Constraints for spin-dependent short-range forces from GRANIT

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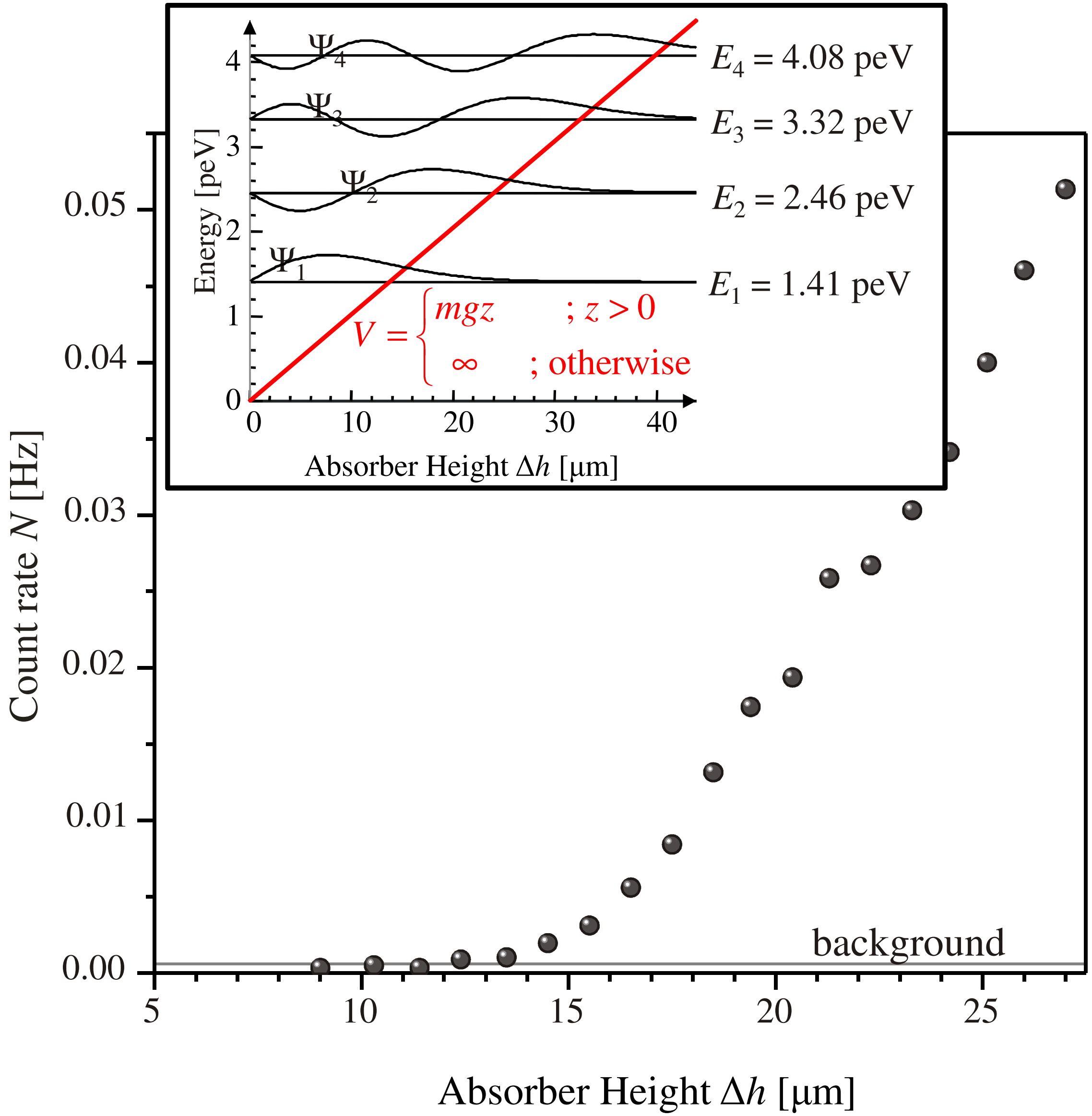
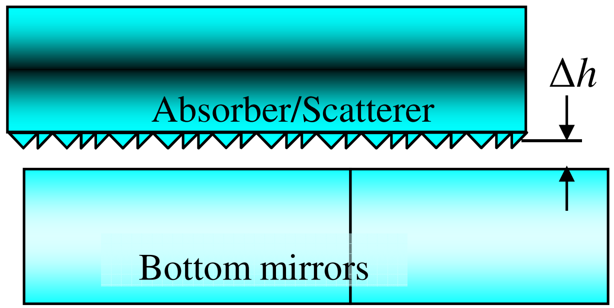
Observation of gravitationally bound quantum states





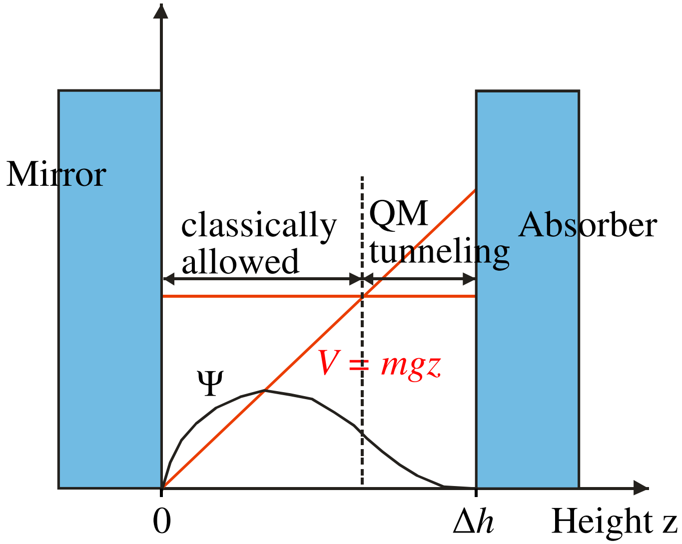
Phenomenological model: The tunneling model

$$\tau_{\text{passage}} = \frac{L}{v_{\text{hor}}}$$

$$T(\Delta h, n) = N_0 \beta_n \exp\left(-\Gamma_n \tau_{\text{passage}}\right)$$

$$\Gamma_n = w_n \cdot P_{n,\text{tunnel}}(\Delta h) \cdot \varepsilon_{\text{absorber}}$$

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

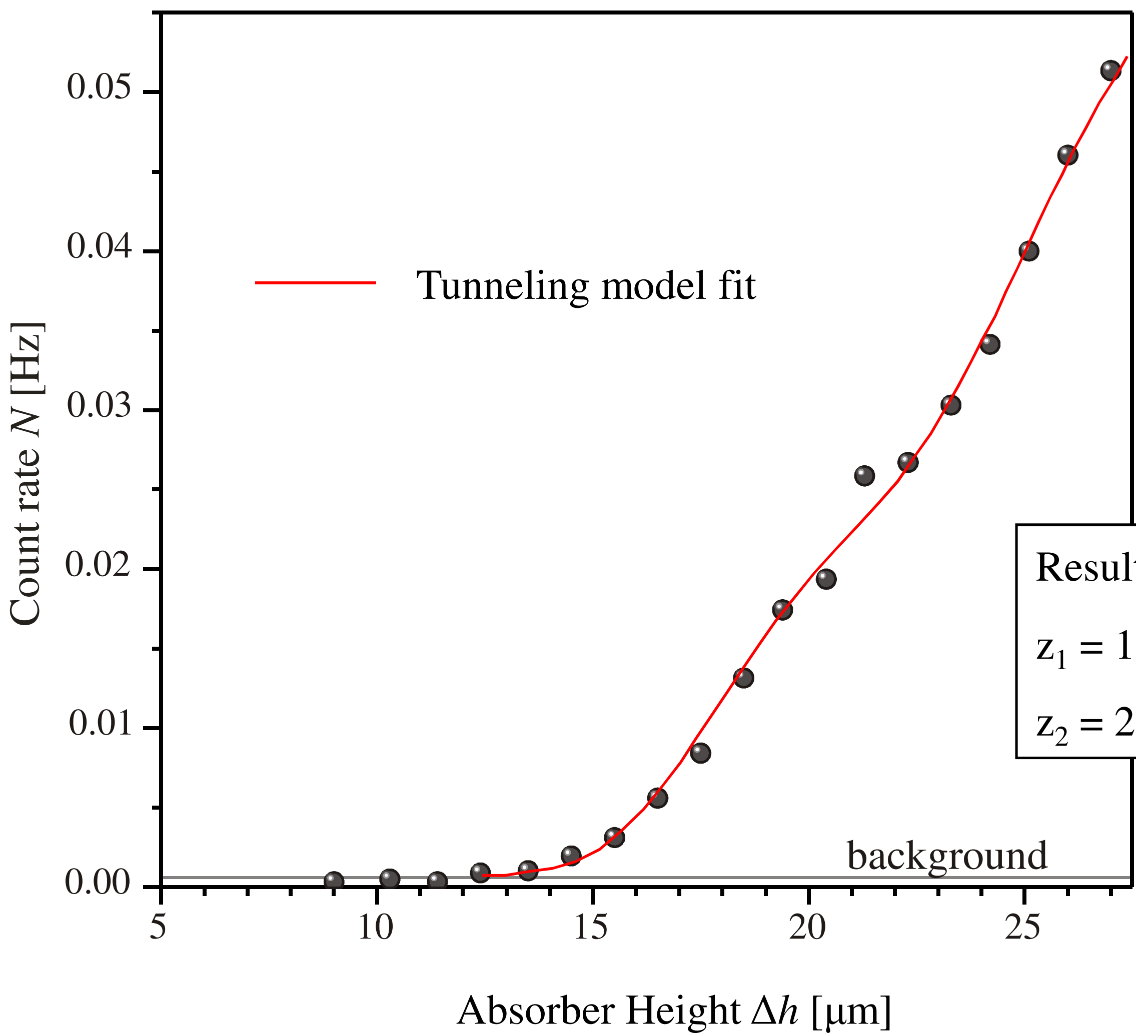


Characteristic length scale:

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

$$N = \sum_n N_0 \beta_n \exp\begin{cases} -\alpha \frac{L}{v_{\text{horiz}}} \exp\left(-\frac{4}{3}\left(\frac{\Delta h - z_n}{l_0}\right)^{3/2}\right) & ;\ \Delta h > z_n \\ -\alpha \frac{L}{v_{\text{horiz}}} & ;\ \text{otherwise} \end{cases}$$

Detection of the size of the quantum states



Results:

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

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

Comparison to theory,

undisturbed wave functions:

$z_1 = 13.7\ \mu\text{m}$

$z_2 = 24.0\ \mu\text{m}$

Why are only the eigenstates discussed?

Neutron flux N after slit:

$$N \propto \int_{v_{hor}} f(v_{hor}) \int \left| \Psi\left(z, \tau_{\text{passage}} = \frac{L}{v_{hor}} \right) \right|^2 dz \quad \text{with} \quad \psi(z, \tau_{passage}) = \sum_n C_n \psi_n(z) e^{\frac{i}{\hbar} E_n \tau_{passage}} e^{-\frac{1}{2\hbar}\Gamma_n \tau_{passage}}$$

Initial occupation numbers: $C_n = \int \psi_{\text{in}}\left(z, \tau_{\text{passage}} = 0\right) \psi_n(z)\, dz$

$$N \propto \int_{v_{hor}} f(v_{hor}) \sum_{n,k} C_n^* C_k \langle \psi_n | \psi_k \rangle e^{\frac{i}{\hbar}(E_n - E_k)\tau_{passage}} e^{-\frac{1}{2\hbar}(\Gamma_n + \Gamma_k)\tau_{passage}}$$

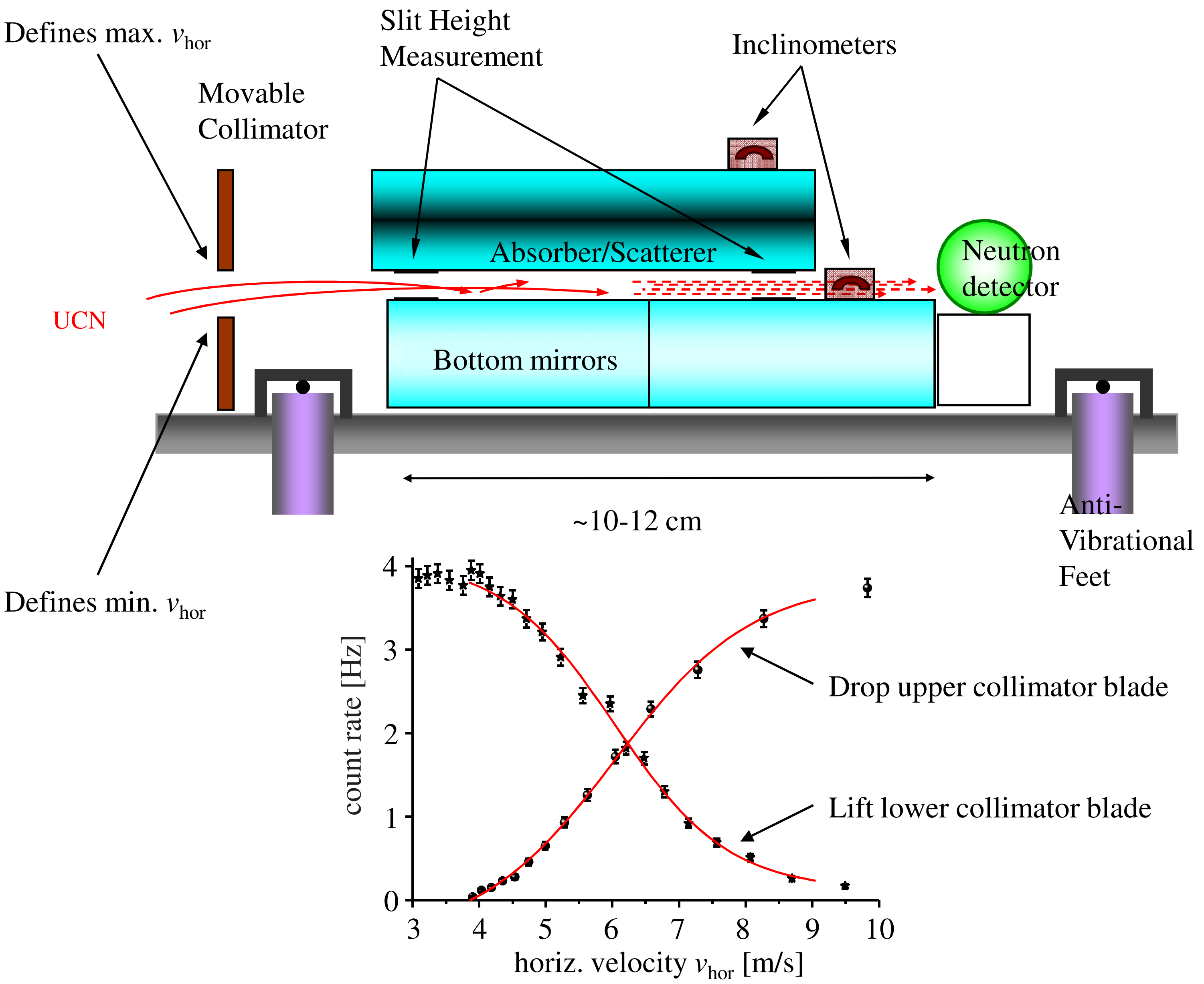
Doesn't vanish for n ≠ k!

(Non-unitary Hamiltonian)

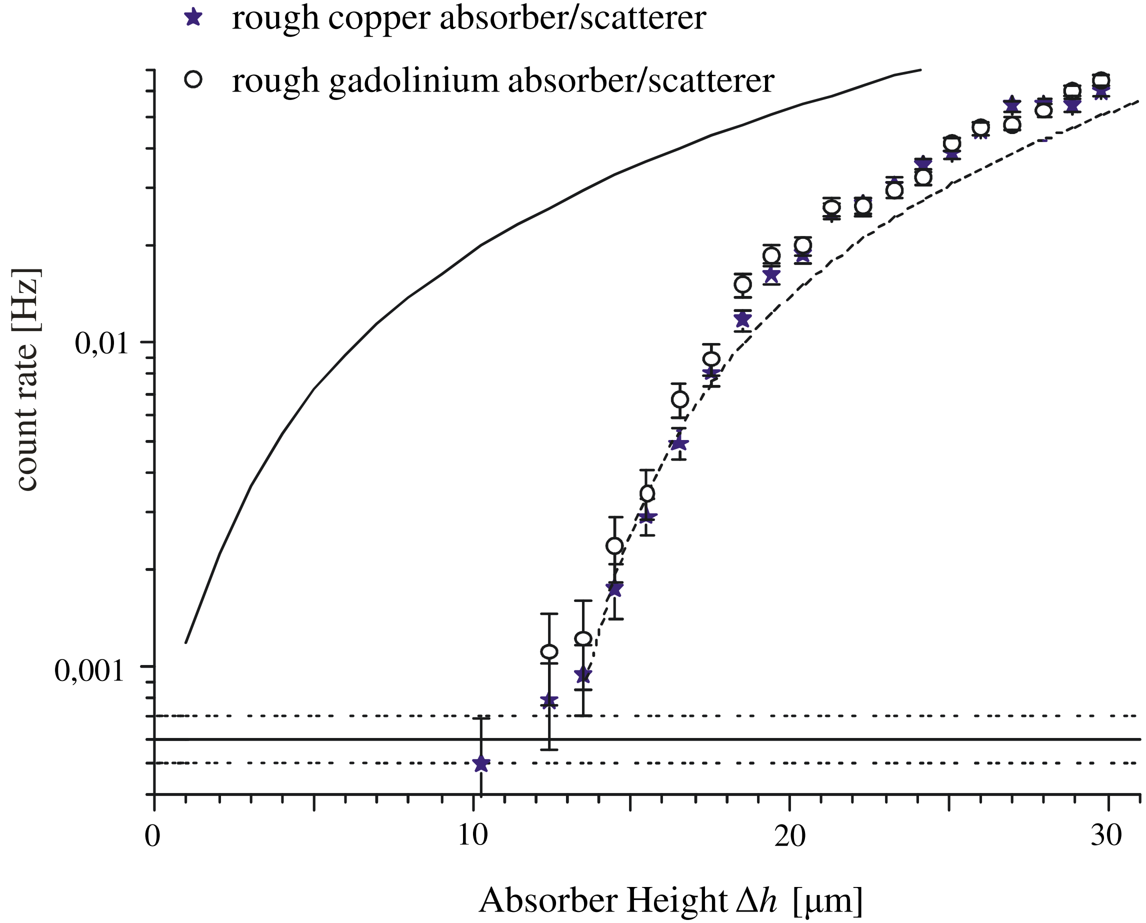
$$= \int_{v_{hor}} f(v_{hor}) \sum_n |C_n|^2 e^{-\frac{1}{\hbar}\Gamma_n \tau_{passage}} + \int_{v_{hor}} f(v_{hor}) \sum_{n \neq k} C_n^* C_k \langle \psi_n | \psi_k \rangle e^{\frac{i}{\hbar}(E_n - E_k)\tau_{passage}} e^{-\frac{1}{\hbar}\frac{\Gamma_n + \Gamma_k}{2}\tau_{passage}}$$

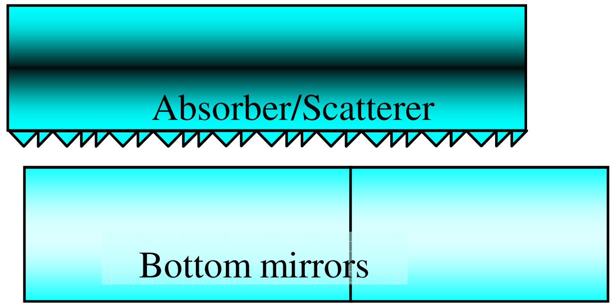
This term is small for polychromatic neutron beam

The horizontal velocity spectrum



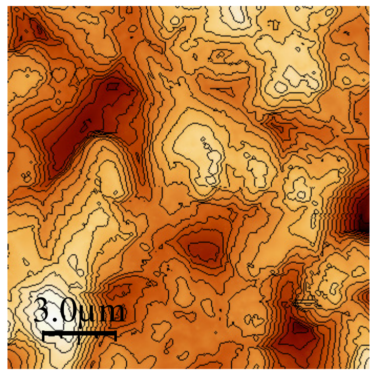
How does an absorber work?





Roughness (2002):

- Standard Deviation: 0.7 µm
- Correlation length: ~ 7 µm



Lesson: It's the roughness which removes neutrons. A high imaginary part of the potential does not, since the neutron cannot penetrate.
(see A. Yu. Voronin et al., PRD 73, 44029 (2006))

Cf. Optics: $$R_\perp = \left|\frac{1-n}{1+n}\right|$$

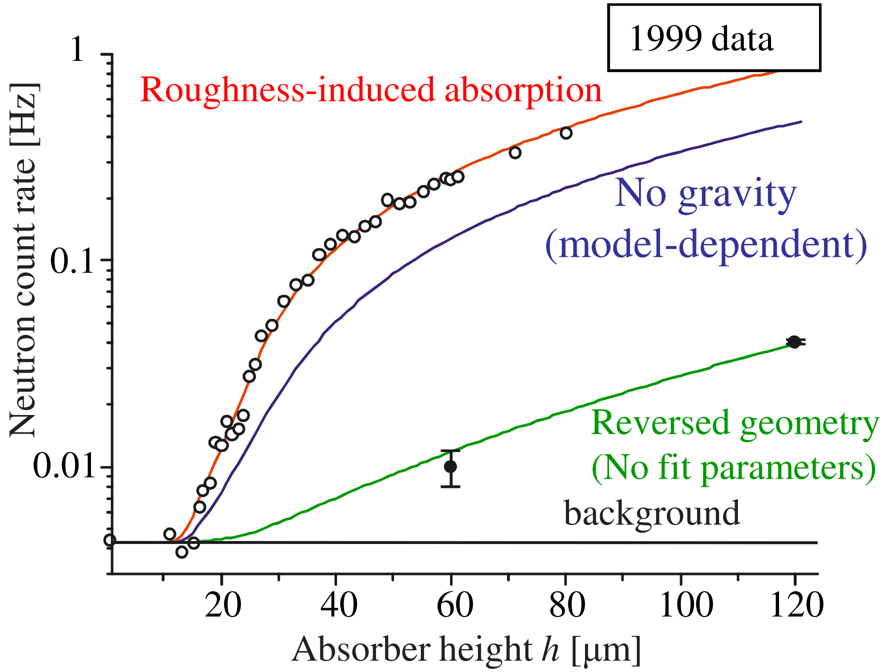
Theoretical description:

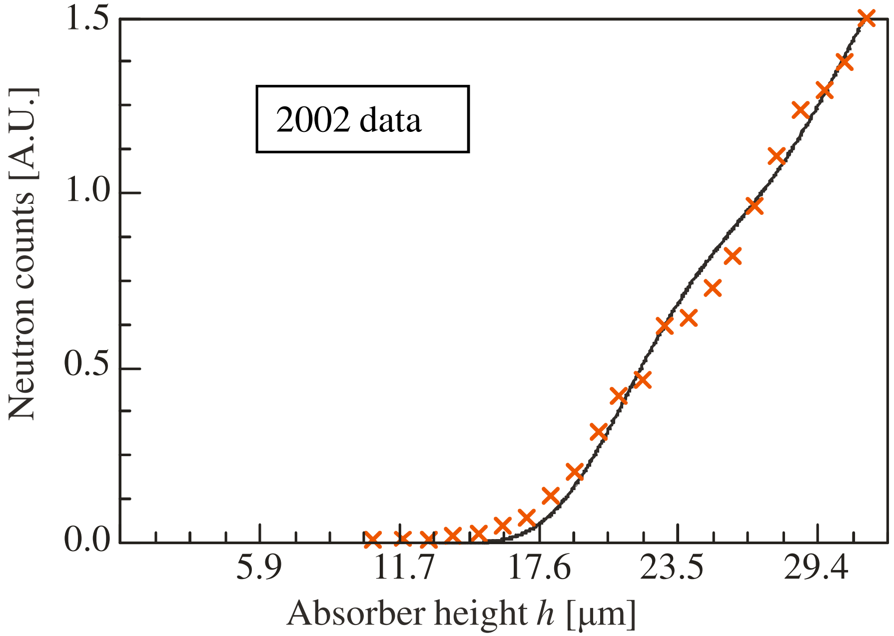
- Tunneling model

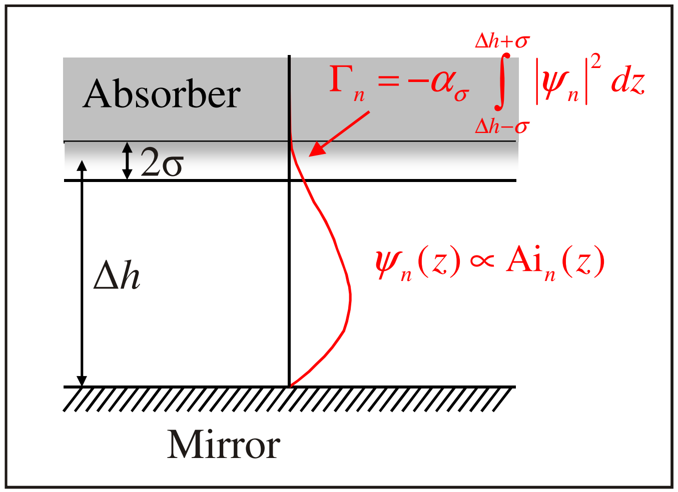
  V. Nesvizhevsky, Eur. Phys. J. C40 (2005) 479

- QM, Flat absorber doesn’t work:
- Roughness-induced absorption:

  A.Westphal et al., Eur. Phys. J. C51, 367 (2007)

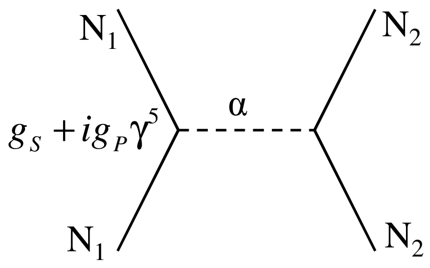






Application: Search for a new pseudoscalar boson (Axion-like Particle)

Original Proposal for Axion (F. Wilczek, 1978 and others): prediction, as a consequence of a possible solution to the "Strong CP Problem":



Modern Interest: Dark Matter candidate.

All couplings to matter are weak.

Signature of a new pseudoscalar boson: New Short-Range Potential

Monopole-monopole: $$V(r) = -g_S{}^1 g_S{}^2 \frac{(\hbar c)}{4\pi r} \exp(-r/\lambda) \quad \text{with } \lambda = \frac{\hbar c}{m_\alpha c^2}$$

Looks like 5th force, which is motivated now by theories with extra dimensions. Limits from our experiment exist, but other methods give better limits.

(Westphal et al., hep-ph/0301145, hep-ph/0703108, Nesvizhevsky et al., Class. Quant. Grav. 21, 4557 (2004))

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

Most often done with electrons as polarized particle. Coupling Constants depend on the species.

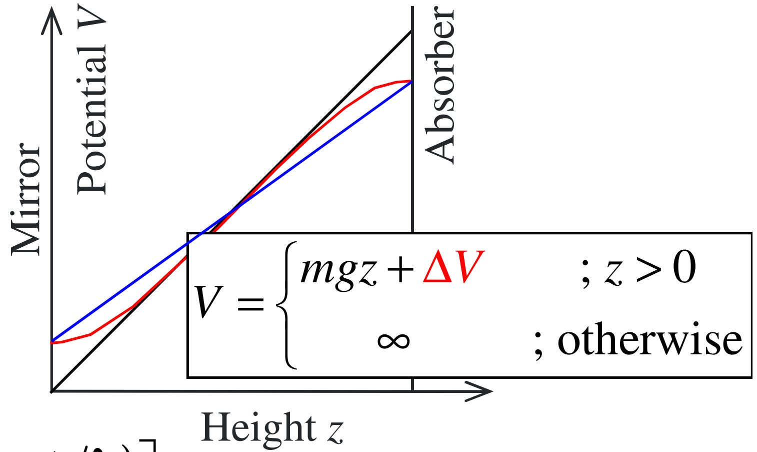
Dipole-dipole: $$V(r) \propto g_P{}^1 g_P{}^2 \left[(\sigma_1 \cdot \sigma_2) f(r) + (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) g(r) \right]$$

Disappears for an unpolarized source

Effect on Gravitationally Bound States

Integration of 2nd potential over mirror:

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



Inclusion of absorber:

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

After dropping the invisible constant piece, $V_{\mathrm{slit}}(z)$ is linear in z

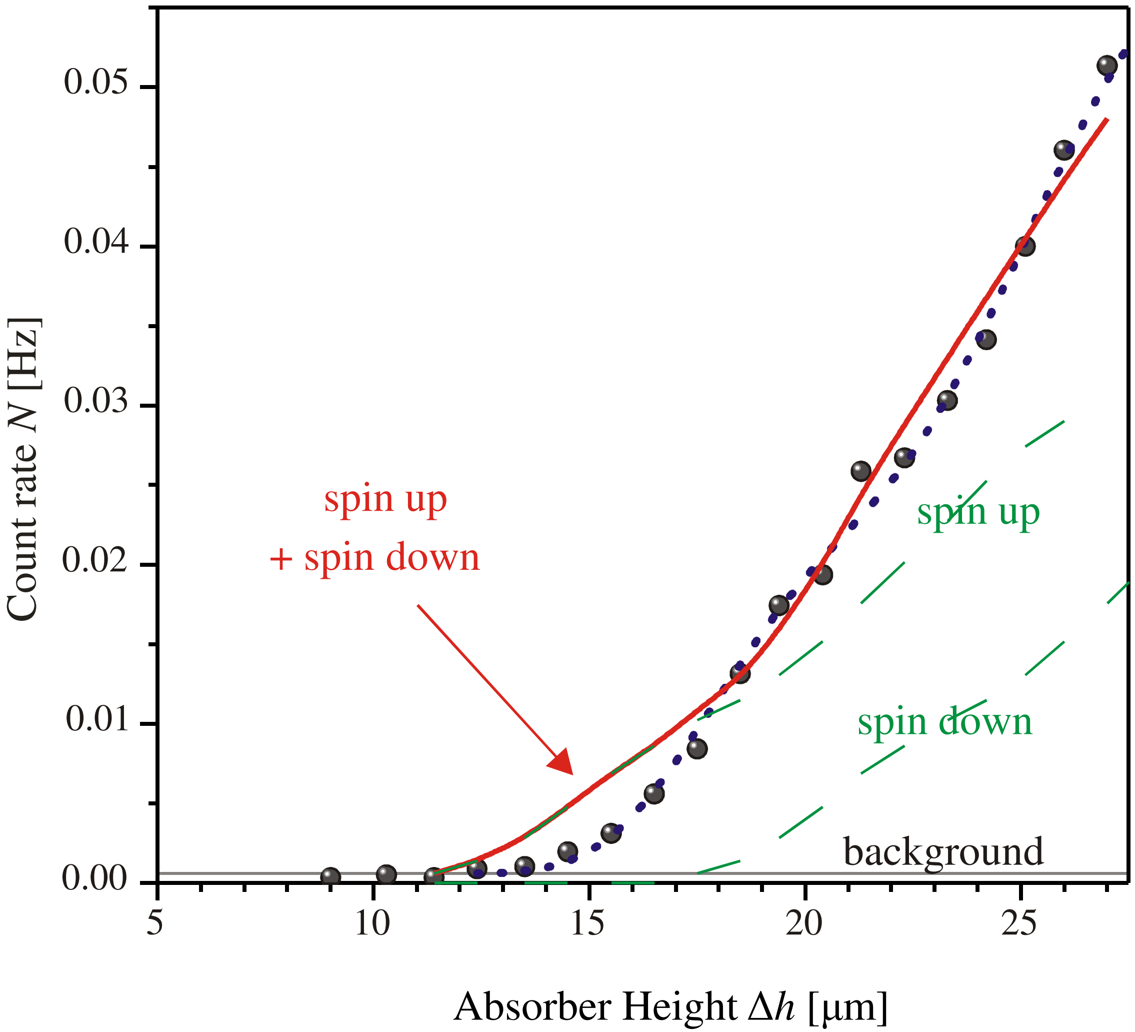
$$g \rightarrow g_{\mathrm{eff}} = g \pm g_S{}^N g_P{}^n \frac{2(\hbar c)^2 \rho_{\mathrm{m}}}{8 m_{\mathrm{n}}{}^3 c^2}$$

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

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

Extraction of our Limit

Why can we use unpolarized neutrons?



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

(PRD 75, 075006 (2007),

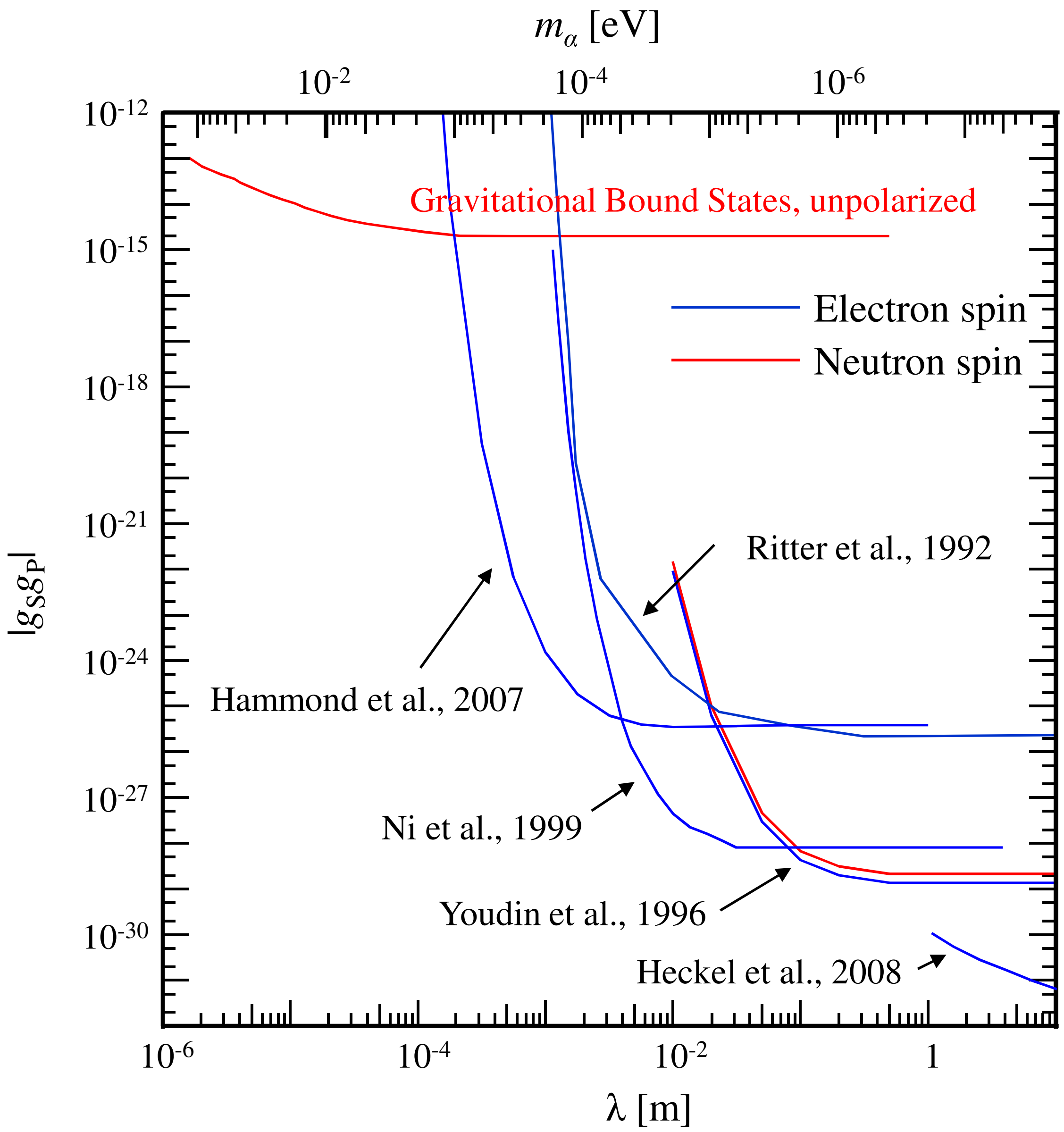
hep-ph/0610339,

hep-ph/0703108))

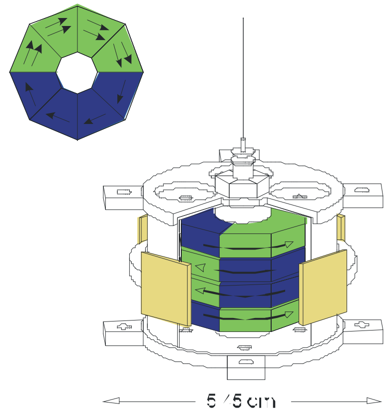
Sensitivity to magnetic field gradients:

Signal > 1 mT/cm

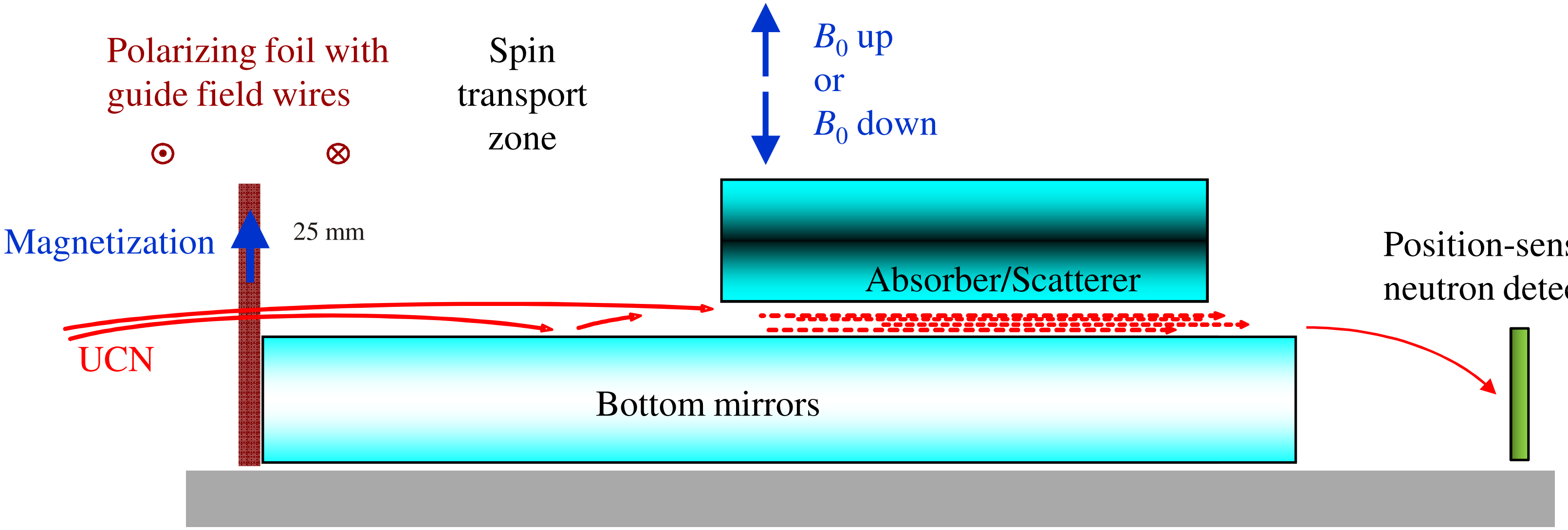
Exclusion Plot for new spin-dependent forces

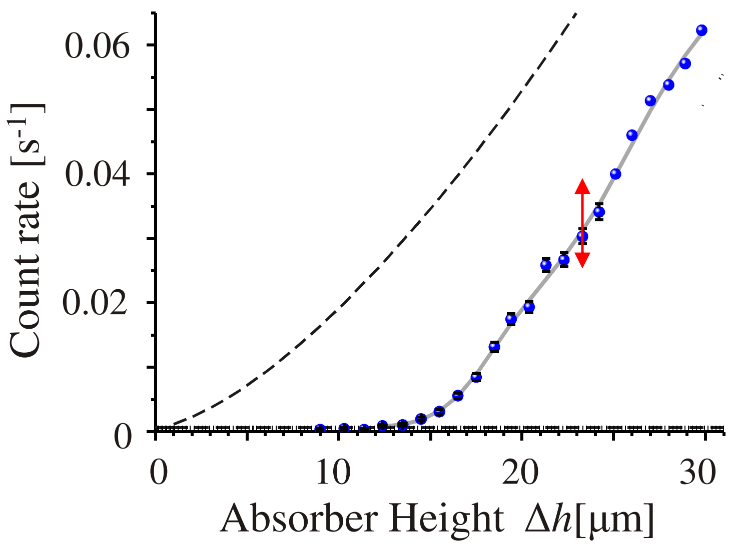


Heckel et al., 2008:



Projected improvement: Polarized experiment





Sensitivity gain due to relative measurement, stronger UCN source, wider mirror, longer run time.

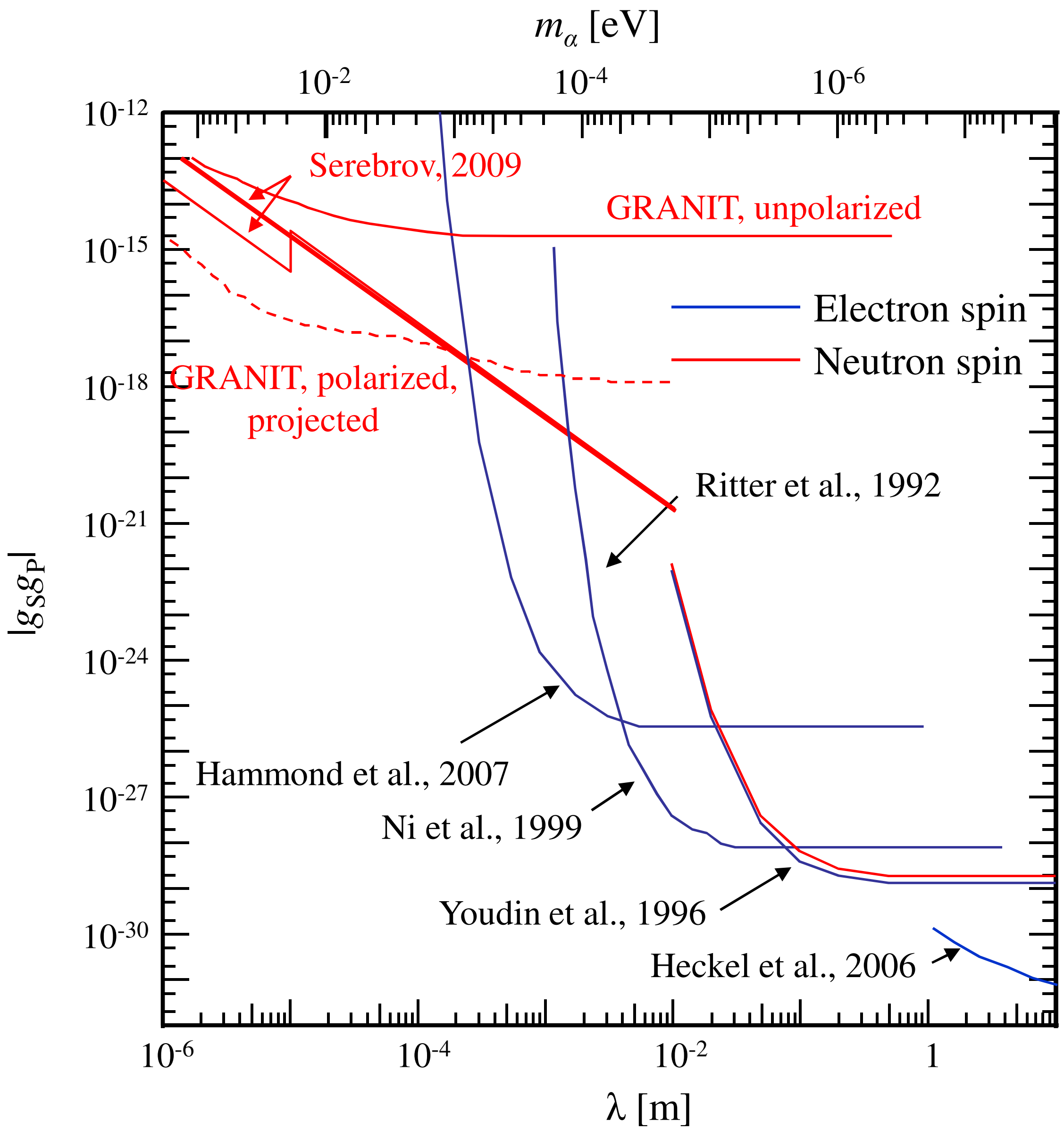
False effect: Transverse Stern-Gerlach (Cross-check: velocity-dependence, dependence on size of holding field)

False effect due to magnetic field gradient > 1 µT/cm from ferromagnetic particles in mirror or stone (Cross-check: demagnetization)

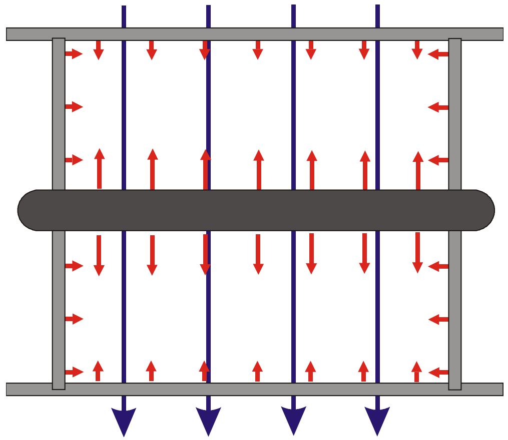
Experiment to be performed in 2010

S. Baeβler et al., NIM, 2009

Exclusion Plot for new spin-dependent forces



Serebrov 2009, Zimmer 2008:



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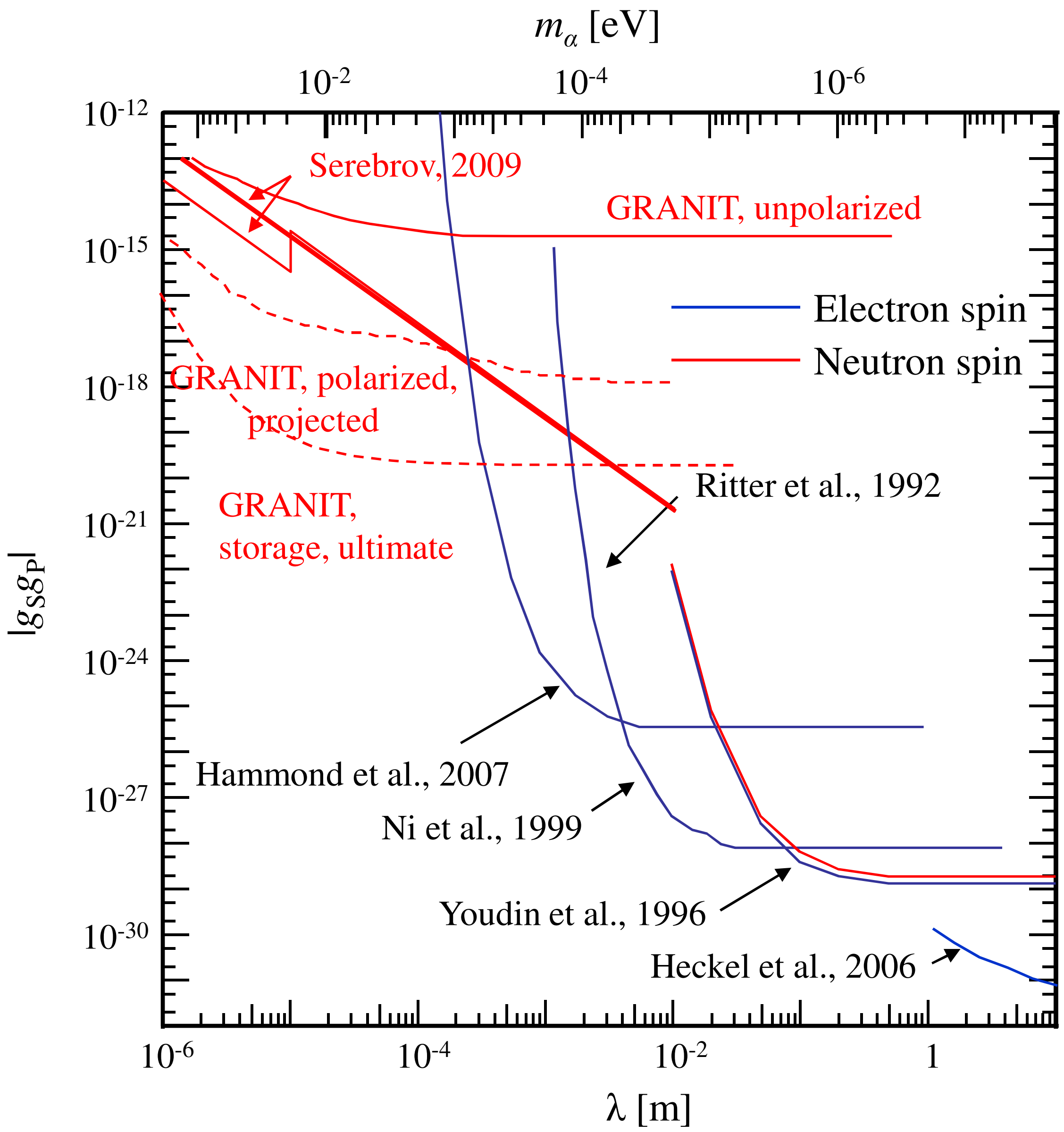

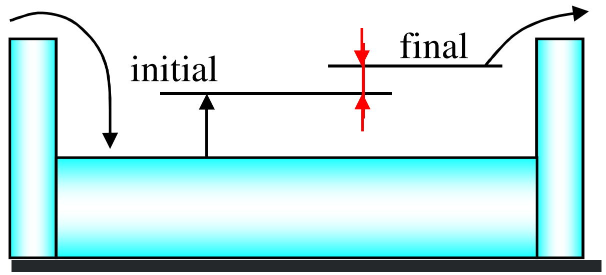

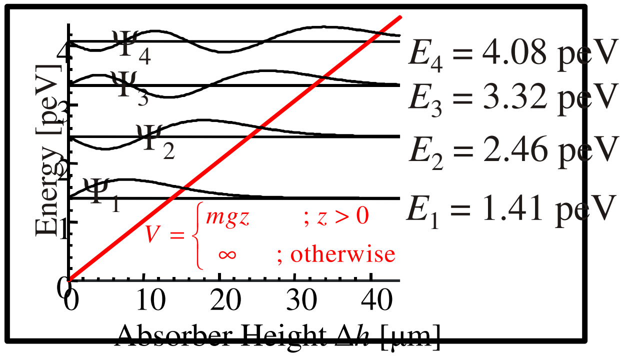

$$E_k \rightarrow E_k + \langle k | \Delta V_{\text{mirror}}(z) | k \rangle$$

$$\text{Assume, } \frac{\Delta(E_k - E_n)}{E_k - E_n} \sim 10^{-6}$$

Summary

• Gravitationally Bound Quantum States detected with Ultracold Neutrons

• Characteristic size is ~ μm

• Applications in fundamental physics: Limits on fifth forces, limits on spin-dependent forces, and others

• Future: Replace transmission measurements (with its need to rely on absorber models) by energy measurements. Ultimately, $\Delta E/E \sim 10^{-6}$ @ $E \sim peV$ might be reached.

Thank you for your interest!