Constraint on the Coupling of Axion-like Particles to Matter with an Ultracold Neutron Experiment

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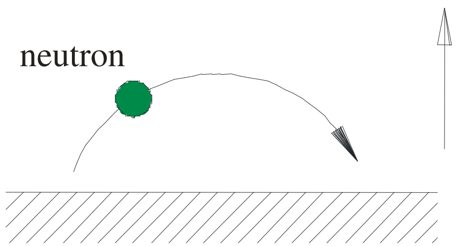
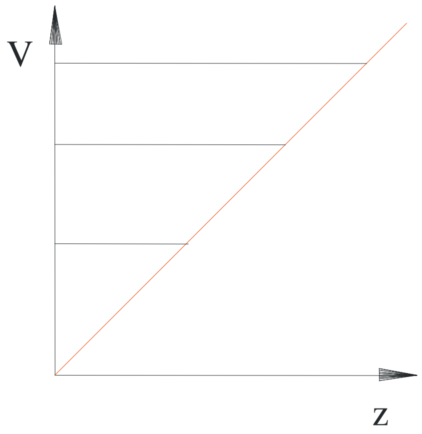
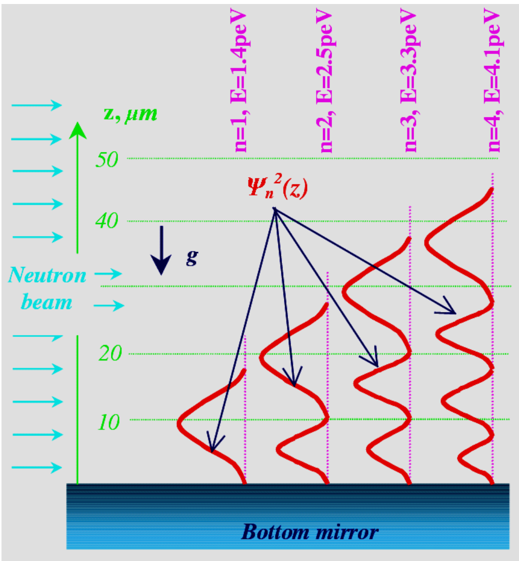
Gravitational Bound states – The idea



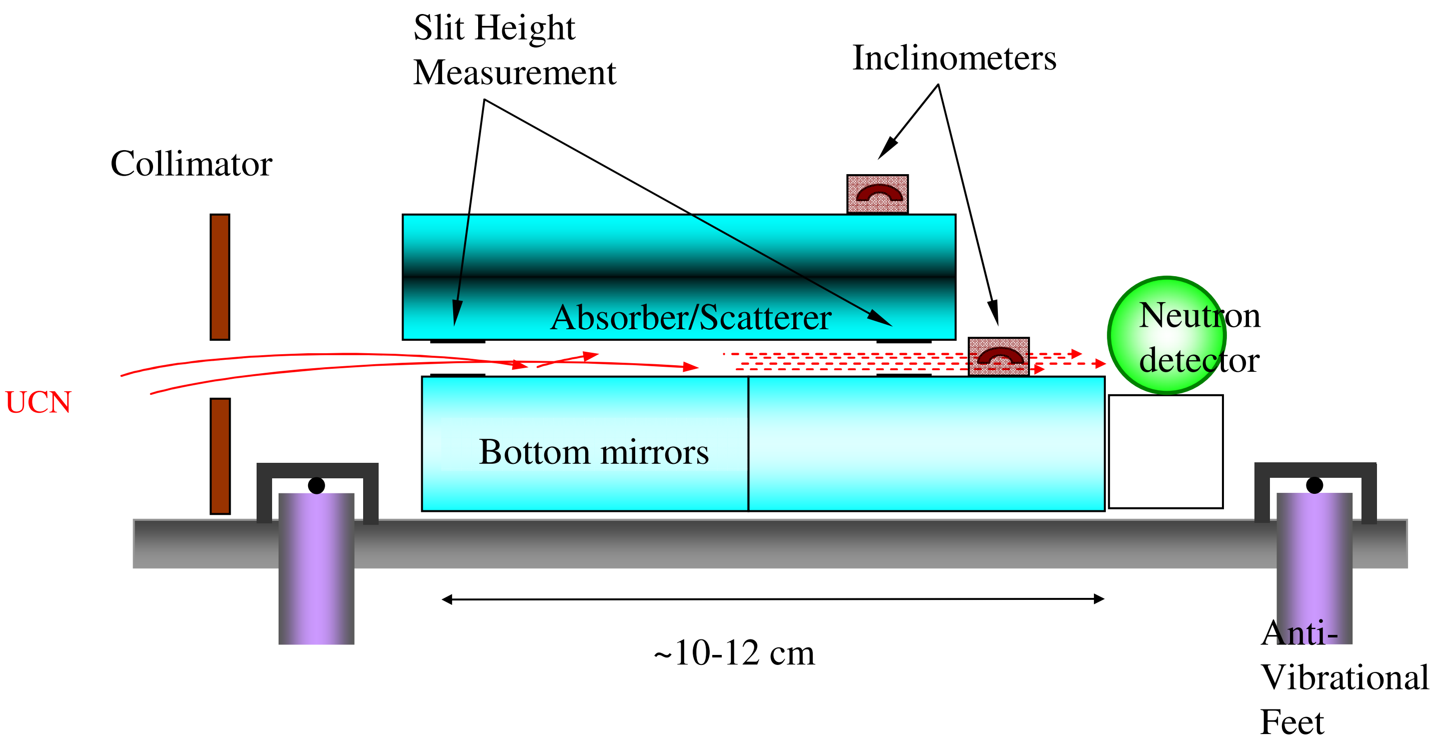




Early proposals:

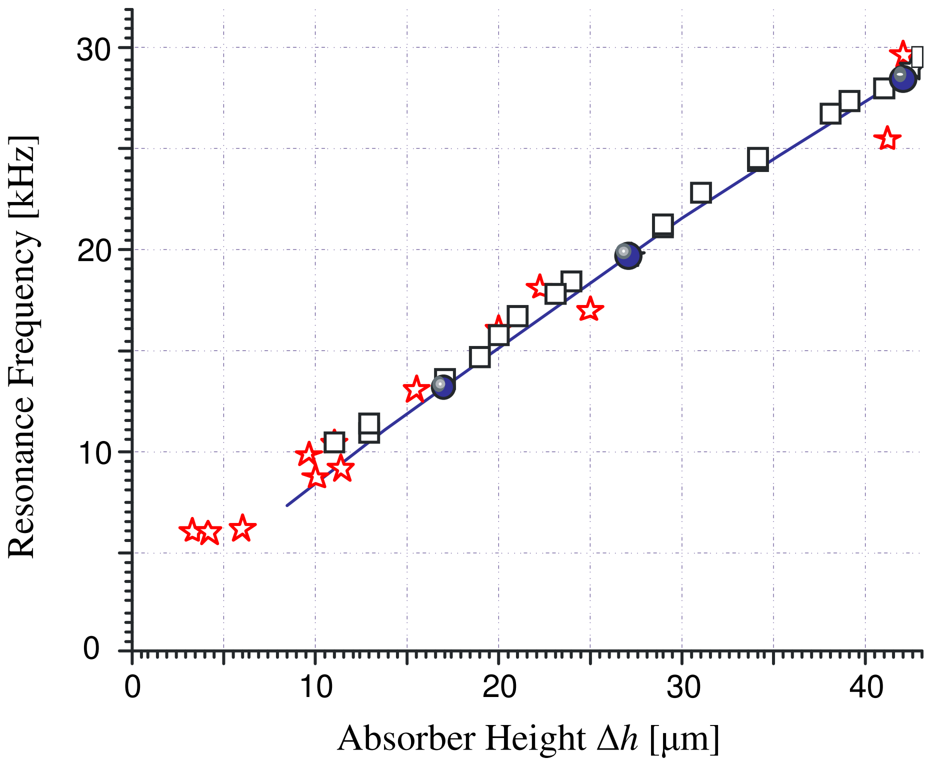
- Neutrons: V.I. Lushikov (1977/78),
  A.I. Frank (1978)
- Atoms: H. Wallis et al. (1992)

Gravitational Bound states – The experiment



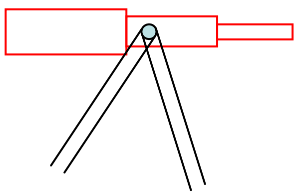
- Effective (vertical) temperature of neutrons is ~20 nK
- Background suppression is a factor of ~10^8-10^9
- Absolute horizontal leveling precision is ~10^{-6} rad
- Parallelism of the bottom mirror and the absorber/scatterer is ~10^{-6}

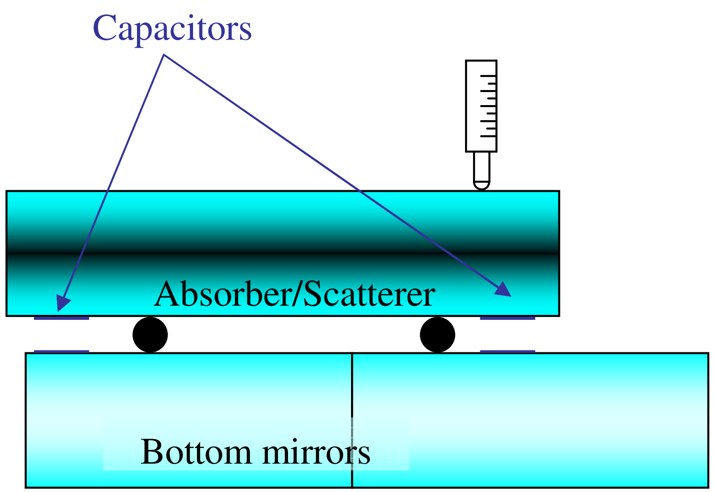
Calibration of the Absorber Height



Tools:

- Capacitors (To be calibrated)
- Long-Range Microsocope (☆)
- Wire Spacers (●)
- Micrometric Screw (□)



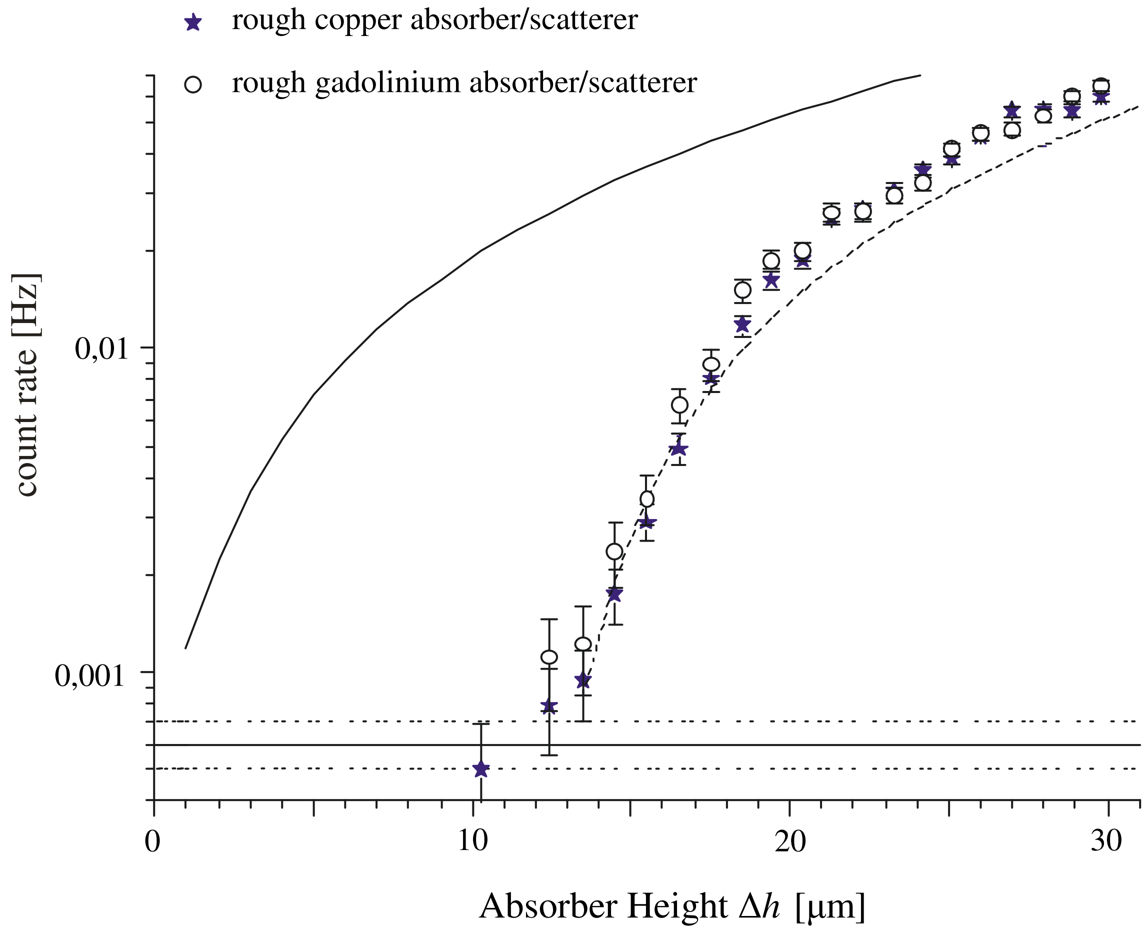


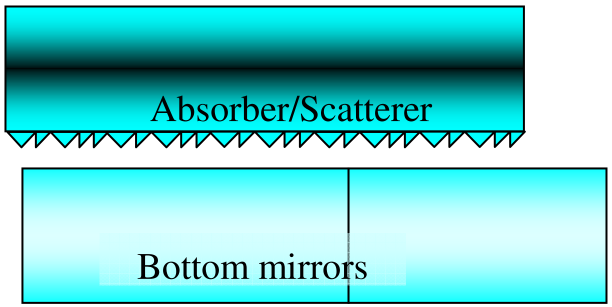
Uncertainty in Δh:

Reached: 1-1.6 µm

Possible: < 0.5 µm

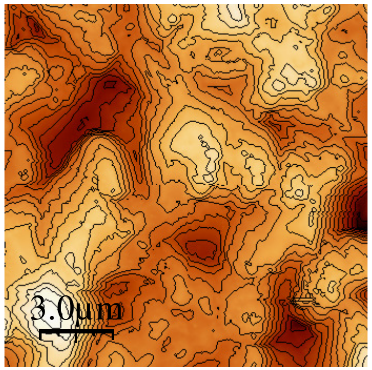
How does an absorber work?





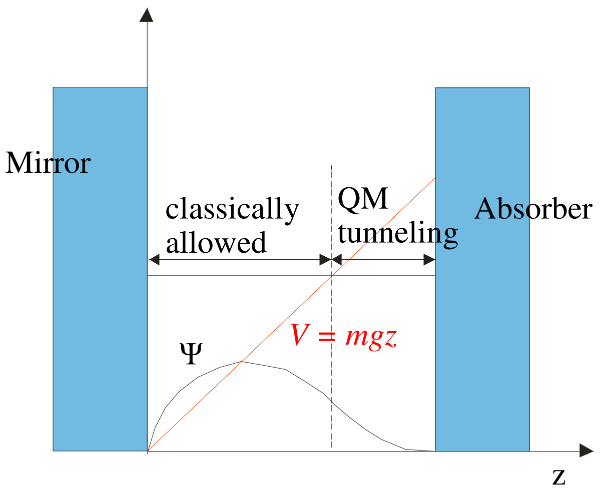
Roughness (2002):

- Standard Deviation: 0,7 µm
- Correlation length: ~ 5 µm



Lesson: It's the roughness which absorbs neutrons. A high imaginary part of the potential doesn't, since the neutron cannot enter.
(see A. Yu. Voronin et al., PRD 73, 44029 (2006))

The tunneling model

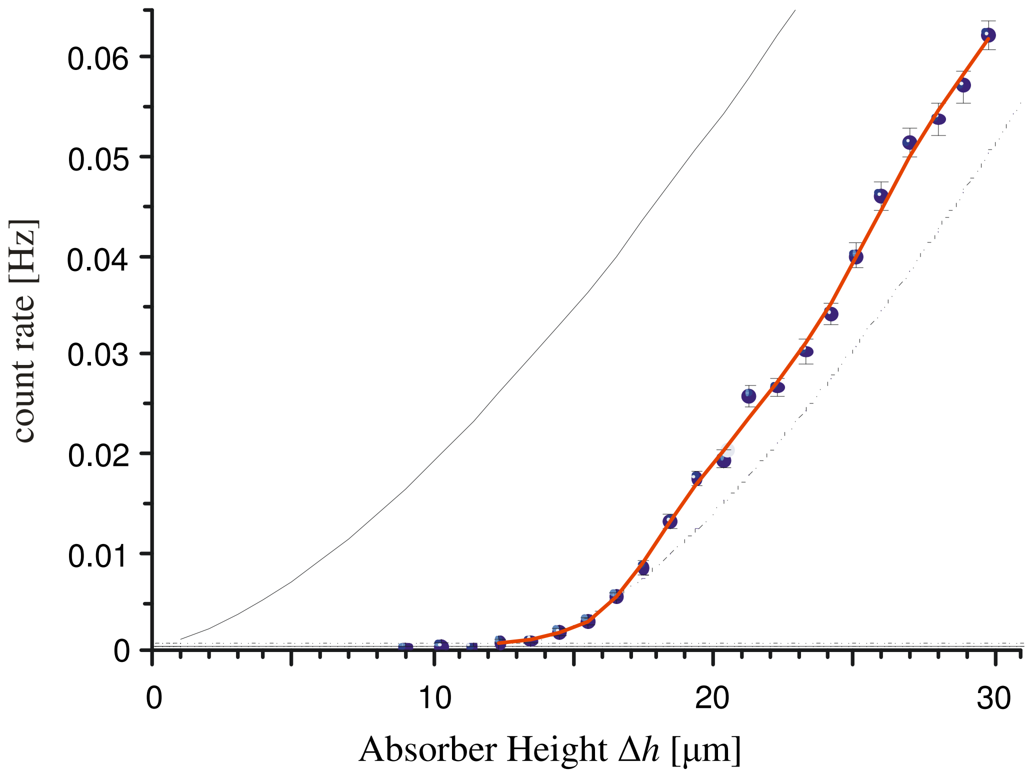


$$F(\Delta h, n) = N\beta_n \exp\left(-\frac{\tau_{\text{passage}}}{\tau_{n,\text{tunnel}}}\right)$$

$$= N\beta_n \exp\left(-\alpha \frac{L}{v_{\text{horiz}}} \chi(\Delta h, n)\right)$$

$$\chi(\Delta h, n) = \begin{cases} \exp\left(-\frac{4}{3}\left(\frac{\Delta h - z_n}{l_0}\right)^{3/2}\right) & ; \Delta h > z_n \\ 1 & ; \text{otherwise} \end{cases}$$

Characteristic length scale: $l_0 = \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 5.87\ \mu\text{m}$

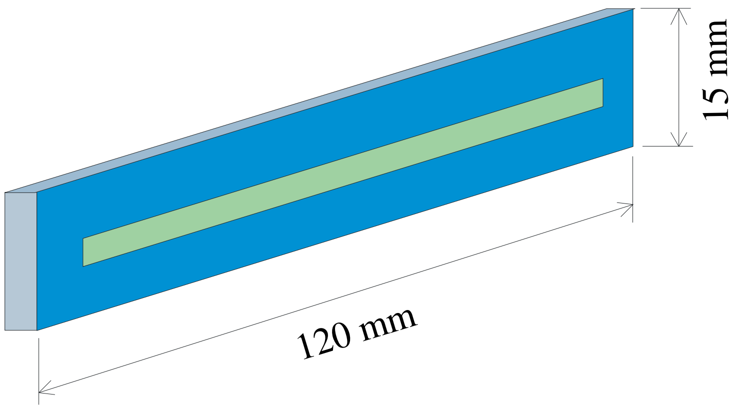


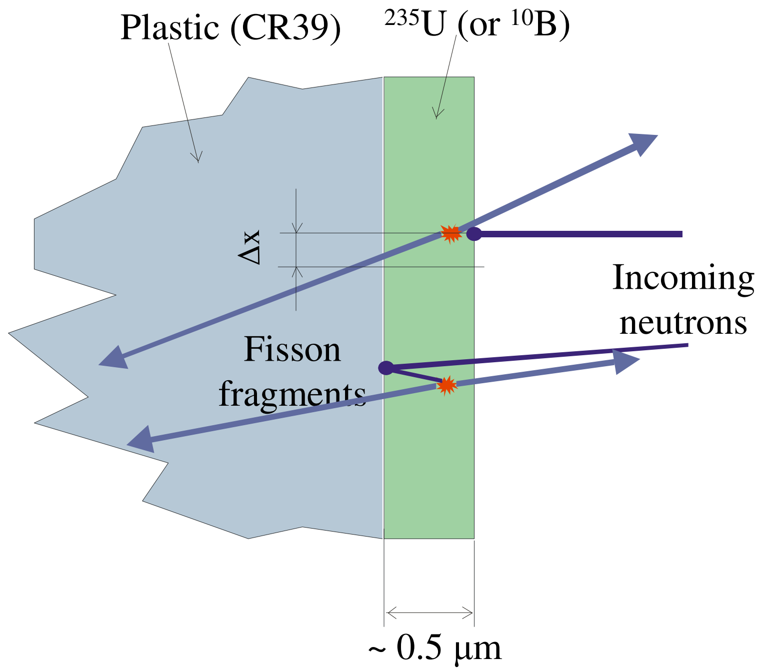
Results:

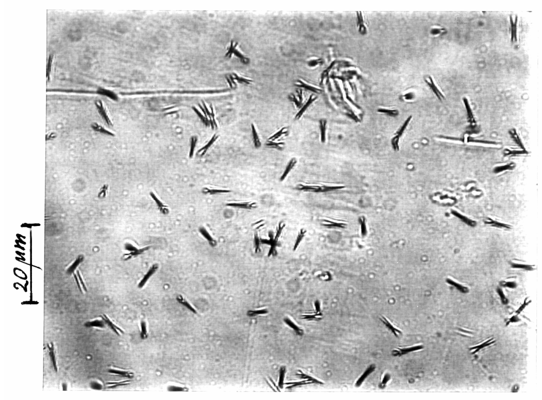
$z_1 = 12.2 \pm 1.8(\text{syst}) \pm 0.7(\text{stat})\ \mu\text{m}$

$z_2 = 21.6 \pm 2.2(\text{syst}) \pm 0.7(\text{stat})\ \mu\text{m}$

Position-Sensitive Detector

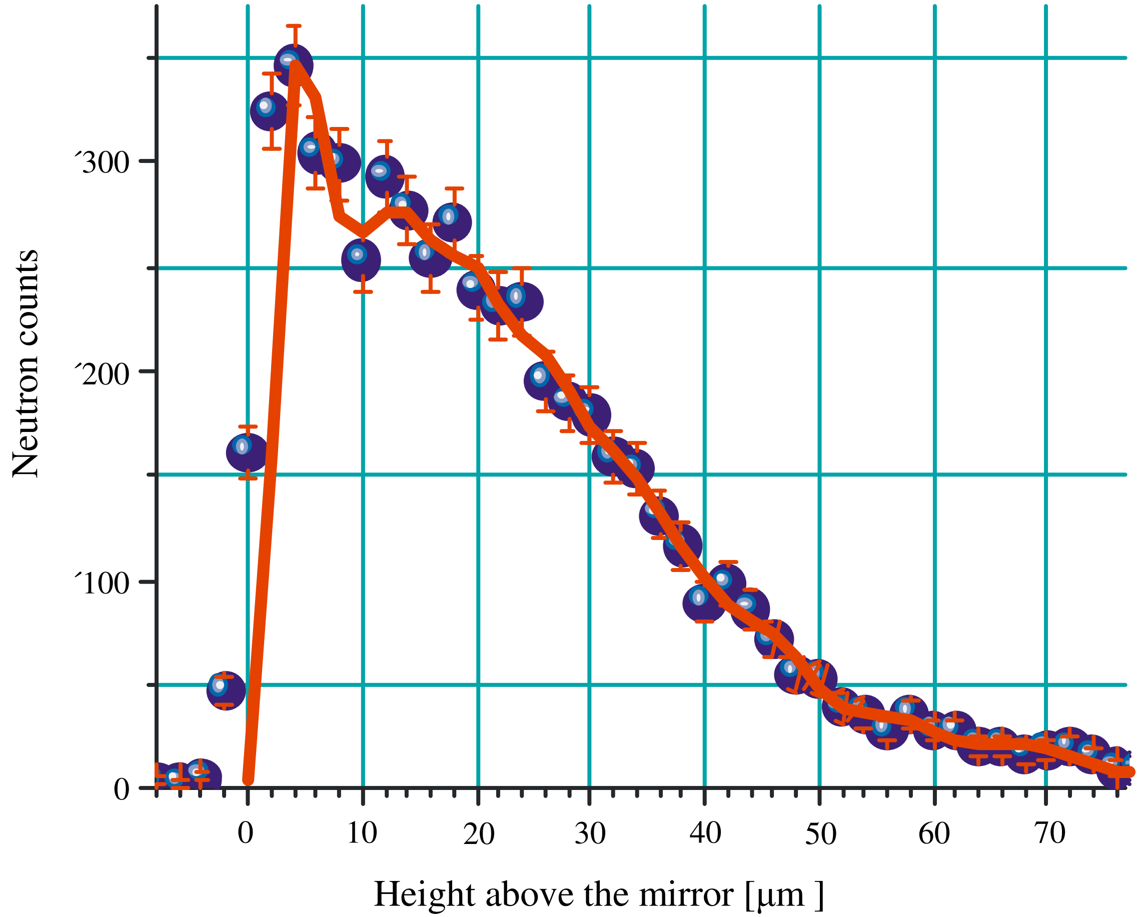


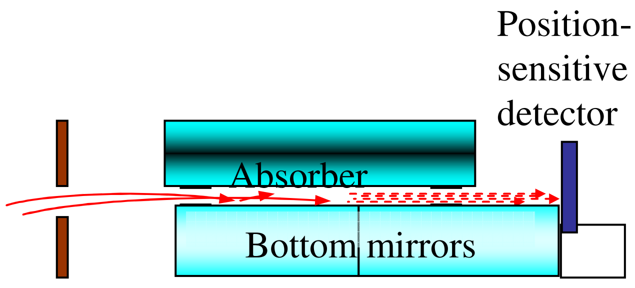




Picture of developed detector with tracks

Results with the Position-Sensitive Detector





Motivation for the Axion

Original Proposal: F. Wilczek, 1978

Solution to the "Strong CP Problem": The electrical dipole moment d_n of the neutron is …

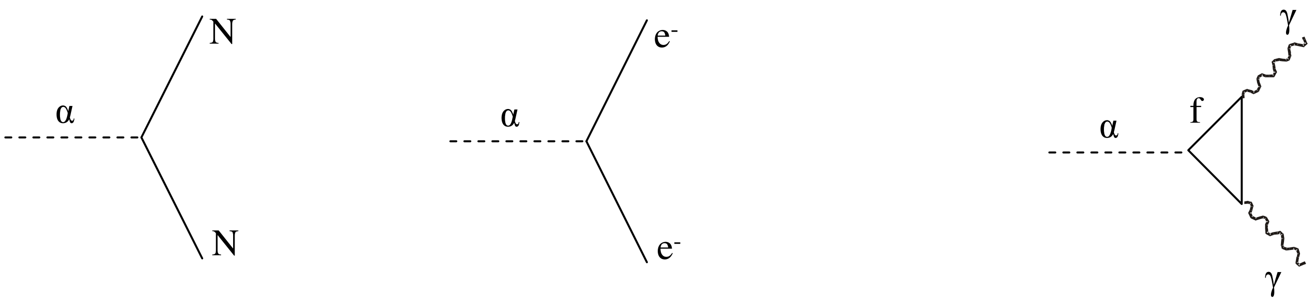
- Latest experimental limit: $|d_n| < 2.9 \times 10^{-26}$ ecm (90% C.L.)
- Prediction from the Standard Model, perturbative: $|d_n| = 10^{-31}..10^{-32}$ ecm
- Prediction from QCD, non-perturbative: $|d_n| = \Theta \cdot 10^{-16}$ ecm (+ perturbative terms)

A slightly more constraining result can be derived from atomic EDMs

If there were an Axion, then $\Theta = 0$.

Modern interest:

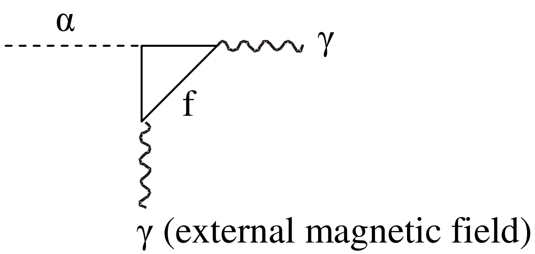
Axion is a candidate for dark matter. All couplings are weak.



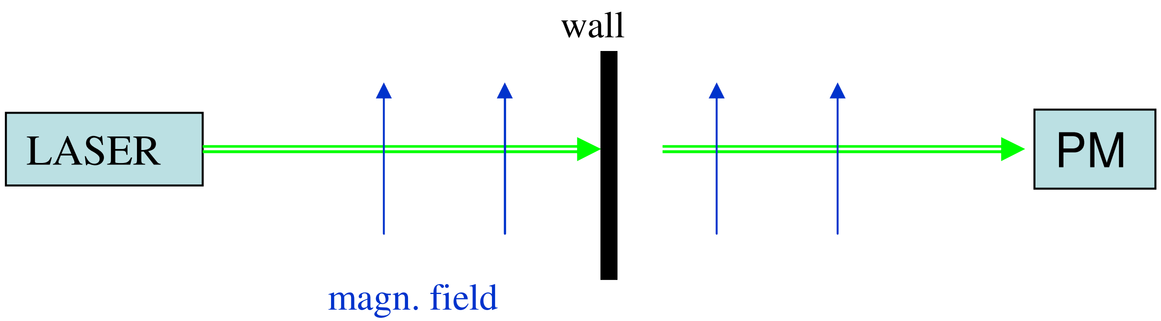
Possible experimental signatures

Incomplete List:

- Astronomy und Cosmology
- Particle accelerators (additional decay modes)
- Conversion of Galactic Axions in a magnet field into microwave photons:



- Light shining through walls:



Three Macroscopic Potentials

scalar-scalar: $$V(r) = -g_S{}^1 g_S{}^2 \frac{1}{4\pi r} \exp(-r/\lambda)$$

Allowed range: λ = 20 µm … 200 mm (corresponding to $m_\alpha = 10^{-2}$ eV .. 10^{-6} eV)

Looks like 5th force (see Hartmut‘s talk).

scalar-pseudoscalar: $$V(r) = -g_S{}^1 g_P{}^2 \frac{\sigma_2 \cdot \hat{r}}{8\pi m_2 c}\left[\frac{1}{r\lambda} + \frac{1}{r^2}\right]\exp(-r/\lambda)$$

Most often done with electrons as polarized particle. Coupling Constants are not equal.

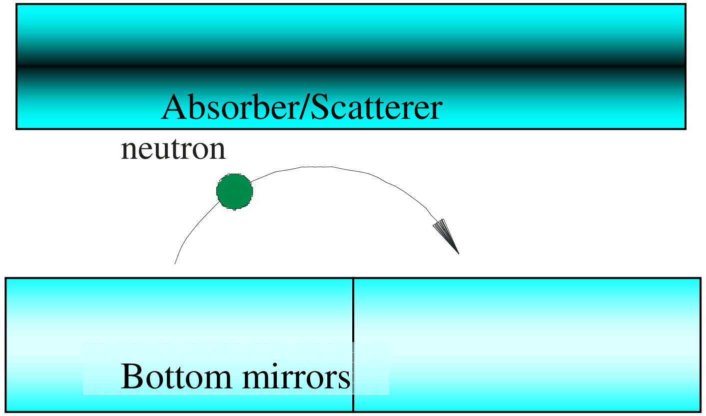
pseudoscalar-pseudoscalar: $$V(r) = -g_P{}^1 g_P{}^2 \frac{1}{16\pi m_1 m_2 c}\left[(\sigma_1 \cdot \sigma_2) f(r) + (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) g(r)\right]$$

Disappears for an unpolarized source

Effect on Gravitationally Bound States

Integration of 2nd potential over mirror:

$$V(z) = -g_S{}^N g_P{}^n \frac{\hbar \rho_\mathrm{m} \lambda}{8 m_\mathrm{n}{}^2 c} \exp(-z/\lambda) \underbrace{(\sigma_n \cdot \hat{z})}_{\pm 1}$$



Inclusion of absorber:

$$W(z) = \pm g_S{}^N g_P{}^n \frac{\hbar \rho_\mathrm{m} \lambda}{8 m_\mathrm{n}{}^2 c} \underbrace{\left[\exp(-z/\lambda) - \exp(-(\Delta h - z)/\lambda)\right]}_{\frac{2z}{\lambda} + \text{const.}}$$

After dropping the invisible constant piece,

$W(z)$ is linear in z

$$g \rightarrow g_\mathrm{eff} = g \pm g_S{}^N g_P{}^n \frac{2 \hbar \rho_\mathrm{m}}{8 m_\mathrm{n}{}^3 c}$$

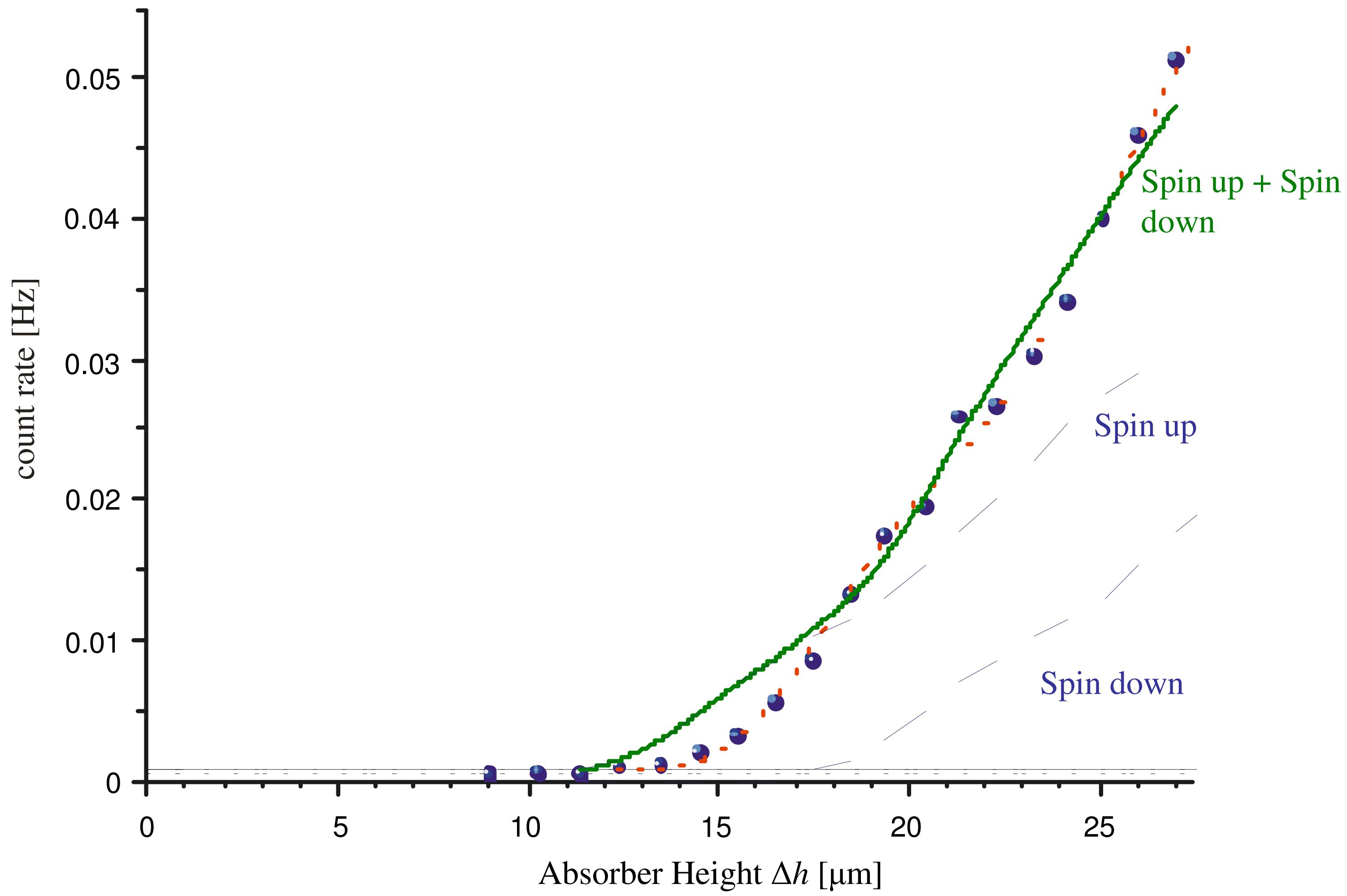
Our limits are calculated from a shift of the turning point by 3 μm.

$$z_1 = 2.34 \sqrt[3]{\frac{\hbar^2}{2 m^2 g}} = 13.7\ \mu\mathrm{m}$$

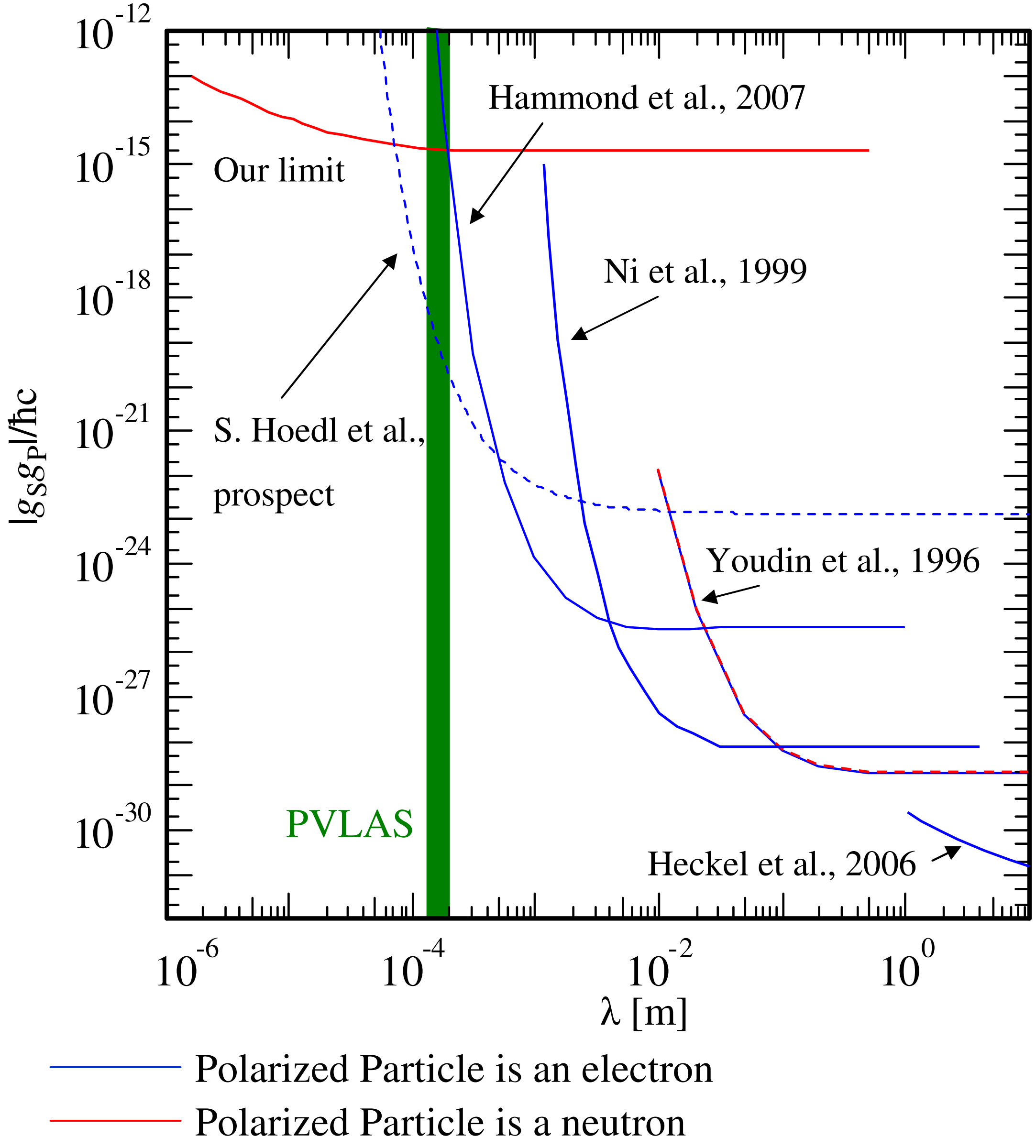
$$z_2 = 4.09 \sqrt[3]{\frac{\hbar^2}{2 m^2 g}} = 24.0\ \mu\mathrm{m}$$

Extraction of our Limit

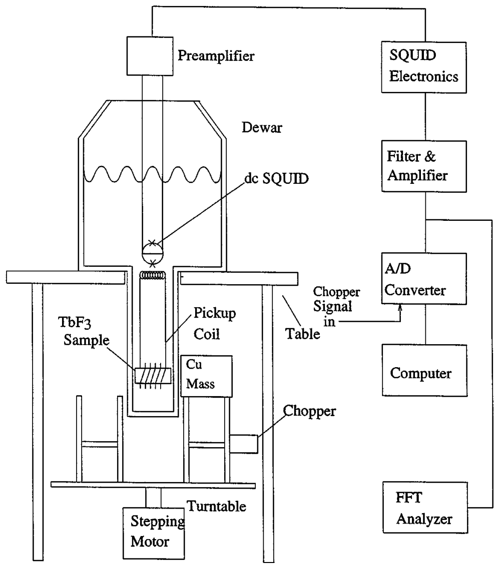
Why can we use unpolarized neutrons?



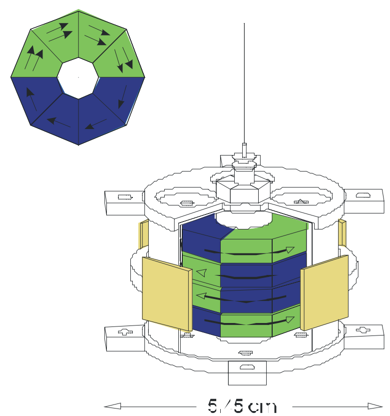
Exclusion Plot



Ni et al., 1999:



Heckel et al., 2006:



Summary

• Gravitationally Bound Quantum States detected with Ultracold Neutrons

• Characteristic size is ~ µm

• Interaction with Axion would change potential

• Bound State Size is expected from Standard Gravitation

⇒ Exclusion of a strong Axion potential