ATOMINSTITUT

qBOUNCE

A quantum bouncing ball gravity spectrometer

Hartmut Abele
Humboldt Kolleg: From the Vacuum to the Universe
30. June 2016

Austrian Free fall at large distances

~~World Record 40.000 m~~

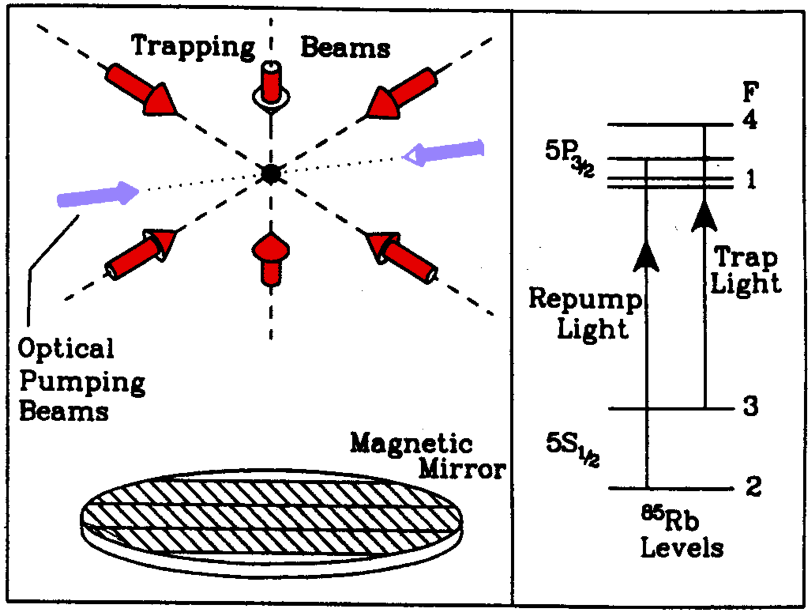
Dr. Alan Eustace
41.424 m

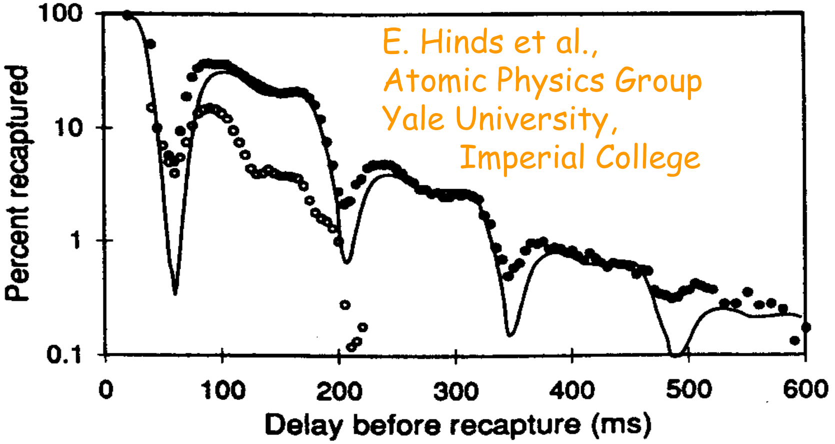
40 km jump, Source: S. Schwarz

Felix Baumgartner

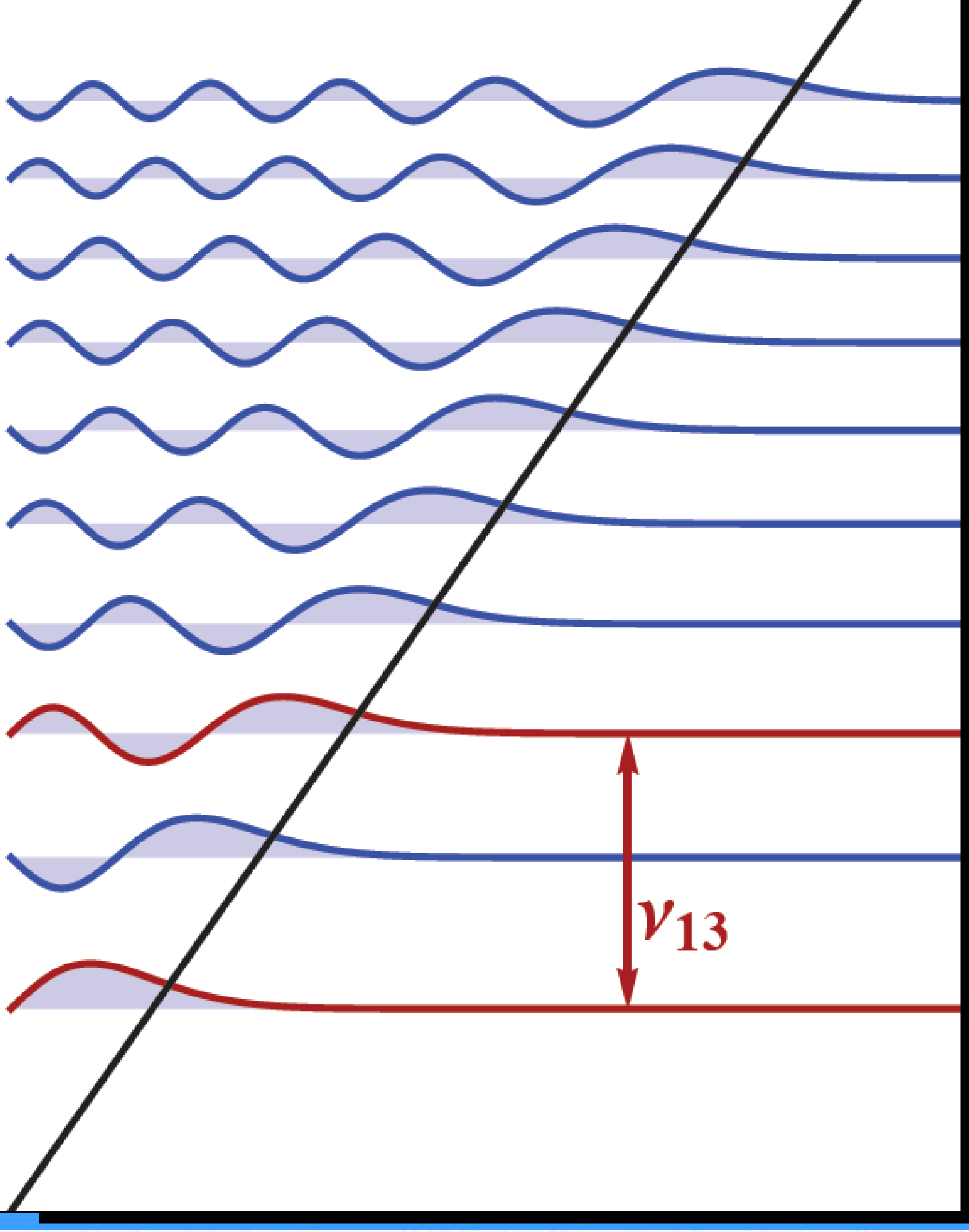
Alan Eustace
***1956/57**

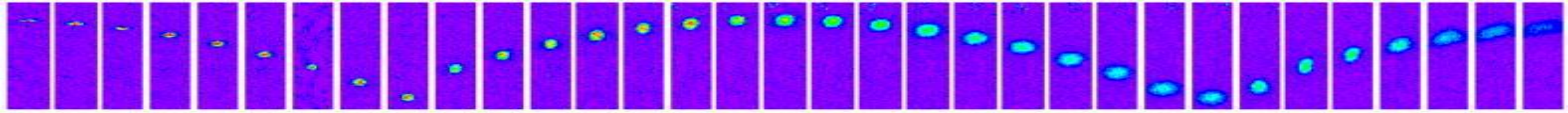
Rb Atoms Bouncing in a Stable Gravitatonial Cavity





E. Hinds et al.,
Atomic Physics Group
Yale University,
Imperial College

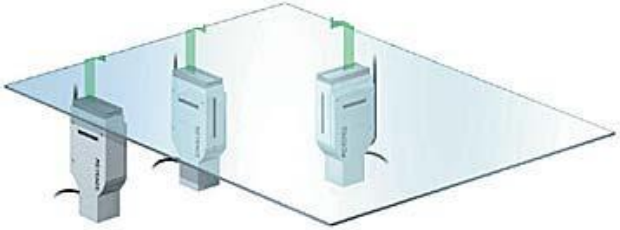




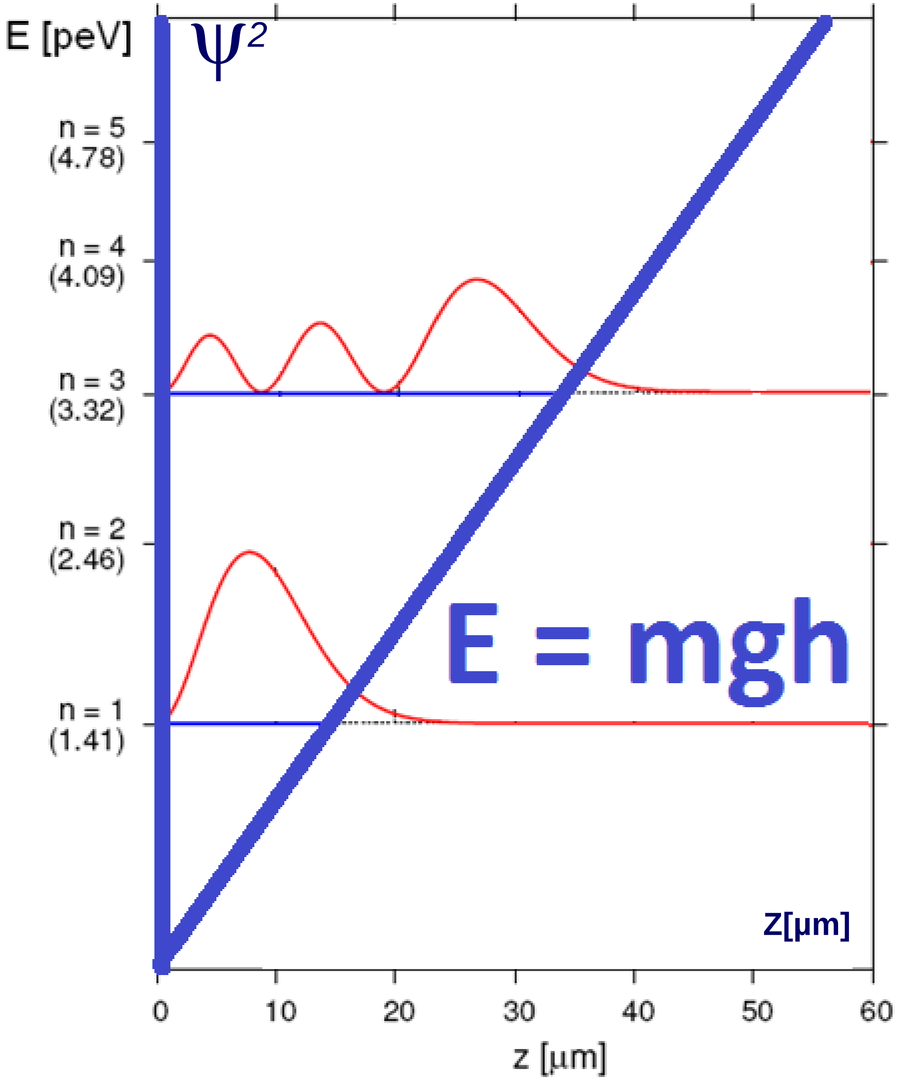
qBOUNCE: Quantum States in the Gravity Potential

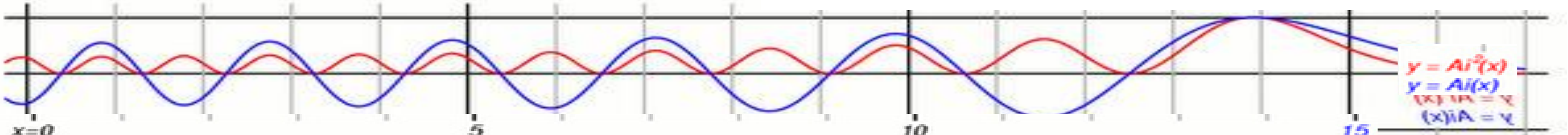
- Schrödinger Equation

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z)$$

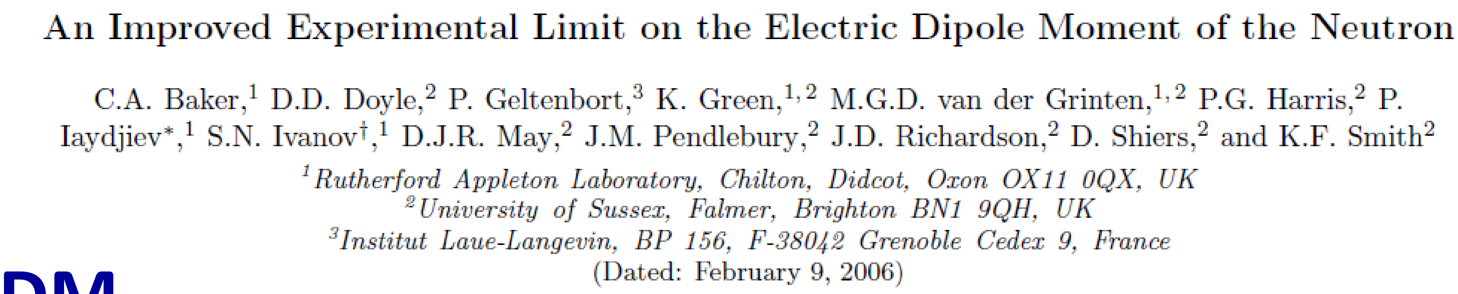


- Bound States
- Discrete energy levels
- Ground state 1.4 peV
- Airy-Functions





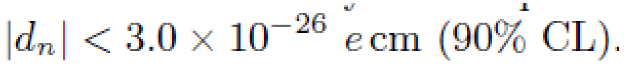
EDM Experiments



An Improved Experimental Limit on the Electric Dipole Moment of the Neutron

C.A. Baker,[1] D.D. Doyle,[2] P. Geltenbort,[3] K. Green,[1,2] M.G.D. van der Grinten,[1,2] P.G. Harris,[2] P. Iaydjiev*,[1] S.N. Ivanov†,[1] D.J.R. May,[2] J.M. Pendlebury,[2] J.D. Richardson,[2] D. Shiers,[2] and K.F. Smith[2]

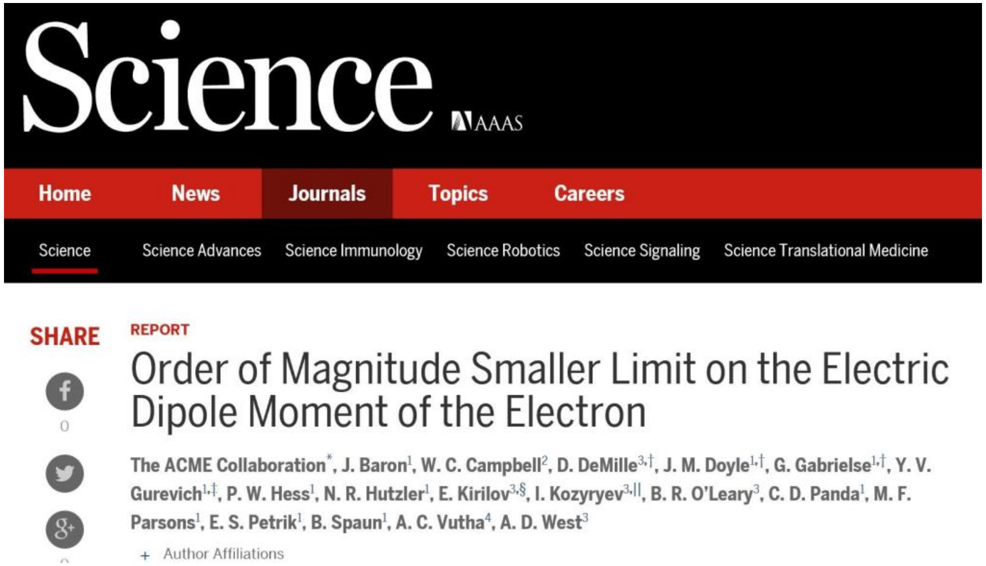
[1] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK*
[2] *University of Sussex, Falmer, Brighton BN1 9QH, UK*
[3] *Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France*
(Dated: February 9, 2006)



$|d_n| < 3.0 \times 10^{-26}$ e cm (90% CL).

- **n EDM** Bodek Talk
- $\Delta E = 10^{-21}$ eV

- **Atom EDM**



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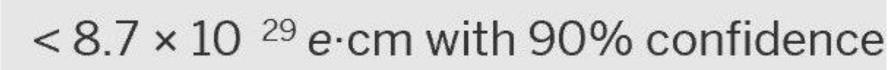
REPORT

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*, J. Baron[1], W. C. Campbell[2], D. DeMille[3,†], J. M. Doyle[1,†], G. Gabrielse[1,†], Y. V. Gurevich[1,‡], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,§], I. Kozyryev[3,||], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], A. D. West[3]

+ Author Affiliations



$< 8.7 \times 10^{29}$ e·cm with 90% confidence

- $\Delta E = 10^{-18}$ eV

Gabrielse Talk

Motivation for high precision tests with neutrons:

extreme sensitivity or precision

- Energy $\Delta E = 10^{-21}$ eV
- Momentum $\Delta p/p = 10^{-11}$
- Angle $\Delta \varphi = 10^{-11}$ rad
- Decay rate: 10^{6} /s/m

- Neutral
- Polarisability extremely small

- **By a hair's breadth**

review article:
H.A., The neutron. Its properties and basic interactions,
Prog. Part. Nucl. Phys. 60 1-81 (2008)

Observables: more than a dozen related to particle physics and cosmology

DFG/FWF Priority Programme 1491 : Precision experiments in particle- and astrophysics with cold and ultracold neutrons,

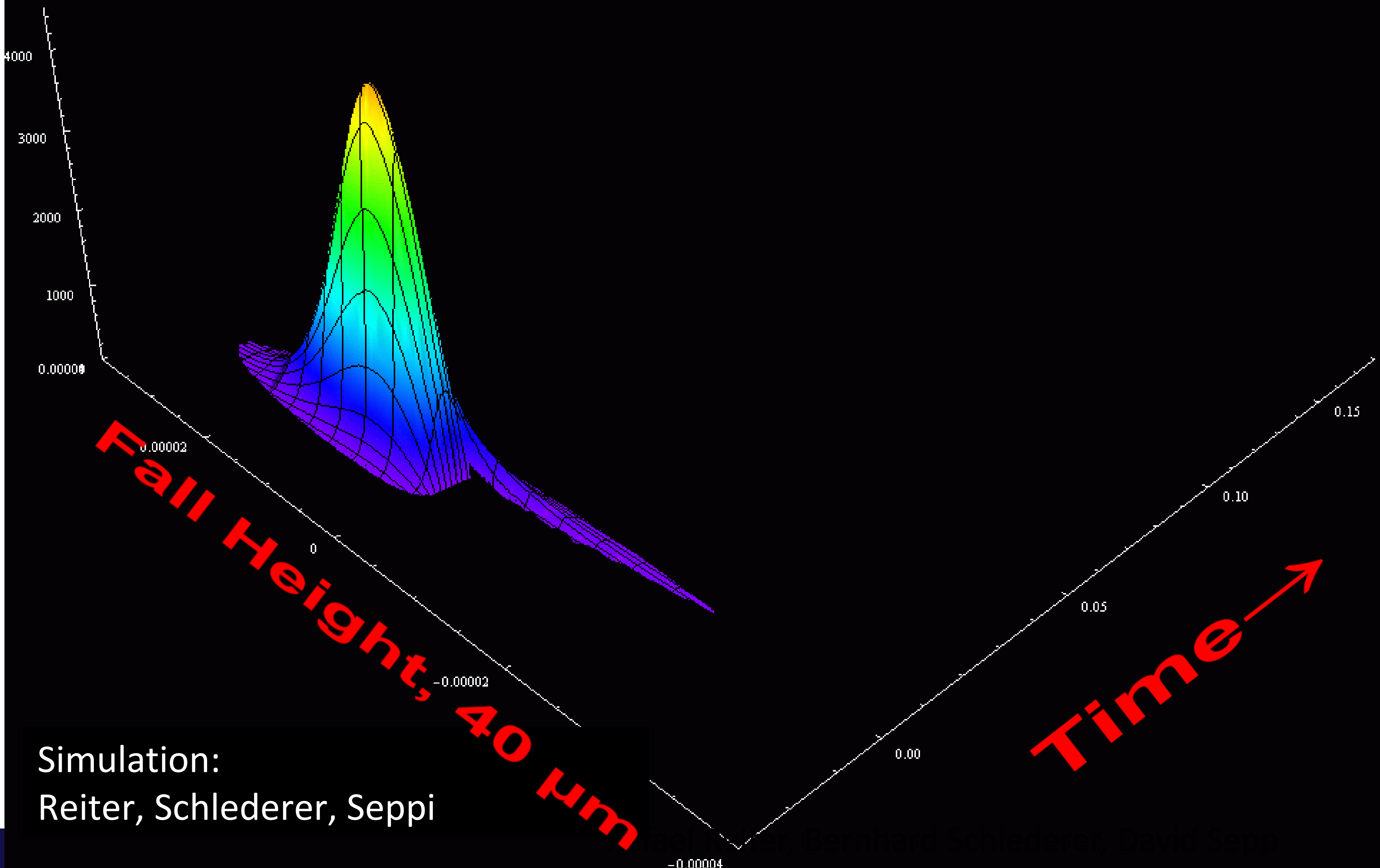
- Participating Institutions:
  - IST Braunschweig
  - Univ. Heidelberg
  - ILL
  - Univ. Jena
  - Univ. Mainz
  - Exzellenzcluster ‚Universe' München
  - Techn. Univ. München*
  - PTB Berlin
  - Techn. Univ. Wien*
- Priority Areas
  - CP-symmetry violation and particle physics in the early universe.
  - The structure and nature of weak interaction and possible extensions of the Standard Model.
  - Tests of gravitation with quantum objects
  - Charge quantization and the electric neutrality of the neutron.
- New Infrastructure (UCN-Source, cold Neutrons)

\- *** Coordinators first round (S. Paul, H.A.)**

Outline of my talk: gravity tests at short distances

- Priority Programme 1491*, DFG & FWF*
- *q*Bounce- Realization of a
  Quantum Bouncing Ball Gravity Spectrometer
  - Fall height: 40µm
  - Mirror, polished glass
- Gravity Resonance Spectroscopy
- Test of Newton's Law at short distances
  - Search for hypothetical gravity-like forces, effects of string theories, higher dimensional field theories etc.
  - Limits on theories describing the expansion of the universe
- Measurements of Airy-Functions in the gravity potential of the Earth
- Search for a charge of the neutron

Show Case I: *free fall at short distances*

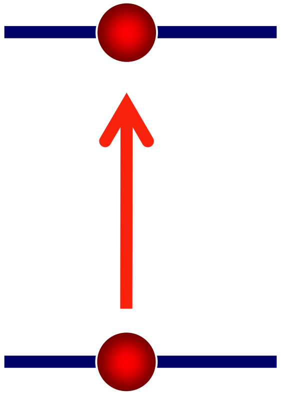


Simulation:
Reiter, Schlederer, Seppi

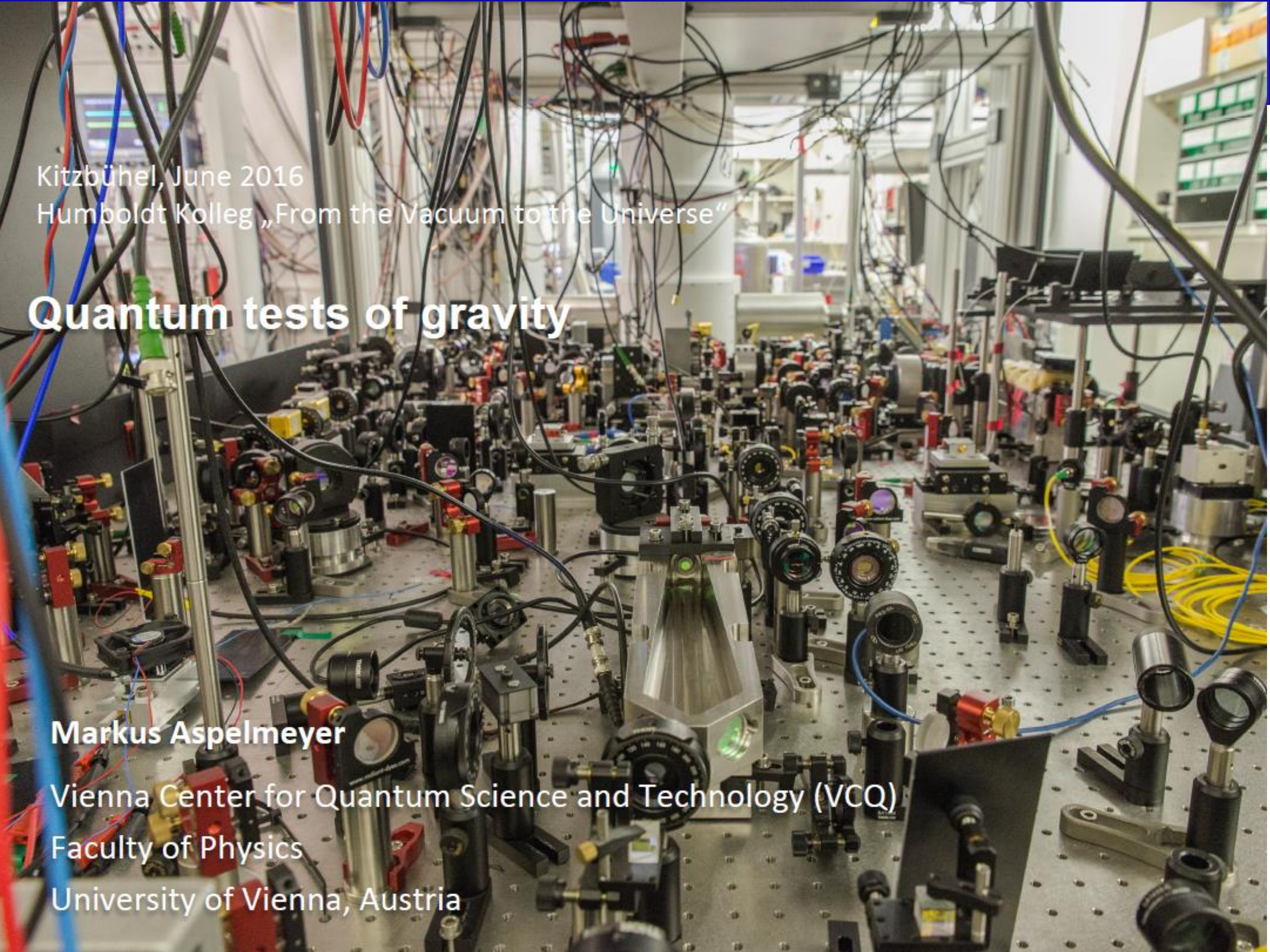
Frequency: Resonance Spectroscopy

- Quantum System, 2-Level System
- Coupling

$$E = h\nu$$



- Example:
  - NMR:
    - Magnetic Moment in
    - outer magnetic field
    - RF-field drives Transitions
  - Rabi – Spectroscopy
  - Ramsey Spectroscopy: Clocks, Spin Echo, EDM
- All Spectroscopy methods so far use electromag fields or a coupling to a electromag. potential



Kitzbühel, June 2016
Humboldt Kolleg „From the Vacuum to the Universe“

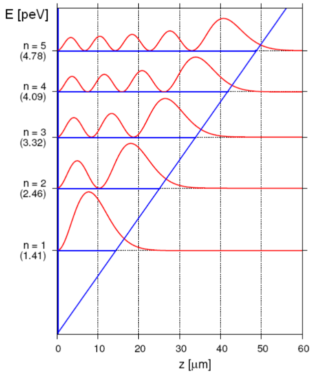
Quantum tests of gravity

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)
Faculty of Physics
University of Vienna, Austria

Gravity Resonance Spectroscopy

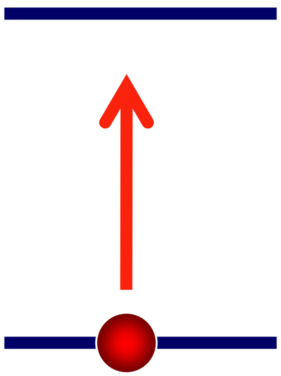
- Quantum System, 2-Level System
- Coupling



$$E = h\nu$$

- GRS: Neutron
  - gravity field of earth,
  - oscillating Mirror

  drives transitions



|3 > 3.32 peV

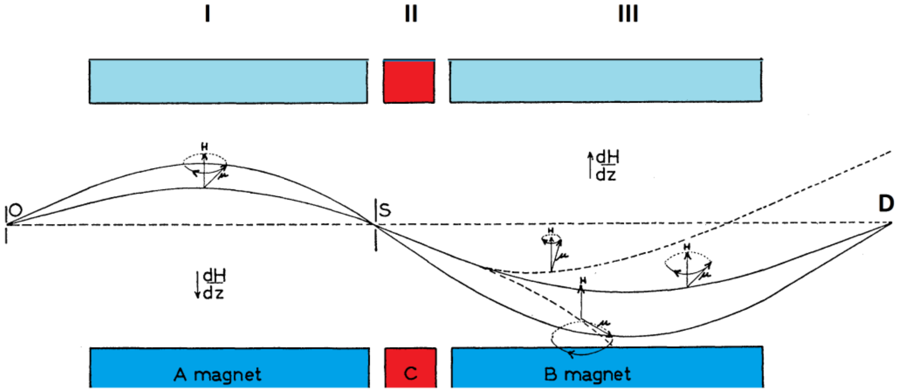
|1 > 1.4 peV

***q*Bounce:**
Vibrating mirror

Demonstration Gravity Resonance Spectroscopy:Jenke et al., Nature Physics 2011

Show Case II: Rabi-type Spectroscopy of Gravity

- **NMR Spectroscopy Technique to *explore magnetic moments***



- 3 Regions:
  - I: 1st State selector/ Polarizer
  - II: Coupling
    - RF field
  - III: 2nd State Selector / Analyzer

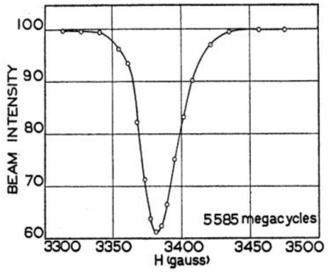
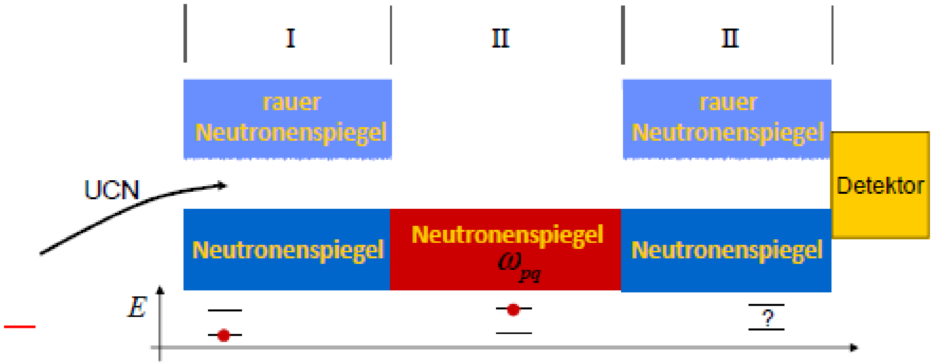


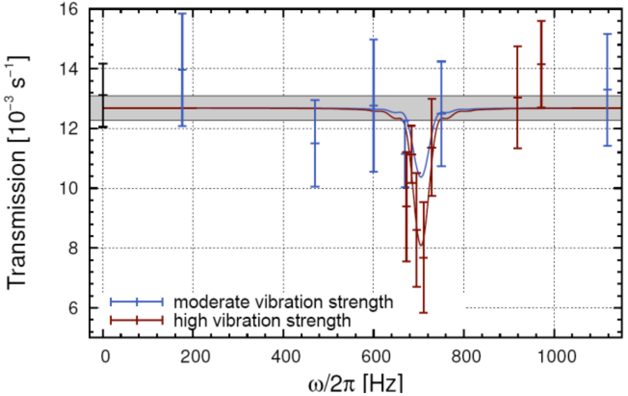
FIG. 4. Resonance curve of the Li^7 nucleus observed in LiCl.

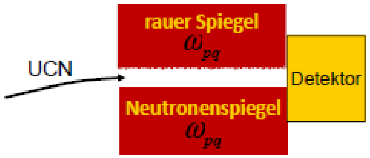
- **Gravity Resonance Spectroscopy Technique to *explore gravity***



- 3 Regions:
  - I: 1st State selector/ Polarizer
  - II: Coupling
    - Vibr. mirror
  - III: 2nd State Selector / Analyzer

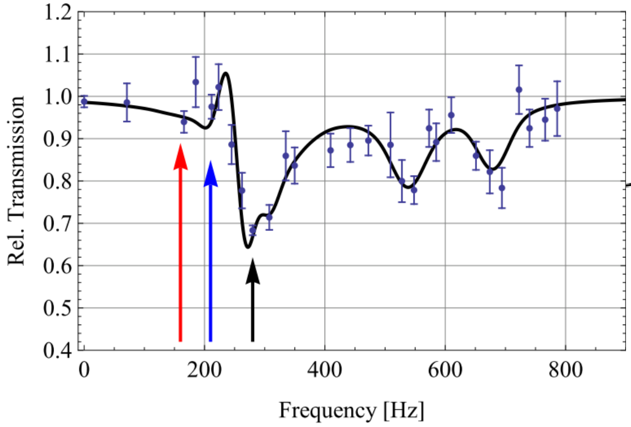
*q*Bounce – Gravity Resonance Spectroscopy

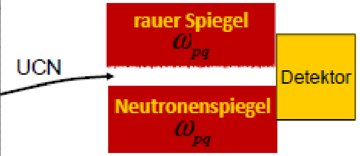




|1> ↔ |3>

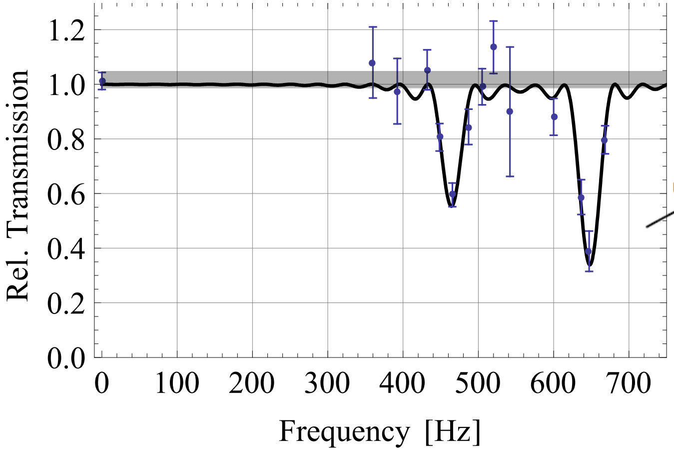
- **T. Jenke et al. NP 2011**

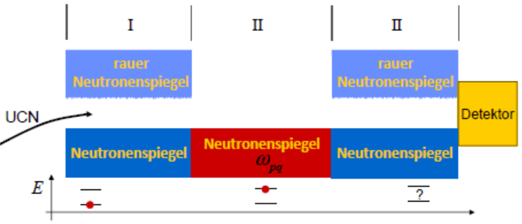




|1> ↔ |2> : 266 Hz
|1> ↔ |3> : 563 Hz
|2> ↔ |3> : 296 Hz
|2> ↔ |4> : 701 Hz

- **T. Jenke et al. PRL 2014**





|1> ↔ |3> : 462 Hz
|1> ↔ |4> : 647 Hz

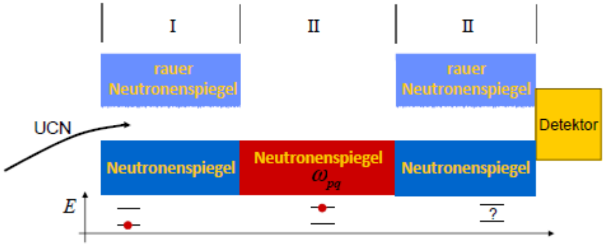
- **C. Cronenberg et al.**

Results

Transitions 1-3 and 1-4 observed

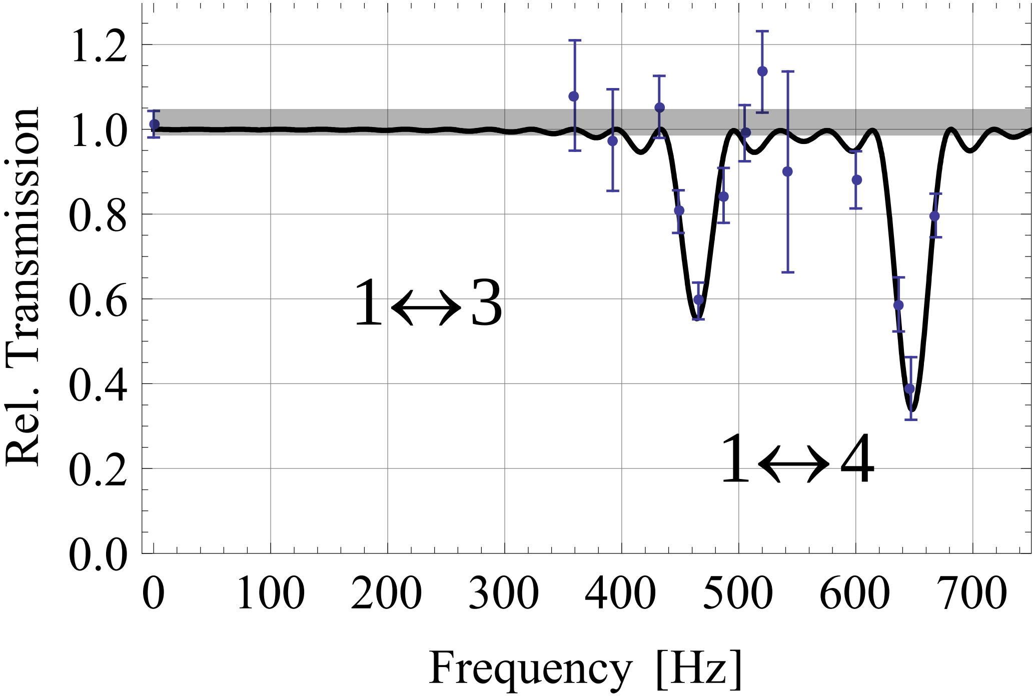
1-3: (46±5)% Intensity drop

1-4: (61±7)%



60 measurements

@ 2.1 mm/s



Preliminary,

$$\nu_{13} = 463.74^{+1.05}_{-1.10}\,\mathrm{Hz}$$

$$\nu_{14} = 648.24^{+1.46}_{-1.53}\,\mathrm{Hz}$$

Thesis Cronenberg

Priority Programme 1491

- Research Area A: *CP-symmetry violation and particle physics in the early universe*
  - **Neutron EDM** $\Delta E = 10^{-23}$ eV
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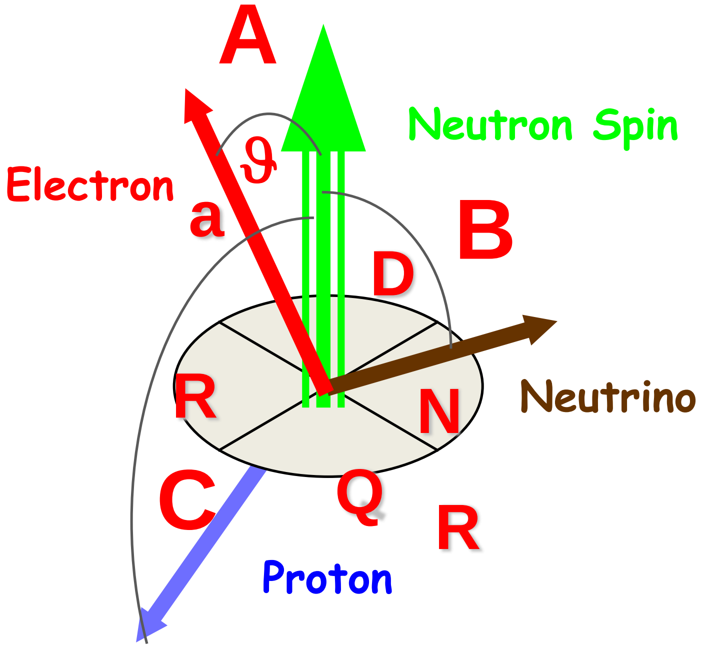
  - **Neutron β-decay** V – A Theory
- Research Area C: *Test of gravitation with quantum interference*
  - **Neutron bound gravitational quantum states**
- Research Area D: *Charge quantization and the electric neutrality of the neutron*
  - **Neutron charge**
- Research Area E: *New measuring techniques*
  - ***Particle detection***
  - ***Magnetometry***
  - ***Neutron optics***

Neutron Alphabet deciphers the SM

Parameters

- Strength: G_F
- Quark mixing: V_{ud}
- Ratio: $\lambda = g_A/g_V$



$$\tau^{-1} = V_{ud}^{2} G_{F}^{2} (1+3\lambda^{2}) \frac{f^{R} m_{e}^{5} c^{4}}{2\pi^{3}\hbar^{7}}$$

$$d\Gamma \propto \mathcal{N}(E_e)\left\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle\cdot\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]\right.$$
$$\left. +\vec{\sigma}\cdot\left[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e\cdot\langle\vec{J}\rangle + R\langle\vec{J}\rangle\times\frac{\vec{p}_e}{E_e}\right]\right\}d\Omega_e d\Omega_\nu dE_e,$$

Observables

- Lifetime τ
- Correlation A
- Correlation B
- Correlation C
- Correlation a
- Correlation D
- Correlation N
- Correlation Q
- Correlation R
- Beta Spectrum
- Proton Spectrum
- Beta Helicity

a bit history:

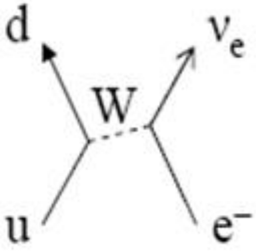
λ from neutron *β*-decay

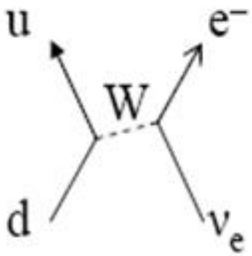
- -1.1900(200), PDG (1960)
- -1.2500(200), PDG (1975)
- -1.2610(40), PDG (1990)
- -1.2594(38), Gatchina (1997)
- -1.2660(40), M, ILL (1997)
- **-1.2740(30), PERKEO II (1997)**
- -1.2686(47), Gatchina, ILL (2001)
- **-1.2739(19), PERKEO II (2002)**
- **-1.2762(13), HD, ILL (2006)**
- −1.27590(+409)(−445), UCNA (2011)
- -1.2756(30), UCNA (2013)
- **-1.2748^{+13}_{-14} PERKEO II (2013)**

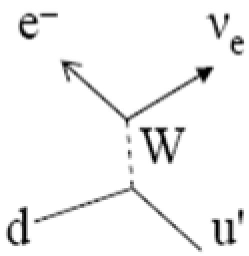
Why ratio $\lambda = g_A / g_V$ from Neutrons?

- Processes with the same Feynman-Diagram

Primordial element formation	$n + e+ \rightarrow p + \nu'_e$	$\sigma_v \sim 1/\tau$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_v \sim 1/\tau$
	$n \rightarrow p + e^- + \nu'_e$	τ
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$	
	$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$
Neutron star formation	$p + e^- \rightarrow n + \nu_e$	
Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$	
Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.	
W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.	







$$f_\pi g_{\pi NN} = g_A \frac{m_n + m_p}{2}$$

Courtesy of D. Dubbers

Beyond SM

- **A search for**
  - right-handed admixtures to the left-handed feature of the Standard model. They are forbidden in the Standard-Model, but, as a natural consequence of symmetry breaking in the early universe, they should be found in neutron-decay. Signatures are a W_R mass with mixing angle z.
  - scalar and tensor admixtures g_S and g_T to the electroweak interaction. g_S and g_T are also forbidden in the Standard model but supersymmetry contributions to correlation coefficients or the Fierz interference term b can approach the 10^{-3} level.
- **A precision measurement of**
  - the weak-magnetism form factor f_2 prediction of electroweak theory. Such an experiment would be one of the rare occasions, where a strong test of the underlying structure itself of the Standard model becomes available.
- **Supersymmetry search in the LHC era:**
  - one could expect small deviations in the low-energy tests, such as deviations from CKM unitarity, but no effect at the LHC, especially if the supersymmetry spectrum is below one TeV, but the spectrum is compressed, or if some of the superpartners are light and others are heavy (a variant on the "split-SUSY" scenario)

Courtesy M. Ramsey-Musolf

Weak Magnetism form factor f_2

Neutron Decay Transition Matrix:

$$\boxed{T_{fi} = \frac{G_F}{\sqrt{2}} V_{ud} \cdot \langle p | \gamma_\mu (1-\gamma_5) | n \rangle \cdot (\bar{\nu}\gamma^\mu (1-\gamma_5) e)}$$

$$V_\mu = \langle p | [\, f_1(k^2)\gamma_\mu + \frac{f_2(k^2)}{2m_p}\sigma_{\mu\nu}k^\nu + i f_3(k^2) k_\mu] | n \rangle$$

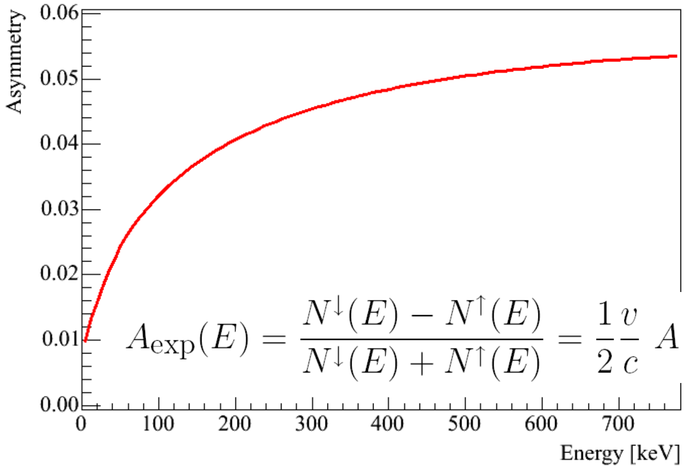
f_2 Weak Magnetism Form Factor (SM prediction)

Electron Asymmetry:

$$A_0 = -2\,\frac{\lambda^2+\lambda}{1+3\lambda^2}$$

$$A(E) = A_0(1 + c + a_{\mathrm{wm}}(\lambda, f_2)\; E)$$

2 % additional *E*–dependence of *A*



$$A_{\mathrm{exp}}(E) = \frac{N^\downarrow(E) - N^\uparrow(E)}{N^\downarrow(E) + N^\uparrow(E)} = \frac{1}{2}\frac{v}{c}\, A\; P\; F$$

SM tests on 10^{-4} level

Theory

- Recalculation of corrections induced by the “weak magnetism”, the proton recoil and the radiative corrections.
  - Ref.[1]: A. N. Ivanov, M. Pitschmann, and N. I. Troitskaya, PRD **88**, 073002 (2013)
  - Ref.[2]: A. N. Ivanov, R. Höllwieser, N. I. Troitskaya, and M. Wellenzohn, PRD **88**, 065026 (2013)
  - Ref.[3]: A. N. Ivanov, M. Pitschmann, N. I. Troitskaya, and Ya. A. Berdnikov, PRC **89**, 055502 (2014)

Experiment PERC

- High statistic measurements:
- Today: High Average Flux: $\Phi = 2 \times 10^{10}$ cm^{-2}s^{-1}
- Decay rate of 1 MHz / metre
- Thesis C. Klauser (2013) Polarizer $\Delta P/P = 10^{-4}$, Spin Flipper $\Delta f/f = 10^{-4}$

Priority Programme 1491

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Gravity at short distances: String theories

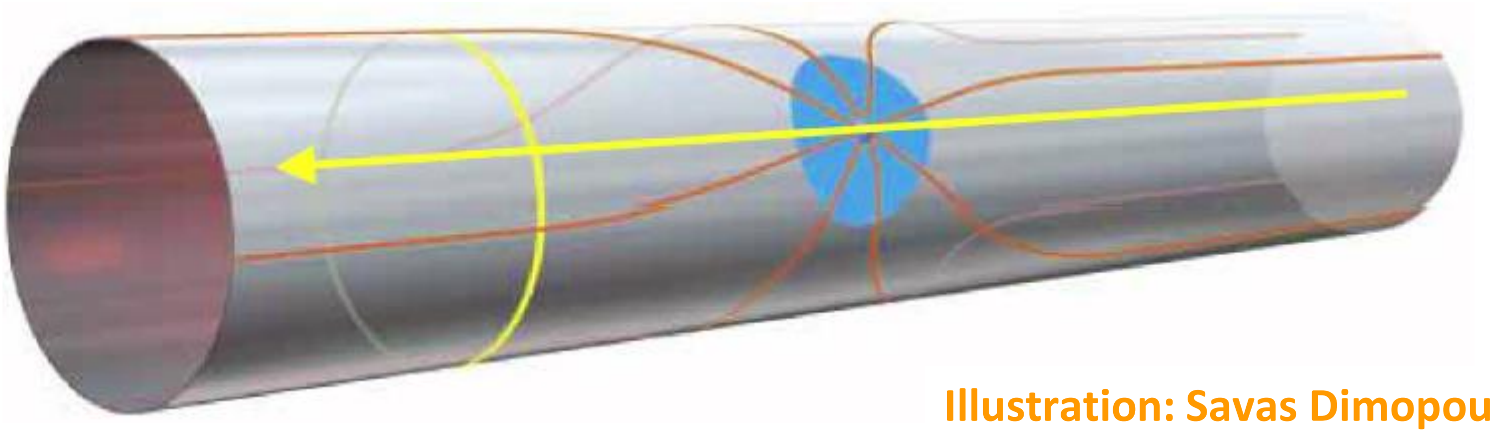


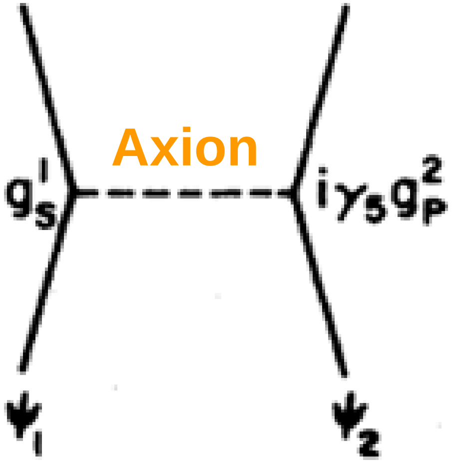
Illustration: Savas Dimopoulos

- Adelberger: In oder to see the true strength of gravitation, you have to be very close … .

Access: test of gravitation with quantum objects

- ***q*****Bounce** gives access to all gravity-parameters:
  - **mass, distance, energy momentum, torsion[1], curvature**
- ***q*****Bounce** allows constraints on any possible new interaction at the level of sensitivity
- Observe or restrict dark matter / dark energy

- Examples for Hypothetical gravity-like forces
  - Axions-exchange?
  - Chameleons?



- limits on axion and chameleon fields:

T. Jenke et al., PRL 2014

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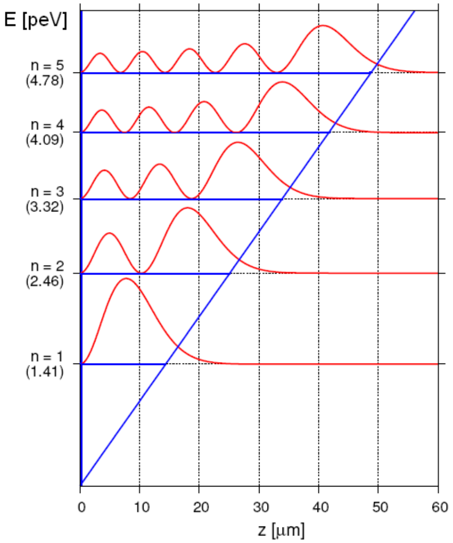
[1] A. Ivanov, M. Pitschmann, PRD 2014

Neutrons test Newton

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

- **Strength α**
- **Range λ**



For a neutron with mass m_n,
gravitational constant G,
mass m_E and density ρ of the earth with radius R_E
($r = R_E + z$),
V(r) is usually approximated by

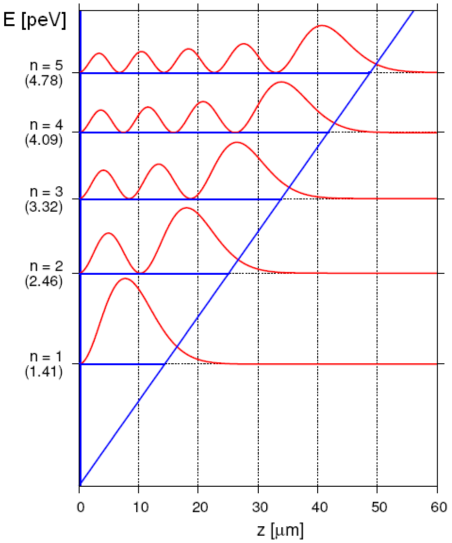
$$V(z) = m_n g z$$

$$V(z,\lambda) = 2\pi m_n \rho \alpha \lambda^2 G e^{-2|z|/\lambda} = \alpha \times 2 \times 10^{-12}\,\text{peV}$$

Neutrons test Newton

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

- **Strength α**
- **Range λ**



Hypothetical Gravity Like Forces

Extra Dimensions:
The string and D_p-brane theories predict the existence of extra space-time dimensions

Infinite-Volume Extra Dimensions: Randall and Sundrum

Exchange Forces from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and (pseudo)vector bosons

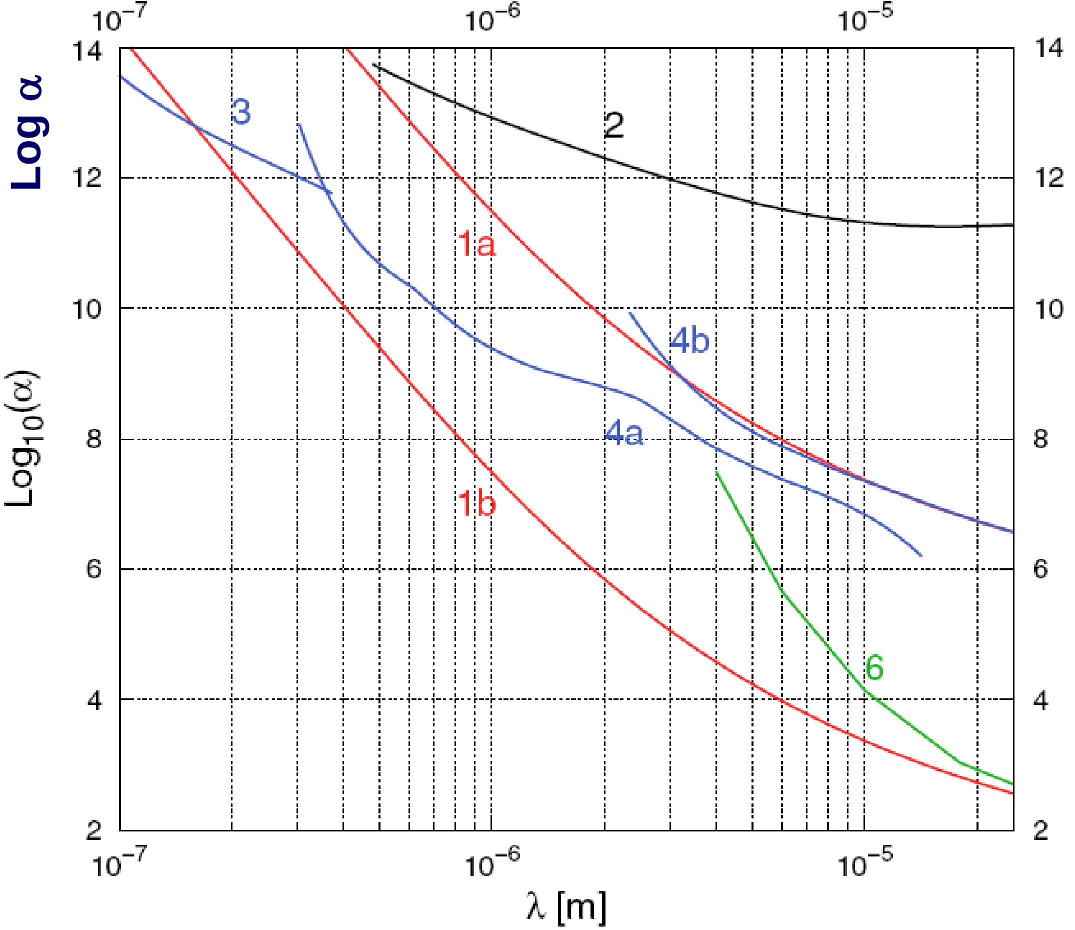
- **Axion - - - - - - - - - - - - - - - - - - -**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999) - - - -** **→$10^6 < \alpha < 10^9$**

Supersymmetric large Extra Dimensions (B.& C.) - - - - **→ $\alpha < 10^6$**

Limits on hypothetical gravity-like forces

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

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



Casimir Force

Atom

- **Example Rb**

$$\boxed{V(r)=\frac{3\hbar c}{2\pi}\frac{a_0}{r^4}}$$

r = 1 µm

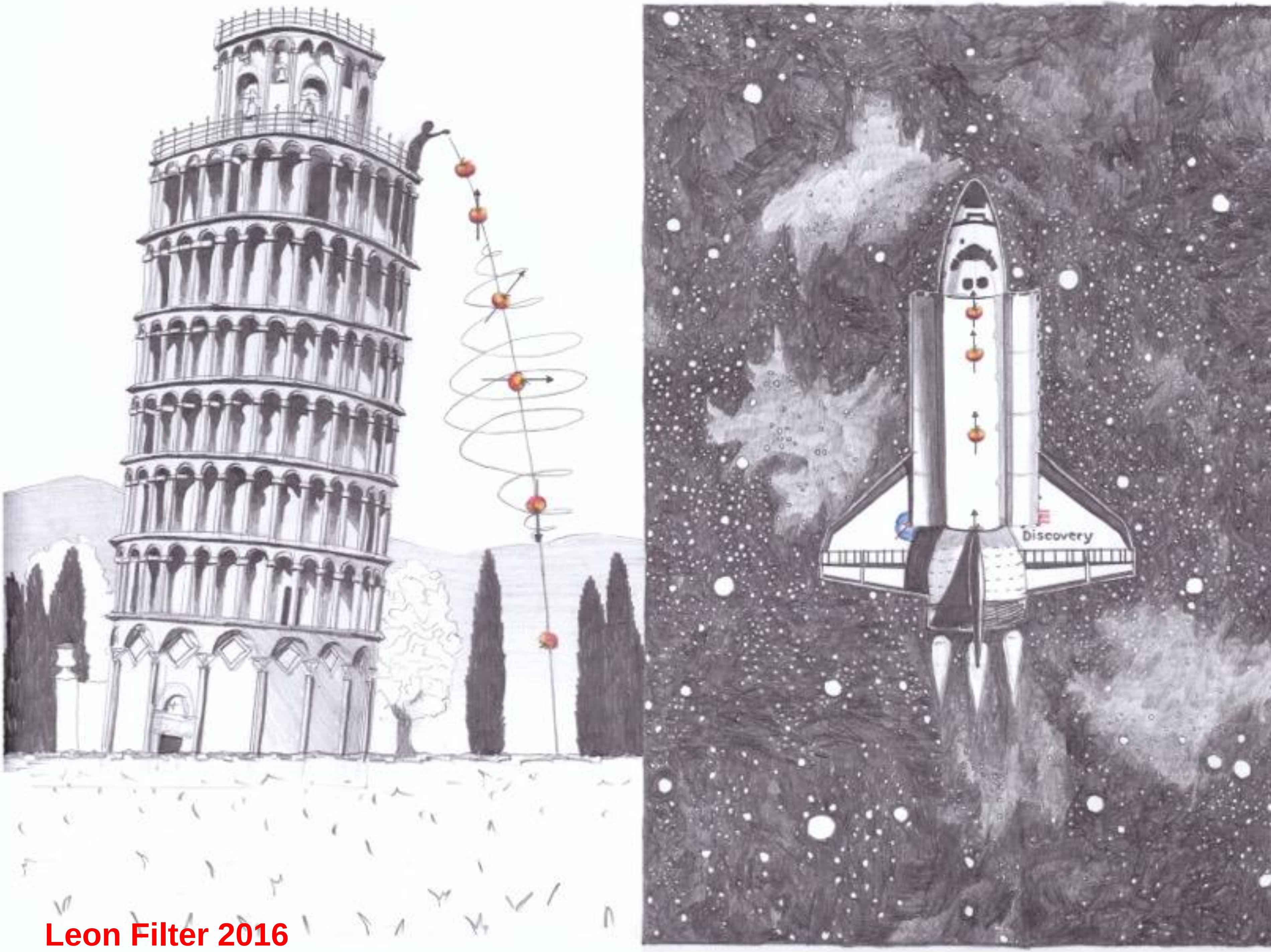
$$\boxed{\begin{aligned}a_0&=2,3\times10^{-23}\\ V(r)&=\frac{3\hbar c}{2\pi}\frac{a_0}{r^4}\\ &=0.6\,\text{peV}\end{aligned}}$$

Neutron:

Casimir force absent

- **Polarizability extremely small:**

$$\boxed{\begin{aligned}a_n&=11.6\times10^{-4}\,\text{fm}^3\\ D&=4\pi\varepsilon_0 a_n E\\ &=6\times10^{-41}\,\text{eV}\times E\left[\frac{\text{V}}{\text{m}}\right]\\ &=10^{-18}\,\text{peV}\end{aligned}}$$

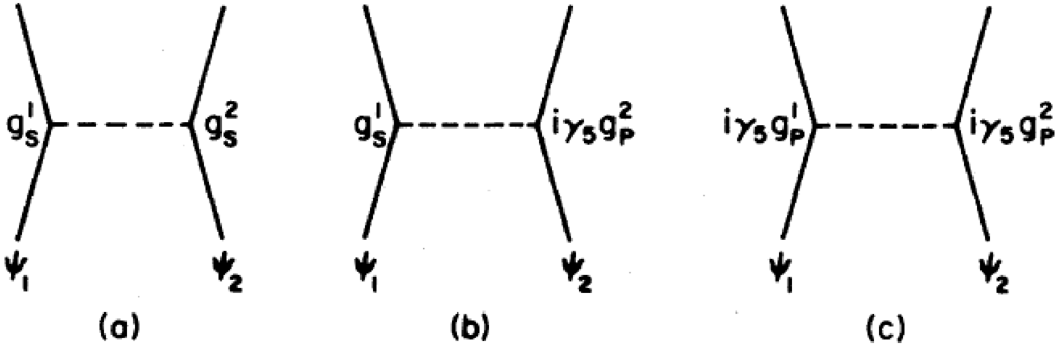


Leon Filter 2016

Limits on Axions

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

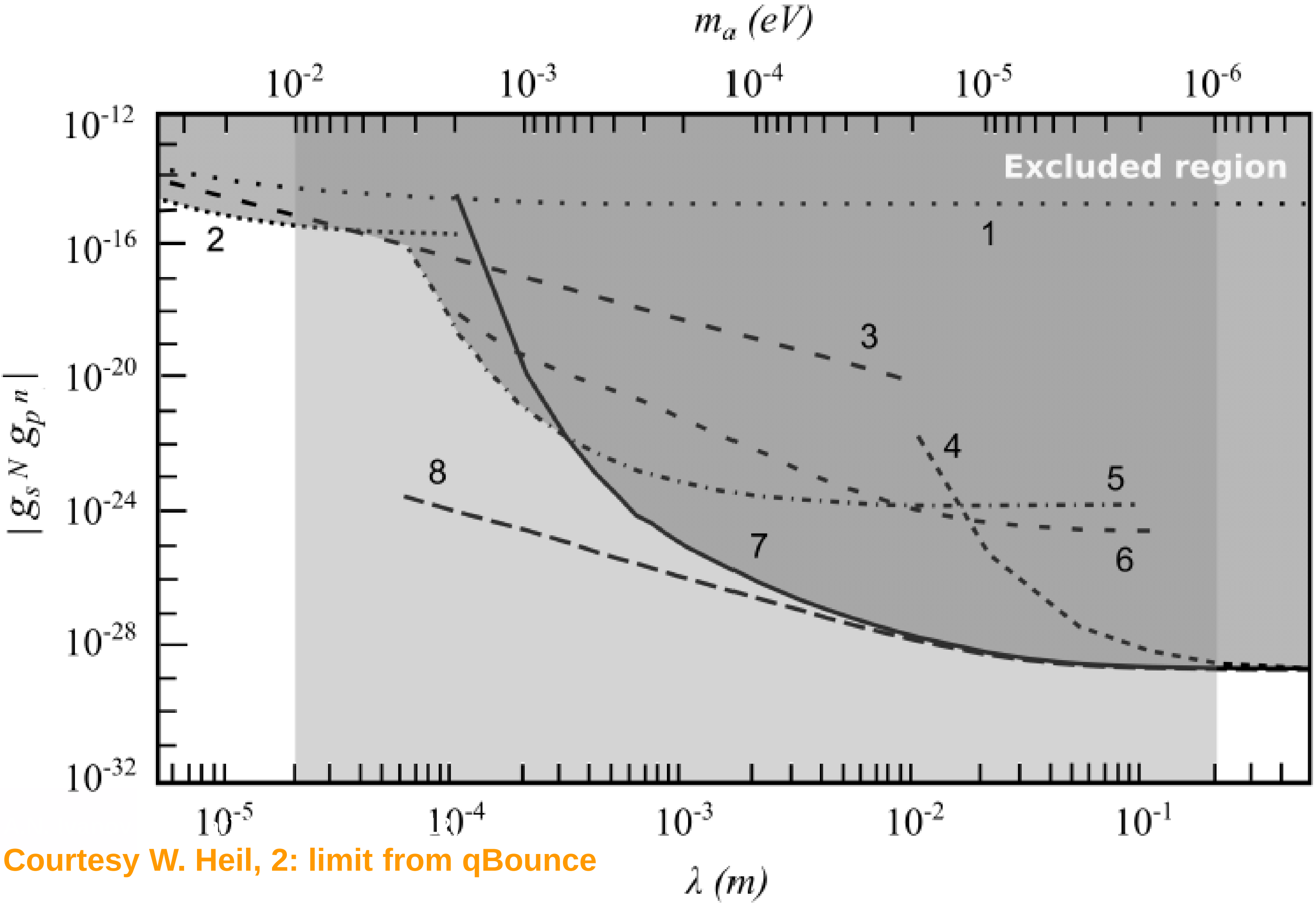
- **SM: 0 < $\theta < 2\pi$**
- **EDM neutron→ $\theta < 10^{-10}$**
- **Axion: Spin-Mass coupling $g_s g_p/\hbar c$: $\theta = 0$**



J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

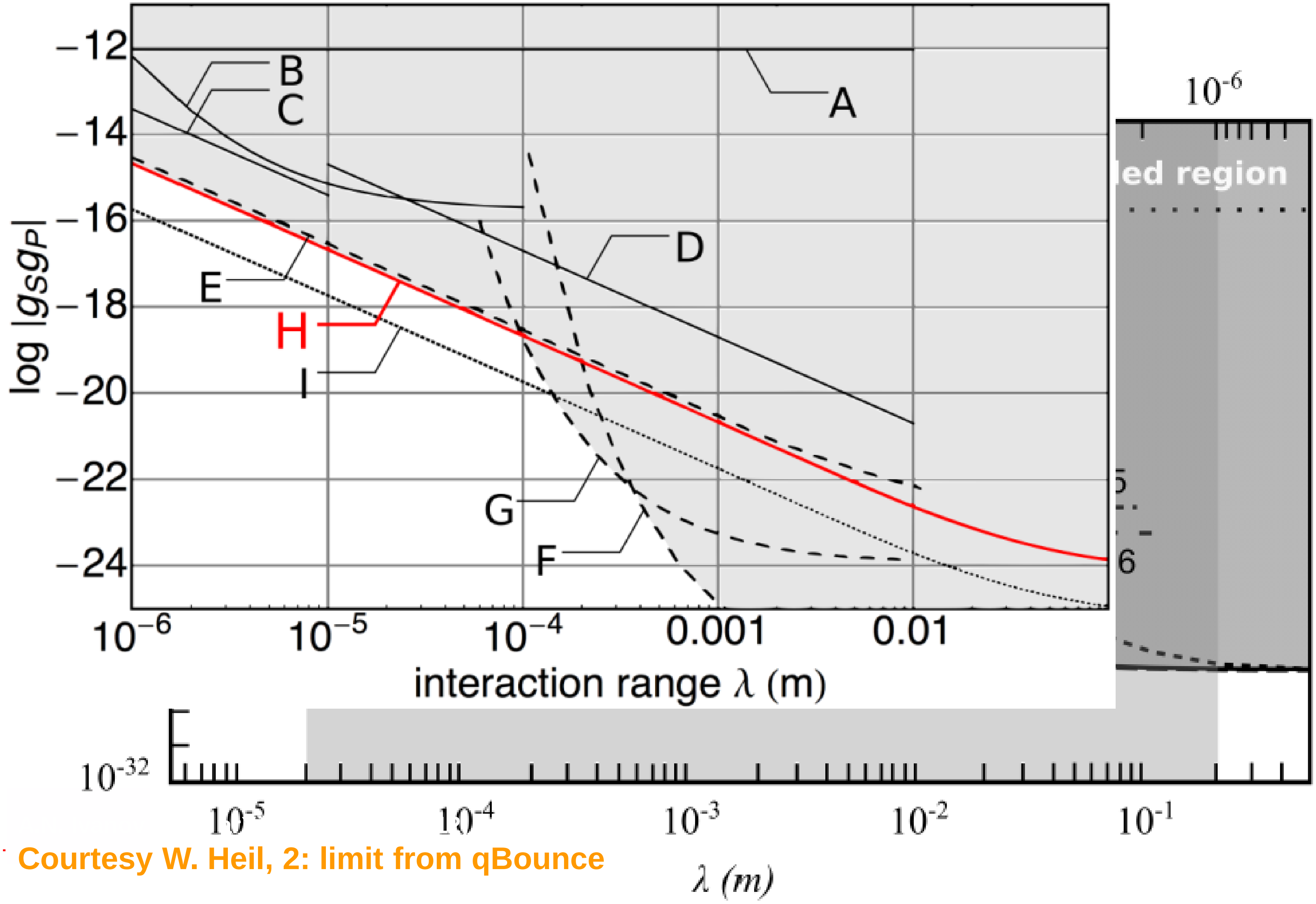
$$V(\vec{r}) = \hbar g_s g_p \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Axion-like forces



Courtesy W. Heil, 2: limit from qBounce

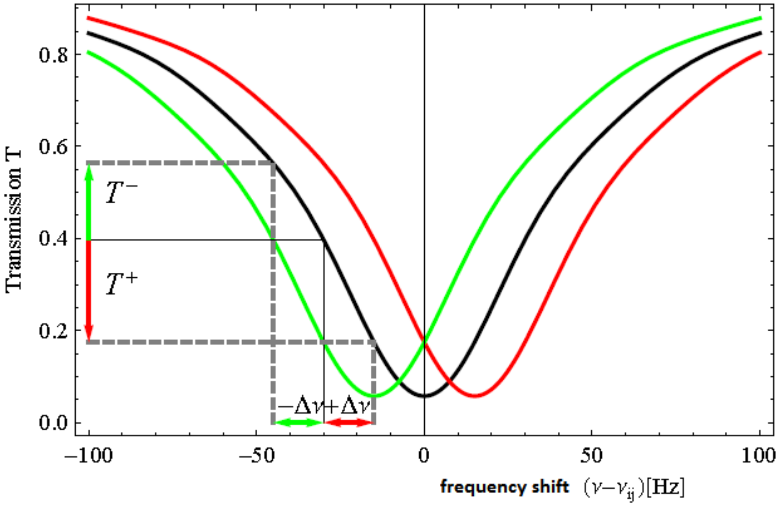
Axion-like forces



Courtesy W. Heil, 2: limit from qBounce

Applications I:
Spin-dependant short-ranged interactions

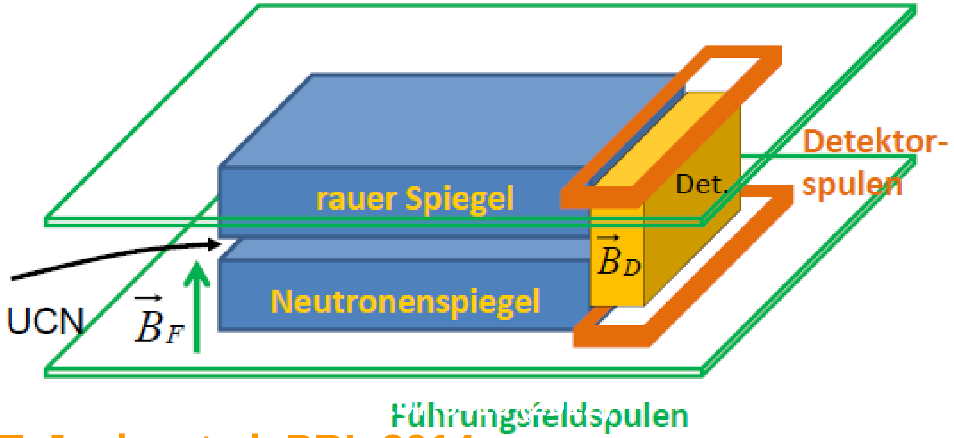
$$V_{\text{axion}} = \frac{g_s g_p \hbar}{8\pi m_n c}\,\vec{\sigma}\cdot\vec{n}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)$$

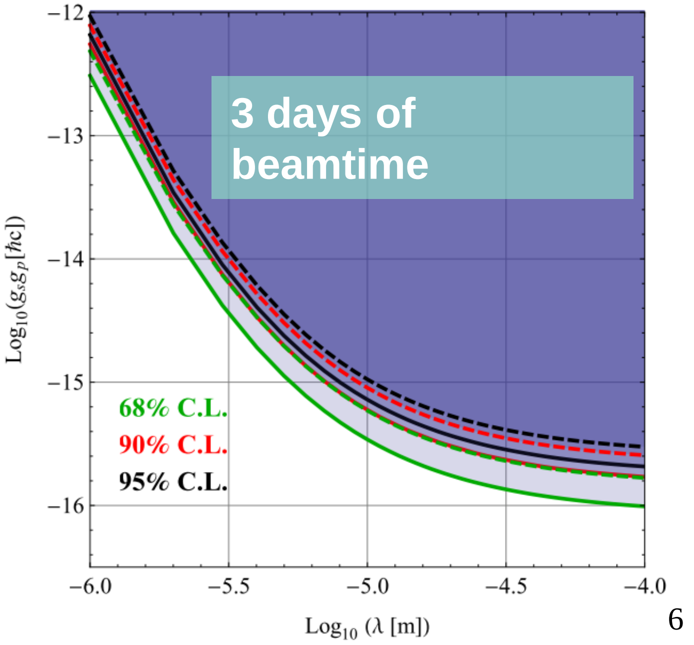


discovery potential [Setup 2010]:

$$g_s g_p/\hbar c \ge \frac{3\cdot 10^{-16}}{\sqrt{days}}$$

$$(\lambda = 10\,\mu\text{m}, 68\%\,\text{C.L.})$$





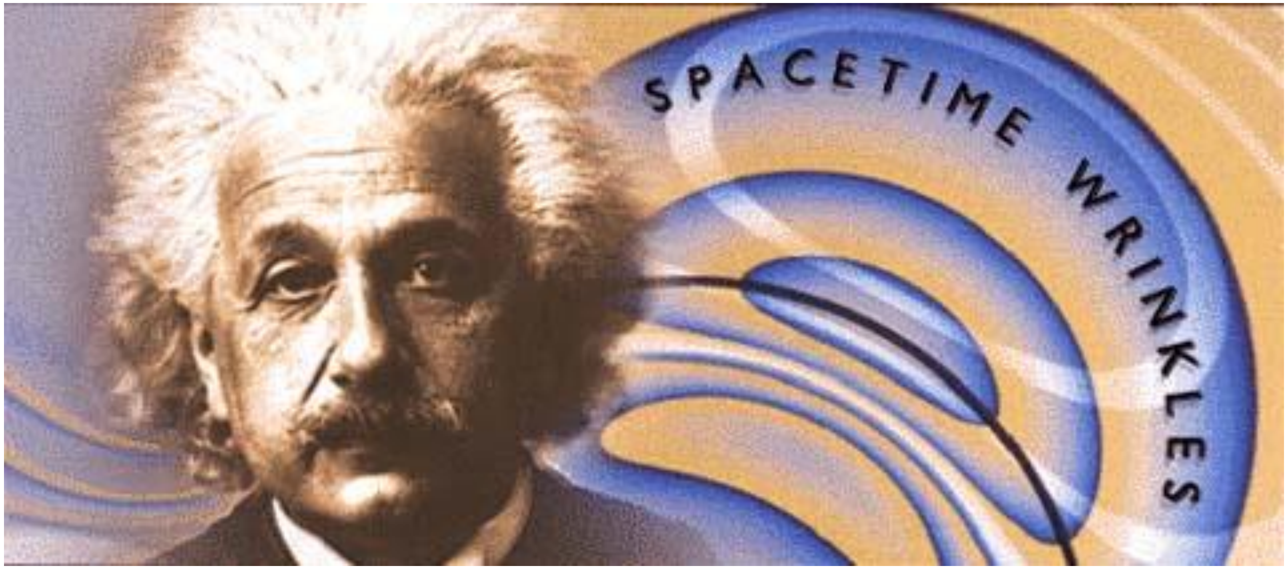
3 days of beamtime

T. Jenke et al. PRL 2014

Parameters of Gravity: $R_{\mu\nu}$, $T_{\mu\nu}$

- Einstein:
  - Curvature $R_{\mu\nu}$ ↔ Energy Momentum Tensor $T_{\mu\nu}$

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

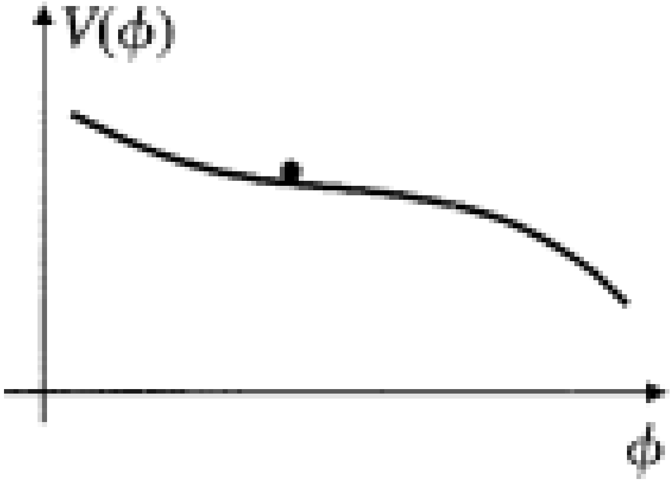


Quintessence Theories

- It could well be that the universe is not in a vacuum state at all and has a dynamical evolution
- Scalar field ϕ as a Perfect fluid

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu}$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

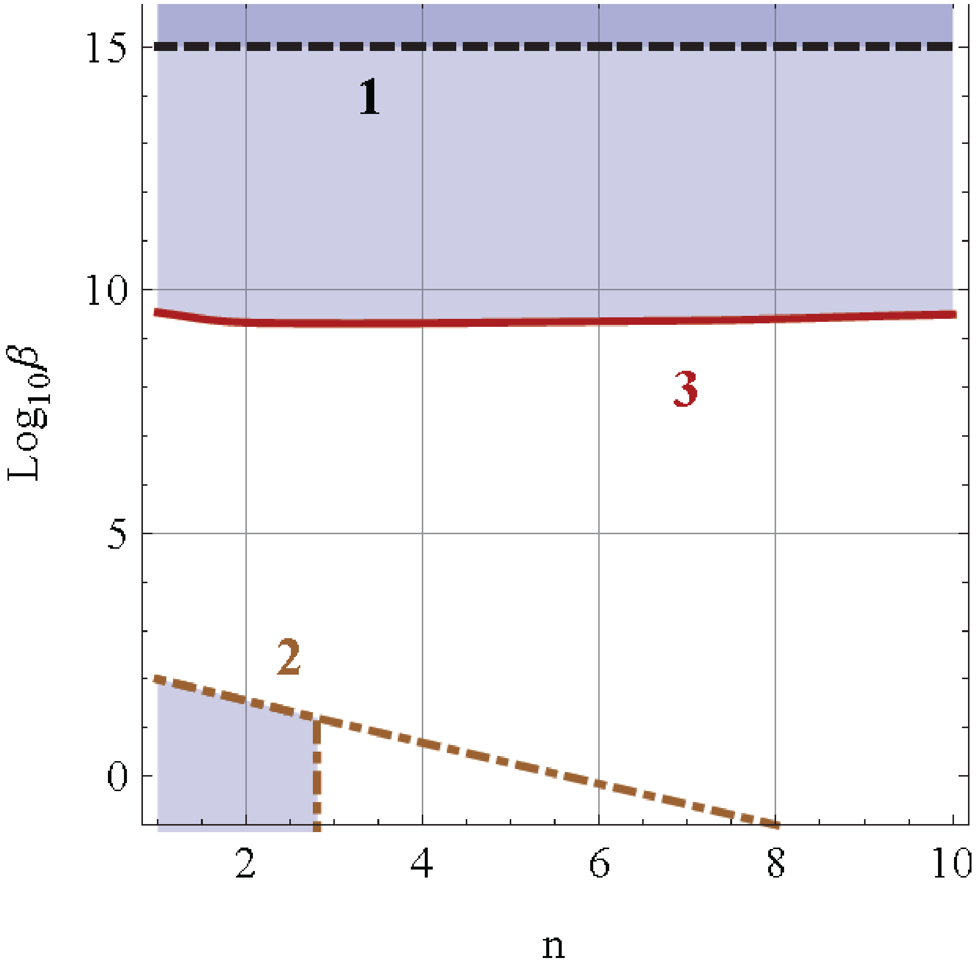


$$T_{\mu\nu} \approx -V(\phi) g_{\mu\nu}:$$

Experiments on the Planck Scale: $\beta^{-1} = M/M_{Pl}$

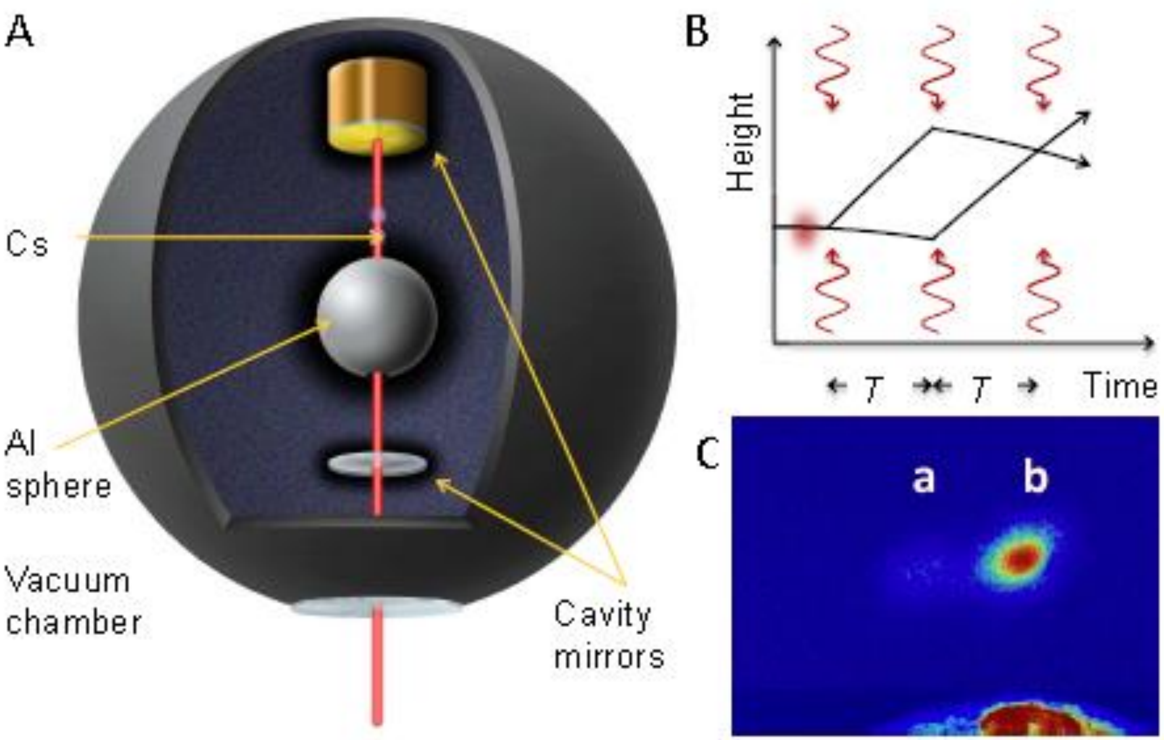
- Chameleon fields, Brax et al. PRD **70,** 123518 (2004)
- 2 Parameters β, n
- Λ self interation

$$V_{\mathrm{eff}}(\phi) = V(\phi) + e^{\beta\phi/M_{\mathrm{Pl}}}\rho.$$



T. Jenke et al., Gravity Resonance Spectroscopy constrains dark matter and dark energy scenarios, Physical Review Letters 112, 151105 (2014)

Hamilton et al.

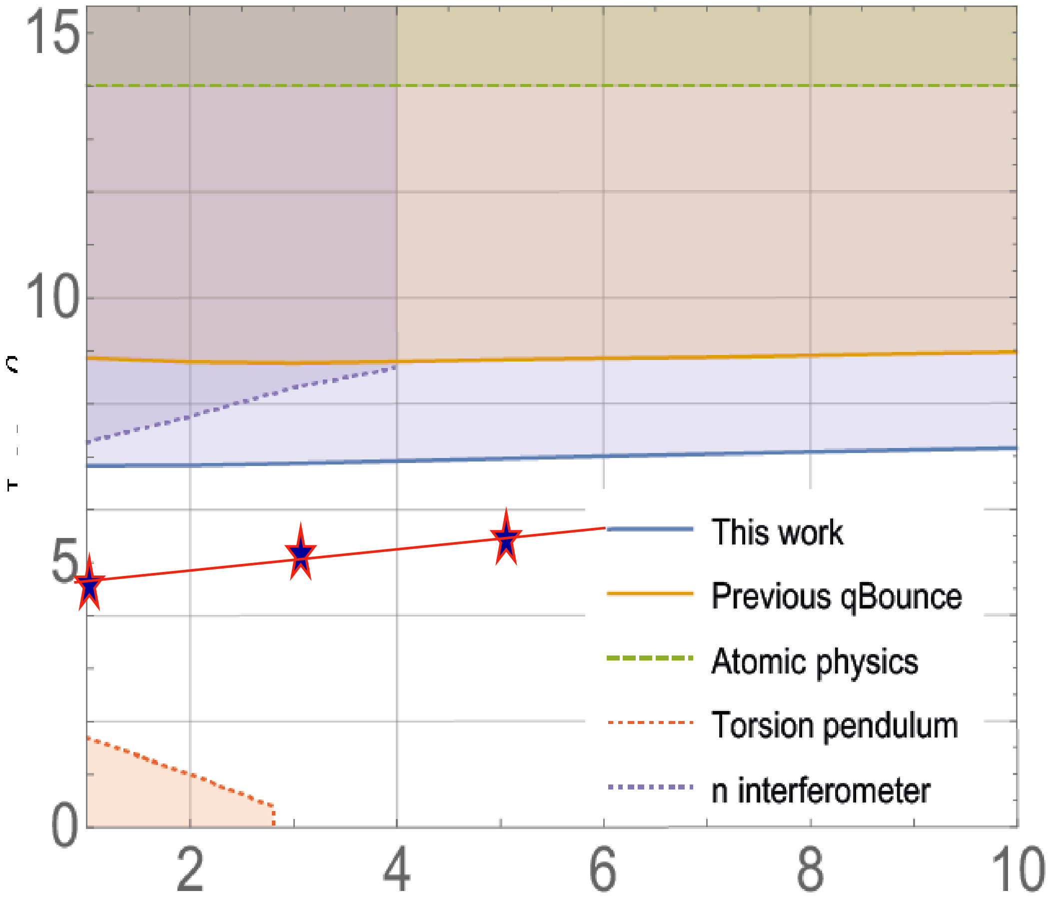


Hamilton et al., Science 2015

Dark Energy – Scalar Fields: G. Cronenberg

- Chameleon fields, Brax et al. PRD **70,** 123518 (2004)
- 2 Parameters β, n

$$V_{\text{eff}}(\phi) = V(\phi) + e^{\beta\phi/M_{\text{Pl}}}\rho.$$



J. Schmiedmayer,
H.A. Science 2015

T. Jenke et al., Gravity Resonance Spectroscopy constrains dark matter and dark energy scenarios, Physical Review Letters 112, 151105 (2014)

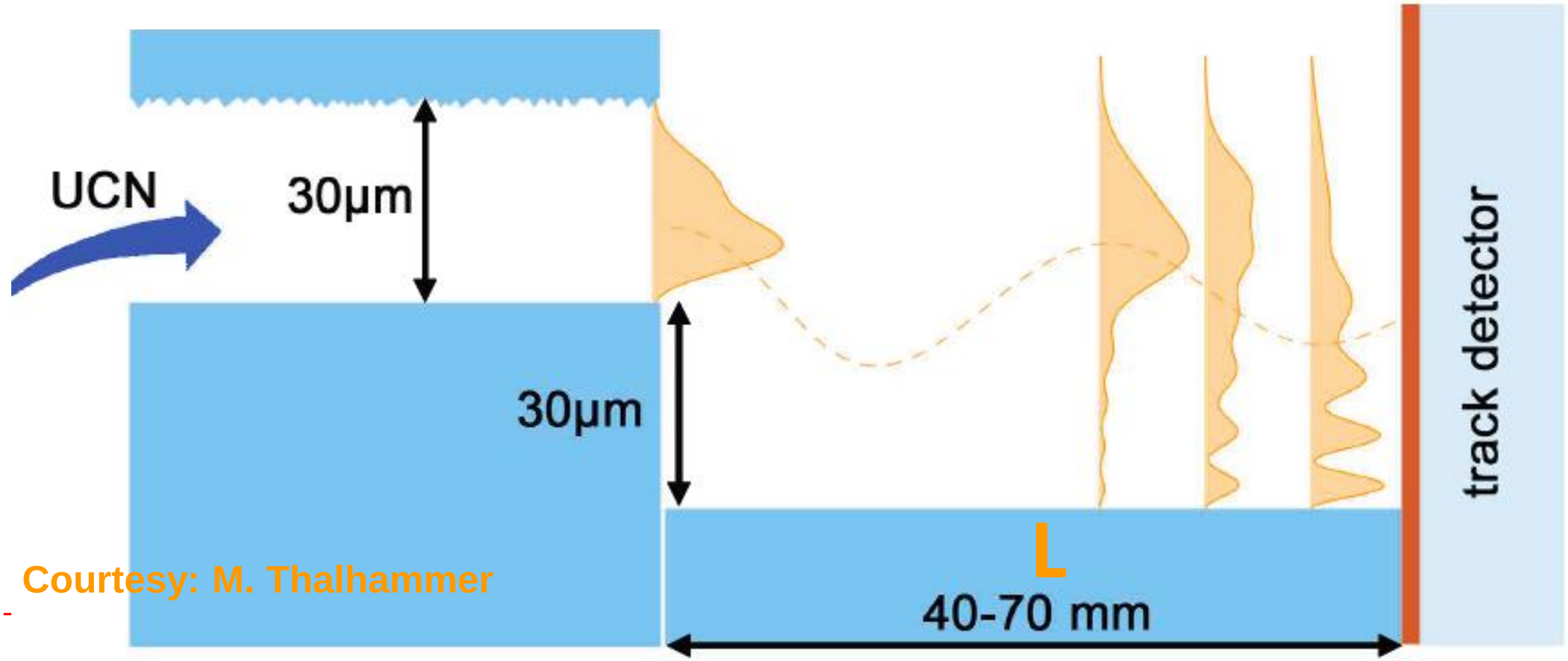
H. Lemmel et al., Neutron Interferometry constrains dark energy chameleon fields, Physical Letters B 743, 310 (2015)

M. Thalhammer, T. Jenke et al.

- Snapshots with spatial resolution detectors ~ 1.5 μm

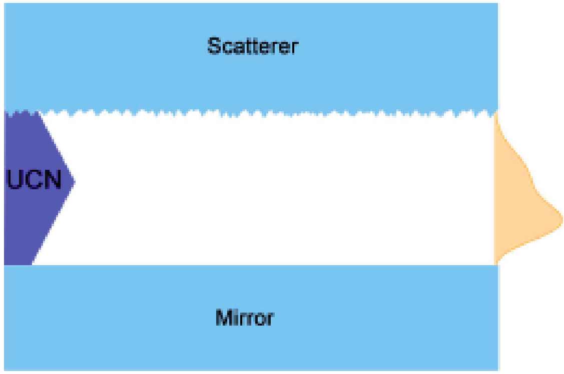
$$\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar} \psi_n(z)$$

$$\psi_n(z) \sim Ai[\frac{z}{z_0} - \frac{E_n}{E_0}]; c_n = \int_0^{\infty} \Psi(z,0)\psi(z)dz$$



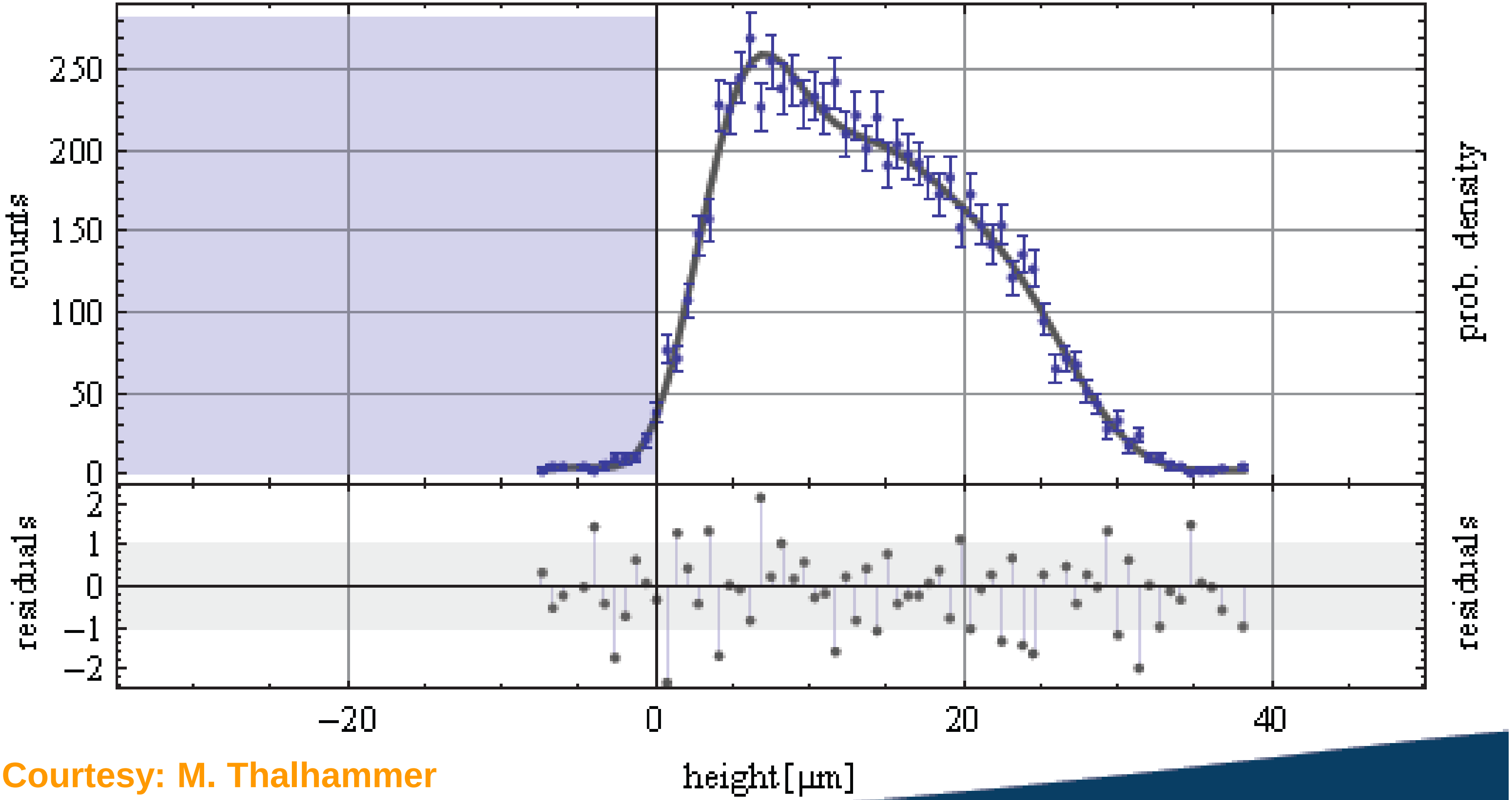
Courtesy: M. Thalhammer

Preparation L = 0



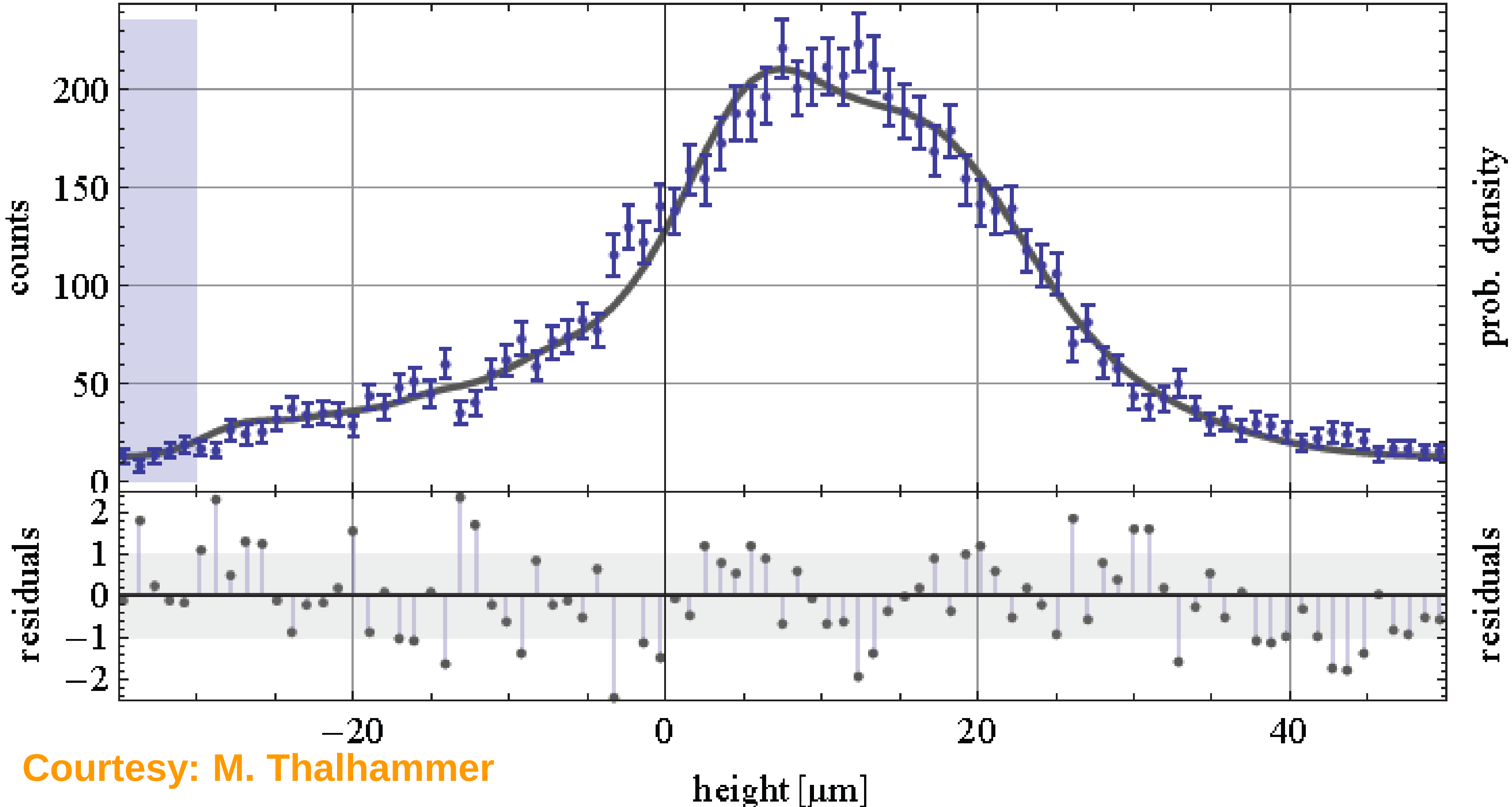
$$|\Psi_I(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

$|c_1|^2 = 45\%$
$|c_2|^2 = 36\%$
$|c_3|^2 = 18\%$
preliminary



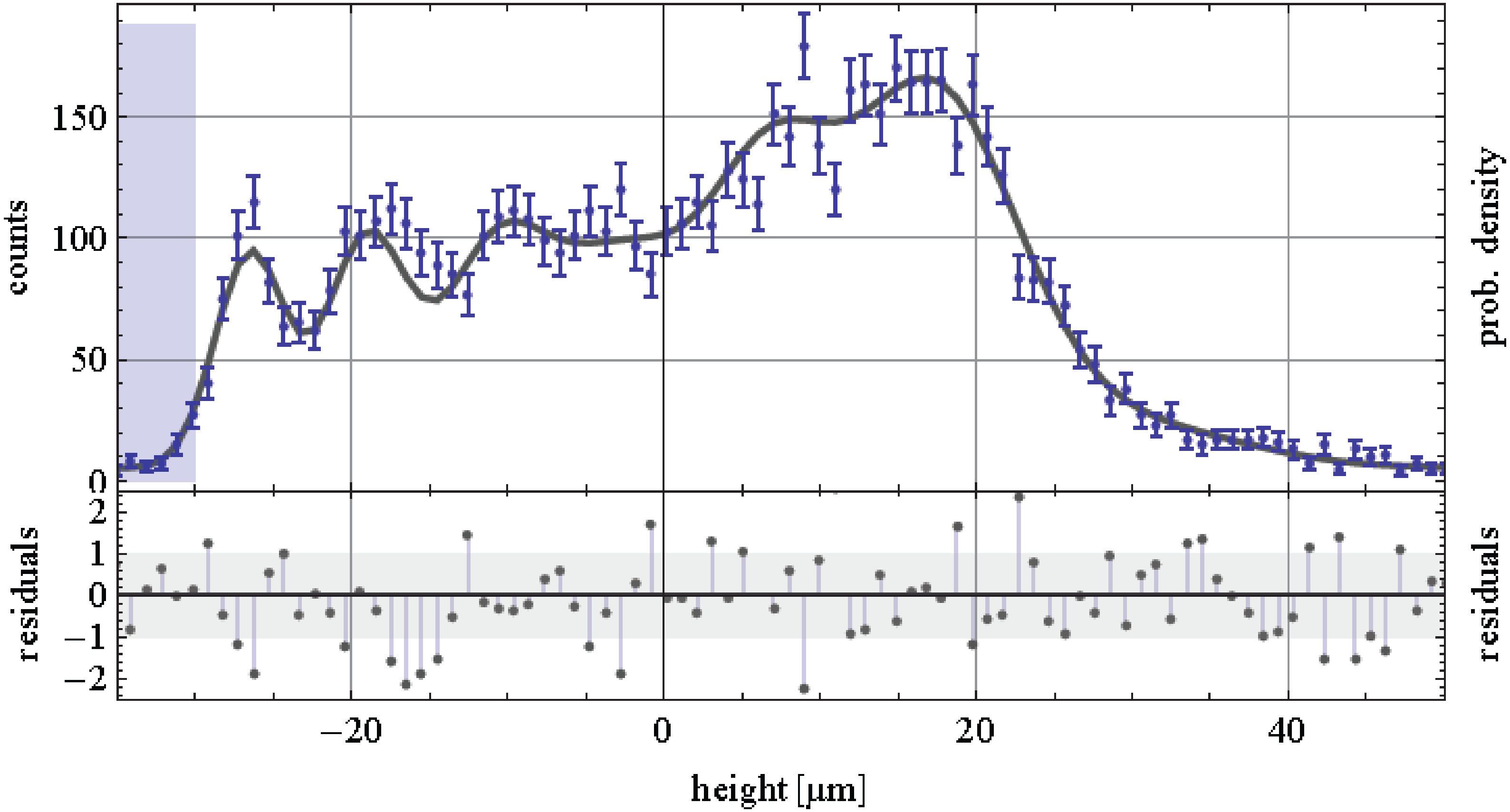
Courtesy: M. Thalhammer

2nd bounce, 2nd turning point, L = 41 mm



Courtesy: M. Thalhammer

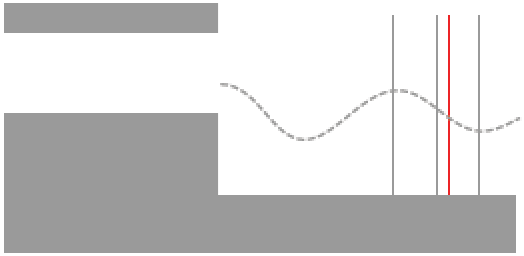
Move downwards, L = 51 mm

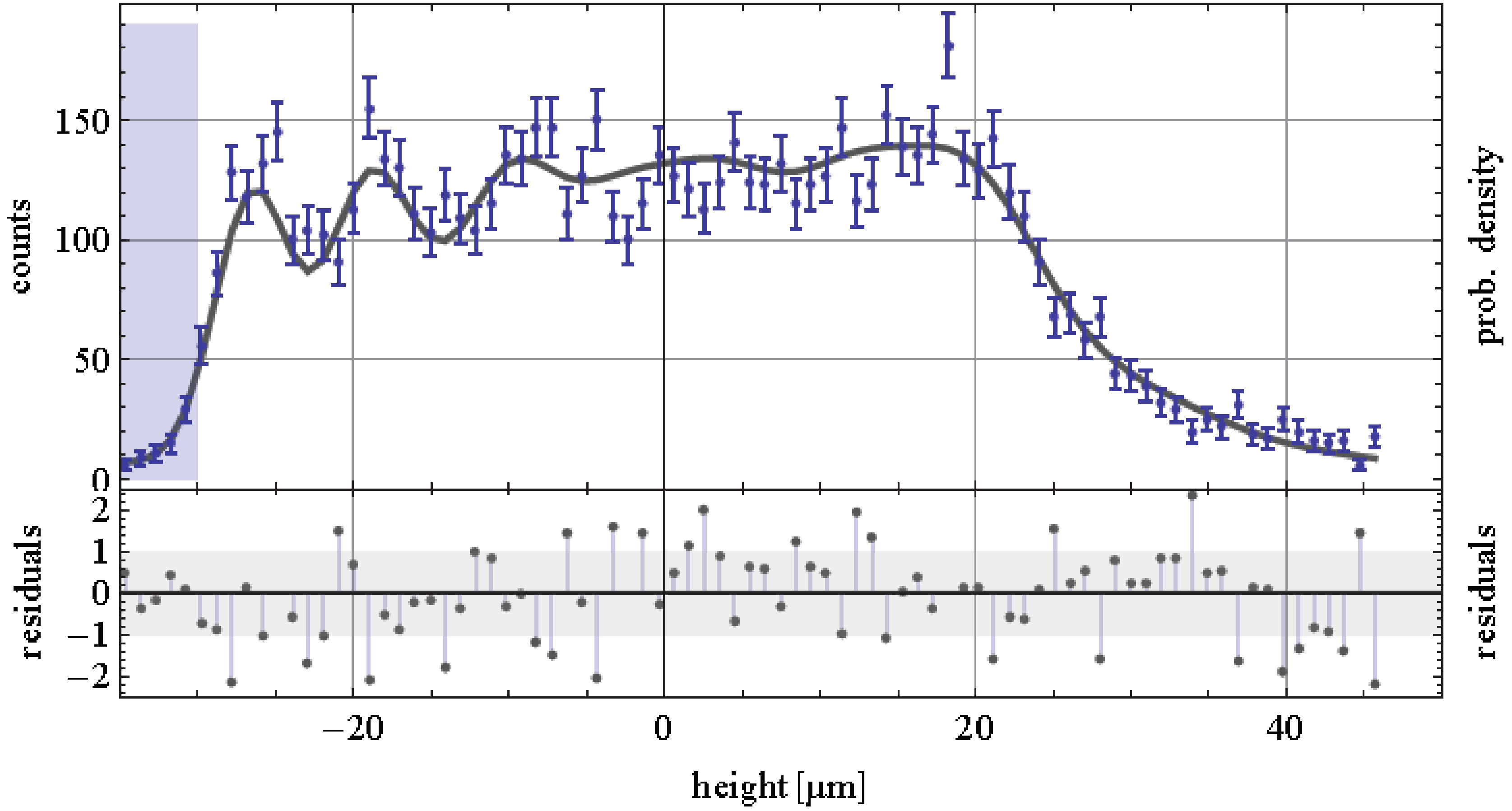


Courtesy: M. Thalhammer

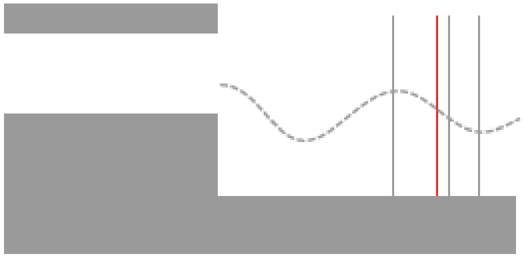
L = 54 mm

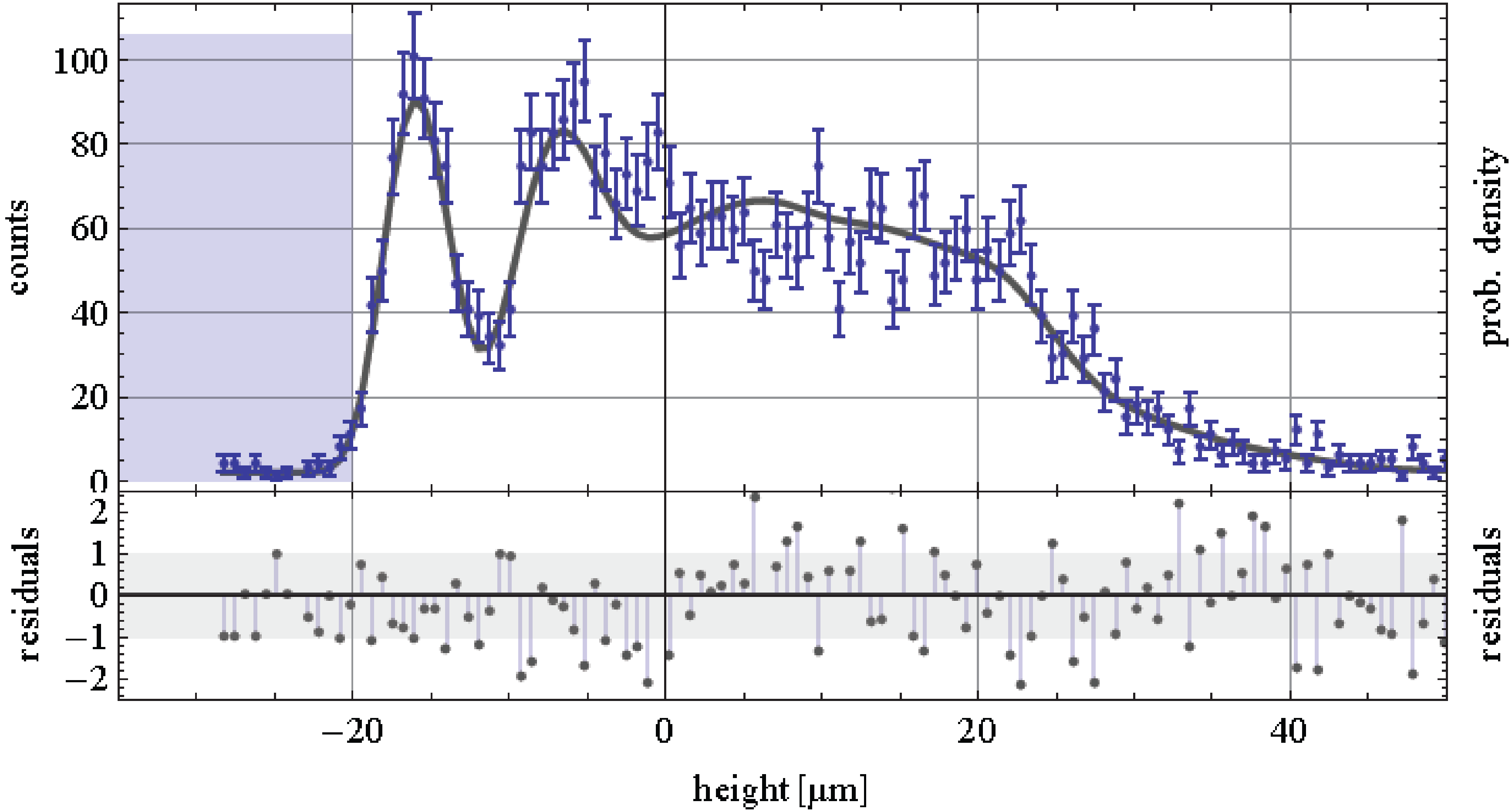
54 mm




counts
150
100
50
0
residuals
2
1
0
−1
−2
−20
0
20
40
height [μm]
prob. density
residuals

L = 51 mm @ 20 µm





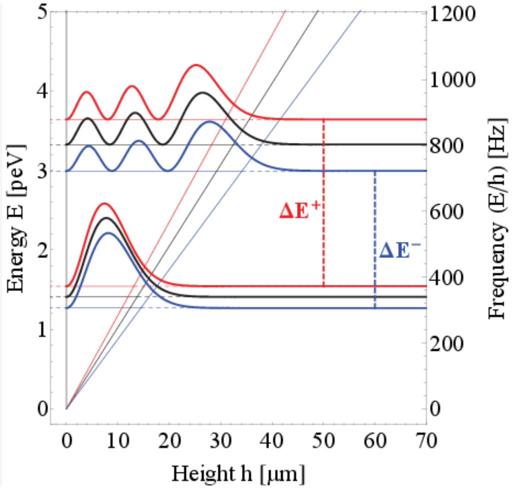
counts
100
80
60
40
20
0
prob. density
residuals
2
1
0
−1
−2
residuals
−20
0
20
40
height [µm]

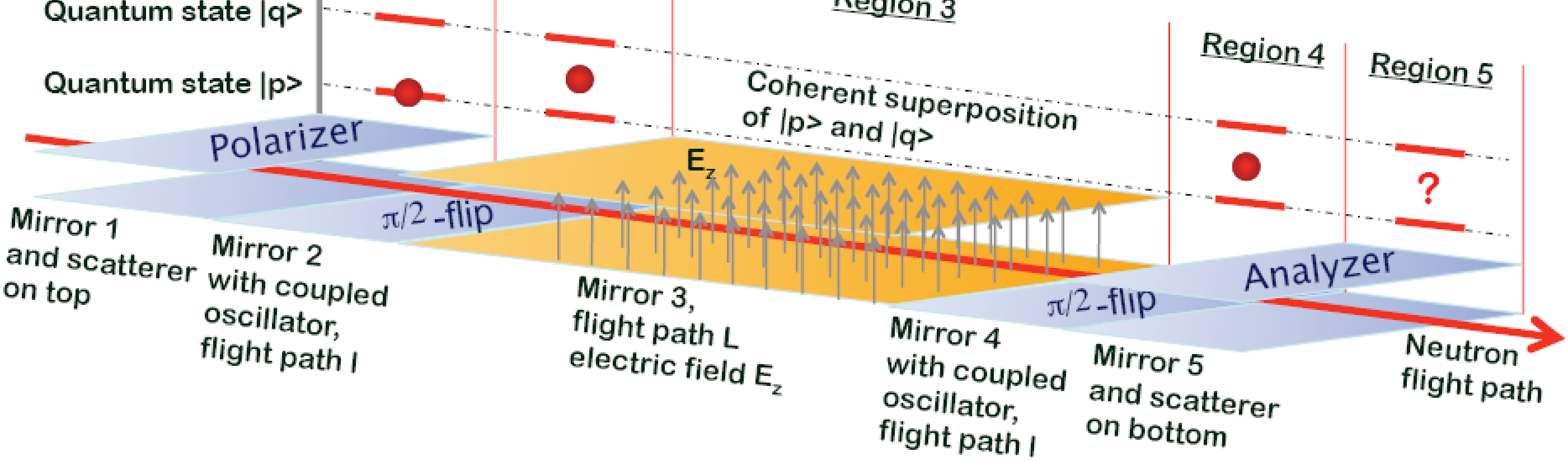
Systematic effects

- Polarizability effects: 10^{-30} eV
- Tidal effects: 10^{-19} eV
- 1 kg in close approximation: 10^{-18} eV
- The inclination of setup is stabilized to 10^{-27} eV level
- roughness and waviness: below 10^{-19}eV
- External magnetic field gradients are suppressed by a factor of 20. → 10^{-23} eV
- The experiment is evacuated to approx. 10^{-4} mbar

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 limit by two orders of magnitude**





The Neutron Physics Group at Atominstitut

- Gravity tests with quantum objects
  - G. Cronenberg, T. Jenke, H. Filter, P. Geltenbort (ILL), H. Lemmel, M. Thalhammer, T. Rechberger, J. Herzinger, U. Schmidt (HD), T. Lauer (TUM), Collaboration HD, TUM, ILL
- Neutron Beta Decay, PERC collaboration
  - J. Erhart, E. Jericha, D. Moser, P. Haydn, G. Konrad, M. Klopp, H. Saul, X. Wang, Collaboration with HD, MZ, TUM, ILL
- Interferometry
  - G. Badurek, H. Rauch, Y. Hasegawa, M. Zawisky, J. Summhammer, S. Sponar, H. Geppert, B. Demirel,
- Neutron Radiography
  - M. Zawisky,
- N_TOF/USANS: E. Jericha, C. Weiß, H. Rauch, G. Badurek,H. Leeb, Griesmayer

The Team at Atominstitut

- Gravity tests with quantum objects
  - T. Jenke, G. Cronenberg, H. Filter, K. Mitsch, Martin Stöger, Tamara Putz, P. Geltenbort (ILL), M. Heumesser, H. Lemmel, M. Thalhammer, T. Rechberger, P. Schmidt, J. Herzinger, Collaboration ILL (P. Geltenbort), HD (U. Schmidt)