*q*Bounce-

Realization of a

Quantum Bouncing Ball Gravity Spectrometer

and

new 5th force limits

Hartmut Abele
Mykonos, 27 June 2011

*q*BOUNCE

the dynamics of ultra-cold neutrons in the gravity potential

the free Fall

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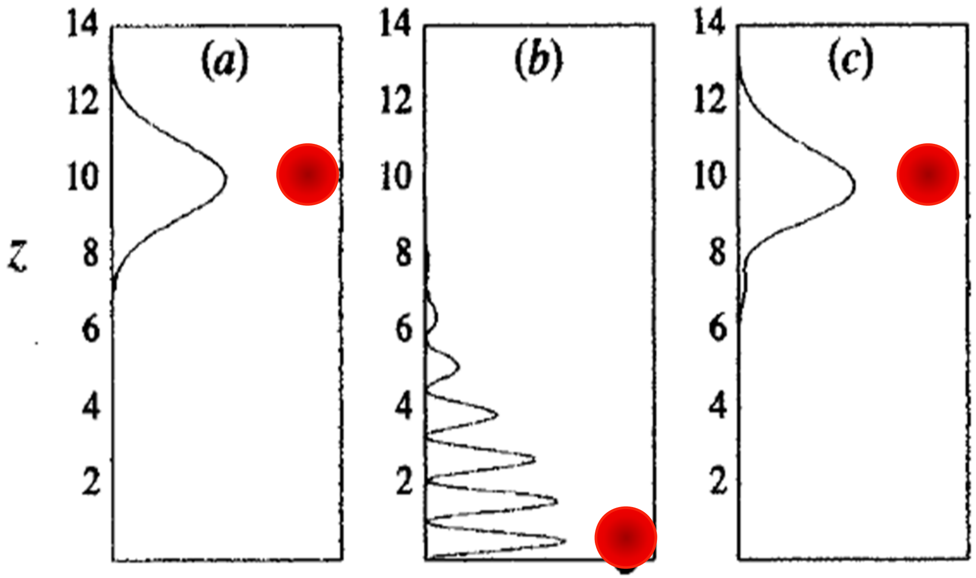
the free Fall



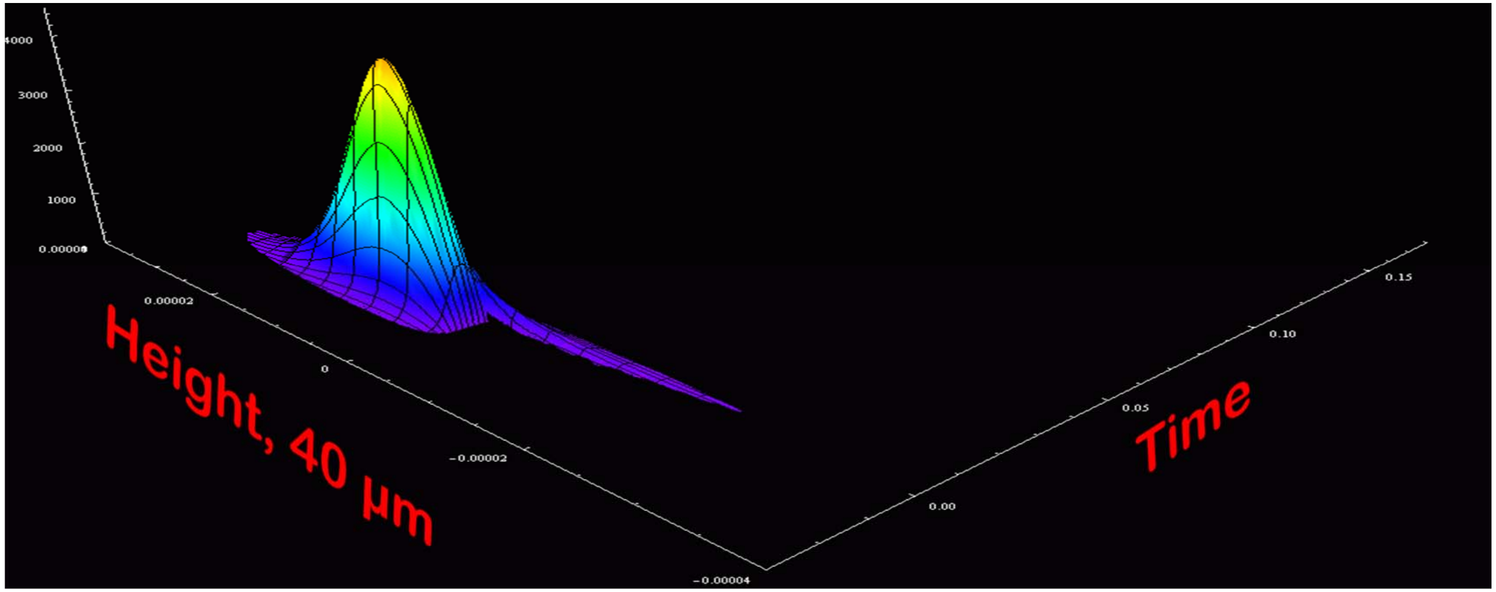
- Quantum interference: sensitivity to fifth forces coming from extra dimensions string theories (higher dimensional field theories) or axion fields

- Theory:
  Kajari et al., Inertial and gravitational mass in quantum mechanics,
  Appl. Phys. B **100**, 43 (2010)
- Julio Gea-Banacloche, Am. J. Phys.(1999)
- H.A. et al., PRD (2010)

qBOUNCE

the dynamics of ultra-cold neutrons in the gravity potential

- Quantum interference: sensitivity to fifth forces coming from extra dimensions / string theories (higher dimensional field theories) or axion fields



- Rafael Reiter, Bernhard Schlederer, David Seppi, Projeketarbeit TU Wien 2009, Supervisor H. Leeb


NEUTRONS
FOR SCIENCE
ESRF
INSTITUT LAUE-LANGEVIN
EMBL

Neutron Production

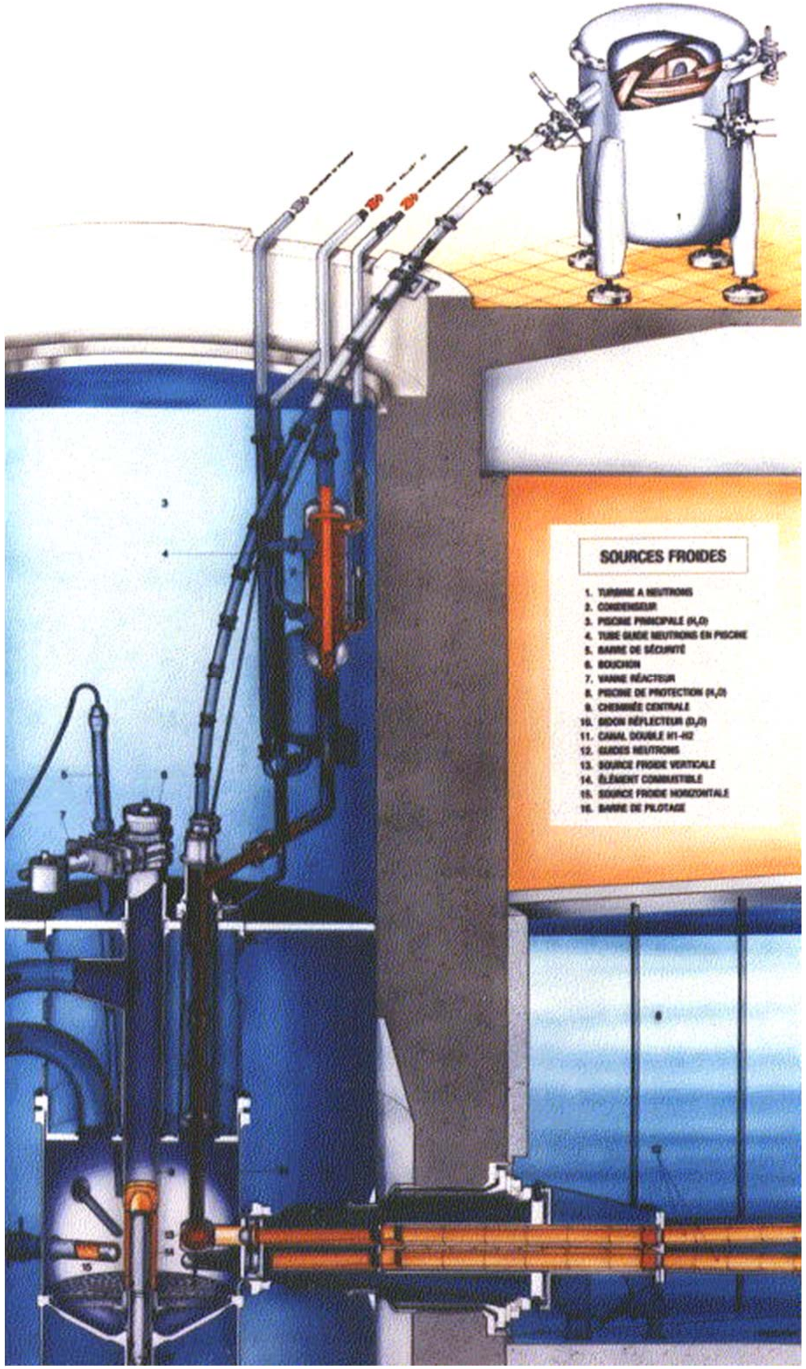
Fission: 2 MeV

Thermal: 25meV, 300K

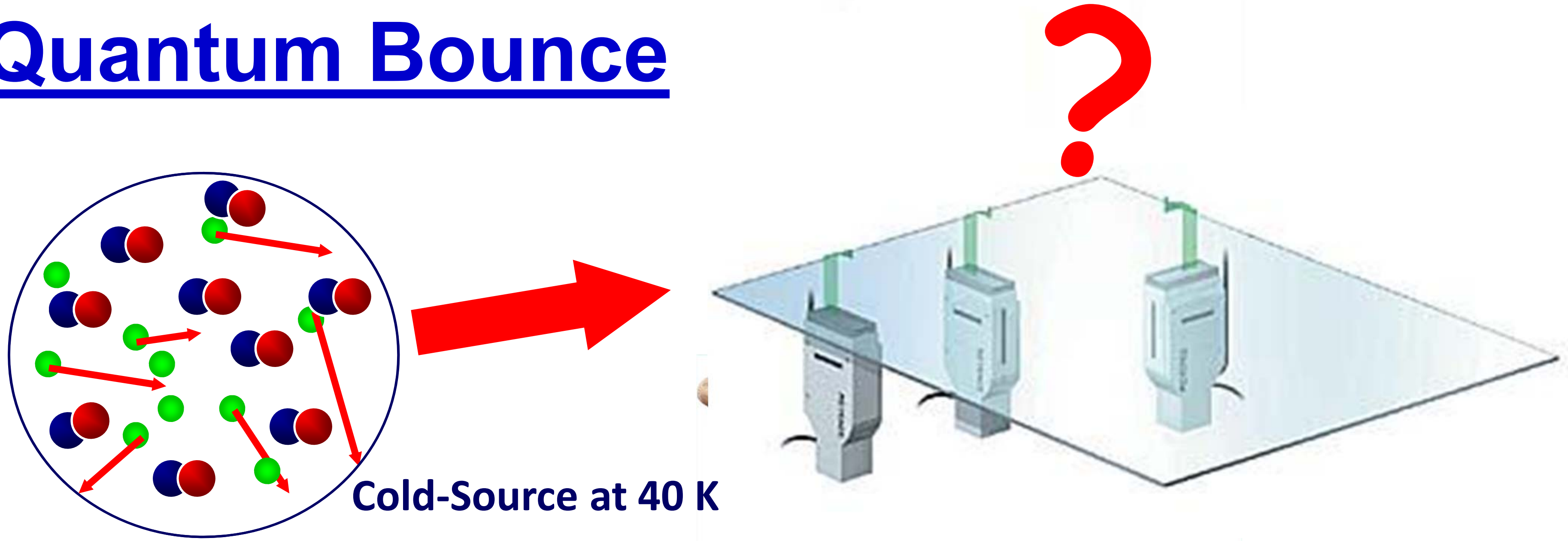
Cold: 4 meV, 40K

ultra cold: 100 neV, 1mK

Gravity Experiment: 1 pico-eV



Quantum Bounce

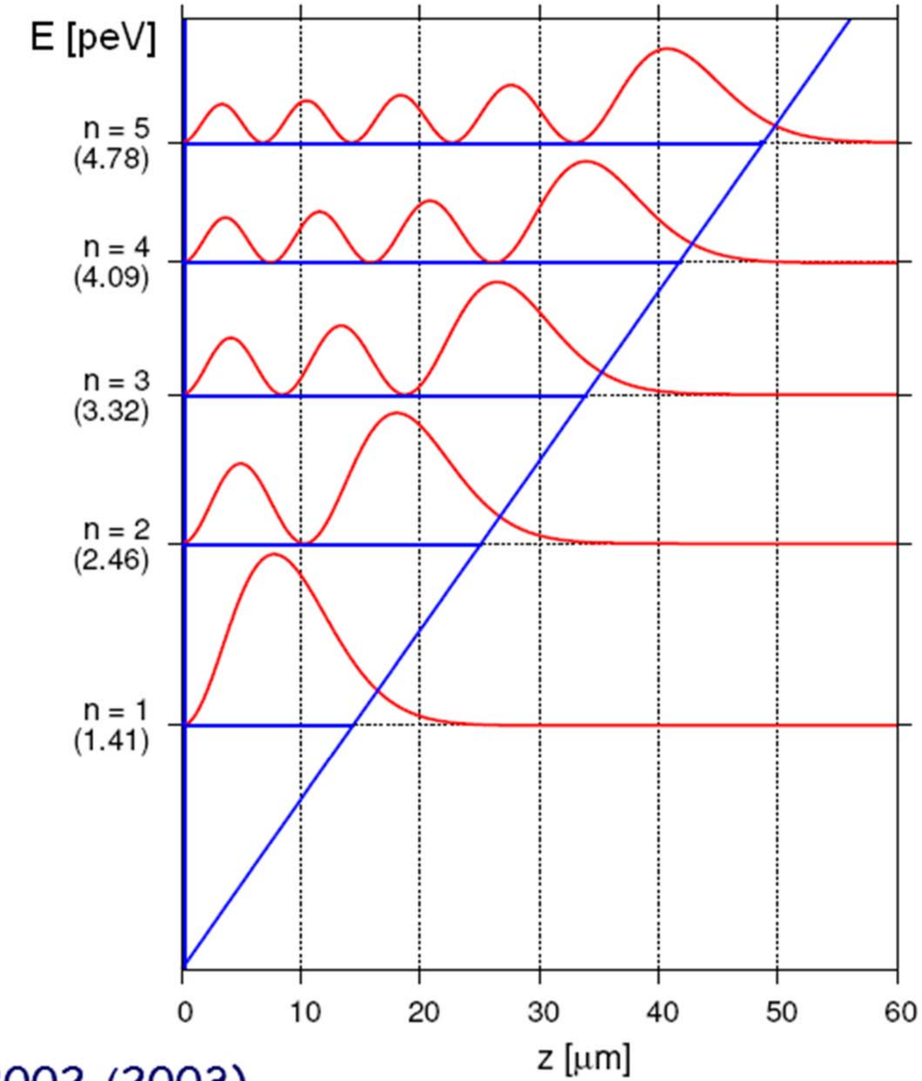


- **System Neutron & Earth**
  - Neutron bound in the gravity potential of the earth
  - <r> = 6 µm
  - Ground state energy of 1.4 peV
  - 1 dim.
  - Schrödinger Equ.
    - Airy Functions

- **Hydrogen Atom**
  - Electron bound in proton potential
  - Bohr radius <r> = 1 A
  - Ground state energy of 13 eV
  - 3 dim.
  - Schrödinger Equ.
    - Legrendre Polynomials

First Demonstration of Quantum States in the Gravity Potential

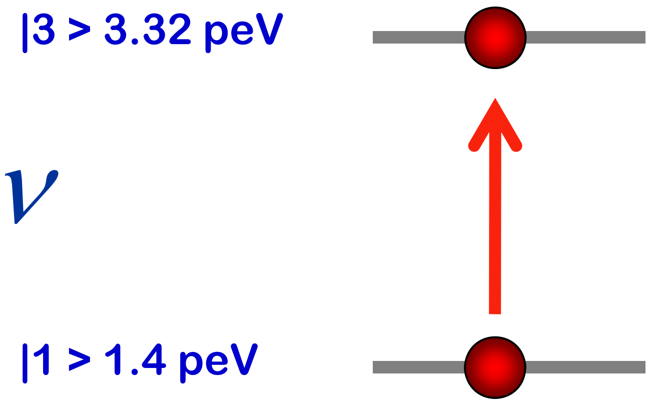
- Bound States
- Discrete energy levels
- Ground state 1.4 pico-eV
- Airy-Functions



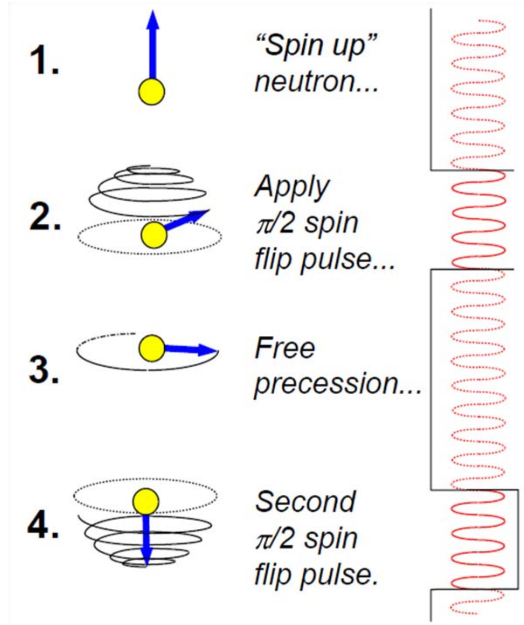
Demonstration of Quantum States
in the Gravity Potential of the Earth
Nesvizhevsky, H.A. et al.
Nature 2002

Nature 415 299 (2002), Phys. Rev. D 67 102002 (2003).

Resonance Spectroscopy



$$E = h\nu$$



- atomic clocks
- nuclea… magnetic resonance spectroscopy
- spin e… …nique
- quantum …
- gamma resonan… …py
- fluorescence spectrosco… biology

measurements of the electromagnetic interaction

nEDM Sensitivity: energy shift $\Delta E = 10^{-23}$ eV

This talk: **Gravity Resonance Spectroscopy**

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

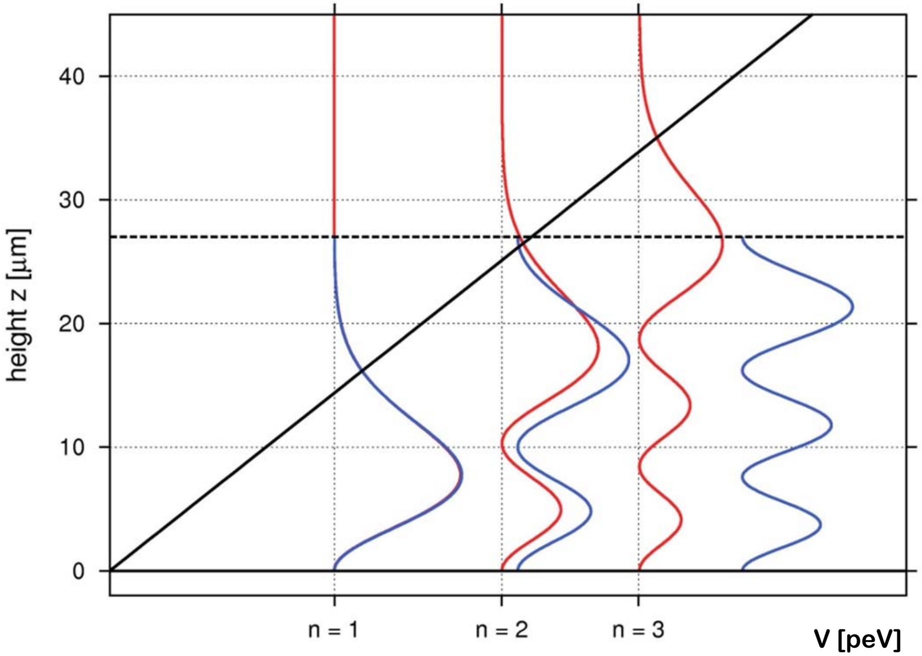
$$\varphi_n(l)=0$$

solutions: Airy-functions

scales:

energies: peV
length: μm

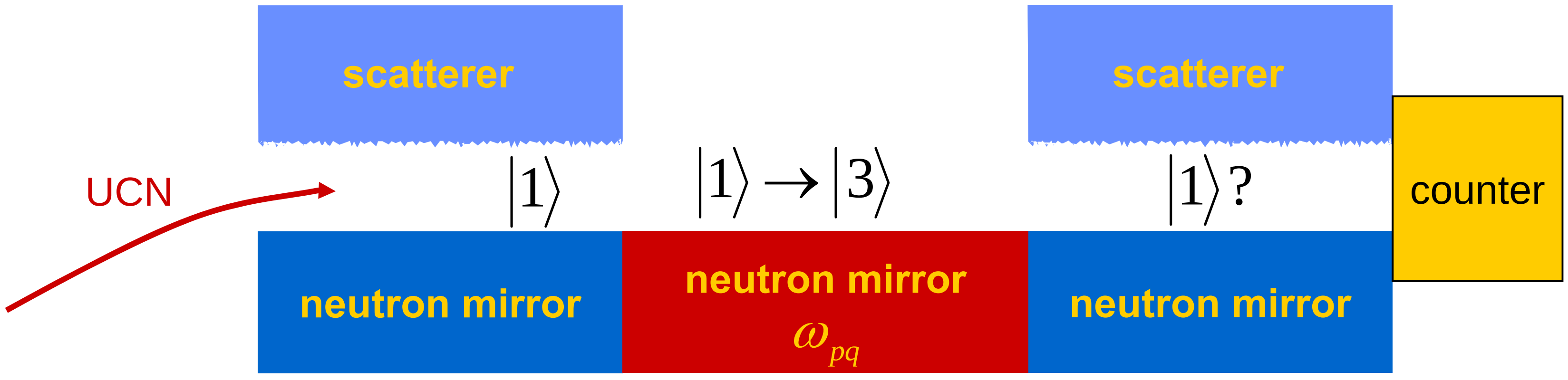
	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	3.97peV



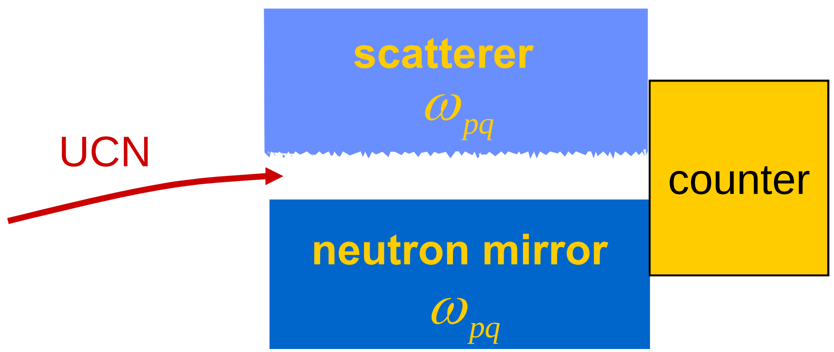
neutron mirror

On the way towards a Resonance Spectroscopy Technique

• First Idea: „Standard“ Rabi Experiment



• Better Idea: Simplified Setup, „Rabi Flopping with Damping“



- proof of technique possible
- simple (well-known) setup
- avoids „steps“
- better transmission (short)
- perfectly PF2-compatible

- in principle (probably) limited by knowledge of gap height l (can be removed by measuring > 1 resonance)

T. Jenke, PhD Thesis, 2011

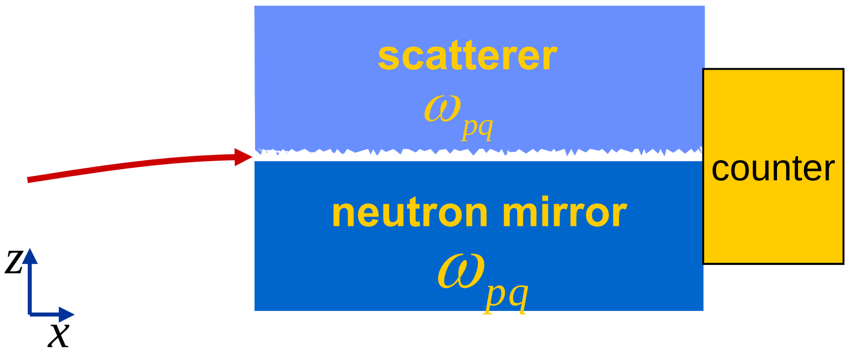
Rabi flopping with damping

$$V(z,t) = mgz + V\theta(-z + A\sin(\omega t)) + V(z - l - A\sin(\omega t))$$

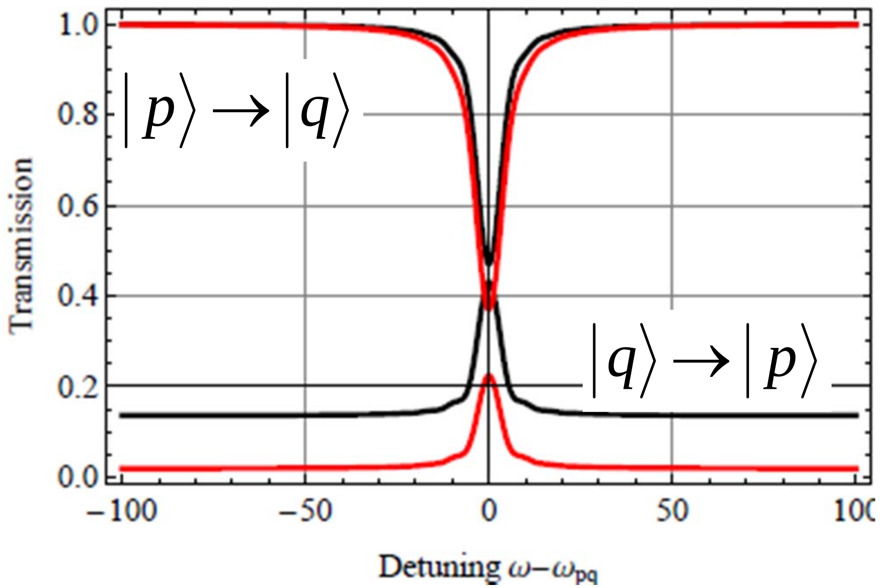
$$\left\{-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + V(z,t)\right\}\psi(z,t) = i\hbar\psi(z,t)$$

$$\frac{\partial}{\partial t}\begin{pmatrix} c_p(t) \\ c_q(t) \end{pmatrix} = \frac{i}{2}\begin{pmatrix} (\delta + i\Gamma_p) & \Omega_R \\ \Omega_R^* & (-\delta + i\Gamma_q) \end{pmatrix}\begin{pmatrix} c_p(t) \\ c_q(t) \end{pmatrix}$$

$$\Omega_R = \sqrt{(-(\Gamma_q - \Gamma_p) + i\delta)^2 + \omega_R^2}$$

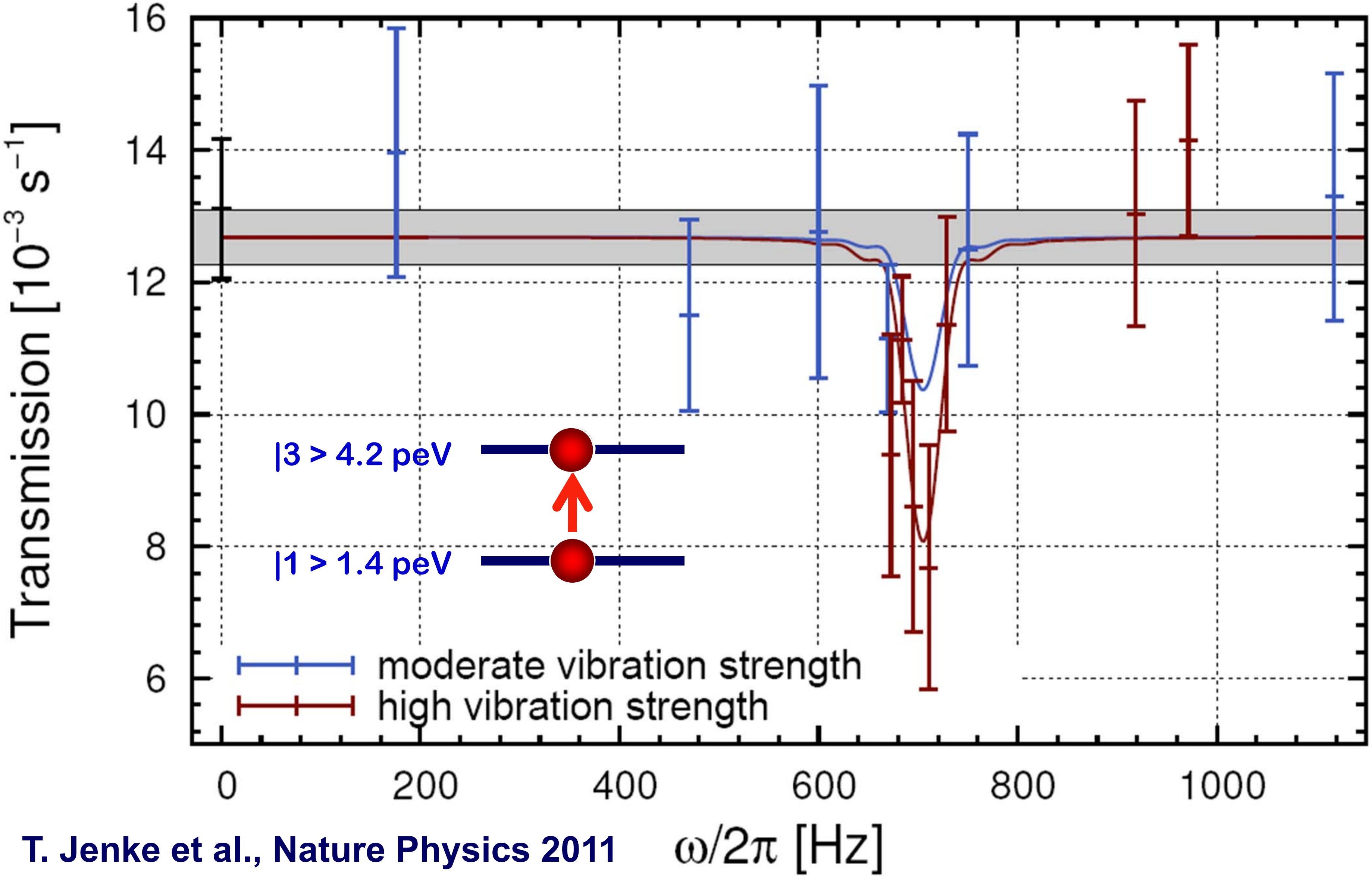


$$\Gamma_p \approx 0$$
$$\Gamma_q >> 0$$



T. Jenke, PhD Thesis, 2011

Gravity Resonance Spectroscopy and Excitation



T. Jenke et al., Nature Physics 2011

$$|1\rangle \longrightarrow |2\rangle, |1\rangle \longrightarrow |3\rangle,$$
$$|2\rangle \longrightarrow |3\rangle, |2\rangle \longrightarrow |4\rangle$$

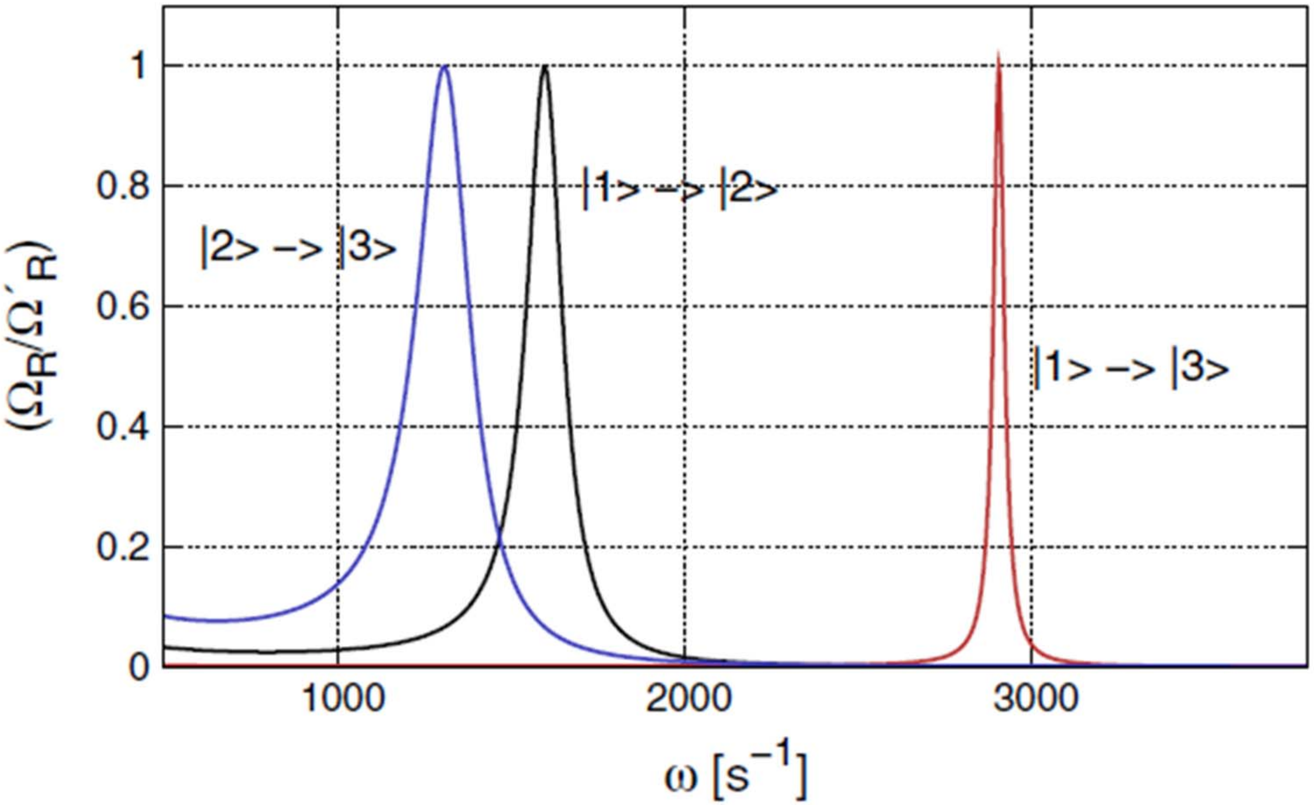
$$(H_0 + H_1 + W(t))\,\psi(z, t) == i\psi(z, t)$$

$$H_0 = -\partial_z{}^2 + z$$

$$H_1 = -i\gamma$$

$$W(t) = z_0 \mathrm{Sin}[\omega t] + i\omega z_0 \mathrm{Cos}[\omega t]\,\partial_z$$

Gravity Resonance 2010

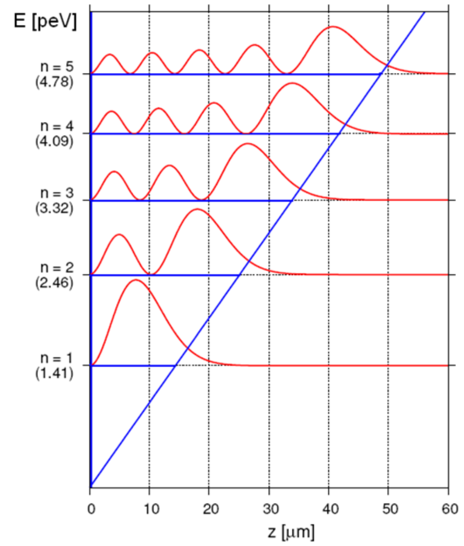


$$\begin{pmatrix} c_1'[t] \\ c_2'[t] \\ c_3'[t] \end{pmatrix} == \begin{pmatrix} -\frac{\gamma 1}{2} + i\,\delta_{12} & -e^{-i\,\phi 12}\,\omega_{r12} & 0 \\ e^{i\,\phi 12}\,\omega_{r12} & -\frac{\gamma 2}{2} & -e^{-i\,\phi 23}\,\omega_{r23} \\ 0 & e^{i\,\phi 23}\,\omega_{r23} & -\frac{\gamma 3}{2} - i\,\delta_{23} \end{pmatrix} . \begin{pmatrix} c_1[t] \\ c_2[t] \\ c_3[t] \end{pmatrix}$$

Neutrons test Newton

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

- **Strength α**
- **Range λ**



Hypothetical Gravity Like Forces

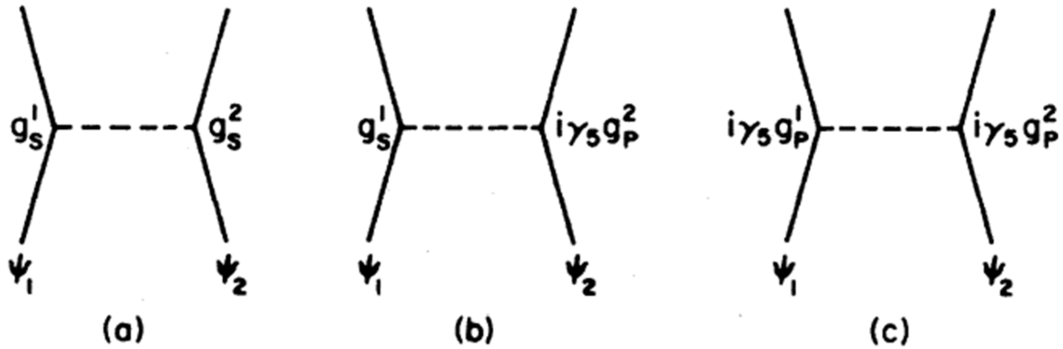
	Theory predictions	Our sensitivity
Deviations from Newton's Law due to Large Extra Dimensions	"Gauge fields in the bulk can mediate repulsive forces $10^6 < \alpha < 10^8$ times stronger than gravity at submillimetre distances." *ADD, PRD59 ,086004 (1999)*	$\alpha = 7.6\text{x}10^3$ at λ=5µm.
Dark Energy	According to CB, arXiv:gr-qc/0606108, the cosmological may be linked to the size of the extra dimensions, which would lead to deviations at λ=5µm and $\alpha < 10^6$.	$\alpha = 7.6\text{x}10^3$ at λ=5µm.
Dark matter Searches	Axions are serious candidates for dark matter in the astrophysical window, $10\mu eV < m_{Axion} < 10 eV$. This corresponds to $0.2\mu m < \lambda < 2cm$ for the axion coupling $g_s g_p / \hbar c$.	$g_s g_p / \hbar c <$ 5.3x10^{-23} at λ=5µm $g_s g_p / \hbar c <$ 1.6x10^{-26} at λ=5mm

Limits on Axions/CP-Violation

- **SM: 0 < $\theta < 2\pi$**

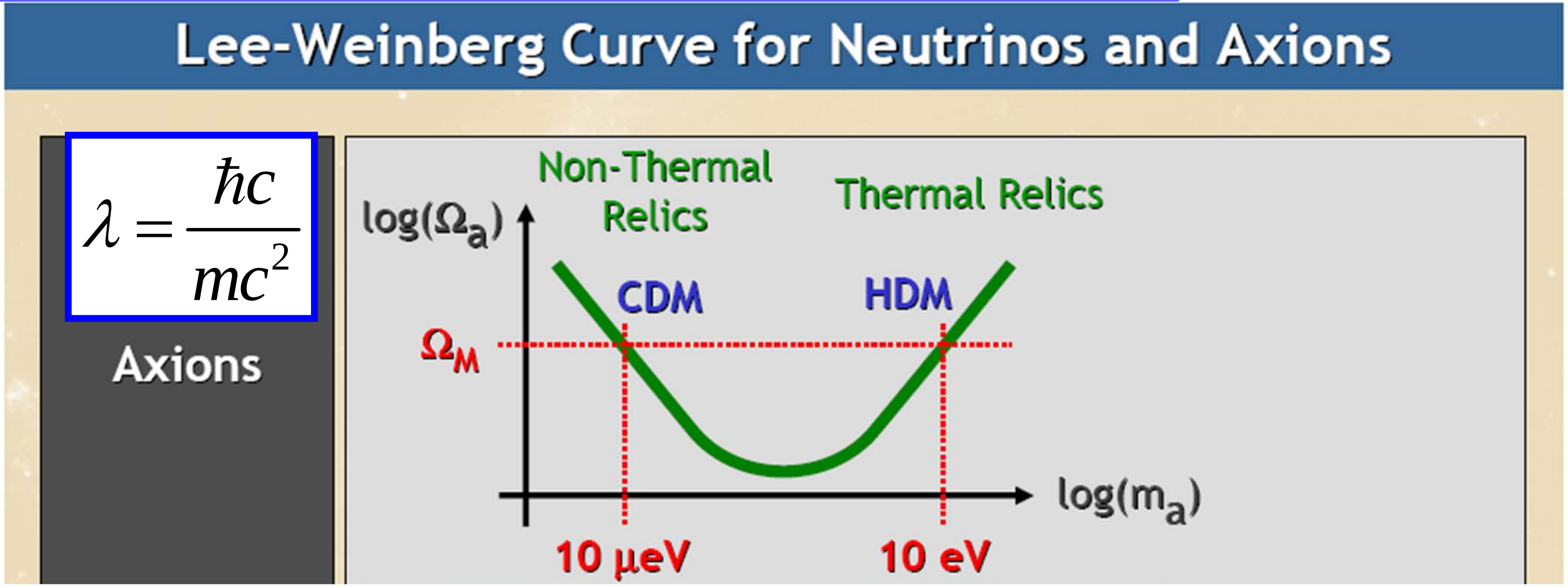
$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu}) + \bar{q}(i\not{D} - \mathcal{M})q + \frac{\theta}{16\pi^2}\mathrm{tr}(\tilde{G}_{\mu\nu}G^{\mu\nu})$$

- **EDM neutron→ $\theta < 10^{-10}$**
- **Axion: Spin-Mass coupling $g_s g_p/\hbar c$: $\theta = 0$**



$$V(\vec{r}) = \hbar g_s g_p \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Science week TU Munich 08, Georg Raffelt:



$\lambda = 2\ \mathrm{cm}$ $\lambda = 0.2\ \mu\mathrm{m}$

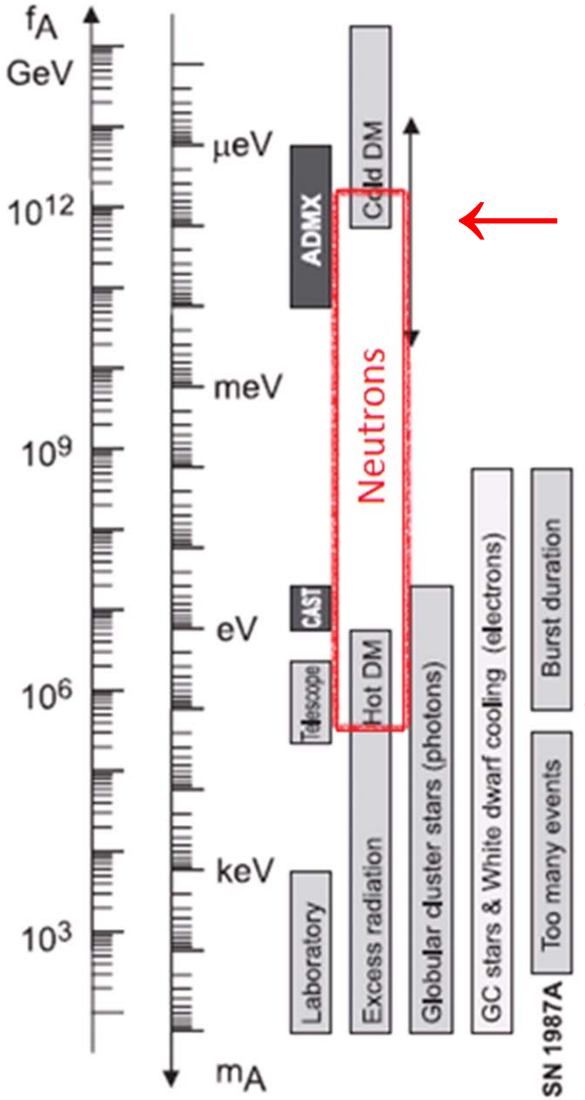
$$\Delta\phi(z) = -\alpha_a \cdot \frac{\hbar^2 \rho_1 \lambda}{8m^3} e^{-z/\lambda} + \alpha_a \cdot \frac{\hbar^2 \rho_2 \lambda}{8m^3} e^{-(h-z)/\lambda}$$

$$= -2\pi\alpha_{\text{eff.}} \cdot \lambda^2 \cdot G_4 \cdot \left(\rho_1 e^{-z/\lambda} - \rho_2 e^{-(h-z)/\lambda}\right)$$

$$\alpha_{\text{eff.}} = \alpha_a \cdot \frac{\hbar^2}{16\pi G_4 \cdot m^3} \cdot \lambda^{-1} \quad , \quad \alpha_a := \frac{g_s g_p}{\hbar c}$$

A. Westphal, H.A. et al. 2007

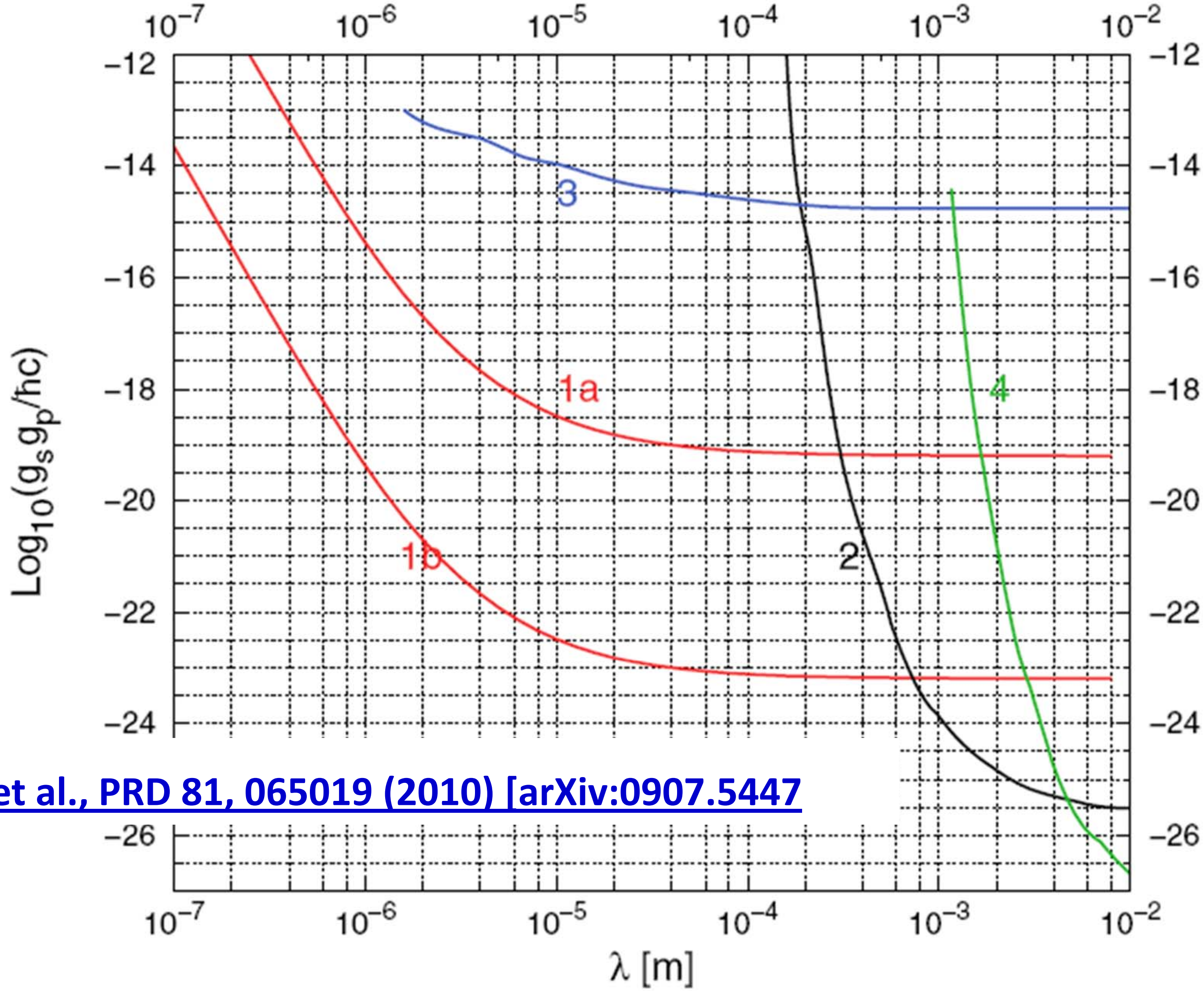
PDG Exclusion Ranges



$\lambda = 2\ \text{cm}$

$\lambda = 0.2\ \mu\text{m}$

2007: Best Limits on axionlike-coupling strength from neutrons and quantum states in axion window



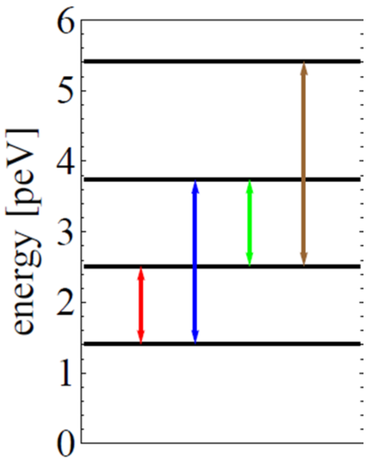
H.A. et al., PRD 81, 065019 (2010) [arXiv:0907.5447

PRELIMINARY

Experimental Data (2010/2011)

Axion Limits for
Axion masses between
1μeV < m < 10eV

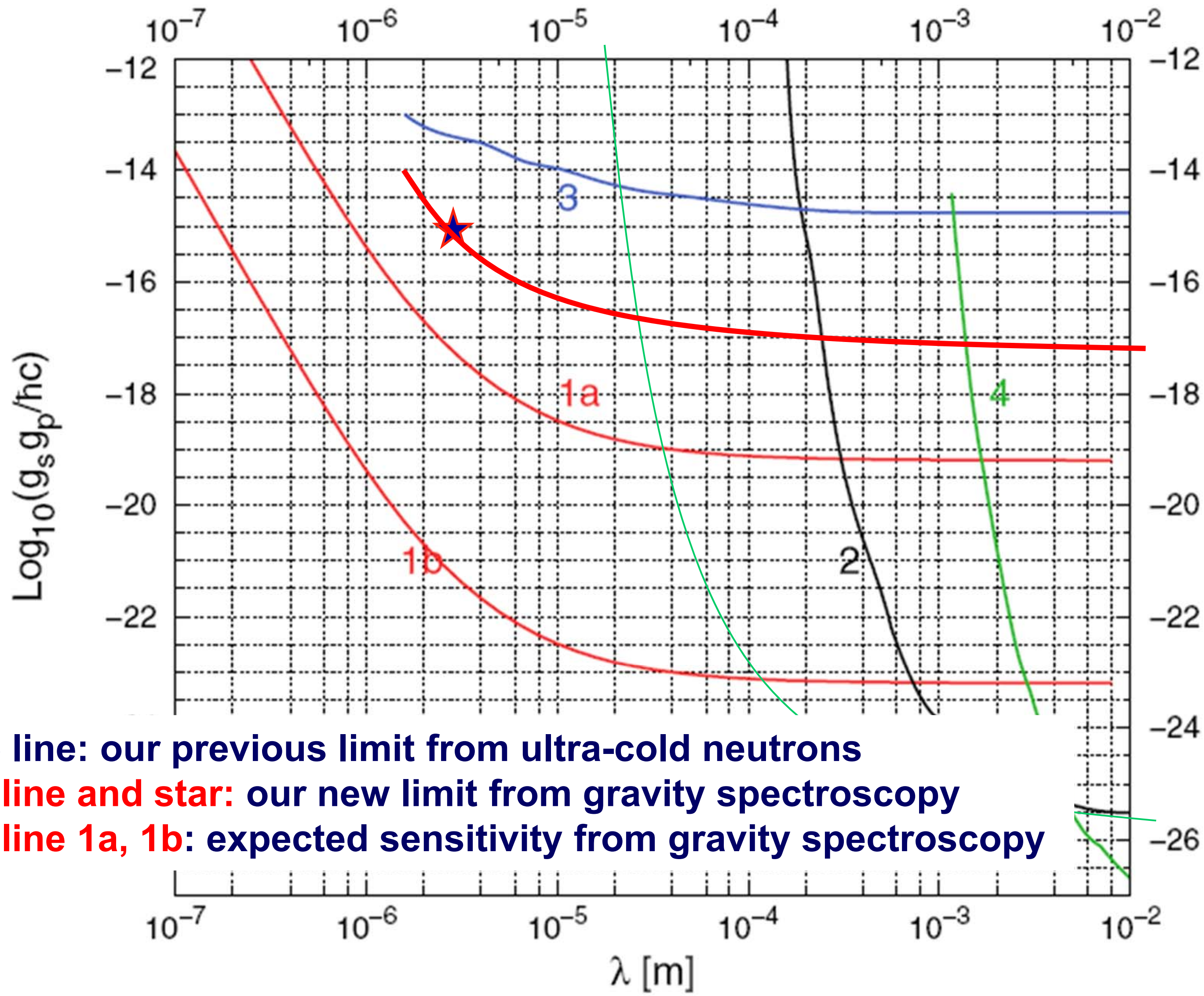
Observed Transitions



|1> ↔ |2> : 266 Hz
|1> ↔ |3> : 563 Hz
|2> ↔ |3> : 296 Hz
|2> ↔ |4> : 701 Hz

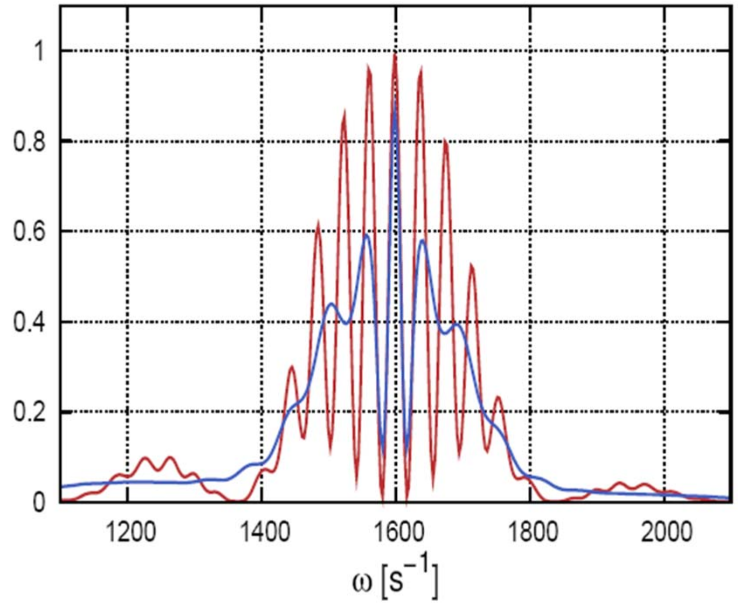
- Repeat expt with Polarized Neutrons
- Spin up: red
- Spin down: black
- Limit on
- Spin-Mass-Coupling

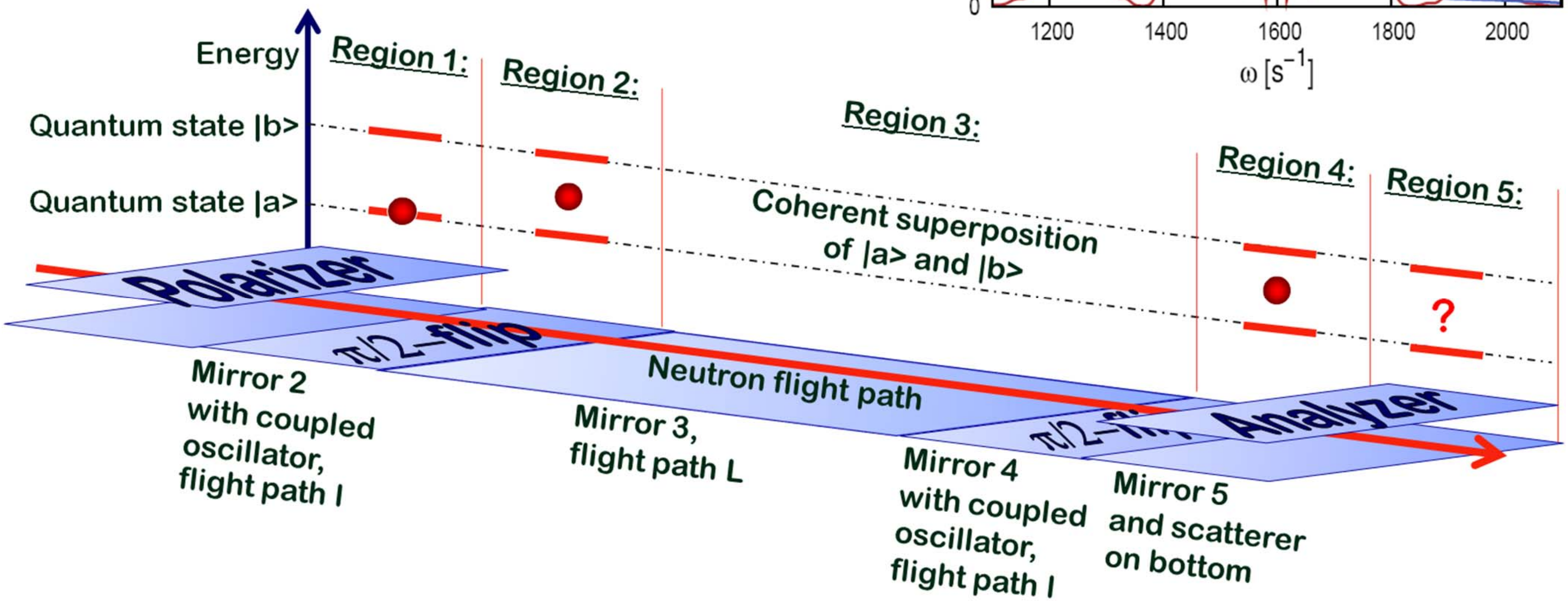
qBounce-Limits on axionlike-coupling strength



The Future: Ramsey-Method

$$\alpha = 3\times10^{3}, \Delta E = 6\times10^{-21}\text{eV}$$

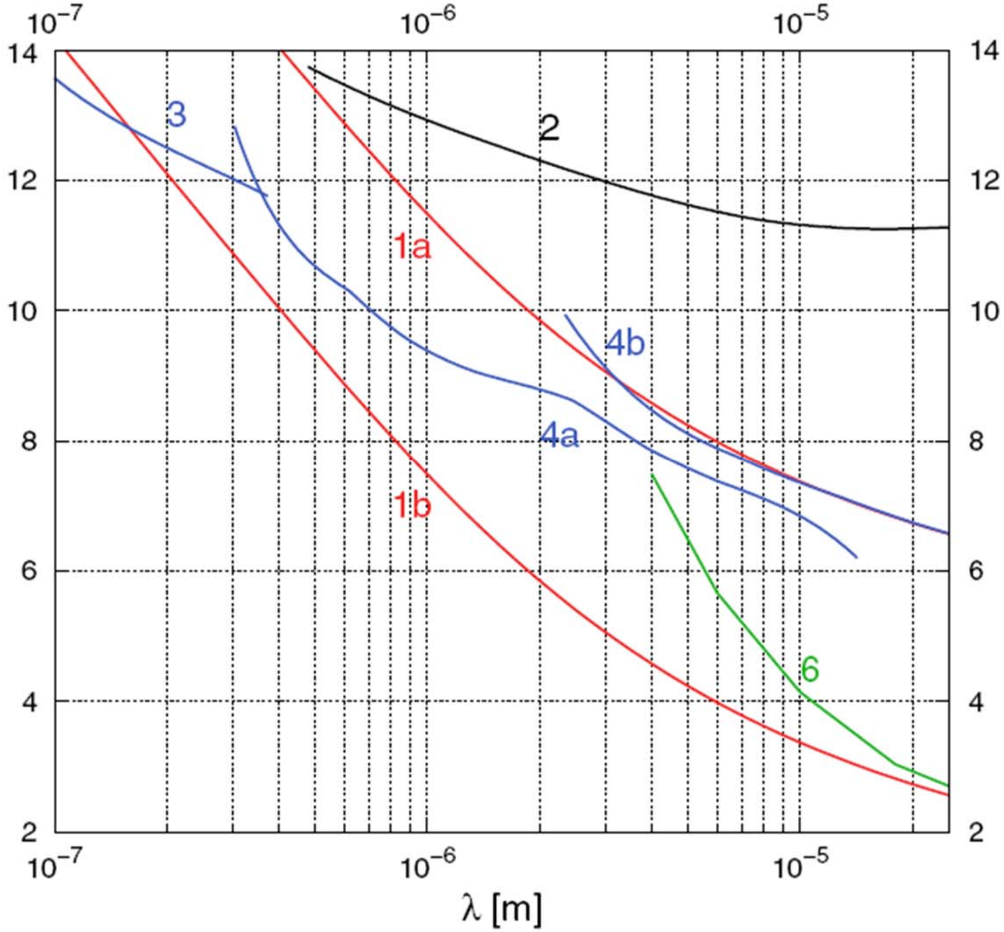




$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

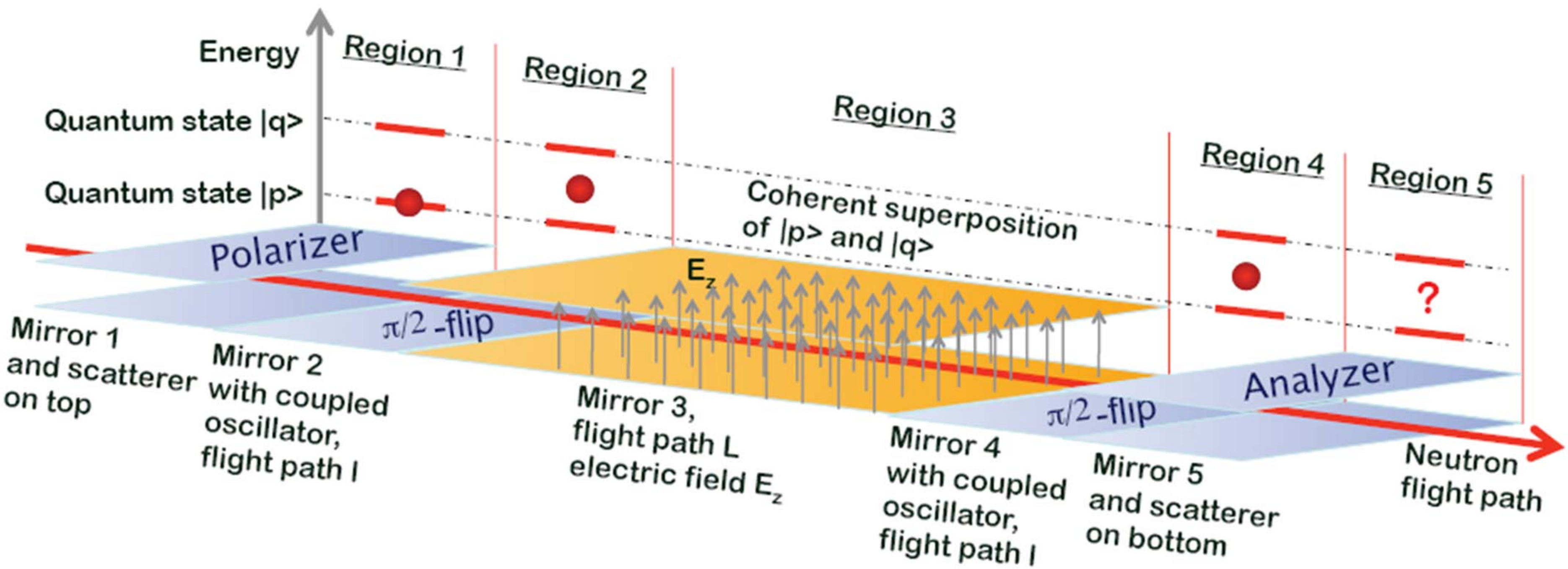
Limits on hypothetical gravity-like forces

- **So far best limits from AFM**
  - **False effects from Casimir or Van der Waals forces**
- **Neutrons:**
  - **Polarizability extremely small**



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.*
- **Improve limits by one to two orders of magnitude**



The Team at Atominstitut

- Gravity tests with quantum objects
  - M. Adam, G. Cronenberg, T. Jenke, H. Saul, T. Lins, D. Stadler, P. Geltenbort (ILL), H. Lemmel, U. Schmidt (Heidelberg), Thorsten Lauer (Mainz),H.A.
- Vienna University of Technology
- University of Heidelberg
- University of Mainz

qBOUNCE Summary

- Progress Report with Galileo in Quantum Land
  - qBounce: first demonstration of the quantum bouncing ball
    - Dynamics: time evolution of coherent superposition of Airy-eigenfunctions
  - Realization of Gravity Resonance Spectroscopy:
    - Coherent Rabi-Transitions,
    - |1> →|2>
    - |1> →|3>, see Nature Physics, 1 June 2011
    - |2> → |3>, |2> → |4>
  - New Tool for
    - A Search for a deviation from Newton‘s Law at short distances, where polarizability effects are extremely small ,

      see H.A. et al., PRD 81, 065019 (2010) [arXiv:0907.5447
    - A quantum test of the equivalence principle
  - Direct limits on axion coupling at short distances,

see arXiv:hep-ph/0703108