

GRS: T.J., H.A. et al., Nature Physics 2011

Gravity and Quantum Mechanics

Schrödinger equation:

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z)$$

boundary conditions:

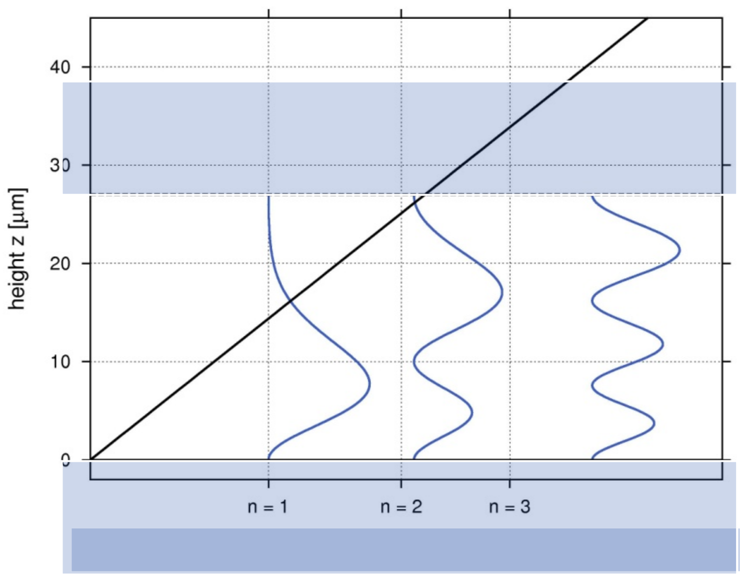
$$\varphi_n(0)=0$$

with 2nd mirror at height

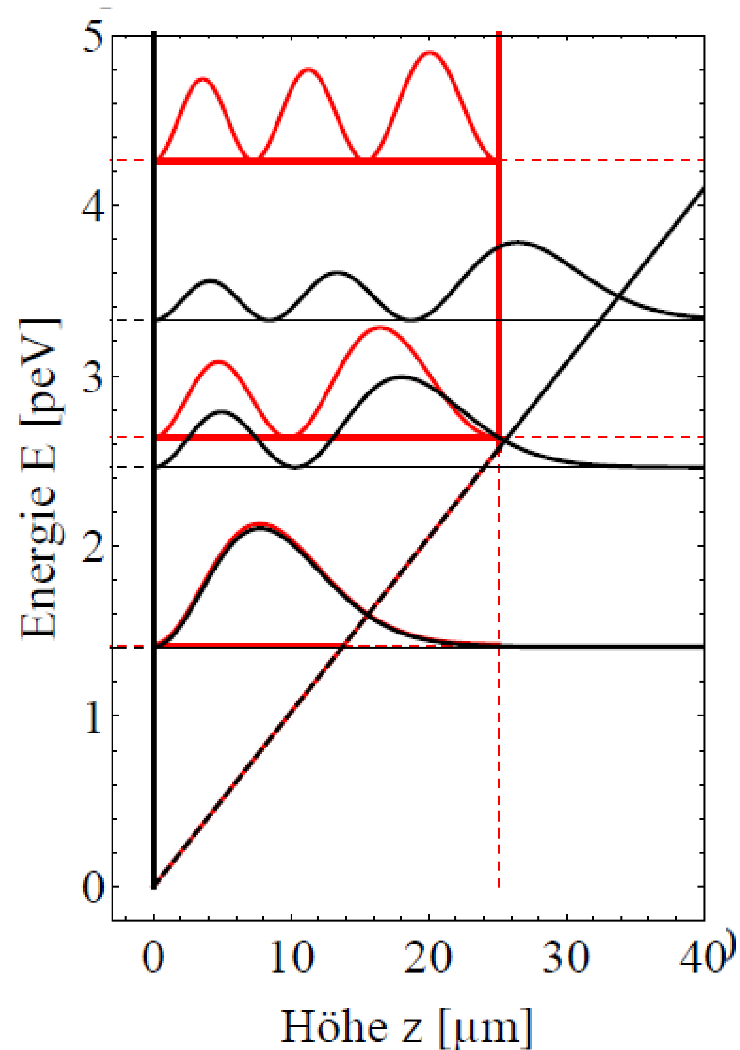
$$\varphi_n(l)=0$$

E_n	E_n
1.41peV	1.41peV
2.46peV	2.56peV
3.32peV	4.2 peV

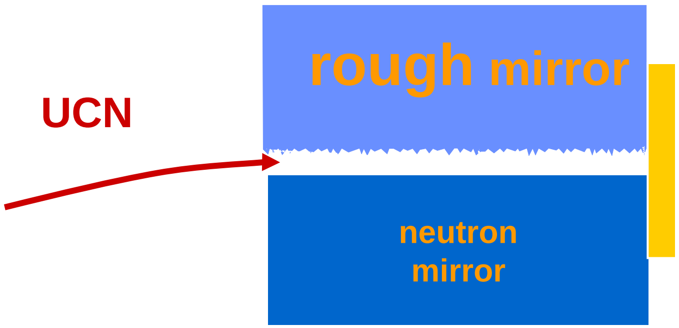
Solutions: Airy-functions: Ai & Bi



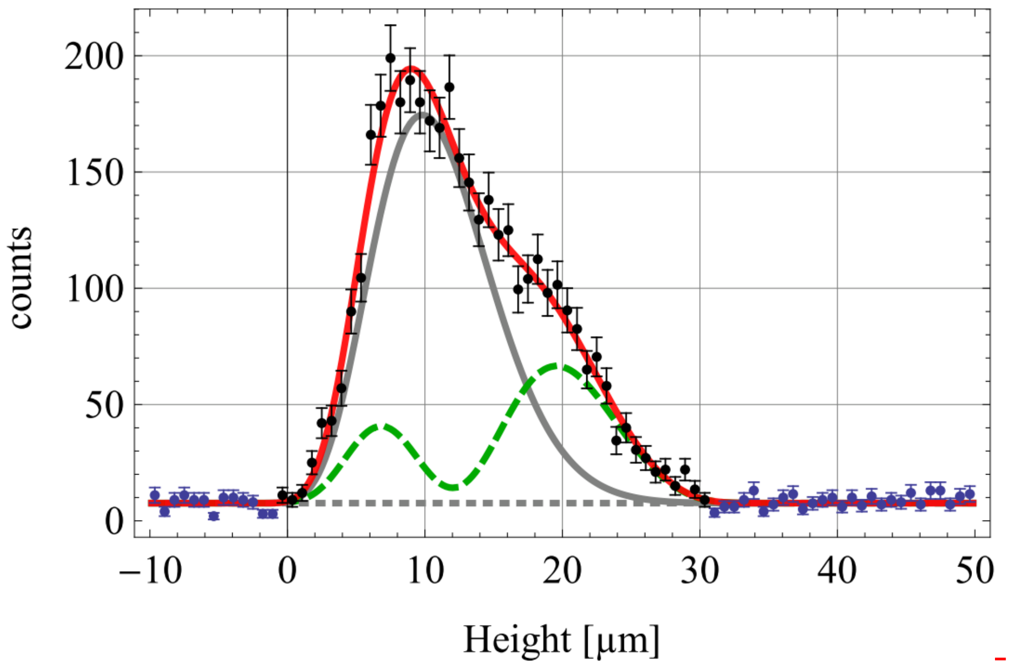
~ 1 µm
Surface roughness



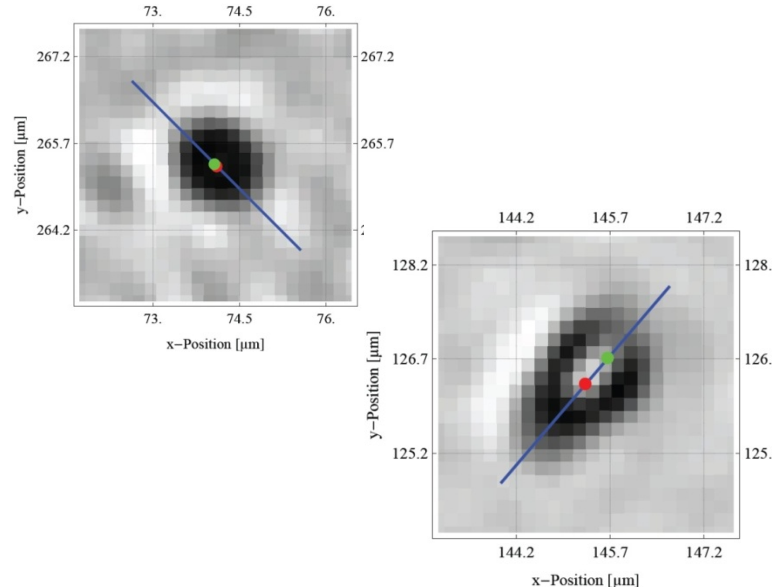
State Selection by a rough neutron mirror



$$|\psi|^2 = \sum_n |c_n(t_1)|^2 |\varphi_n(z)|^2$$



- 4.5 days of beam time
- 3600 events
  (background subtracted)



- fit: $N \cdot |\psi|^2 * PSF(\sigma) * f(t)$
- free parameters: $|c_n(t_1)|^2, l, N, z_0$
- result:

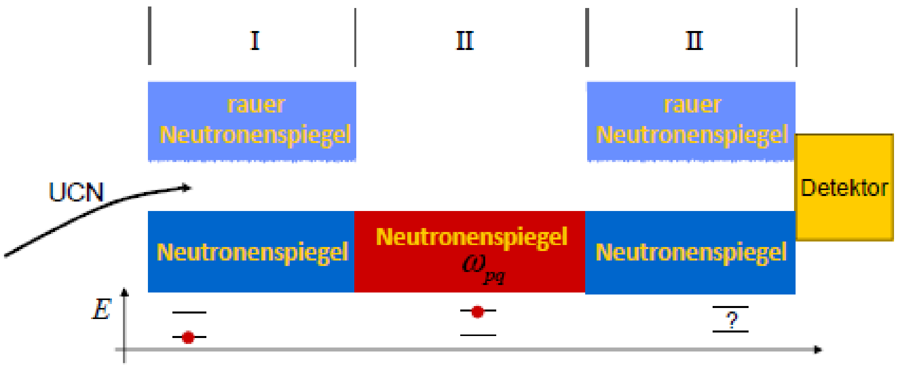
$$|c_1(t_1)|^2 = 0{,}70$$

$$|c_2(t_1)|^2 = 0{,}30$$

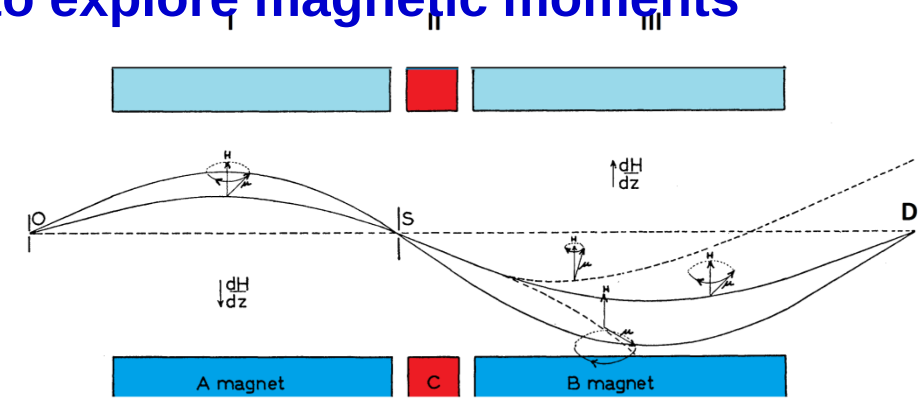
$$|c_3(t_1)|^2 = 0{,}00$$

Show Case II: Rabi-type Spectroscopy of Gravity

Gravity Resonance Spectroscopy Technique to explore gravity



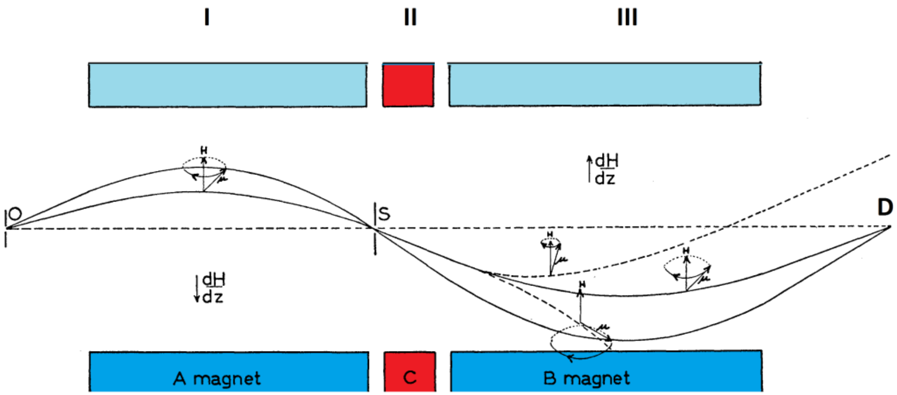
NMResonance Spectroscopy Technique to explore magnetic moments



- 3 Regions:
  - I: 1st State selector/ Polarizer
  - II: Coupling
    - RF field
    - Vibr. mirror
  - III: 2nd State Selector / Analyzer

Rabi Spectroscopy

NMResonance Spectroscopy Technique to explore magnetic moments



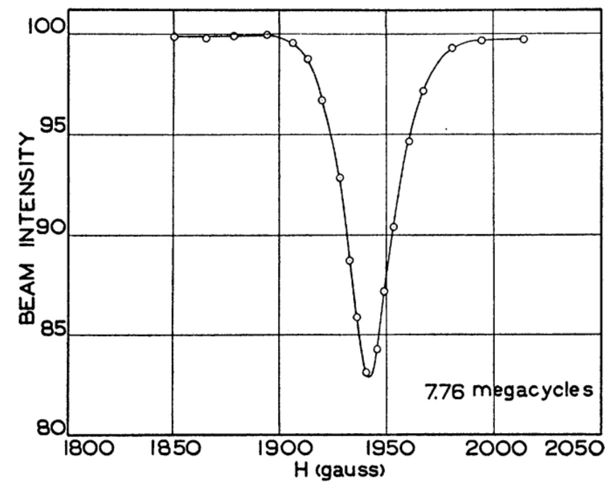
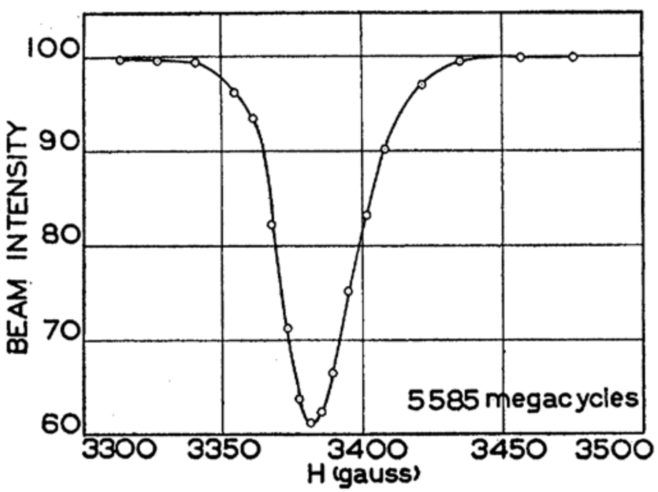
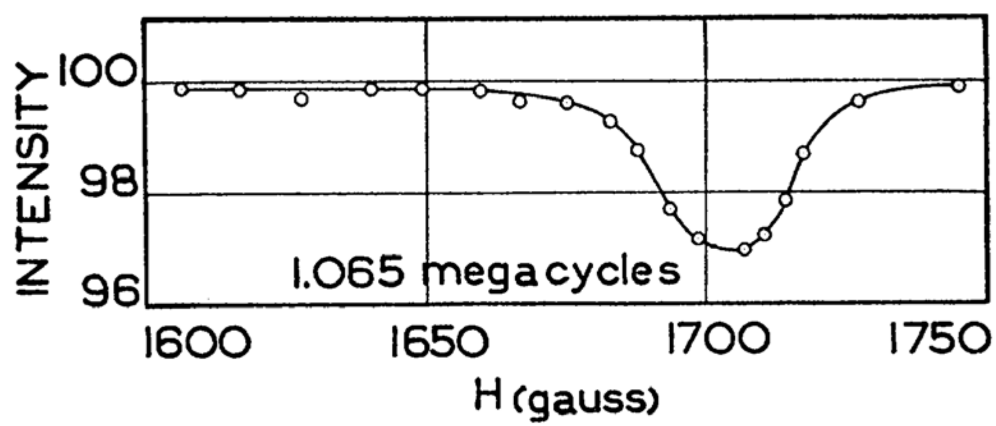


FIG. 5. Resonance curve of the F^{19} nucleus observed in NaF.

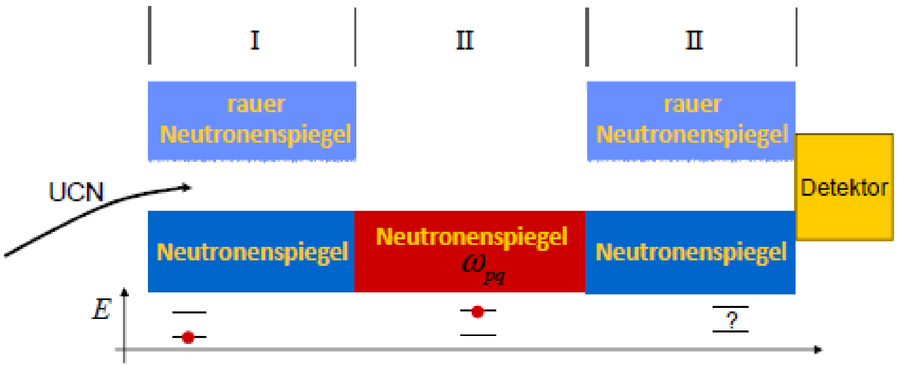


IG. 4. Resonance curve of the Li^7 nucleus observed in LiCl.

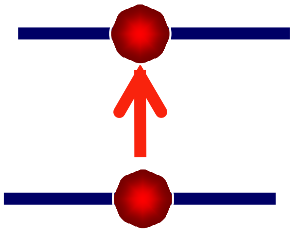


. 3. Resonance curve of the Li^6 nucleus observed in Li

Show Case II: Rabi-type Spectroscopy of Gravity



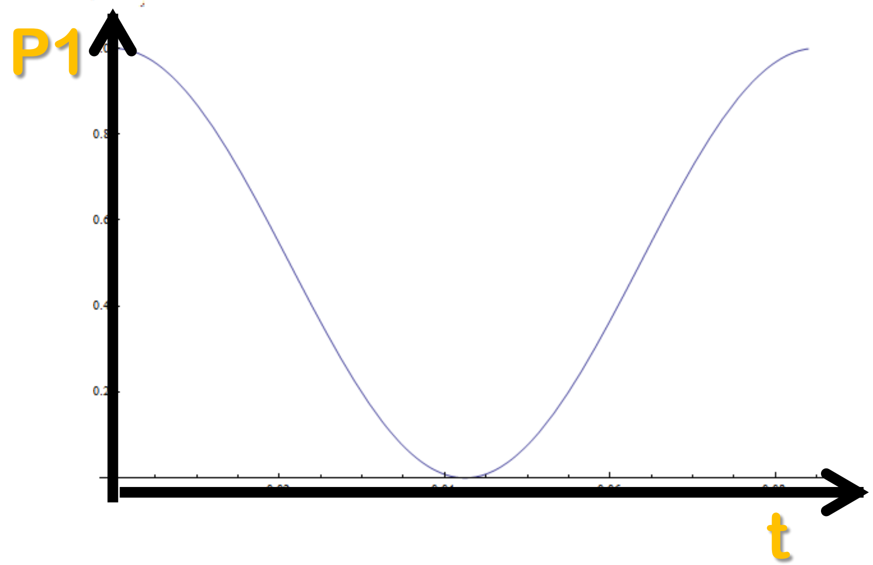
$$\omega_{21} = \frac{E_2 - E_1}{\hbar}$$



$$\Omega_R \times t = \pi$$

$$\Omega'_R = \sqrt{\Omega_R^2 + (\omega_{pq} - \omega)^2} = \sqrt{\Omega_R^2 + \delta^2}$$

$$P(t) = \left(\frac{\Omega_R}{\Omega'_R}\right)^2 \sin^2\left(\frac{\Omega'_R}{2} t\right)$$



Frequency Reference for Gravitation

- Based on 2 natural constants:
  - Mass of the neutron ***m***
  - Planck constant ***ħ***

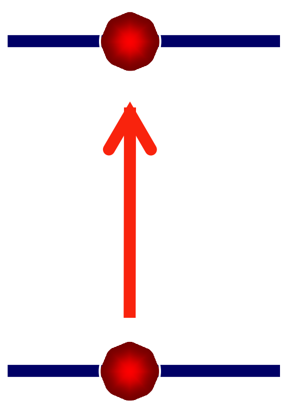
  Plus Acceleration of earth ***g***

$$\omega_0 = \left(\frac{9\pi^2 m g^2}{8\hbar} \right)^{1/3}$$

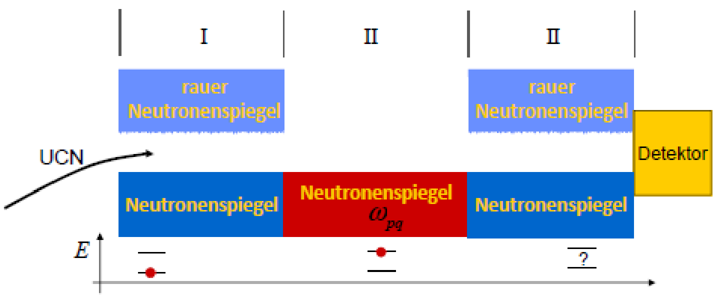
$$E_n = \hbar \omega_0 \left(n - \frac{1}{4} \right)^{2/3}$$

$$\omega_{pq} = \frac{E_q - E_p}{\hbar} = \omega_q - \omega_p$$

|3 > 3.32 peV



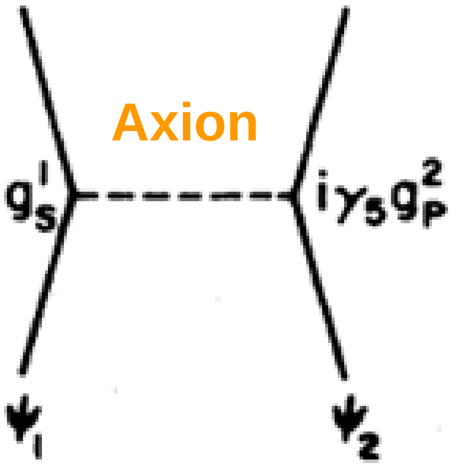
|1 > 1.4 peV



Discoveries: the dark universe

- **Spectroscopy of Gravity**
  - **It does not use electromagnetic forces**
  - **It does not use coupling to em Potential**

- **Hyothetical gravity-like forces**
  - **Axions?**
  - **Chameleons?**



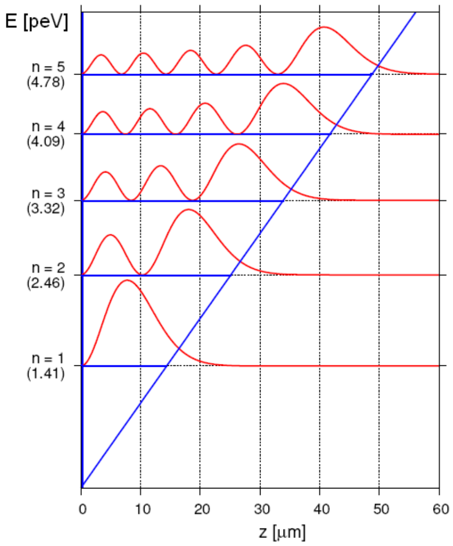
10^{-14} eV Scale

- **constraint on any possible new interaction**

Neutrons test Newton

$$V(r) = G\frac{m_1 \cdot m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)$$

- **Strength α**
- **Range λ**



For a neutron with mass m_n,
gravitational constant G,
mass m_E and density ρ of the earth with radius R_E
($r = R_E + z$),
V(r) is usually approximated by

$$V(z) = m_n g z$$

$$V(z,\lambda) = 2\pi m_n \rho \alpha \lambda^2 G e^{-2|z|/\lambda} = \alpha \times 2 \times 10^{-12}\,\mathrm{peV}$$

Sensitivity

$$V(r) = G\frac{m_1 \cdot m_2}{r}(1+\alpha \cdot e^{-r/\lambda})$$

$$V(z,\lambda) = 2\pi m_n \rho \alpha \lambda^2 G e^{-2|z|/\lambda} = \alpha \times 2 \times 10^{-12}\,\text{peV}$$

- **Count rate: 0.1s^{-1}**
- **N = 10^6 after 50 days**
- **Observation time T = 130ms**

$$\Delta\varphi \times \Delta N = 2\pi$$

$$N = 10^6 \rightarrow \Delta\varphi = 10^{-3}$$

$$\varphi = \omega \times t = E \cdot t / \hbar$$

$$\Delta\varphi = \Delta E \cdot t / \hbar$$

$$\Delta E = \Delta\varphi\hbar / T = 0.33\hbar / s$$

H. A. et al.,
PRD 81, 065019 (2010) [arXiv:0907.5447]

Fifth force: Δφ

$$\Psi(z,t) = \sum C_n e^{-iE_n t/\hbar}\psi_n(z)$$

$$N = 10^6$$

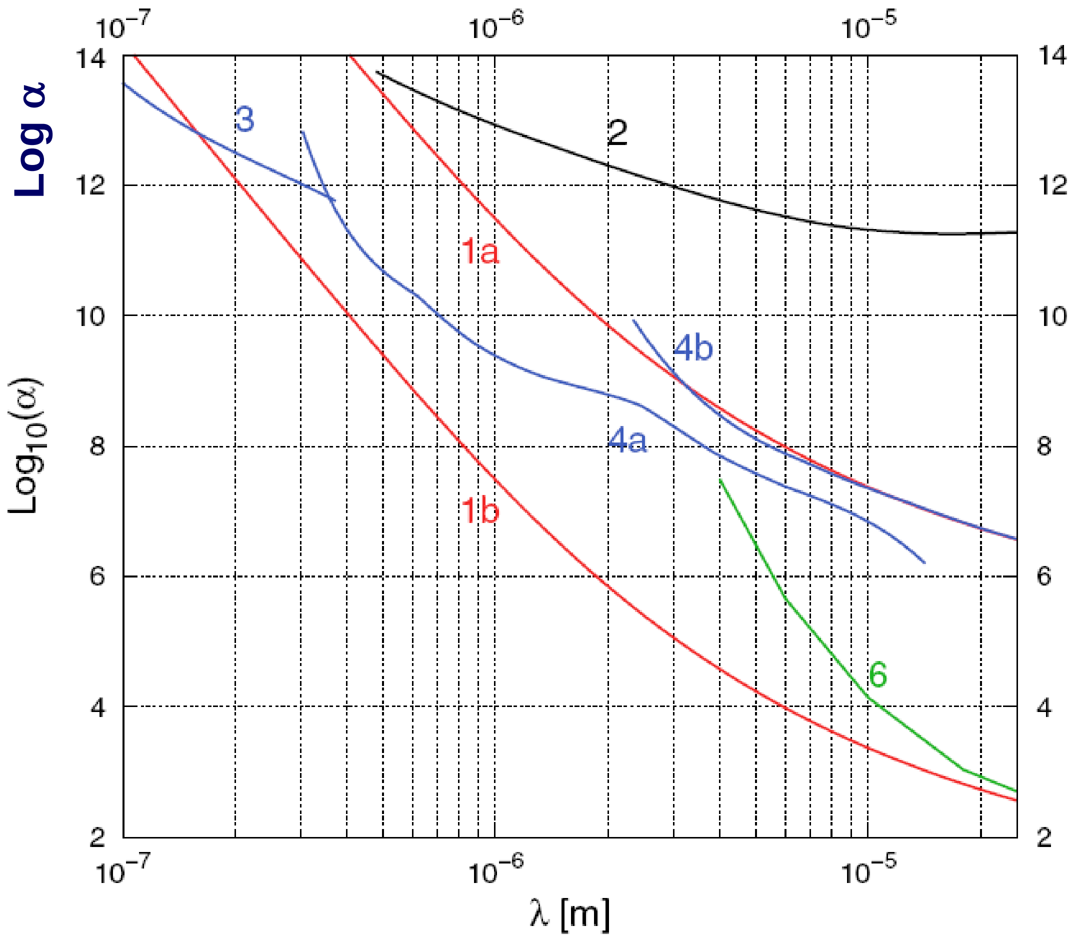
$$\Delta E = 4.8 \times 10^{-5}\,\text{peV}$$

$$\alpha = 7 \times 10^7 \rightarrow 7 \times 10^4 \rightarrow 7 \times 10^3, \Delta E = 4.8 \times 10^{-21}\,\text{eV}$$

Limits on hypothetical gravity-like forces

$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

- **So far best limits from AFM**
  - large effects from Casimir or Van der Waals forces
- **Neutrons:**
  - Polarizability extremely small



Casimir Force

Atom

- **Example Rb**

$$V(r) = \frac{3\hbar c}{2\pi}\frac{a_0}{r^4}$$

r = 1 Micron

$$a_0 = 2,3 \times 10^{-23}$$

$$V(r) = \frac{3\hbar c}{2\pi}\frac{a_0}{r^4} = 0.6\,\text{peV}$$

Neutron:

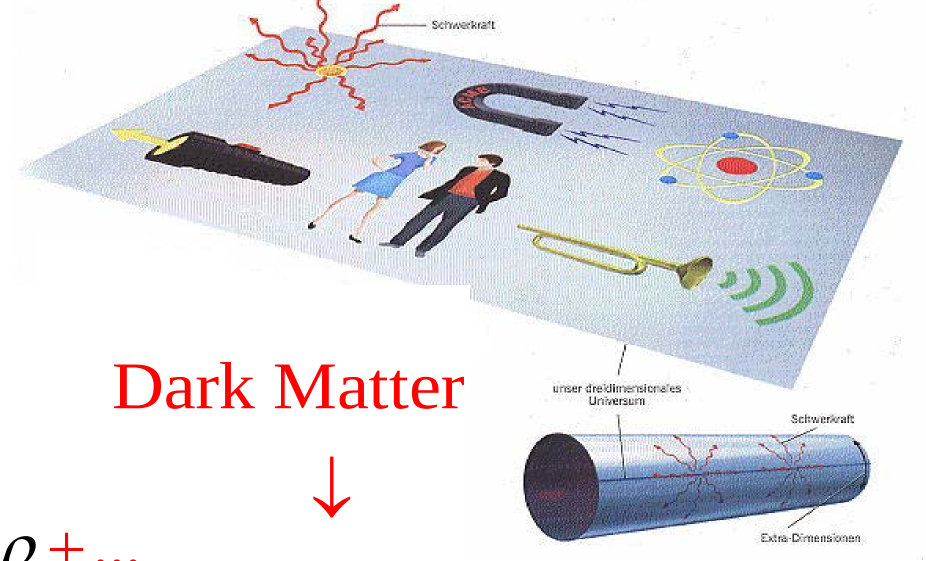
Casimir force absent

- **Polarizability extremely small:**

$$a_n = 11.6 \times 10^{-4}\,\text{fm}^3$$

$$D = 4\pi\varepsilon_0 a_n E = 6 \times 10^{-41}\,\text{eV} \times E\left[\frac{\text{V}}{\text{m}}\right] = 10^{-18}\,\text{peV}$$

Friedman DGL



Hubble parameter: $H \equiv \frac{\dot{a}}{a}$

Dark Matter ↓

Friedman Eq.: $H^2 + \ldots = \frac{8\pi}{3} G_N \rho + \ldots$

↑ new Gravity ↑ Vacuum Energy

Axions

→ 0.2 μm < λ < 2 cm

accelerated universe: $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho - 2\rho_\Lambda)$

B&C '05: Cosmological Constant linked to Size of extra dimensions

→ λ ~ 5μm, α < 10^6

$$V(r) = G\frac{m_1 \cdot m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)$$

ADD '99: Repulsive forces

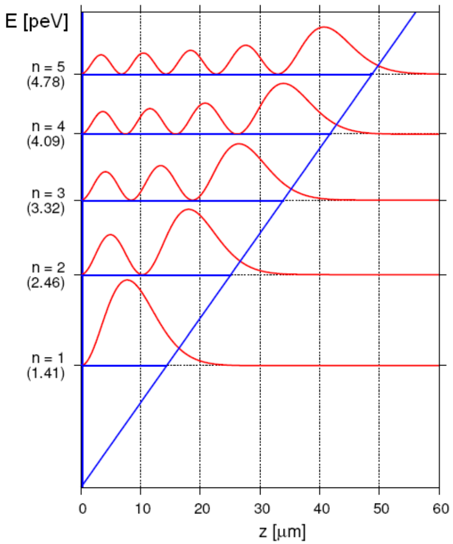
gauge fields in the bulk

→Strength α = 10^6 – 10^9, range λ < 40 μm,

Neutrons test Newton

$$V(r) = G\frac{m_1 \cdot m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)$$

- **Strength α**
- **Range λ**



Hypothetical Gravity Like Forces

Extra Dimensions:
The string and D_p-brane theories predict the existence of extra space-time dimensions
Infinite-Volume Extra Dimensions: Randall and Sundrum
Exchange Forces from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and (pseudo)vector bosons

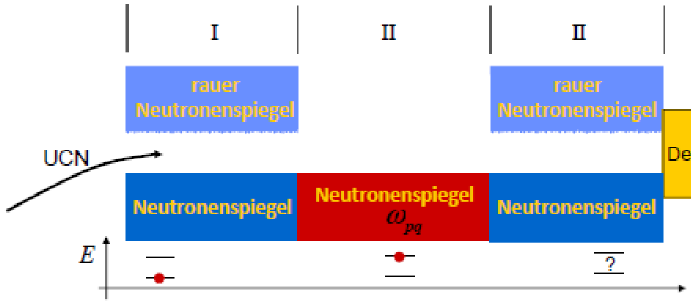
- **Axion - →** **0.2 µm < λ < 0.2 cm**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999) - - - - →$10^6 < \alpha < 10^9$**

Supersymmetric large Extra Dimensions (B.& C.) - - - - → $\alpha < 10^6$
Chameleon fields-

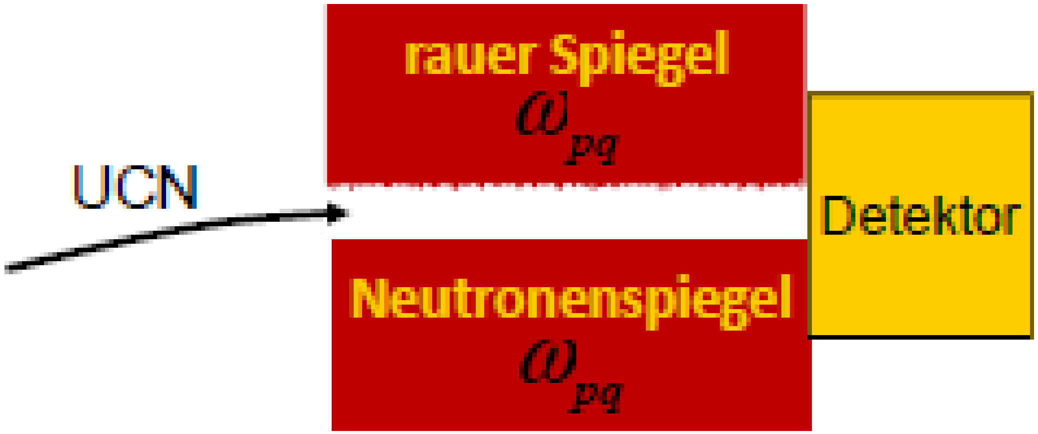
Show Case III: Search for gravity-like forces

Resonance Spectroscopy Technique to explore gravity

Rabi-type experiment:

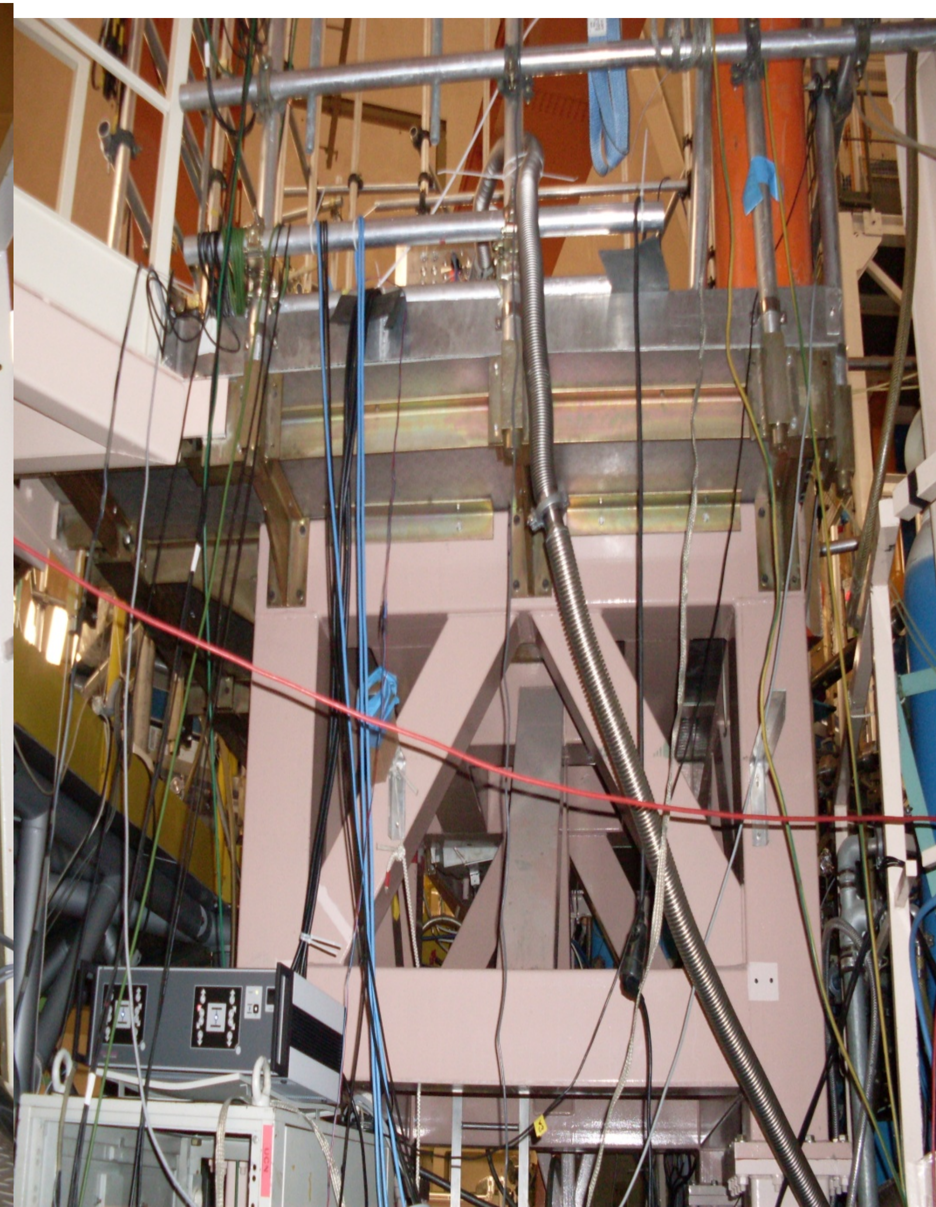


Rabi-type experiment with damping



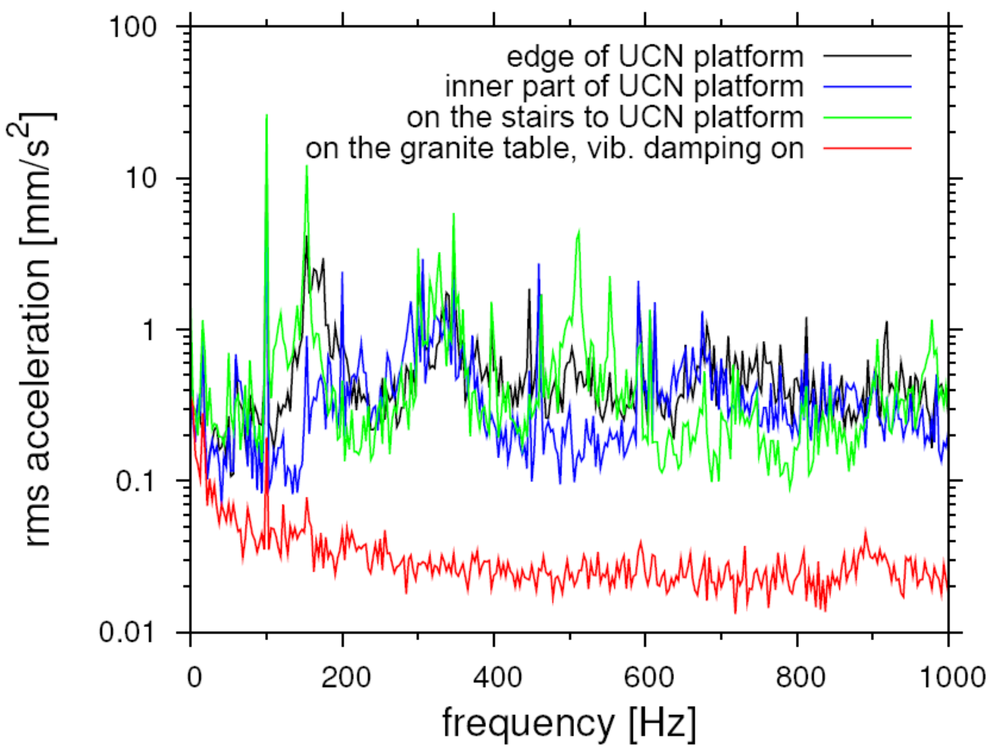
- realization of gravity resonance method possible
- simple setup, no steps
- high(er) transmission
- upper mirror introduces 2nd boundary condition


HellermannTyton
500

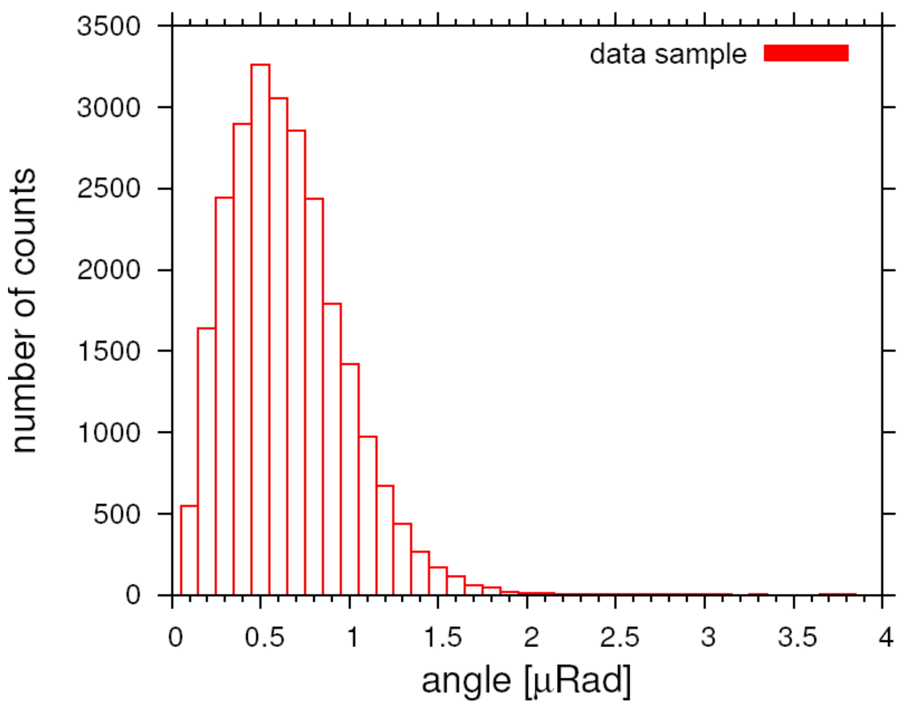


Stability

Vibrations



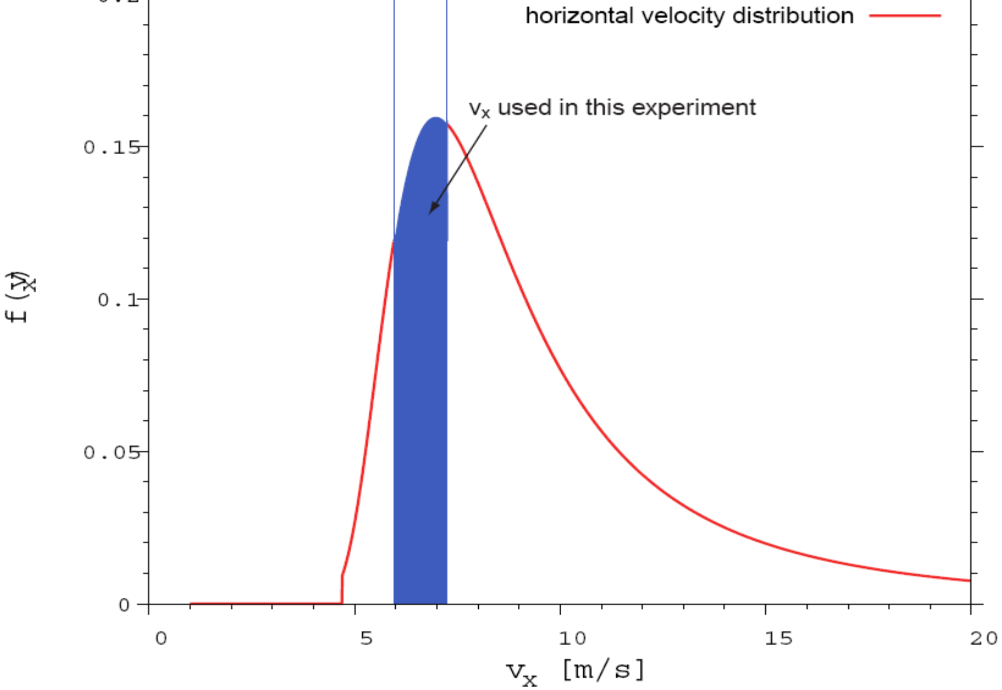
Inclinometers

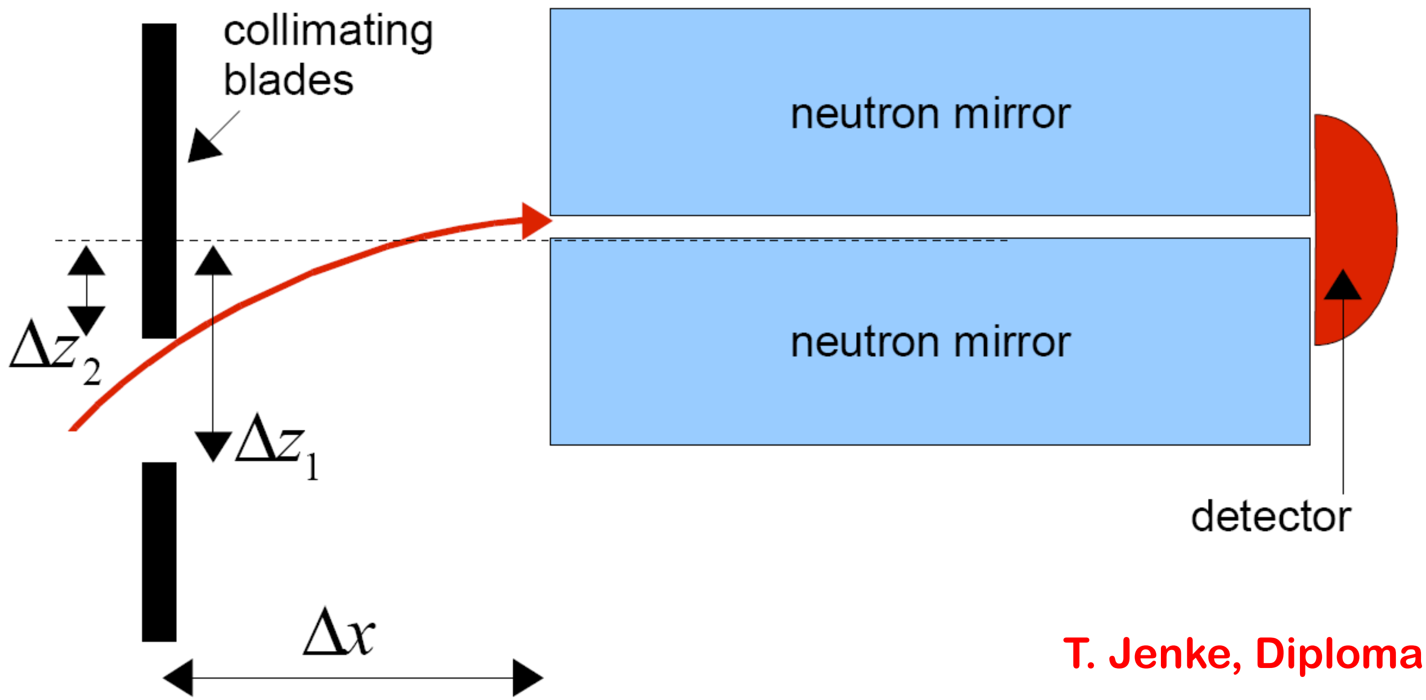


D. Stadler, Diploma thesis, 2009

Horizontal velocity

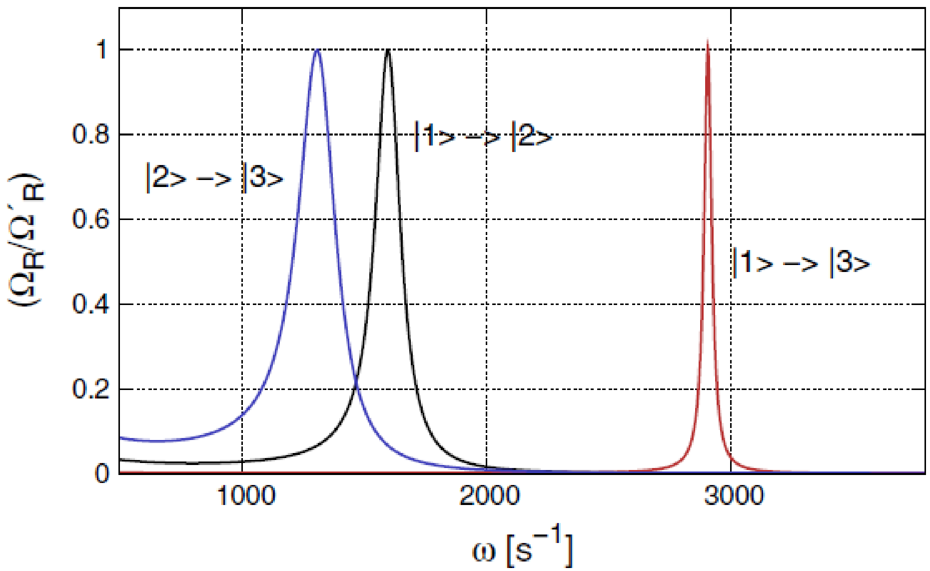
- $6\ m/s < v_x < 7.2\ m/s$

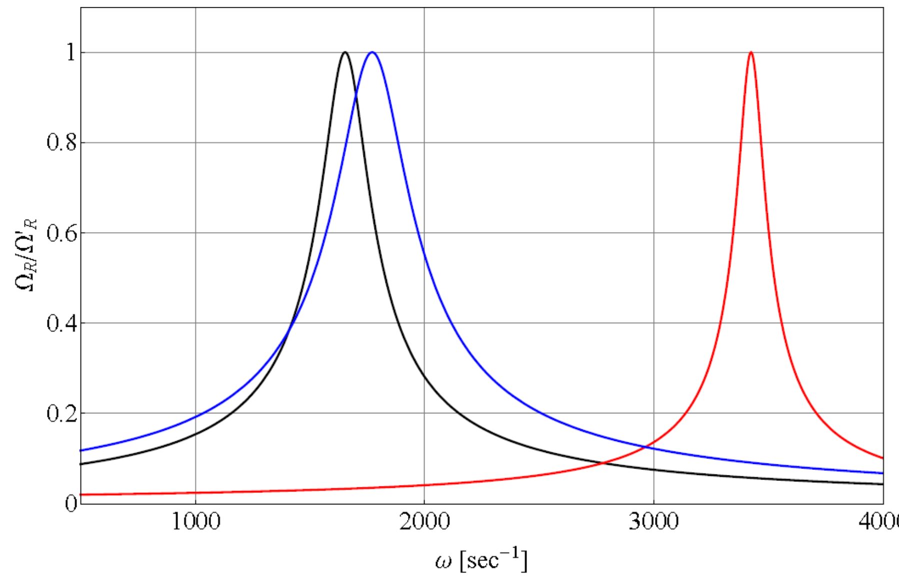




T. Jenke, Diploma thesis, 2008

Gravity Resonance



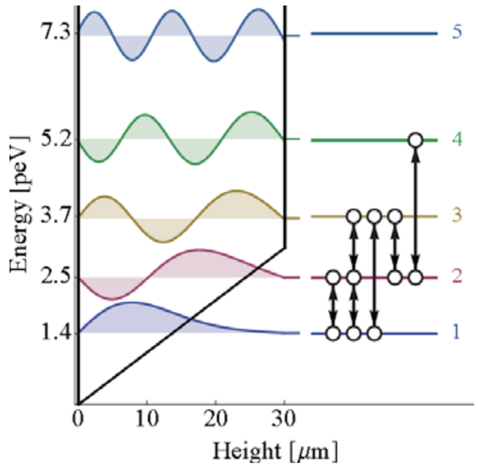


$$\begin{pmatrix} \dot{b}_1(t) \\ \dot{b}_2(t) \\ \dot{b}_3(t) \\ \dot{b}_4(t) \end{pmatrix} = \begin{pmatrix} -\frac{\gamma_1}{2} & -S_{21} & 0 & 0 \\ S_{21} & -\frac{\gamma_2}{2} & -S_{32} & 0 \\ 0 & S_{32} & -\frac{\gamma_3}{2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} b_1(t) \\ b_2(t) \\ b_3(t) \\ \dot{b}_3(t) \end{pmatrix}$$

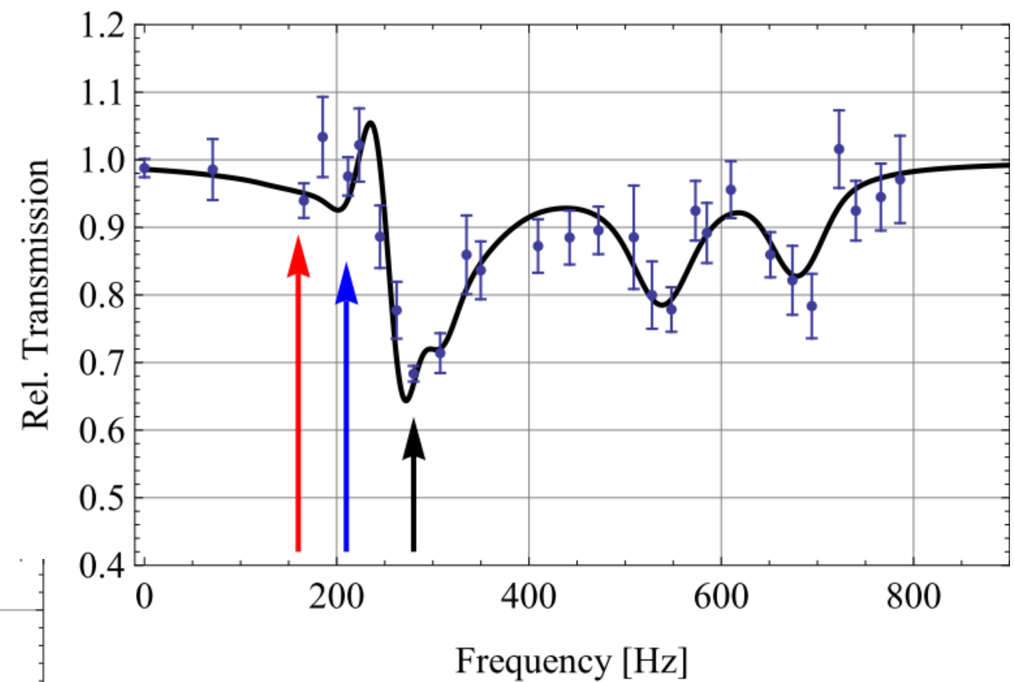
$$\begin{pmatrix} \dot{b}_1(t) \\ \dot{b}_2(t) \\ \dot{b}_3(t) \\ \dot{b}_4(t) \end{pmatrix} = \begin{pmatrix} -\frac{\gamma_1}{2} & 0 & -S_{31} & 0 \\ 0 & -\frac{\gamma_2}{2} & 0 & -S_{42} \\ S_{31} & 0 & -\frac{\gamma_3}{2} & 0 \\ 0 & S_{42} & 0 & -\frac{\gamma_4}{2} \end{pmatrix} \cdot \begin{pmatrix} b_1(t) \\ b_2(t) \\ b_3(t) \\ \dot{b}_3(t) \end{pmatrix}$$

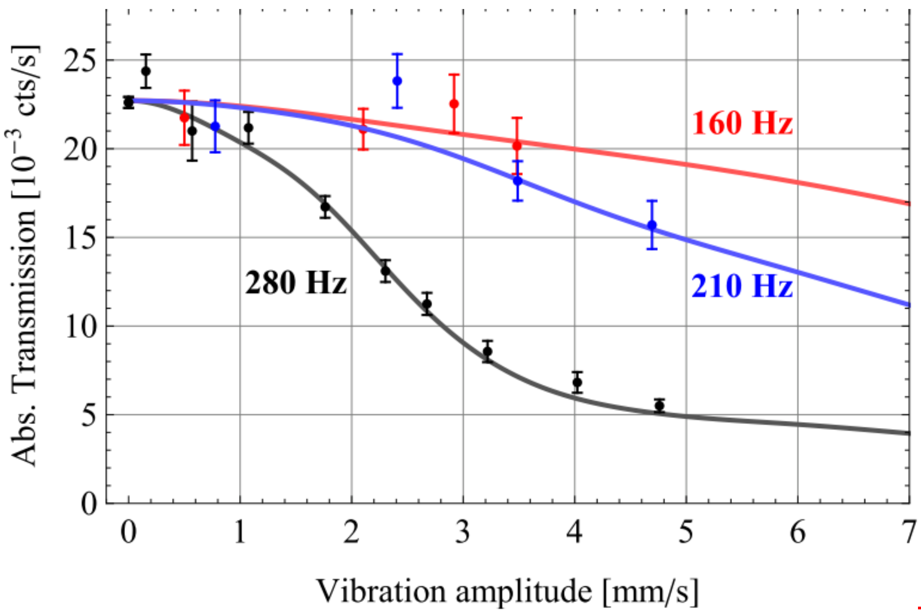
Gravity Resonance Spectroscopy 2012

50 days of beam time,
116 measurements
[data 2010]



$|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$, $|2\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |4\rangle$





- **stat. Significance:** 48σ
- **stat. accuracy:** $\nu_{12} = 258.2\,\text{Hz} \pm 0.8\%$
  $\nu_{23} = 280.4\,\text{Hz} \pm 1.0\%$
  $\nu_{13} = 539.1\,\text{Hz} \pm 0.5\%$
  $\nu_{24} = 679.5\,\text{Hz} \pm 2.2\%$
- **contrast:** 68%

10^{-14} eV Scale

Quintessence Theories

- It could well be that the universe is not in a vacuum state at all and has a dynamical evolution
- Scalar field ϕ as a Perfect fluid

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu + p g_{\mu\nu}$$

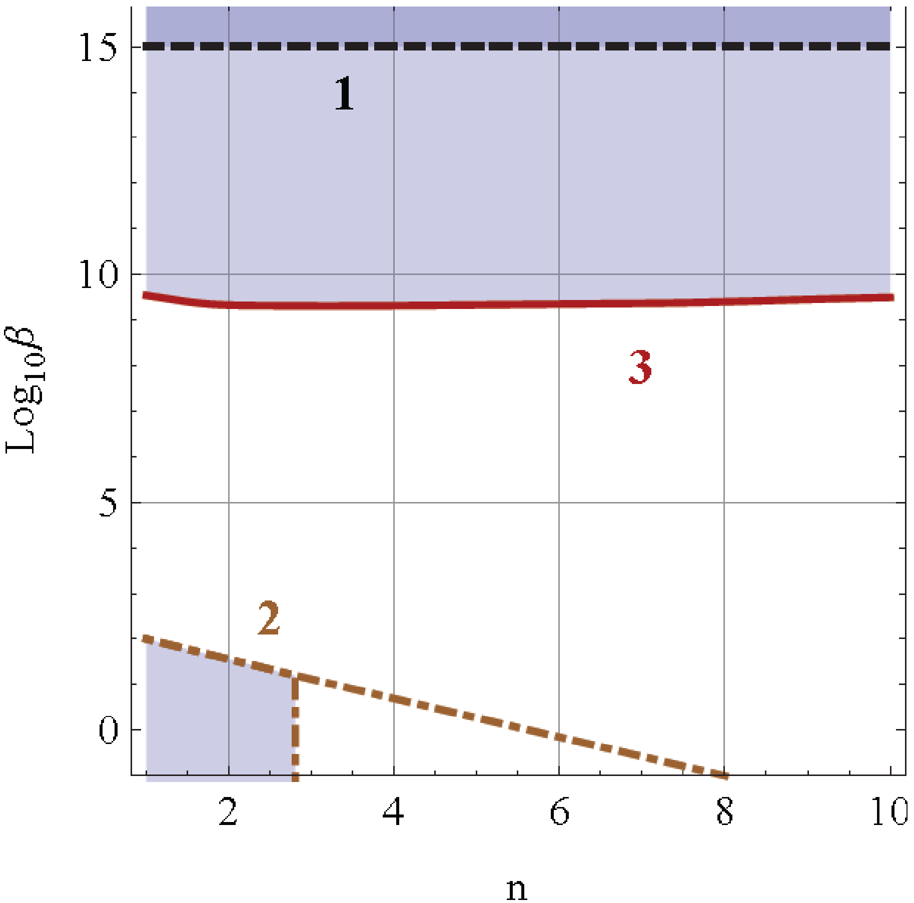
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)$$

Dark Energy – Scalar Fields

- Chameleon fields, Brax et al. PRD **70,** 123518 (2004)
- 2 Parameters β, n

$$V_{\rm eff}(\phi) = V(\phi) + e^{\beta\phi/M_{\rm Pl}}\rho.$$



qBounce and Chameleons

- Bounds on coupling β
  - By comparing transition frequency with theoretical expectation:

$$\omega_{ab} - \omega_{ab}^{\text{theo}} = \beta \frac{m}{M} \left(\langle a|\phi(z)|a\rangle - \langle b|\phi(z)|b\rangle \right)$$

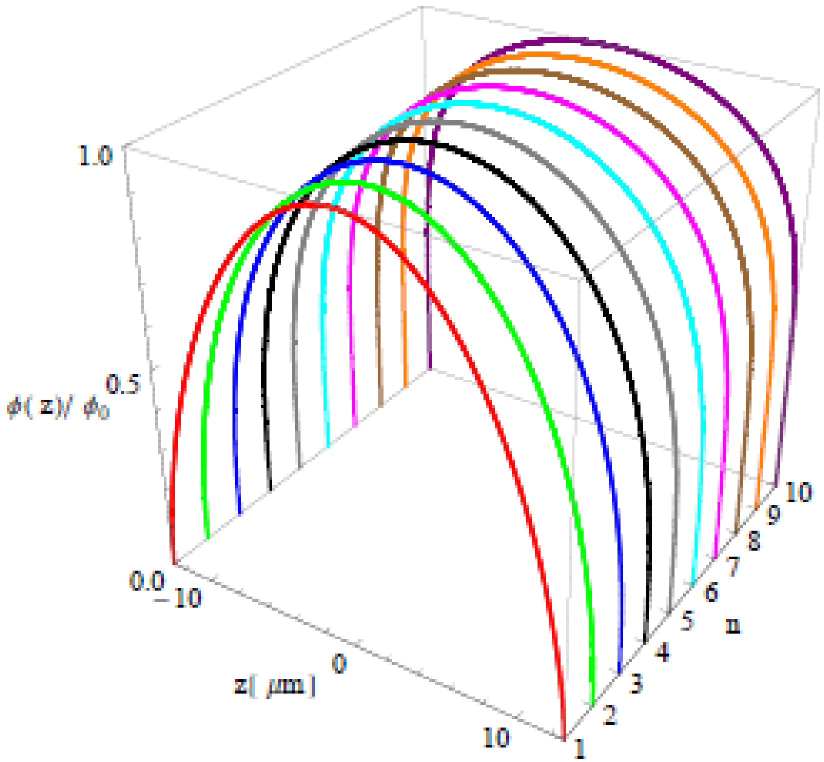


FIG. 2: The profiles of a chameleon field, calculated in the strong coupling limit as the solutions of Eq.(81) in the spatial region $z^2 \leq \frac{d^2}{4}$ and $n \in [1, 10]$.

  - as long as $\beta > 10^5$
  - Cite as: arXiv:1207.0419v1

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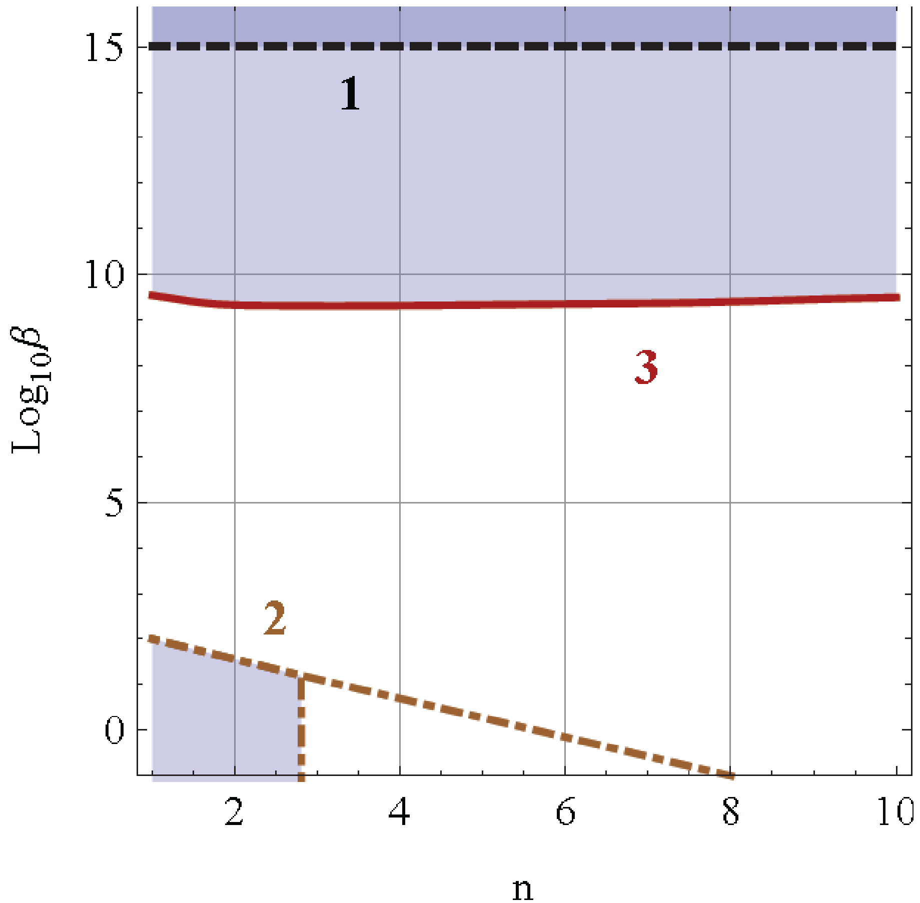

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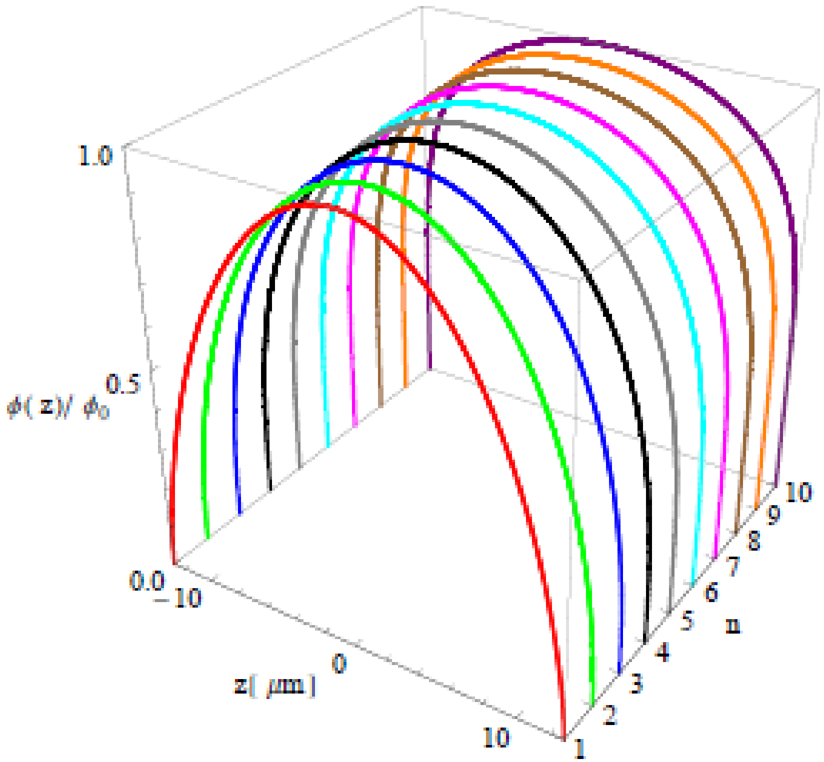
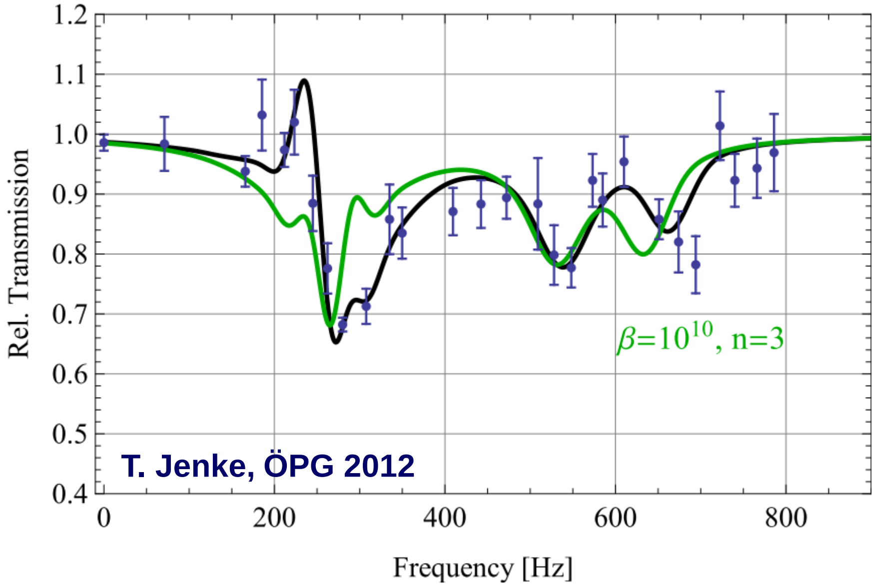
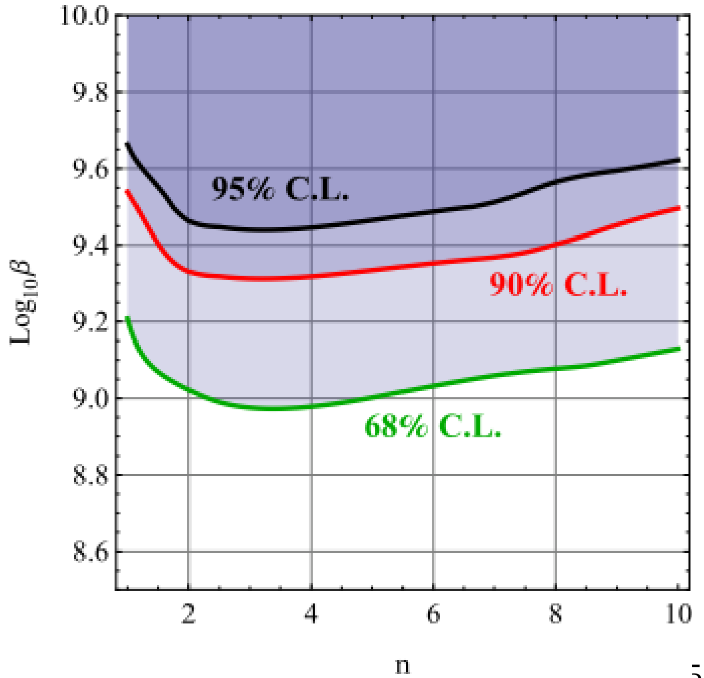


FIG. 2: The profiles of a chameleon field, calculated in the strong coupling limit as the solutions of Eq.(81) in the spatial region $z^2 \leq \frac{d^2}{4}$ and $n \in [1, 10]$.

Applications II:
Strongly coupled chameleons

$$V_{\text{Chameleon}} = \beta \frac{m}{M_{Pl}} \Lambda \left(\frac{n+2}{\sqrt{2}} \frac{\Lambda}{d} \left(\frac{d^2}{2} - z^2 \right) \right)^{\frac{2}{n+2}}$$





Dark Energy – Scalar Fields

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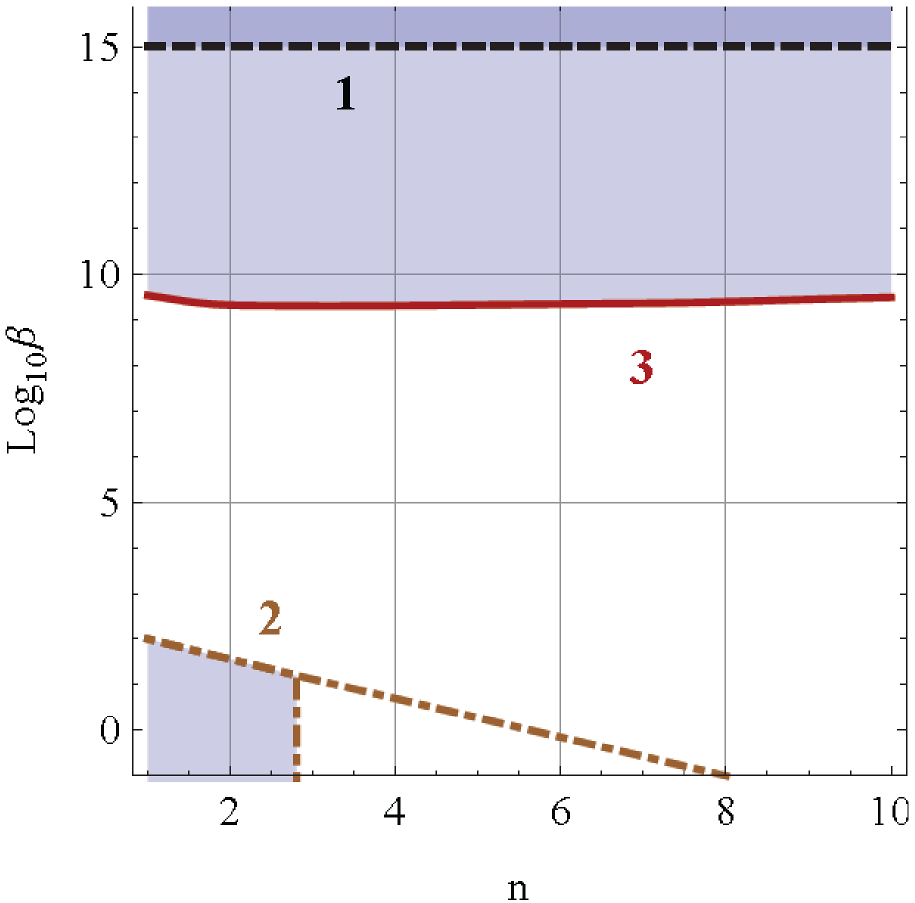
- 2 Parameters β, n

$$V_{\rm eff}(\phi) = V(\phi) + e^{\beta\phi/M_{\rm Pl}}\rho.$$

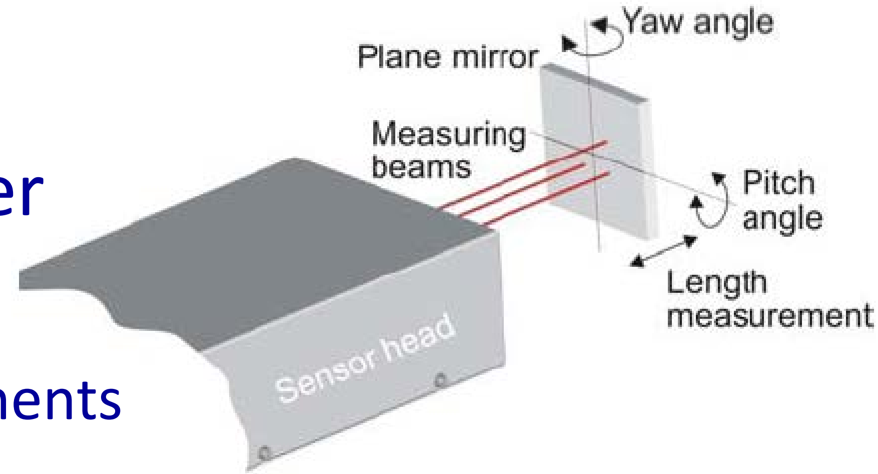


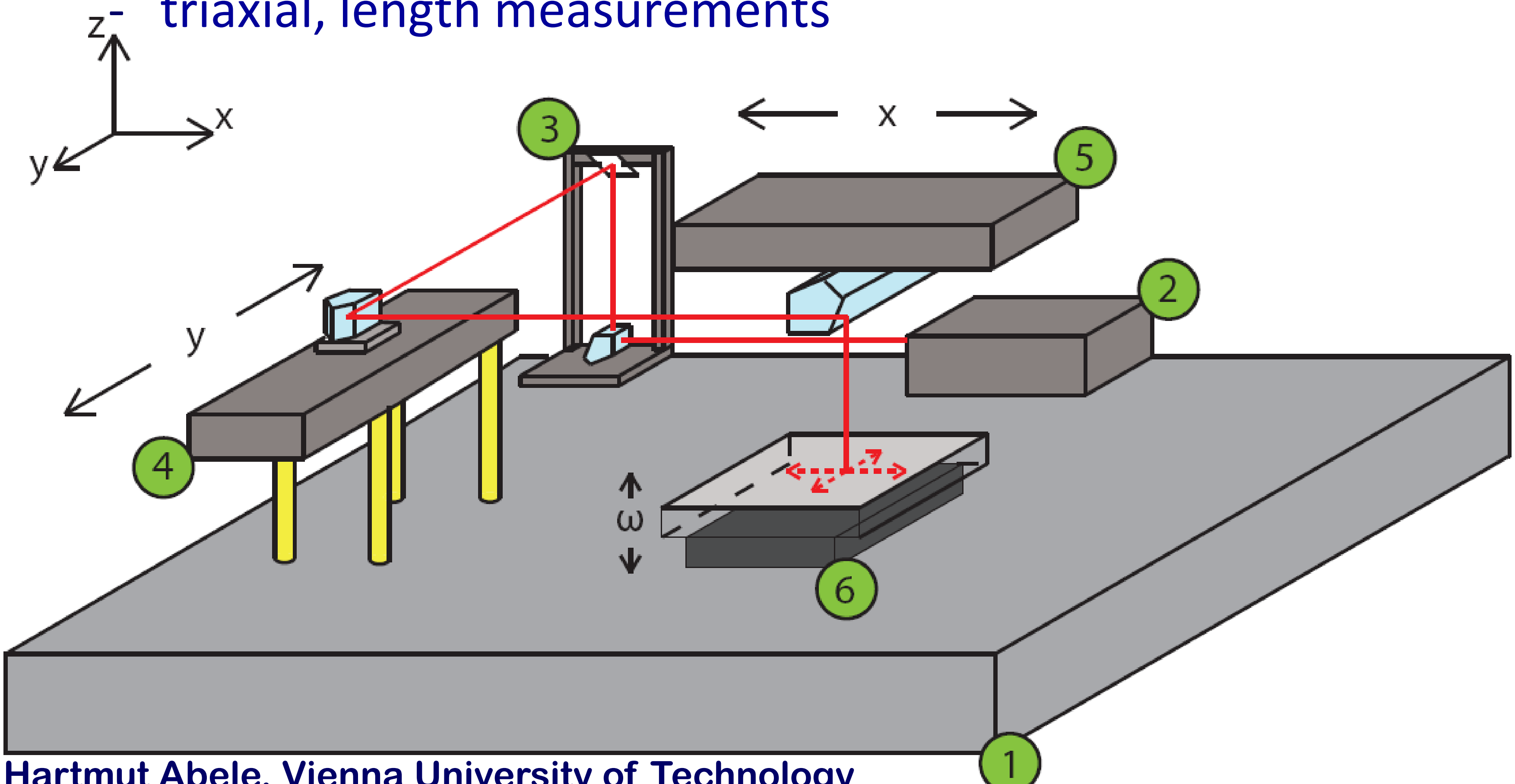
Systematic effects

- Polarizability effects: 10^{-30} eV
- Tidal effects: 10^{-19} eV
- 1 kg in close approximantion: 10^{-19} eV
- The inclination of setup is stabilized to 10^{-27} eV level
- roughness and waviness: below 10^{-19}eV
- External magnetic field gradients are suppressed by a factor of 20.
- The experiment is evacuated to approx. 10^{-4} mbar

Neutron Mirror

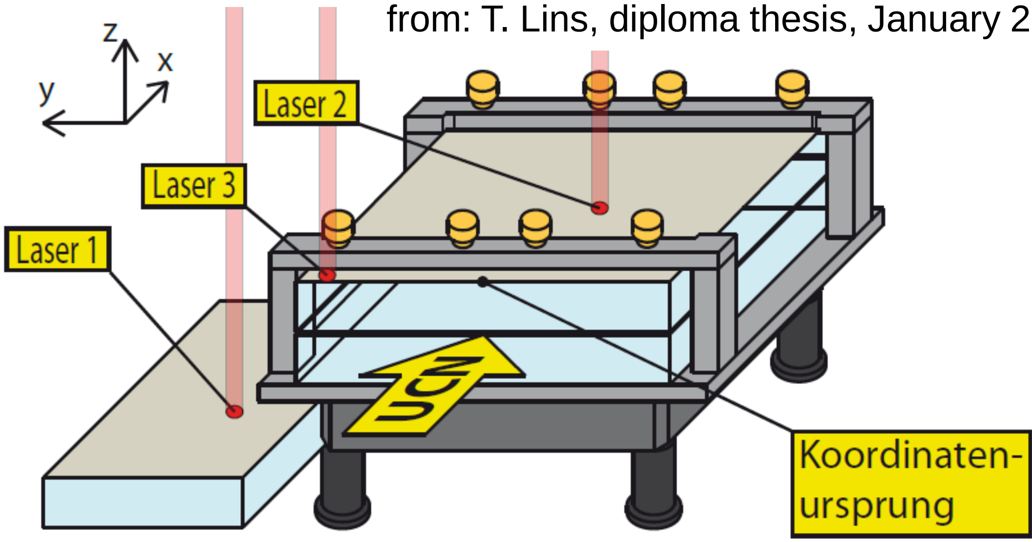
- triple-beam interferometer
  - nm precision
  - Laser interferomic measurements
  - triaxial, length measurements

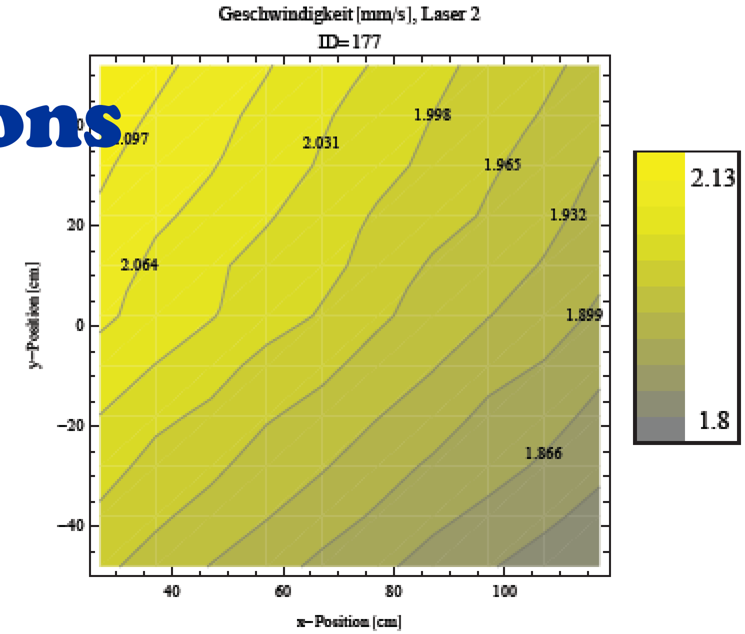


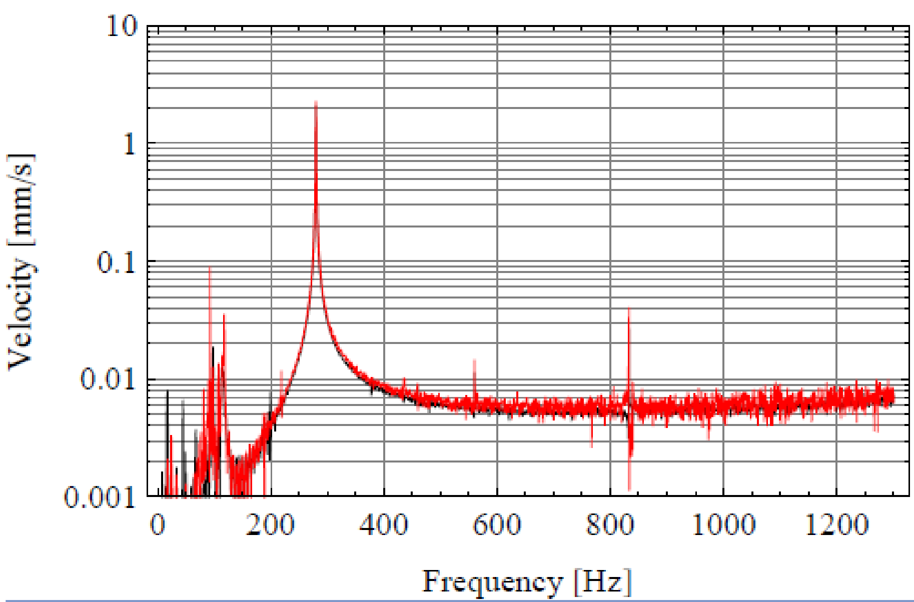


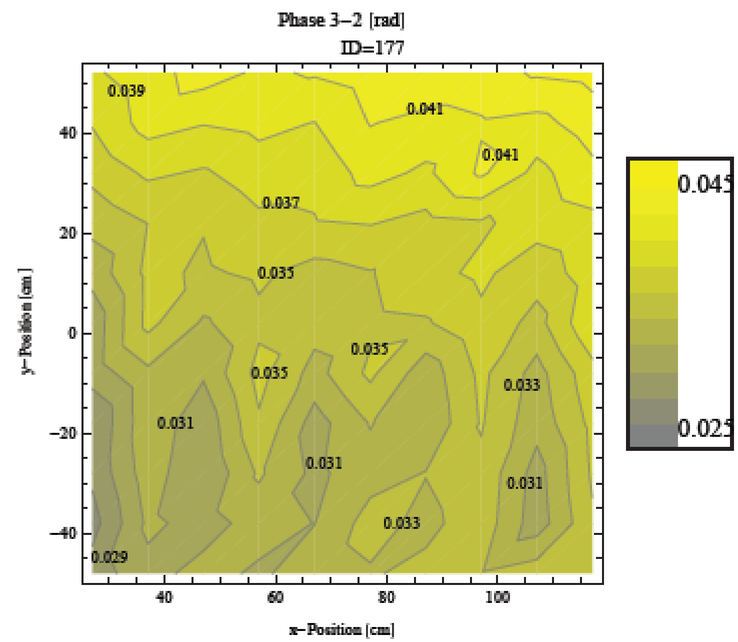
The key technology: Controlling the vibrations

from: T. Lins, diploma thesis, January 2011

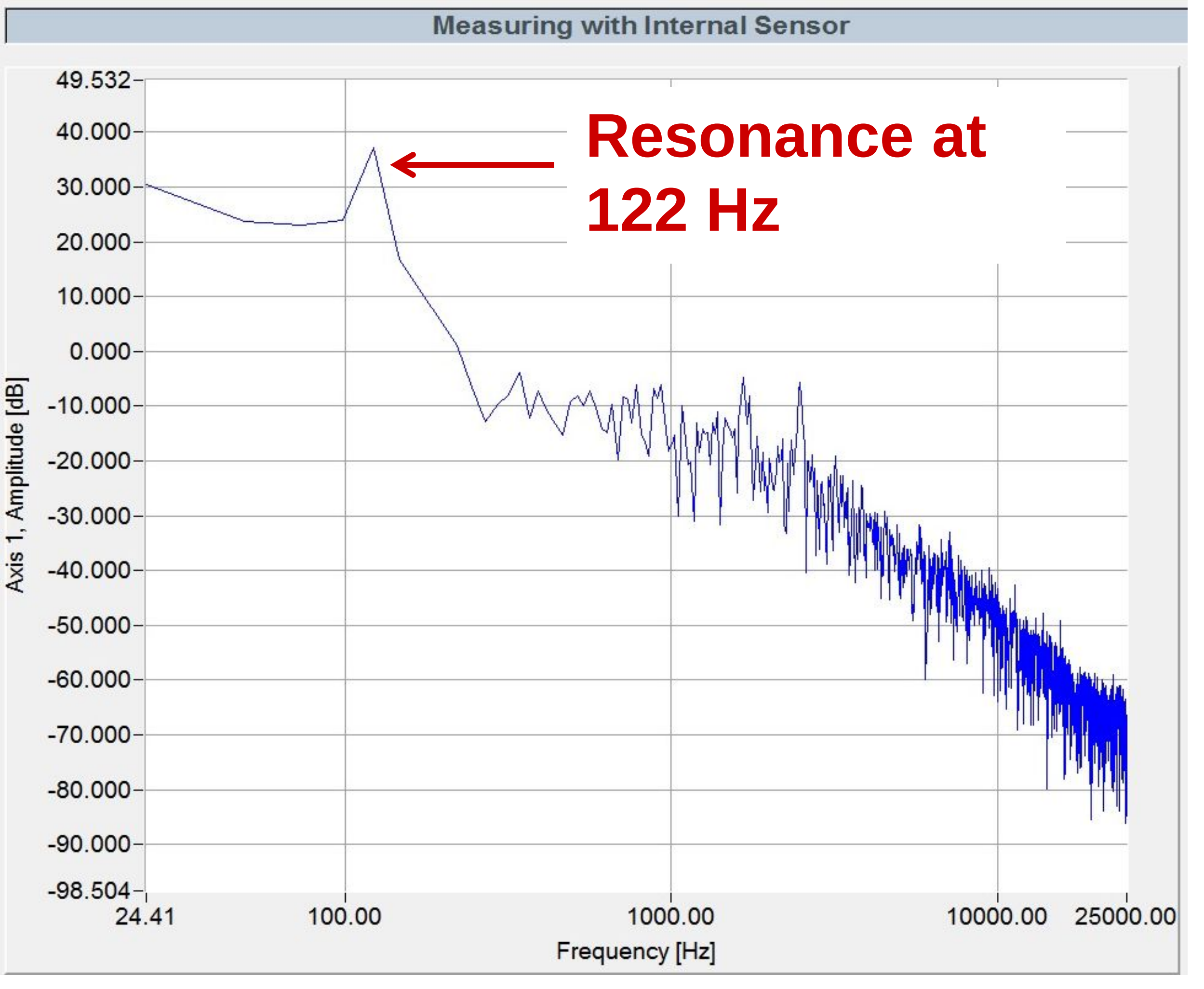




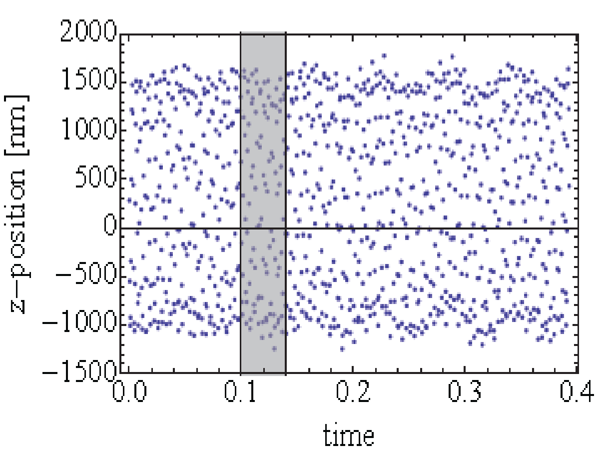


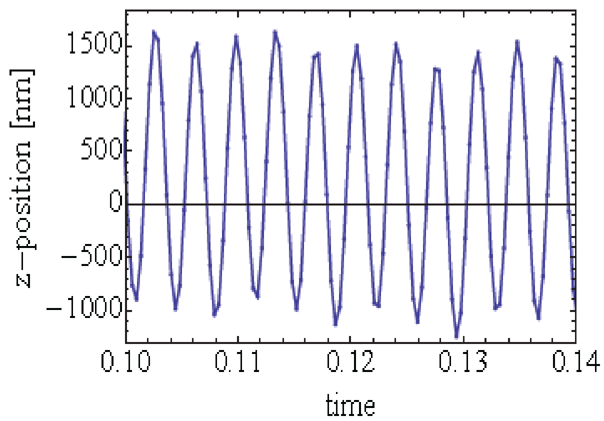


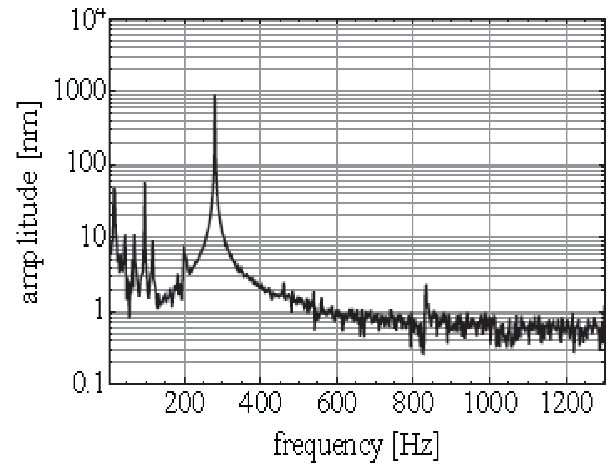
Response Function of the Vibration Control System

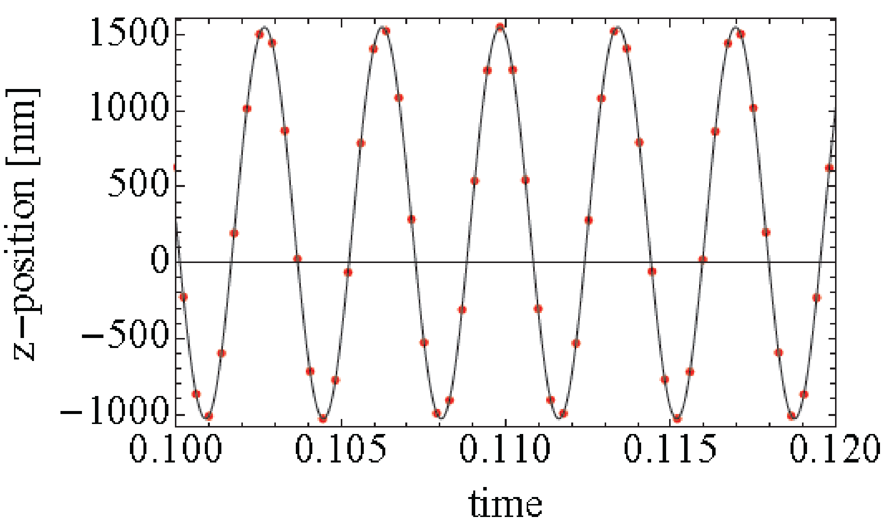


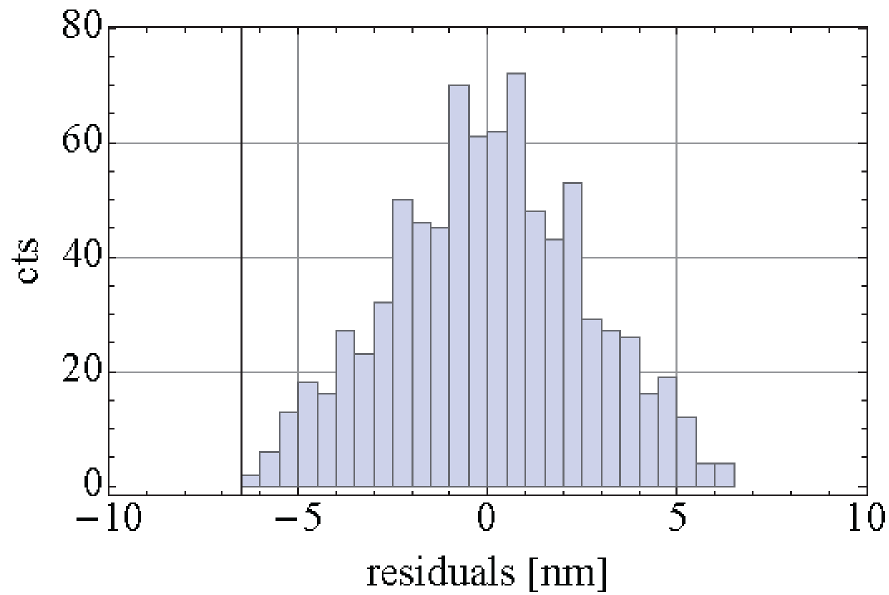
Frequency


z−position [nm]
time


z−position [nm]
time


amplitude [nm]
frequency [Hz]


z−position [nm]
time

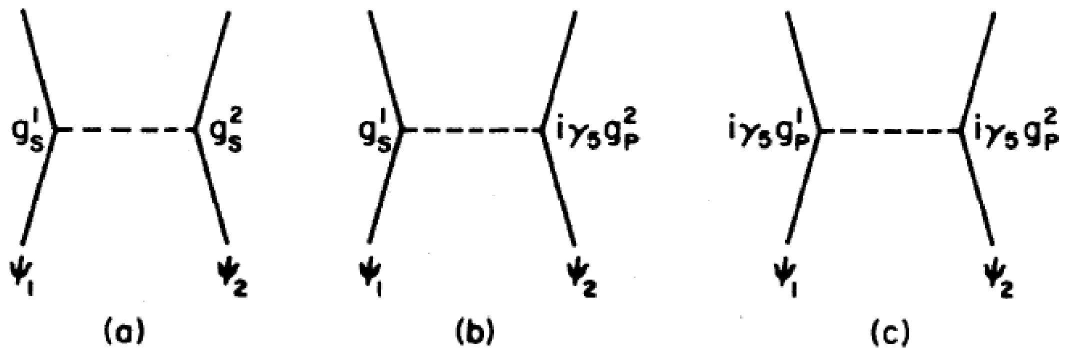

cts
residuals [nm]

Limits on Axions

- **SM: $0 < \theta < 2\pi$**

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu}) + \bar{q}(i\not{D} - \mathcal{M})q + \frac{\theta}{16\pi^2}\mathrm{tr}(\tilde{G}_{\mu\nu}G^{\mu\nu})$$

- **EDM neutron→ $\theta < 10^{-10}$**
- **Axion: Spin-Mass coupling $g_s g_p/\hbar c$: $\theta = 0$**



J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

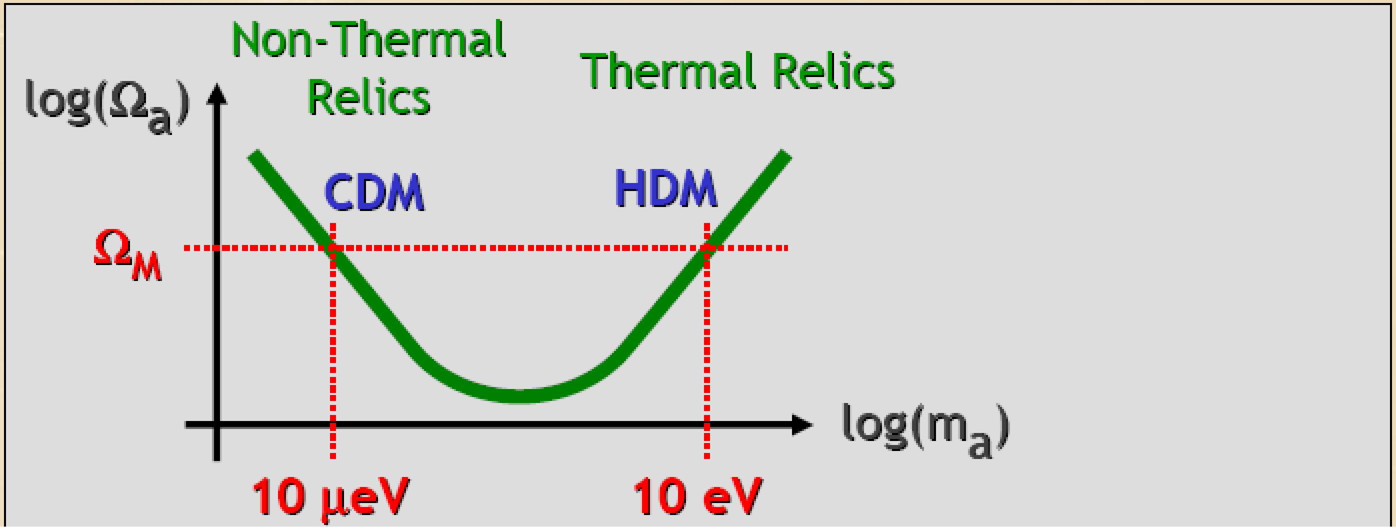
$$V(\vec{r}) = \hbar g_s g_p \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Science week TU Munich 08, Georg Raffelt:

Lee-Weinberg Curve for Neutrinos and Axions

$$\lambda = \frac{\hbar c}{mc^2}$$

Axions



$$\lambda = 0.2\ \mu\text{m}$$

$$\lambda = 2\ \text{cm}$$

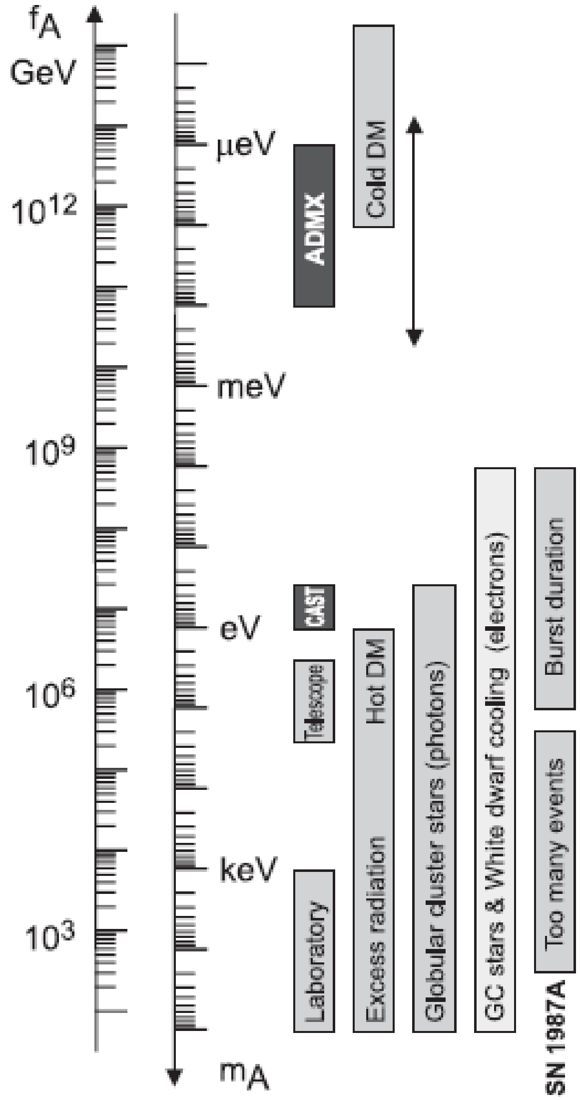
$$\Delta\phi(z) = -\alpha_a \cdot \frac{\hbar^2 \rho_1 \lambda}{8m^3} e^{-z/\lambda} + \alpha_a \cdot \frac{\hbar^2 \rho_2 \lambda}{8m^3} e^{-(h-z)/\lambda}$$

$$= -2\pi\alpha_{\text{eff.}} \cdot \lambda^2 \cdot G_4 \cdot \left(\rho_1\, e^{-z/\lambda} - \rho_2\, e^{-(h-z)/\lambda}\right)$$

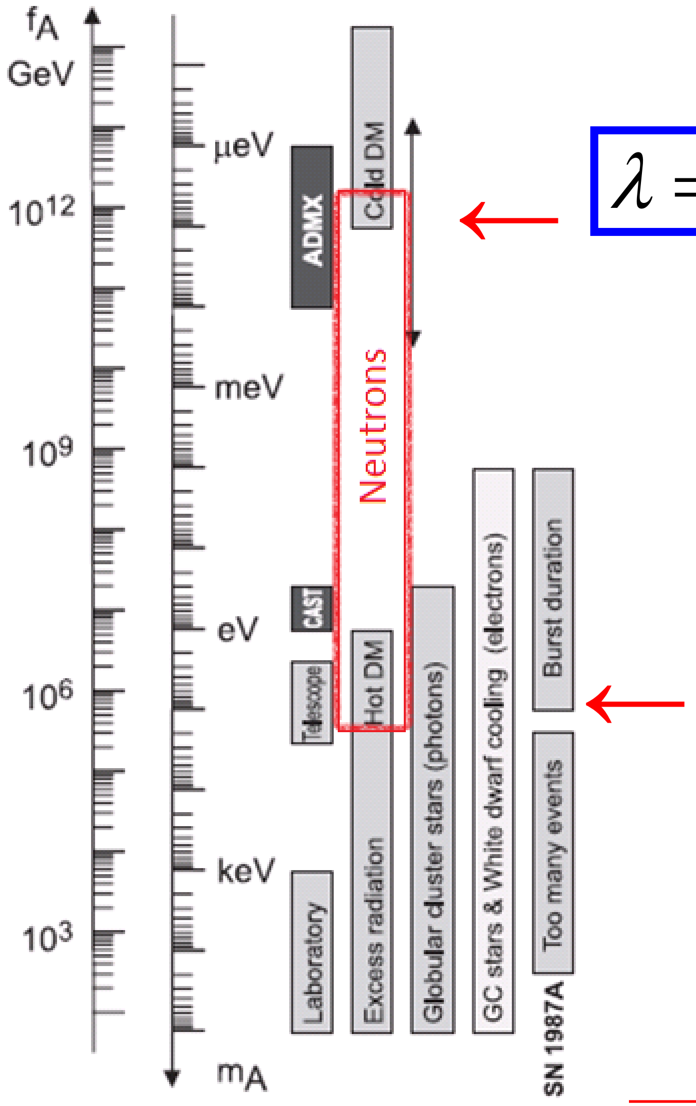
$$\alpha_{\text{eff.}} = \alpha_a \cdot \frac{\hbar^2}{16\pi G_4 \cdot m^3} \cdot \lambda^{-1} \quad , \quad \alpha_a := \frac{g_s g_p}{\hbar c}$$

A. Westphal, H.A. et al. 2007

AXION: PDG Exclusion Ranges



PDG Exclusion Ranges on Axion masses

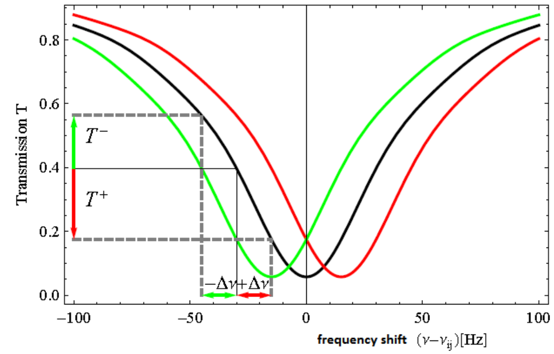


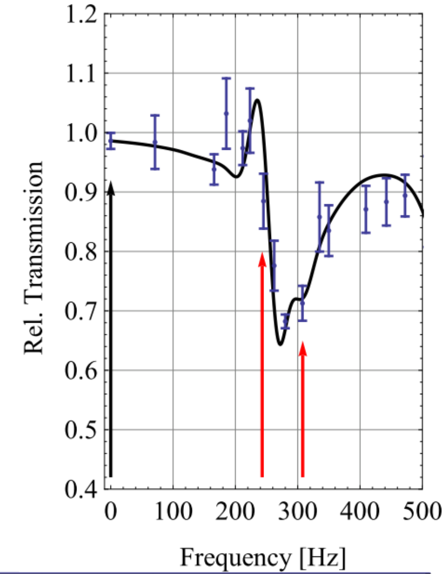
$\lambda = 2$ cm

$\lambda = 0.2$ μm

Applications I: Spin-dependant short-ranged interactions

$$V_{\text{axion}} = \frac{g_s g_p \hbar}{8\pi m_n c}\, \vec{\sigma}\cdot\vec{n} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)$$

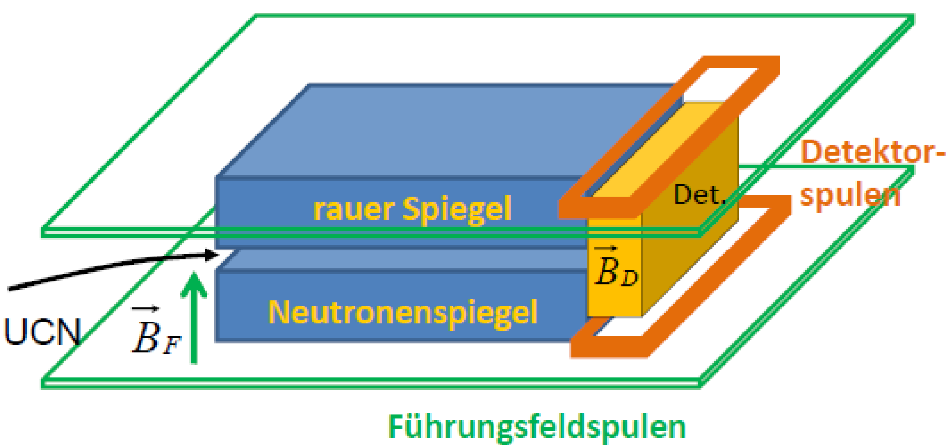


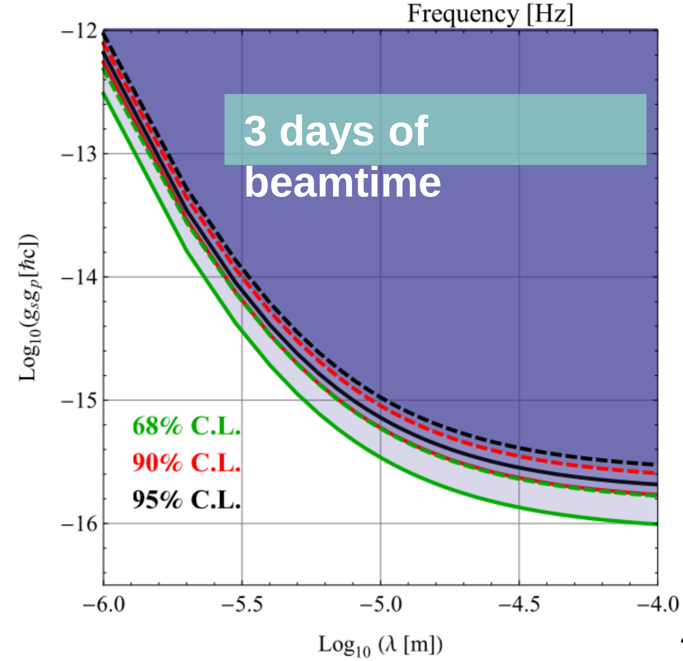


discovery potential [Setup 2010]:

$$g_s g_p / \hbar c \geq \frac{3\cdot 10^{-16}}{\sqrt{days}}$$

$$(\lambda = 10\,\mu\text{m}, 68\%\,\text{C.L.})$$





Casimir Force

Atom

- **Example Rb**

$$V(r) = \frac{3\hbar c}{2\pi}\frac{a_0}{r^4}$$

r = 1 Micron

$$a_0 = 2{,}3 \times 10^{-23}$$

$$V(r) = \frac{3\hbar c}{2\pi}\frac{a_0}{r^4} = 0.6\,\text{peV}$$

Neutron:

Casimir force absent

- **Polarizability extremely small:**

$$a_n = 11.6 \times 10^{-4}\,\text{fm}^3$$

$$D = 4\pi\varepsilon_0 a_n E = 6 \times 10^{-41}\,\text{eV} \times E\left[\frac{\text{V}}{\text{m}}\right] = 10^{-18}\,\text{peV}$$

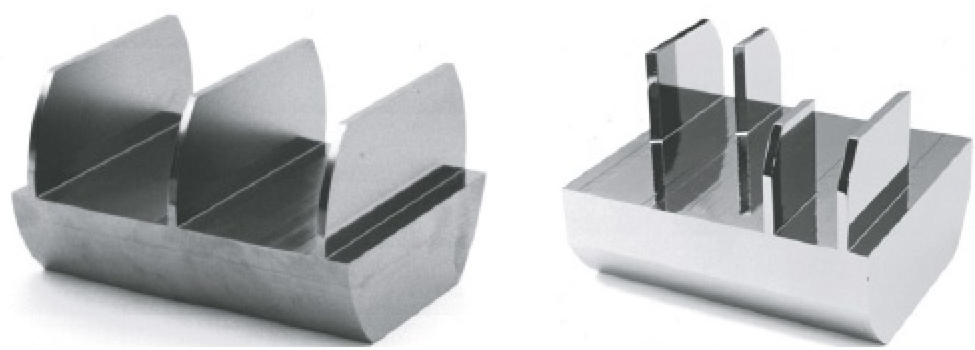
Priority Programme 1491

- Research Area A: *CP-symmetry violation and particle physics in the early universe*
  - **Neutron EDM** $\Delta E = 10^{-23}$ eV
- Research Area B: *The structure and nature of weak interaction and possible extensions of the Standard Model*
  - **Neutron β-decay** V – A Theory
- Research Area C: *Relation between gravitation and quantum theory*
  - **Neutron bound gravitational quantum states**
- Research Area D: *Charge quantization and the electric neutrality of the neutron*
  - **Neutron charge**
- Research Area E: *New measuring techniques*
  - ***Particle detection***
  - ***Magnetometry***
  - ***Neutron optics***

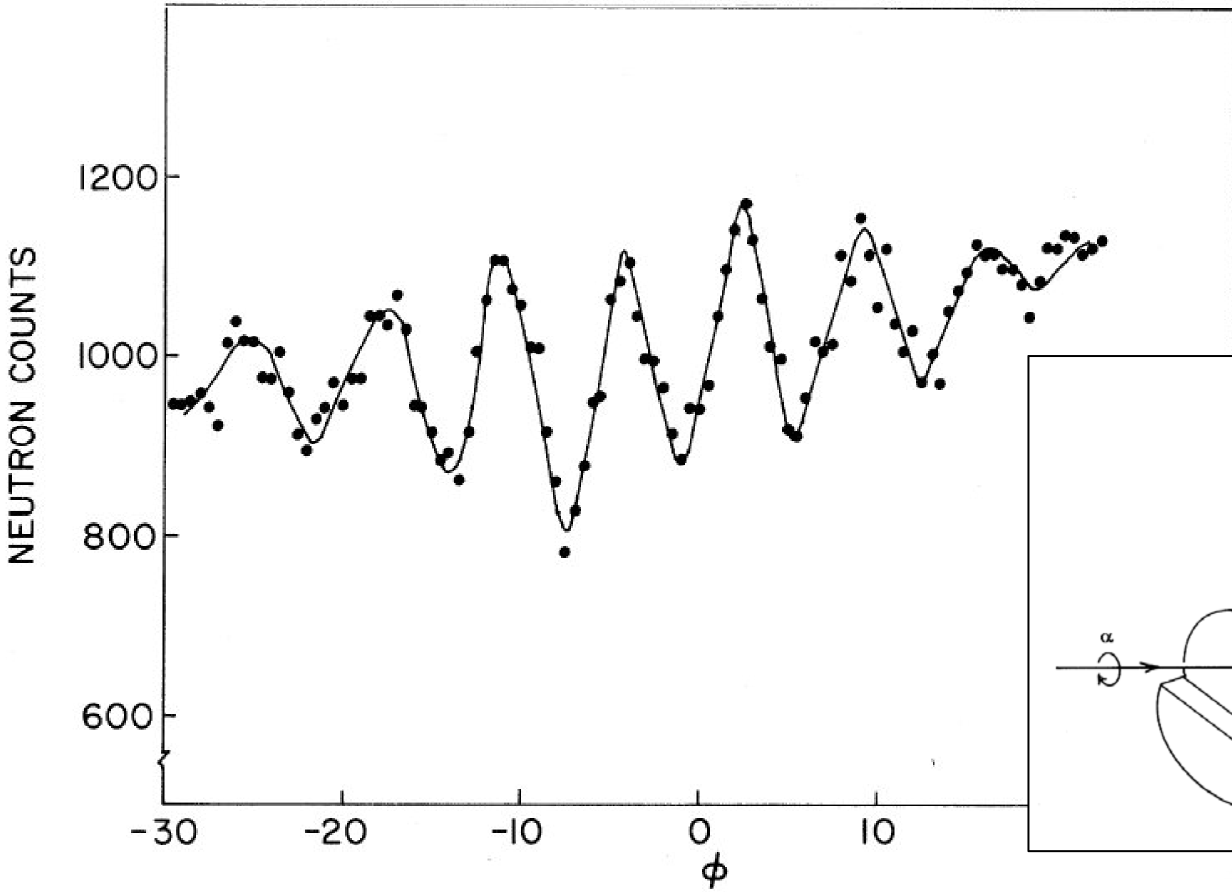
Test of Gravitation with Quantum Objects

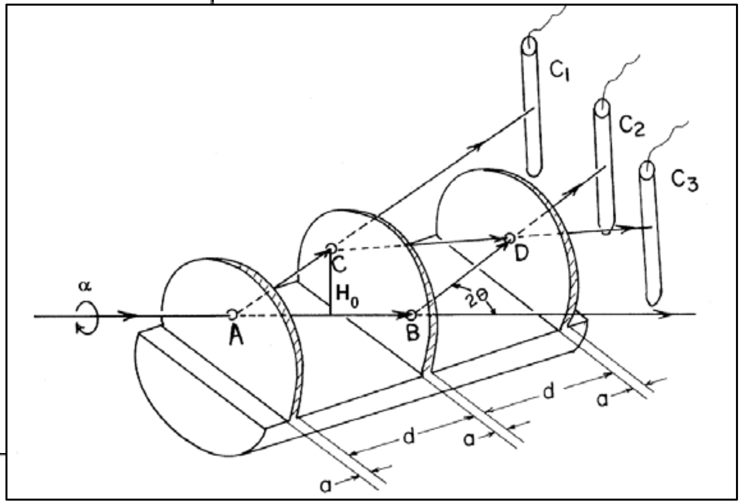
M. Zawisky: Neutron Interferometry

- Rauch, Treimann, Bonse:
  - Test of a Single Crystal Neutron Interferometer“, Physics Letters 47 A (1974) 369-371



COW-Experiment





$$q_{\text{grav}} = g_{\text{COW}}(1+\epsilon)$$

$$\begin{aligned} q_{\text{grav}} &= \left(q_{\text{exp}}^2 - q_{\text{Sagnac}}^2\right)^{1/2} - q_{\text{bend}} \\ &= (60.12^2 - 1.45^2)^{1/2} - 1.42 \text{ rad} \\ &= 58.72 \pm 0.03 \text{ rad.} \end{aligned}$$

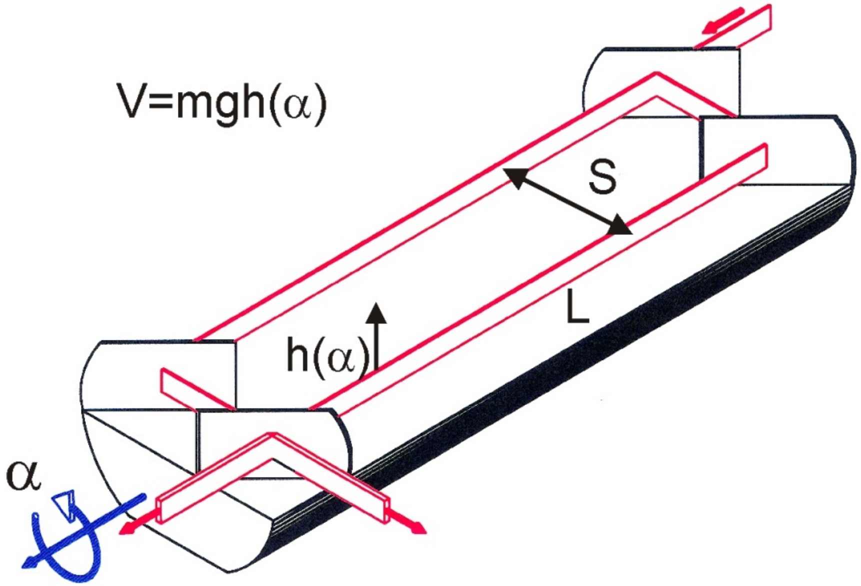
$$\text{theoretical prediction } q_{\text{grav}} = 59.2 \pm 0.1 \text{ rad}$$

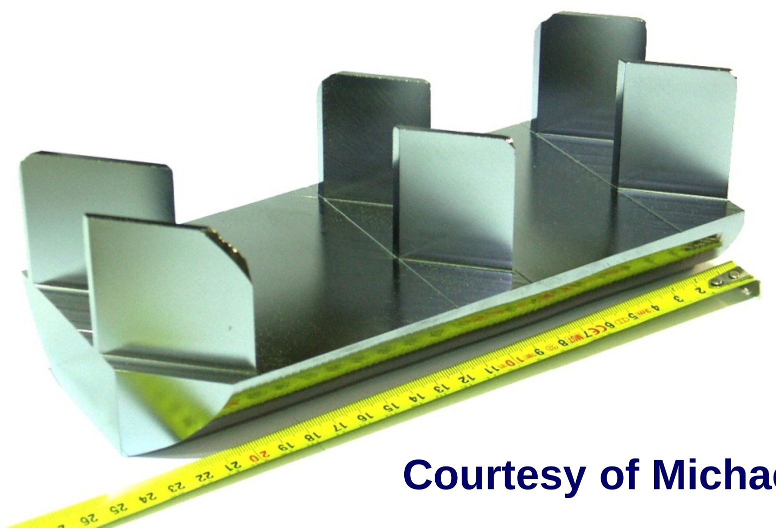
Table 12
History of gravity-induced interference experiments with symmetric (sym.) and skew-symmetric silicon interferometers

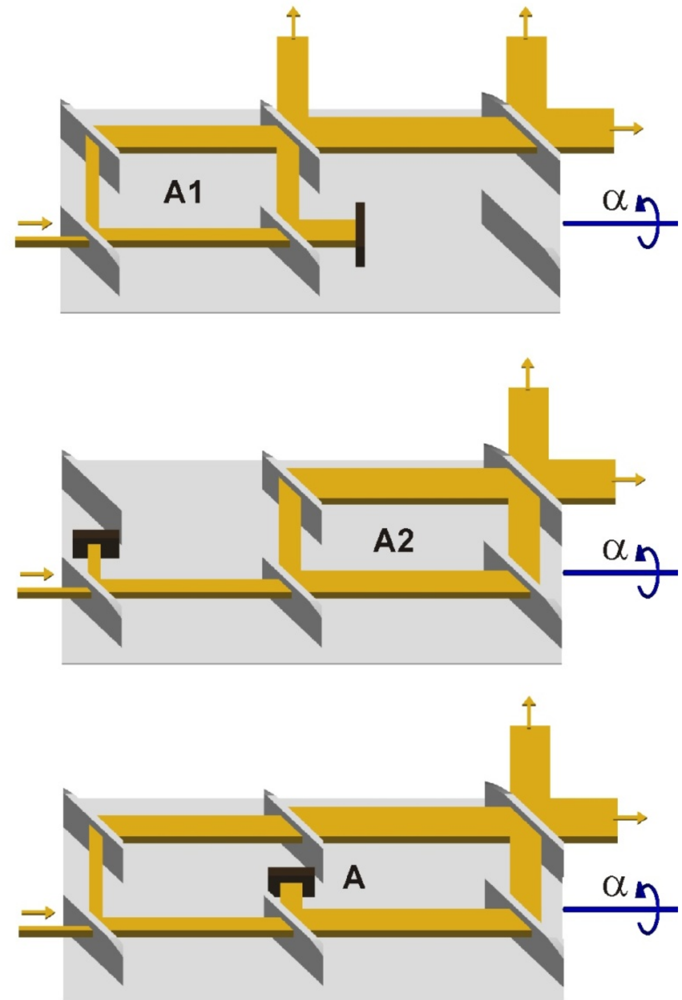
Ref.	Interferometer	λ (nm)	A_0 (cm^2)	Θ_B (deg)	q_{COW} (theory) (rad)	q_{COW} (exp) (rad)	q_{bend} (rad)	Agreement with theory (%)
[380]	Sym.#1	1.445(2)	10.52(2)	22.10(5)	59.8(1)	54.3(2.0)		12
[386]	Sym.#2	1.419(2)	10.152(4)	21.68(1)	56.7(1)	54.2(1)	3.30(5)	4.4
		1.060(2)	7.332(4)	16.02(1)	30.6(1)	28.4(1)	2.48(5)	7.3
[382]	Sym. #2	1.417(1)	10.132(4)	21.65(1)	56.50(5)	56.03(3)	1.41(1)	0.8
[383]	Skew-sym.							
(440)	Full range	1.078(6)	12.016(3)	34.15(1)	50.97(5)	49.45(5)	2.15(4)	3.0
	Rest. range	1.078(6)	12.016(3)	34.15(1)	50.97(5)	50.18(5)	2.03(4)	1.5
(220)	Full range	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	97.58(10)	1.07(2)	3
	Rest. range	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	99.02(10)	1.01(2)	1.5
[383]	Large Sym.							
(440)	Full range	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	223.38(30)	4.02(3)	0.6
(220)	Rest. range	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	221.85(30)	4.15(3)	0.9

The restricted (rest.) range data means that the tilt angle $|\alpha| = 11°$. The two wavelengths of [383] are diffracted by the (220) or (440) lattice planes. The table is based on [21].

New Plans







Courtesy of Michael Zawisky, Vienna University of Technology

some key features of the new setup at ILL-S18 (France) :

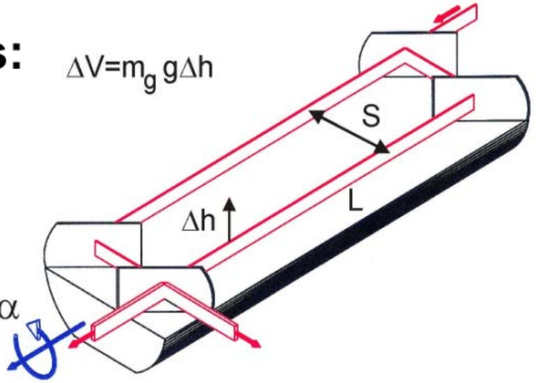
- Larger areas, higher sensitivity (gain factor ≥ 5 at 2.72Å to previous experiments)
- Small rotations reduce bending effects
- Thick base + rotation along an axis of elastic symmetry reduce crystal bending
- Three different areas selectable without changing the setup
- By comparison of the phase shift gained by A1 and A2 diffraction corrections within the crystal lamellas cancel out to first order
- Several harmonics (2.72, 1.36, 0.91Å) available with identical beam geometry
- Narrow wavelength distribution 5×10^{-3}
- Nearly perfect symmetric lattice orientation, no offset in α-rotation and simplification of the dynamical diffraction model

Courtesy Michael Zawisky, Vienna University of Technology

New features: 6 inch (15,2 cm)

thicker base, smaller contact area
Length 30 cm, beam sep aration 6 cm, beam area 150 cm²(COW), step plates for simultaneous gravitation + high angular resolution experiments

Improved sensitivitiy for COW gravitation experiments:



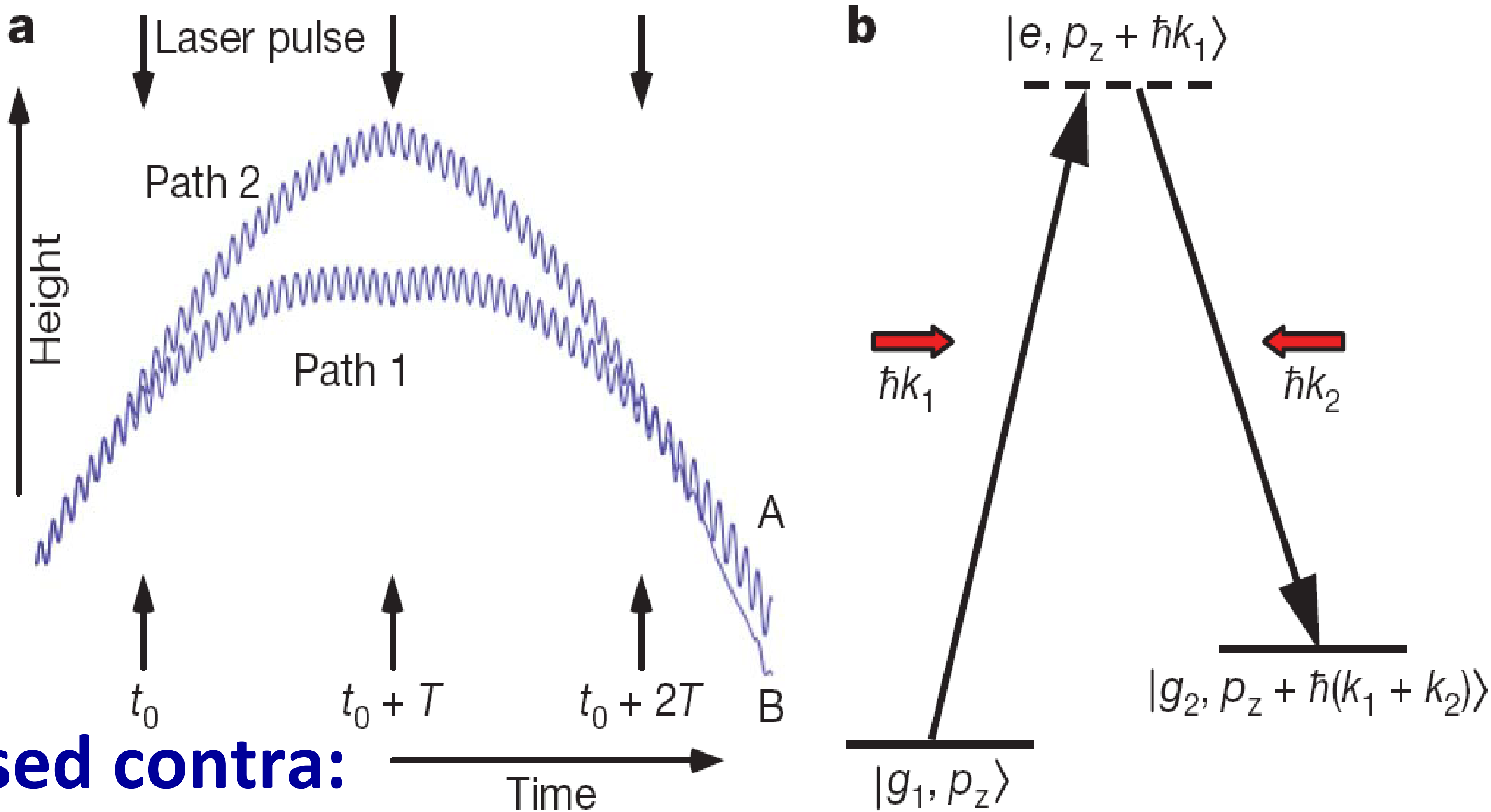
$$\frac{\Delta g}{g} = 6 \times 10^{-8}$$

Improved angular sensitivity:

$$\delta\theta = 10^{-6} \text{ sec of arc } \; (5 \times 10^{-12}\, rad)$$

$$\Delta q \geq 2 \times 10^{-10}\, nm^{-1}$$

Müller, Peters, Chu. Claim Red shift, Nature 2010

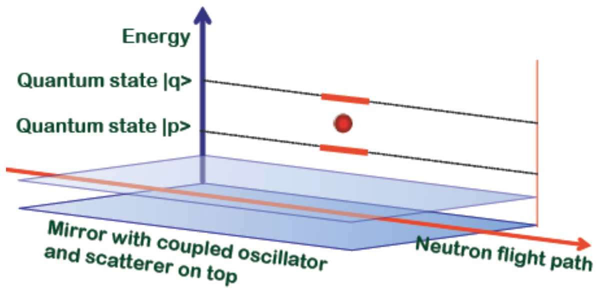


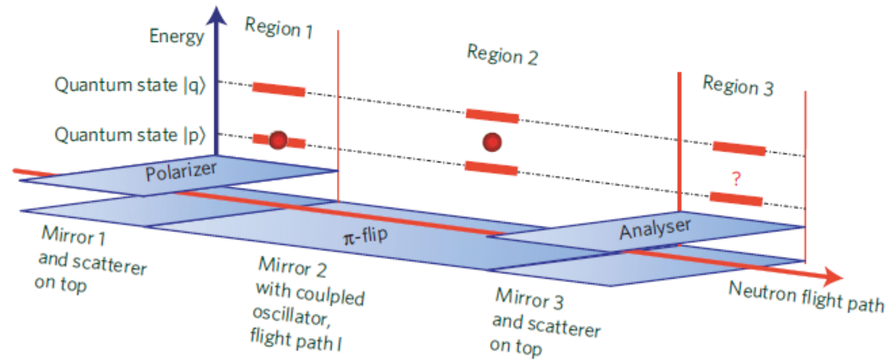
sed contra:

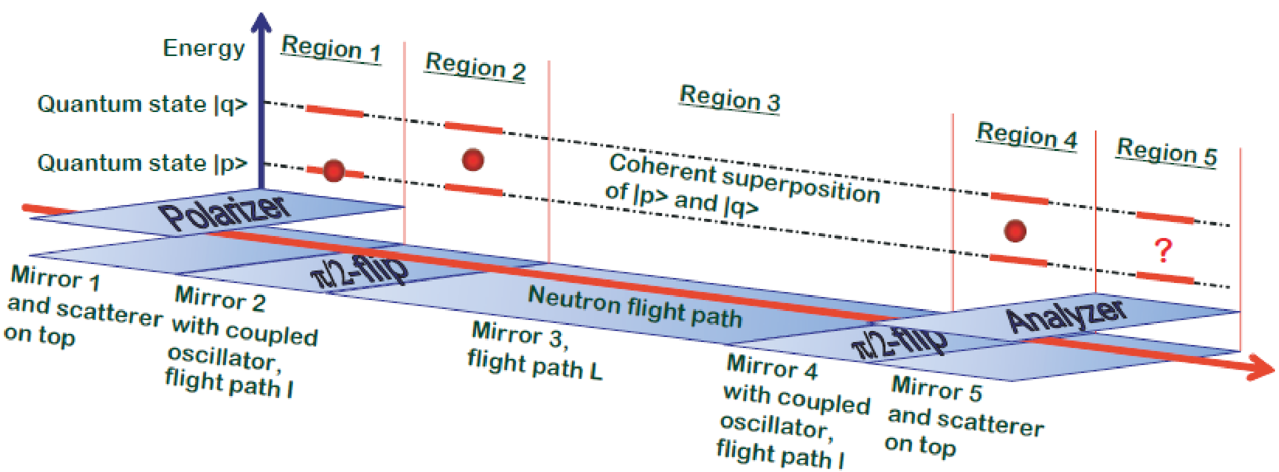
Wolf, Blanchet, Reynaud,Salomon, Cohen-Tannoudji:

a rock is not a clock, see also Greenberger, Schleich, Rasel et al.

Outlook





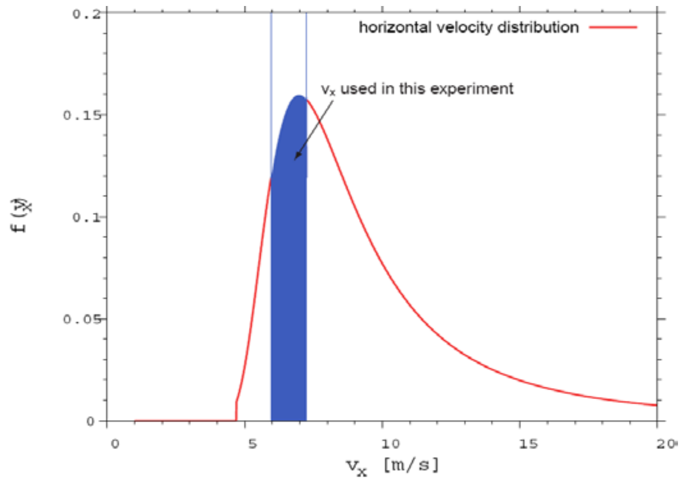


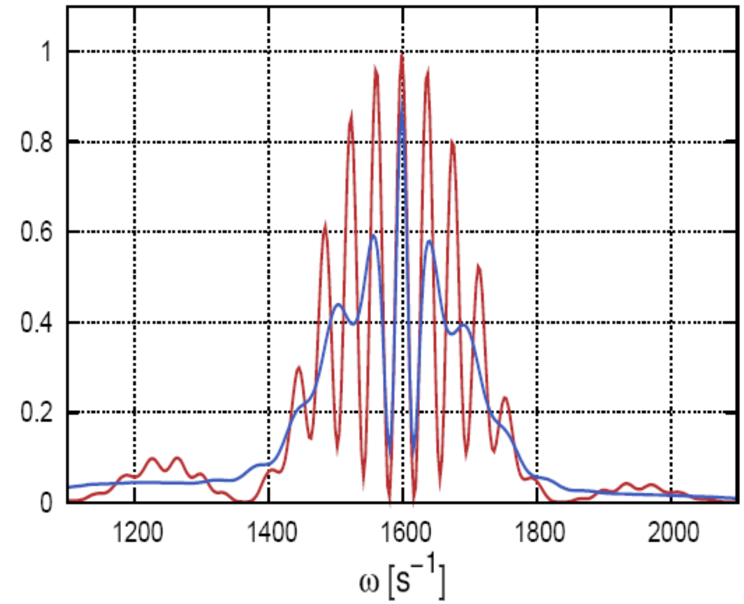
- **Tests of Newton's Inverse Square Law of Gravity at micron distances**

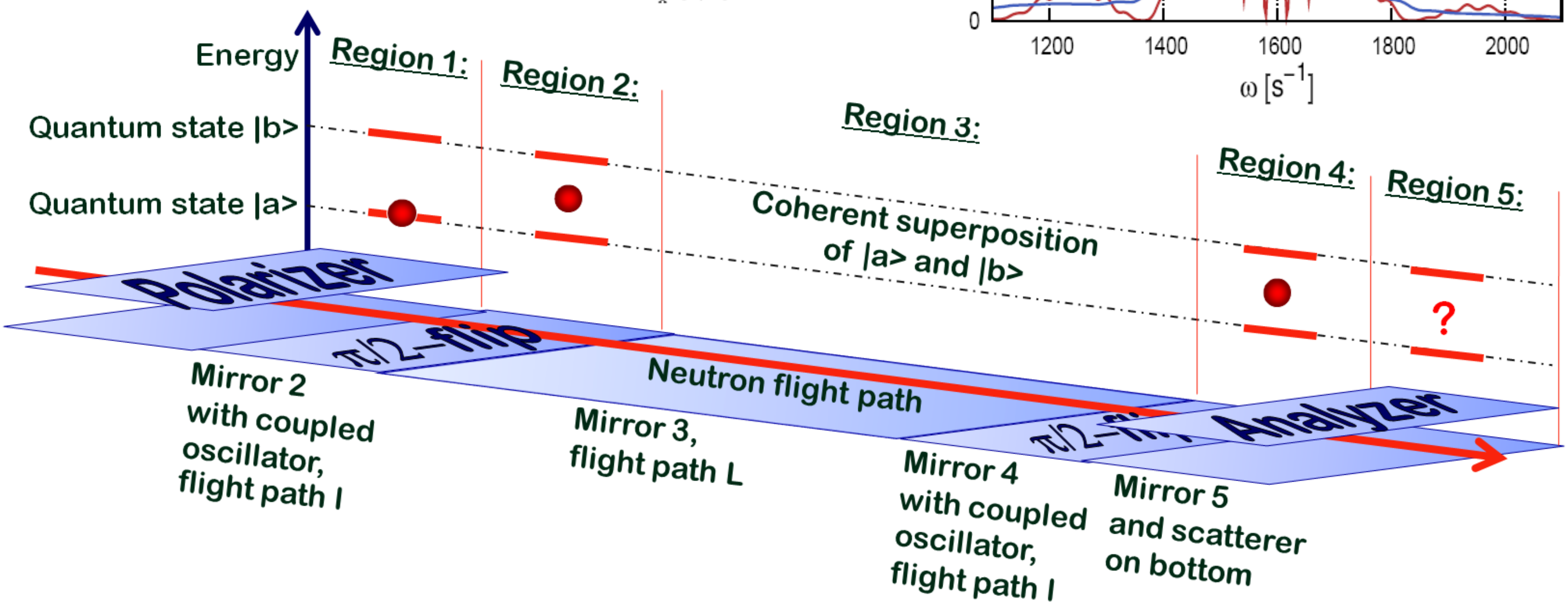
- **Search for an electric charge of the neutron**

Proposal: H. A. et al., Phys.Rev. D81,065019 (2010)

The Future: Ramsey-Method

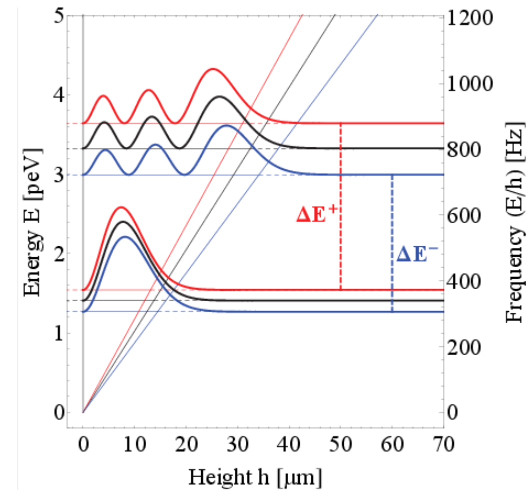


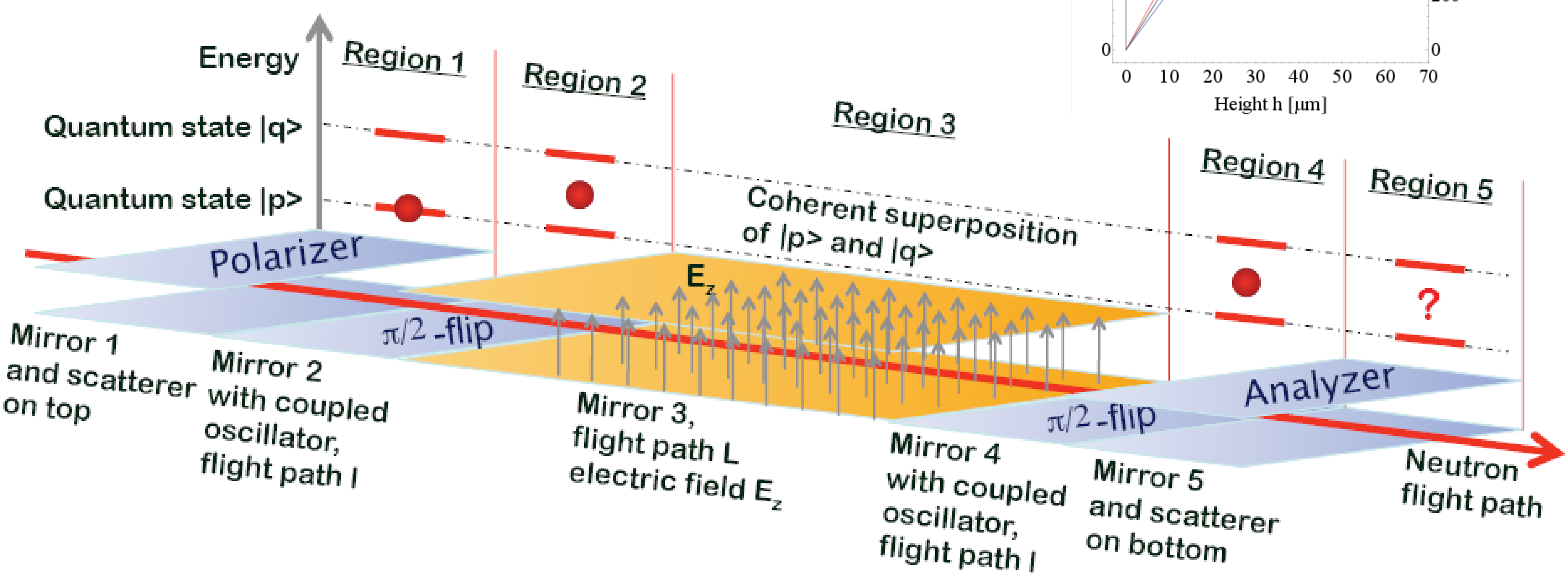




Charge quantization and the electric neutrality of the neutron.

- Since the Standard Model value for q_n *requires extreme fine tuning, the* smallness of this value may be considered as a hint for GUTs, where q_n *is equal to zero.*
- **Improve limit by two orders of magnitude**





… a need for best sources

Distance between electrodes on mirrors [μm]	Electric field [kV/mm]
24	52
51	39
76	33
100	27

discovery potential:

$$\delta q_n \left(t = 1\, day \right) = 3 \cdot 10^{-20} q_e$$

using less than 10.000 neutrons…

The Team at Atominstitut

- **Gravity tests with quantum objects**
  - G. Cronenberg, H. Filter, T. Jenke, H. Lemmel, M. Thalhammer, Collaboration HD, TUM, ILL: P. Geltenbort (ILL), U. Schmidt (HD), T. Lauer (TUM),
- **Neutron Beta Decay, PERC collaboration**
  - J Erhart, E.Jericha, C.Goesselsberger, C.Klauser, G.Konrad, H. Saul

    X.Wang, Collaboration with HD, MZ, TUM, ILL
- **Interferometry**
  - Y. Hasegawa, H. Geppert, M.Zawisky, T.Potocar, D.Erdösi, S.Sponar
- **Neutron Radiography**
  - M. Zawisky,
- **N_TOF/USANS**, E. Jericha, G. Badurek,

qBOUNCE Summary

- Progress Report with Galileo in Quantum Land
  - qBounce: first demonstration of the quantum bouncing ball
    - Dynamics: time evolution of coherent superposition of Airy-eigenfunctions
  - Realization of Gravity Resonance Spectroscopy:
    - Coherent Rabi-Transitions,
    - $|1\rangle \rightarrow |2\rangle$
    - $|1\rangle \rightarrow |3\rangle$, see Nature Physics, 1 June 2011
    - $|2\rangle \rightarrow |3\rangle$, $|2\rangle \rightarrow |4\rangle$
  - New Tool for
    - A Search for a deviation from Newton's Law at short distances, where polarizability effects are extremely small ,
      see H.A. et al., PRD 81, 065019 (2010) [arXiv:0907.5447]
    - A quantum test of the equivalence principle
  - Direct limits on axion coupling / chameleons at short distances,