

Title: Ultra-Cold Neutrons and the Quantum Bouncing Ball

Speakers:

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 21, 2022 - 10:45 AM

URL: <https://pirsa.org/22090019>

the quantum bounce & gravity resonance spectroscopy

Lorentz violation
beyond-Riemann
and entropic gravity

HARTMUT ABELE, TU WIEN

21 SEPTEMBER 2022

A QUANTUM BOUNCE

The Neutron and some properties

● Abundance

- earth: 50% neutrons 50% protons
- elsewhere: 14% n, 86 % p
- 1s after Big Bang: 17% n, 83% p

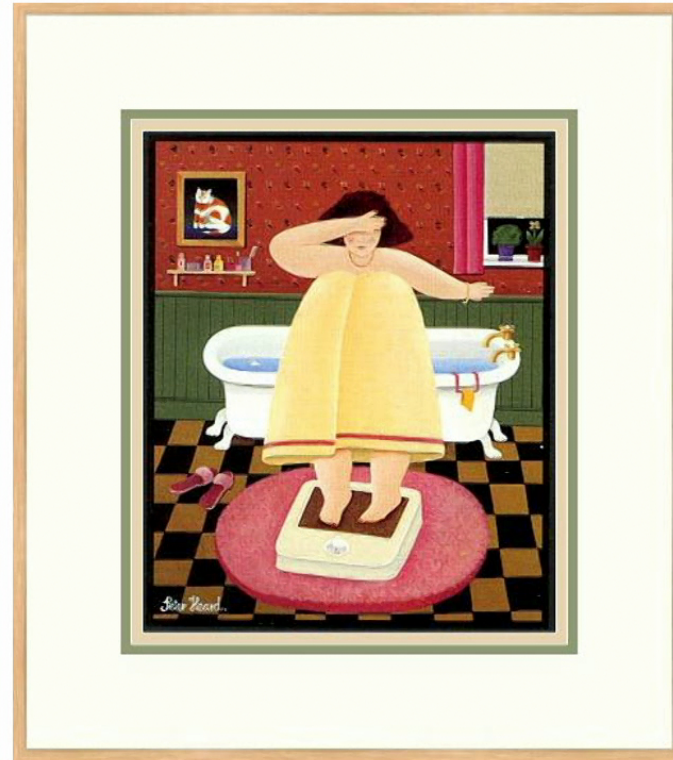
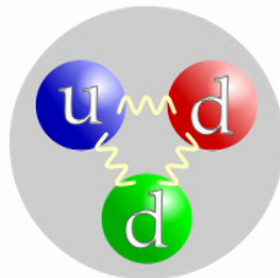
● Lifetime

- $\tau = 878\text{s}$

● Spin $\frac{1}{2}$



● Size 1 fm



Weight in kilograms

The Neutron and some properties

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- earth: 50% n 50% p
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Lifetime

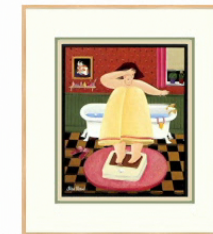
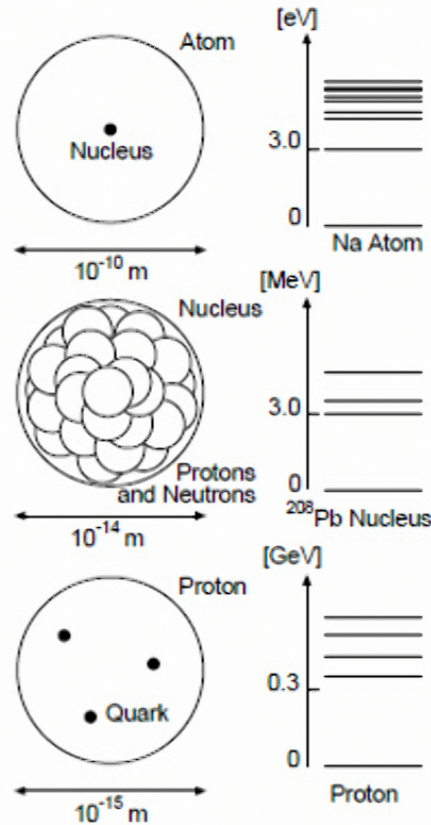
- $\tau = 878\text{s}$

Spin $\frac{1}{2}$



Size??

- Compton wavelength = 10^{-15} m
- De Broglie = $1.8 \cdot 10^{-10}\text{ m}$ for 2200 m/s



Weight in kilograms

Size of the neutron

$$d_n = 10^{-15} \text{ m}$$

$$\lambda_c = \frac{h}{mc}$$

$$\lambda_{\text{DeBroglie}} = \frac{h}{mv} = 1,8 \text{ \AA}$$

$$d_n = 10^{-13} \\ < 10^{-26}$$

$$V = 2200 \text{ m}$$

$$C = 10 \text{ m}$$

$$\lambda_c = \frac{h}{mc}$$

$$\lambda_{\text{DeBroglie}} = \frac{h}{mv} = 1,8 \text{ \AA}$$
$$= 80 \text{ nm}$$

$$< 10^{-26} \text{ eV}$$

$$V = 2200 \text{ m/s}$$

$$V = 5 \text{ m/s}$$

Neutron Interferometer

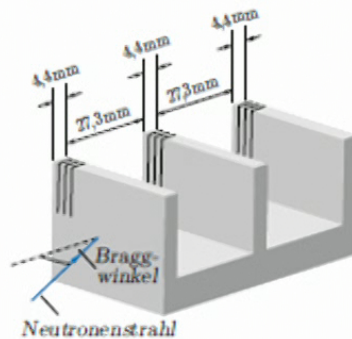


Abbildung 3.12 Perfektkristall-Interferometer für Neutronen

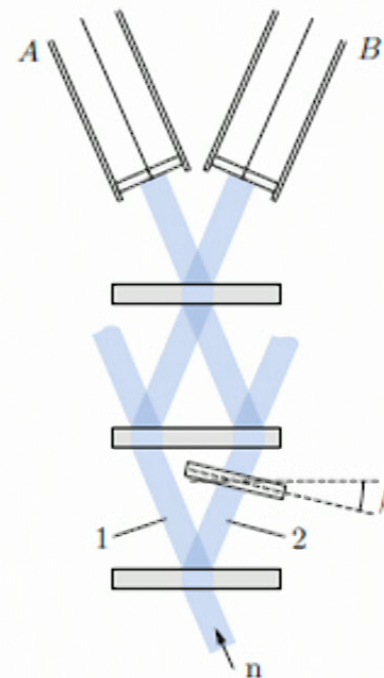


Abbildung 3.14 Phasenschieber im Teilstrahl 2

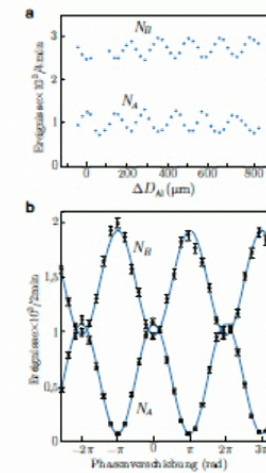


Abbildung 3.15 Zählrate in den Zählrohren A und B als Funktion der Phasenverschiebung. a aus H. Rauch (1974), b aus M. Arfken (1977)

$$\lambda_c = \frac{h}{mc}$$

$$\lambda_{\text{DeBroglie}} = \frac{h}{mv} = 1,8 \text{ \AA}$$

$$V = 2200$$

$$\lambda_c = 500 \text{ \AA} = 80 \text{ nm}$$

$$V = 5 \text{ m/s}$$

Neutron and vertical slit

Quantum mechanical neutron break

Measurement of a confinement induced neutron phase

H. Rauch*, H. Lemmel*, M. Baron*† & R. Loidl*†

* Atominstitut der Österreichischen Universitäten, A-1020 Wien, Austria

† Institut Laue-Langevin, BP 156, F-38042 Grenoble, France

- Order of magnitude:
 - Neutron 1 fm, $E = 25$ meV
 - De Broglie Wavelength 0.18 nm
 - Slit 33 μm

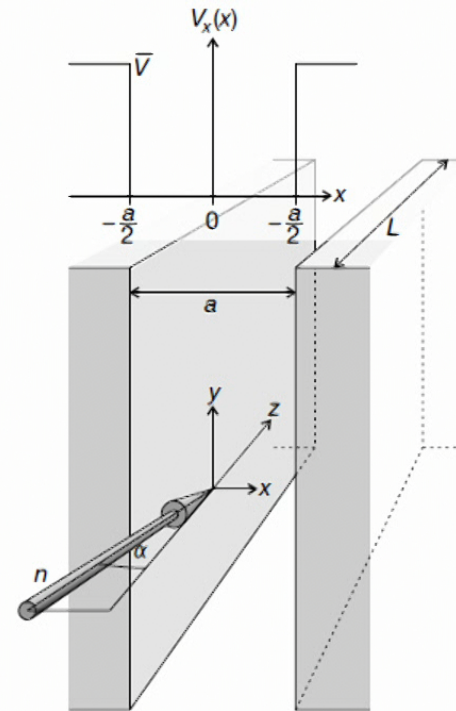


Figure 1 Sketch of the slit structure and of the related neutron-wall interaction potential. Arrow denotes neutron beam n ; $\bar{V}$, neutron optical potential; a , width of potential; L , length of the slit.

Neutron and vertical slit

Quantum mechanical neutron break

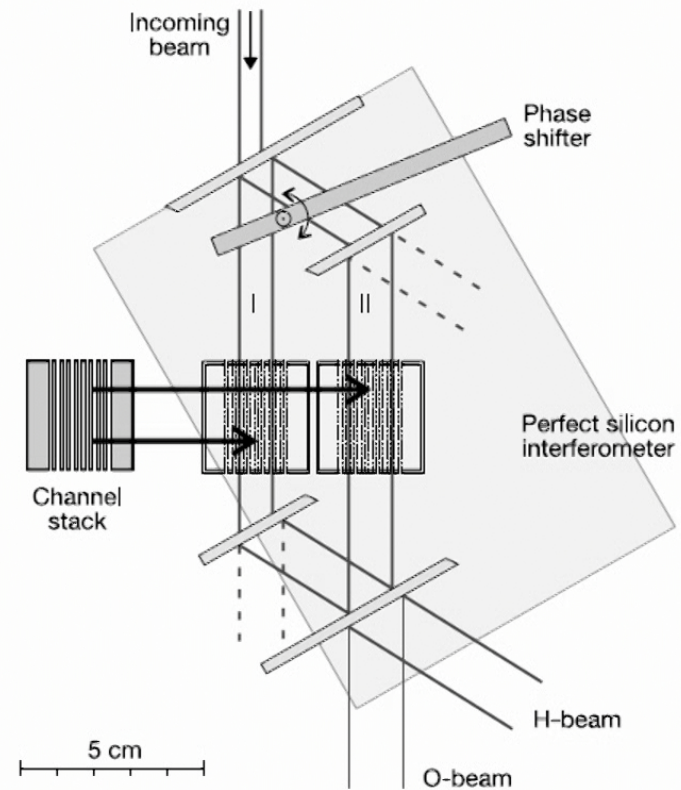
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 - Neutron 1 fm, $E = 25$ meV
 - De Broglie Wavelength 0.18 nm
 - Slit 33 μm



Compton MC

$$\lambda_{\text{DeBroglie}} = \frac{h}{mv} = 1,8 \text{ \AA}$$

$$V = 220$$

$$\lambda_{\text{Coherence}} = 500 \text{ \AA} = 80 \text{ nm}$$

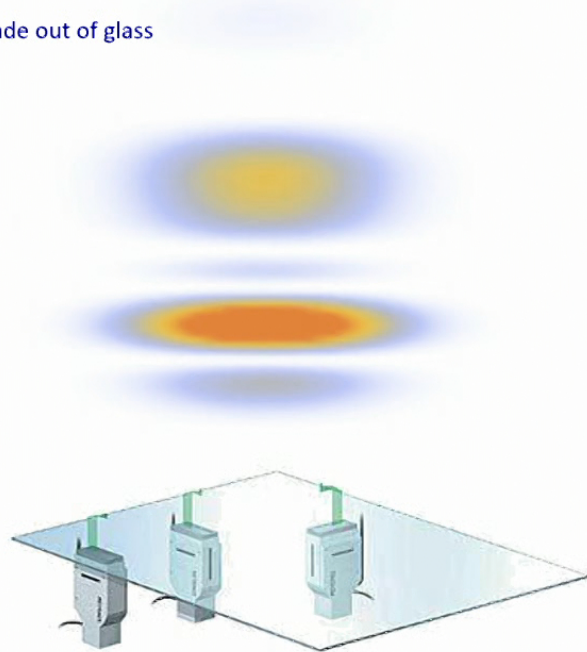
$$V = 5 \text{ mV}$$

$$d = 1 \text{ m}$$

FREE FALL AT SHORT DISTANCES

- A simple gravitationally interacting quantum system

- A neutron with mass and spin
 - falling in the Earth's gravity potential
- and a neutron reflector
 - made out of glass



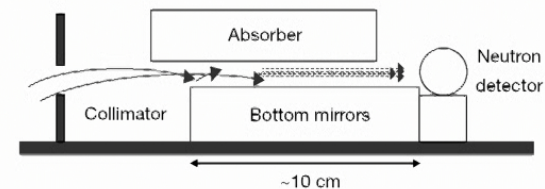
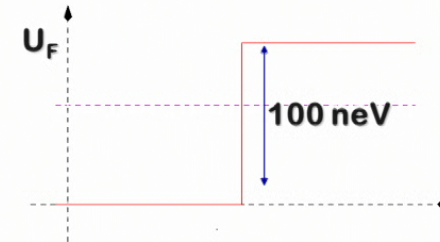
Abele, Jenke, Lemmel, Nature 2019

- Reactor neutrons at ILL

- 25 meV

- Ultra-cold Neutrons

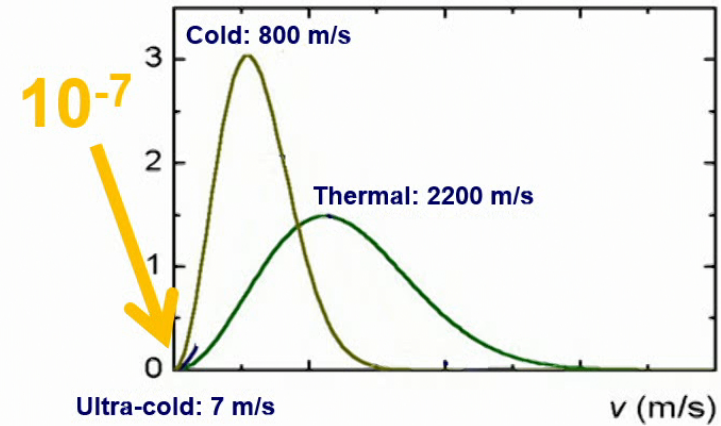
- @PF2 – ILL: T. Jenke
- $v = (7 \pm 1) \text{ m/s}$
- $U_F \sim 100 \text{ neV}, 1 \dots 6 \text{ peV}$



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

Institut Laue – Langevin
European Neutron Source





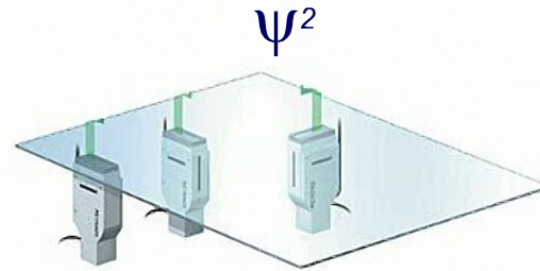
- Fission Neutrons: 2 MeV
- Thermal Neutrons: 25 meV
- Cold Source: 4 meV
- Ultra-cold Neutrons: 100 neV
- Gravity experiment: 2 peV

qBOUNCE: Quantum States in the Gravity Potential

- Schrödinger Equation

$$-\frac{\hbar^2}{2m} \frac{d^2\Psi}{dz^2} + mgz\Psi = E\Psi$$

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} = E\psi$$



- Characteristic length and energy scale

$$z_0 = -\left(\frac{\hbar^2}{2m^2g}\right)^{1/3} = 5.87\mu\text{m} \quad E_0 = -\left(\frac{\hbar^2mg^2}{2}\right)^{1/3} = 0.602\text{peV}$$

- Change of variable

$$\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0}$$

- Airy's Equation, and general Solution with AiryAi and AiryBi

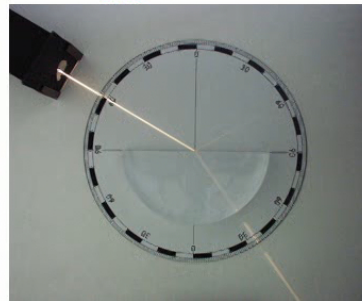
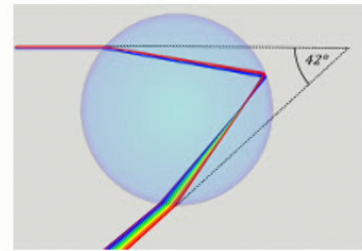
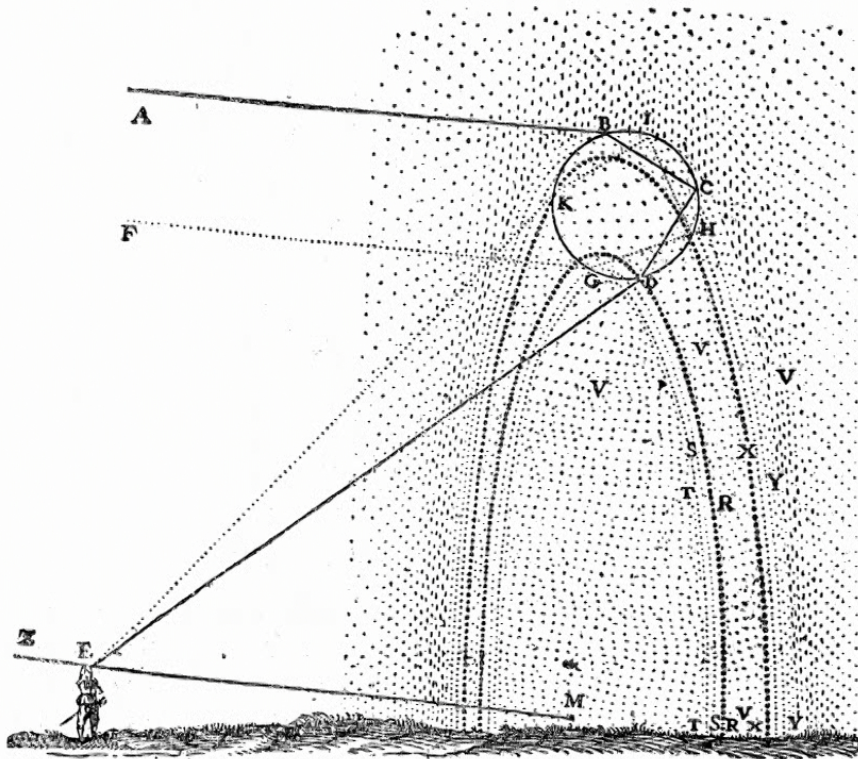
$$-\frac{d^2\Psi}{d\tilde{z}^2} + \tilde{z}\Psi = 0$$

$$\psi(z) = aA_i(z) + bB_i(z)$$

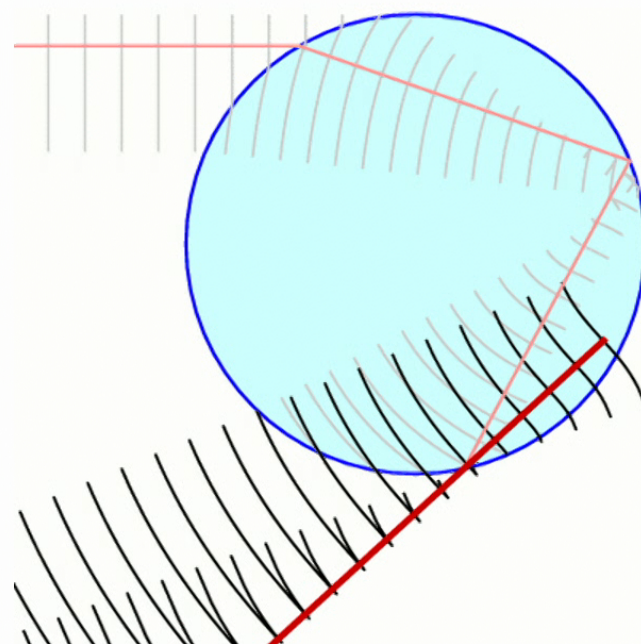
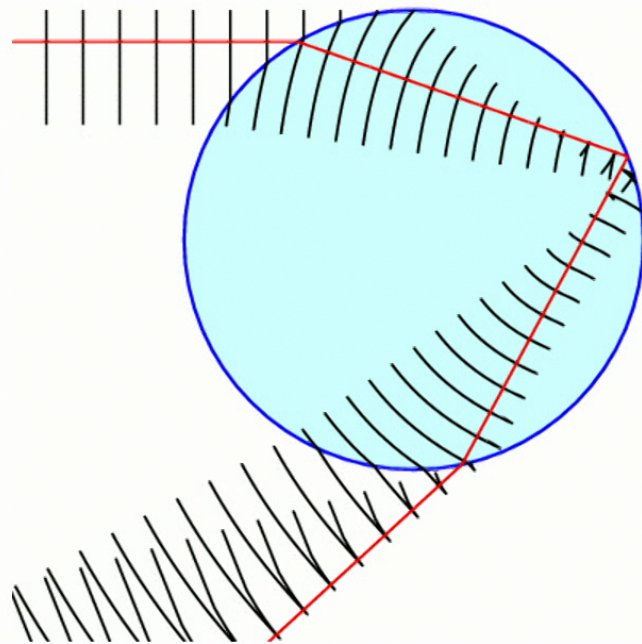


The **Rainbow**: Descartes *DE L'ARC-EN-CIEL*

- Light beam that hits a rain drop is refracted toward the middle of the drop and then repeatedly reflected into the drop again



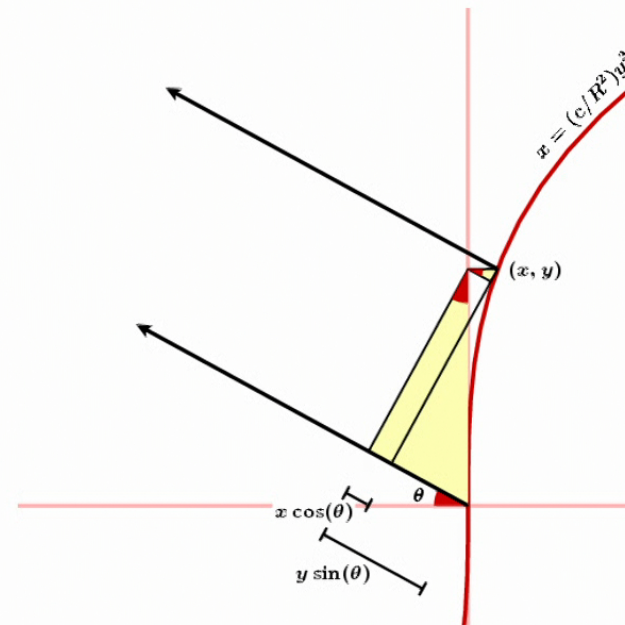
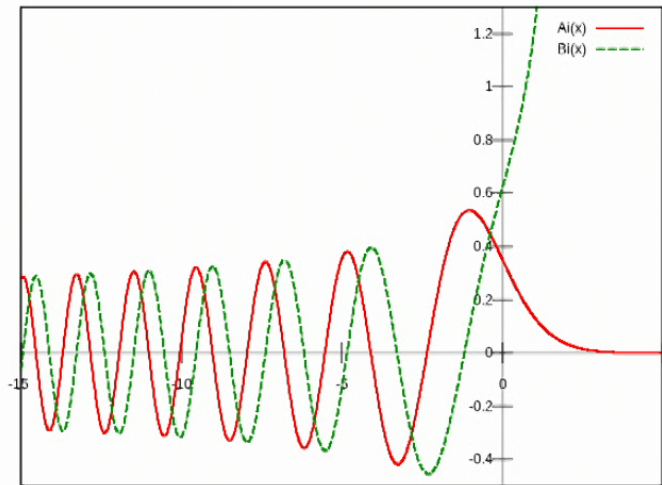
The rainbow again



George Biddell Airy

The Airy – Funktion:

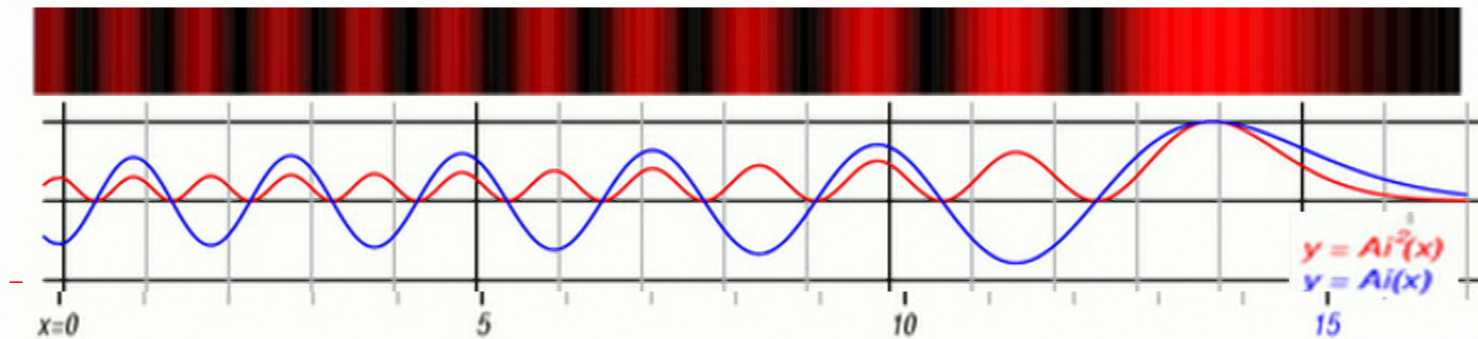
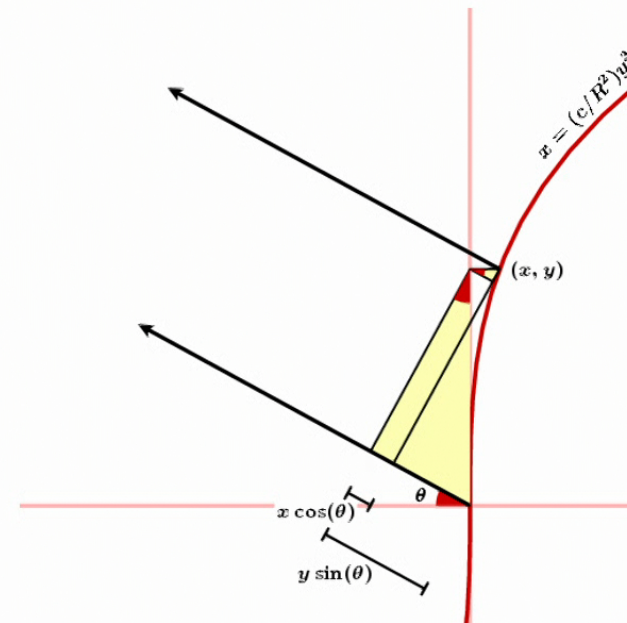
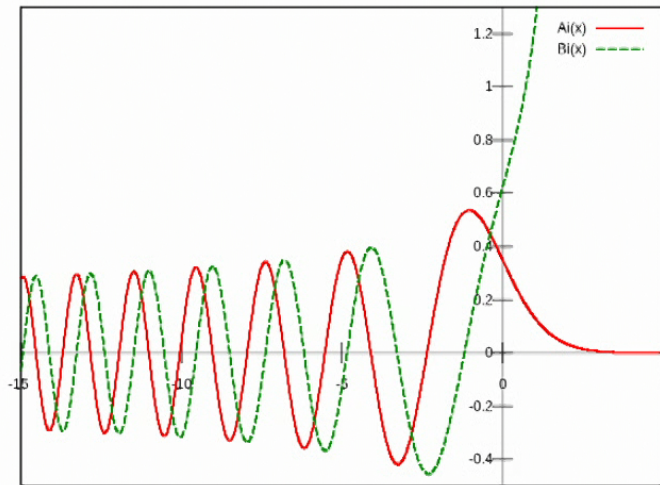
Airy functions



George Biddell Airy

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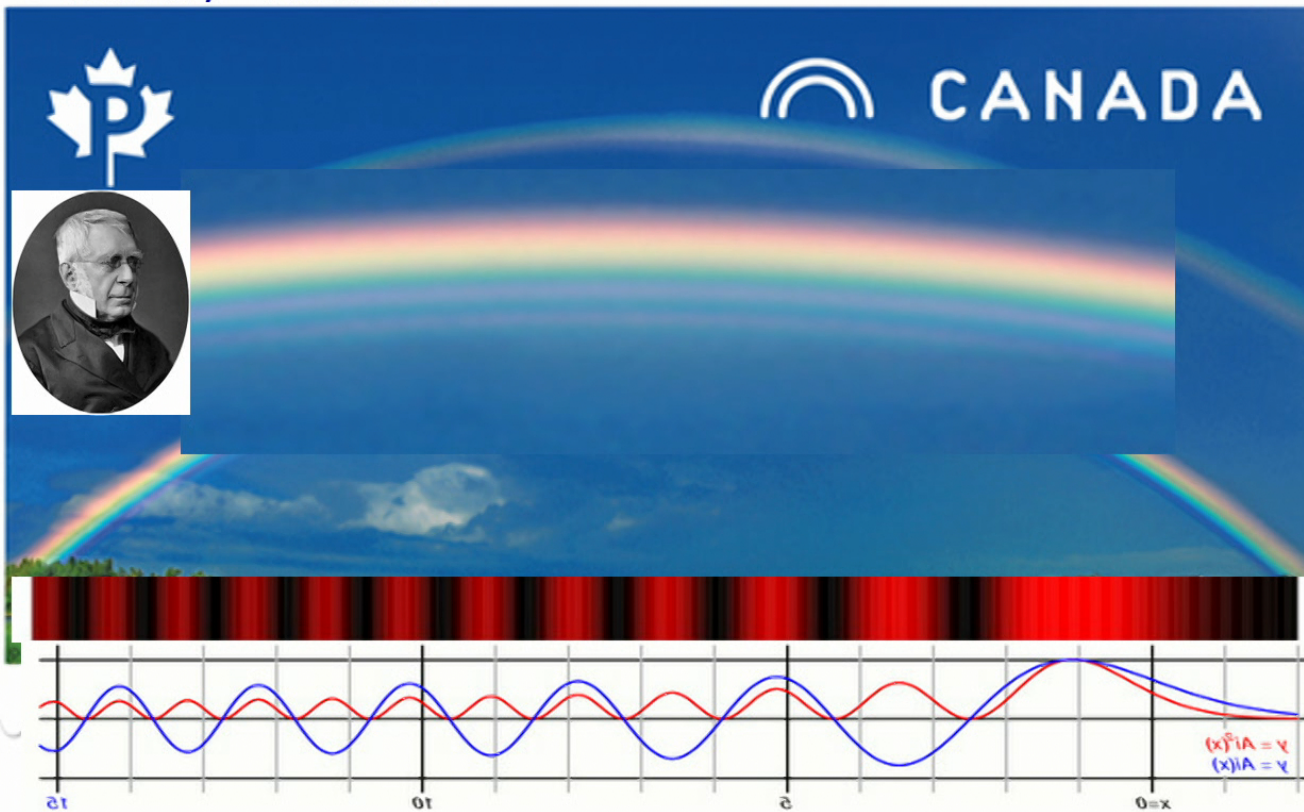
Airy functions



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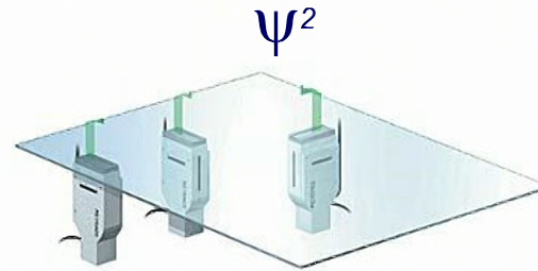


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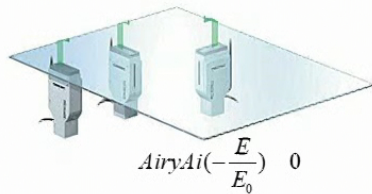
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qBOUNCE: Quantum States in the Gravity Potential

- Energy Eigenvalues are given by the Zeros of AiryAi

$$\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0} \quad E_0 = -\left(\frac{\hbar^2 m_g^2 g^2}{2m_i}\right)^{1/3}$$

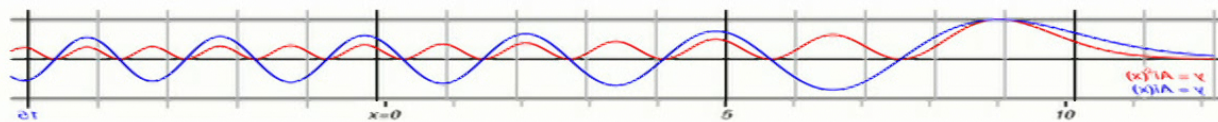
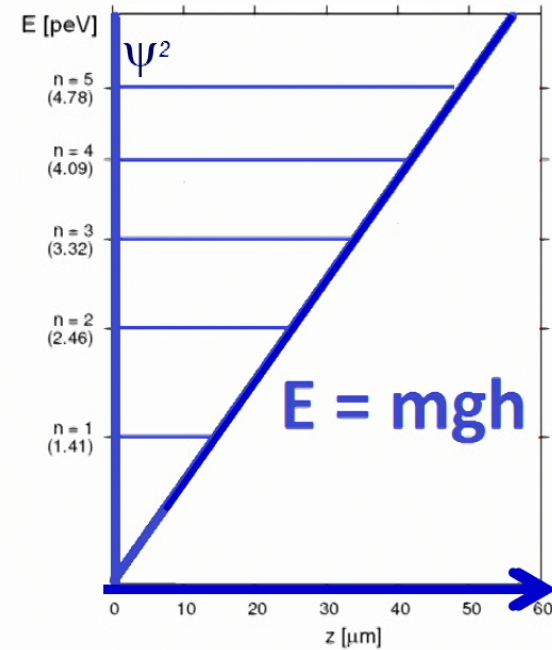


Zeros of A_i	
1	-2.33810
2	-4.08794
3	-5.52055
4	-6.78670
5	-7.94413
6	-9.02265
7	-10.04017

$$E_1 = (2.33810) \left(\frac{\hbar^2 m g^2}{2}\right)^{1/3}$$

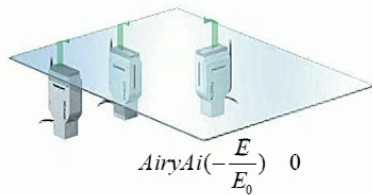
$$E_2 = (4.08794) \left(\frac{\hbar^2 m g^2}{2}\right)^{1/3}$$

$$E_3 = (5.52055) \left(\frac{\hbar^2 m g^2}{2}\right)^{1/3}$$



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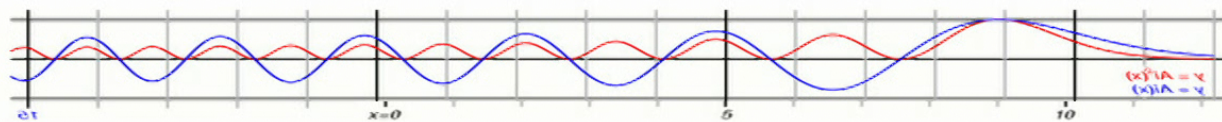
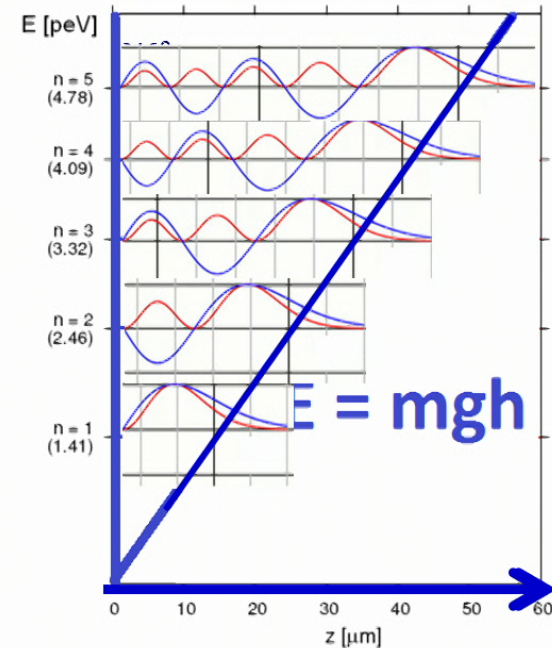


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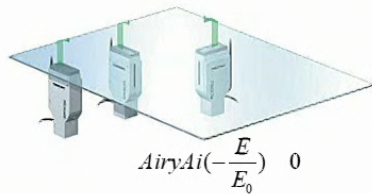
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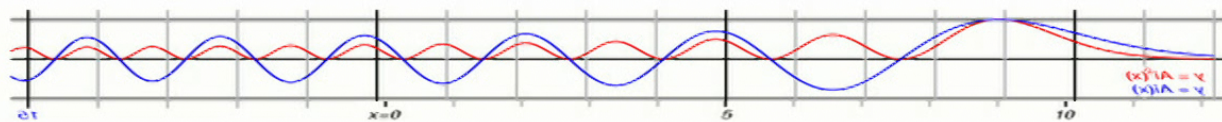
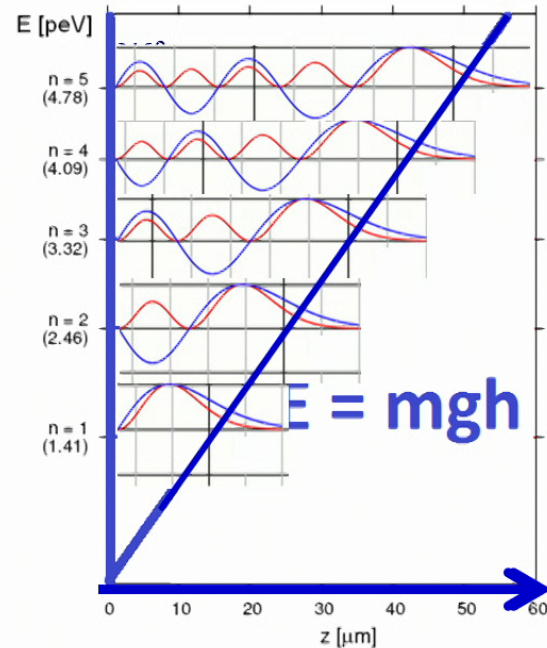
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$$\Psi_1(\tilde{z}, t) = c_1 A_1(\tilde{z}) \times e^{-i(E_1/\hbar) \times t}$$

$$\Psi_2(\tilde{z}, t) = c_2 A_2(\tilde{z}) \times e^{-i(E_2/\hbar) \times t}$$

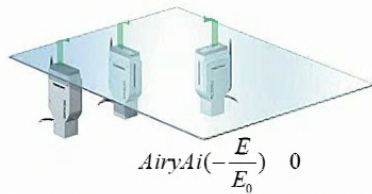
$$\Psi_3(\tilde{z}, t) = c_3 A_3(\tilde{z}) \times e^{-i(E_3/\hbar) \times t}$$

$$\Psi(\tilde{z}, t) = \sum_{n=1}^{\infty} A_n(\tilde{z}) \times e^{-i(E_n/\hbar) \times t}$$

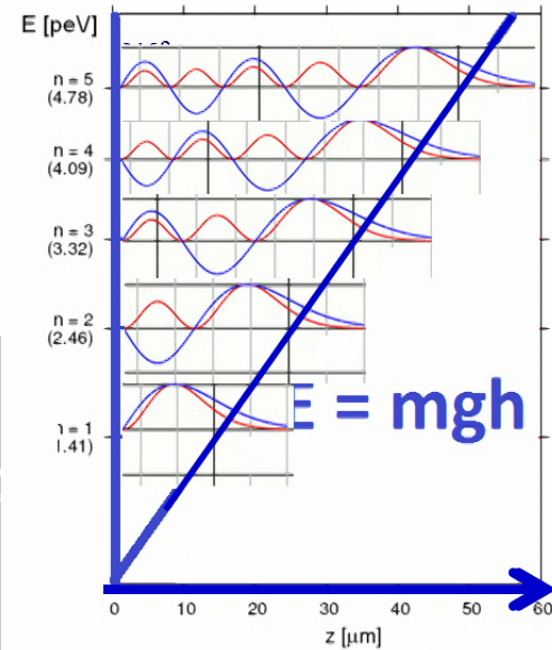
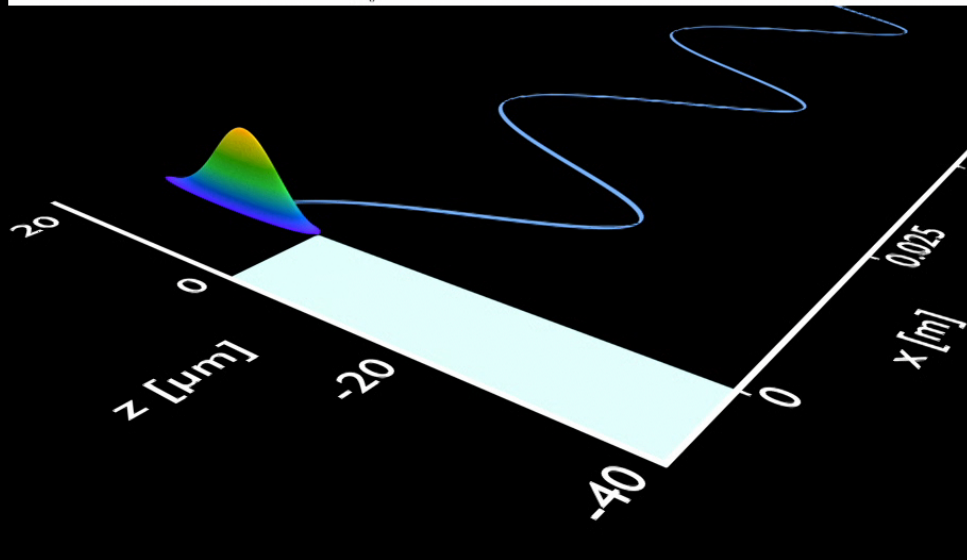


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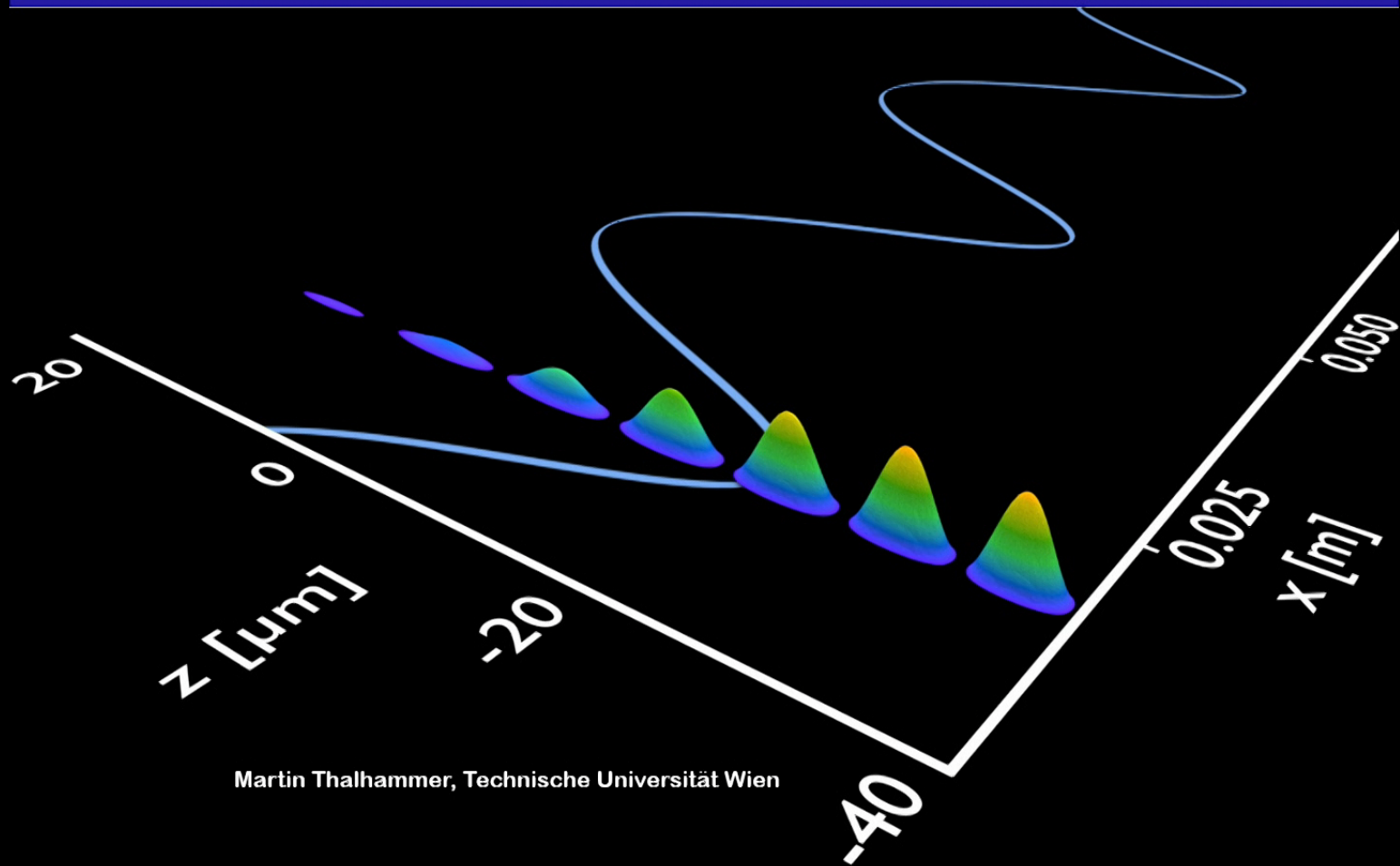
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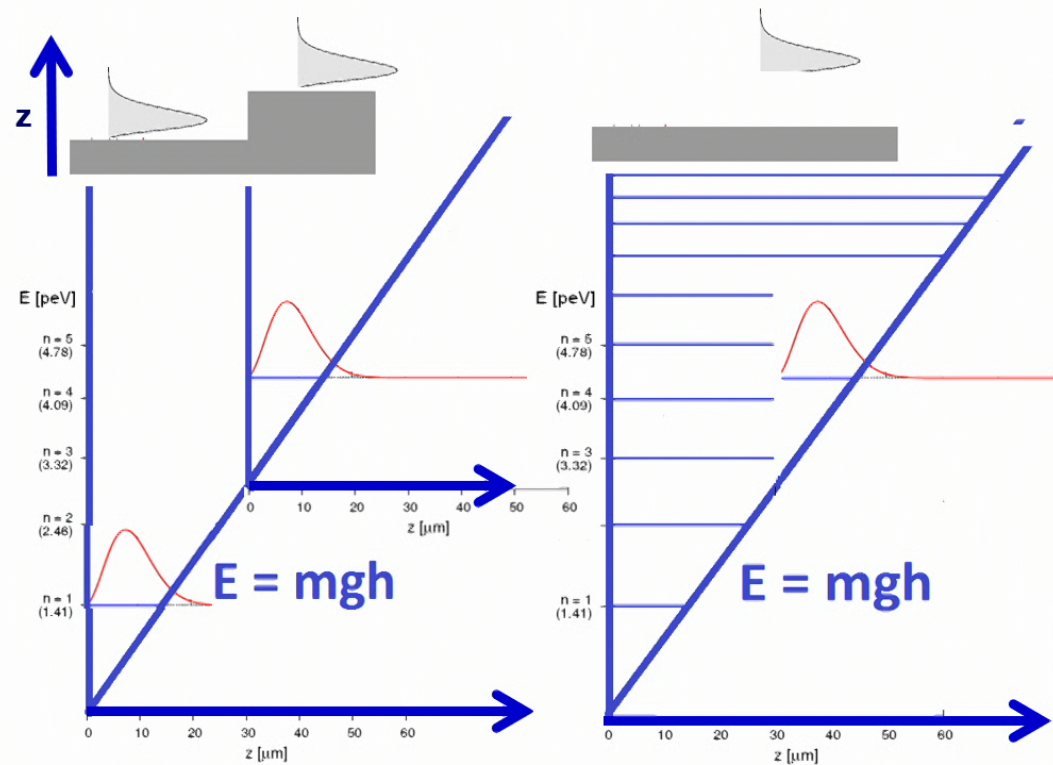


*q*BOUNCE

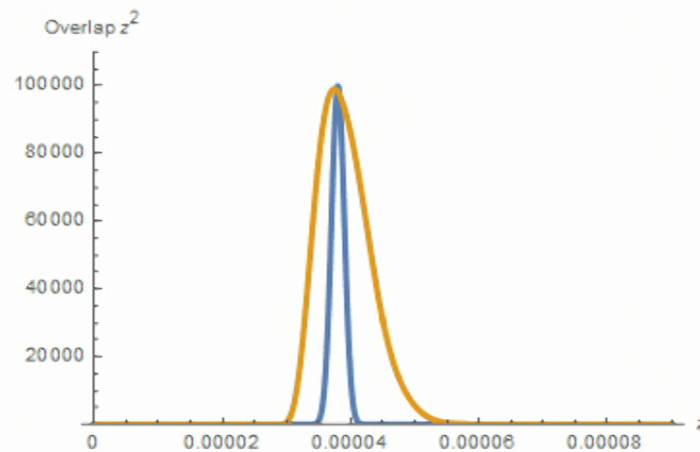


Martin Thalhammer, Technische Universität Wien

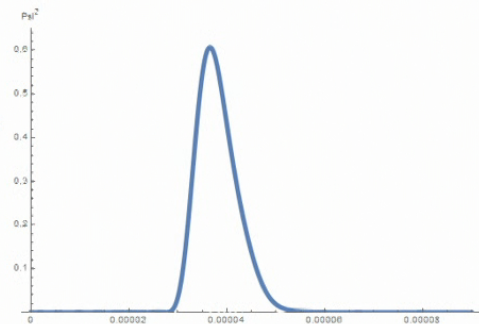
Step Potential



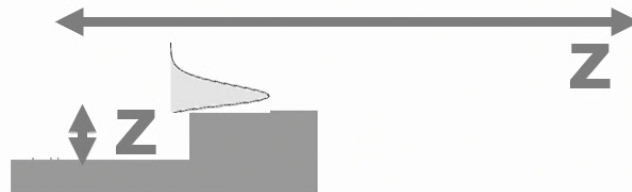
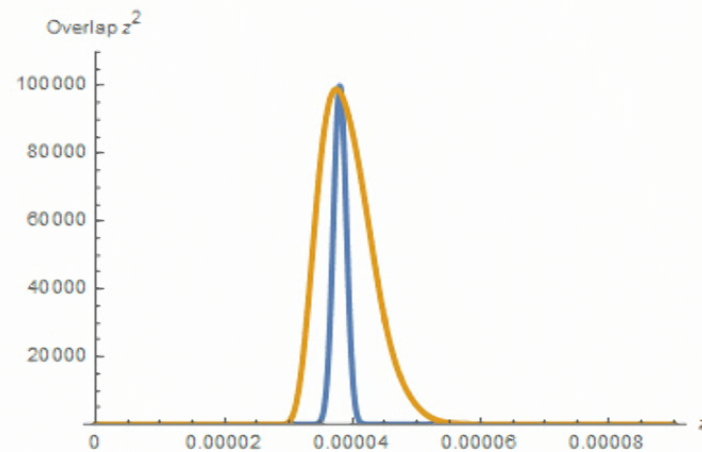
“Fourier”-Airy Series



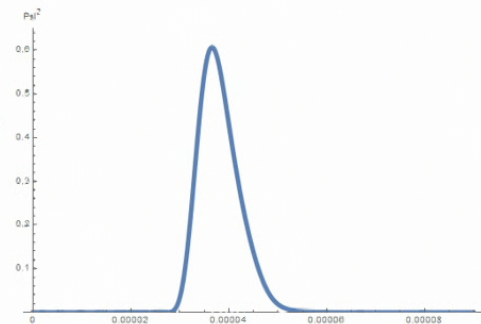
$$\begin{aligned}\Psi_1(\tilde{z}, t) &= c_1 A i_1(\tilde{z}) \times e^{-i(E_1/\hbar) \times t} \\ \Psi_2(\tilde{z}, t) &= c_2 A i_2(\tilde{z}) \times e^{-i(E_2/\hbar) \times t} \\ \Psi_3(\tilde{z}, t) &= c_3 A i_3(\tilde{z}) \times e^{-i(E_3/\hbar) \times t} \\ &\dots \\ \Psi(\tilde{z}, t) &= \sum_{n=1}^{\infty} A i_n(\tilde{z}) \times e^{-i(E_n/\hbar) \times t}\end{aligned}$$



“Fourier”-Airy Series



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Tool: State Selector

Schrödinger equation:

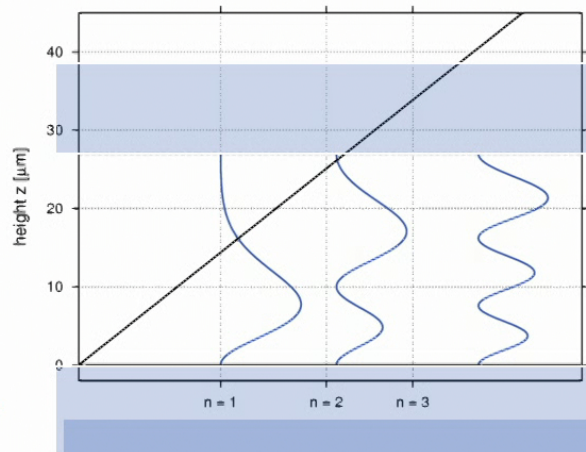
$$\left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial z^2} + mgz \right) \varphi_n(z) = E_n \varphi_n(z)$$

boundary conditions:

$$\varphi_n(0) = 0$$

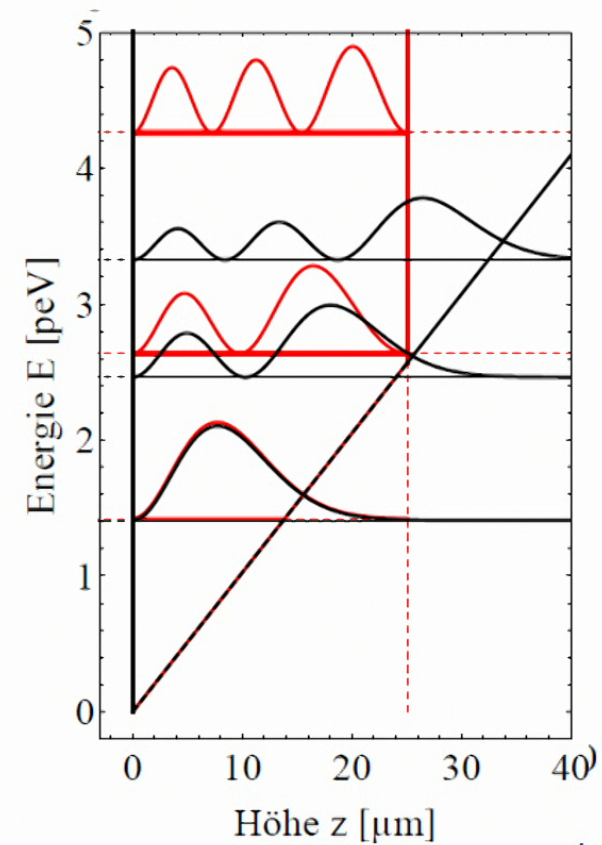
with 2nd mirror at height

$$\varphi_n(l) = 0$$



	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	4.2 peV

Solutions: Airy-functions: Ai & Bi



Courtesy Jenke

31

Tool: State Selector

Schrödinger equation:

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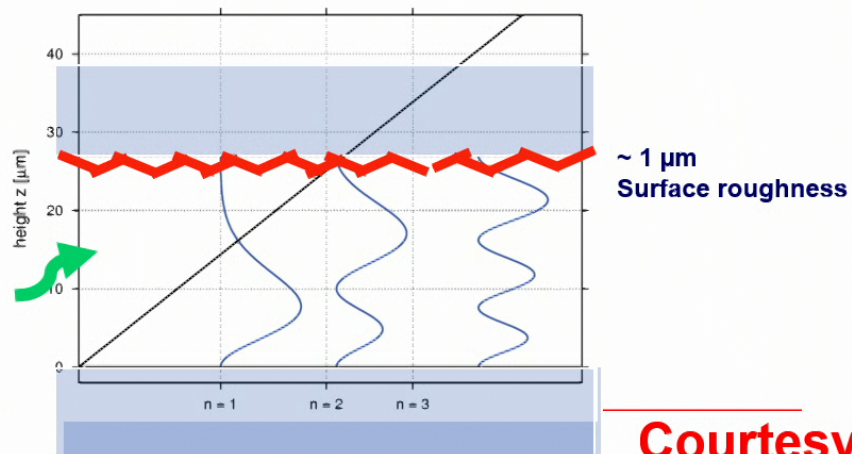
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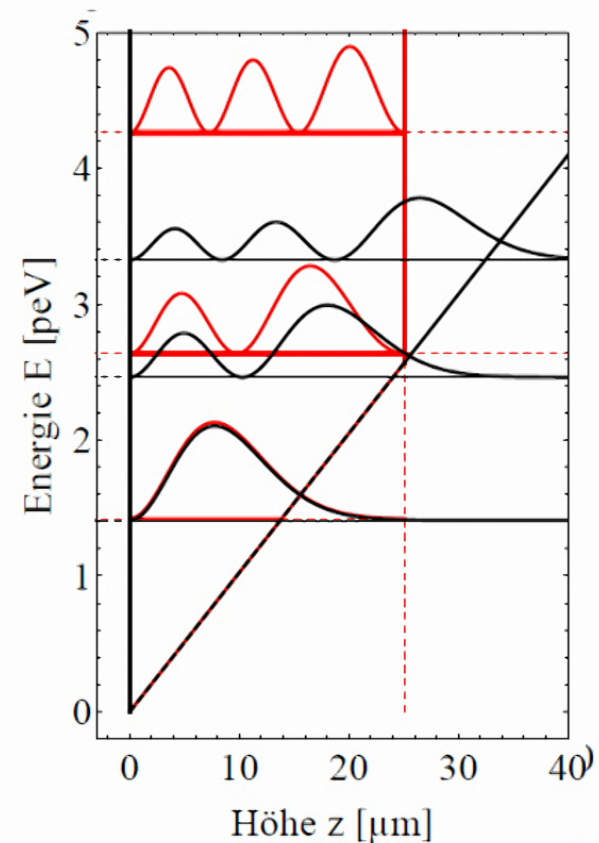
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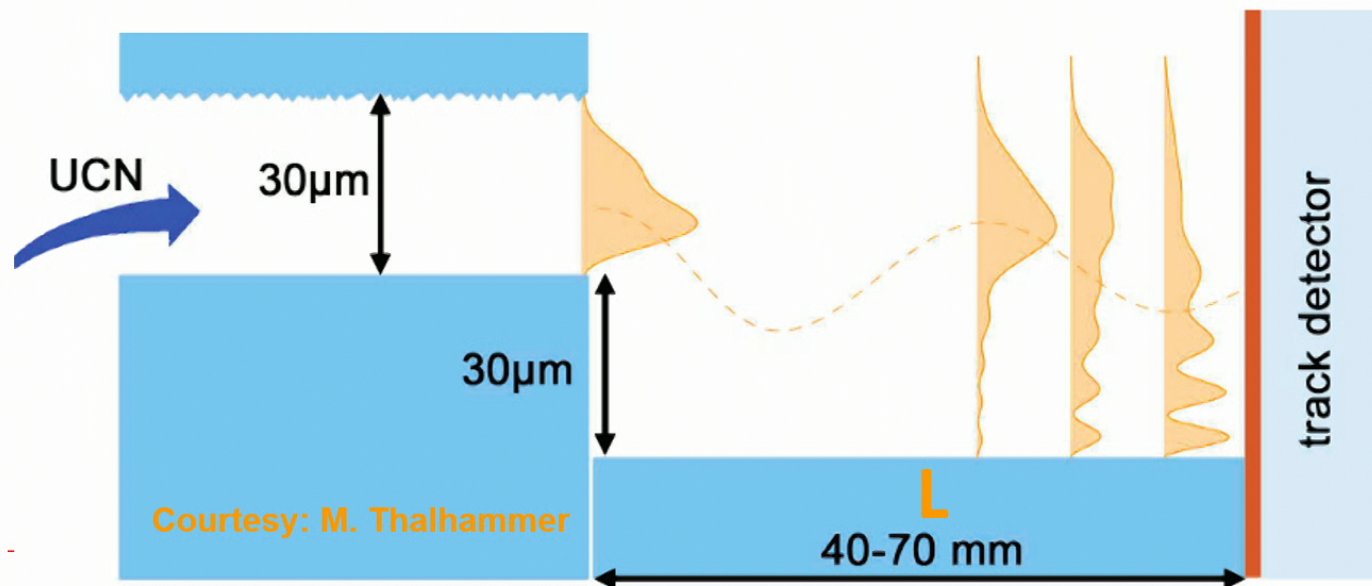
31

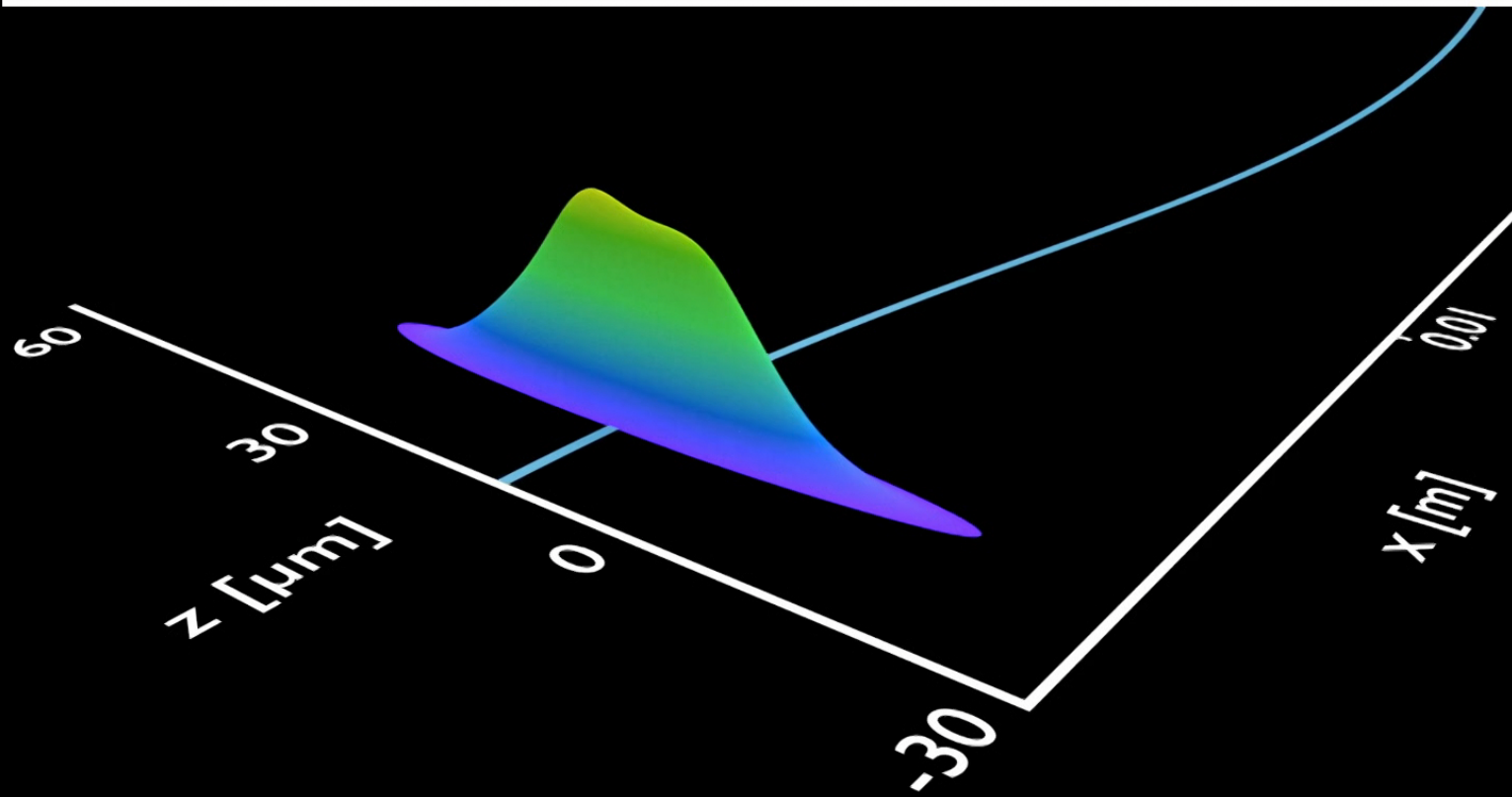
M. Thalhammer, T. Jenke et al.

- Snapshots with spatial resolution detectors $\sim 1.5 \mu\text{m}$

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

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



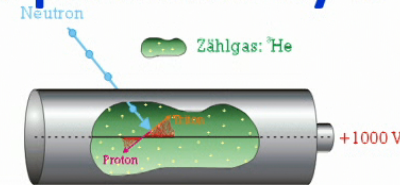


How are Neutrons detected?

- Convert a neutron into charged particles by a nuclear reaction

- Neutron converter

- $^3\text{He} + n$	$\rightarrow ^3\text{H} + p + 0.76 \text{ MeV}$	5330 b
- $^6\text{Li} + n$	$\rightarrow ^3\text{H} + \alpha + 4.49 \text{ MeV}$	940 b
- $^{157}\text{Gd} + n$	$\rightarrow ^{158}\text{Gd} + \gamma + e^- (29-181 \text{ keV})$	254000 b
- $^{10}\text{B} + n$	$\rightarrow ^7\text{Li} + \alpha + 2.79 \text{ MeV} (6\%)$	3838 b
	$\rightarrow ^7\text{Li}^* + \alpha + 2.31 \text{ MeV} (94\%)$	
	$^7\text{Li} + \gamma (0.48 \text{ MeV})$	

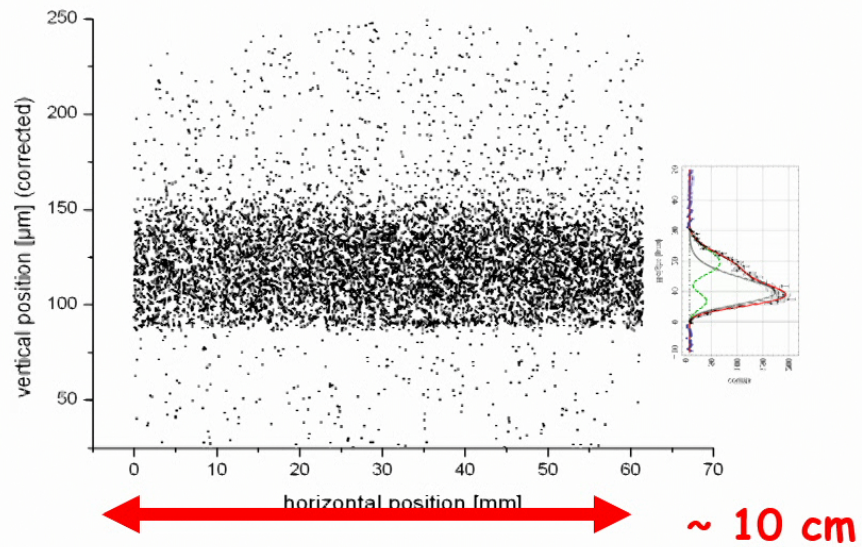
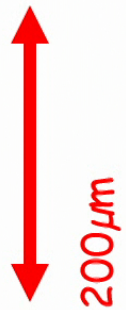
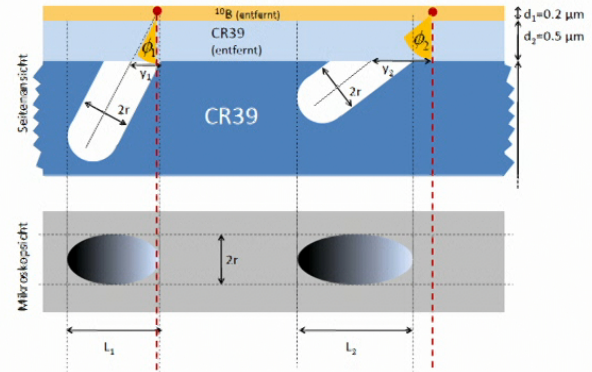
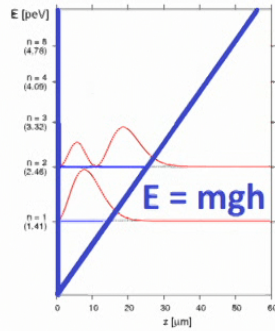
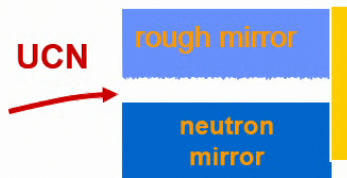


- Detectors for ionising particles:

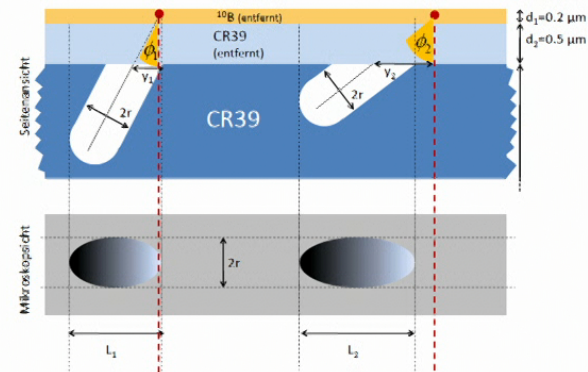
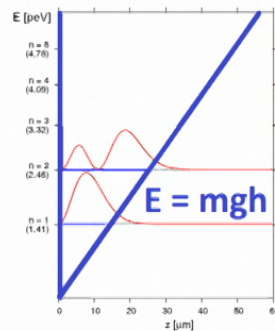
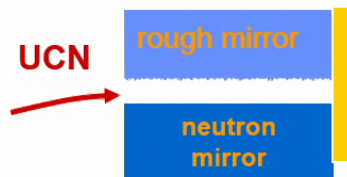
- Gas detectors
- Szintillation detectors
- Solid state detectors

Courtesy: Dr. Martin Klein, CDT

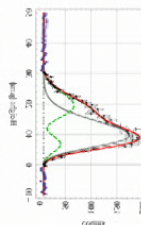
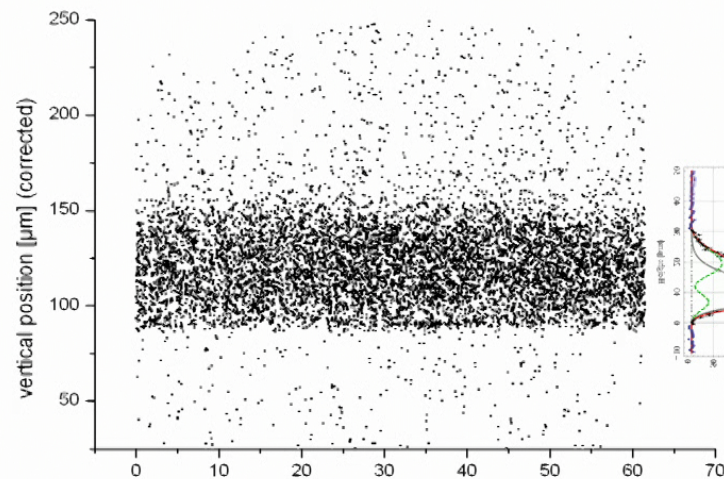
Airy - Quantum States 1 & 2



Airy - Quantum States 1 & 2

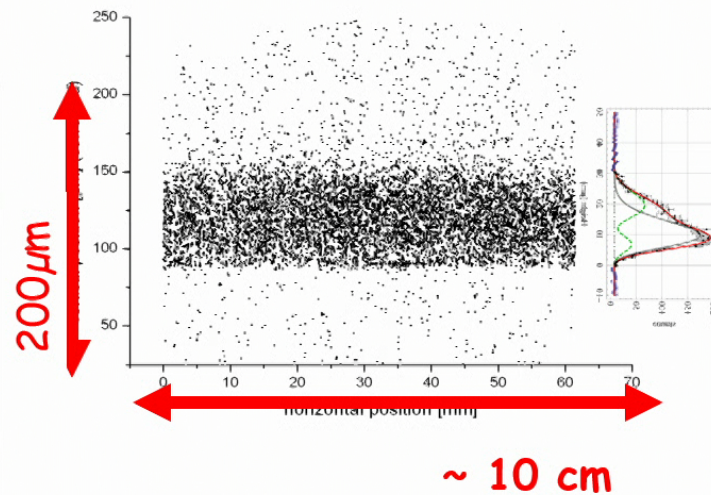
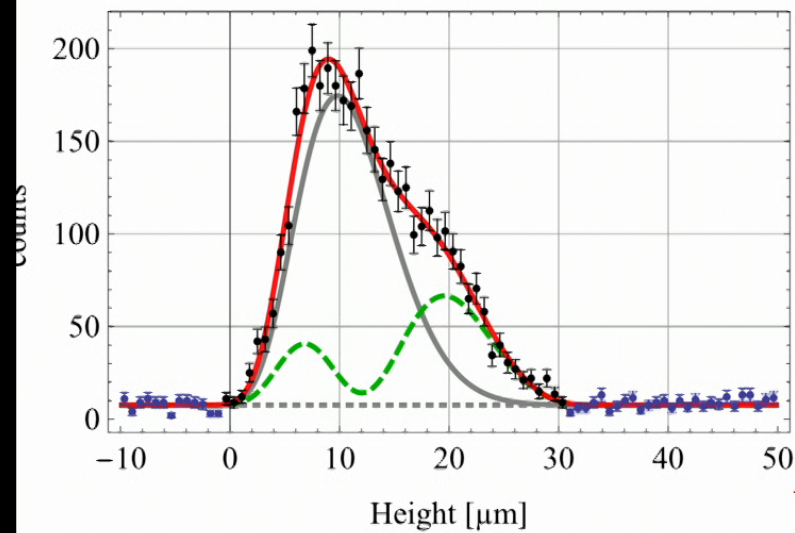
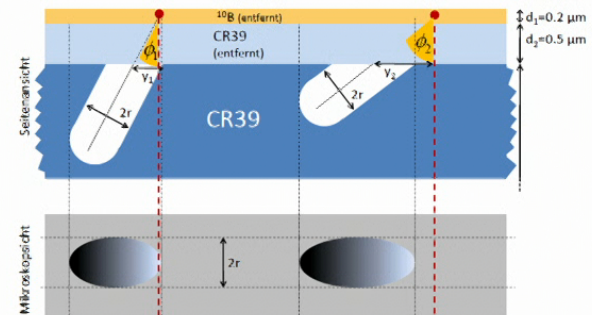
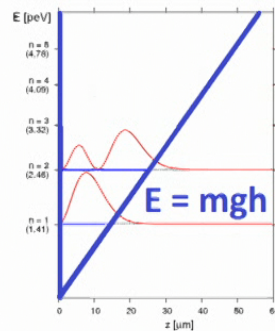
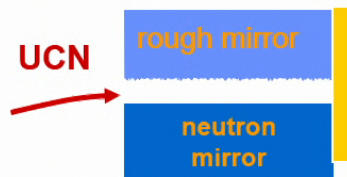


200 μm



~ 10 cm

Airy - Quantum States 1 & 2



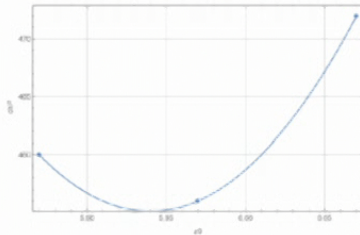


Combined fit preliminary results

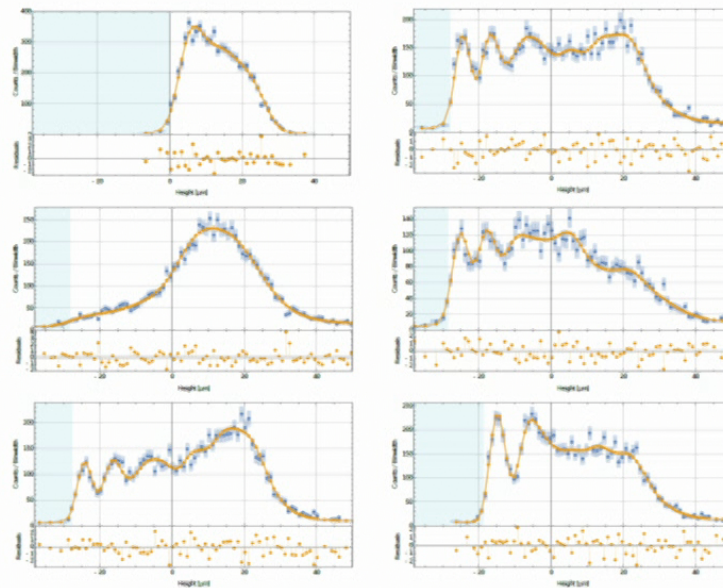
- **z0 theory**

- # Datapoints: 452
- Degrees of freedom: 411
- Chi2: 459.46
- Significance: 4.94 %
- z0: 5.869 μm

- **z0 fit**

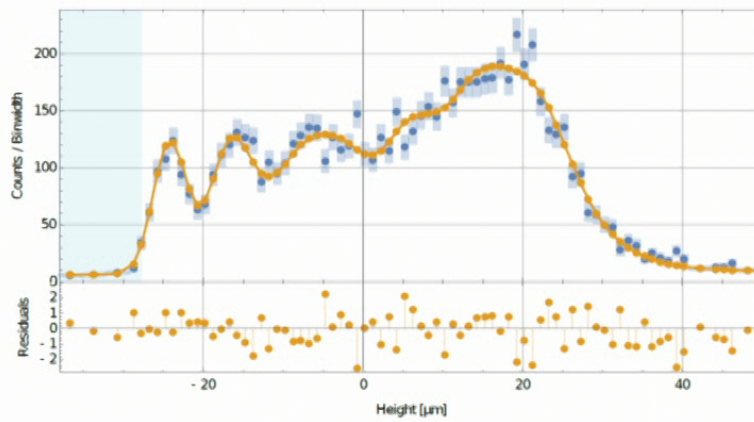


$$z0 = 5.940 \pm 0.032 \mu\text{m}$$

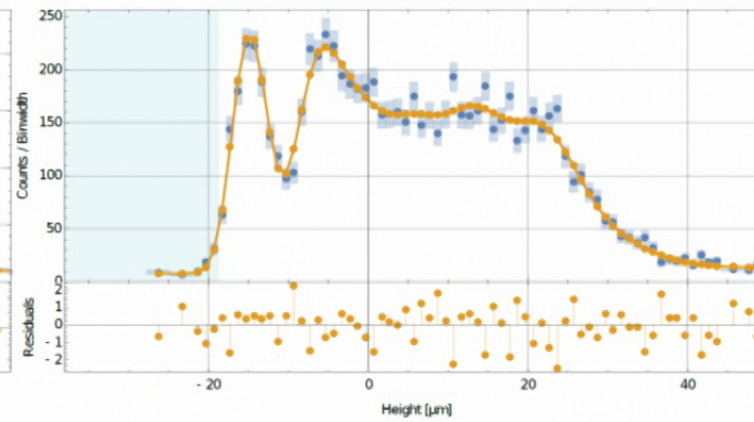




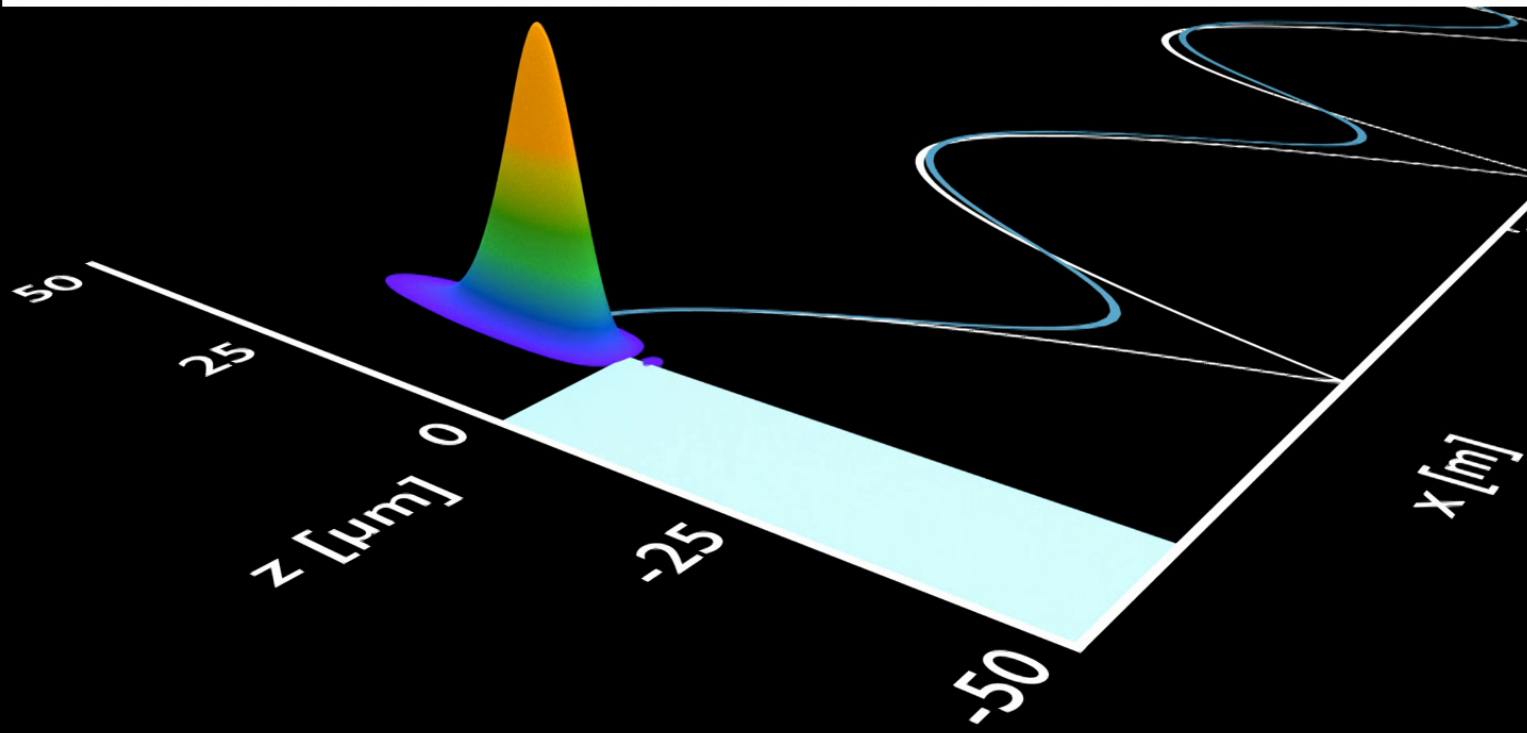
51 mm



@ 30 μm step



@ 20 μm step



Phaenomena
Exhibition
Penemünde
Germany



Newton, Gravitation & Equivalence

There are two basic elements:

- an equation for the gravitational field as influenced by matter,

$$F(r) = -G \frac{M \cdot m_g}{r^2}$$

$$\Phi(r) = \frac{GM}{r}$$

- and an equation for the response of matter to this field

$$\vec{F} = m_i \vec{a}$$

- The weak equivalence principle

$$m_i = m_g$$



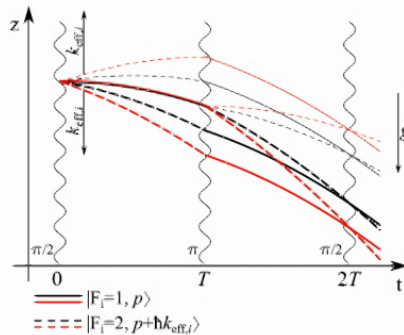
qBOUNCE & equivalence principle

● Application

- **A quantum test of the equivalence principle based on a single neutron as object, no classical path**
 - So far equivalence tests have been performed on 2 different objects falling on classic paths:

$$\eta = 2 \frac{|a_1 - a_2|}{|a_1 + a_2|}$$

- WEP: $2.7 \cdot 10^{-15}$ level tested: Ti Pt
- Microscope, September 2022



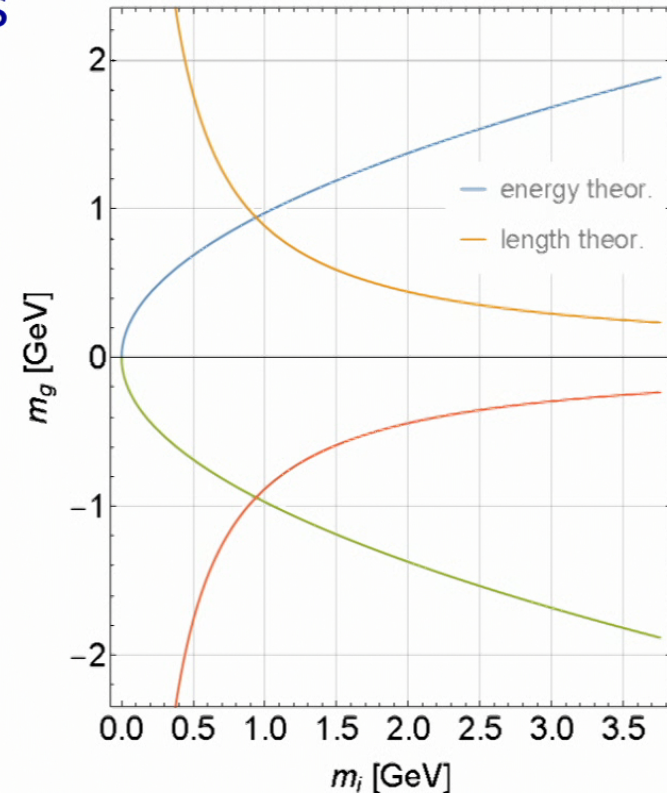
21.09.2022

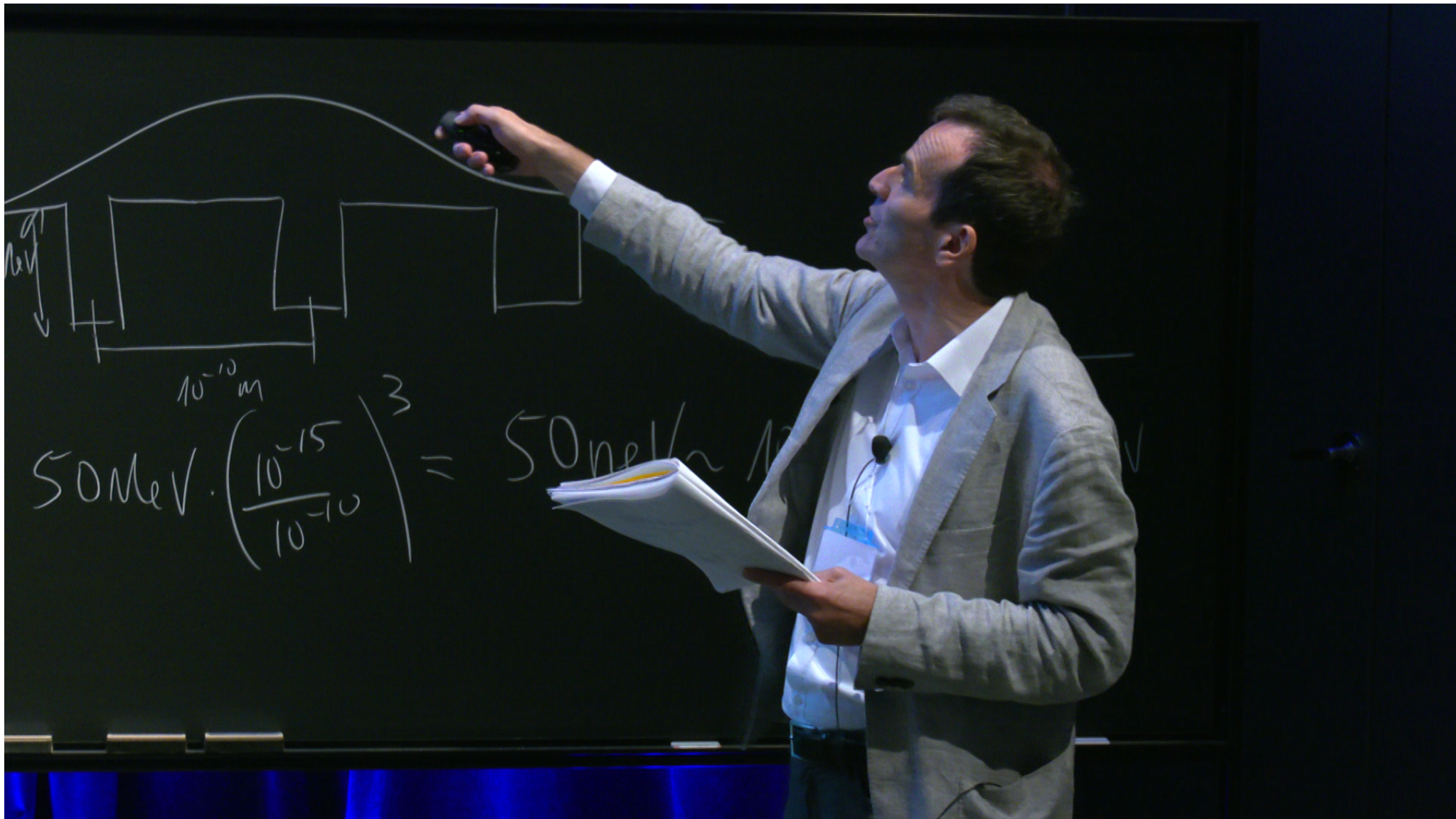
Quantum Aspects of the Bouncing Ball

- WEP and q Bounce: one object, no classical path
- Inertial and gravitational mass
 - Energy E_0
 - Distance z_0

$$E_0 = -\left(\frac{\hbar^2 m_g^2 g^2}{2m_i}\right)^{1/3} = 0.602 \text{ peV}$$

$$z_0 = -\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} = 5.87 \mu\text{m}$$





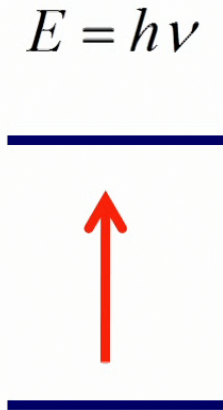
Frequency: Resonance Spectroscopy

- Quantum System, 2-Level System
- Coupling

- Example:

- NMR:
 - Magnetic Moment in
 - outer magnetic field
 - RF-field drives Transitions
- Rabi – Spectroscopy
- Ramsey Spectroscopy: Clocks, Spin Echo, EDM

$$4d_n E_{el} = \Delta\omega\hbar$$



Gravity Resonance Spectroscopy

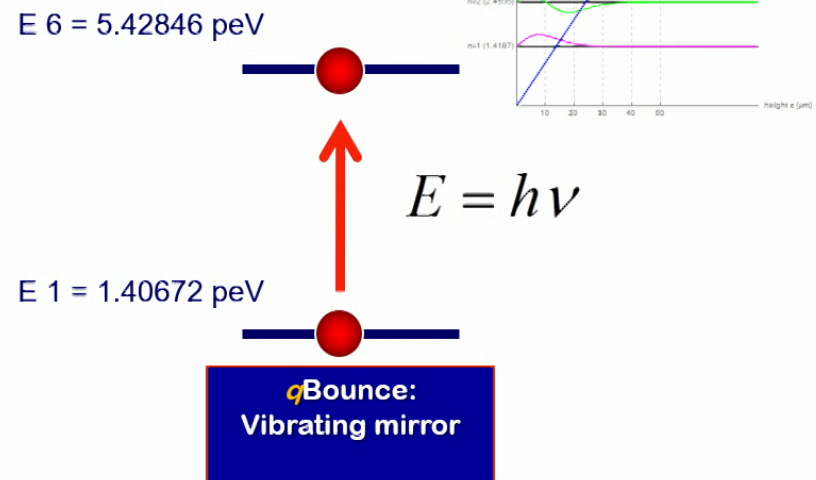
- Quantum System, multi-Level System
- Coupling: Oscillating Mirror

- GRS: Neutron

- Gravity field of the earth
- Oscillating mirror drives transitions

- No lasers, no coupling to electromagnetic potential

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



Energy Eigen States in Gravity Potential

$$\Delta E = \hbar \omega$$

$$|2\rangle \rightarrow |7\rangle$$

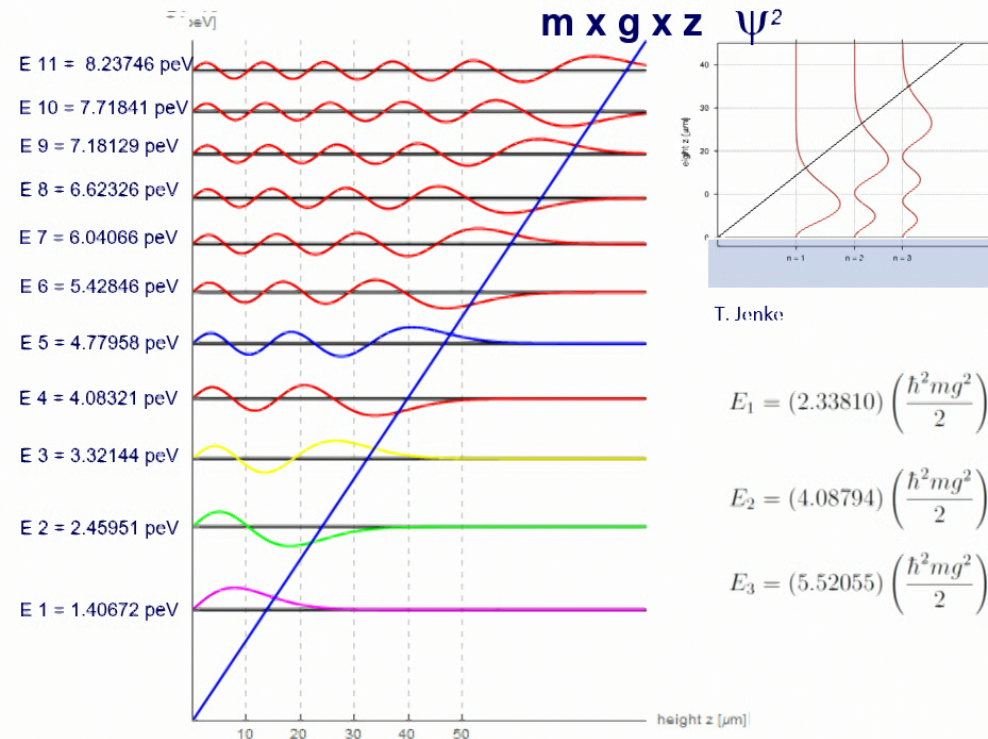
$$|1\rangle \rightarrow |6\rangle$$

$$|2\rangle \rightarrow |5\rangle$$

$$|2\rangle \rightarrow |4\rangle$$

$$|1\rangle \rightarrow |3\rangle$$

$$|1\rangle \rightarrow |4\rangle$$



$$|1\rangle : 70\%$$

$$|2\rangle : 30\%$$

$$|3\rangle : 0\%$$

$$E_1 = (2.33810) \left(\frac{\hbar^2 m g^2}{2} \right)^{\frac{1}{3}}$$

$$E_2 = (4.08794) \left(\frac{\hbar^2 m g^2}{2} \right)^{\frac{1}{3}}$$

$$E_3 = (5.52055) \left(\frac{\hbar^2 m g^2}{2} \right)^{\frac{1}{3}}$$

A neutron as an ideal object to study gravitation at small distances

A neutron

- is neutral
- has small polarizability
- probes small distances on the nm ... μm – scale
- gives access to gravity-parameters:
 - **mass, distance, energy momentum, torsion**

Casimir Force and Van der Waals Force

Atom

- Example Rb
Energy shift for Rb
Atom at $r = 1 \mu\text{m}$
distance to surface

$$a_0 = 2,3 \times 10^{-23}$$

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

$$= 0.6 \text{ peV}$$

Neutron

- Casimir force
absent
- Polarizability
extremely small:

$$a_n = 11.6 \times 10^{-4} \text{ fm}^3$$

$$D = 4\pi\epsilon_0 a_n E$$

$$= 6 \times 10^{-41} \text{ eV} \times E \left[\frac{\text{V}}{\text{m}} \right]$$

$$= 10^{-18} \text{ peV}$$

Spectroscopy with cold and ultra-cold neutrons
H.A. T Jenke, G Konrad
EPJ Web of Conferences 93, 2015

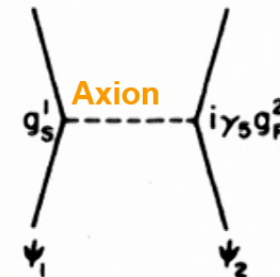
Aim: gravity experiments with neutrons
with a sensitivity level of $10^{-21} \text{ eV} = 10^{-9} \text{ peV}$

A neutron as an ideal object to study gravitation at small distances

A neutron

- is neutral
- has small polarizability
- probes small distances on the nm ... μm – scale
- gives access to gravity-parameters:
 - **mass, distance, energy momentum, torsion**
- couples to scalar fields (if there is a coupling)
- allows constraints on any possible new interaction at the level of sensitivity
 - Examples for hypothetical gravity-like forces or
 - **Dark Matter / Dark Energy fields**
 - **Chameleons? Symmetrons? ...**
- has a spin
 - **Axions-exchange?**

Hypothetical New Interaction

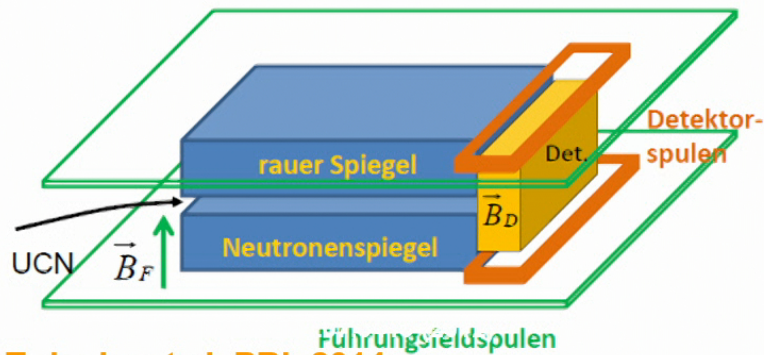


Applications I: Spin-dependant short-ranged interactions

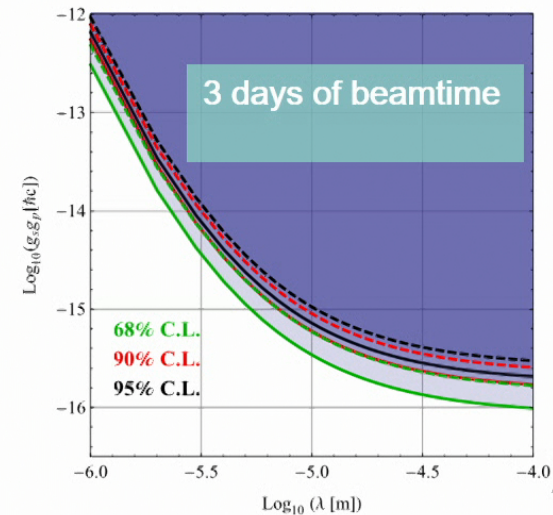
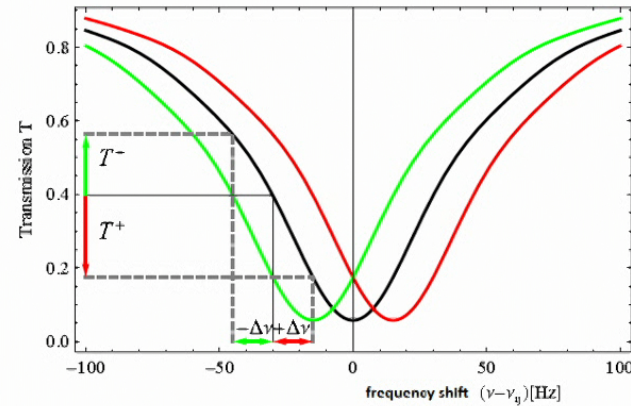
$$V_{\text{axion}} = \frac{g_s g_p \hbar}{8\pi m_n c} \vec{\sigma} \cdot \vec{n} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right)$$

discovery potential [Setup 2010]:

$$g_s g_p / \hbar c \geq \frac{3 \cdot 10^{-16}}{\sqrt{\text{days}}} \quad (\lambda = 10 \mu\text{m}, 68\% \text{ C.L.})$$



T. Jenke et al. PRL 2014

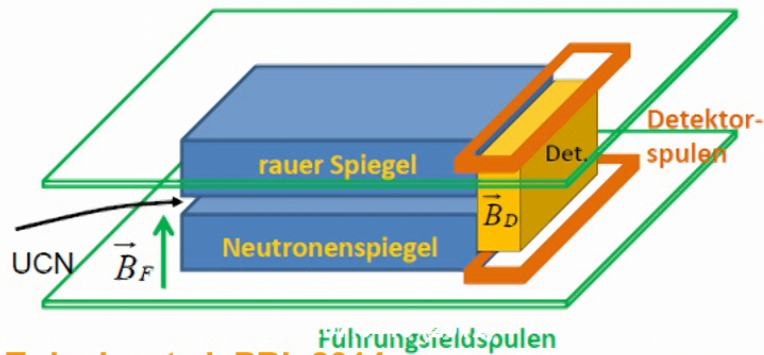


Applications I: Spin-dependant short-ranged interactions

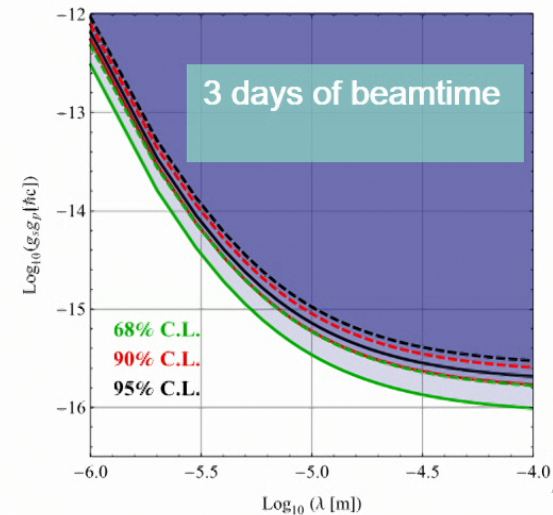
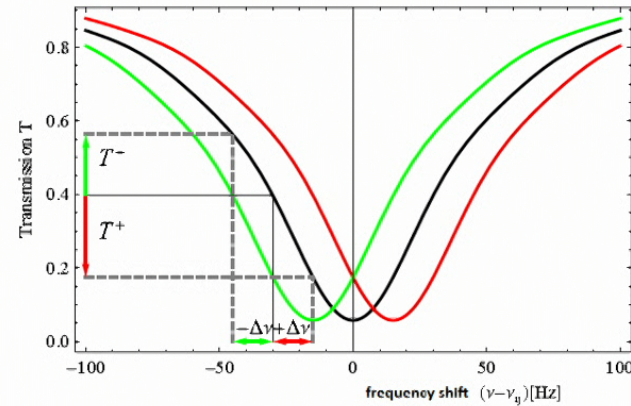
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T. Jenke et al. PRL 2014

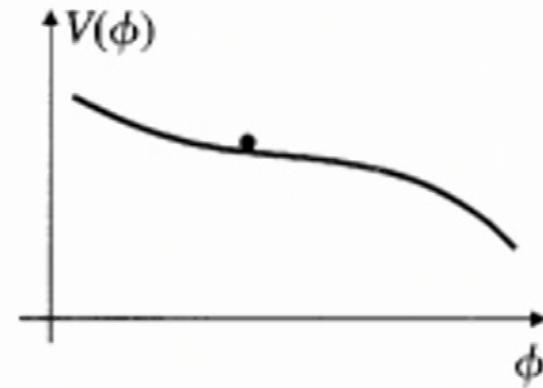


Dark Energy Quintessence Theories

- 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

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

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



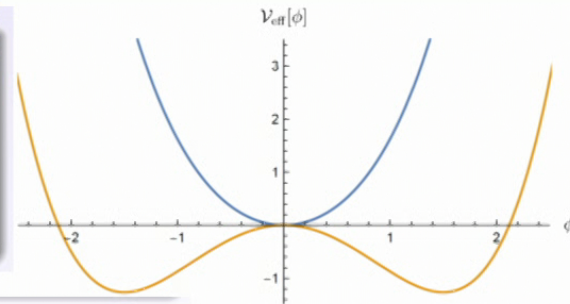
$$T_{\mu\nu} \approx -V(\phi)g_{\mu\nu}$$

Symmetrons (M. Pitschmann, P. Brax)

Symmetron

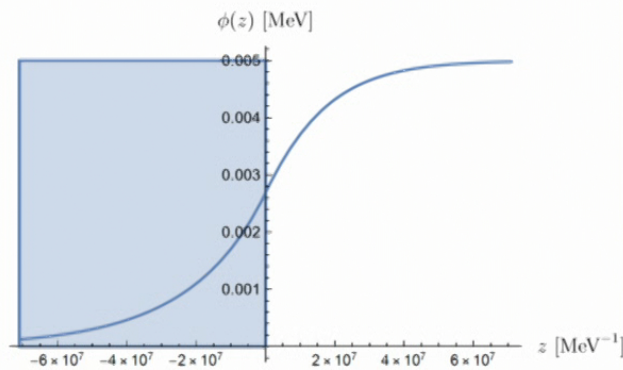
- "Invented" by K. Hinterbichler & J. Khoury in 2010^a
- based on *Spontaneous Symmetry Breaking* similar to the *Higgs mechanism* but with a real scalar field ϕ

^aPRL **104**, 231301 (2010)



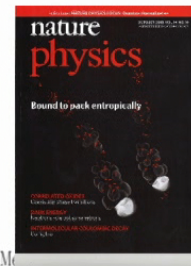
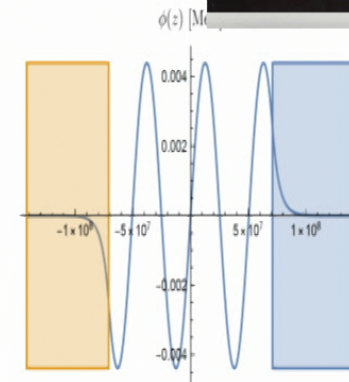
2 Phases

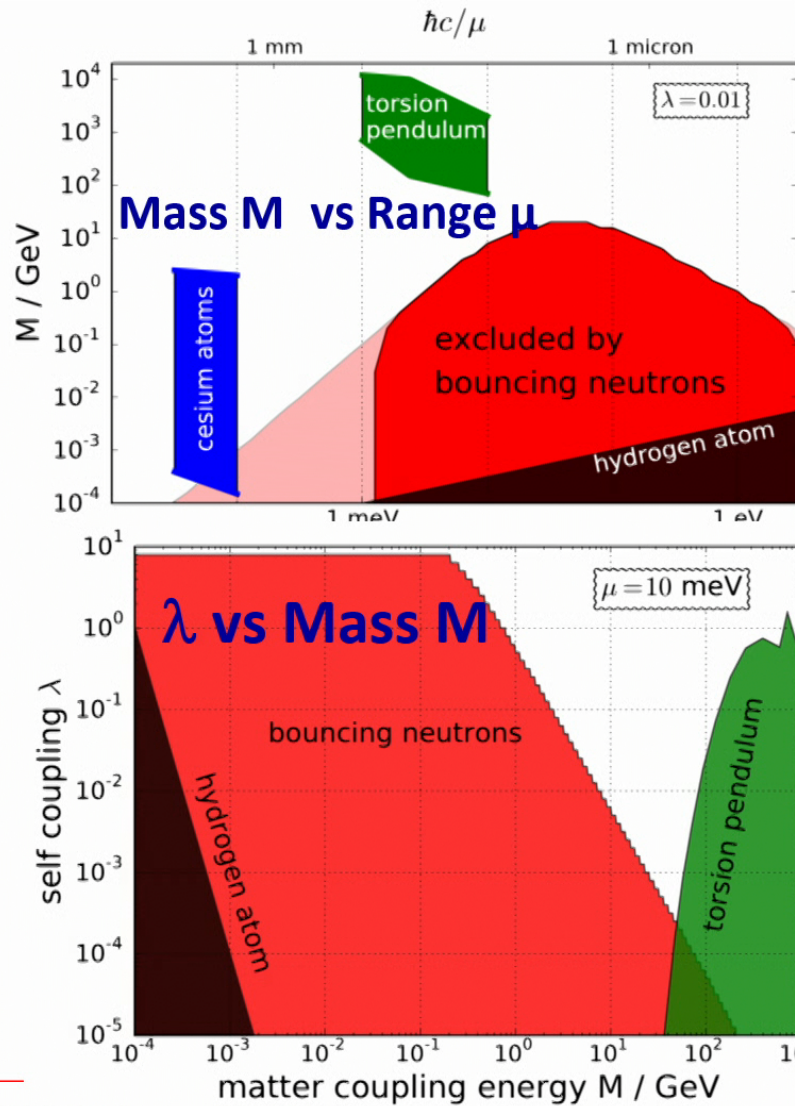
- 1 Spontaneous Symmetry Breaking: $\frac{\rho}{M^2} < \mu^2$ ("vacuum value" $\phi_V = \pm \frac{\mu}{\sqrt{\lambda}}$)
- 2 Symmetric Phase: $\frac{\rho}{M^2} \geq \mu^2$ "dense matter"



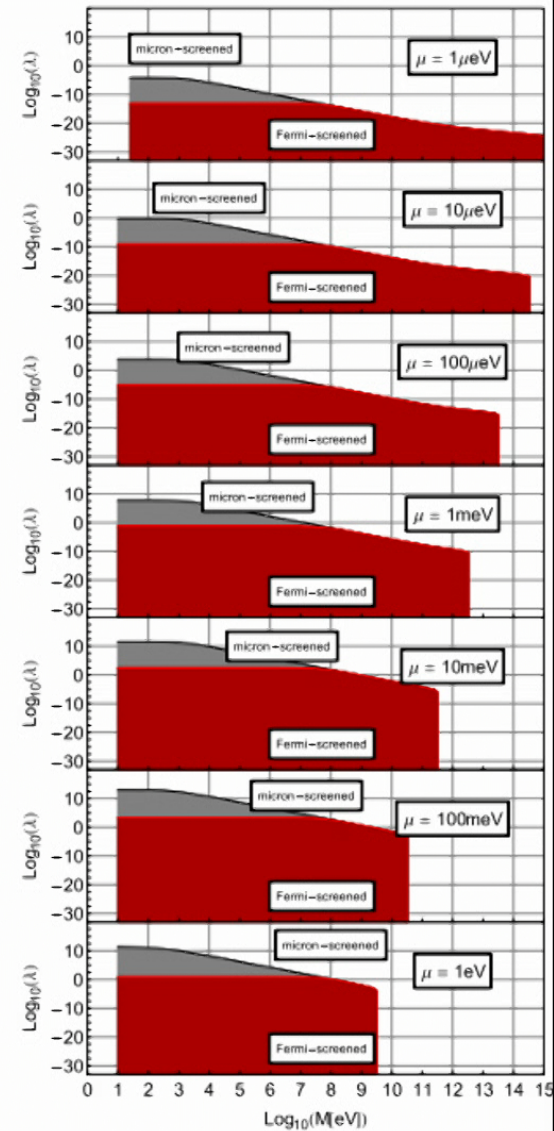
$$\begin{aligned}\lambda &= 10^{-10} \\ \mu_{\text{eff}} &= 5 \times 10^{-8} \text{ MeV} \\ M &= 5 \times 10^4 \text{ MeV} \\ k &= 0.537\end{aligned}$$

$$\begin{aligned}\rho_M &= 1.082 \times 10^{-5} \text{ MeV}^4 \\ \rho_{\text{eff}} &= 4.570 \times 10^{-6} \text{ MeV}^4\end{aligned}$$





Cronenberg et al., NP 2018



In this issue **NATURE PHYSICS FOCUS: Quantum thermalization**

nature physics

OCTOBER 2018 VOL 14 NO 10
www.nature.com/naturephysics

Bound to pack entropically

CORRELATED OXIDES
Coexisting phase transitions

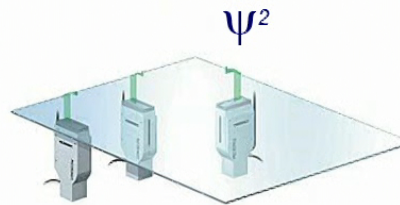
DARK ENERGY
Neutrons rule out symmetrons

INTERMOLECULAR COULOMBIC DECAY
Going bio

qBOUNCE: Quantum States

- Schrödinger Equation

$$-\frac{\hbar^2}{2m} \frac{d^2\Psi}{dz^2} + mgz\Psi = E\Psi$$



$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} = E\psi$$

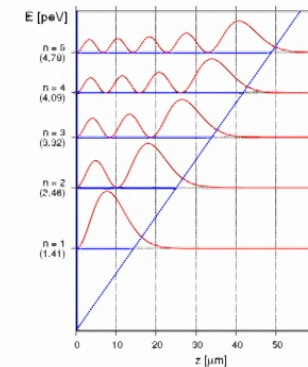
- Characteristic length and energy scale

$$z_0 = -\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} = 5.87 \mu\text{m} \quad E_0 = -\left(\frac{\hbar^2 m_g^2 g^2}{2m_i}\right)^{1/3} = 0.602 \text{peV}$$

- Change of variable $\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0}$

- Airy's Equation, and general Solution with AiryAi and AiryBi

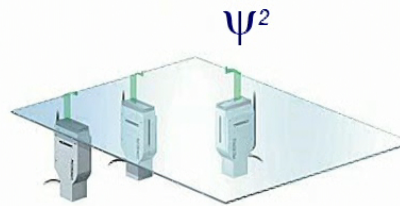
$$-\frac{d^2\Psi}{d\tilde{z}^2} + \tilde{z}\Psi = 0 \quad \psi(z) = aA_i(z) + bB_i(z)$$



qBOUNCE: Quantum States

- Schrödinger Equation

$$-\frac{\hbar^2}{2m} \frac{d^2\Psi}{dz^2} + mgz\Psi = E\Psi$$



$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} = E\psi$$

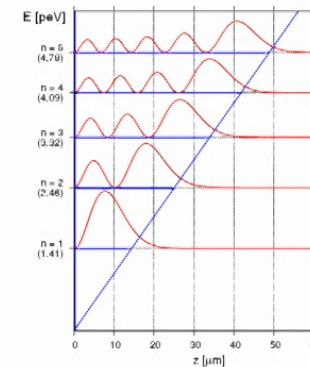
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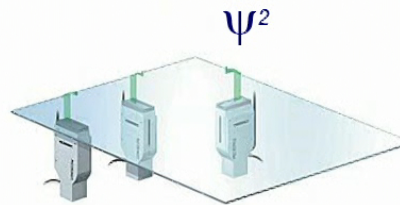
$$-\frac{d^2\Psi}{d\tilde{z}^2} + \tilde{z}\Psi = 0 \quad \psi(z) = aA_i(z) + bB_i(z)$$



qBOUNCE: Quantum States

- Schrödinger Equation

$$DM: -\frac{\hbar^2}{2m} \frac{d^2\psi}{dz^2} + mgz + V(\text{Axion}) = E\psi$$



$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dz^2} = E\psi$$

- Characteristic length and energy scale

$$z_0 = -\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} = 5.87 \mu\text{m} \quad E_0 = -\left(\frac{\hbar^2 m_g^2 g^2}{2m_i}\right)^{1/3} = 0.602 \text{peV}$$

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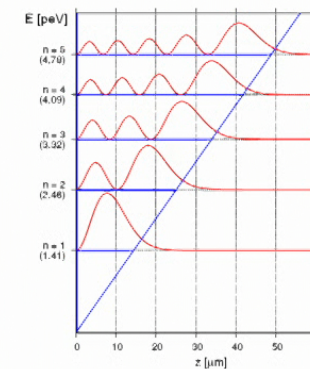
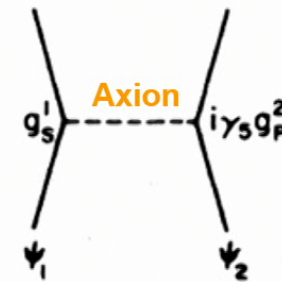
- Airy's Equation, and general Solution with AiryAi and AiryBi

$$-\frac{d^2\Psi}{d\tilde{z}^2} + \tilde{z}\Psi = 0 \quad \psi(z) = aA_i(z) + bB_i(z)$$

T. Jenke et al., Gravity Resonance Spectroscopy

constrains dark matter and dark energy scenarios, Physical Review Letters 112, 151105 (2014)

Hypothetical New Interaction



Gravity Resonance Spectroscopy and Precision Experiments at Low Energy

- Is gravity an entropic force (E. Verlinde)

- Decoherence-free entropic gravity: Model and experimental tests, AJ Schimmoller, G McCaul, H Abele, DI Bondar, Physical Review Research 3, 033065 (2021)

- What about gravity theories based on geometries other than those of Riemann, Riemann-Cartan, etc. ("beyond-Riemann gravity")

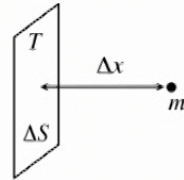
- Quantum gravitational states of ultracold neutrons as a tool for probing beyond-Riemann gravity, A. Ivanov, M. Wellenzohn, H. Abele, Phys. Lett. B. 822 (2021) 136640

- Is Lorentz Invariance violated?

- Probing of violation of Lorentz invariance by ultracold neutrons in the Standard Model Extension
- AN Ivanov, M Wellenzohn, H Abele, Phys. Lett. B, Physics Letters B 797, 134819 (2019)

Verlinde: Gravity as entropic force

- Black holes



$$\Delta S = 2\pi k_B, \quad \Delta x = \frac{\hbar}{mc}$$

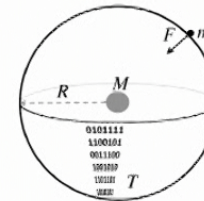
$$\Delta S = 2\pi k_B \cdot \frac{mc}{\hbar} \Delta x, \quad F\Delta x = T\Delta S$$

- Relationship between temperature and acceleration

$$k_B T = \frac{1}{2\pi} \frac{\hbar a}{c} \Rightarrow F = m \cdot a$$

- Entropy and information, N (Bits)

$$N \sim A, \quad N = \frac{Ac^3}{G\hbar}$$



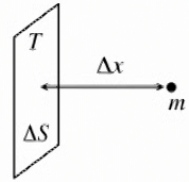
- Energy E is equally distributed, Bits N:

$$E = \frac{1}{2} N k_B T, \quad E = Mc^2, \quad A = 4\pi R^2$$

$$F = G \frac{Mm}{R^2}$$

Verlinde: Gravity as entropic force

- Black holes



$$\Delta S = 2\pi k_B, \quad \Delta x = \frac{\hbar}{mc}$$

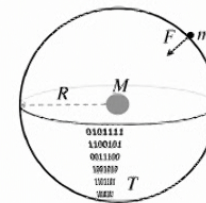
$$\Delta S = 2\pi k_B \cdot \frac{mc}{\hbar} \Delta x, \quad F\Delta x = T\Delta S$$

- Relationship between temperature and acceleration

$$k_B T = \frac{1}{2\pi} \frac{\hbar a}{c} \Rightarrow F = m \cdot a$$

- Entropy and information, N (Bits)

$$N \sim A, \quad N = \frac{Ac^3}{G\hbar}$$



- Energy E is equally distributed, Bits N:

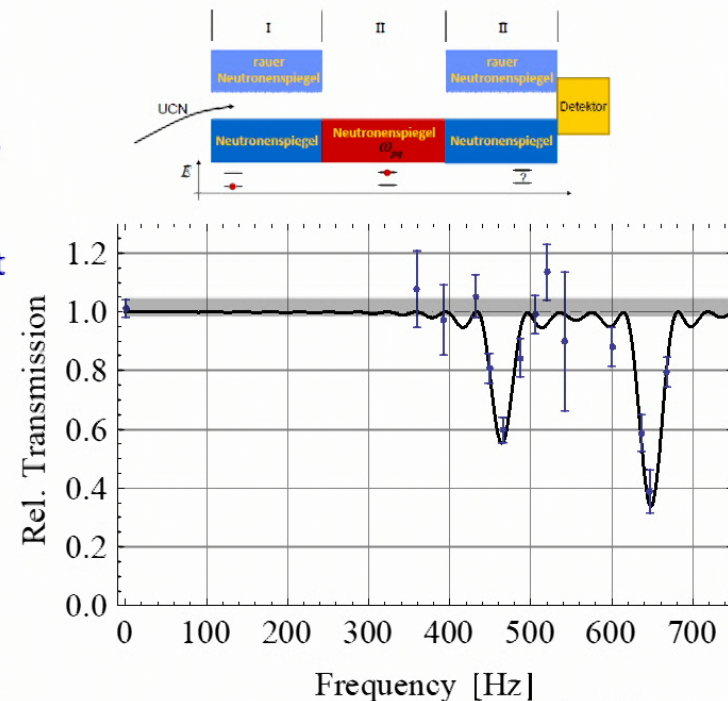
$$E = \frac{1}{2} N k_B T, \quad E = Mc^2, \quad A = 4\pi R^2$$

$$F = G \frac{Mm}{R^2}$$

*q*BOUNCE and decoherence-free entropic gravity

Problems:

- entropic forces are by nature too noisy and thus destroy quantum coherence
- it could be modeled as an environment in an open quantum system. Small objects must be very strongly coupled to the gravity environment.
- But the strong coupling must lead to ample wave function collapse and quantum decoherence.
- However, such decoherence is not observed in cold neutron experiments. Thus, entropic gravity cannot be true.



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

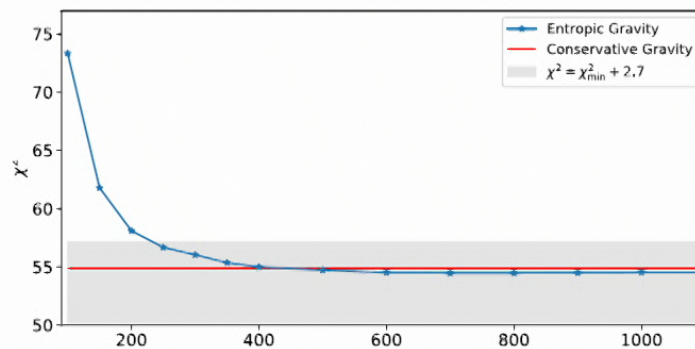
$$\nu_{14} = 648.24^{+1.46}_{-1.53} \text{ Hz}$$

*q*BOUNCE and decoherence-free entropic gravity

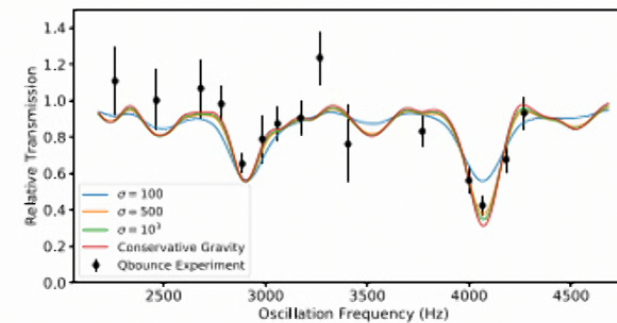
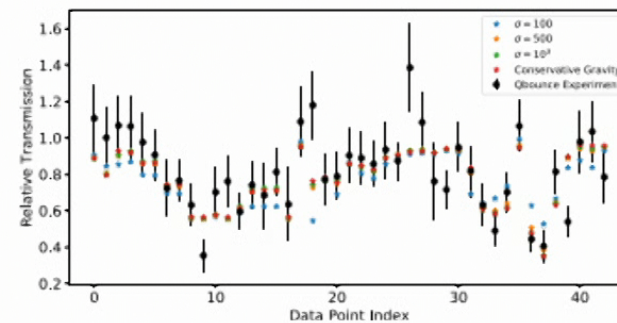
$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar} \left[\frac{\hat{p}^2}{2m}, \hat{\rho} \right] + \mathcal{D}(\hat{\rho}) \quad \mathcal{D}(\hat{\rho}) = \frac{mgx_0\sigma}{\hbar} \left\{ \exp\left(-\frac{i\hat{x}}{x_0\sigma}\right) \hat{\rho} \exp\left(+\frac{i\hat{x}}{x_0\sigma}\right) - \hat{\rho} \right\}$$

$$x_0 = \left(\frac{\hbar^2}{2m^2g} \right)^{1/3}$$

- D. Bondar suggested, arbitrarily low decoherence can be achieved by simply increasing the positive dimensionless coupling constant σ , which is a free parameter of this model. In the limit $\sigma \rightarrow \infty$, the model recovers Newtonian gravity as a potential force.



AJ Schimmoller, G McCaul, H Abele, DI Bondar, *Physical Review Research* 3, 033065 (2021)



qBOUNCE as a tool for probing of beyond-Riemann gravity

- Effective non-relativistic potential of beyond-Riemann gravity interactions
 - For the experimental analysis of the BRG and LV interactions by using the quantum gravitational states of UCNs Kostelecký and Li proposed

$$H = H_0 + \Phi_{RG} + \Phi_{BRG} = \frac{\vec{p}^2}{2m} - m\vec{g} \cdot \vec{z} + \Phi_{nRG} + \Phi_{nBRG},$$

$$\Phi_{nBRG} = H_\phi + H_{\sigma\phi} + H_g + H_{\sigma g},$$

where the operators H_j for $j = \phi, \sigma\phi, g$ and σg are equal to [6]

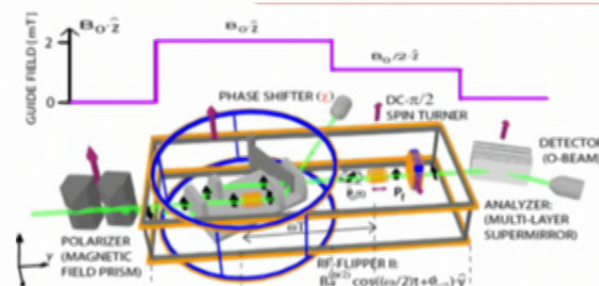
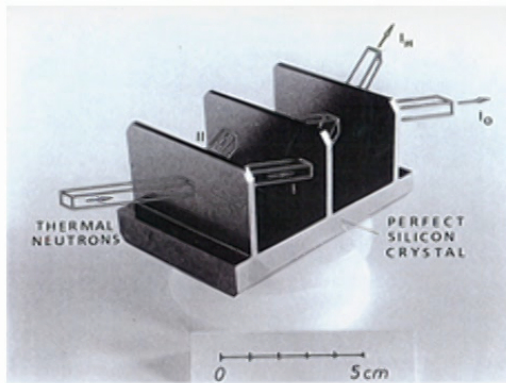
$$\begin{aligned} H_\phi &= (k_\phi^{NR})_n \vec{g} \cdot \vec{z} + (k_{\phi p}^{NR})_n^j \frac{1}{2} \left(p^j (\vec{g} \cdot \vec{z}) + (\vec{g} \cdot \vec{z}) p^j \right) + (k_{\phi pp}^{NR})_n^{jk} \frac{1}{2} \left(p^j p^k (\vec{g} \cdot \vec{z}) + (\vec{g} \cdot \vec{z}) p^j p^k \right), \\ H_{\sigma\phi} &= (k_{\sigma\phi}^{NR})_n^j \sigma^j (\vec{g} \cdot \vec{z}) + (k_{\sigma\phi p}^{NR})_n^{jk} \frac{1}{2} \sigma^j \left(p^k (\vec{g} \cdot \vec{z}) + (\vec{g} \cdot \vec{z}) p^k \right) + (k_{\sigma\phi pp}^{NR})_n^{jk\ell} \frac{1}{2} \sigma^j \left(p^k p^\ell (\vec{g} \cdot \vec{z}) + (\vec{g} \cdot \vec{z}) p^k p^\ell \right), \\ H_g &= (k_g^{NR})_n^j g^j + (k_{gp}^{NR})_n^{jk} p^j g^k + (k_{gpp}^{NR})_n^{jk\ell} p^j p^k g^\ell, \\ H_{\sigma g} &= (k_{\sigma g}^{NR})_n^{jk} \sigma^j g^k + (k_{\sigma gp}^{NR})_n^{jk\ell} \sigma^j p^k g^\ell + (k_{\sigma gpp}^{NR})_n^{jk\ell m} \sigma^j p^k p^\ell g^m. \end{aligned}$$

qBOUNCE as a tool for probing of beyond-Riemann gravity

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$$H = H_0 + \Phi_{RG} + \Phi_{BRG} = \frac{\vec{p}^2}{2m} - m\vec{g} \cdot \vec{z} + \Phi_{nRG} + \Phi_{nBRG},$$

$$\delta H = (k_{\phi}^{NR})_n \vec{g} \cdot \vec{z} + (k_{\sigma\phi}^{NR})_n^j \sigma^j \vec{g} \cdot \vec{z} + (k_{\sigma g}^{NR})_n^{jk} \sigma^j g^k$$



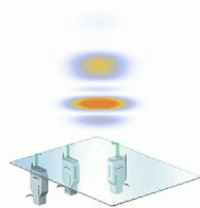
$$A_+ = \frac{1}{\sqrt{2}} (\langle +|_{z'} + \langle -|_{z'}) \cdot \frac{1}{\sqrt{2}} (e^{i\phi_+} |+\rangle_{z'} + e^{i\phi_-} |-\rangle_{z'})$$

$$\frac{g_n}{g} = 1 - \frac{(k_{\phi}^{NR})_n}{m_n} \quad (k_{\phi}^{NR})_n < 1 \times 10^{-2} \text{ GeV} \quad |(k_{\phi}^{NR})_n + (k_{\sigma\phi}^{NR})_n^j \hat{s}^j| < 2.5 \times 10^{-2} \text{ GeV}$$

qBOUNCE as a tool for probing of beyond-Riemann gravity

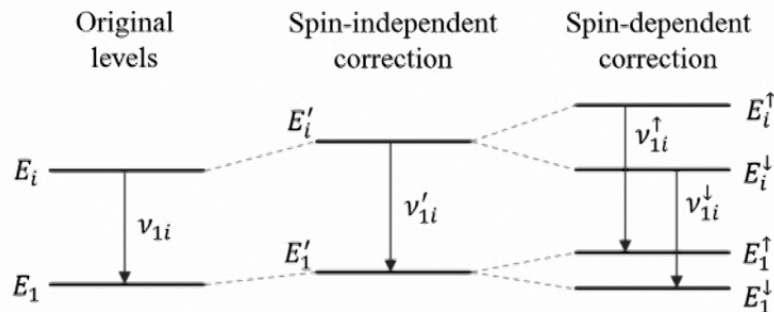
- Effective non-relativistic potential of beyond-Riemann gravity interactions
 - For the experimental analysis of the BRG and LV interactions by using the quantum gravitational states of UCNs Kostelecký and Li proposed

qBOUNCE + GRS



$$\frac{g_n}{g} = 1 - \frac{(k_\phi^{\text{NR}})_n}{m_n}$$

$$\delta H = (k_\phi^{\text{NR}})_n \vec{g} \cdot \vec{z} + (k_{\sigma\phi}^{\text{NR}})_n \sigma^j \vec{g} \cdot \vec{z} + (k_{\sigma g}^{\text{NR}})_n \sigma^j g^k$$



$$|(k_\phi^{\text{NR}})_n| < 10^{-3} \text{ GeV}$$

FIG. 1. Splitting of the neutron energy levels.

qBOUNCE and Lorentz Violation (LV), mgSME

- Lorentz violation must arise spontaneously in such a way that the LV coefficients are treated as dynamical fields that acquire nonzero vacuum expectation values.
- Schrödinger Equation

$$LV: -\frac{\hbar^2}{2m} \frac{d^2\psi}{dz^2} + mgz + V(LV\text{-terms}) = E\psi$$

$$S = S_{\text{EH}} + S_{\text{LV}} + S_{\psi}.$$

Gravitational Searches for Lorentz Violation with Ultracold Neutrons

C. A. Escobar^{1,*} and A. Martín-Ruiz^{2,3,†}

$$H_{\text{NR}} = \frac{1}{2}mc^2 h_{00} - h_{0k} p^k c - \frac{1}{4m} h_{00} p^2 - \frac{1}{2m} h_{jk} p^j p^k.$$

$$V_1 = \frac{1}{2}mc^2 h_{00},$$

$$V_2 = -c \left(h_{0k} \hat{p}^k + \frac{1}{2} h_{0k,k} \right),$$

$$V_3 = -\frac{1}{4m} \left(h_{00} \delta_{ij} \hat{p}^i \hat{p}^j + h_{00,i} \hat{p}^i + \frac{1}{4} h_{00,ii} \right),$$

$$V_4 = -\frac{1}{2m} \left(h_{jk} \hat{p}^j \hat{p}^k + h_{jk,j} \hat{p}^k + \frac{1}{4} h_{jk,jk} \right),$$

$$S_{\text{LV}} = \frac{1}{2\kappa} \int e \left(-uR + s^{\mu\nu} R_{\mu\nu}^T + t^{\mu\nu\alpha\beta} C_{\mu\nu\alpha\beta} \right) d^4x,$$

$$c_{\mu\nu}^n = \bar{c}_{\mu\nu}^n + \tilde{c}_{\mu\nu}^n \text{ and } s_{\mu\nu} = \bar{s}_{\mu\nu} + \tilde{s}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

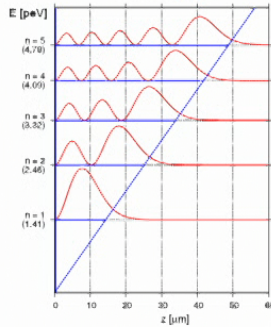
AN Ivanov, M Wellenzohn, H Abele,
Phys. Lett. B, Physics Letters B 797, 134819 (2019)

*q*BOUNCE and Lorentz Violation (LV), mgSME

● Ivanov

$$i\frac{\partial\psi}{\partial t} = H\psi, \quad H = -\frac{1}{2m}\Delta + mgz + \Phi_{\text{nLV}}.$$

$$\delta\nu_{pq} = \frac{1}{2\pi\hbar} \int_0^\infty dz \left(\psi_p^\dagger(z) \Phi_{\text{nLV}} \psi_p(z) - \psi_q^\dagger(z) \Phi_{\text{nLV}} \psi_q(z) \right) \text{ Hz},$$



$$S = S_{\text{EH}} + S_{\text{LV}} + S_\psi.$$

$$S_{\text{LV}} = \frac{1}{2\kappa} \int e \left(-uR + s^{\mu\nu} R_{\mu\nu}^T + t^{\mu\nu\alpha\beta} C_{\mu\nu\alpha\beta} \right) d^4x,$$

$$c_{\mu\nu}^n = \bar{c}_{\mu\nu}^n + \tilde{c}_{\mu\nu}^n \text{ and } s_{\mu\nu} = \bar{s}_{\mu\nu} + \tilde{s}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

$$|2\bar{c}_{zz}^n + \bar{c}_{00}^n| < 2.2 \times 10^{-3}.$$

transitions $|q \uparrow\rangle \rightarrow |p \uparrow\rangle$ or $|q \downarrow\rangle \rightarrow |p \downarrow\rangle$

$$\delta\nu_{pq} = \left\{ (2\bar{c}_{zz} + \bar{c}_{00}) - [(4\bar{d}_{0z} + 2\bar{d}_{z0} - \varepsilon_{zmn}\bar{g}_{mn0})\delta_{z\ell} + \varepsilon_{lmn}\bar{g}_{mn0} - 2\varepsilon_{z\ell m}(\bar{g}_{m0z} + \bar{g}_{mz0})] \langle S_\ell \rangle \right\} \frac{E_p - E_q}{6\pi} \text{ Hz},$$

$$\delta\nu_{31} = (2\bar{c}_{zz}^n + \bar{c}_{00}^n) \frac{E_3 - E_1}{6\pi\hbar} \text{ Hz} = 154.341 (2\bar{c}_{zz}^n + \bar{c}_{00}^n) \text{ Hz},$$

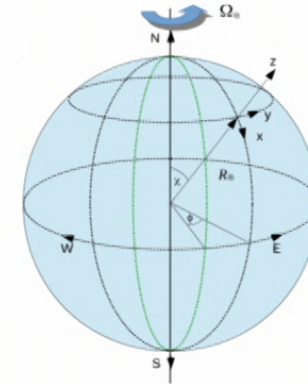
$$\delta\nu_{41} = (2\bar{c}_{zz}^n + \bar{c}_{00}^n) \frac{E_4 - E_1}{6\pi\hbar} \text{ Hz} = 215.747 (2\bar{c}_{zz}^n + \bar{c}_{00}^n) \text{ Hz},$$

- For the 2019 sensitivity of qBounce we get

$$|5 m \bar{c}_{ZZ}^n + \sin \chi m (\bar{g}_{X0Y}^n - \bar{g}_{Y0X}^n) \langle S_x \rangle| < 2.1 \times 10^{-3} \text{ GeV},$$

$$|5 m \bar{c}_{ZZ}^n + \sin \chi \cos \chi \bar{g}_Q^n \langle S_y \rangle| < 2.1 \times 10^{-3} \text{ GeV},$$

$$|5 m \bar{c}_{ZZ}^n - \cos \chi (4 \tilde{d}_Z^n + 2 \bar{H}_{XY}^n) \langle S_z \rangle| < 2.1 \times 10^{-3} \text{ GeV}.$$



- With $|\bar{c}_{ZZ}^n| < 4.4 \times 10^{-4}$ we get

$$|\bar{g}_{X0Y}^n - \bar{g}_{Y0X}^n| < 10^{-4},$$

$$|\bar{g}_Q| < 1.3 \times 10^{-4} \text{ GeV},$$

$$|\tilde{d}_Z^n + \frac{1}{2} \bar{H}_{XY}^n| < 2.3 \times 10^{-5} \text{ GeV},$$

- Neutron Sector:

Combination	Result
$ \bar{c}_{ZZ}^n $	$< 4.4 \times 10^{-4}$
$ \bar{c}_{XX}^n $	$< 2.2 \times 10^{-4}$
$ \bar{c}_{ZZ}^n $	$< 2.2 \times 10^{-4}$
$ \bar{g}_{X0Y}^n - \bar{g}_{Y0X}^n $	$< 10^{-4}$
$ \bar{g}_Q $	$< 1.3 \times 10^{-4} \text{ GeV}$
$ \tilde{d}_Z^n + \frac{1}{2} \bar{H}_{XY}^n $	$< 2.3 \times 10^{-5} \text{ GeV}$
$ \bar{b}_Z^n $	$< 1.4 \times 10^{-24} \text{ GeV}$

Motivation for high precision tests with neutrons: extreme sensitivity or precision

● Energy $\Delta E = 10^{-21}$ eV

- Search for an electric dipole moment, neutron
- $d_n < 3 \times 10^{-26}$ ecm
- Ramsey's Spectroscopy Method of Separated Oscillating Field by NMR

● Energy $\Delta E = 1 \times 10^{-16}$ eV

- Ramsey's Spectroscopy Method of Separated Oscillating Field by GRS
- (Jenke, Rechberger, Bosinar, Micko, Sedmik, HA)

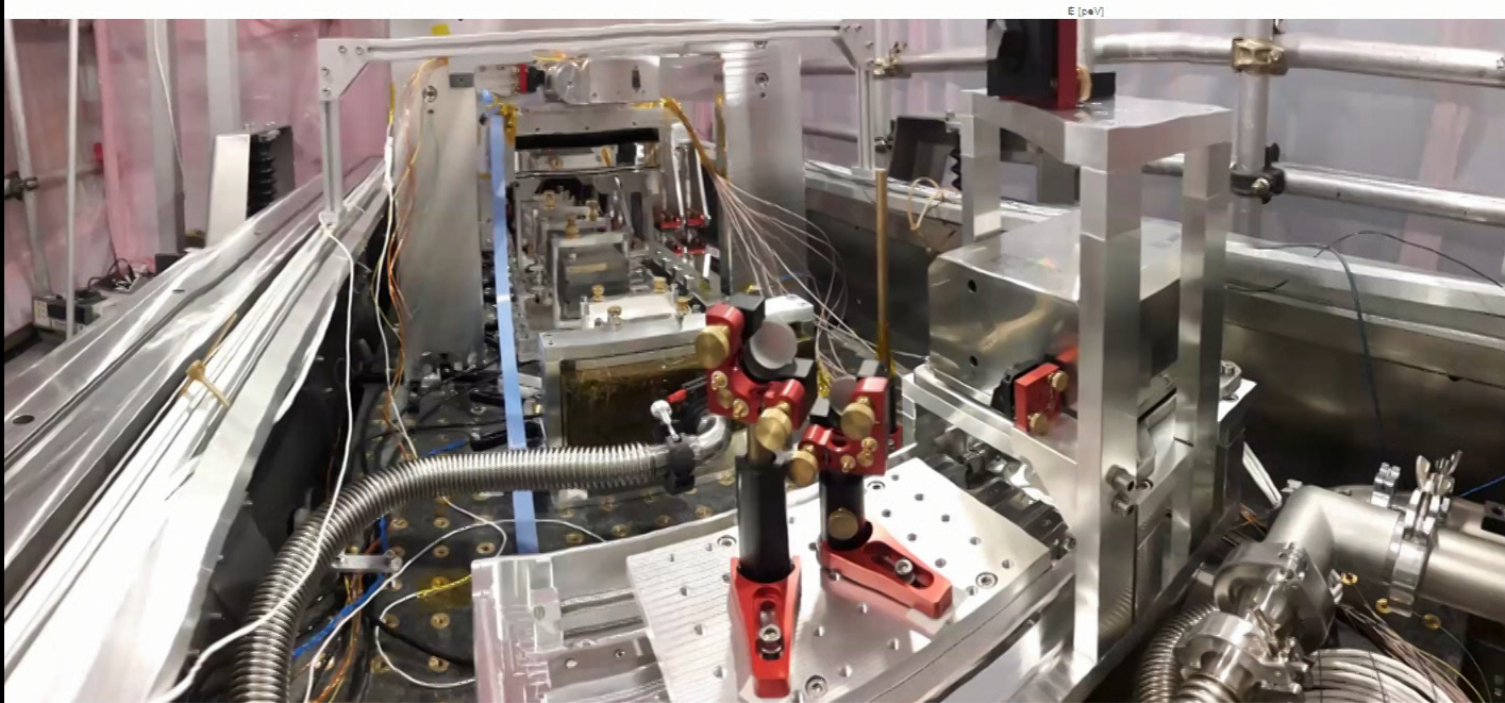
● Energy $\Delta E = 4 \times 10^{-18}$ eV, ACME

- Search for an electric dipole moment, electron
- ThO, $d_e < 9 \times 10^{-29}$ ecm
- YbF, talk B. Sauer

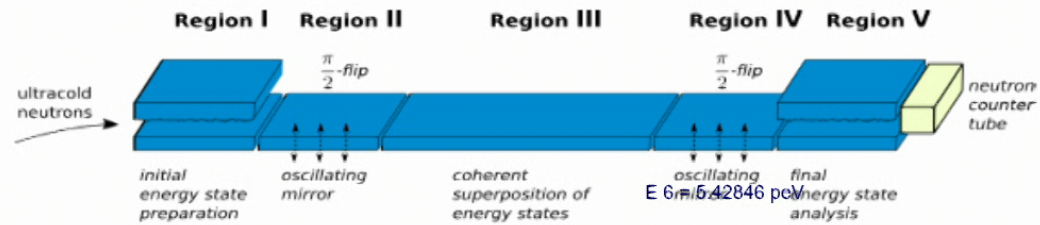
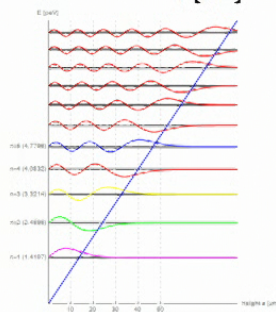
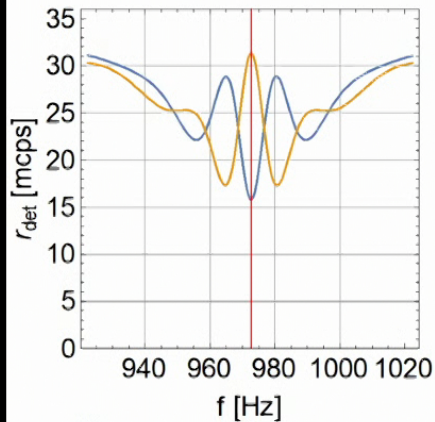
● Energy $\Delta E = 2 \times 10^{-15}$ eV

- Rabi's Spectroscopy Method by GRS

Jakob Micko + Tobias Jenke: experiments in 2020/21



Jakob Micko: first Results, Transition $1 \rightarrow 6$ @ 972 Hz

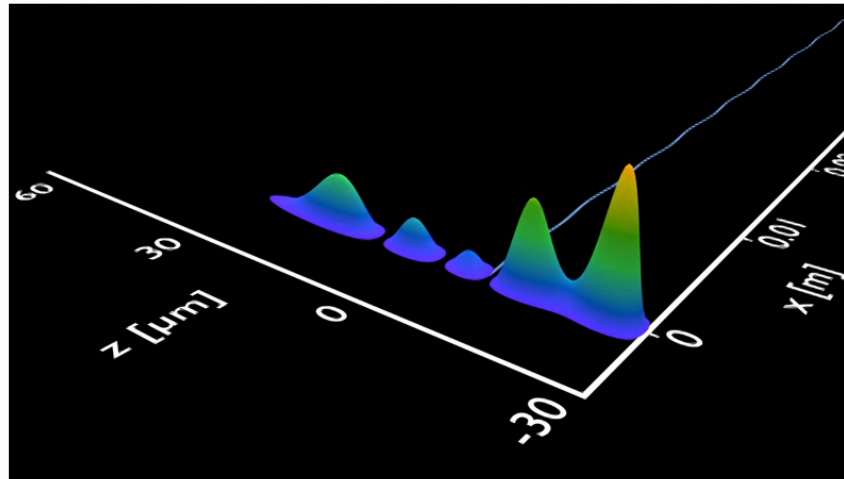
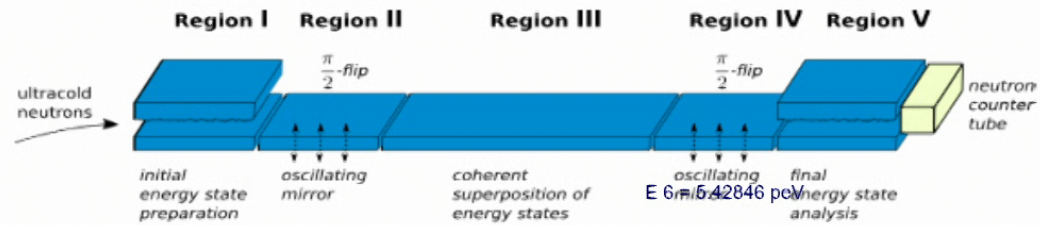
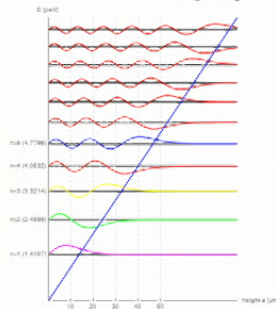
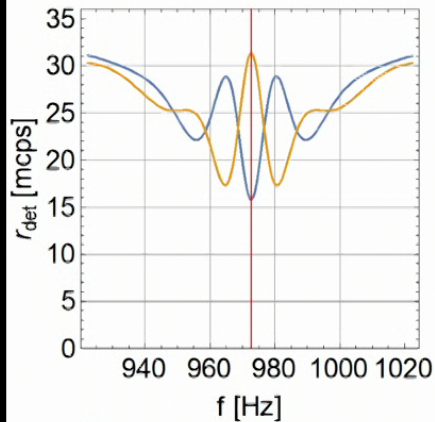


- Measure in phase (blue)
- Measure out of phase (yellow)
- Measure, where gradient is largest

Reflect on all surfaces

- velocities in range [4;11] m/s (2021)
- Neutron mirror pseudo potential: 100 neV
- Length of setup 0.948 m
- Distance between mirrors $\approx 30 \mu\text{m}$
- Steps in height between mirrors $< 0.5 \mu\text{m}$
- Typical count rates (no oscillation): $r \approx 20 \text{ mcps}$
- Alignment relative to g: $10 \mu\text{rad}$

Jakob Micko: first Results, Transition $1 \rightarrow 6$ @ 972 Hz



Reflect on all surfaces

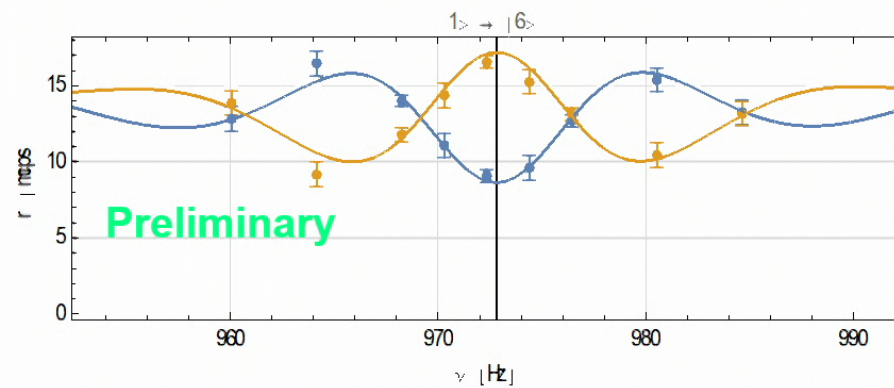
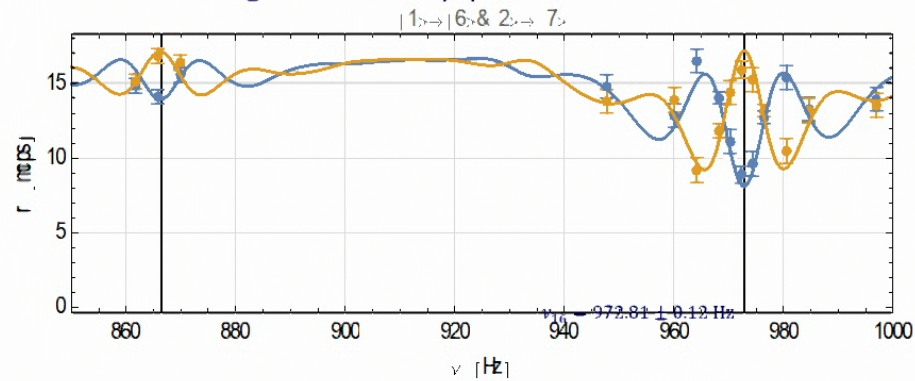
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- Measure, where gradient is largest

Movie: R. Neubacher

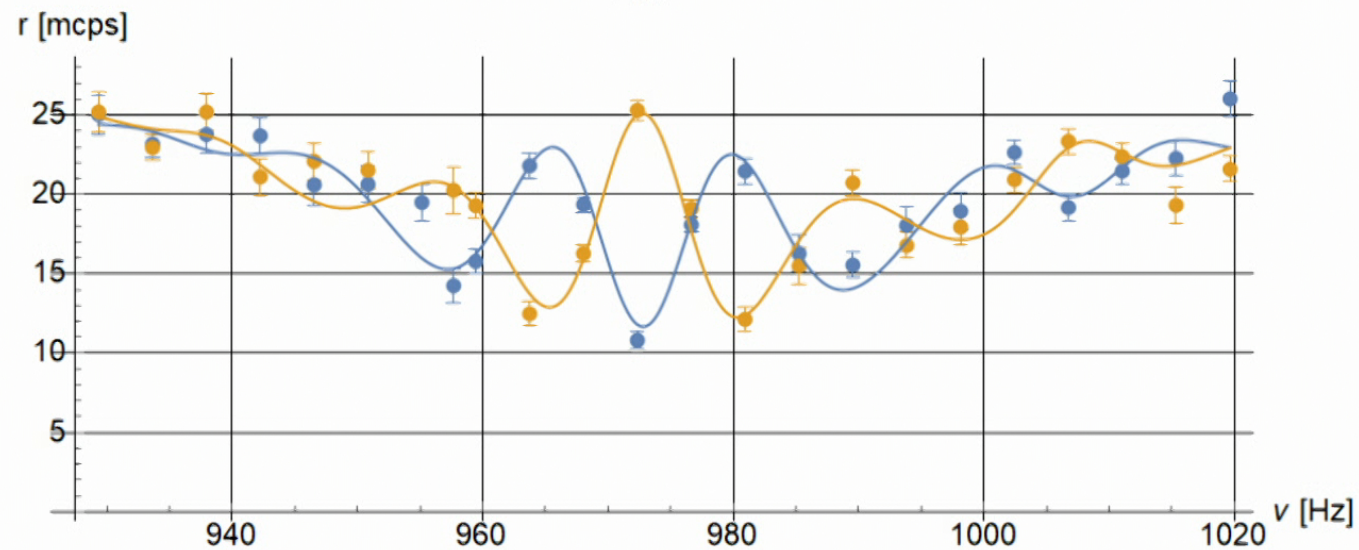
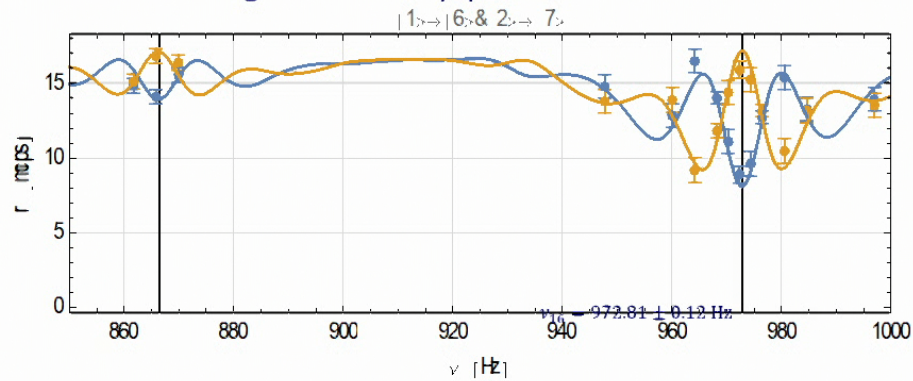
J. Micko: Cycle 2 in 2021@ILL:

- Frequency sweep with π phase
- Highest sensitivity: points measured at



J. Micko: Cycle 2 in 2021@ILL:

- Frequency sweep with π phase
- Highest sensitivity: points measured at



More effects?

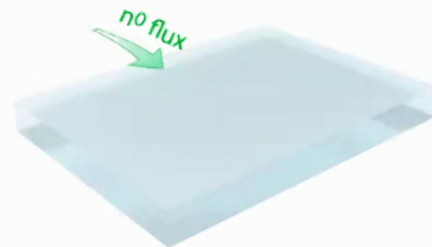
- Misalignment? g decreases
- Coriolis/Sagnac are small
- Steps between regions? Lowers contrast, induces spectator shift small for $|1\rangle \rightarrow |6\rangle$
- Tidal forces? $\frac{\delta g}{g} \approx 10^{-6}$
- Time base off? Using Rb clock since 2020 (cross referenced with second clock referenced to GPS, agree to $< 10^{-10}$)
- Magnetic field gradient? Measured in situ and would eliminate resonance curve
- Finite mirror potential? $l \approx 0.4 \text{ nm}, \Delta E_{ij} < 1 \text{ aeV}$
- Stat. Energy Sensitivity $\Delta E = 10^{-16} \text{ eV}$



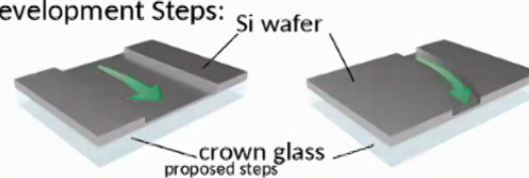
René Sedmik: Storage Solution

Ramsey GRS Outlook

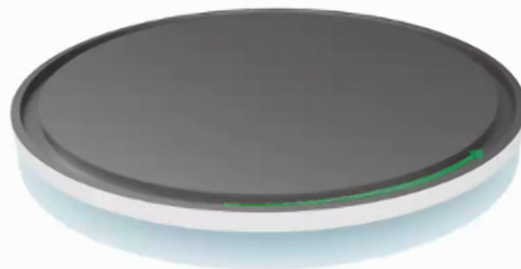
current setup



Development Steps:



Future storage setup:



$\tau \approx 70 \text{ ms}$



$\tau \approx 700 \text{ s}$

Hypothetical improvement
in sensitivity: **10⁴**

Measurement options:
(spin-polarized or not)

$g_S^2, g_{SP}^2, g_P^2, g_V^2, g_A^2, g_T^2$
 $g, e_n + \text{WEP}$

$\bar{c}_{JJ}^n, \bar{g}_{XTY}^n - \bar{g}_{YTX}^n,$
 $\tilde{g}_Q^n, \tilde{d}_Z^n, (k_\phi^{\text{NR}})_n, |(k_{\sigma\phi}^{\text{NR}})_n^J|$

qBounce Collaboration /Support

● TU Wien Experiment

- René Sedmik
- Joachim Bosina
- Jakob Micko
- Joachim Bosina, Atominstitut TU Wien
- Sandeep Suresh Cranganore
- HA

● ILL Grenoble

- Tobias Jenke
- Stephanie Rocchia
- Thomas Brenner

● Tulane University

- Denys Bondar
- Alex Schimmoller
- Gerald McCaul

● TU Wien Theory

- Mario Pitschmann
- Andrey Ivanov
- Manfred Faber
- Martin Suda
- Christian Käding
- Ben Koch

● TU Wien

- Ivica Galic
- Roman Gergen

● Nagoya University, KEK

- Naoto Muto
- Hirohiko M. Shimizu
- Shinsuke Kawasaki et al.

● TU Munich / U Heidelberg

- Peter Fierlinger
- Ulrich Schmidt
- Torsten Lauer