qBounce:
Gravity Resonance Spectroscopy to test Dark Energy and Dark Matter models

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Abstract

We present transitions between quantum states of gravitationally bound neutrons using a Rabi resonance spectroscopy method. Quantum interferences between different states have been observed by inducing transitions by mechanical vibration. The transition frequency depends only on the neutrons mass, Plancks constant and Earth's gravity. This tests Newton's Inverse Square Law of Gravity at the micrometer regime. We are sensitive to hypothetical Fifth Forces and potential large extra dimensions of submillimetre size of space-time.
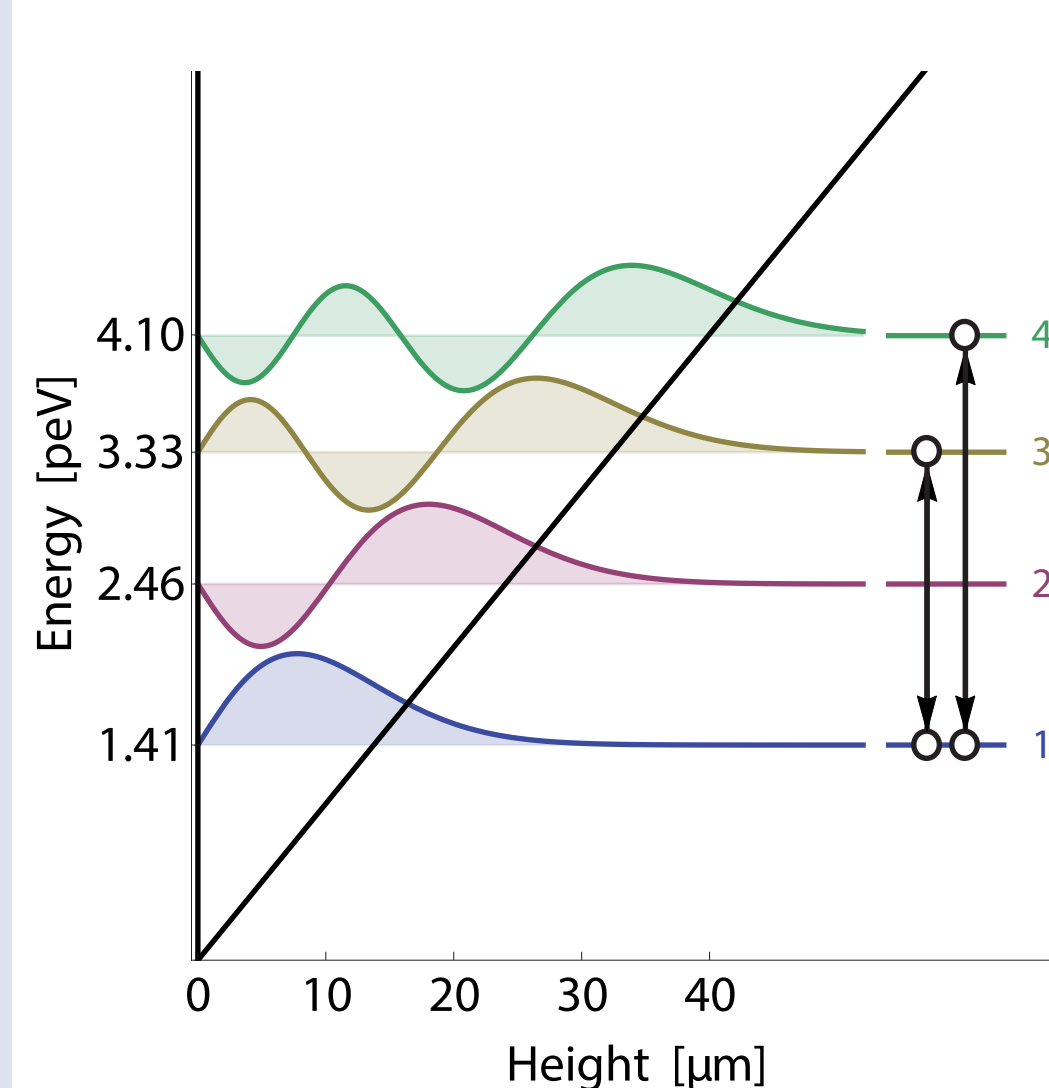
Quantum States in the Earth's Gravity Potential

Solution of the wave function: neutrons in the linear potential with boundary conditions

$$V(z) = mgz$$
$$\psi(z) = c\, Ai\left(\frac{z}{z_0} - \frac{E_n}{E_0}\right)$$

Eigenstates
Coloured curves: first four eigenstates
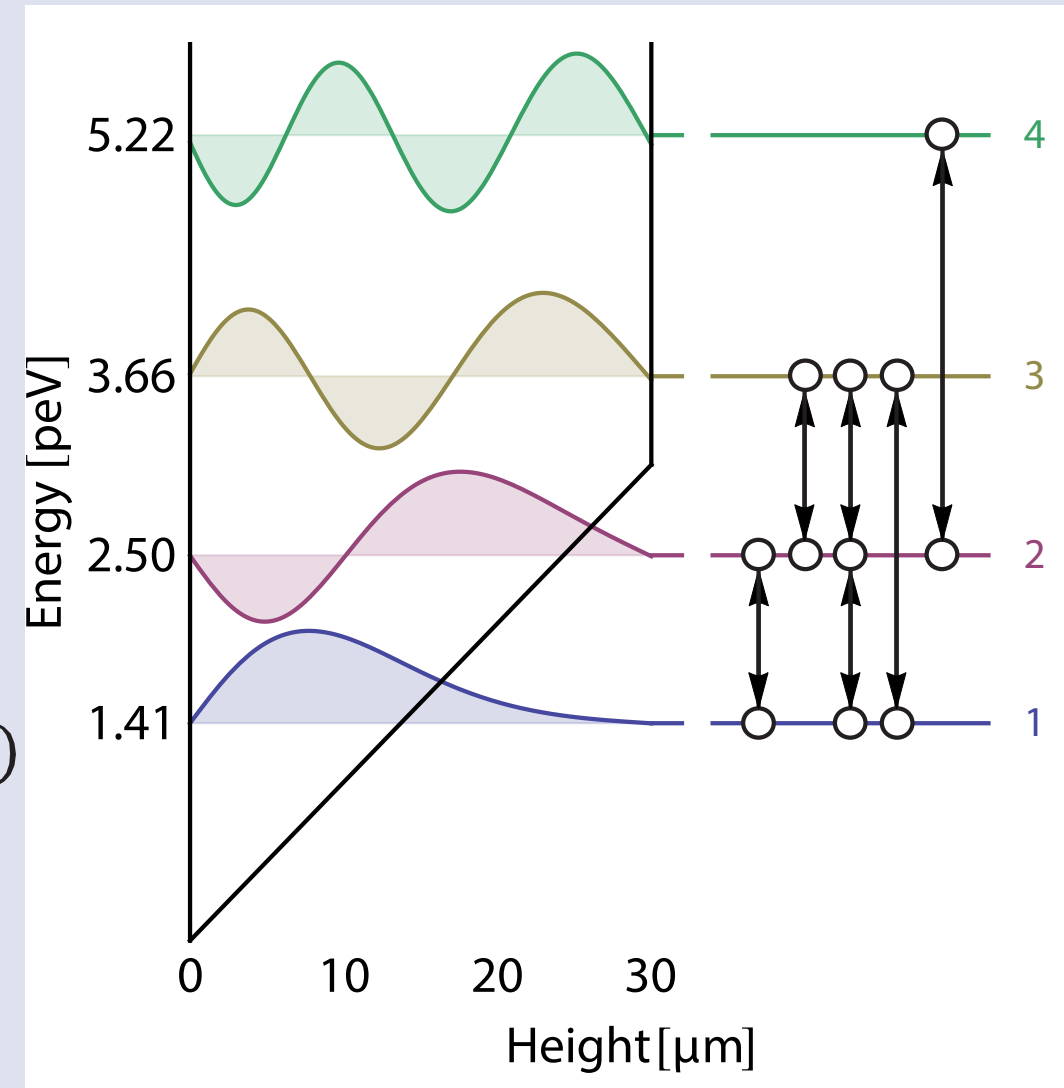Black curve: Gravity and Wall Potential

The eigenergies depend only on $\hbar, g, m_N$.

Adding an additional mirror on top modifies the eigenstates and raises the eigenenergies in dependance of the slit height.
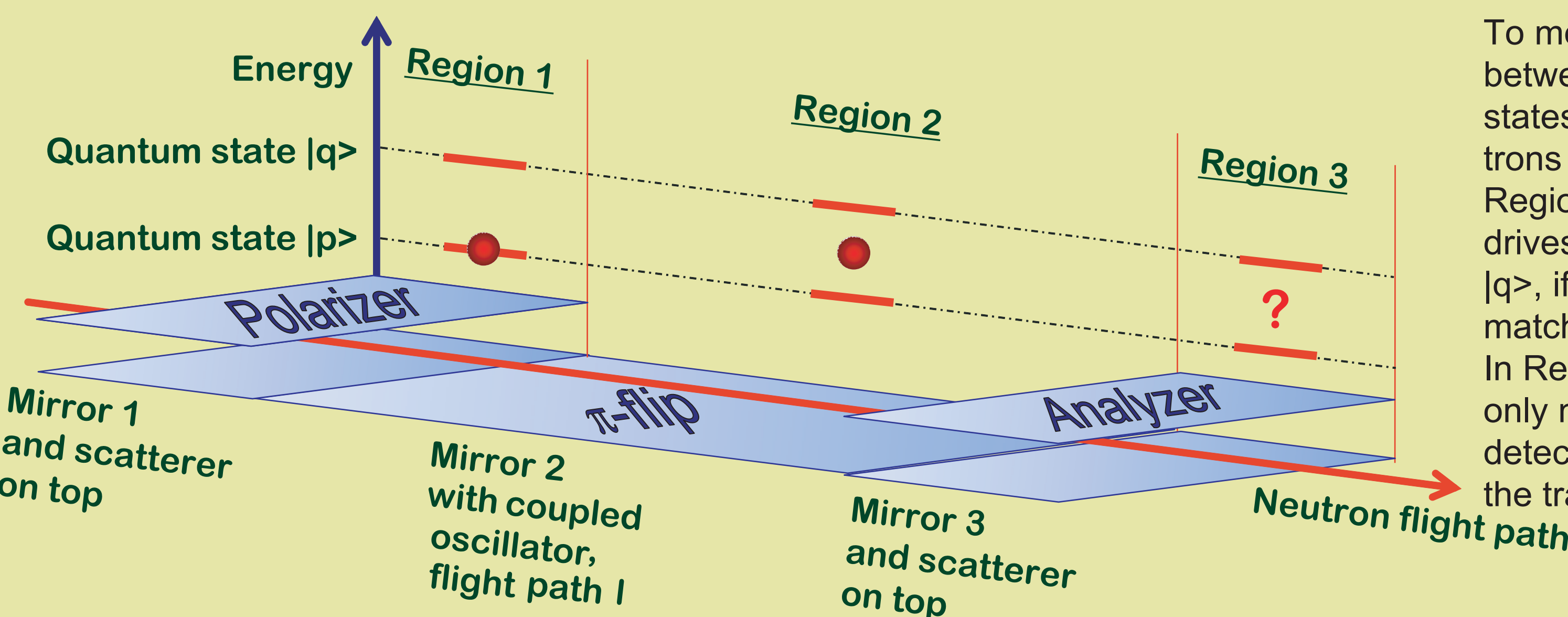
$$\psi(z) = c\, Ai\left(\frac{z}{z_0} - \frac{E_n}{E_0}\right) + d\, Bi\left(\frac{z}{z_0} - \frac{E_n}{E_0}\right)$$

Eigenstates with upper mirror
Coloured curves: first four eigenstates
Black curve: Gravity and Wall Potential

## Gravity Spectroscopy by an Application of Rabi's Method

To measure the energy difference between two gravitational quantum states |p> and |q>, ultra-cold neutrons are prepared into |p> in Region 1. In Region 2, an oscillator drives transitions between |p> and |q>, if the oscillation frequency matches their energy difference. In Region 3, an analyser transmits only neutrons in state |p>. A detector behind this system counts the transmitted neutrons.

Trabsmission drop: The transimission drops upon resonance with a transition. With the three part setup, the transitions 1-3 and 1-4 have been observed at 462 Hz and 647 Hz.
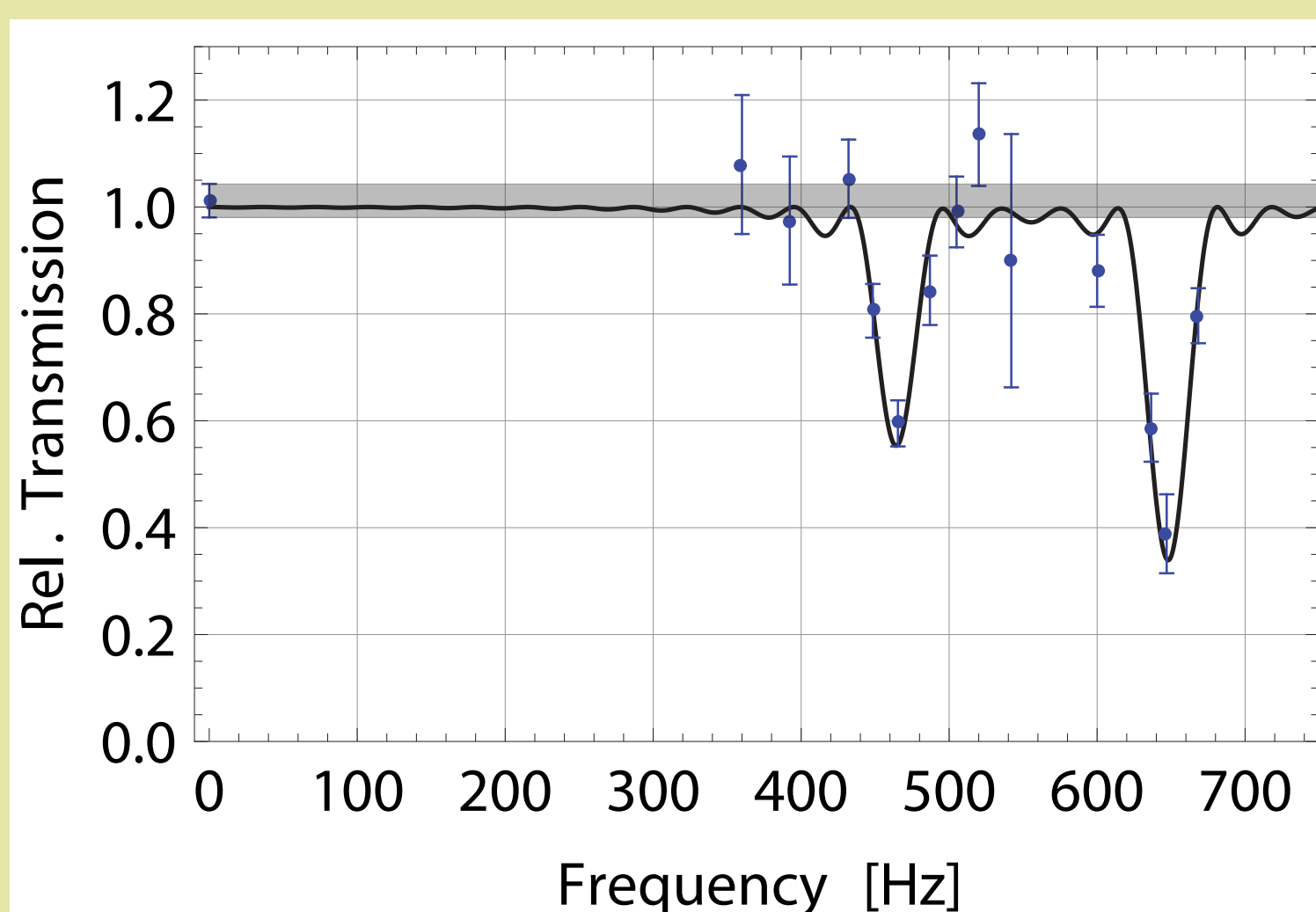
State revival: Additionally the oscillation amplitude can be modified. A minimum of transition is found for a π/2 pulse and the transmission is restored for a π pulse.
Unpublished data taken in 2012 with the three part setup
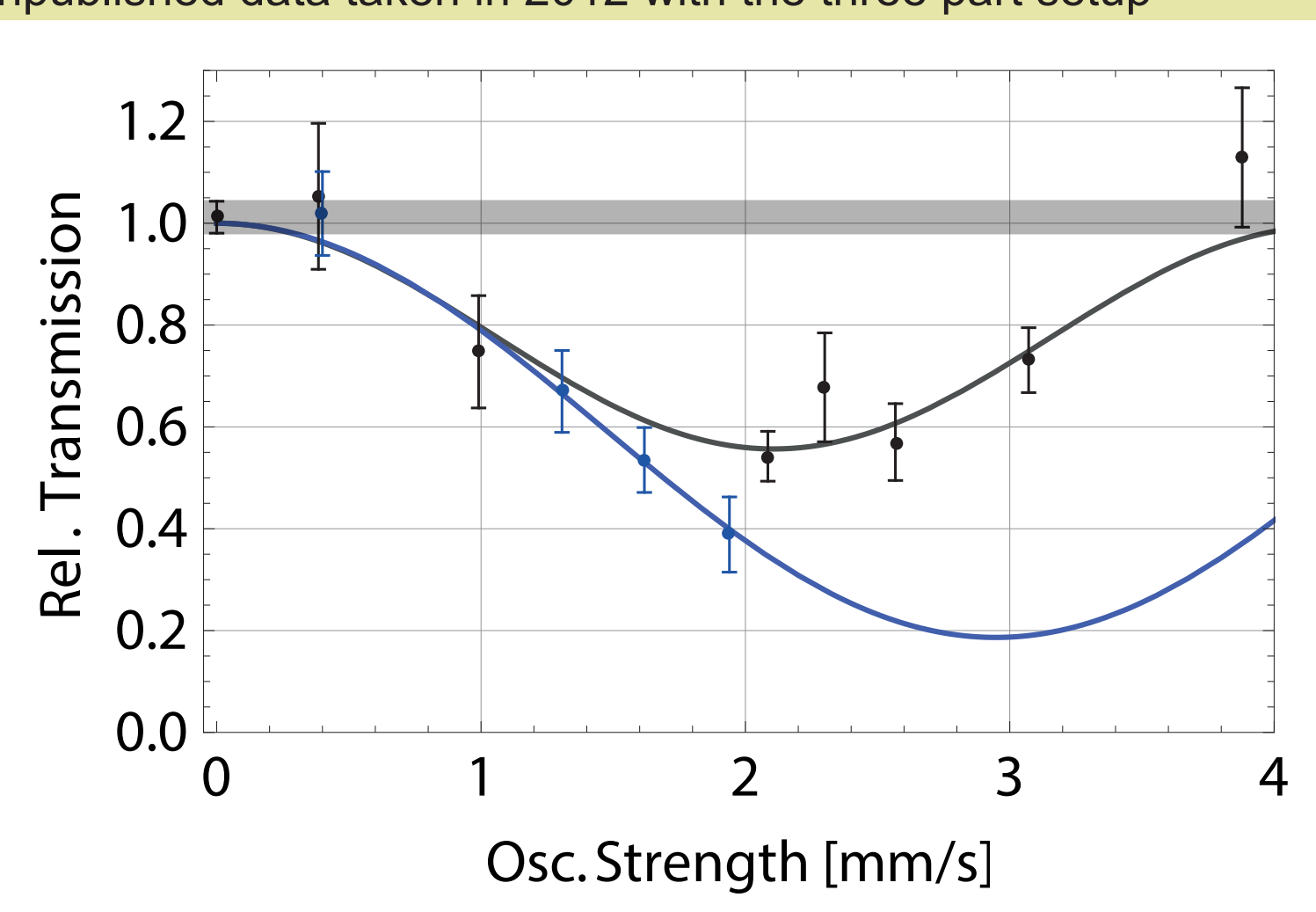
Principle of the State Selector

The state selector consists of two polished glass mirrors as follows:
A solid block with dimensions 15 cm × 15 cm × 3 cm composed of optical glass serves as a mirror for neutron reflection. A second mirror with a surface roughness of about 0.4 µm is placed above the first mirror at a height of 30 µm in order to the first quantum state, while the higher states are removed from the system.

State selection process
**Figure right:** The rough lower surface of the lower glass mirror as seen at a SEM measurement.
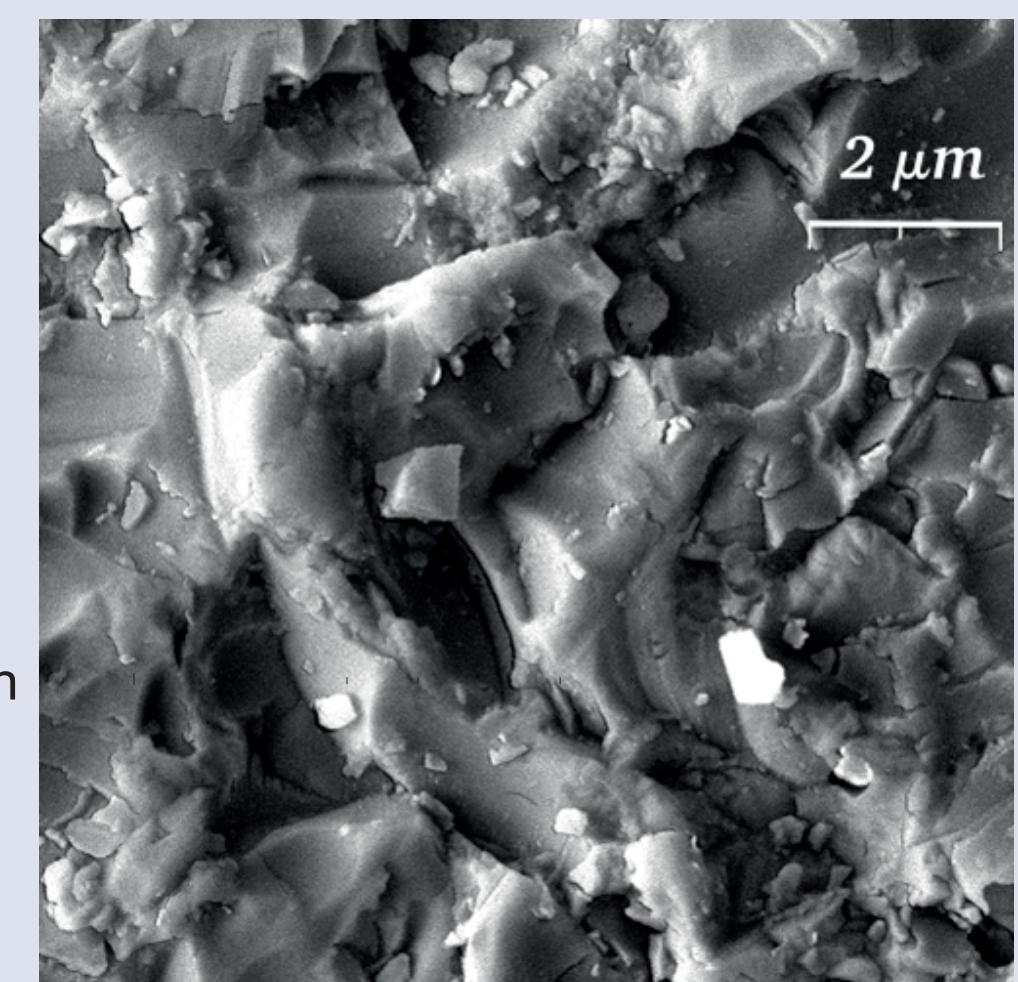
Figure below:
Black Points: measured data
Black Curve: Fit of the height distribution of the neutrons at the exit of the state selector to the black data points.
Dotted/dashed lines: the contributions from the first three eigenstates

Free Fit Parameters:
spatial resolution, height, norm, occupation

State occupation:
1:    59 %
2:    33 %
higher: 8%

Unpublished data from 2012
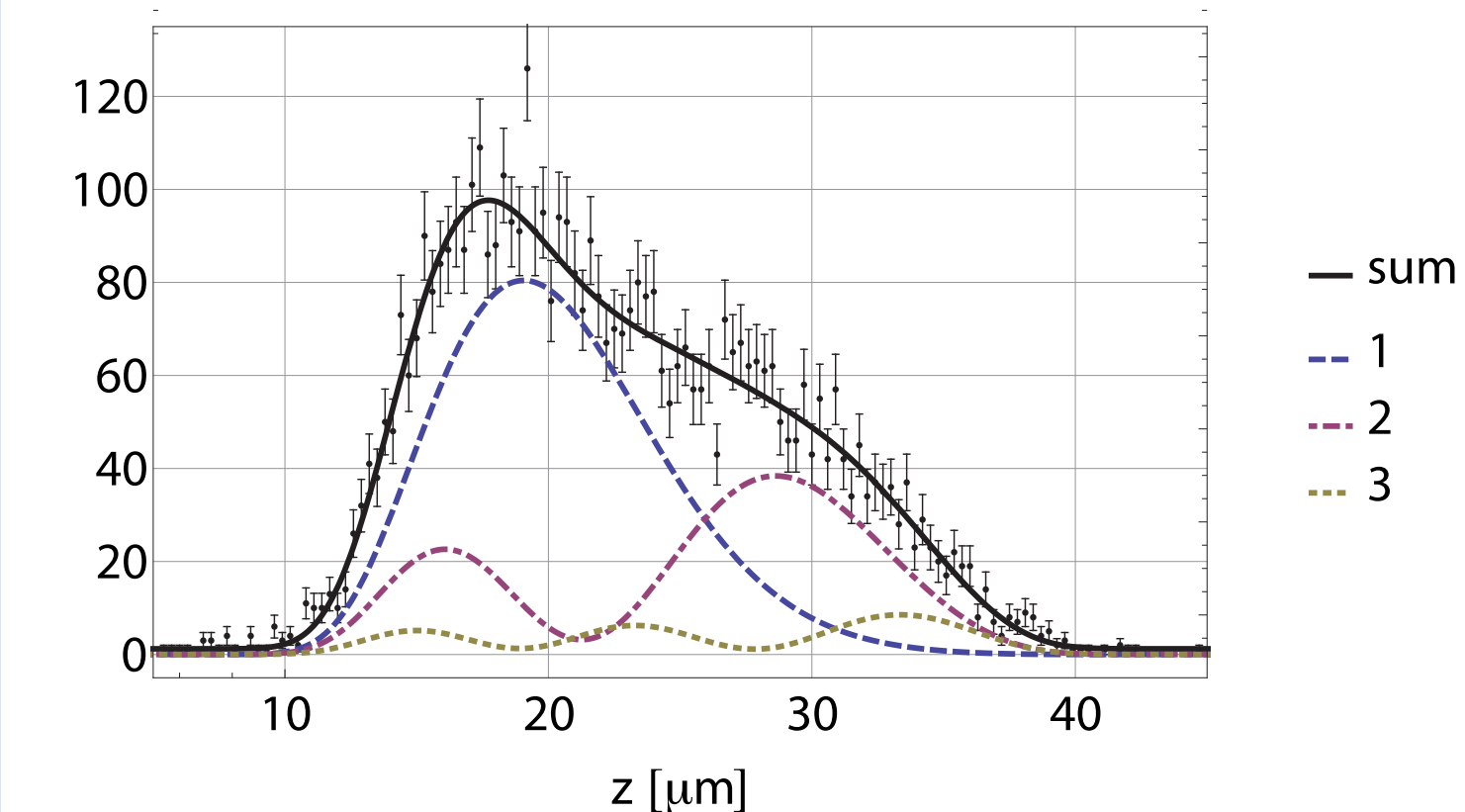
Dark Energy

The unification of all known forces at the Planck scale cannot be formulated in a consistent way without the existence of extra dimensions of space. Therefore, deviations from Newton's gravity law at short distances are expected and can be parametrized by strength α and range λ:

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

Chameleon fields are possible Dark Energy candidates, which are normally hidden by thin shell effects.

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

Brax, Pignol, Phys. Rev. Lett. 107, 11301 (2011)
Ivanov et al., Phys. Rev. D 87, 105013 (2013)
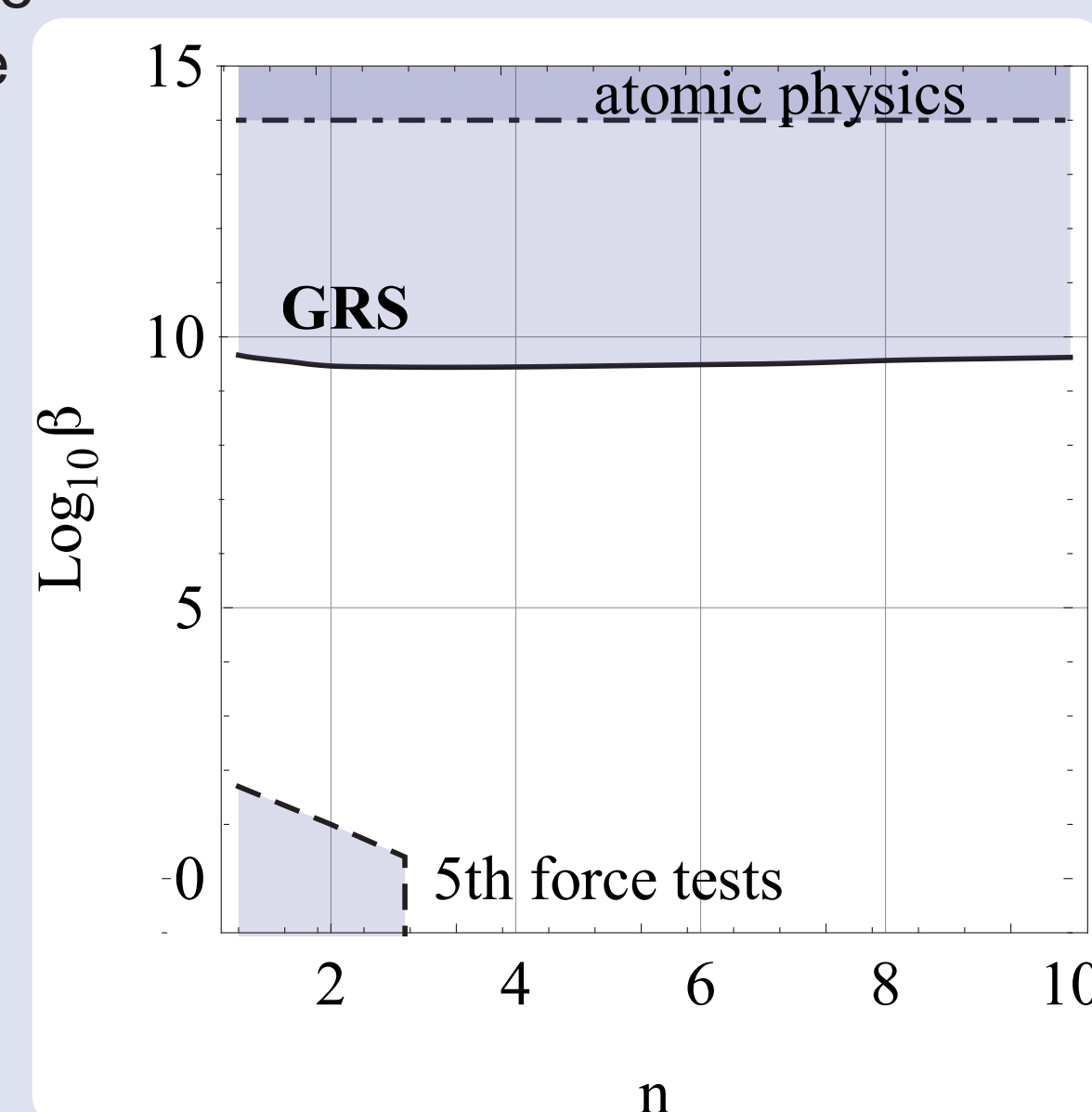
Dark Matter

Our setup is sensitive to Dark Matter candidates axions in the 0.2µm to 2cm regime (10µeV to 1eV), the so-called axion-window.
The experiment was performed by measuring the resonance frequency selectively on the neutrons spin.

$$V(r) = -\hbar g_p g_s \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$
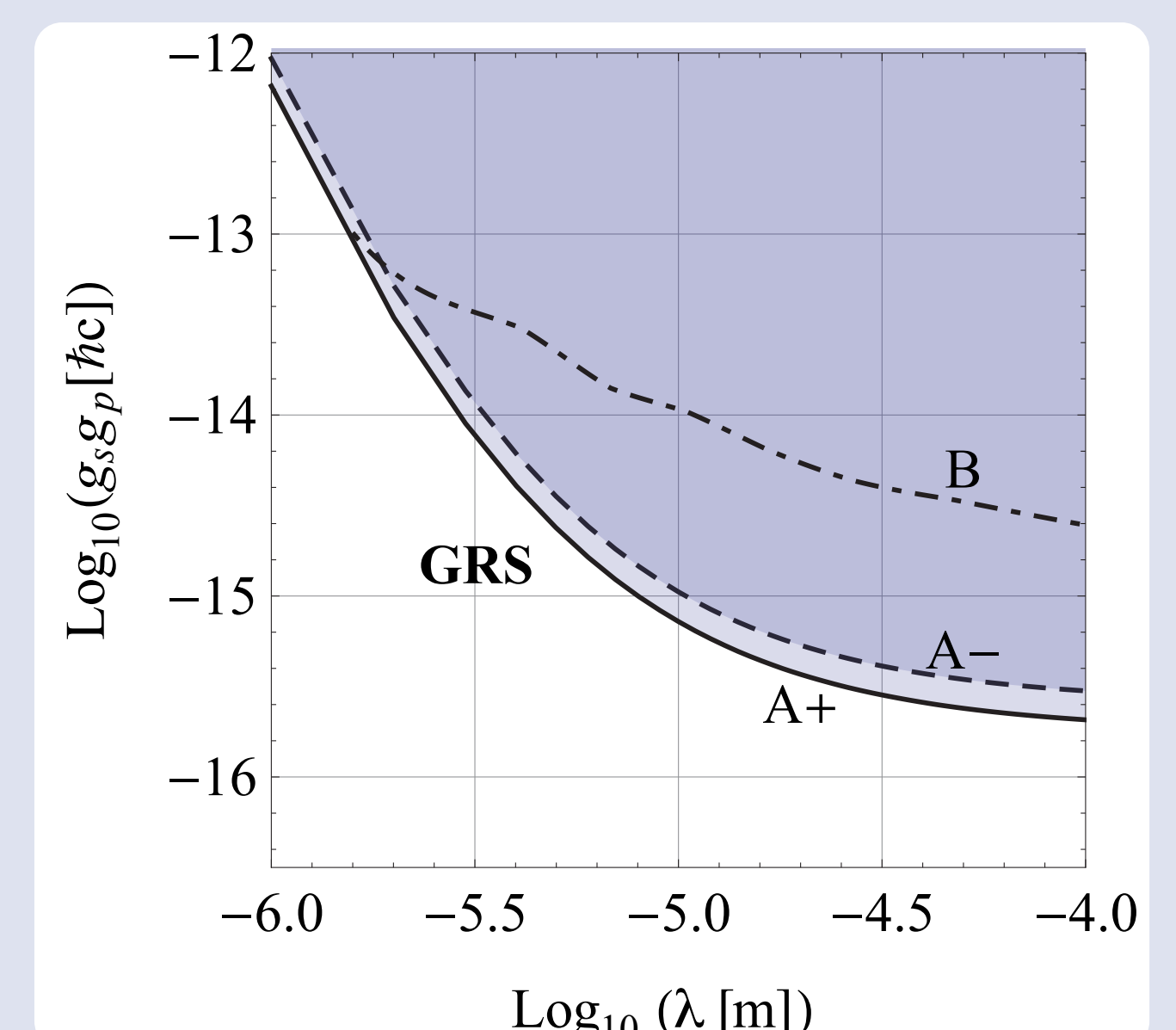
Figure on the left:
Exclusion limits for chameleon fields. Datasets from 2010/2011

Figure on the right:
Limits for the axion-like coupling strength for an attractive and repulsive potential. Datasets from 2010/2011
For a detailed discussion see **arXiv:1208.3875 [hep-ex]**

Predictions from string theory and new physics

	Theory predictions	Our sensitivity
Deviations from Newton's Law due to Large Extra Dimensions	"Gauge fields in the bulk can mediate repulsive forces $10^6 < \alpha < 10^8$ times stronger than gravity at submillimetre distances." *ADD, PRD59 ,086004 (1999)*	$\alpha = 7.6\times10^3$ at λ=5µm.
Dark Energy	A) Cameleon fields, see above B) According to CB, arxiv:gr-qc/0606108, the cosmological constant may be linked to the size of the extradimenstions	$\alpha = 7.6\times10^3$ at λ=5µm.
Dark matter Searches	Axions are serious candidates for dark matter in the astrophysical window, $10\mu eV < m_{axion} < 10eV$. This corresponds to 0.2µm<λ<2cm for the axion coupling $g_s g_p/\hbar c$.	$g_s g_p/\hbar c < 5.3\times10^{-23}$ at λ=5µm $g_s g_p/\hbar c < 1.6\times10^{-26}$ at λ=5mm

Advantages of our method

- Energy only dependent on fundamental values
- small polarisability allowing high precision measurements: small background 10^{-30} eV compared to 10^{-12} eV for atoms

Outlook

The sensitivity can be further improved by changing the setup from an in-flight measurement to a storage setup.
The method allows to improve existing limits of the neutron charge by adding high electric fields to the setup.