Q-Bounce: The dynamics of a quantum wave packet of a neutron in the Earth‘s gravity field

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Outline

- Motivation: Gravity Experiments in the 21st century?!
- How to realize a quantum-bouncing ball with ultracold neutrons with Q-Bounce
- Sensitivity to Non-Newtonian gravity
- Outlook

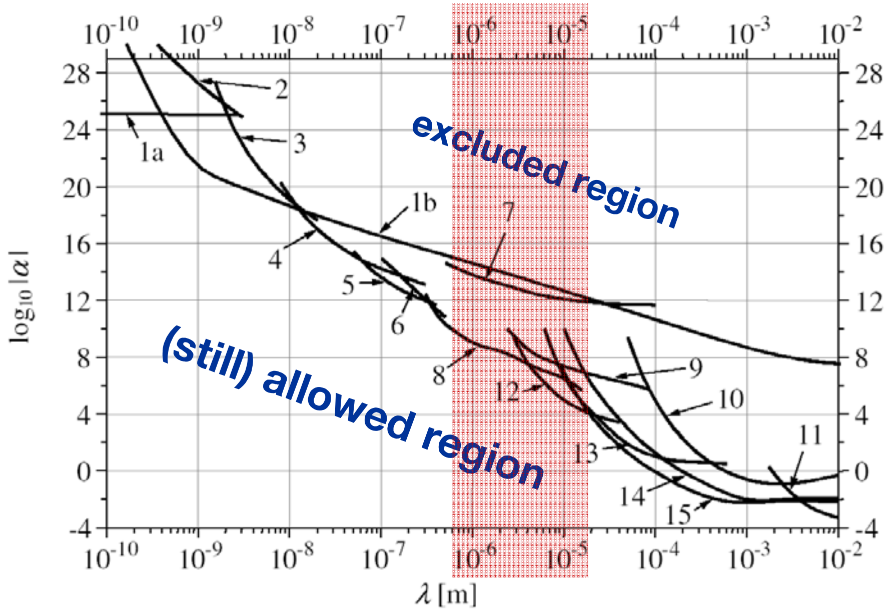
Gravity experiments in the 21st century ?!

Q-Bounce – a gravity experiment with UCN, sensitive to the gravity potential at distances between 1 and 10 microns

Interests:

- test of Newton's law of gravity at short distances (1-10 microns)
- study of the connection between quantum mechanics and gravity
- constrain existing limits for Non-Newtonian gravity

$$\phi(r) = -G_4 \frac{m}{r}(1 + \alpha \cdot e^{-r/\lambda})$$



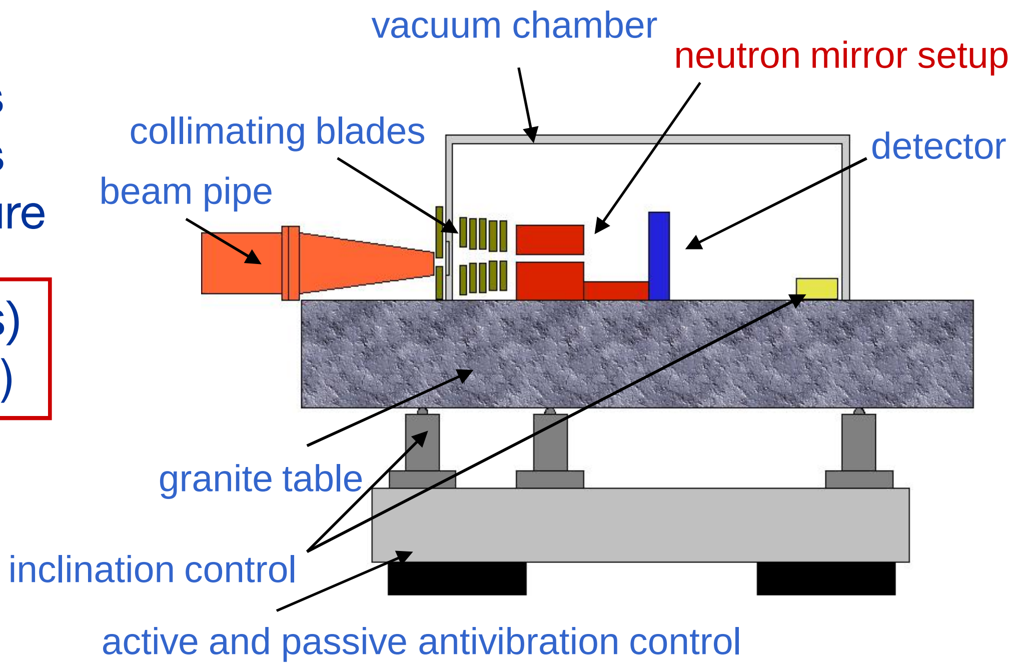
from: U. Schmidt, habilitation theses, PI Heidelberg, 2005

Q-Bounce – An Overview

- successor of the gravity experiments at PF2/ILL (1998-2005)
  [ILL (Grenoble), Physikalisches Institut (Heidelberg), PNPI (St. Petersburg), JINR (Dubna)]
- completely new, portable setup
- designed and constructed at Physikalisches Institut in Heidelberg in 2007/08
- improvements:
  - stability of the setup
  - quality of the neutron mirrors
  - quality of our track detectors
  - automated read-out procedure

- 1^{st} run: 2008 at PF2/ILL (45 days)
- 2^{nd} run: 2009 at PF2/ILL (50 days)

today:
focus on neutron mirror setup
and 1^{st} run



Trapping UCN's in the earth's gravitational field

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:

$$\varphi_n(0)=0$$

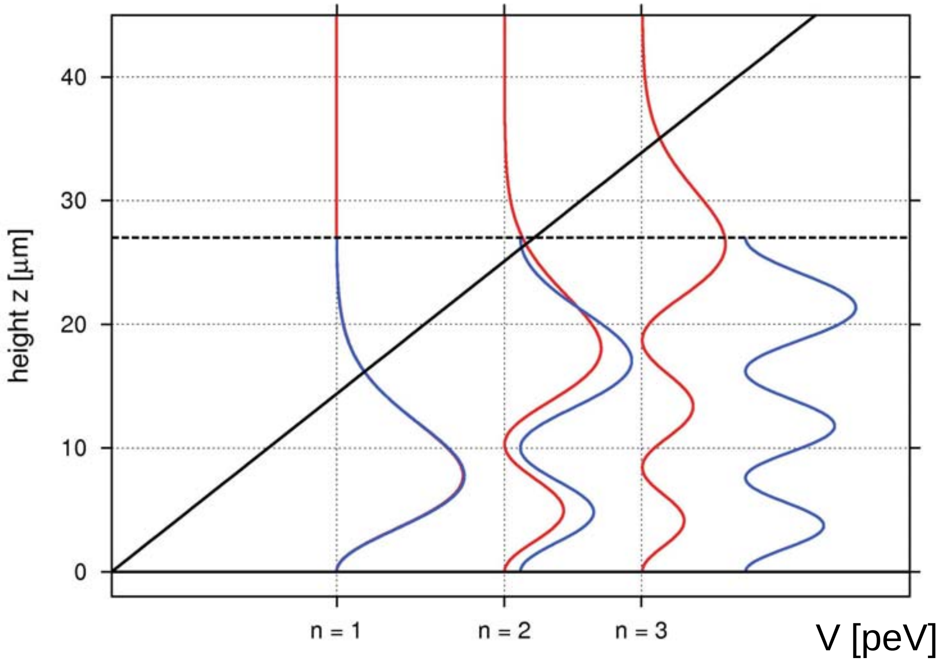
with 2nd mirror at height l

$$\varphi_n(l)=0$$

solutions: Airy-functions

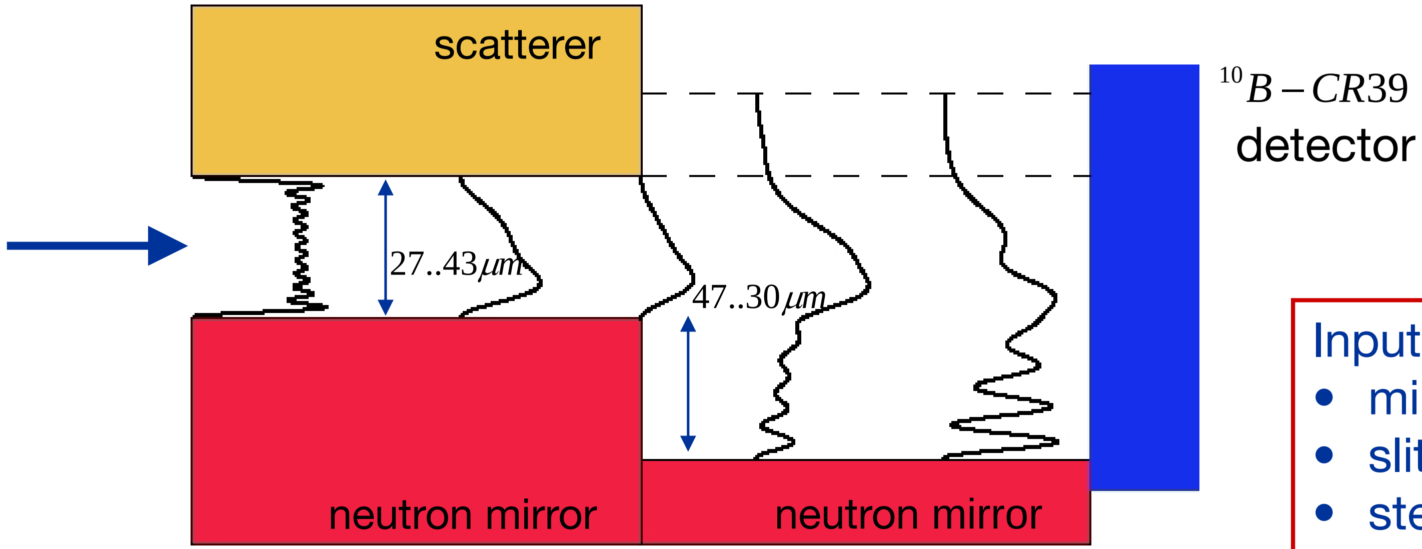
scales: energies: peV
length: μm

	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	3.97peV



neutron mirror

Q-Bounce:
The Neutron Mirror Setup



Input parameters:
- mirror lengths
- slit size
- step size
- $f(v_x)$

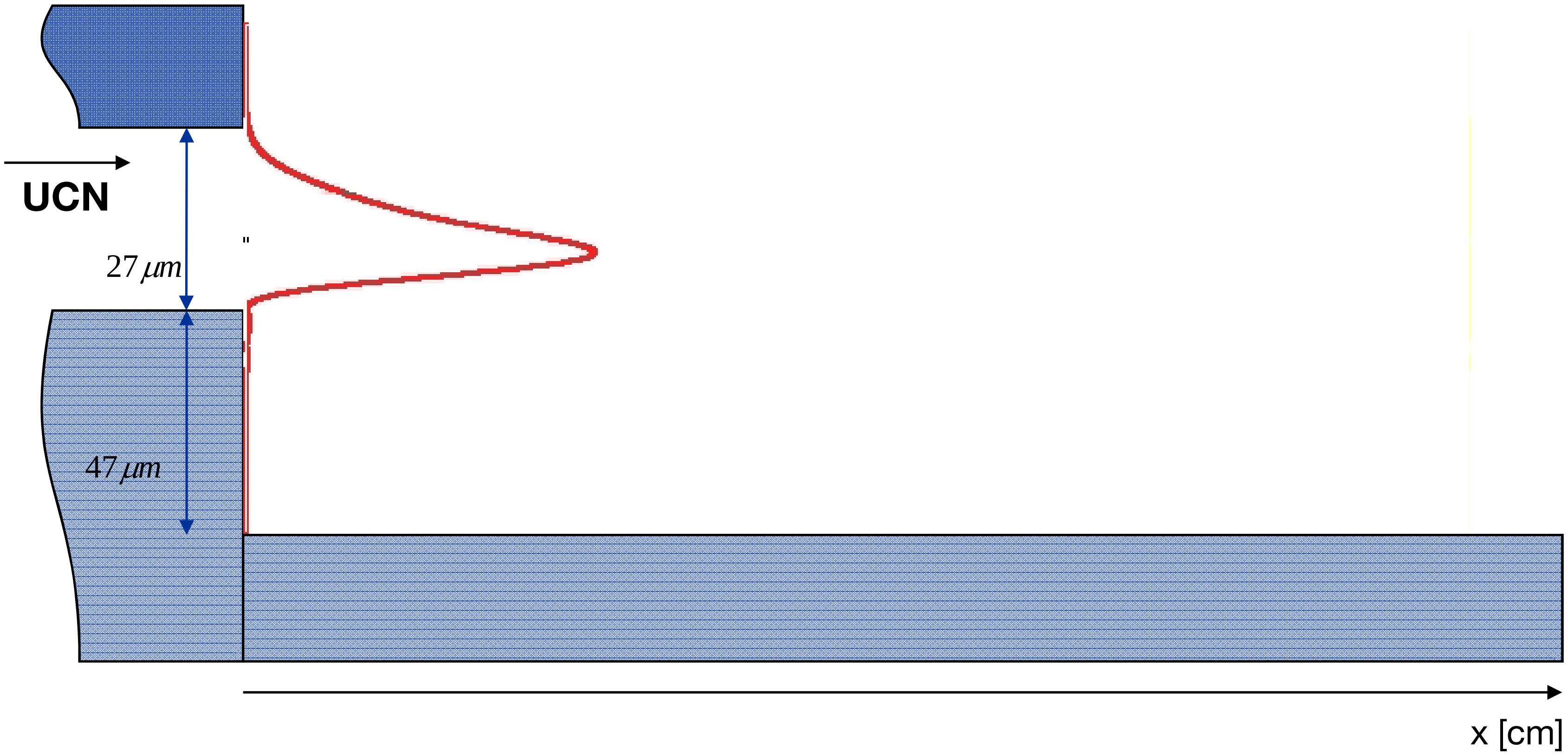
Preparation:

$$\sum_n \left| c_n \varphi_n e^{-iE_n t/\hbar} \right|^2$$

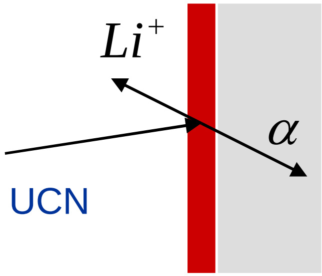
Time evolution:

$$\left| \sum_m d_m \phi_m e^{-iE_m (t-t_0)/\hbar} \right|^2$$

Q-Bounce:
The Neutron Mirror Setup



High-resolution track detector



CR39-plastic with 200nm ^{10}B coating

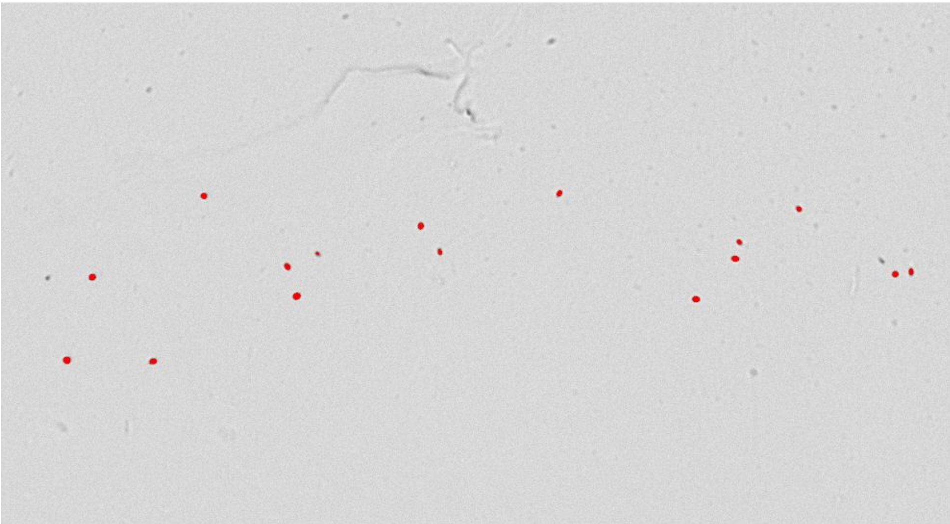
spatial resolution: $< 2\mu m$

^{10}B efficiency: $\approx 93\%$

detector efficiency: $\approx 62\%$

Process:

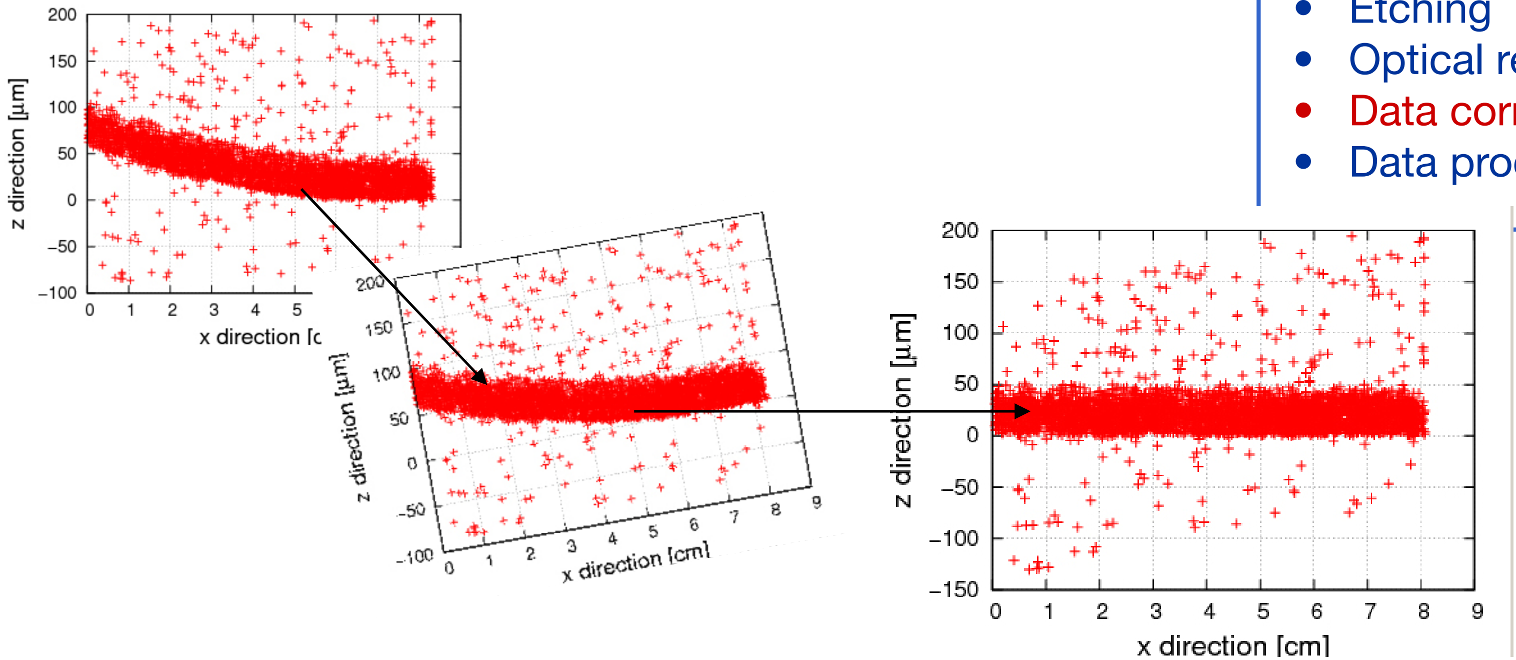
- Cleaning
- Coating
- Exposure with UCN
- Boron removal
- Etching
- Optical readout
- Data correction
- Data processing



State of the Art

- 1st run: summer 2008 (45 days) at PF2/ILL
- 2nd run: spring 2009 (50 days) at PF2/ILL

- 2 preparation measurements: $l_1 = 27\mu m, 43\mu m$
- 8 quantum bouncing ball measurements



Process:
- Cleaning
- Coating
- Exposure with UCN
- Boron removal
- Etching
- Optical readout
- Data correction
- Data processing

Simultaneous fit of TE2 and TE5

setup parametres:

- slit size: $l_1 = 43\mu m$
- step size: $l_2 = 30\mu m$
- spatial resolution: $\sigma = 2\mu m$
- mean evolution time: $\bar{t} = 10.4\ ms$
- stretching: $s_1 = 0.90, s_2 = 0.83$

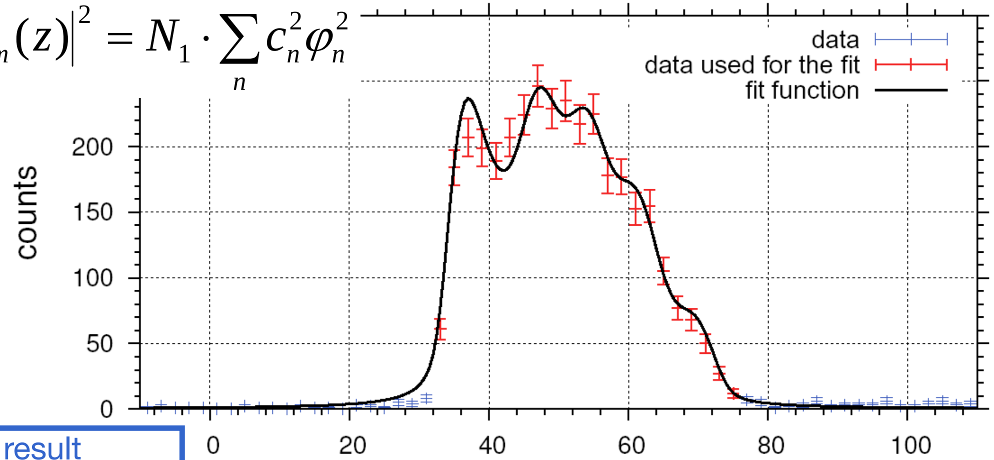
fit parametres:

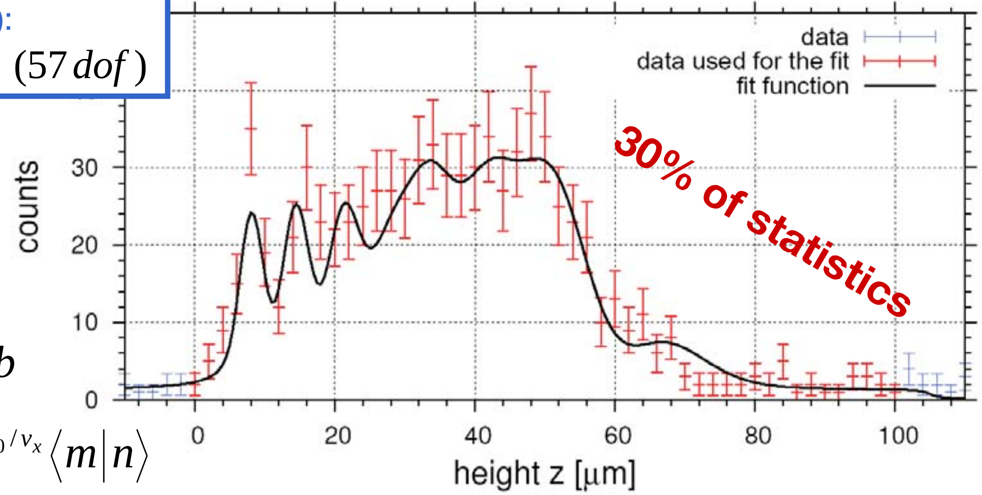
- 6 coefficients: c_n
- norm N_1 and N_2
- background $b = 1.3\ counts$

preliminary result (2008/11/19):

$\chi^2_{red} = 1.13\ \ (57\, dof)$

$$|\psi_{x=10cm}(z)|^2 = N_1 \cdot \sum_n c_n^2 \varphi_n^2$$



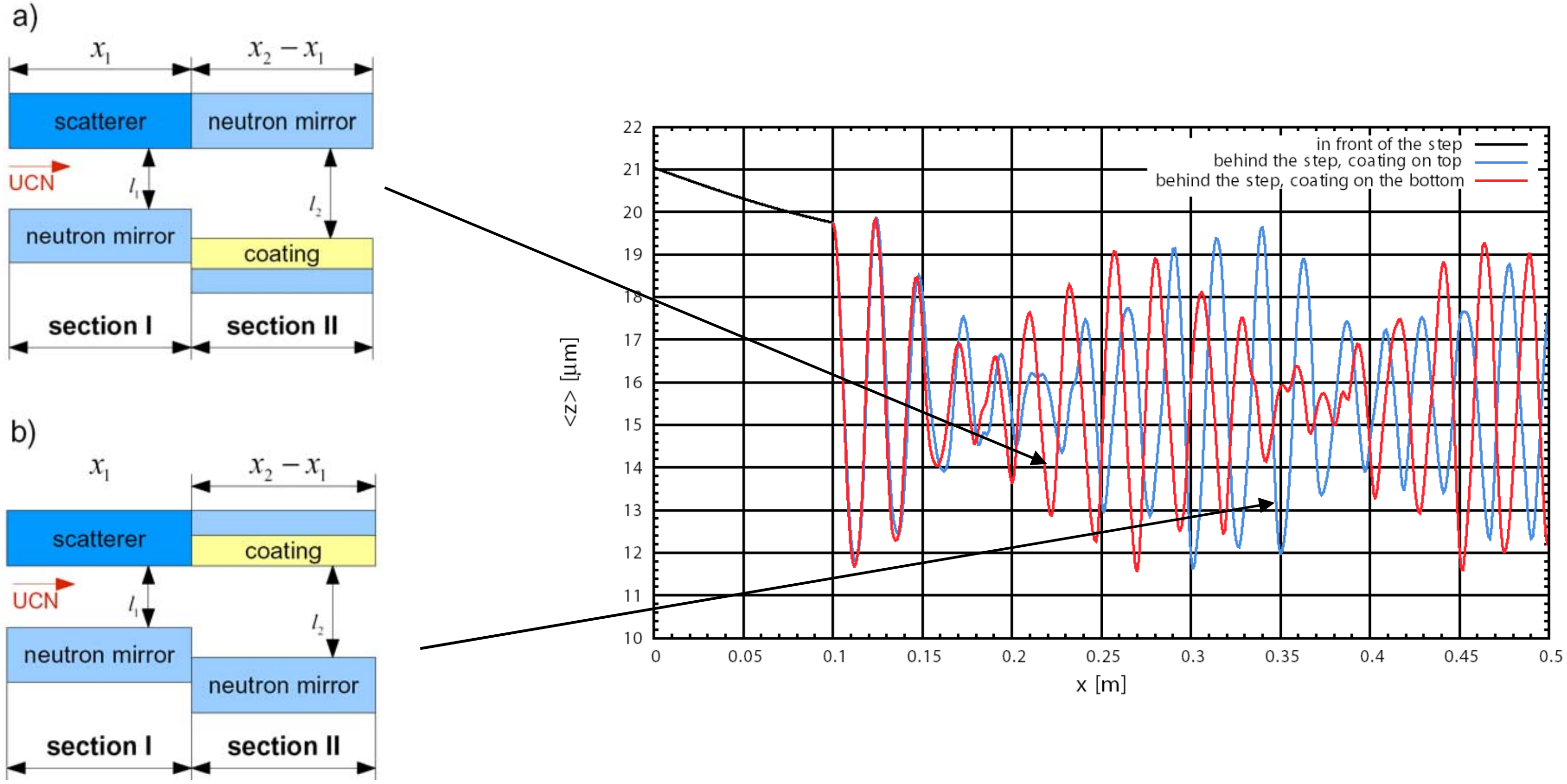


$$|\psi_{x=16cm}(z)|^2 = N_2 \left| \sum_m d_m \phi_m e^{-iE_m/\hbar \cdot (x-x_0)/v_x} \right|^2 + b$$

$$d_m = \sum_n c_n e^{-iE_n/\hbar \cdot x_0/v_x} \langle m|n \rangle$$

Search for Non-Newtonian gravity

$$\phi(r) = -G_4 \frac{m}{r}(1+\alpha\cdot e^{-r/\lambda}) \longrightarrow \phi'(z) = -2\pi\alpha\lambda^2 G_4 m\rho\cdot e^{-z/\lambda})$$



Summary

- It is of interest to probe Newton's Inverse Square Law of Gravity at short distances, e.g. µm-range.
- This is the main goal of the Q-Bounce experiment(s).
- The Q-Bounce setup is working, it is well-characterized and fulfills all criteria to deliver data with small systematic effects.
- Now: Analysis of data.

The Team:
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Appendix

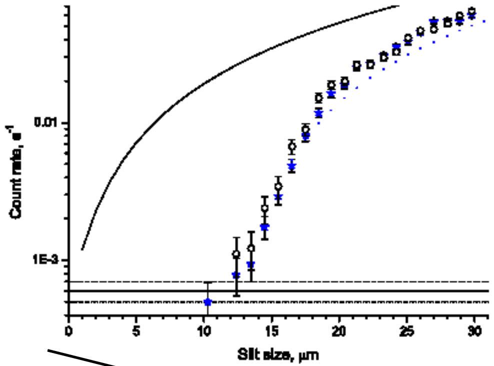
Q-Bounce – An Overview

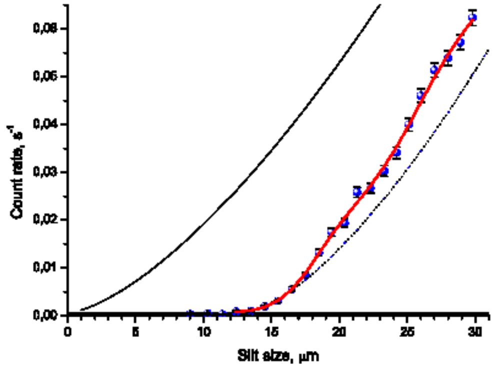
1999 – 2005:

Gravity Experiments in a Collaboration between
ILL (France), Physikalisches Institut (Heidelberg), PNPI (St. Petersburg)

several runs at UCN/PF2 at ILL:
1999, 2002, 2005

- limited by statistics
- problems due to stability of platform





GRANIT experiment
(under construction)

France: ILL, LPSC[1], LMA[2]
Russia: Gatchina, Dubna, St Petersburg,
Mainz, DESY Hamburg

- own, strong source at ILL (under construction)
- completely new experiment with new, complex multi-purpose setup

[1]Laboratoire de Physique Subatomique et de Cosmologie,

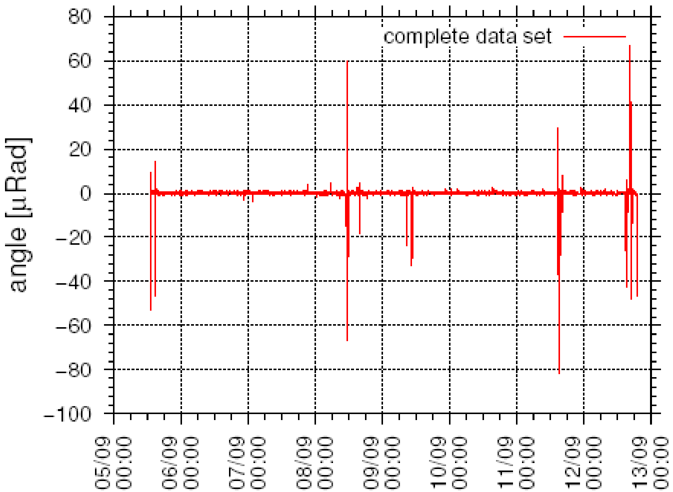
[2]Laboratoire des Matériaux Avancés

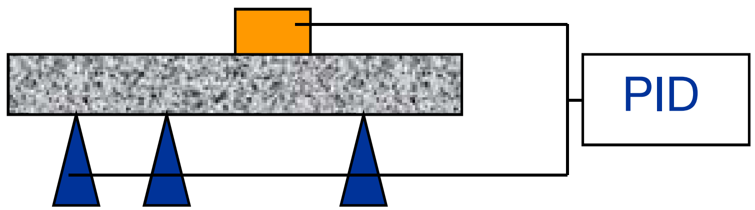
Q-Bounce

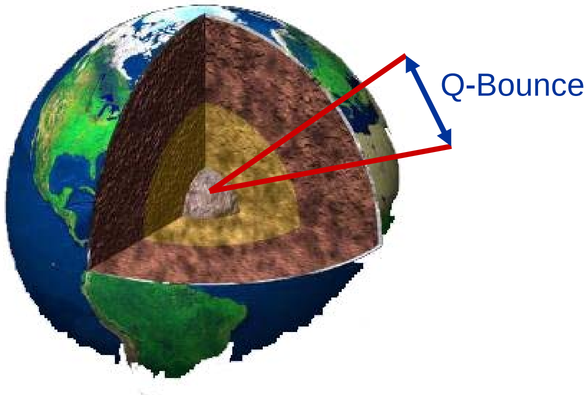
- portable setup
- completely new setup on the basis of the previous one

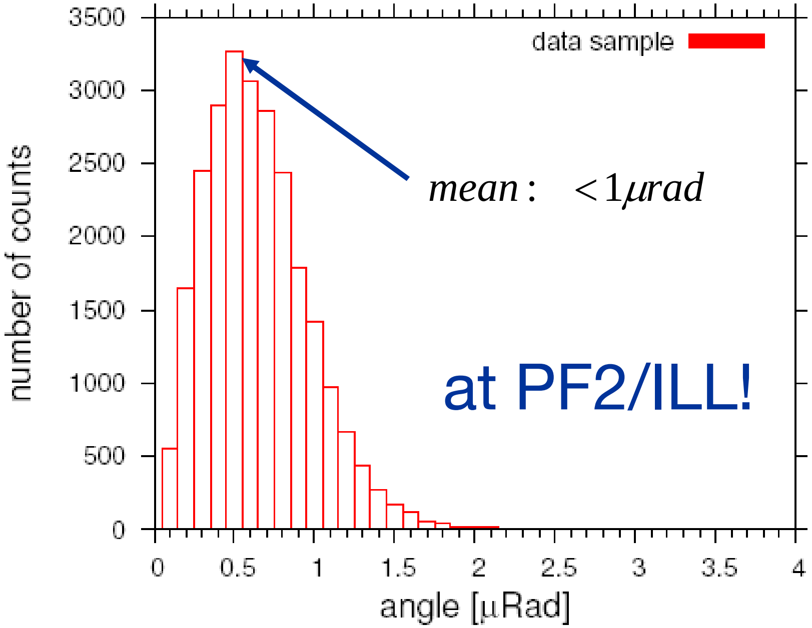
2007: planning, feasibility studies and design
2008: construction,
1st run: 45 days at UCN/PF2 at ILL

Stability of the setup: Inclination control









UCN's for Gravity Experiments
- The natural choice -

neutron properties:

- no charge: $\left(-0.4 \pm 1.1\right) \cdot 10^{-21} e$ Baumann et. al.: Phys.Rev.D37:3107-3112,1988
- small polarizability: $\left(11.6 \pm 1.5\right) \cdot 10^{-4}\, fm^3$ PDG average 2008
- sufficient lifetime for in-flight-experiments
- magnetic moment: $\vec{\mu}_n = -1.913 \vec{\mu}_N \quad \Rightarrow \quad V_{mag} \approx 60 neV / T$

magnetic shielding required!

UCN properties:

- kinetic energy: $E_{kin} < 300 neV$
- velocity: $\left(0 \le v_x \le 15\right) m/s$
- amount: **not enough yet**

Gravity experiments in the 21st century !!!

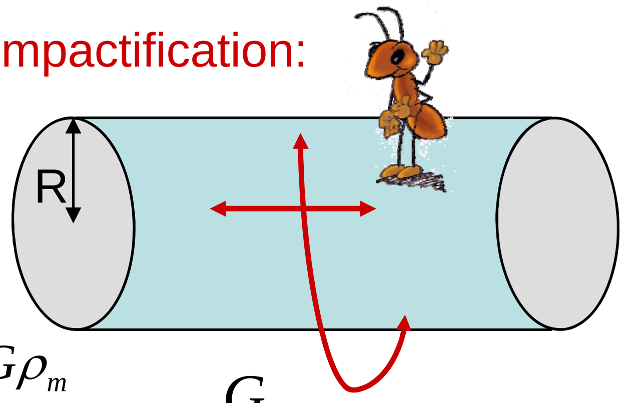
However:
Ideas of the Standard Model and General Relativity seem to be incompatible...

String theory = way out?

pointlike particles ⟶ strings

4D ⟶ 11D

1.: Concept of compactification:



$$m_{Pl} = \sqrt{\frac{\hbar c}{G}} \approx 1.22 \cdot 10^{19}\, GeV$$

$$l_{Pl} = \sqrt{\frac{\hbar G}{c^5}} \approx 1.62 \cdot 10^{-33}\, cm$$

$$\Delta\phi_{grav} = 4\pi\, G\rho_m$$

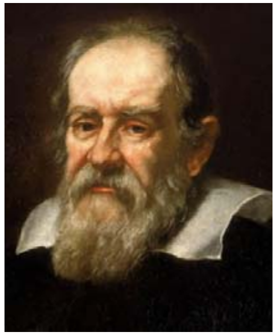
$$\phi_{grav} \sim \frac{G_n}{r^{n-2}}$$

2.: Models with Large Extra Dimensions:

1999: N.Arkani-Hamed, S. Dimopoulos and G. Dvali: Phys.Rev.D, Vol.59, 086004

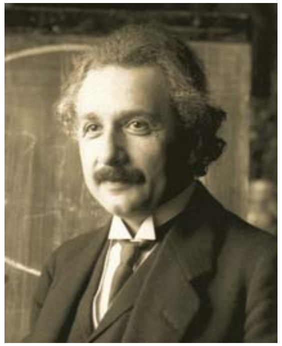
$$R \leq 1mm$$

Gravity experiments in the 21st century ???



Law of falling bodies

Newton's Axioms



General relativity

Situation today:

- Gravity law valid from 10^{-4}m until 10^{15}m.

19 orders of magnitude!

- Equivalence principle limit 2008:

$$\Delta a_{Be,Ti} = (0.6 \pm 3.1) \cdot 10^{-15} m/s^2$$

(PRL **100,** 041101 (2008))

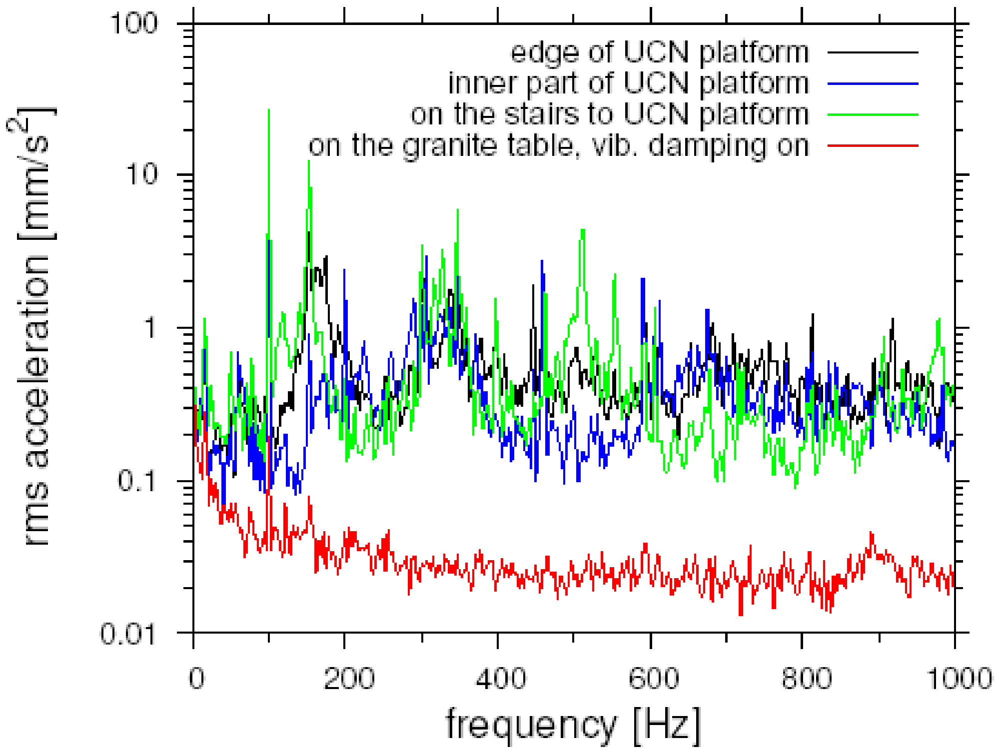
1638 — 1687 — 1915

Vibrations

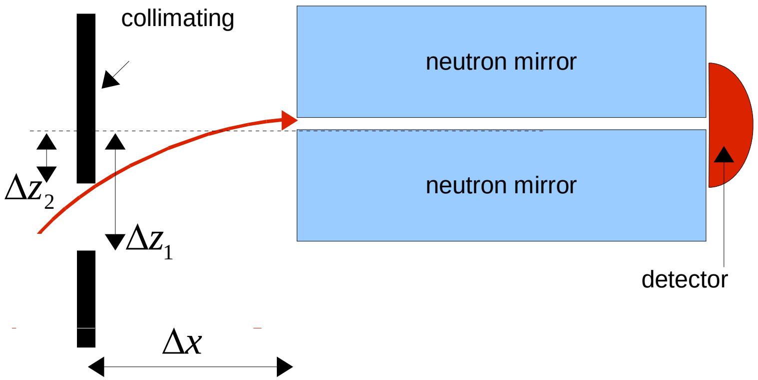
Vibrations may induce state changes!

$$E_m - E_n = \omega_{Vib}$$

$$peV \Rightarrow 10^1..10^3\,Hz$$



Adjusting the horizontal velocity distribution $f(v_x)$



$$(5.95 \leq v_x \leq 7.25)\ m/s$$