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Gravity Resonance Spectroscopy within the qBounce experiment

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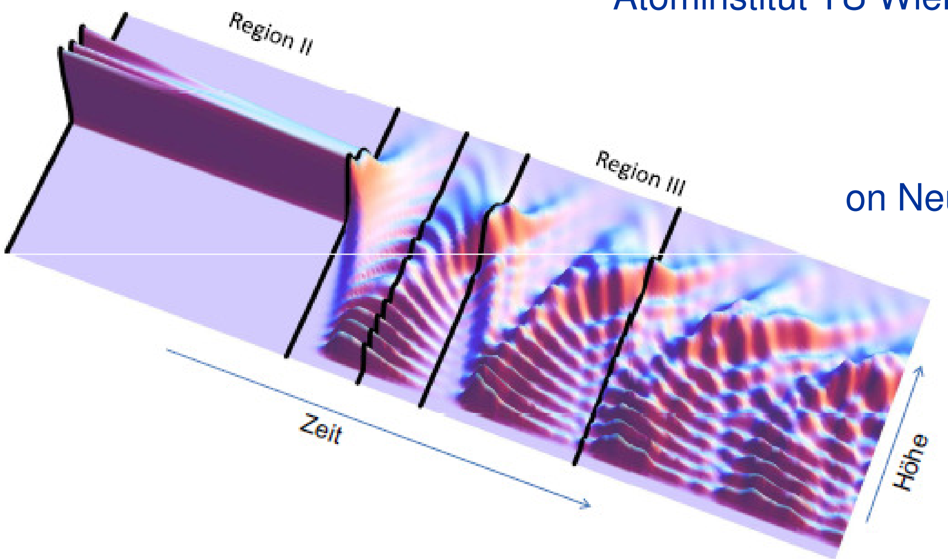


NPPatLPS 2013
ESS Science Symposium
on Neutron Particle Physics at Long Pulse Spallation Sources
Grenoble
March 27th , 2013

Gravity $\xleftrightarrow{UCN}$ 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: $\varphi_n(0)=0 \qquad (\varphi_n(l)=0)$

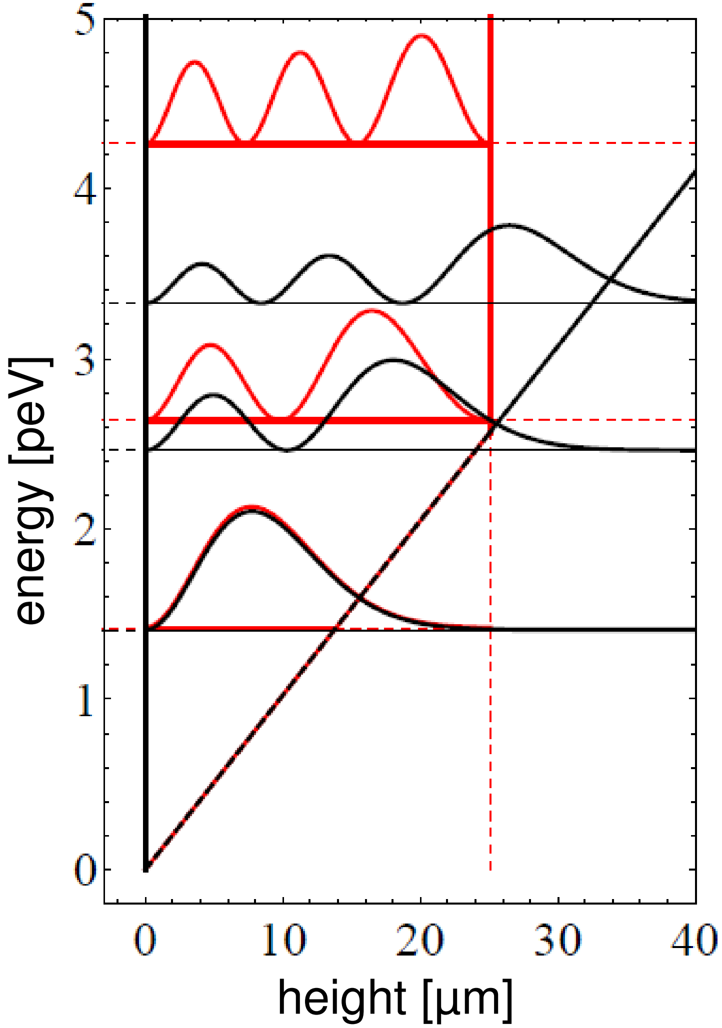
scale factors: $z_0=\sqrt[3]{\frac{\hbar^2}{2m_n^2 g}}\approx 5{,}88\mu m$

$$E_0=m_n g z_0\approx 0{,}6\,\text{peV}$$

$$t_0=\frac{\hbar}{E_0}\approx 1{,}1\,\text{ms}$$

Summary:

- **gravitationally** bound quantum states
- wave functions: Airy-functions
- discrete, **non-eqidistant** energy eigenvalues
- ground state energy: *1,4* peV



Experimental Status:

- 1978: Proposal: *Quantum Bouncer with UCN*
  V.I. Lushchikov, A. Frank, JETP Letters **28**, 559ff (1978)
- *2002: Demonstration of UCN gravity states*
  V.V. Nesvizhevsky et. al., Nature **415**, 297ff (2002)

Outline

Gravity Resonance Spectroscopy within the qBounce experiment

- Motivation: Scientific Case
- Gravity Resonance Spectroscopy
  - The key technologies
  - State of the Art (2010-2011)
- GRS at ESS?
  - Statistics
  - Systematics
- Outlook: Requirements for the ESS

UCNs and short-ranged gravity

Gravity at short distances (µm)

$$V(r) = -G\frac{mM}{r}\left(1-\alpha e^{-\frac{r}{\lambda}}\right)$$

- Large Extradimensions (ADD)

$$10^6 \leq \alpha \leq 10^9 \, (\lambda = 1\mu\mathrm{m})$$

- Cosmological Constant (Burgess et. al.)

$$\alpha \leq 10^6 \, (\lambda = 5\mu\mathrm{m})$$

- Hypothetical short-ranged spin-dependant interactions („axion window")

$$0{,}2\mu\mathrm{m} \leq \lambda \leq 2\mathrm{cm} \quad (10\mu\mathrm{eV}..1\mathrm{eV})$$

- Hypothetical scalar fields
(i.e. chameleon fields)

UCN

quantum mechanics

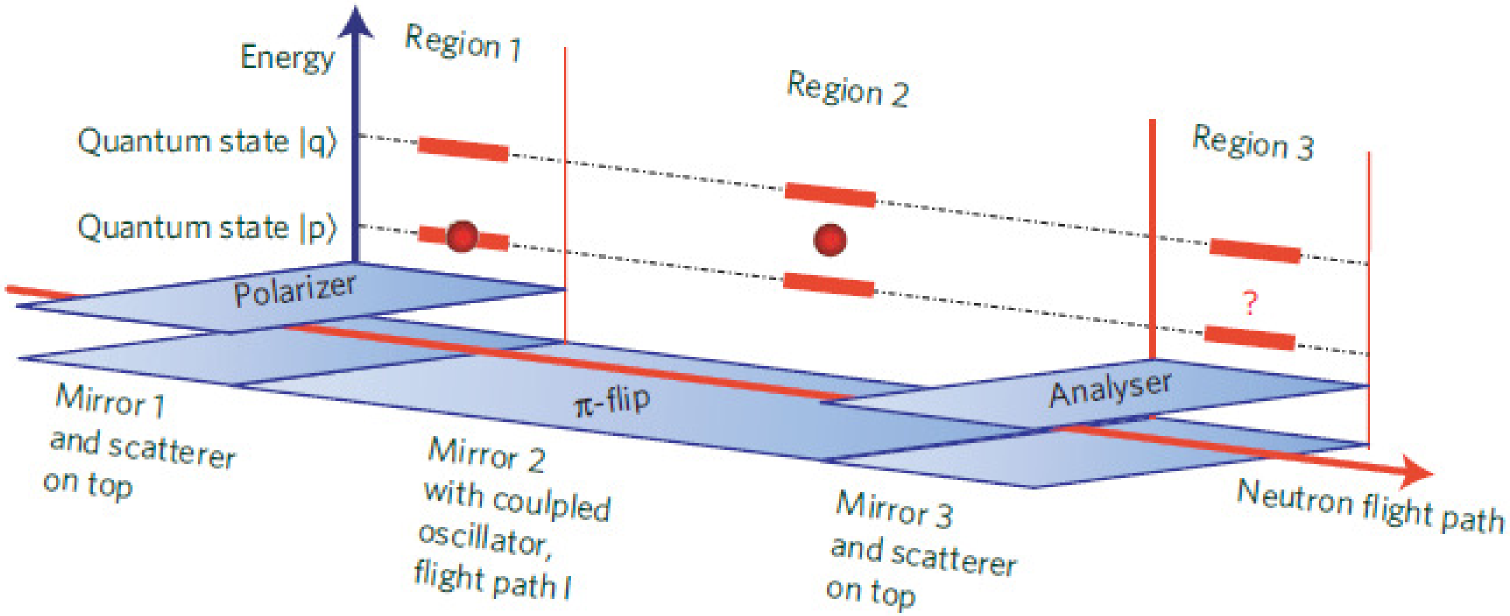
- quantum interference
- highly sensitive methods:
  resonance spectroscopy

$$E = h\nu$$

Other Applications:

- Test of neutrons neutrality
- …

Gravity Resonance Spectroscopy



Region I & III:

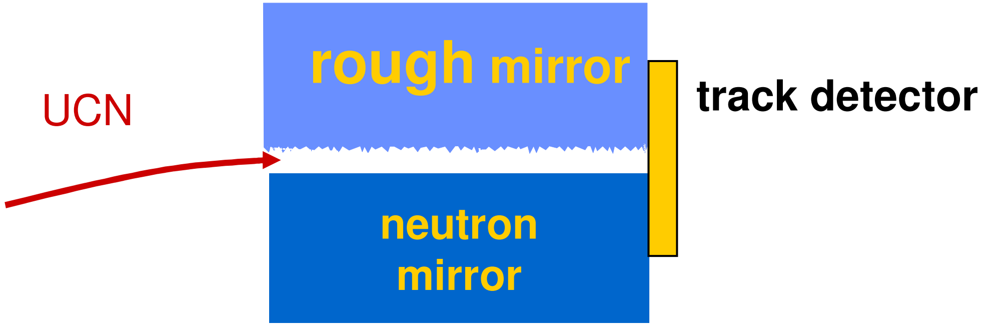
- State selection via rough upper mirror

Region II:

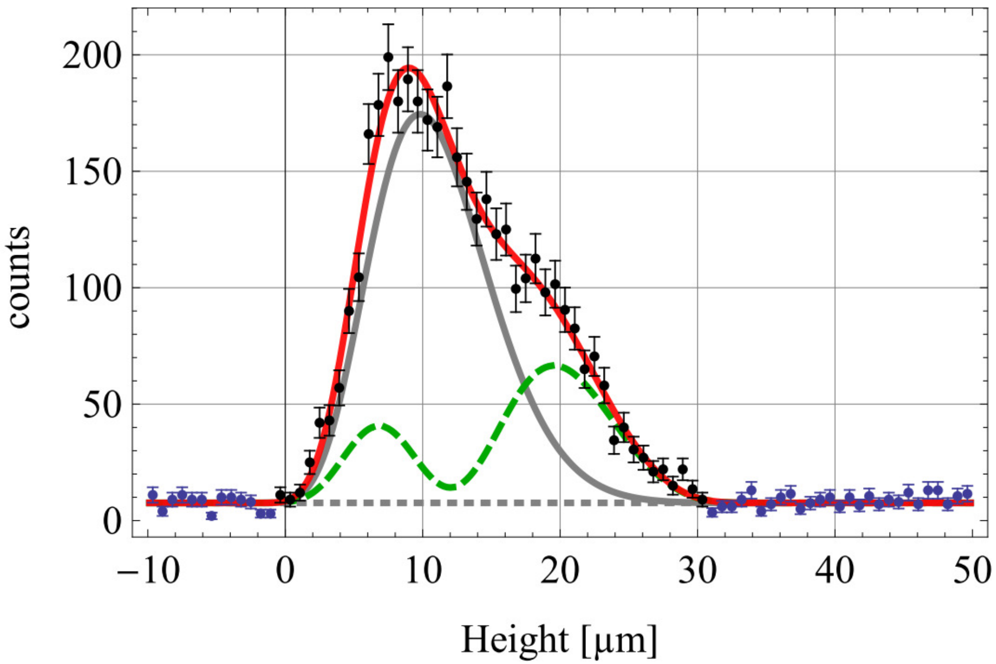
- Mechanical Vibrations (qBounce)
- Magnetic gradient fields (GRANIT)

Proposal: H. Abele, T. Jenke, H. Leeb & J. Schmiedmayer, Phys.Rev. **D81**,065019 (2010)

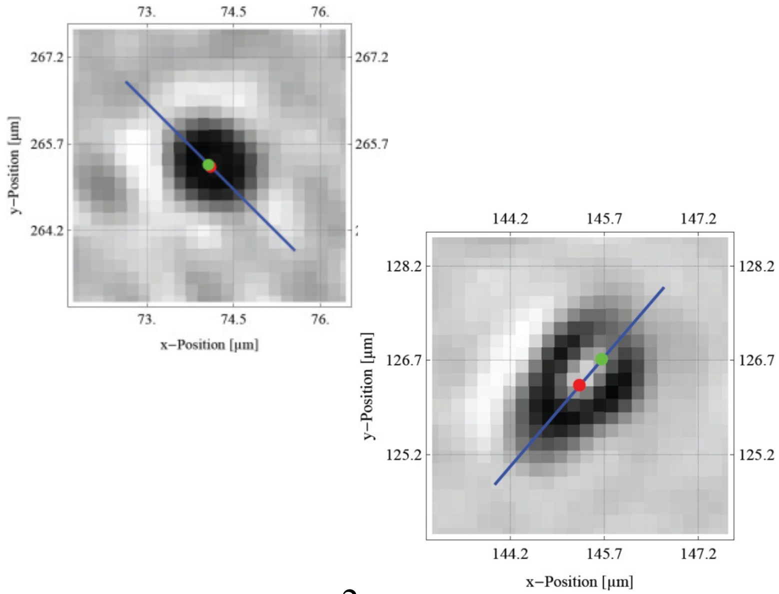
Region I & III: State Selection



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



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

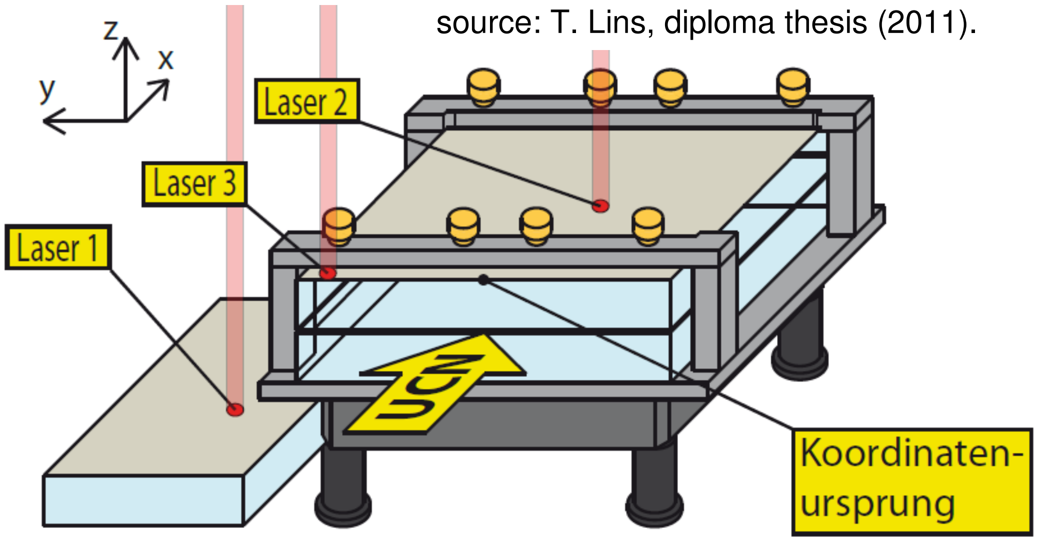


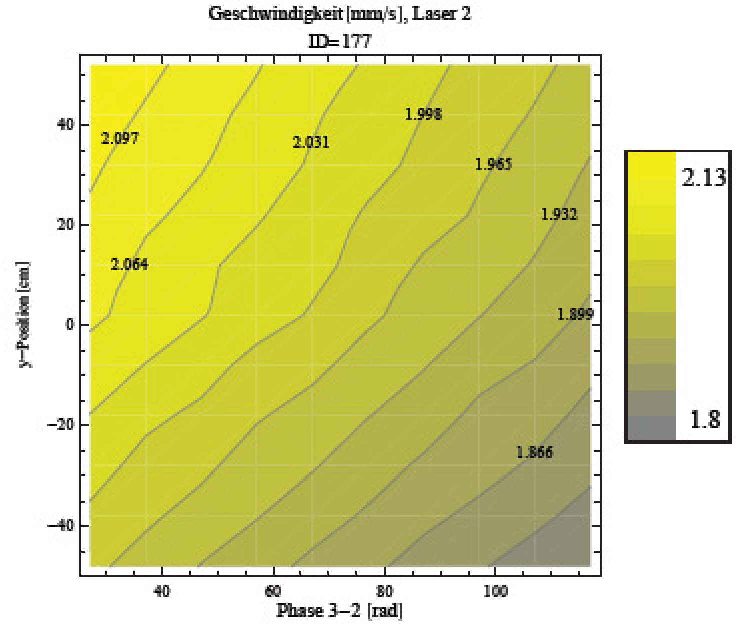
- fit: $N \cdot |\psi|^2 * PSF(\sigma) * f(t)$
- free parameters: $|c_n(t_1)|^2, l, N, z_0$
- result:

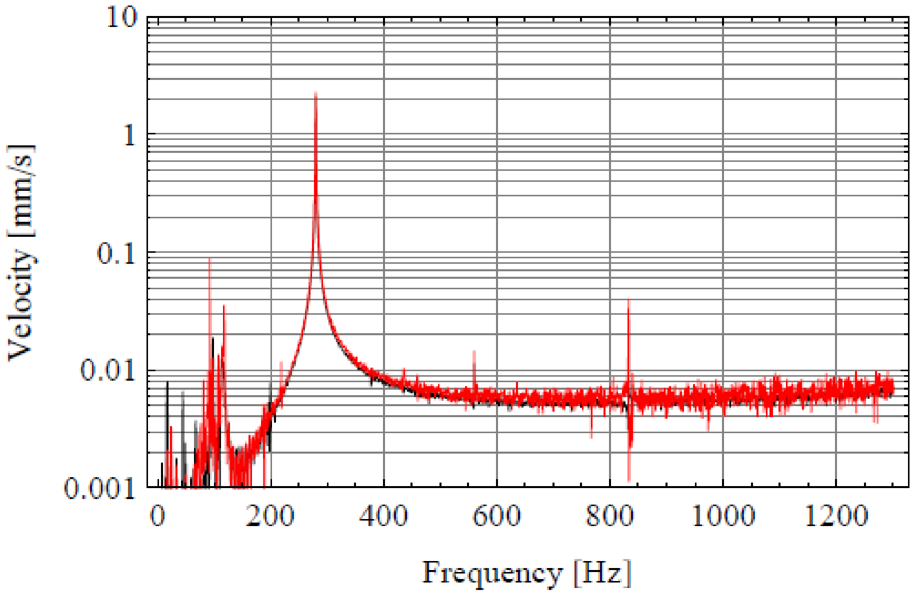
$$|c_1(t_1)|^2 = 0{,}70$$
$$|c_2(t_1)|^2 = 0{,}30$$
$$|c_3(t_1)|^2 = 0{,}00$$

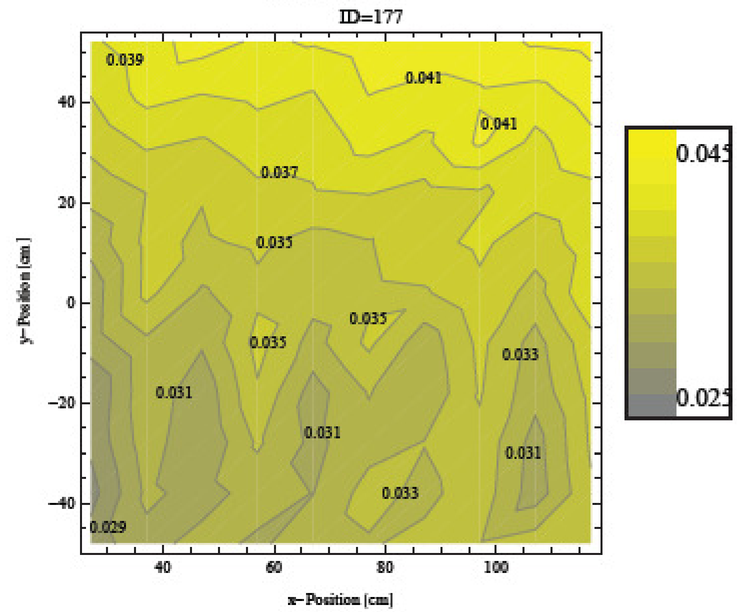
Region II: Vibration control

source: T. Lins, diploma thesis (2011).

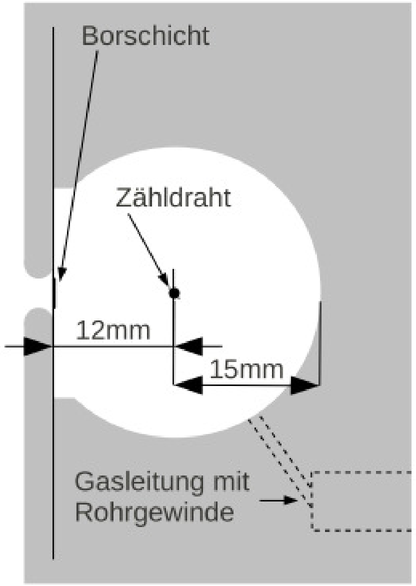


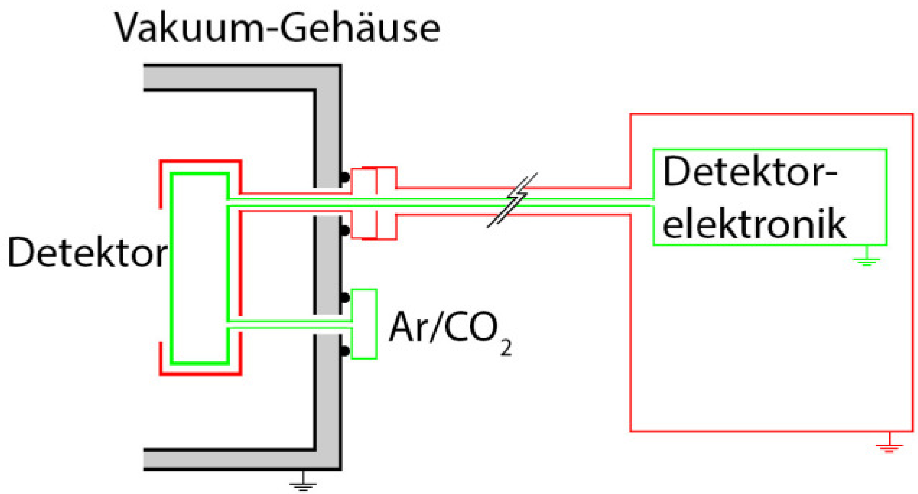






Detector

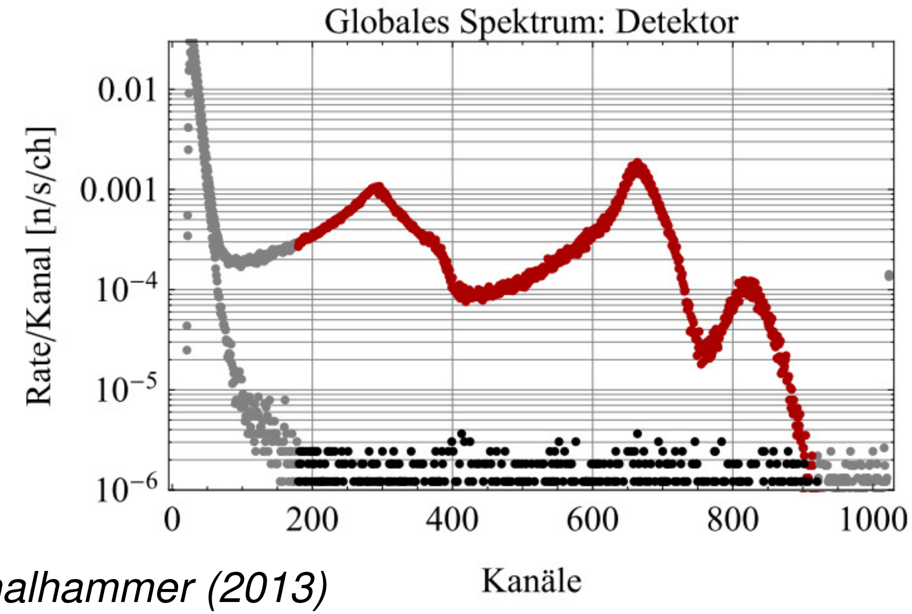




Total detector background
(@PF2 beam position):

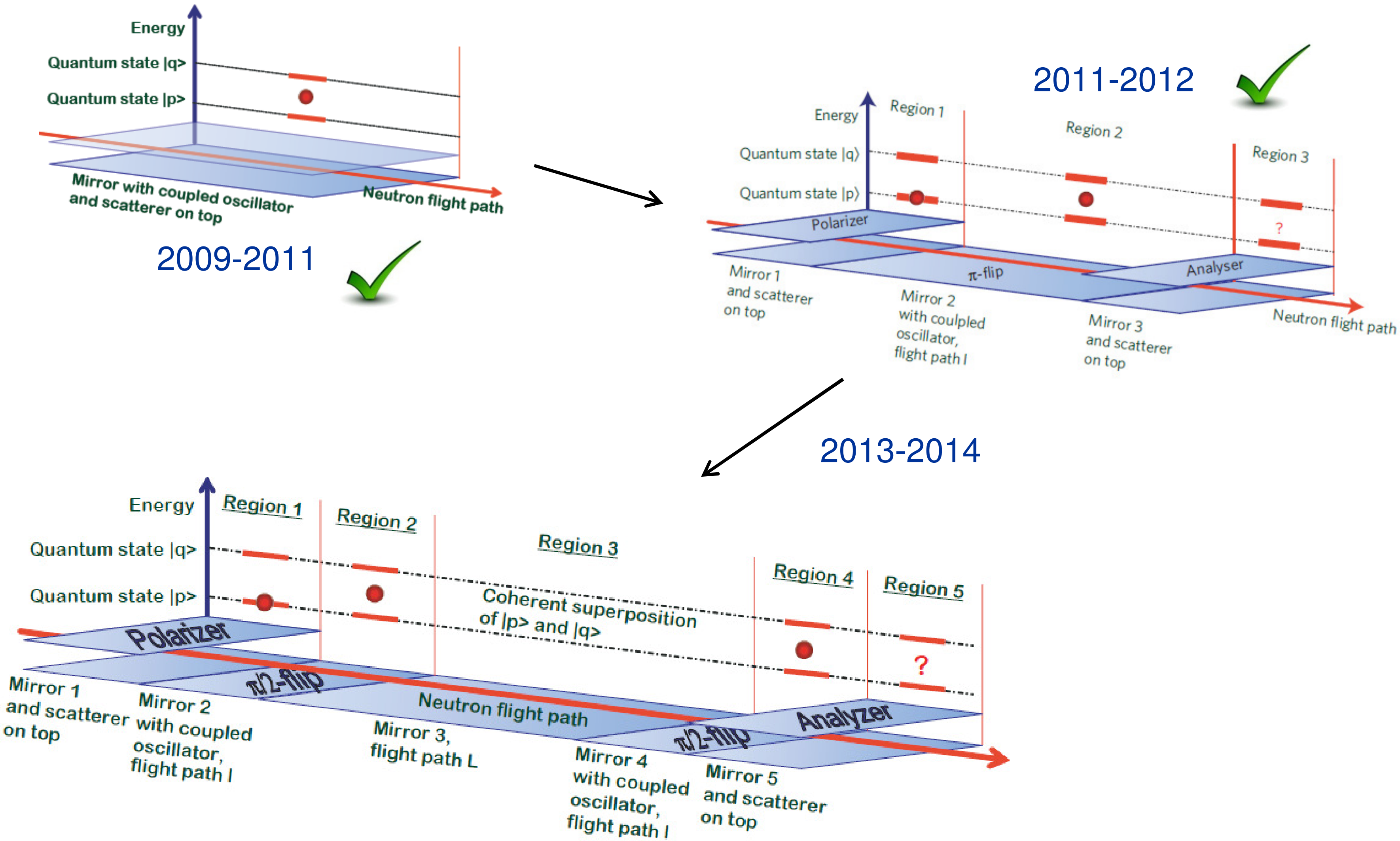
$$R = (0{,}65 \pm 0{,}02) \cdot 10^{-3}\, cts/s$$

Efficiency: $\varepsilon = 86{,}4\%$



Diploma thesis: Heiko Saul (2012) and Martin Thalhammer (2013)

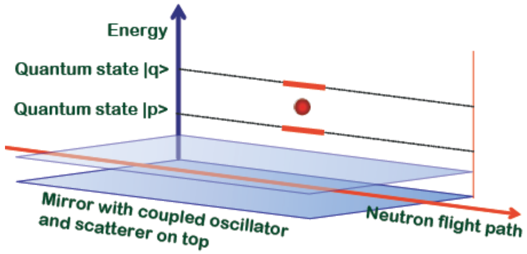
Our Method: Gravity Resonance Spectroscopy



Proposal: H. Abele, T. Jenke, H. Leeb & J. Schmiedmayer, Phys.Rev. **D81**,065019 (2010)

Gravity Resonance Spectroscopy

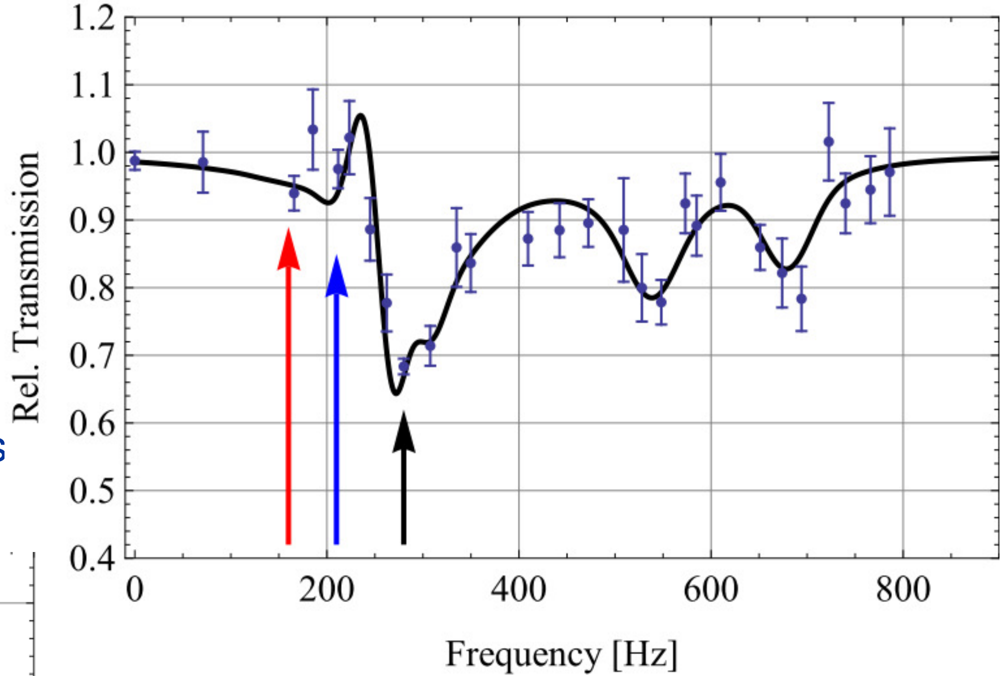
[data 2010]

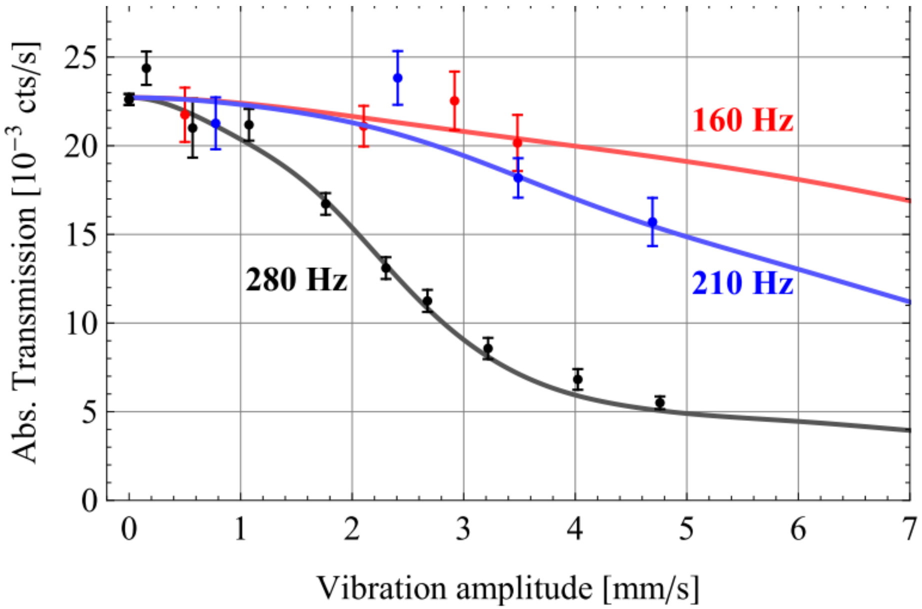


- transitions:

$$|1\rangle \leftrightarrow |2\rangle, |1\rangle \leftrightarrow |3\rangle, |2\rangle \leftrightarrow |3\rangle \text{ and } |2\rangle \leftrightarrow |4\rangle$$

- 50 days of beam time, 116 measurements





- stat. Significance: 48σ
- stat. accuracy: $\nu_{12} = 258.2\,\text{Hz} \pm 0.8\%$

$$\nu_{23} = 280.4\,\text{Hz} \pm 1.0\%$$

$$\nu_{13} = 539.1\,\text{Hz} \pm 0.5\%$$

$$\nu_{24} = 679.5\,\text{Hz} \pm 2.2\%$$

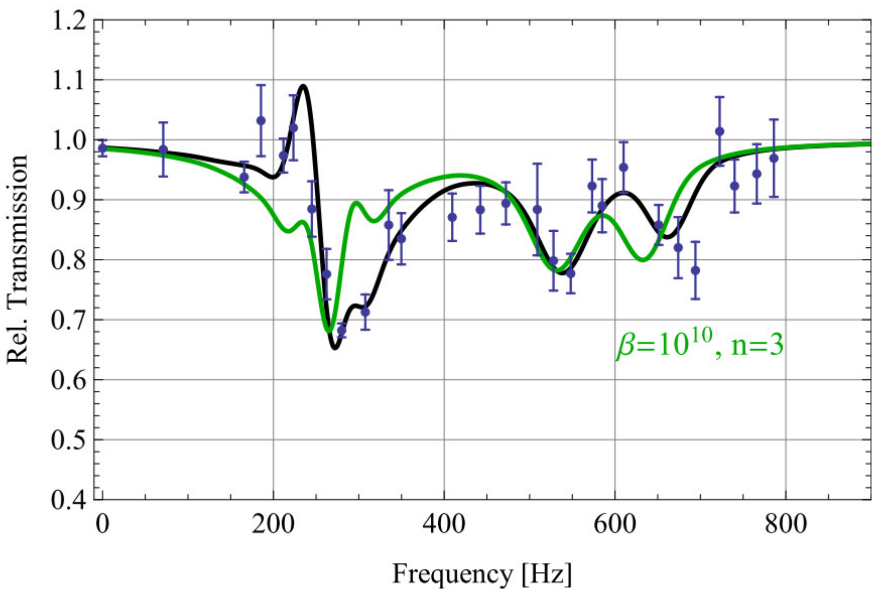
- contrast: 60%

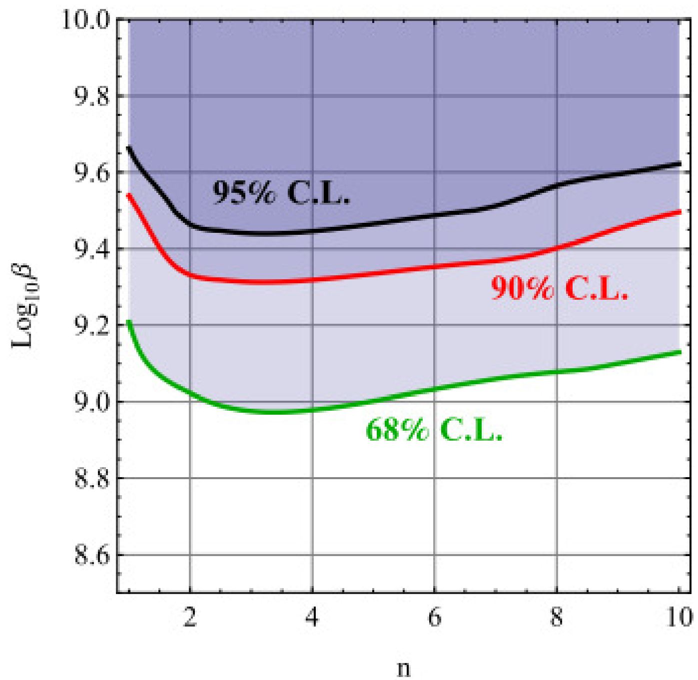
T. Jenke, Dissertation (TU Wien, 2011)
T. Jenke et.al., arXiv:1208.3875 (2012)

Applications I: Strongly coupled chameleons [data 2010]

in collaboration with A.N. Ivanov (TU Vienna)

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





A.N. Ivanov et.al., arXiv:1207.0419 (2012), accepted PRD (March 2013).
T. Jenke et.al., arXiv:1208.3875 (2012)

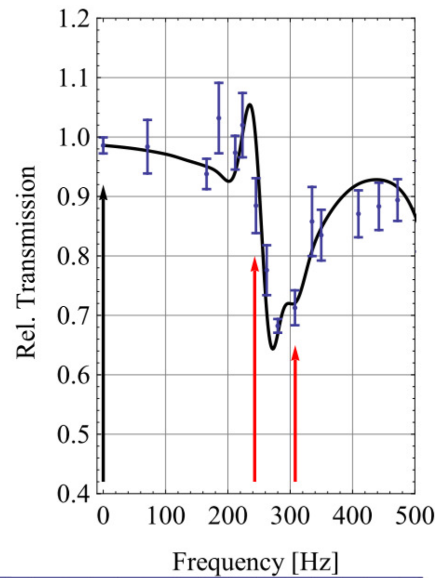
Applications II: Spin-dependant short-ranged interactions

[data 2010 + 2011]

in collaboration with U. Schmidt (PI, Uni Heidelberg) and T. Lauer (FRMII, Garching)

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

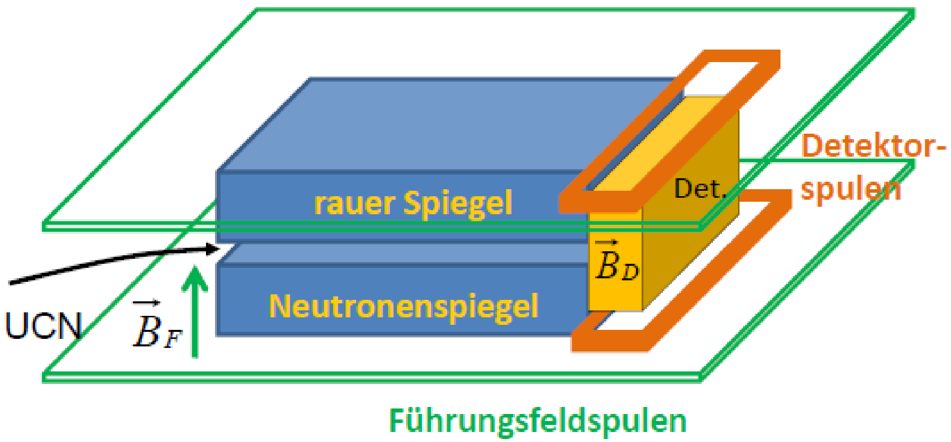
J.E. Moody, F. Wilczek, Phys. Rev. **D30**, 131-138 (1984)



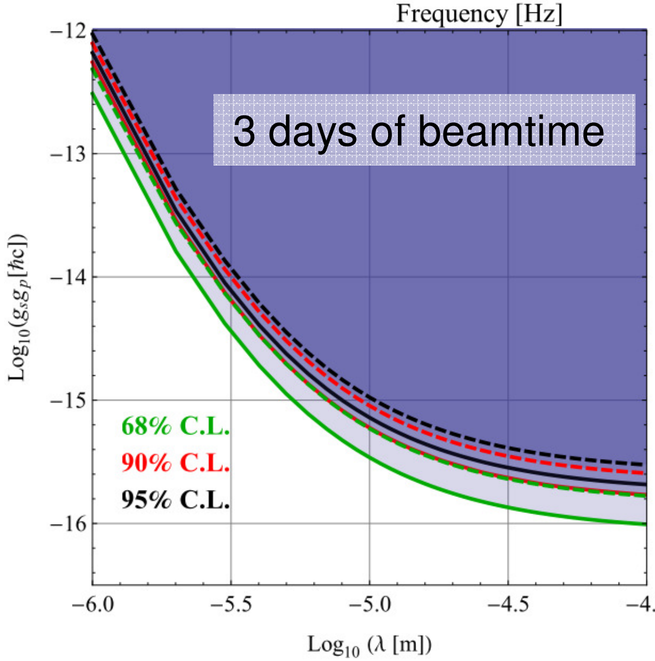
discovery potential [Setup 2010]:

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

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



T. Jenke et.al., arXiv:1208.3875 (2012)



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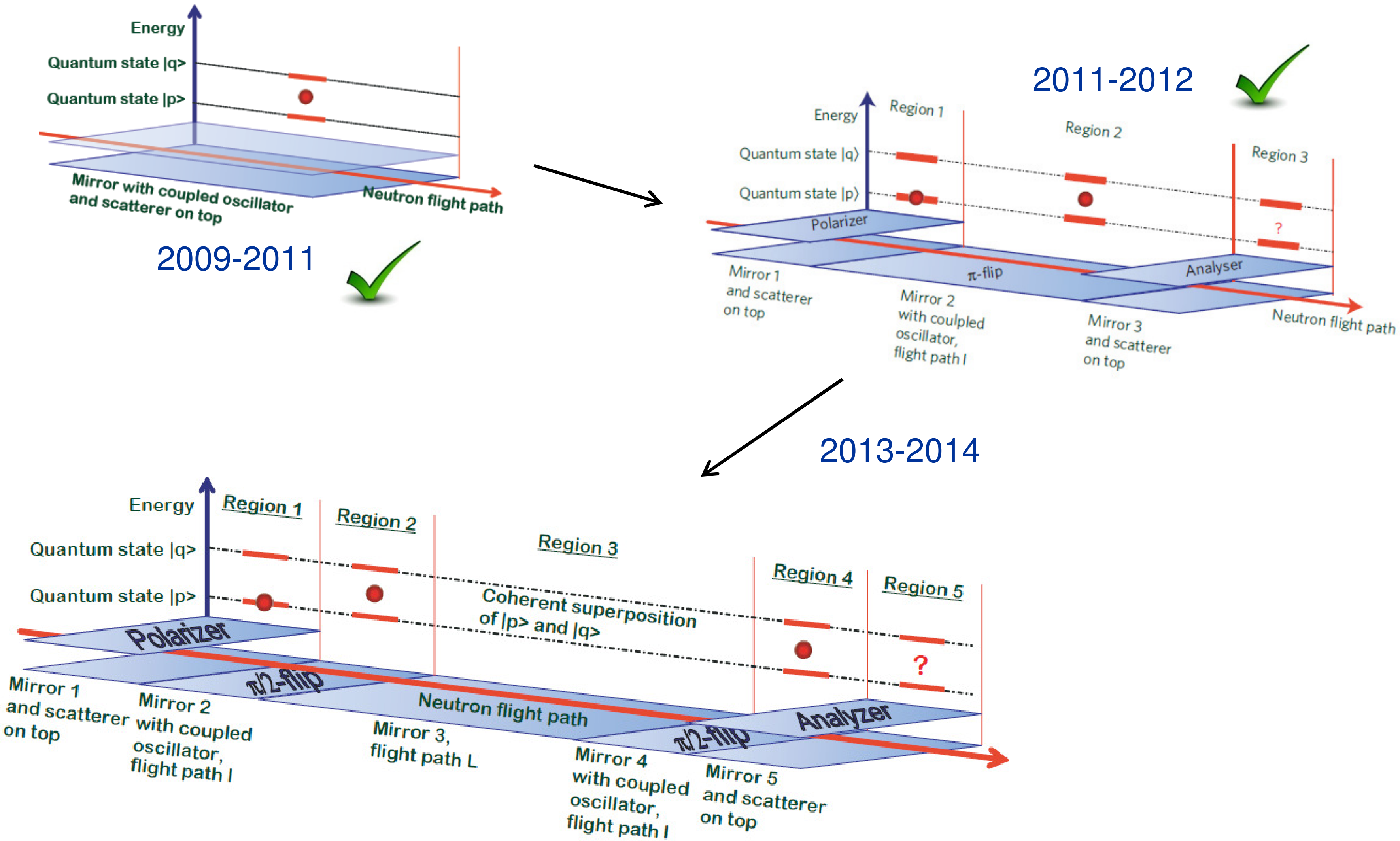
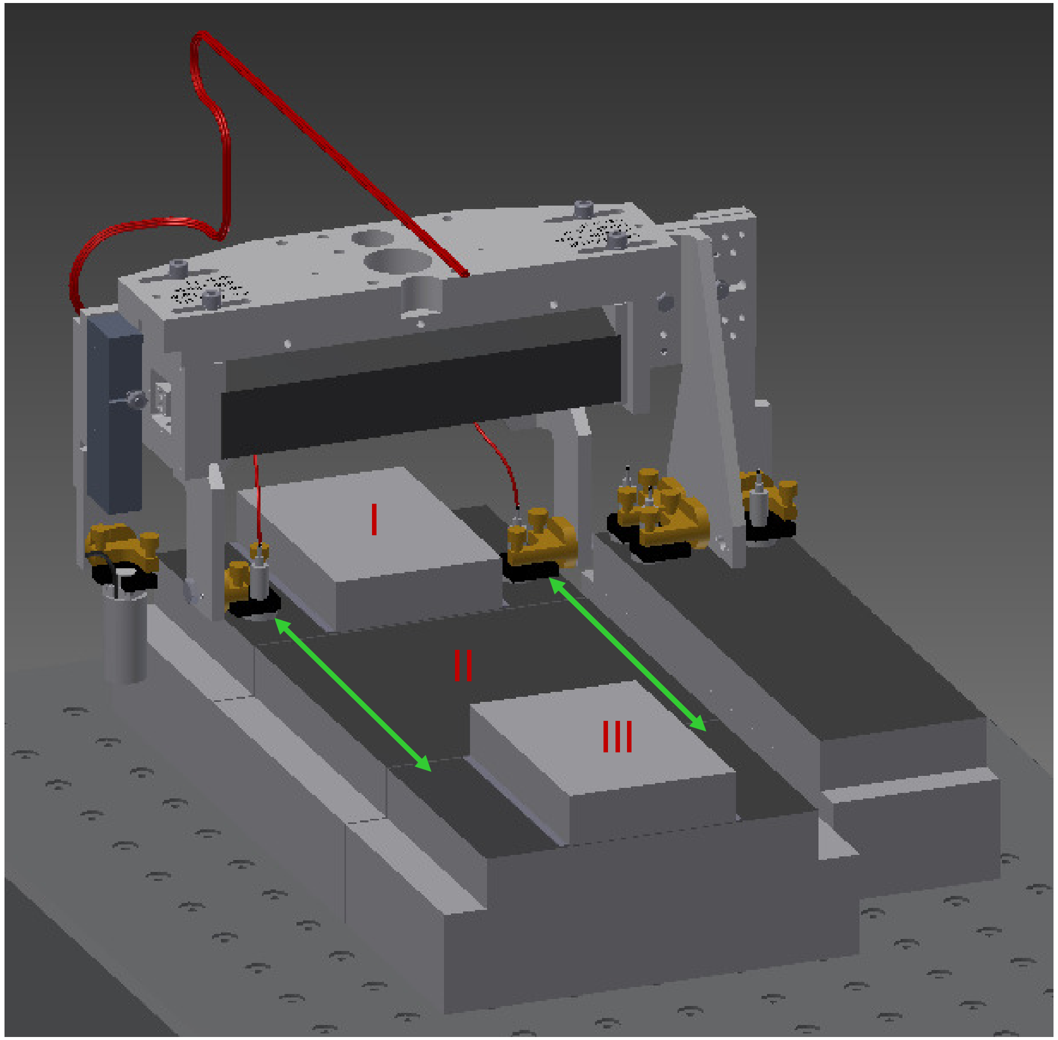


Proposal: H. Abele, T. Jenke, H. Leeb & J. Schmiedmayer, Phys.Rev. **D81**,065019 (2010)

Mind the gap… (since 2012)



Mirror Adjustment Control System

- **Highly stable mount**
- **Adjustment control system:**
  - 1 micro-positioning table (30cm traveling distance)
  - 2 capacitive sensors to measure the
- **Reference system:**
  - 1 reference mirror
  - 3 capacitive sensors

Total positioning error (measurements 2012):

$$\delta_{sys} \leq 140nm$$

(repeatibility)

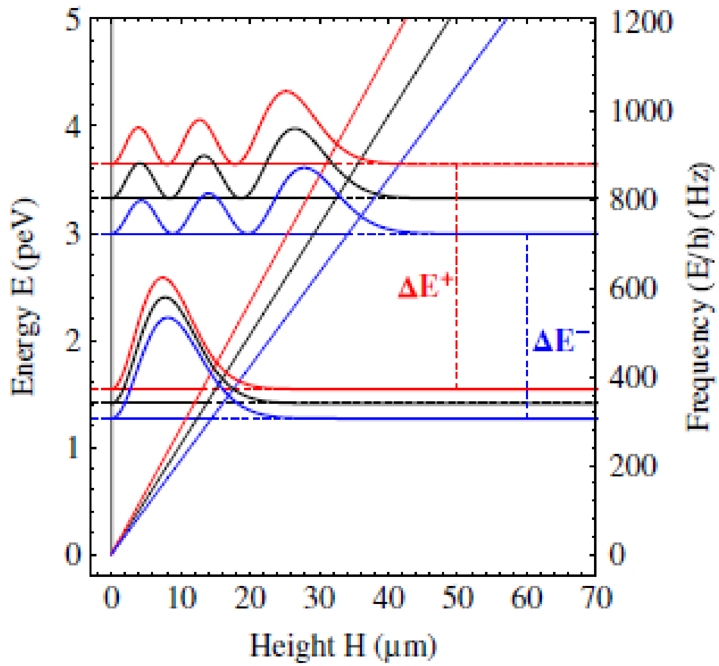
Long-term stability:

$$\delta_{stab} \leq \pm 20nm$$

Design: Hanno Filter & Miklós Horvath

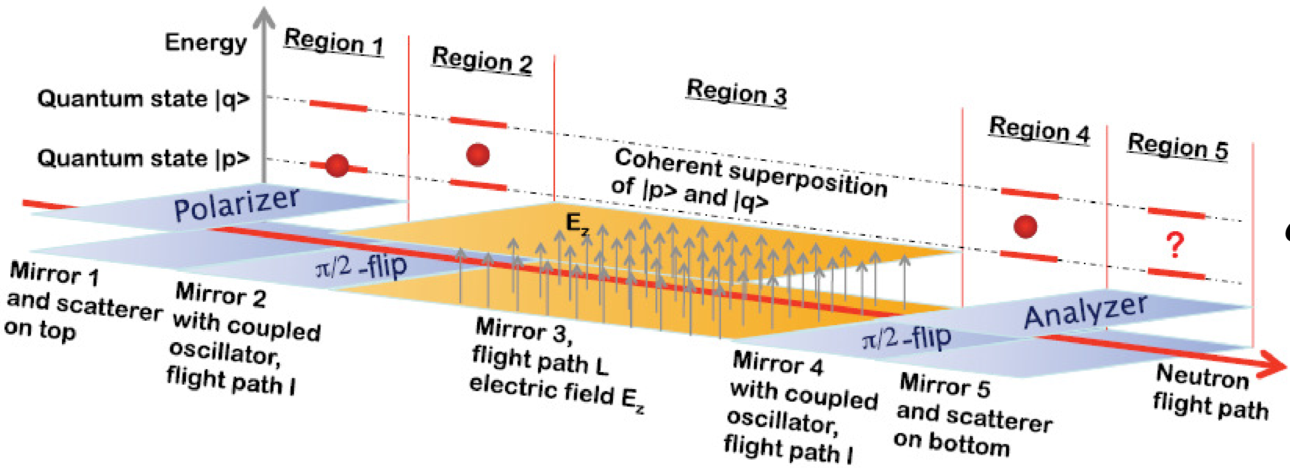
Outlook: Test of neutron's neutrality

- basic ideas:
  - first Ramsey-like experiment to test neutrons's neutrality
  - null experiment
  - higher electric fields by smaller distances feasible



- frequency shift:

$$\frac{\Delta\nu}{\nu_{pq}} = \sqrt[3]{\left(1-\frac{qE_z}{mg}\right)^2} - \sqrt[3]{\left(1+\frac{qE_z}{mg}\right)^2} \approx \frac{4}{3}\frac{qE_z}{mg}$$



discovery potential:

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

using less than 10.000 neutrons…

Proposal: K. Durstberger, T. Jenke, H. Abele, Phys.Rev. **D84**,036004 (2011)

Limitation I: UCN source

- flux at PF2/UCN (gold foil activation):

$$\Phi = 7{,}7 \cdot 10^3 \frac{n}{cm^2 s}$$

- experiment's count rate:
  - 2010:
    - 15cm long setup
- Vacuum chamber and beam pipe separated
    - Velocity: 5,7..9,5 m/s

$$T = 22 \cdot 10^{-3}\, {cts}/{s}$$

  - 2012:
    - 50cm long setup (conventional Rabi)
    - Beam pipe connected to chamber
    - Velocity: 5,7..9,5 m/s

$$T = 10 \cdot 10^{-3}\, {cts}/{s}$$

24.03.2013

MESURE FLUX DE NEUTRONS

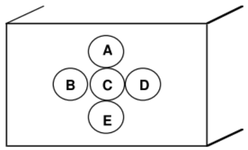
PLANCHE N° **1**

Guide : **PF2**

Dispositif : **UCN**

position des pastilles : Q-bouncer set-up (exp.3-14-253): ZS3, Al foil, shutter, 15 degree bend, 1m guide, 15 degree bend, Al foil of exp

longueur d'onde : 500 Å (7.9 m/s)



Flux de capture thermique
exprimé en n.cm-2.s-1

		mesuré	500 Å
A			
B			
C	1 D	2,11E+06	7,67E+03
D			
E			

moyenne

Observations :

Date d' irradiation : **10. Mrz 09**

Puissance réacteur : **53,4 MW**

Systematic Influences – State of the Art 2012...

- **remarks**:
  - **We measure differences.**
  - **Some experiments are Null Experiments. (q, Axions…)**
  - **The numbers given are State-of-the-Art 2012 and may be corrected for or improved…**
- general frontiers:
  - The moon rotates around the Earth….
  - …and causes tides (ebb and flow), that change g!
- stabilization of the experiment:
  - total, absolute inclination error (2012 @ PF2): $\delta_{inc} = \pm 30 \mu rad$
  - stabilization of inclination of the neutron mirrors (2012 @ PF2): $\delta_{rms} = 2 \mu rad$
- experimental environment:
  - constant magnetic fields cancel
  - external magnetic gradient fields: (2012, 1 layer µ-metal) $\Delta B / \Delta z < \pm 1 \, \mu T / cm$
  - external vibrations (resonant, 2010@PF2) $u_{res}(\nu_{pq}) / u_{env}(\nu_{pq}) < 5 \cdot 10^{-3}$

	$\Delta g / g$
The moon rotates around the Earth	$7 \cdot 10^{-6}$
tides	$4 \cdot 10^{-7}$
total, absolute inclination error	$2 \cdot 10^{-9}$
stabilization of inclination of the neutron mirrors	$2 \cdot 10^{-10}$
constant magnetic fields cancel	–
external magnetic gradient fields	$< 1 \cdot 10^{-4}$
external vibrations	

Systematic Frontiers II...

- quality of the neutron mirrors:
  - roughness*: $R_a < 1.7nm$ — $\overline{?}$
  - waviness (cm)*: $W_{z,\max} < 10nm$

  (* measured externally by SDH, Heidelberg and U. Schmidt, PI Heidelberg)
  - magnetic fields due to ferromagnetic enclosures inside the neutron mirrors* — ?

  (* in measurement at ATI by P. Kregsamer)

- quality of the external vibrations in region II:
  - frequency stability (externally measured via laser beams, 2012) $\Delta\nu/\nu < 1.1 \cdot 10^{-5}$ — $< 1.6 \cdot 10^{-5}$
  - homogeneity of the vibration amplitude -> linear inhomogeneities cancels — –

- correction for incoming flux (reactor power adjustments, control rods, temp. of cold source): correction linear at least to 1% (measured) — $< 1 \cdot 10^{-4}$

$$\Delta T/T \approx (0.5 - 3) \cdot 10^{-2}$$

- roughness of the absorber + inability to measure the slit size — –
  - influence of up to 10% in Damped-Rabi-Setup (1-region)
  - No influence with ordinary Rabi/Ramsey method

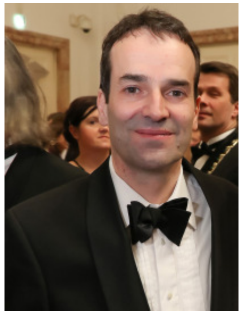
Conclusion: Requirements ESS

- **UCN source**
  - in-flight experiments:
    - high flux
    - high stability
    - simple and reliable…
  - storing experiments (future)
    - high densitiy

- **space & environment:**
  - length > 5m, width > 3m
  - separation of experimental area from experiment control advantageous
  - stable floor
  - decoupling of the experimental area from other experiments (electromagnetic, vibrations…)
  - cleanroom conditions (partly)

The Team

Atominstitut



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