# High Precision Experiments
## *With Cold and Ultra-cold Neutrons*

Hartmut Abele

PSI, 10 September 2013

# DFG/FWF Priority Programme 1491 (2010 – 2016)

- Participating Institutions 2010 - 2013:
  - IST Braunschweig
  - Univ. Heidelberg
  - ILL
  - Univ. Jena
  - Univ. Mainz
  - Exzellenzcluster ‚Universe' München
  - Techn. Univ. München*
  - PTB Berlin
  - Vienna University of Technology*
- Priority Areas
  - CP-symmetry violation and particle physics in the early universe.
  - The structure and nature of weak interaction and possible extensions of the Standard Model.
  - Tests of gravitation with quantum objects
  - Charge quantization and the electric neutrality of the neutron.
- New Infrastructure (UCN-Source, cold Neutrons)

- * Coordinators (S. Paul, H.A. )

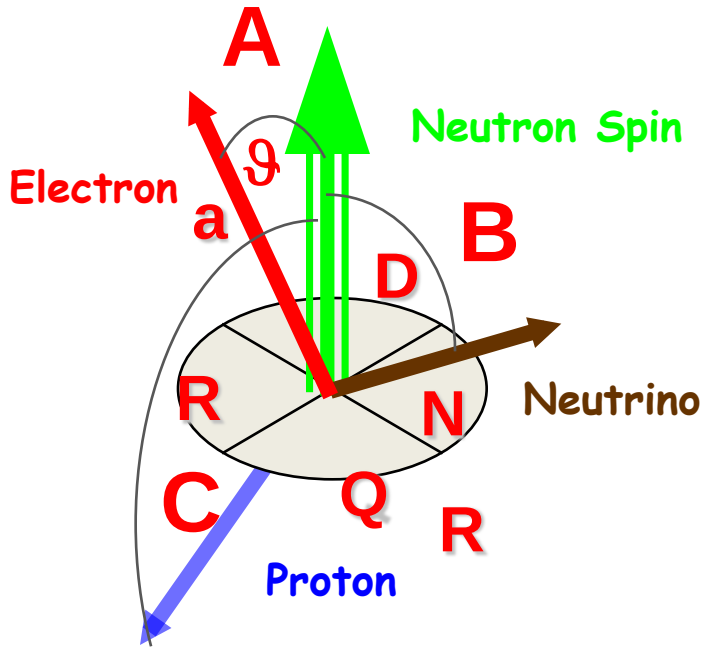
# Priority Programme 1491

- 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***

# Neutron Alphabet deciphers the SM

## SM Parameters

- Strength: $G_F$
- Quark mixing: $V_{ud}$
- Ratio: $\lambda = g_A/g_V$




$$\tau^{-1} = V_{ud}^{\ 2} G_F^{\ 2} (1 + 3\lambda^2) \frac{f^R m_e^{\ 5} c^4}{2\pi^3 \hbar^7}$$

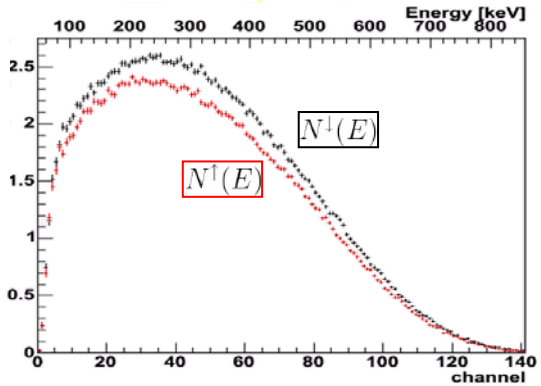
$$d\Gamma \propto \mathcal{N}(E_e)\left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e} + \langle \vec{J} \rangle \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] + \vec{\sigma} \cdot \left[N\langle \vec{J} \rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e \cdot \langle \vec{J} \rangle + R\langle \vec{J} \rangle \times \frac{\vec{p}_e}{E_e}\right]\right\} d\Omega_e d\Omega_\nu dE_e,$$

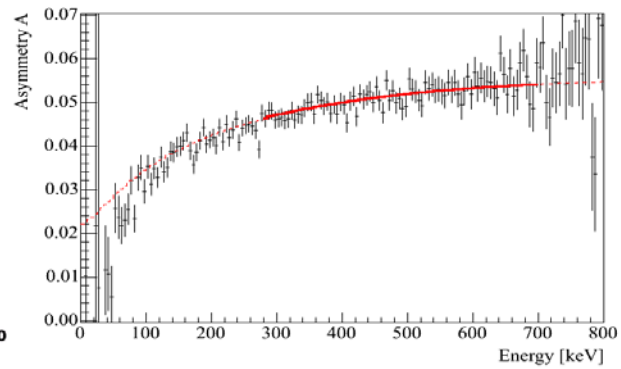
## Observables

- Lifetime $\tau$
- Correlation A
- Correlation B
- Correlation C
- Correlation a
- Correlation D
- Correlation N
- Correlation Q
- Correlation R
- Beta Spectrum
- Proton Spectrum
- Polarized Spectra
- Beta Helicity

# Recent Results: PERKEO Collaboration

**Electron Asymmetry A:**




$A = -0.11972(^{+52}_{-65})$

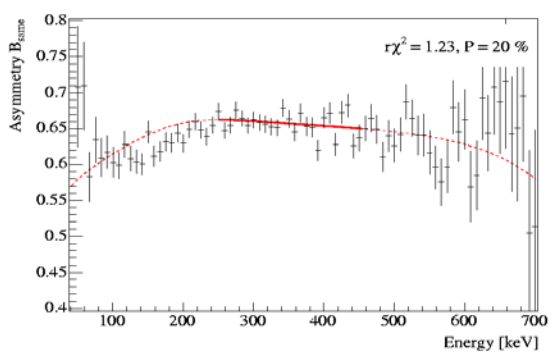
PERKEO II combined:

$\lambda_{PII} = -1.2748(^{+13}_{-14})$

$A_{PII} = -0.11926(^{+47}_{-53})$

Mund et al.,
PRL 110, 172502 (2013)

**Neutrino Asymmetry B:**




$B = 0.9802(50)$

Schumann et a.
PRL 99, 191803 (2007)

**Proton Asymmetry C:**

first precision measurement $C = x_C(A + B)$

$C = -0.2377(36)$

Schumann et al.,
PRL 100, 151801 (2008)

# a bit history:

## $\lambda$ from neutron $\beta$-decay

- -1.1900(200), PDG (1960)
- -1.2500(200), PDG (1975)
- -1.2610(40), PDG (1990)
- -1.2594(38), Gatchina (1997)
- -1.2660(40), M, ILL (1997)
- -1.2740(30), PERKEO II (1997)
- -1.2686(47), Gatchina, ILL (2001)
- -1.2739(19), PERKEO II (2002)
- –1.27590(+409)(–445), UCNA (2011)
- -1.2756(30), UCNA (2013)
- -1.2748($^{+13}_{-14}$) PERKEO II (2013)

## Close to publication:

- aCORN @ NIST
- aSPECT @ Mz, ILL
- PERKEO III @ UHD, ILL, TUW

## New Instruments

- Nab, PERC

# Grand Challenges

- *Sensitive theories beyond the Standard Model*
- Left Right Symmetry
- Supersymmetry
- Tensor or scalar interactions
- GUT

# Key Instrument: PERC

A clean, bright and versatile source of neutron decay products

Univ.Heidelberg & TU Wien, Mainz, ILL,FRM2,TU Munich

- High Flux : $\Phi = 2 \times 10^{10}\ cm^{-2}s^{-1}$

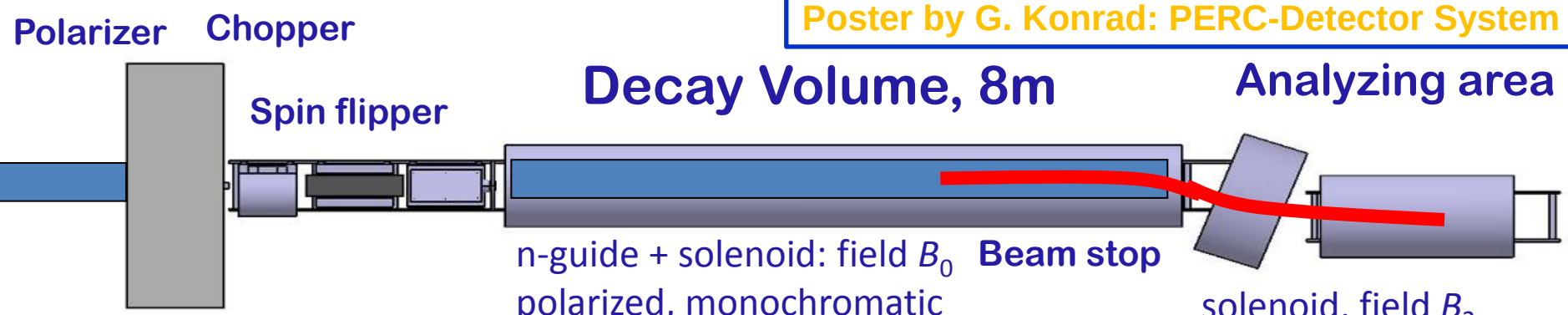
  $\rightarrow$ Decay rate of 1 MHz / metre

- Polarizer: 99.7 ± 0.1 %
- Spin Flipper: 100.05 ± 0.1 %
- Analyzer: 100 % $^3$He-cells

Talk by B. Maerkisch: PERKEO & PERC

Ideal experiment for ESS, Poster, Camille Theroine

Poster by G. Konrad: PERC-Detector System




n-guide + solenoid: field $B_0$
polarized, monochromatic
n-pulse

v- selector

n + γ-beam stop
solenoid, field $B1$

solenoid, field $B_2$
p+ + e− window-frame
p+ + e− beam

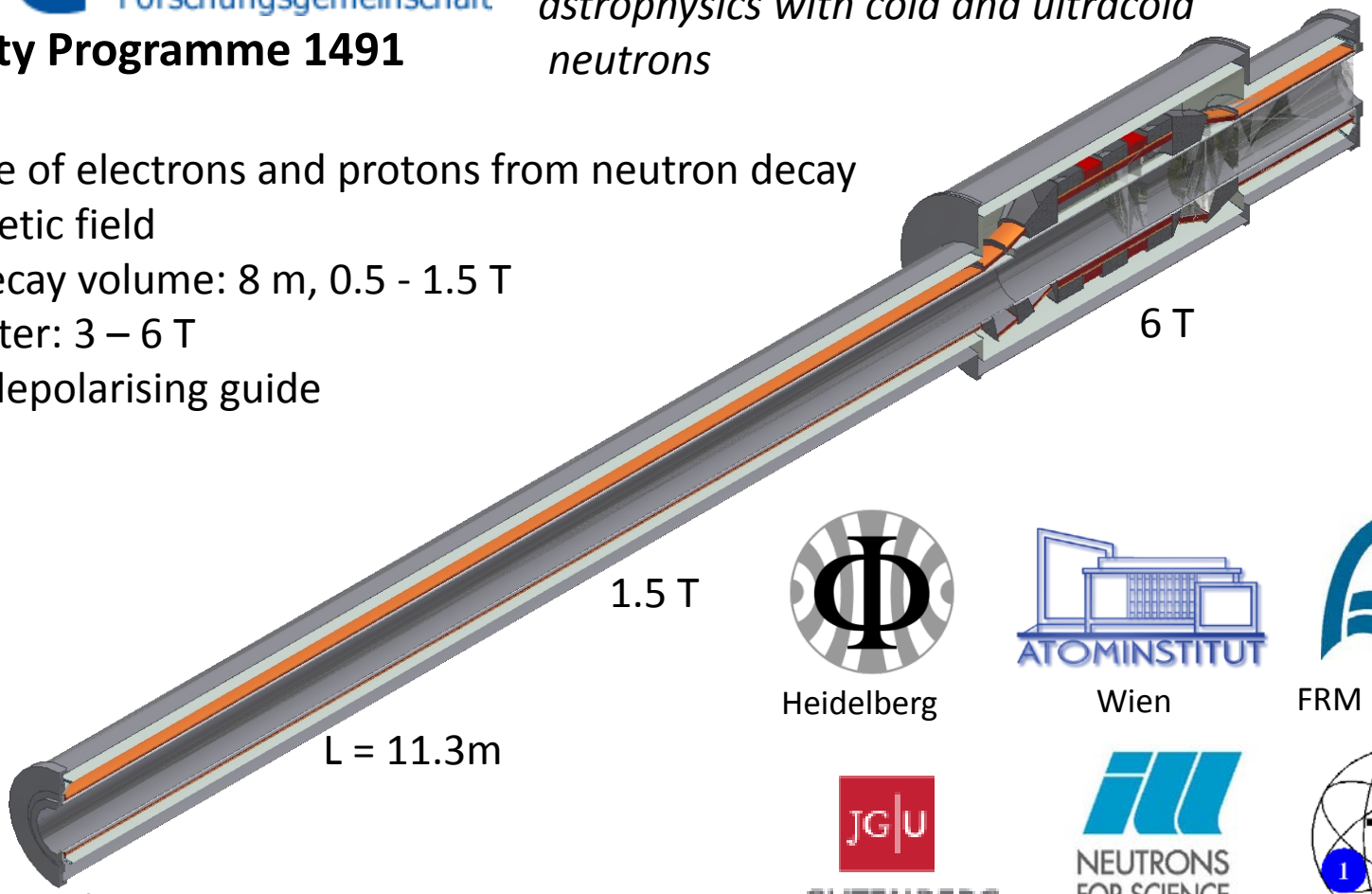
# PERC – a clean bright and versatile source of neutron decay products

DFG Deutsche Forschungsgemeinschaft

**Priority Programme 1491**

*Precision experiments in particle and astrophysics with cold and ultracold neutrons*

- Source of electrons and protons from neutron decay
- Magnetic field
  - Decay volume: 8 m, 0.5 - 1.5 T
  - Filter: 3 – 6 T
- Non-depolarising guide




Preliminary Magnet Design

Heidelberg

Wien

FRM II, München

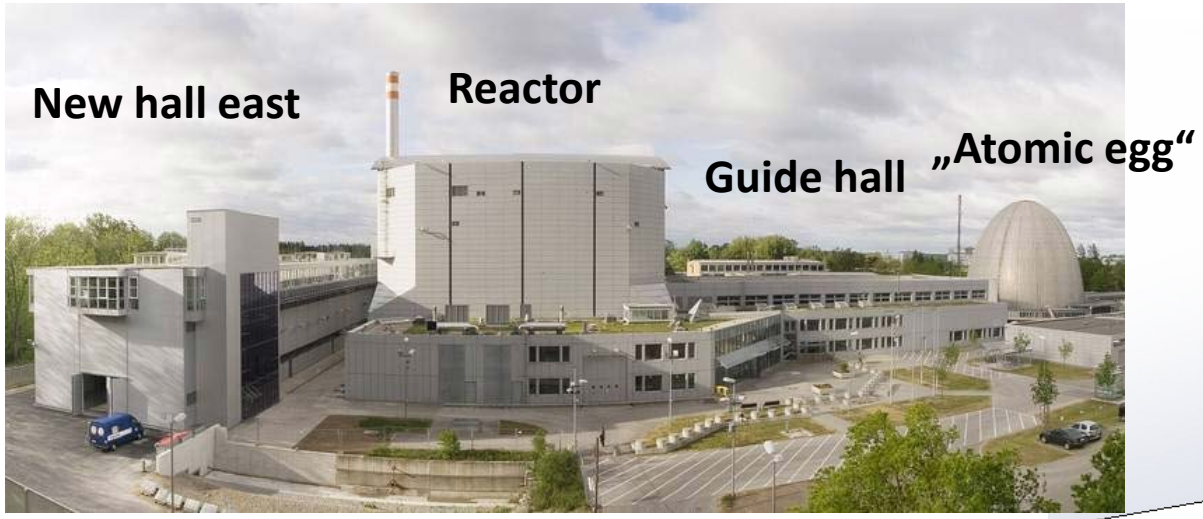
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

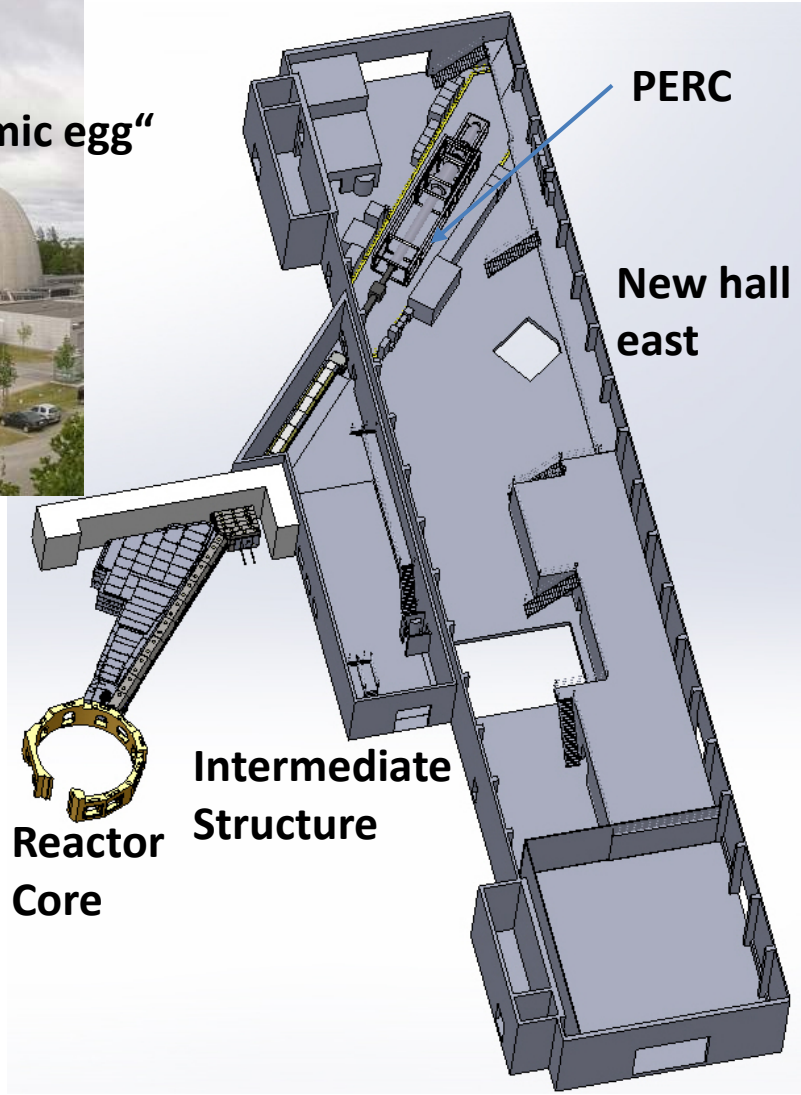
NEUTRONS FOR SCIENCE
Grenoble

München

Bastian Märkisch

# PERC beam site Mephisto at FRM II




- “Empty” new hall
- Neutron guide:
  length 40 m, R = 3000 m, *m* = 2.5
- Expected intensity equal to PF1B at ILL
- Only very few neighbours:
  low background
- Easy ground level access

| SOURCE OF ERROR | COMMENT | SIZE OF CORRECT. | SIZE OF ERROR: |
|---|---|---|---|
| non-uniform n-beam | for $\Delta\Phi/\Phi$ = 10 % over 1 cm width | $2.5\cdot10^{-4}$ | $5\cdot10^{-5}$ |
| other edge effects on e/p-window | for worst case at max. energy | $4\cdot10^{-4}$ | $1\cdot10^{-4}$ |
| magn. mirror effect, contin's n-beam | | $1.4\cdot10^{-2}$ | $2\cdot10^{-4}$ |
| magn. mirror effect, pulsed n-beam | for $\Delta B/B$ = 10 % over 8 m length | $5\cdot10^{-5}$ | $<10^{-5}$ |
| non-adiabatic e/p-transport | | $5\cdot10^{-5}$ | $5\cdot10^{-5}$ |
| background from n-guide | }is separately measurable | $2\cdot10^{-3}$ | $1\cdot10^{-4}$ |
| background from n-beam stop | | $2\cdot10^{-4}$ | $1\cdot10^{-5}$ |
| backscattering off e/p-window | | $2\cdot10^{-5}$ | $1\cdot10^{-5}$ |
| backscattering off e/p-beam dump | | $5\cdot10^{-5}$ | $1\cdot10^{-5}$ |
| backscatt. off plastic scintillator | }for worst case | $2\cdot10^{-3}$ | $4\cdot10^{-4}$ |
| ~ same with active e/p-beam dump | | – | $1\cdot10^{-4}$ |
| neutron polarisation | Status 2010 | $3\cdot10^{-3}$ | $1\cdot10^{-3}$ |

Neutron Poarimetry on the $10^{-4}$ level
Talk Christine Klauser

Dubbers, Baessler, Märkisch, Schumann, Soldner, Zimmer, H.A., arXiv 2007

# What about the lifetime?

- $\tau$ = 888.0 ± 2.3 s NIST
- $\tau$ = 878.5 ± 0.8 s PNPI

- $\tau$ = 879.8 ± 0.75 s

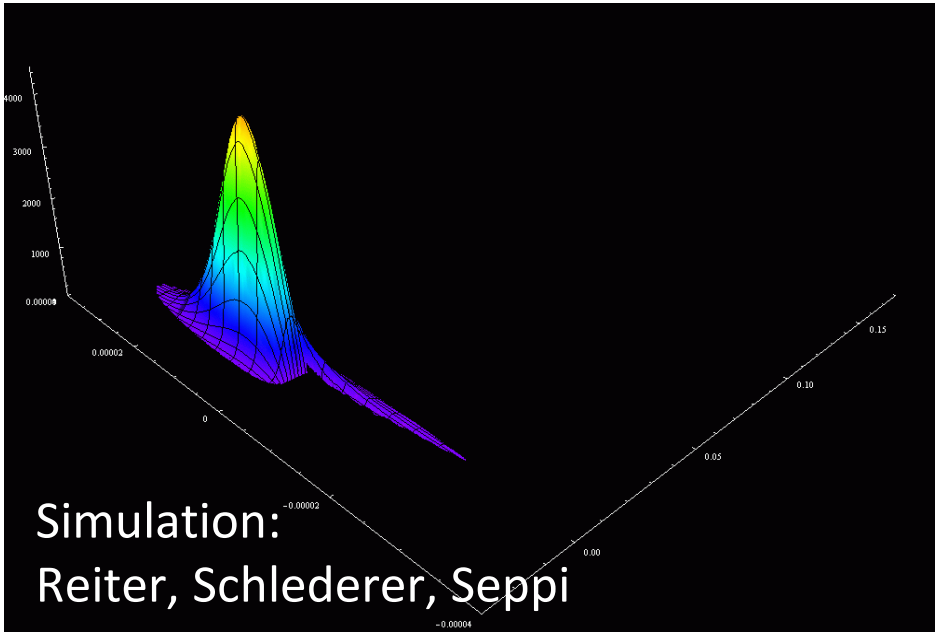
$$\tau^{-1} = V_{ud}{}^2 G_F{}^2 (1 + 3\lambda^2) \frac{f^R m_e{}^5 c^4}{2\pi^3 \hbar^7}$$

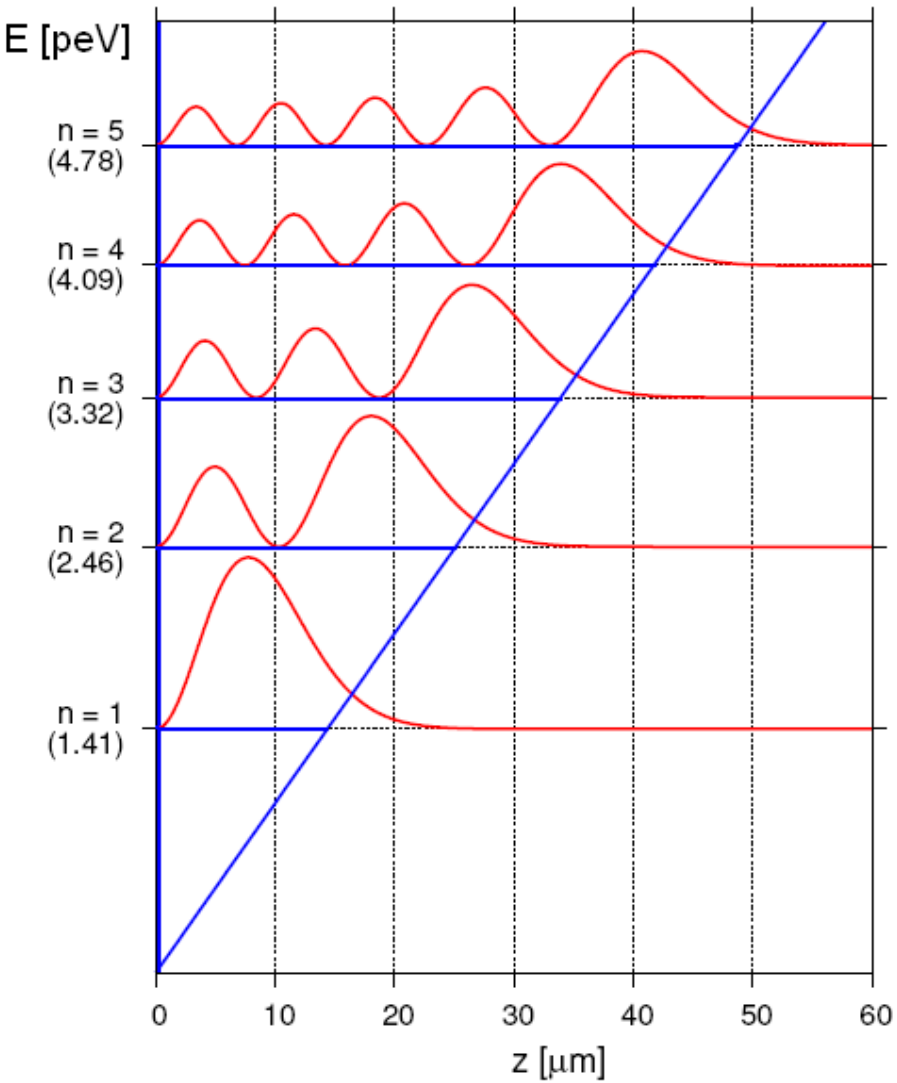
- $\tau$ = 880.2 ± 1.5 s from PERKEO and $0^+ \rightarrow 0^+$

# 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***

# Quantum States in the Gravity Potential




Demonstration of Quantum States
in the Gravity Potential of the Earth
**Nesvizhevsky et al.**
**Nature 2002**

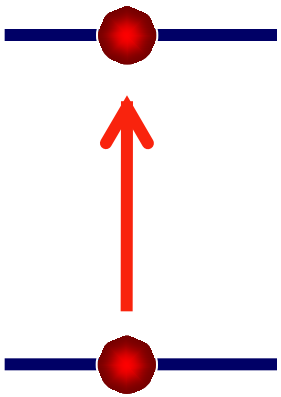
***q*Bounce, 2009**

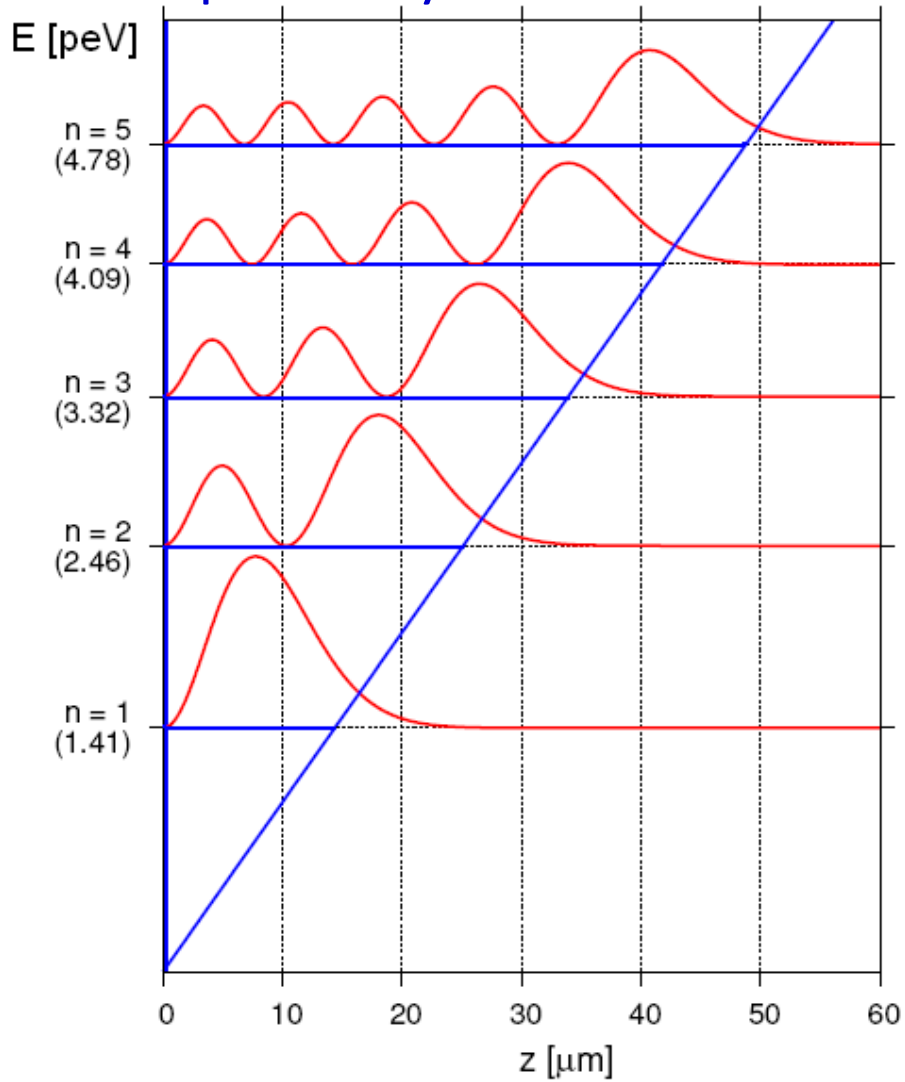
# Rabi-Gravity-Spectroscopy

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

|3 > 3.32 peV

|1 > 1.4 peV



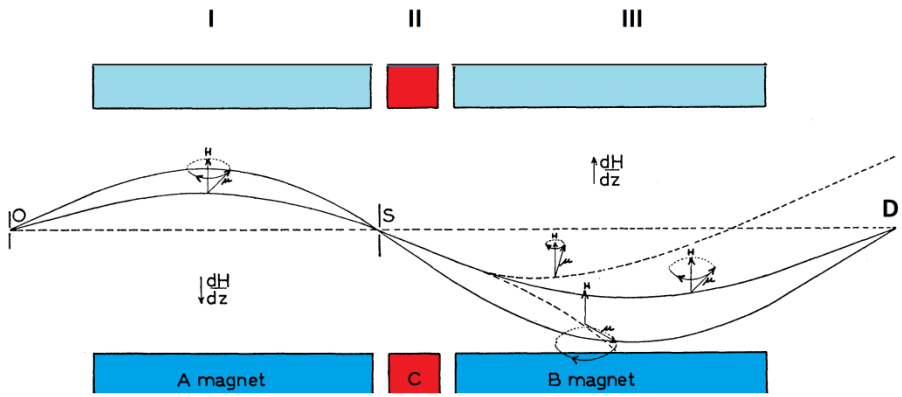



***q*Bounce:**
**Vibrating mirror**

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

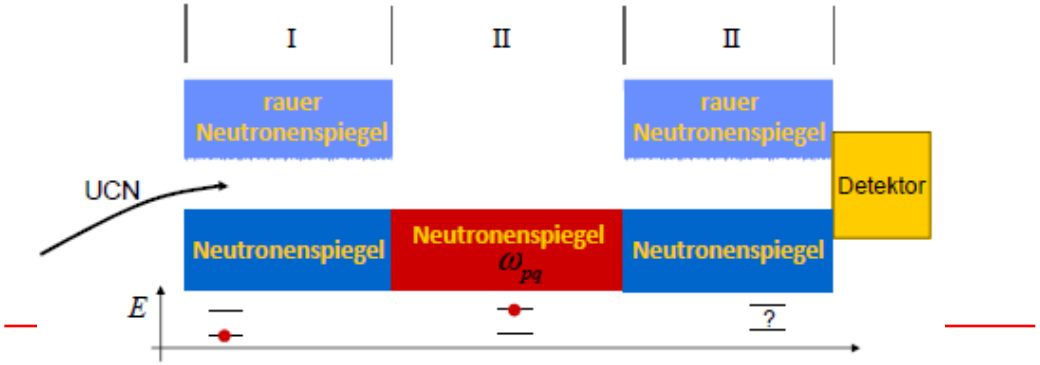
# *Show Case I:* Rabi-type Spectroscopy of Gravity

- **NMR Spectroscopy Technique to explore magnetic moments**



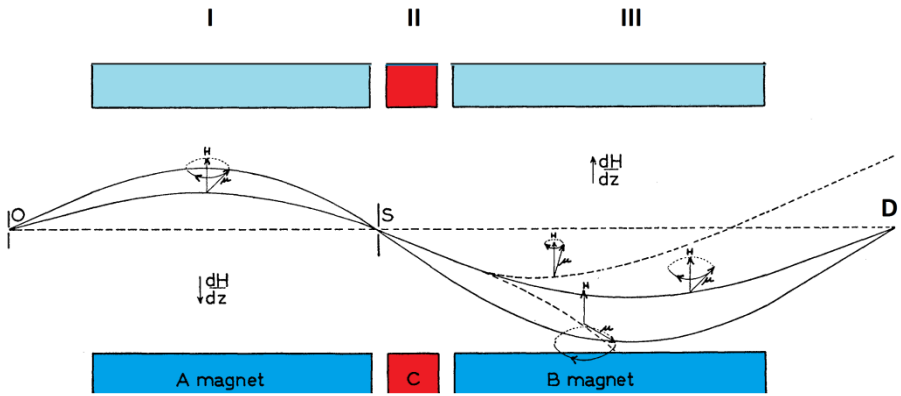

- 3 Regions:
  - I: 1st State selector/ Polarizer
  - II: Coupling
    - RF field
    - Vibr. mirror
  - III: 2nd State Selector / Analyzer

- **Gravity Resonance Spectroscopy Technique to explore gravity**



# Rabi Spectroscopy

## NMResonance Spectroscopy Technique to explore magnetic moments



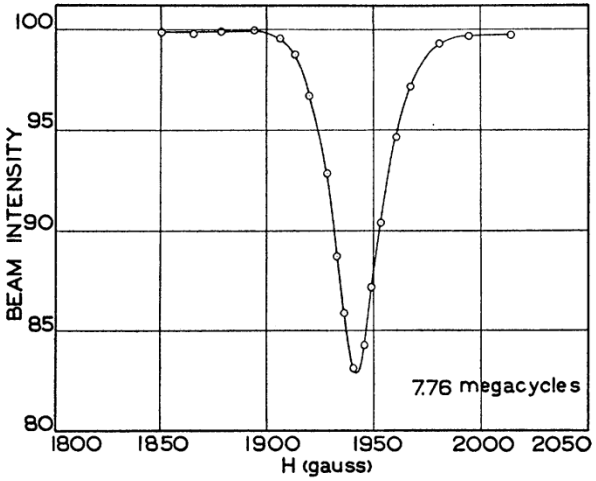
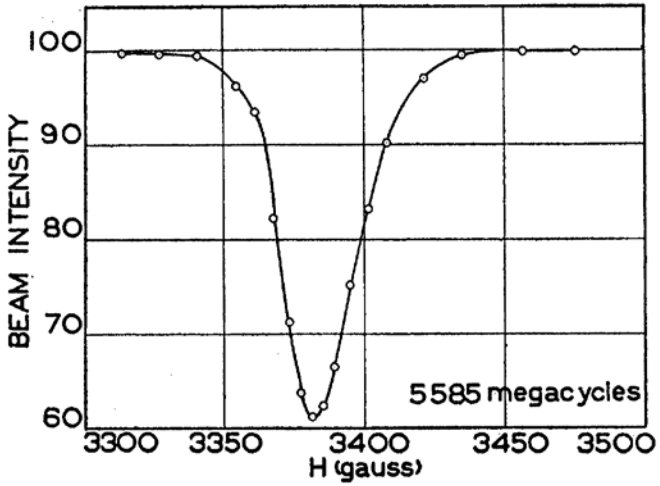
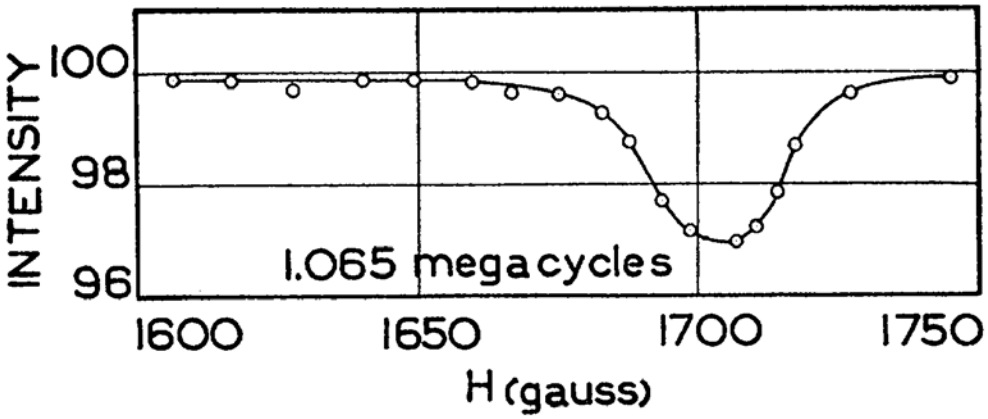




FIG. 5. Resonance curve of the $F^{19}$ nucleus observed in NaF.



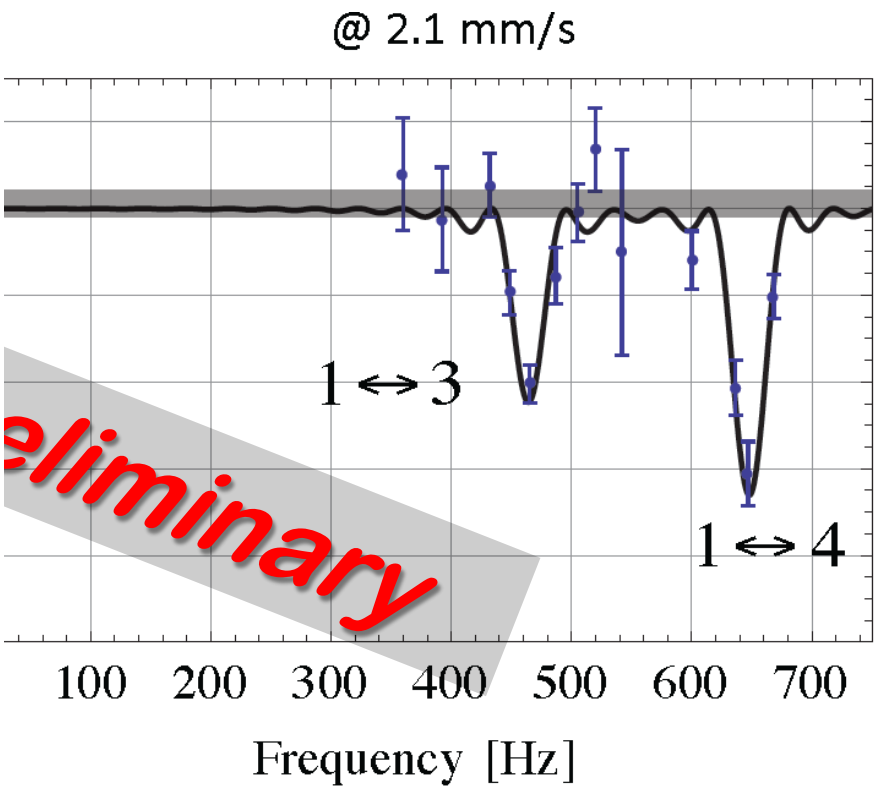




IG. 4. Resonance curve of the $Li^7$ nucleus observed in LiCl.

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

# Rabi 2012 - *preliminary*

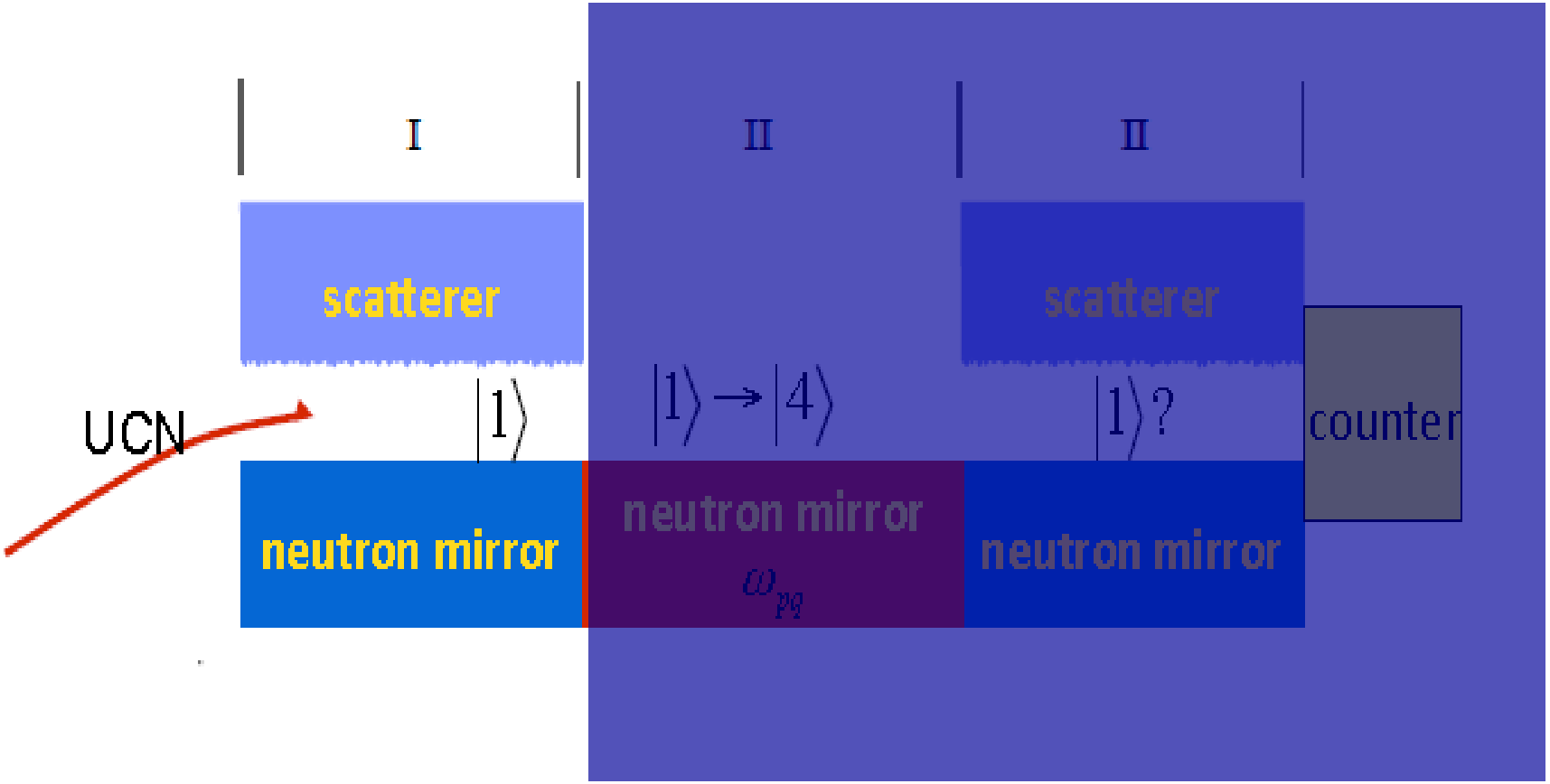
- **Transmission**



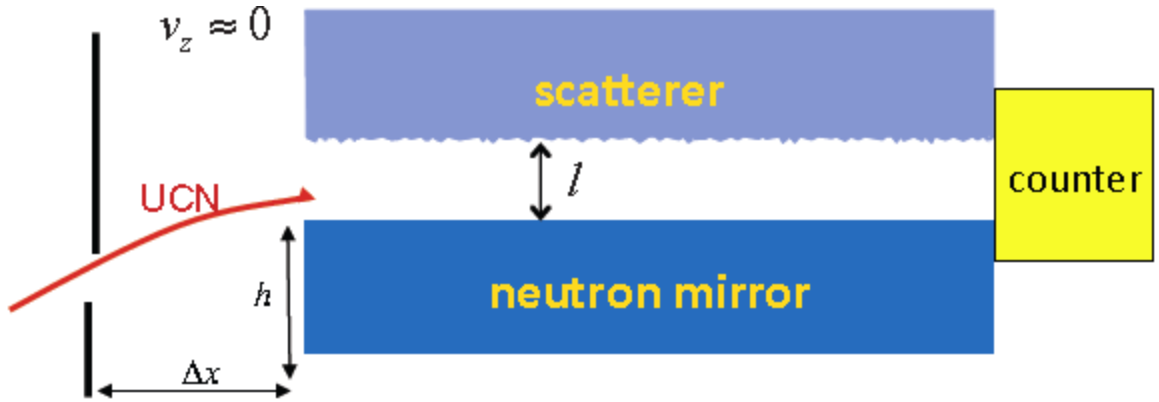

UCN

G. Cronenberg, PhD

# Region I

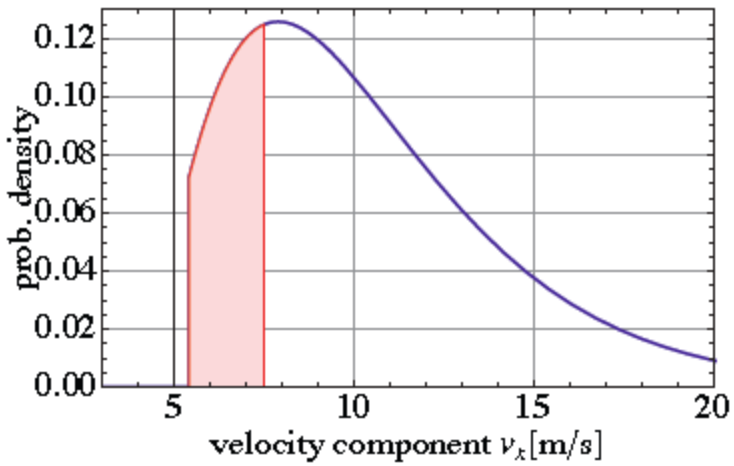

I
II
II
scatterer
scatterer
UCN
$|1\rangle$
$|1\rangle \rightarrow |4\rangle$
$|1\rangle ?$
counter
neutron mirror
neutron mirror
$\omega_{pq}$
neutron mirror

# Preparation: velocity selection




UCNs at PF2

Accept $5.7 < v_x < 9.5$ m/s



# Gravity and Quantum Mechanics

**Schrödinger equation:**

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

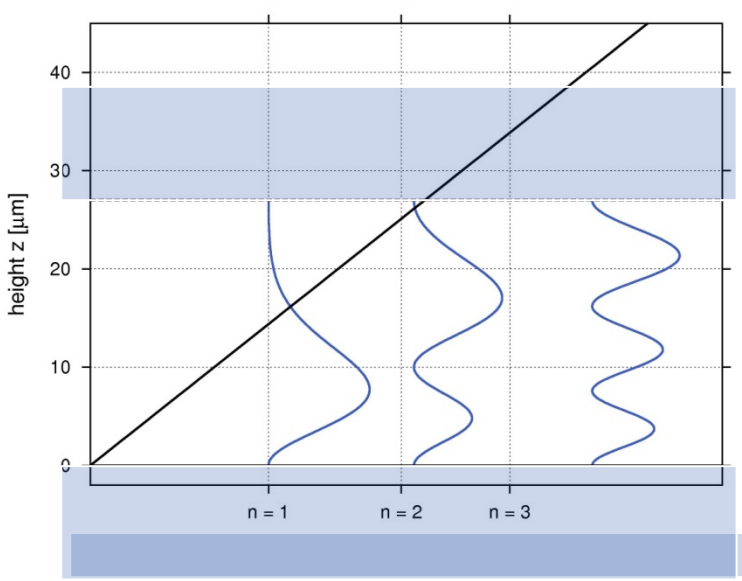
**boundary conditions:**

$$\varphi_n(0)=0$$

**with 2nd mirror at height**

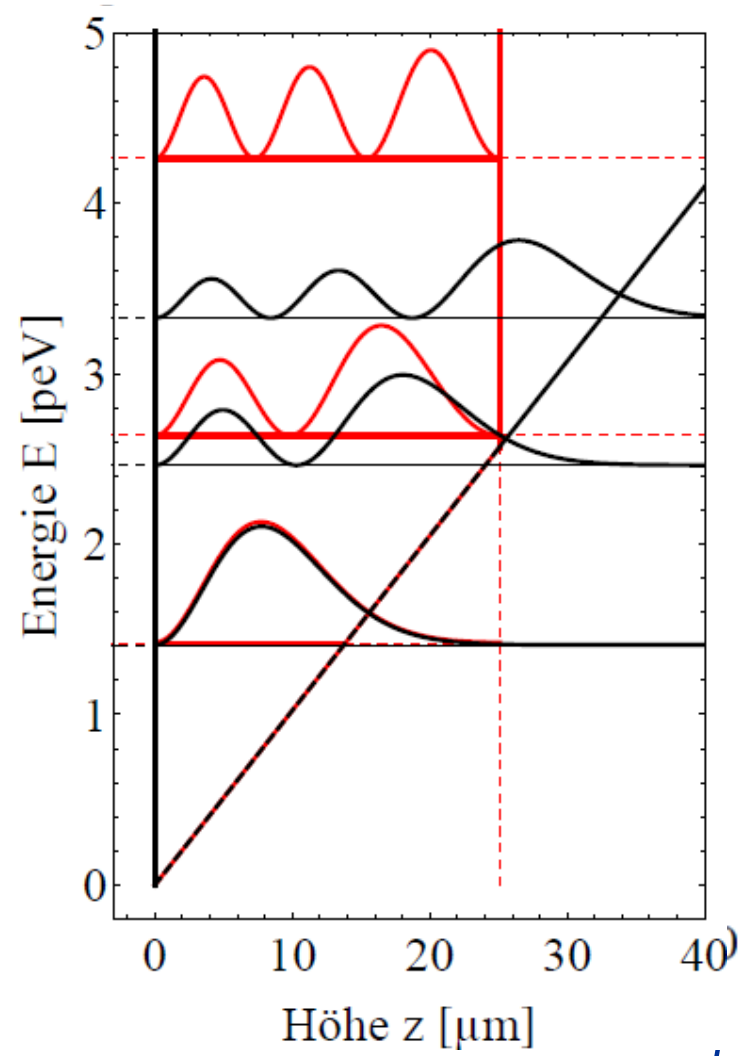
$$\varphi_n(l)=0$$

| $E_n$ | $E_n$ |
|---|---|
| 1.41peV | 1.41peV |
| 2.46peV | 2.56peV |
| 3.32peV | 4.2 peV |



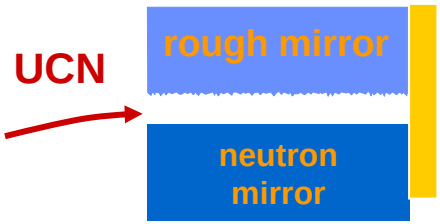

**~ 1 µm**
**Surface roughness**

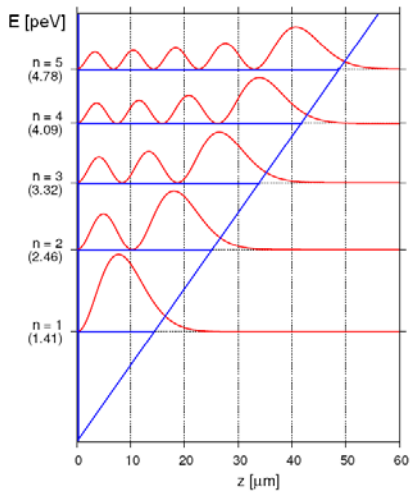
**Solutions: Airy-functions: Ai & Bi**

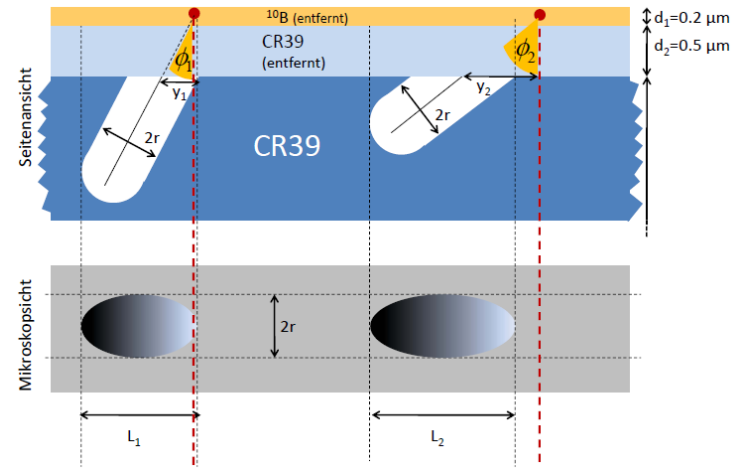


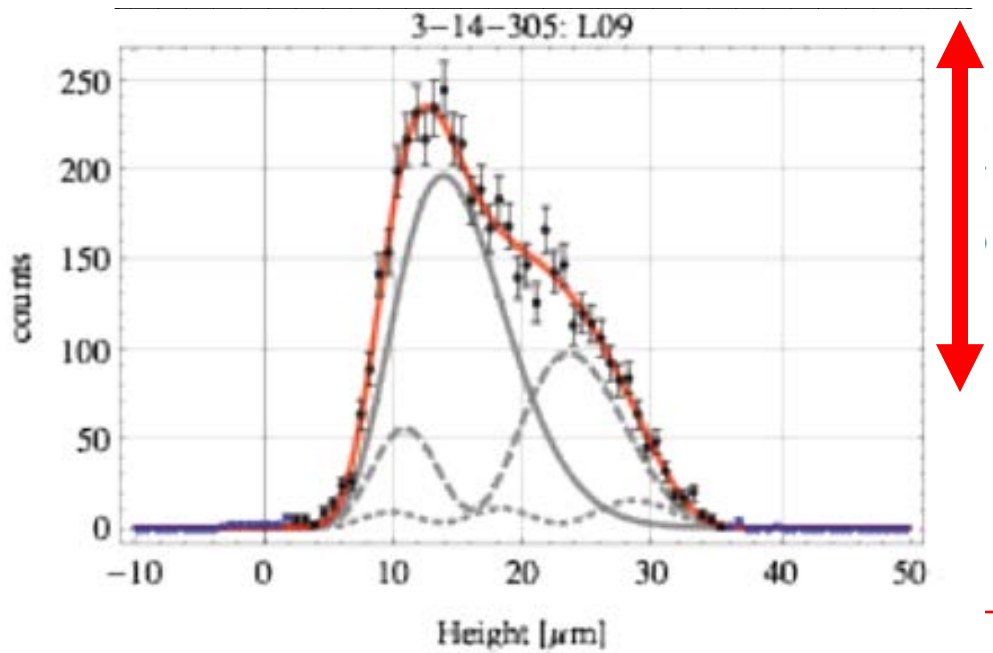
# Region 1: State Selector

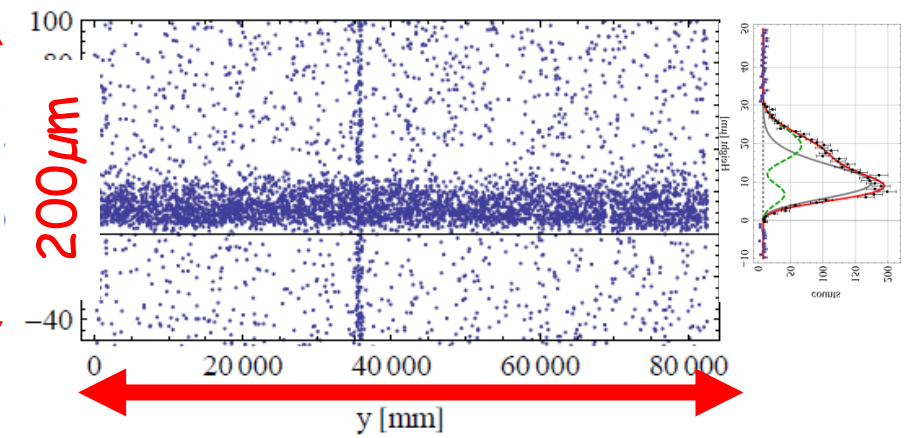
$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$$



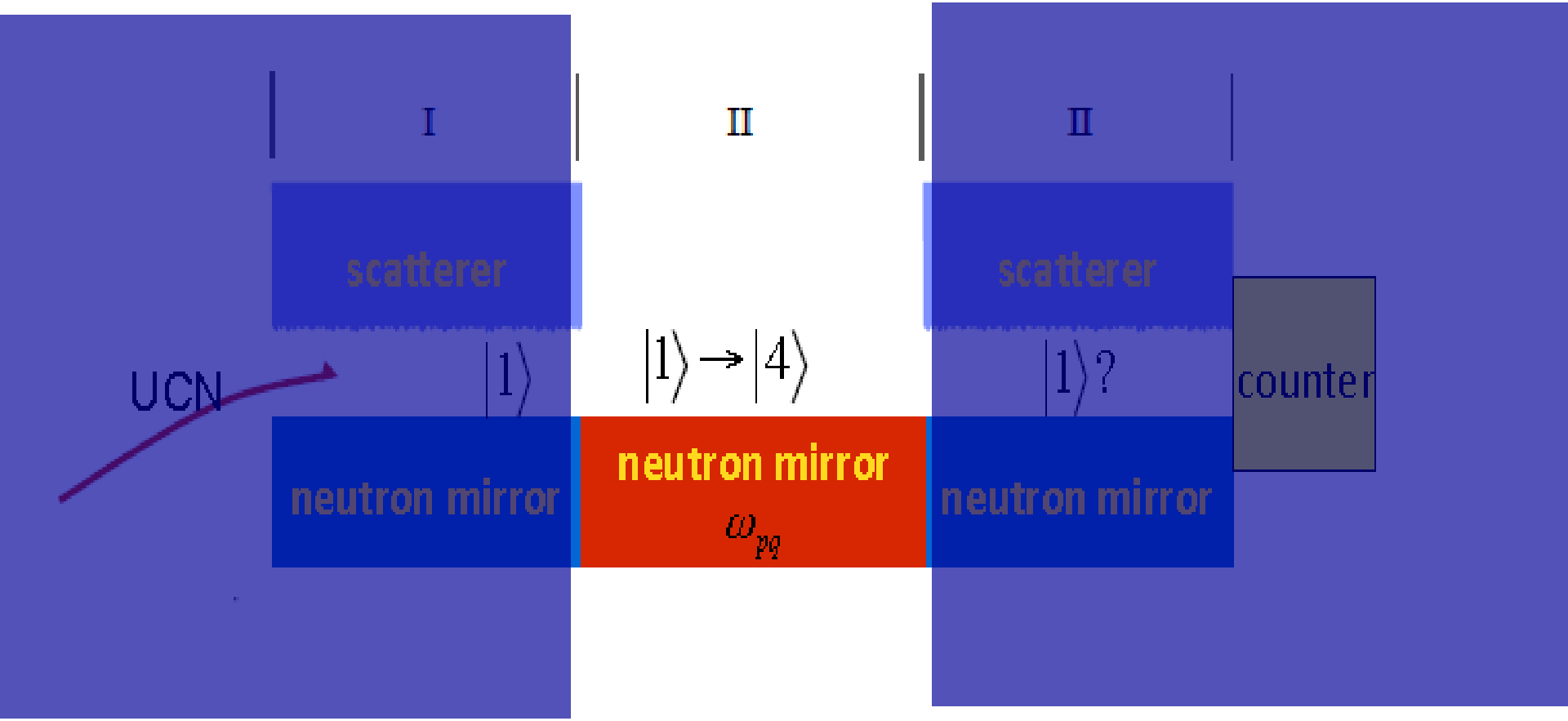



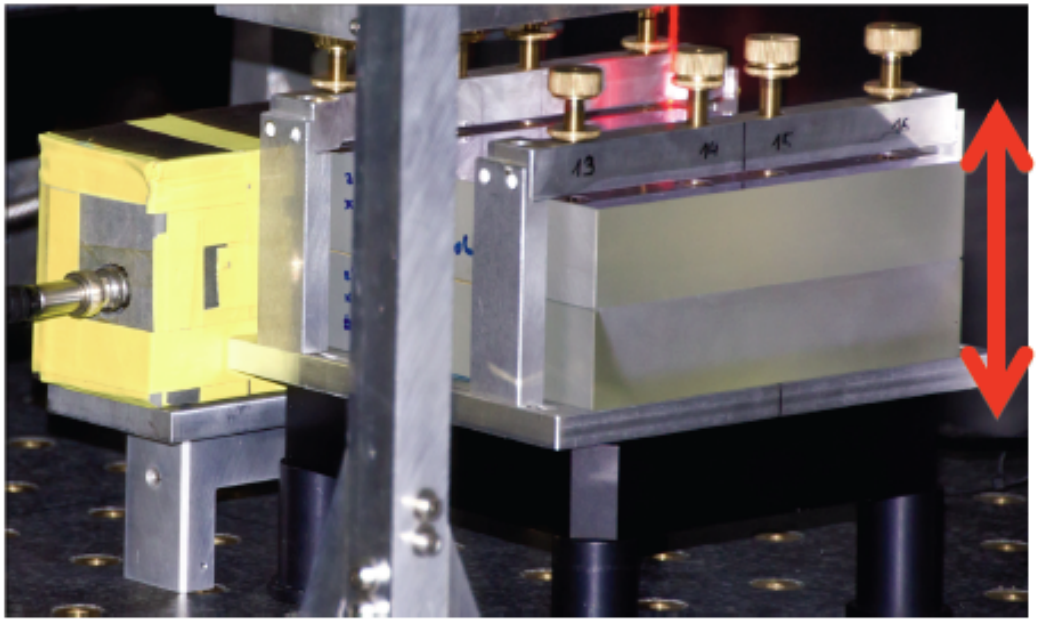

~ 8 cm

# Region II

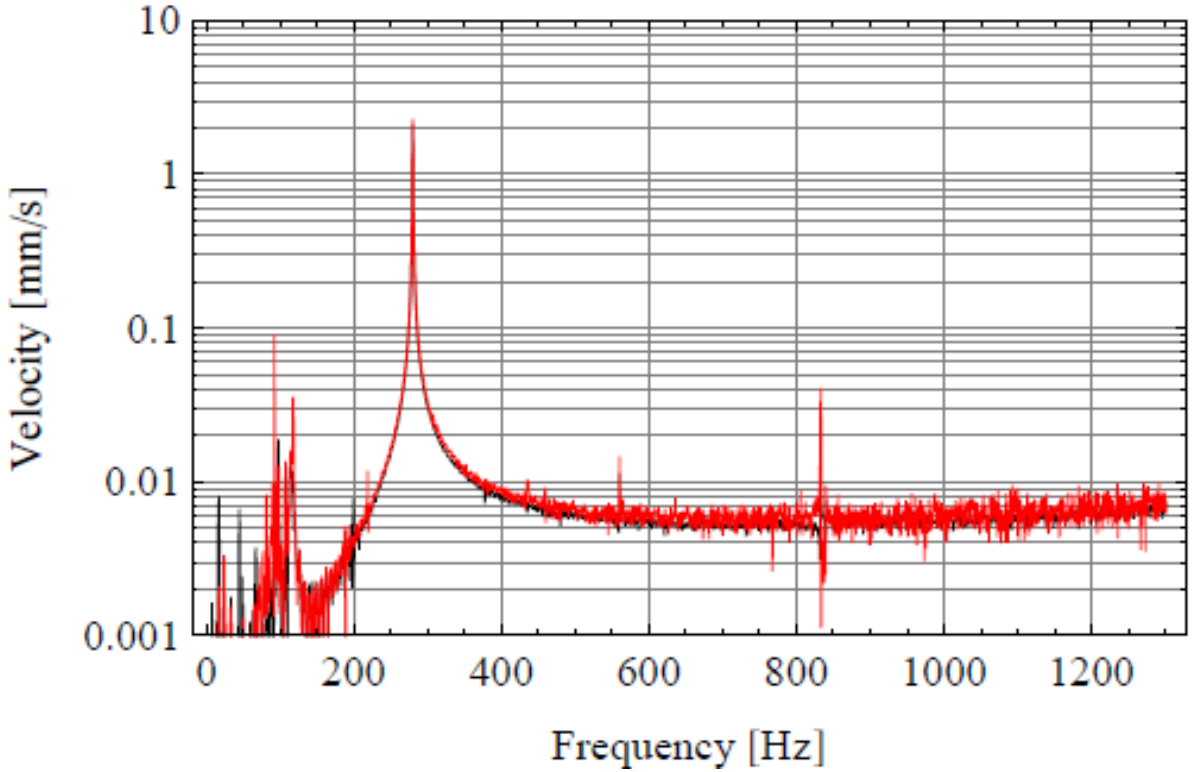

I
II
II
scatterer
scatterer
UCN
$|1\rangle$
$|1\rangle \rightarrow |4\rangle$
$|1\rangle ?$
counter
neutron mirror
neutron mirror
$\omega_{pq}$
neutron mirror

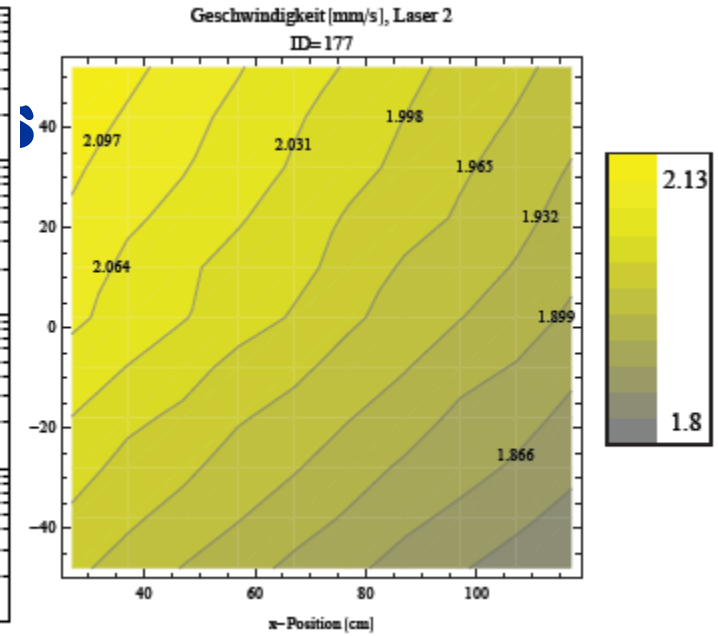
# Region 2: the vibration table

- Oscillation with 4 Piezo actuators
- Internal capazitive sensoren for position/tip/tilt

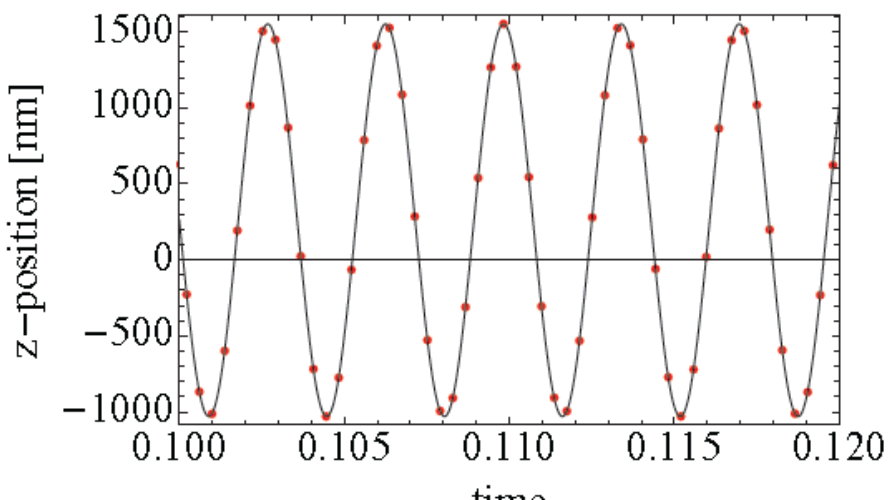


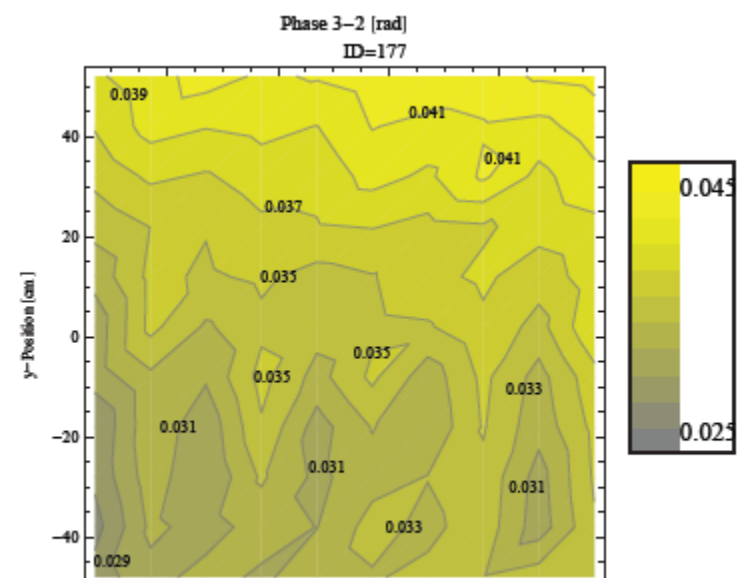
| | |
|---|---|
| Z range | 140 µm |
| Z range closed loop | 100 µm |
| Z resolution closed loop | 0,8 nm |
| Tip/tilt range | ±0,5 mrad |
| Tip/tilt resolution closed loop | 0.05 µrad |
| Tested frequency range | 0-850 Hz |
| Maximal tested amplitude | 4,8 mm/s |



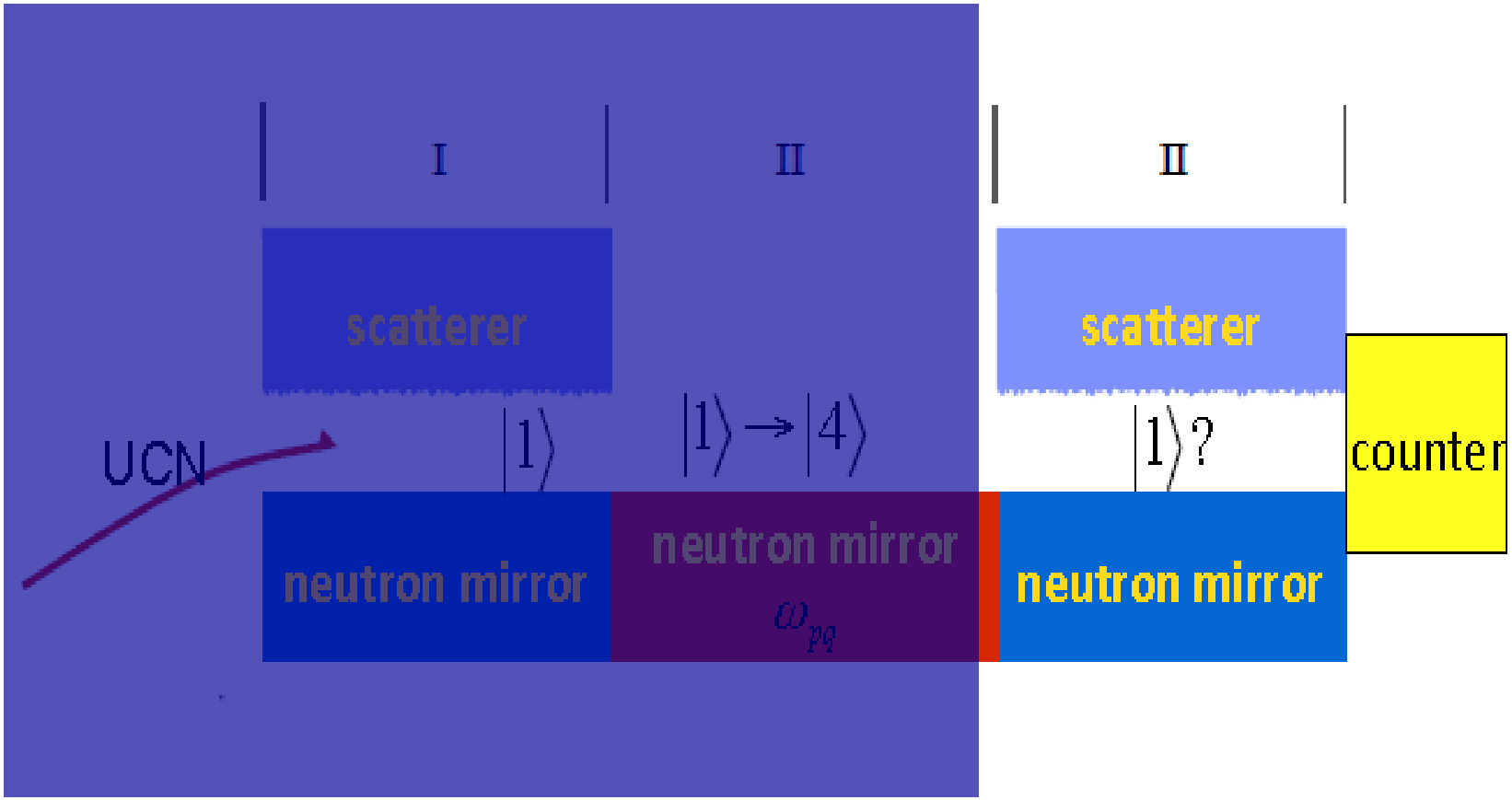




**T. Lins, Diplomarbeit**



# Region III


I
II
II
scatterer
scatterer
UCN
$|1\rangle$
$|1\rangle \rightarrow |4\rangle$
$|1\rangle$?
counter
neutron mirror
neutron mirror
$\omega_{pq}$
neutron mirror

# Detector

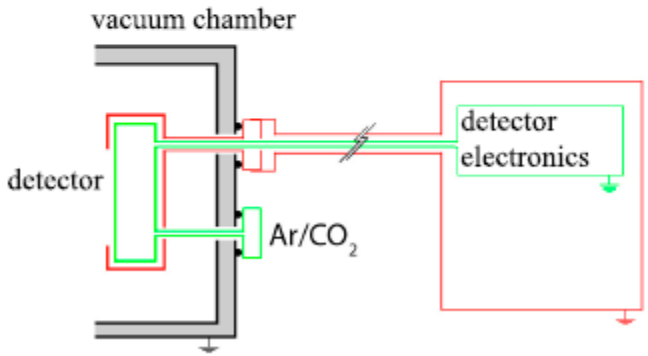
Boron layer: $n + {}^{10}B \rightarrow \alpha + {}^{7}Li^{*} \rightarrow \alpha + {}^{7}Li^{3+} + \gamma$ $ArCo_2$ Counter

Adapted geometry for low background

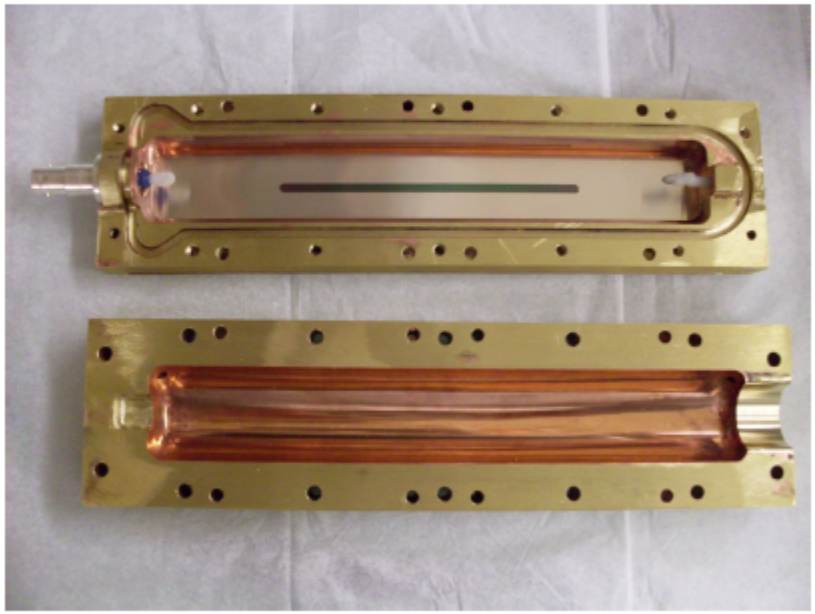
Improved shielding

$\varepsilon = 86.4\ \%$

$R_0 = (0.65 \pm 0.02) \times 10^{-3}\ s^{-1}$



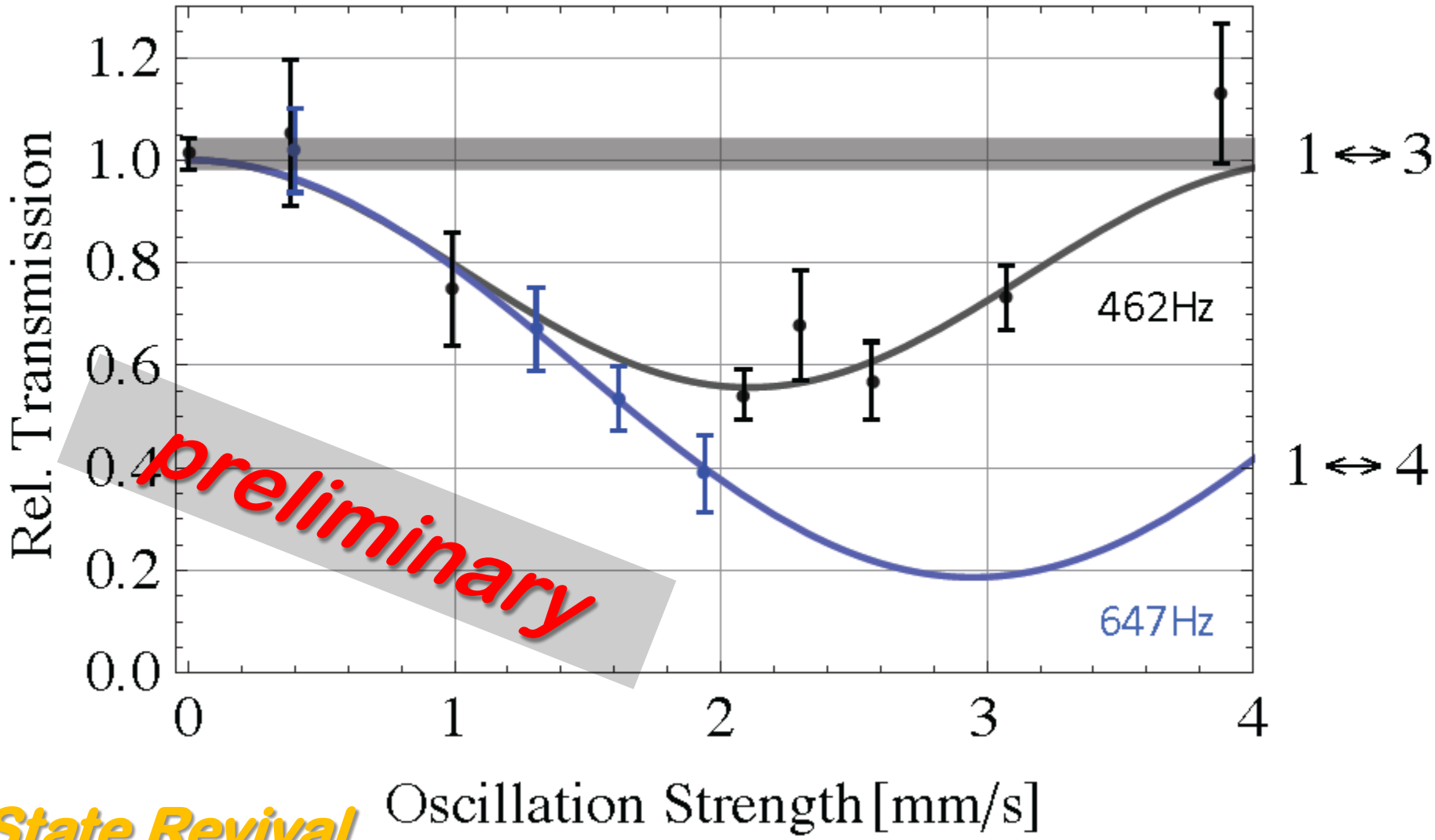

M. Thalhammer, Diplomarbeit 2013



H. Saul, Diplomarbeit 2011

Poster by T. Jenke

# Rabi Oscillation




State Revival

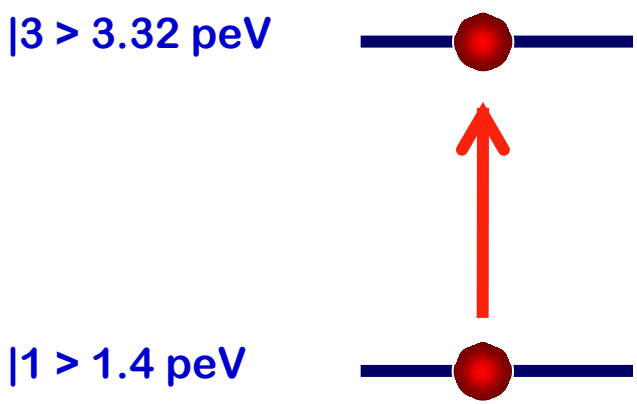
# Frequency Reference for Gravitation

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

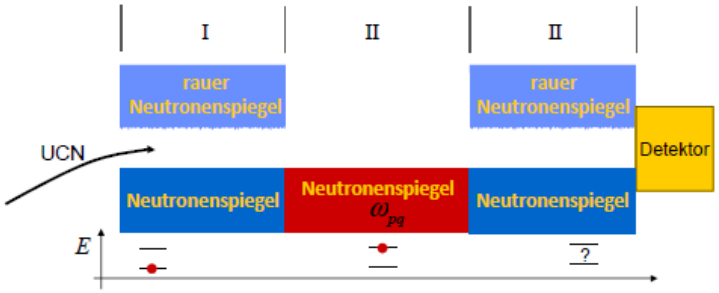
  Plus Acceleration of earth ***g***

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

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



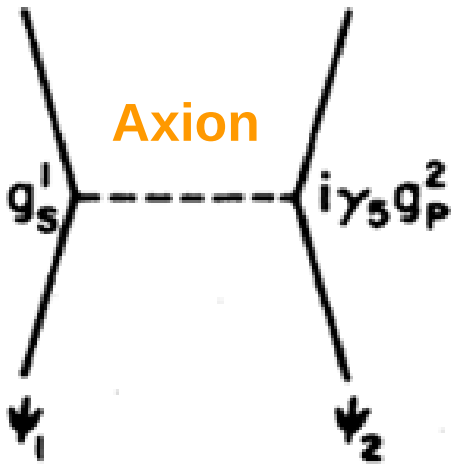

$$\omega_{pq} = \frac{E_q - E_p}{\hbar} = \omega_q - \omega_p$$



# *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?**



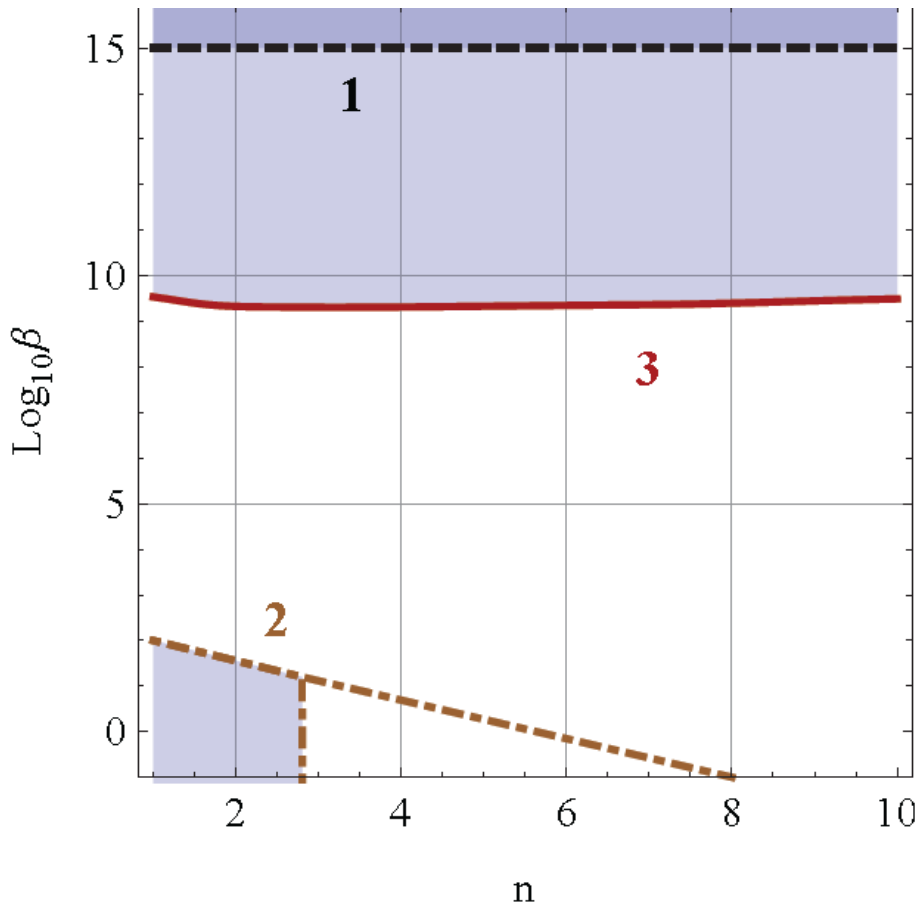

**$10^{-14}$ eV Scale**

- **constraint on any possible new interaction**

# Dark Energy – Scalar Fields

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

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




Poster by G. Cronenberg

# *q*Bounce and Chameleons

- Bounds on coupling $\beta$
  - By comparing transition frequency with theoretical expectation:

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

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

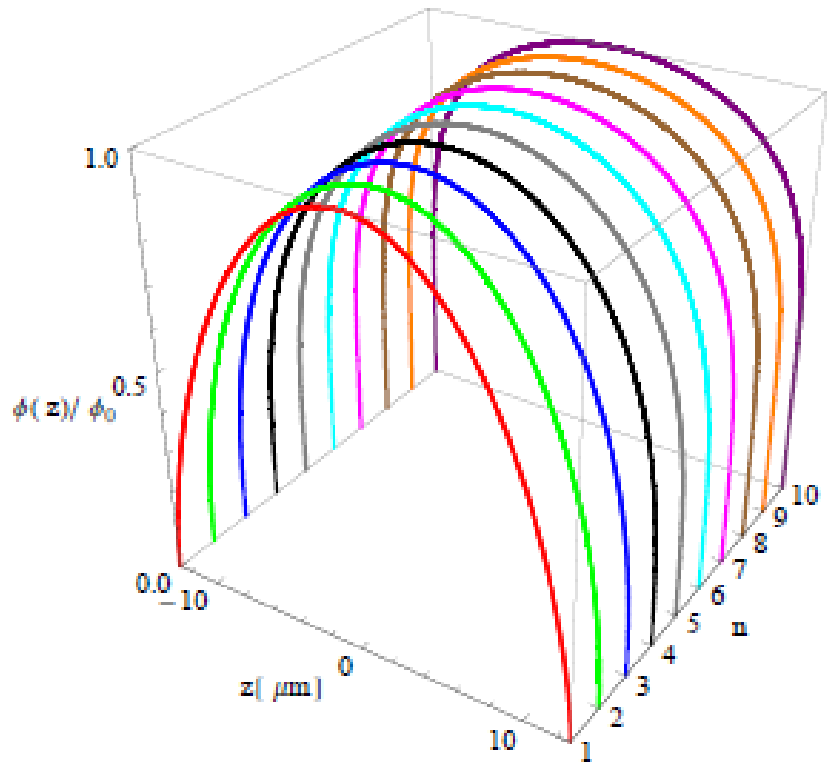
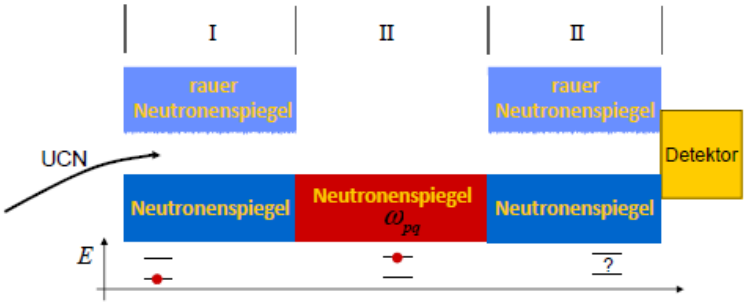



FIG. 2: The profiles of a chameleon field, calculated in the strong coupling limit as the solutions of Eq.(81) in the spatial region $z^2 \leq \frac{d^2}{4}$ and $n \in [1, 10]$.

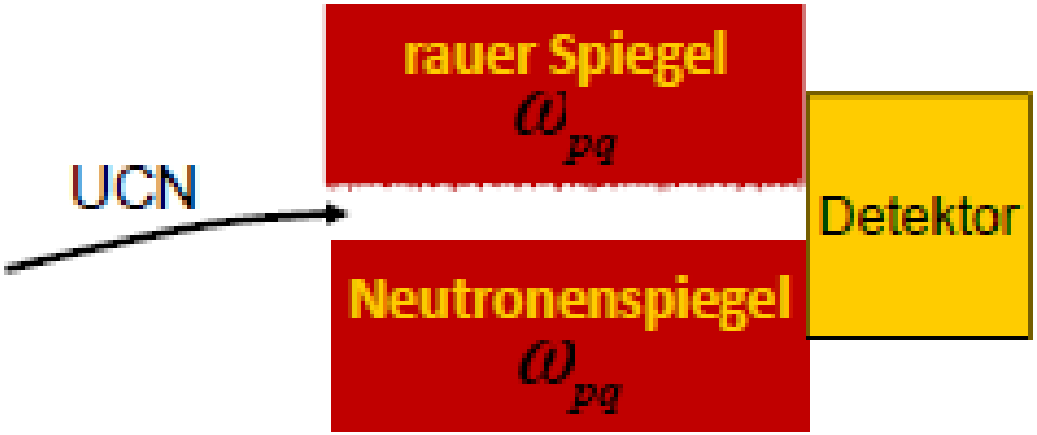
# *Show Case III:* Search for gravity-like forces

## Resonance Spectroscopy Technique to explore gravity

**Rabi-type experiment:**



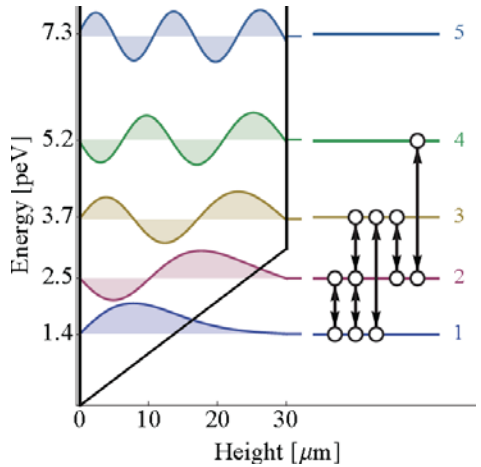

**Rabi-type experiment with damping**



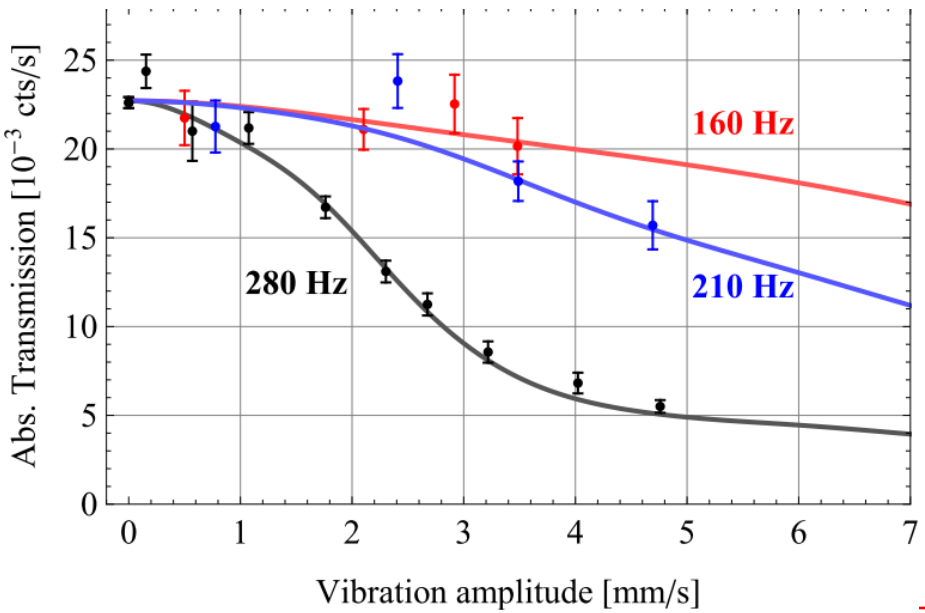

- realization of gravity resonance method possible
- simple setup, no steps
- high(er) transmission
- upper mirror introduces 2nd boundary condition

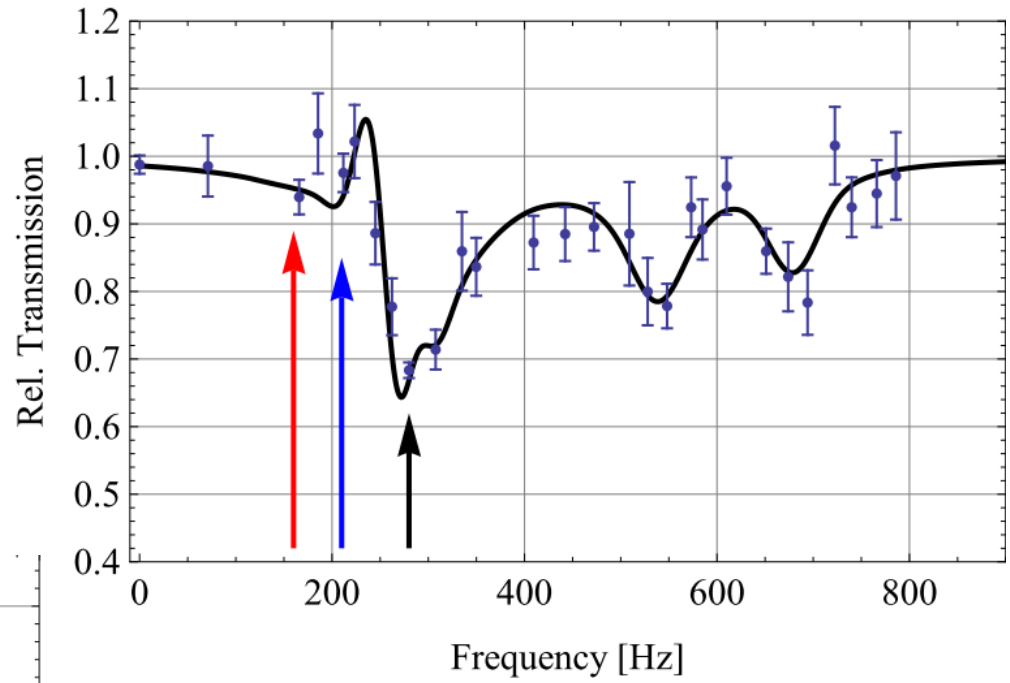
# Gravity Resonance Spectroscopy 2012

**50 days of beam time, 116 measurements**




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




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

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

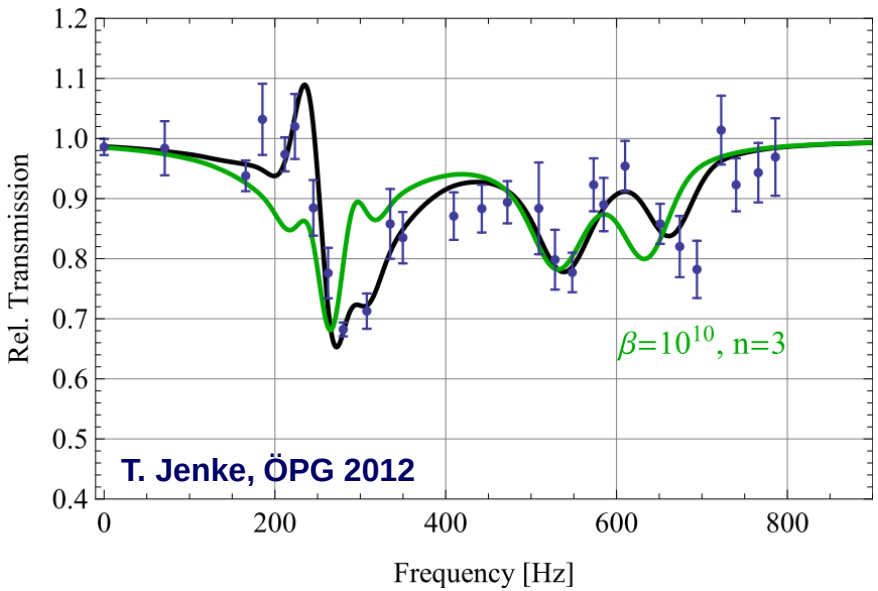
  $\nu_{13} = 539.1\,\text{Hz} \pm 0.5\%$

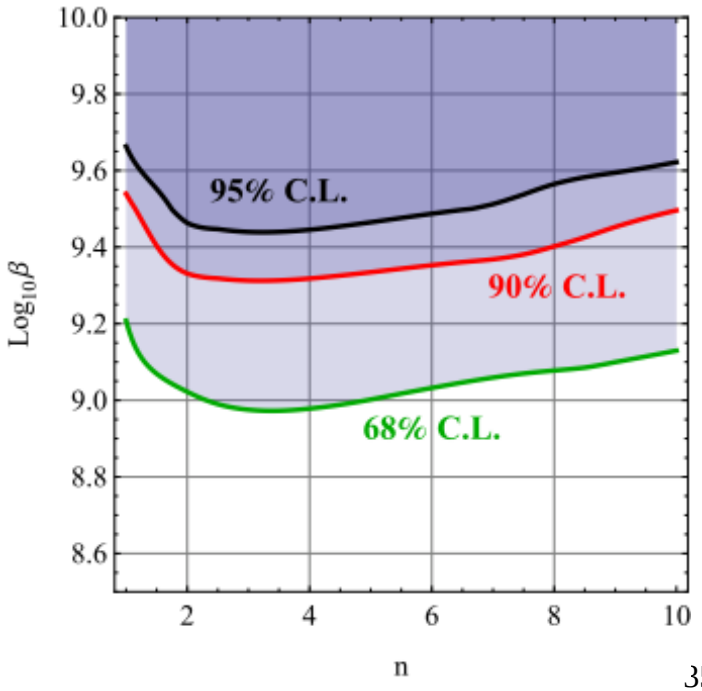
  $\nu_{24} = 679.5\,\text{Hz} \pm 2.2\%$
- **contrast:** 68%

**$10^{-14}$ eV Scale**

# Applications II:
# Strongly coupled chameleons

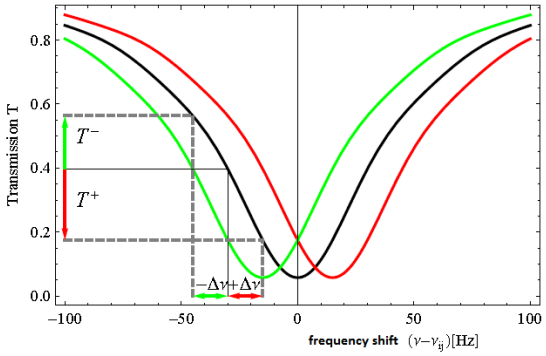
$$V_{\text{Chameleon}} = \beta \frac{m}{M_{Pl}} \Lambda \left( \frac{n+2}{\sqrt{2}} \frac{\Lambda}{d} \left( \frac{d^2}{2} - z^2 \right) \right)^{\frac{2}{n+2}}$$

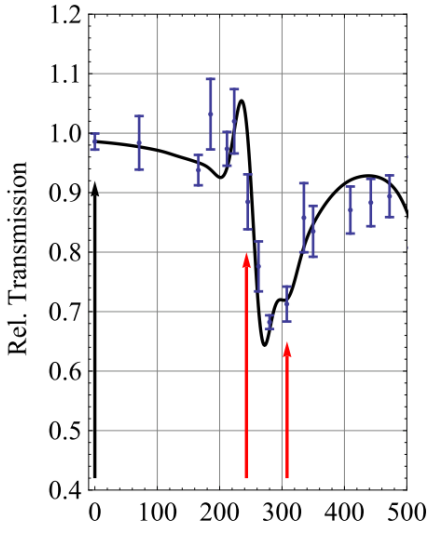


# Applications I:
# Spin-dependant short-ranged interactions

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

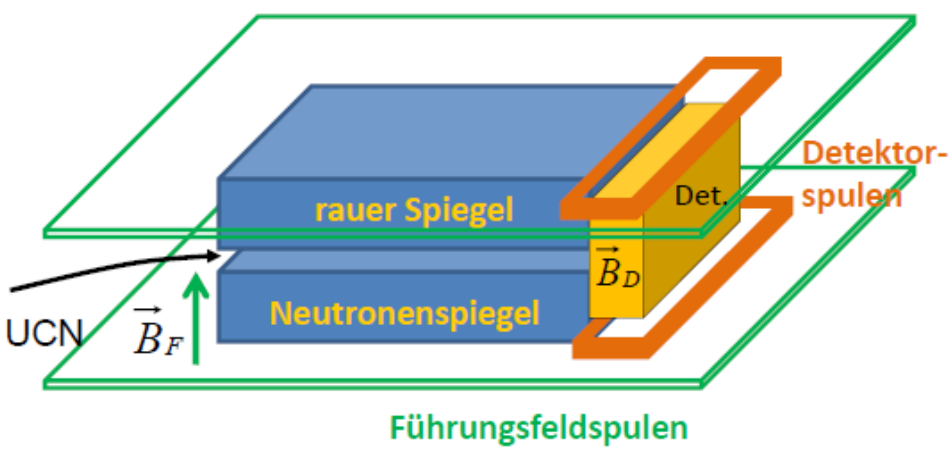


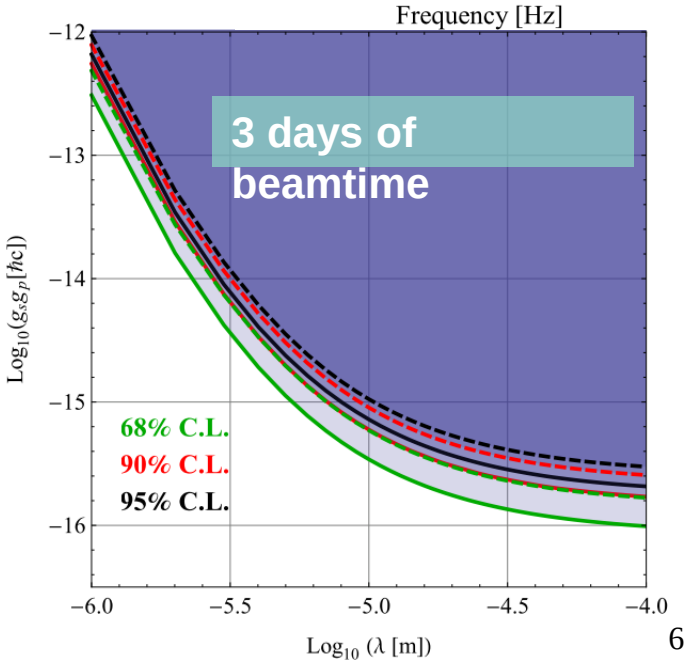




**discovery potential [Setup 2010]:**

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

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

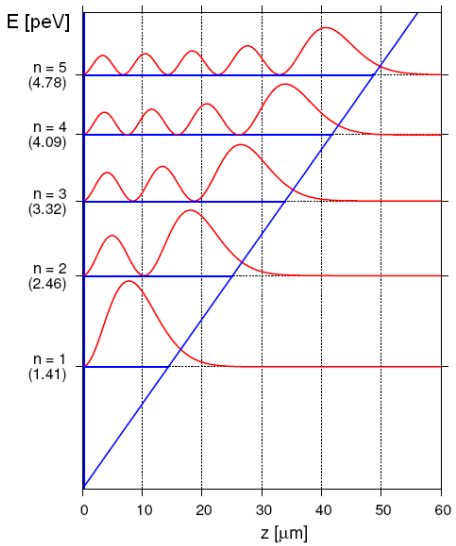


# Neutrons test Newton

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

- **Strength α**
- **Range λ**



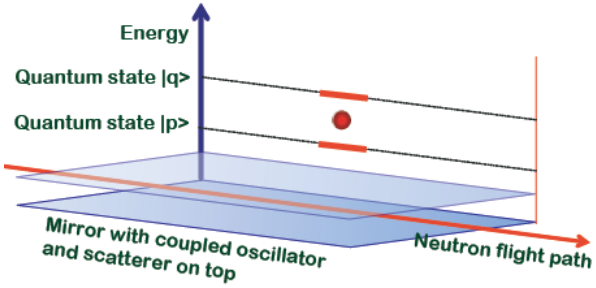

## Hypothetical Gravity Like Forces

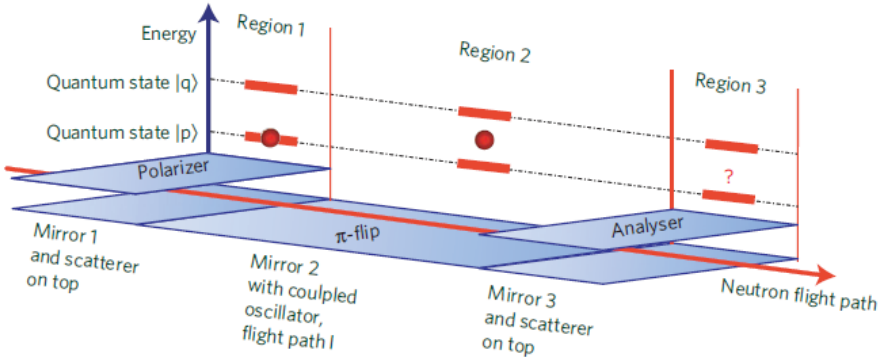
**Extra Dimensions:**
The string and $D_p$-brane theories predict the existence of extra space-time dimensions
**Infinite-Volume Extra Dimensions:** Randall and Sundrum
**Exchange Forces** from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and (pseudo)vector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

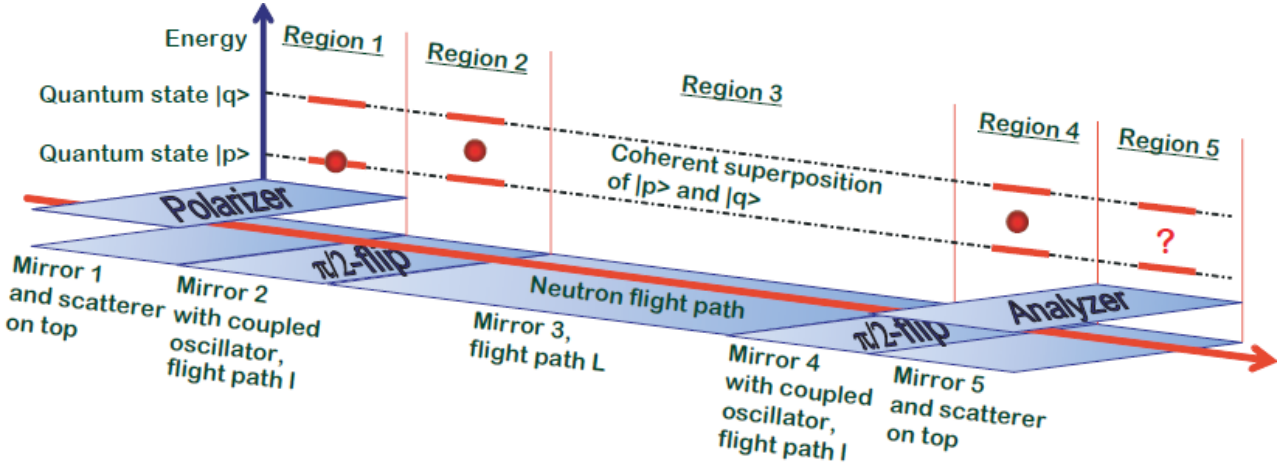
- **Axion** - - - - - - - - - - - - - - - - - - - - - - → **0.2 μm < λ < 0.2 cm**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999)** - - - - - → $10^6 < \alpha < 10^9$

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

# Outlook



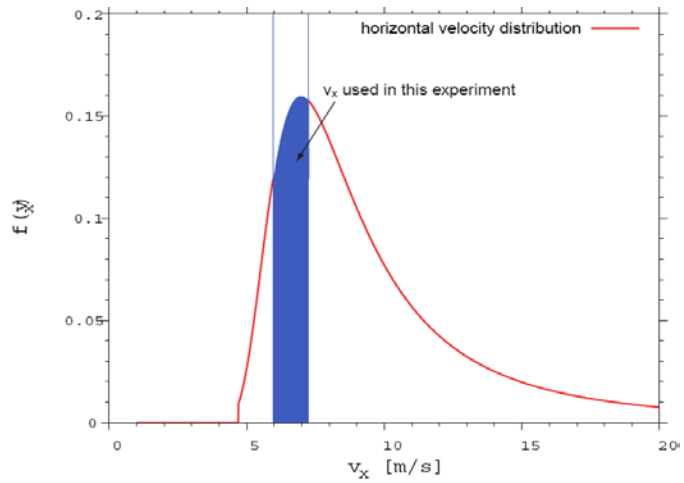



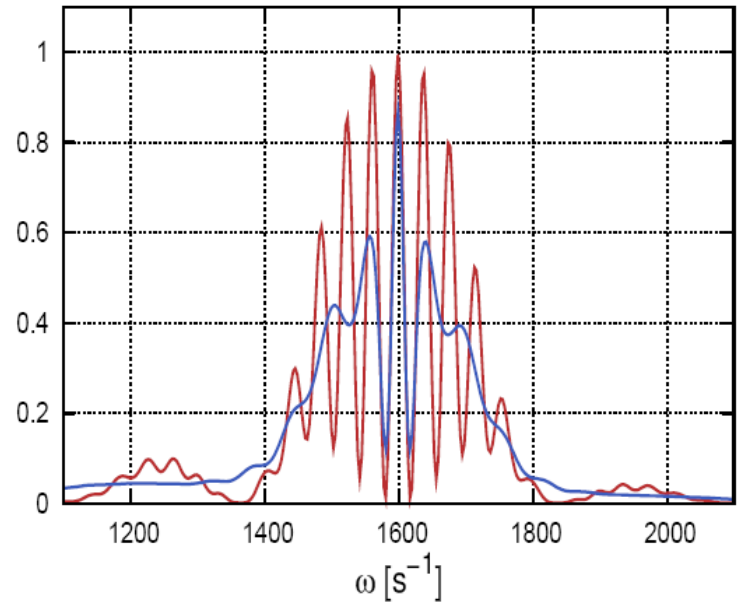



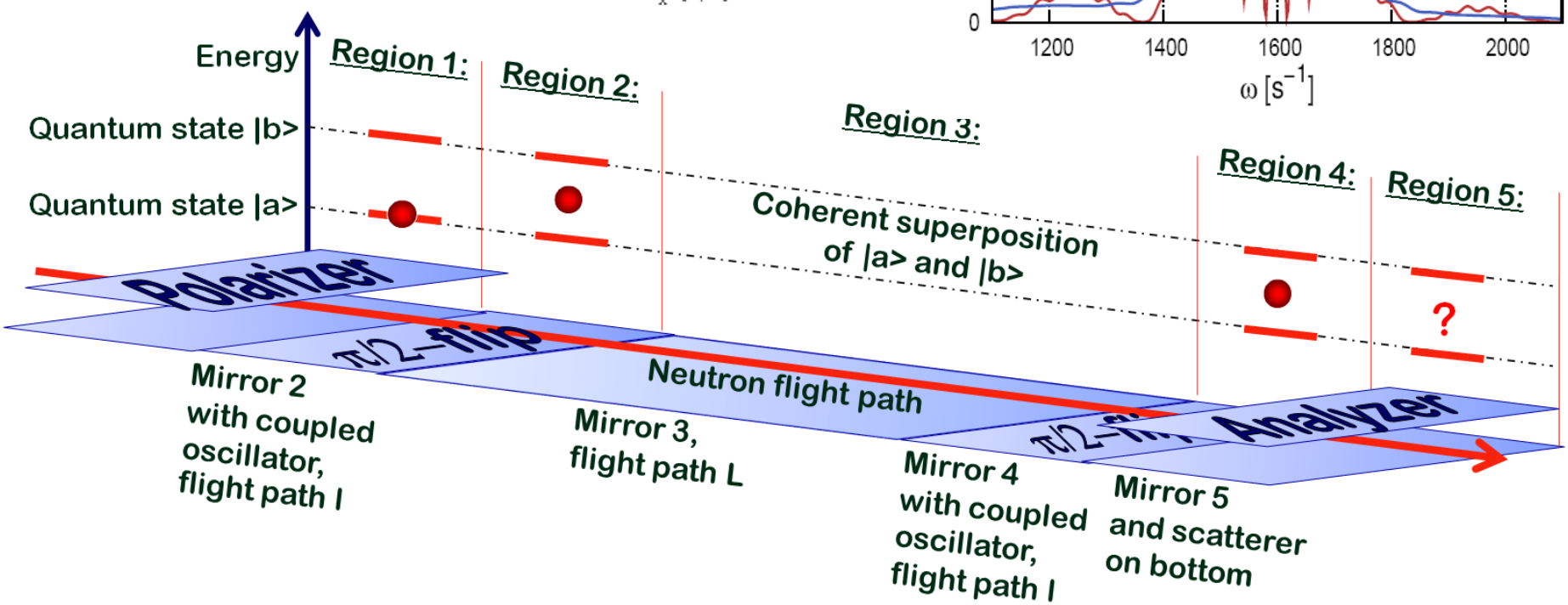

- **Tests of Newton's Inverse Square Law of Gravity at micron distances**
- **Search for an electric charge of the neutron**

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

# The Future: Ramsey-Method



# Priority Programme 1491

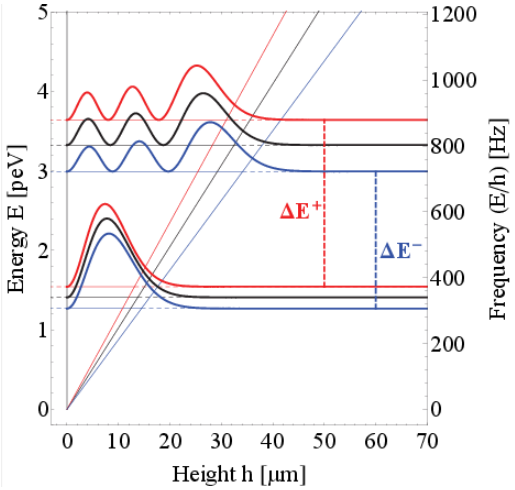
- Research Area A: *CP-symmetry violation and particle physics in the early universe*
  - **Neutron EDM** $\Delta E = 10^{-23}$ eV
- Research Area B: *The structure and nature of weak interaction and possible extensions of the Standard Model*
  - **Neutron β-decay** V – A Theory
- Research Area C: *Relation 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***

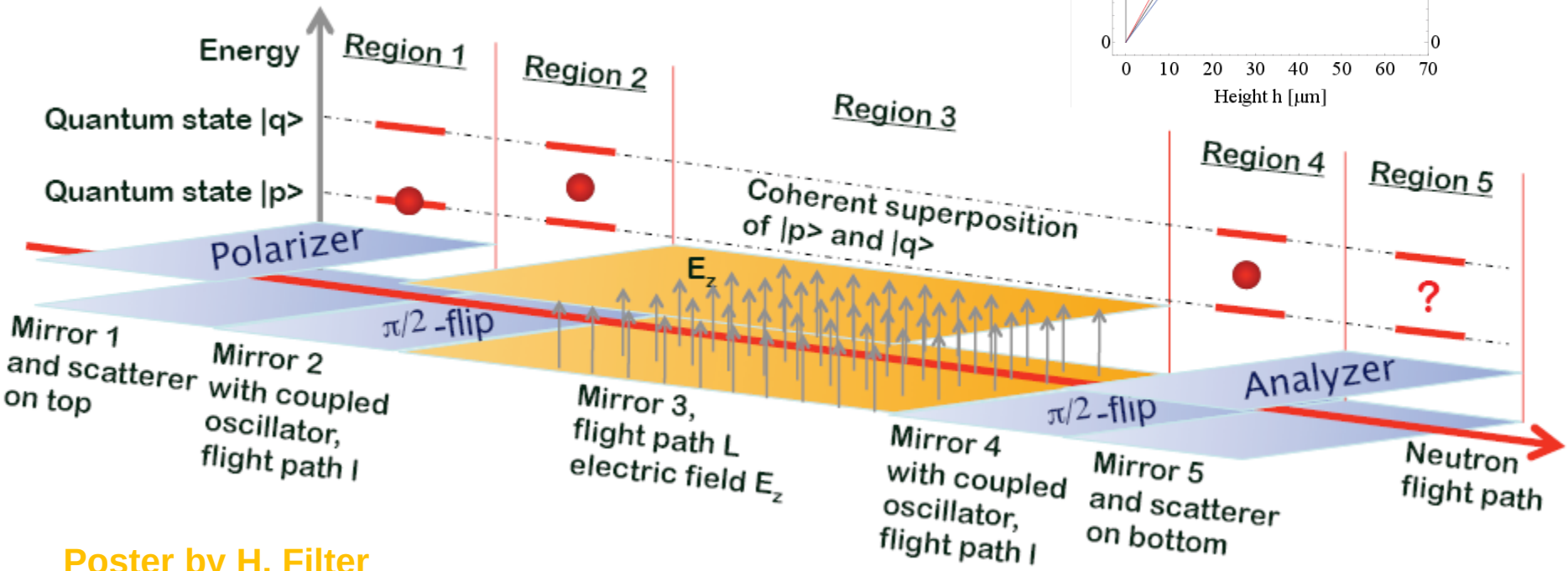
# Charge quantization and the electric neutrality of the neutron.

- 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.*
- **Storage:**

  **Improve limit by two orders of magnitude**

  **45 kV/mm**

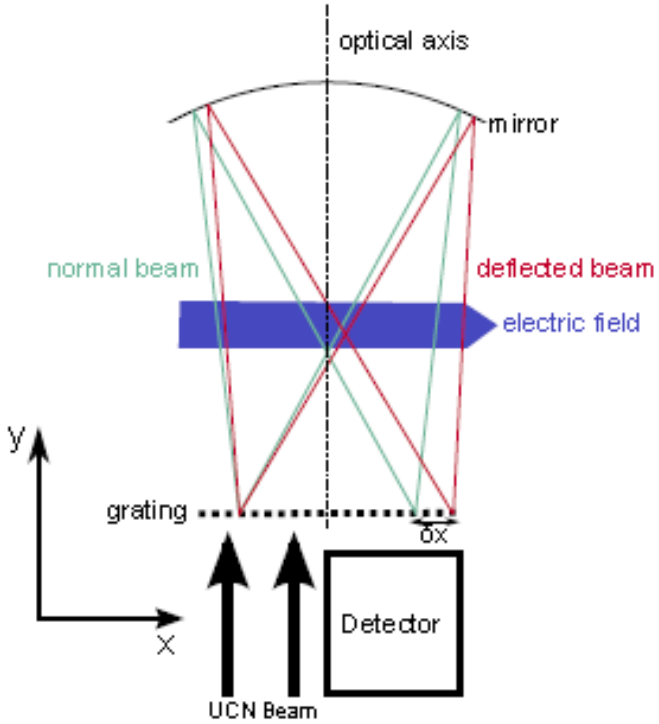


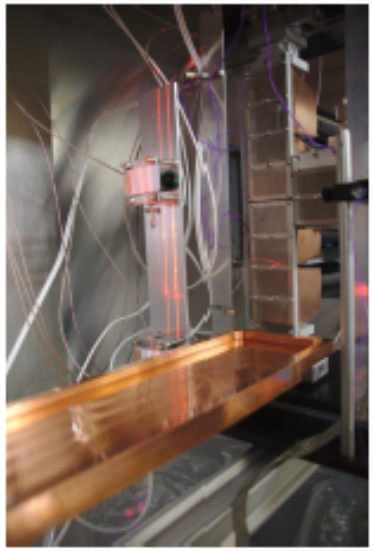



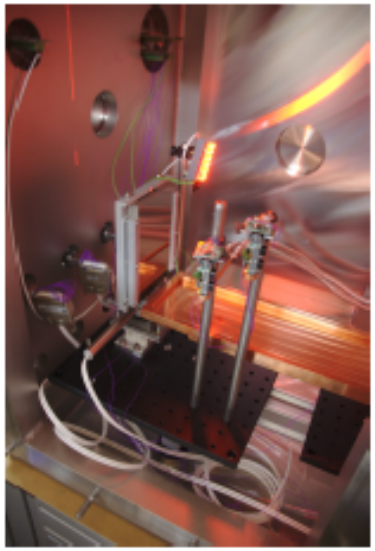

Poster by H. Filter

# Mainz Experiment

- Principle based on Borisovs experiment 1987
- Geometric modifications (see Poster of D. Brose et al.)
- Liquid PFPE as hor. mirror





# Summary and Outlook

Comparison with the experiment of Borisov 1987 with $\delta q_n = 9 \cdot 10^{-20} e/\sqrt{\mathrm{d}}$:

| | Theoretical gain in Sensitivity/$\sqrt{\mathrm{d}}$ | |
|---|---|---|
| **Modification** | **achieved** | **aspired** |
| Increase of slope | 3.5 | 14 |
| Enhancement of electric field | X | 2 |
| Extension of the flight path | 2.25 | X |
| Higher UCN flux | 2.5 | 5 |
| Reduced flux due to extended flight path | 0.5 | X |
| Overall gain | **9.8** | **157.5** |

Measured sensitivity: $\delta F = 8 \cdot 10^{-34} N/\sqrt{\mathrm{d}}$

# 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,

# Summary

- Gravity Resonance Spectroscopy
  - Quantum states in the gravity potential of the earth and coherence superposition
- Search for deviations from Newtons gravity law at short distances
  - Large extra dimensions
  - Dark matter particles
  - Dark energy
- Tests of weak interaction with neutron beta-decay experiments
  - New results published (UCNA, PERKEO)
  - Experiment PERC, Nab
- Scientific Programme SPP 1491