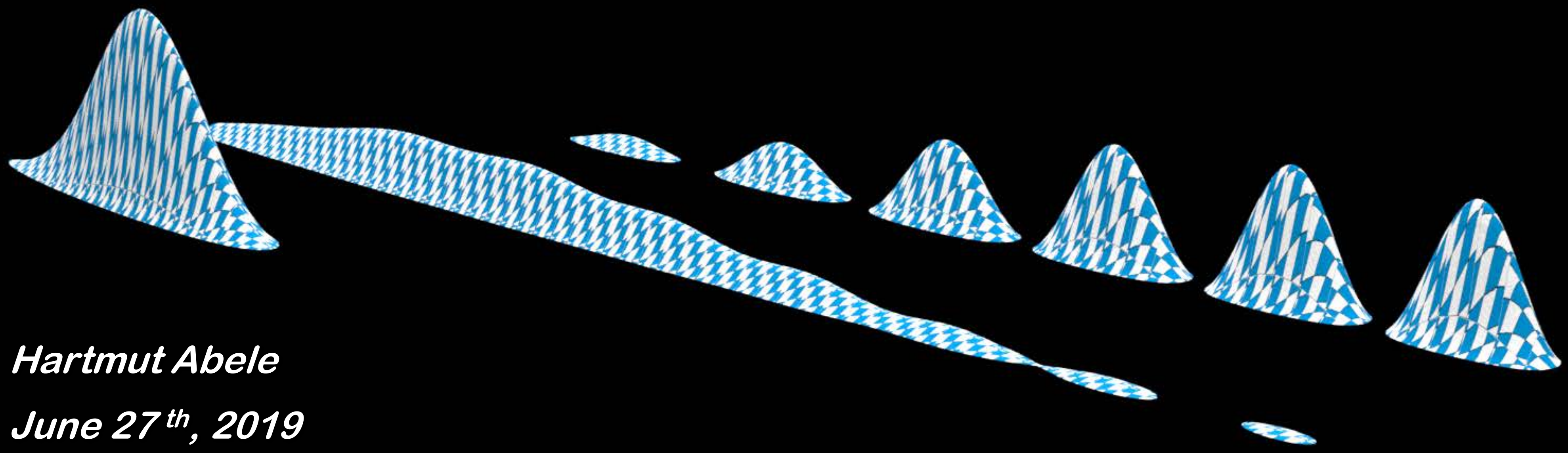
GRAVITY RESONANCE SPECTROSCOPY WITH NEUTRONS AND THE DARK SECTOR

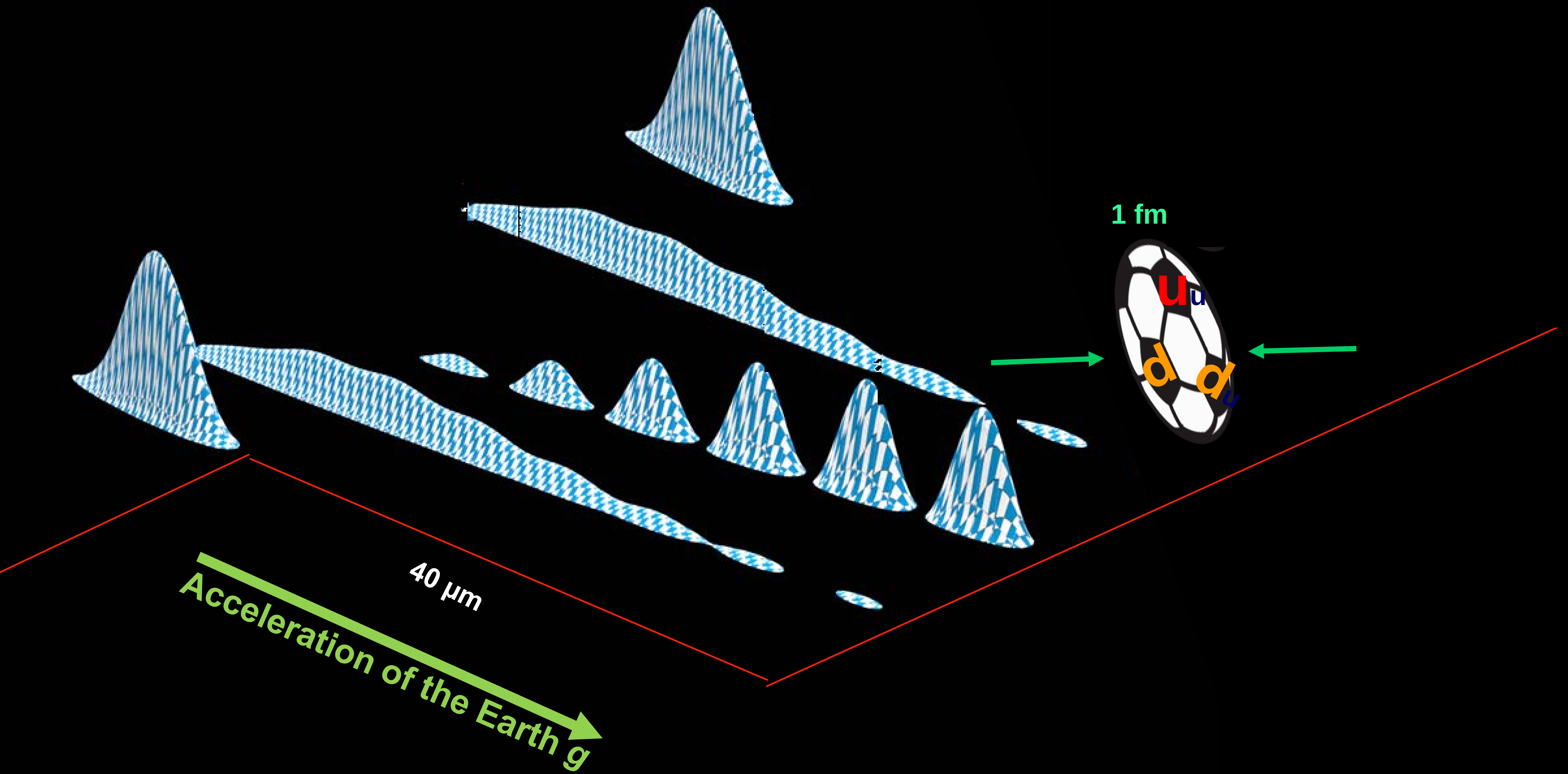
THE QUANTUM BOUNCE WITH NEUTRONS



Hartmut Abele

June 27th, 2019

Workshop on Matter wave interference


1 fm
u
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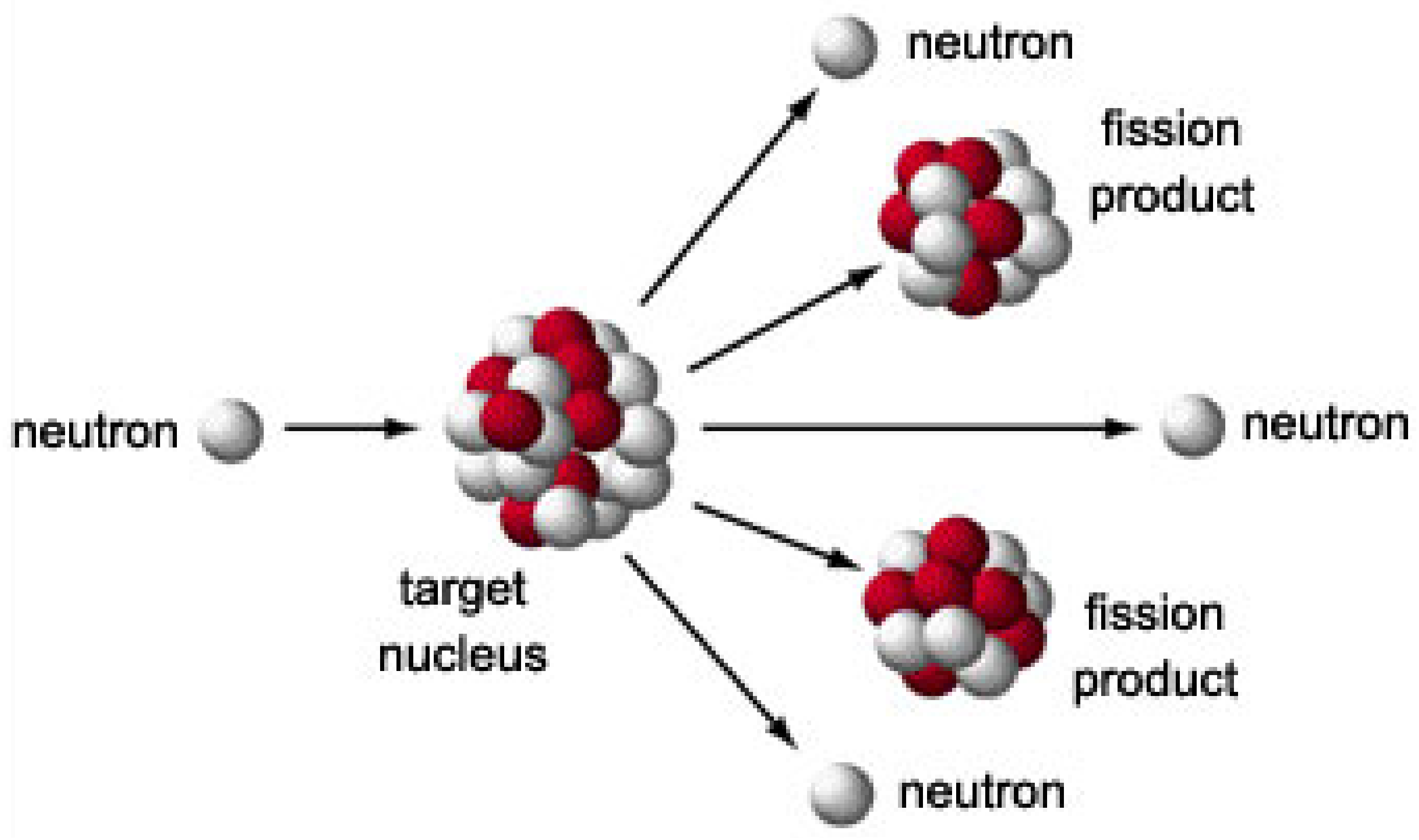
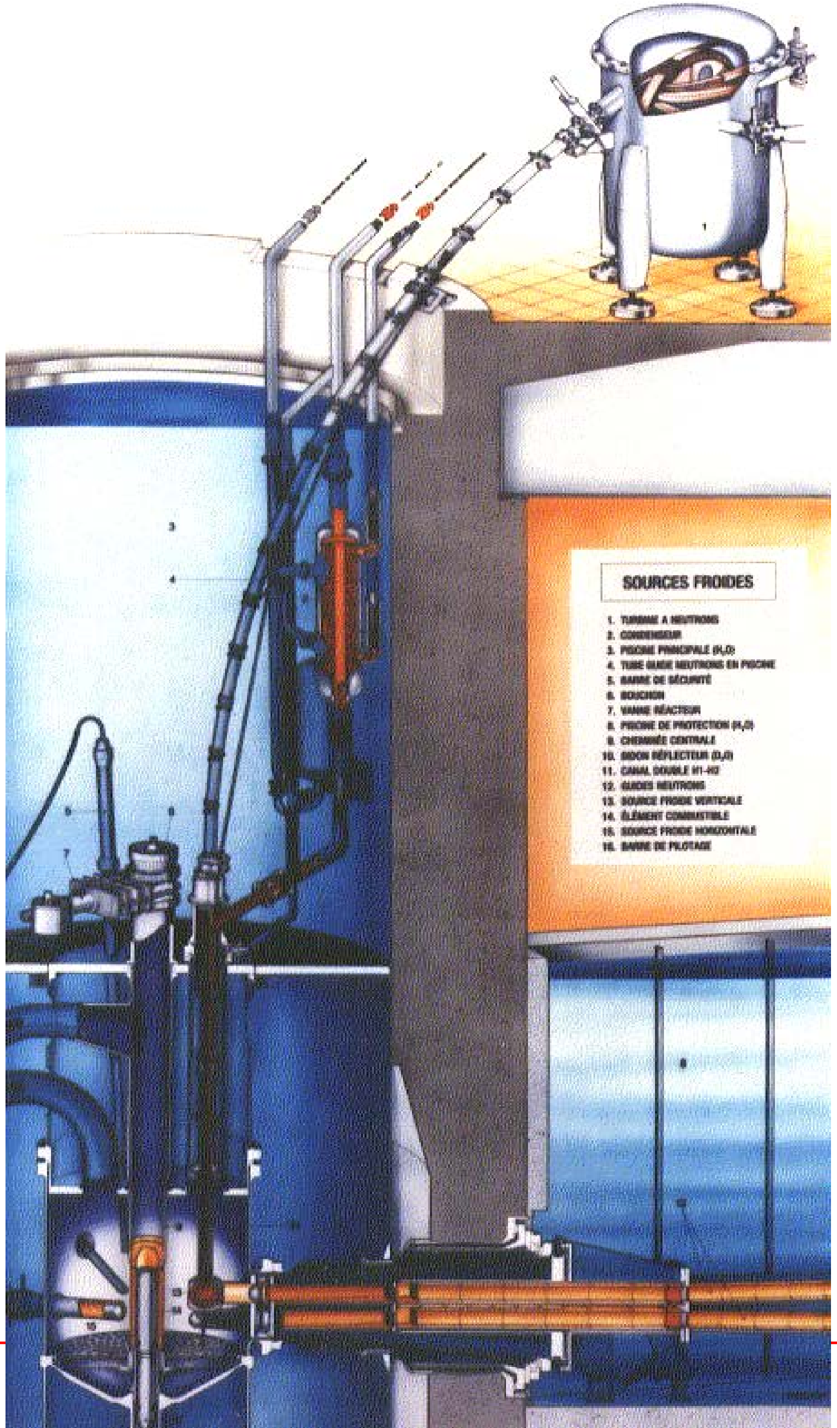
40 µm
Acceleration of the Earth g

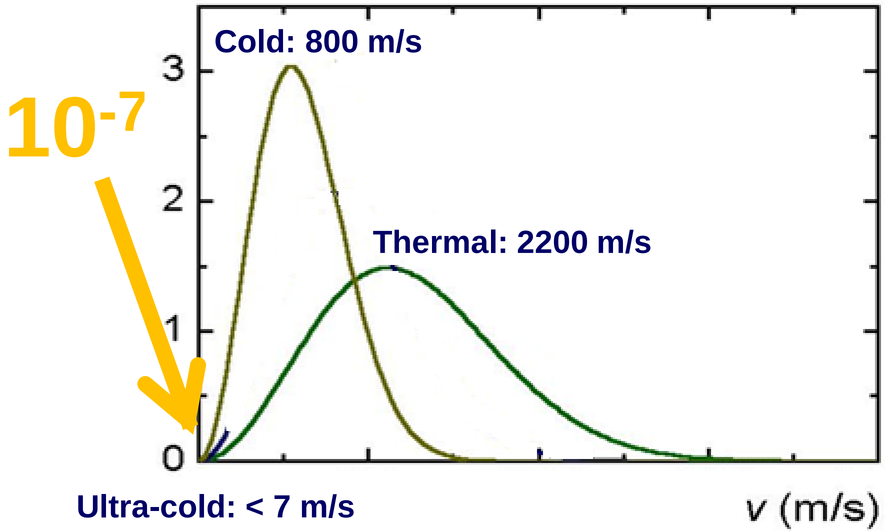
Institut Laue – Langevin
European Neutron Souce

Neutron Production in Research Reactor

- **about 3 neutrons per fission**

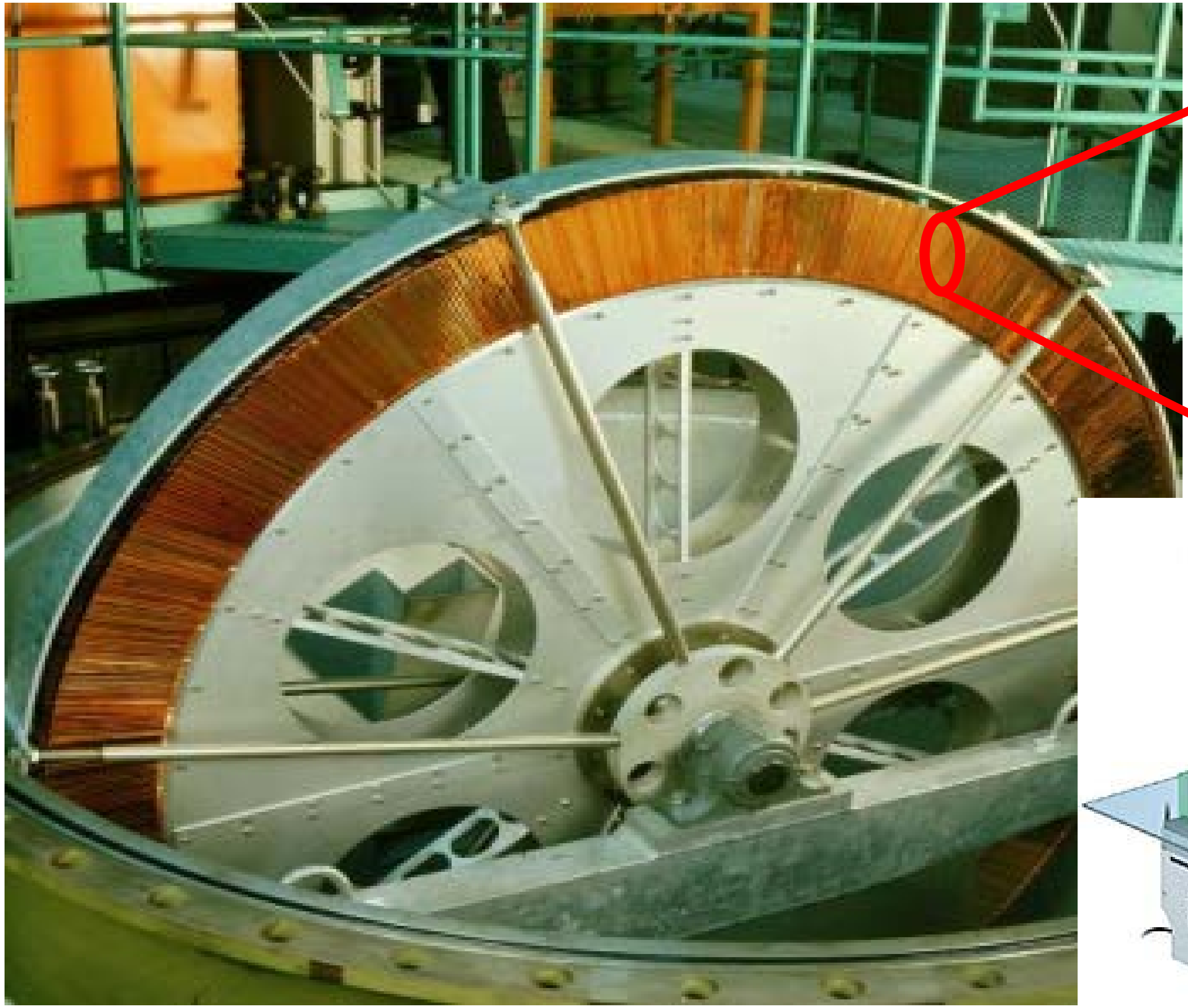


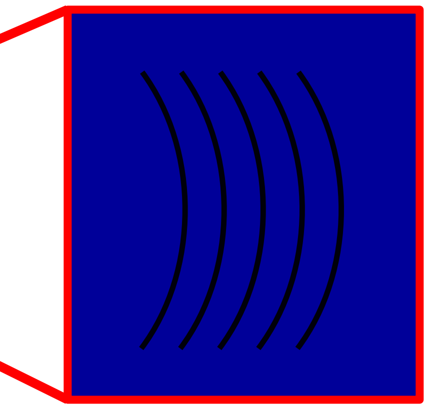


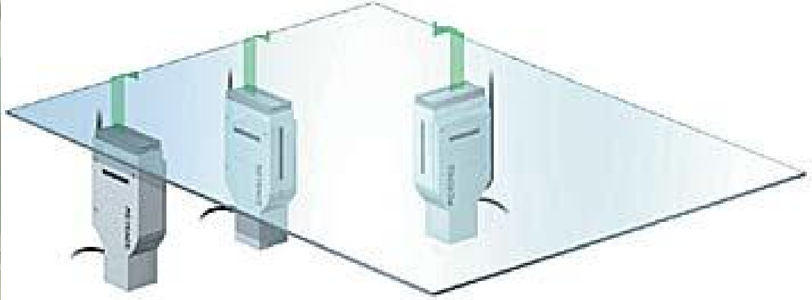


- **Fission Neutrons: 2 MeV**
- **Thermal Neutrons: 25 meV**
- **Cold Source: 4 meV**
- **Ultra-cold Neutrons: 100 neV**
- **Gravity experiment: 2 peV**

Neutrons and Turbine





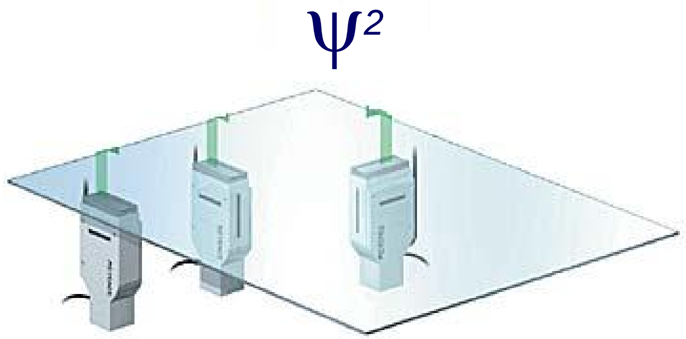


qBOUNCE: Quantum States in the Gravity Potential

- 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

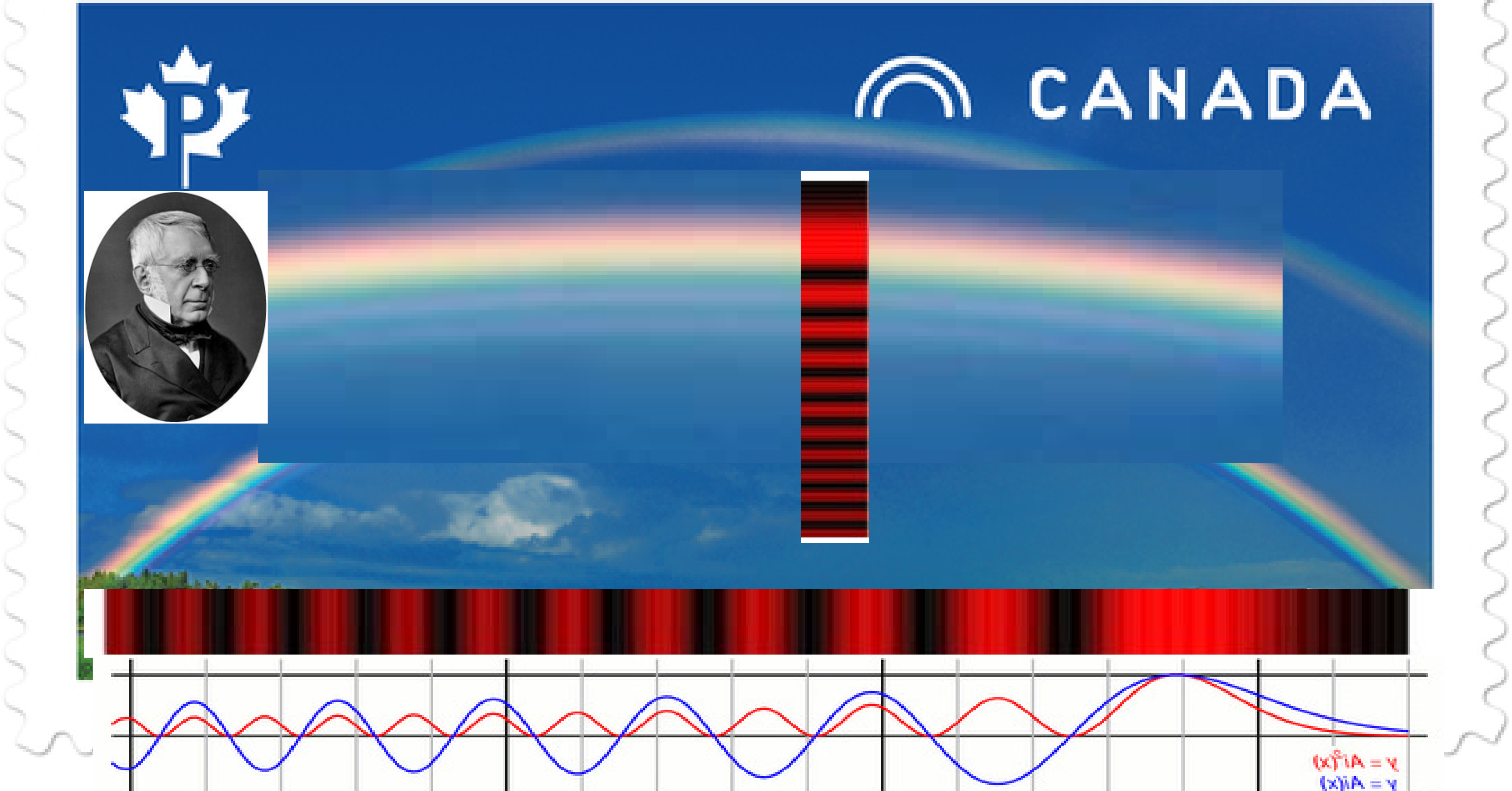
$$z_0 = -\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} = 5.87\,\mu\text{m} \qquad E_0 = -\left(\frac{\hbar^2 m_g{}^2 g^2}{2m_i}\right)^{1/3} = 0.602\text{peV}$$

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

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

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

The Airy – Funktion:

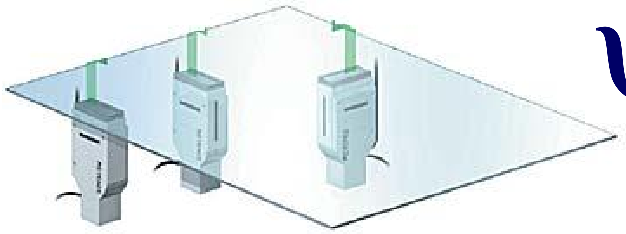


*q*BOUNCE: Quantum States in the Gravity Potential

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

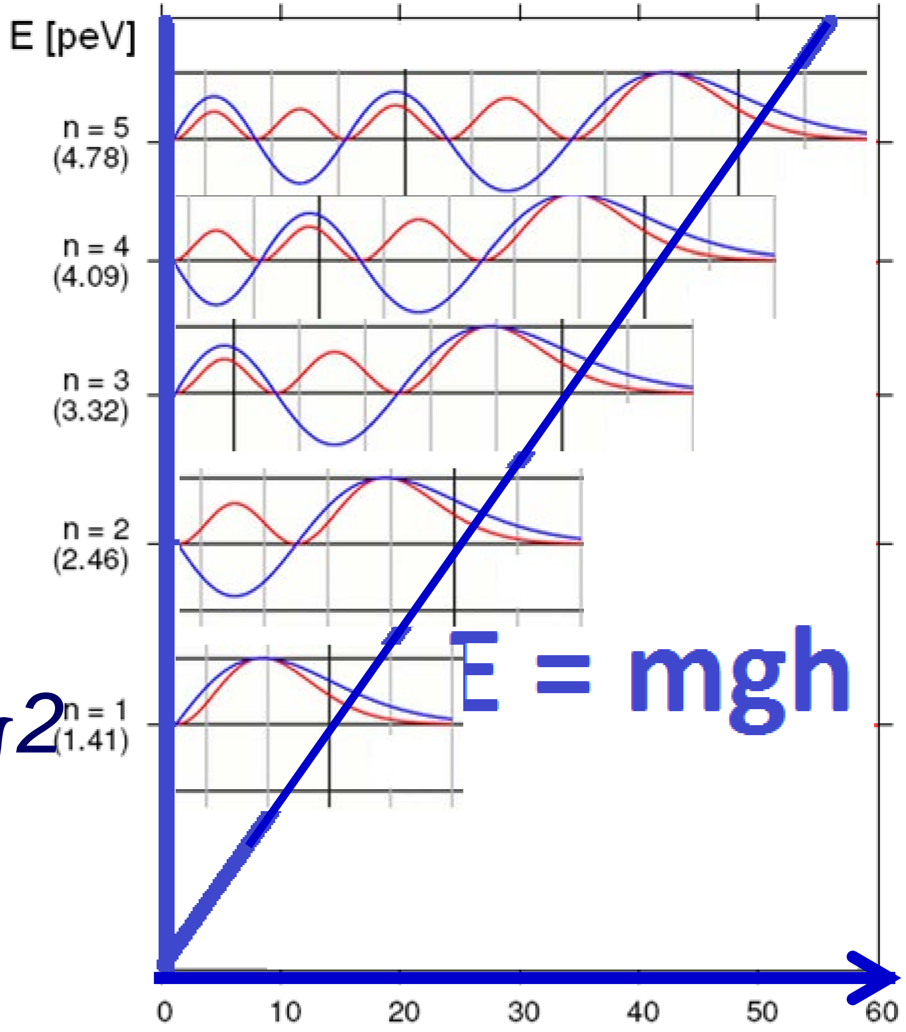
$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z),$$

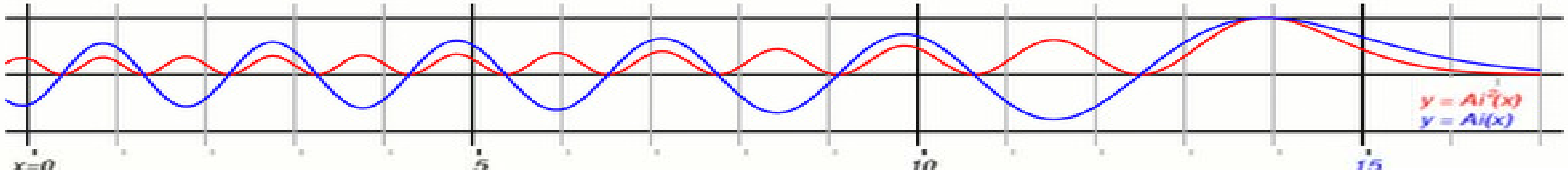
$z_0 =$ $1/3$ μm



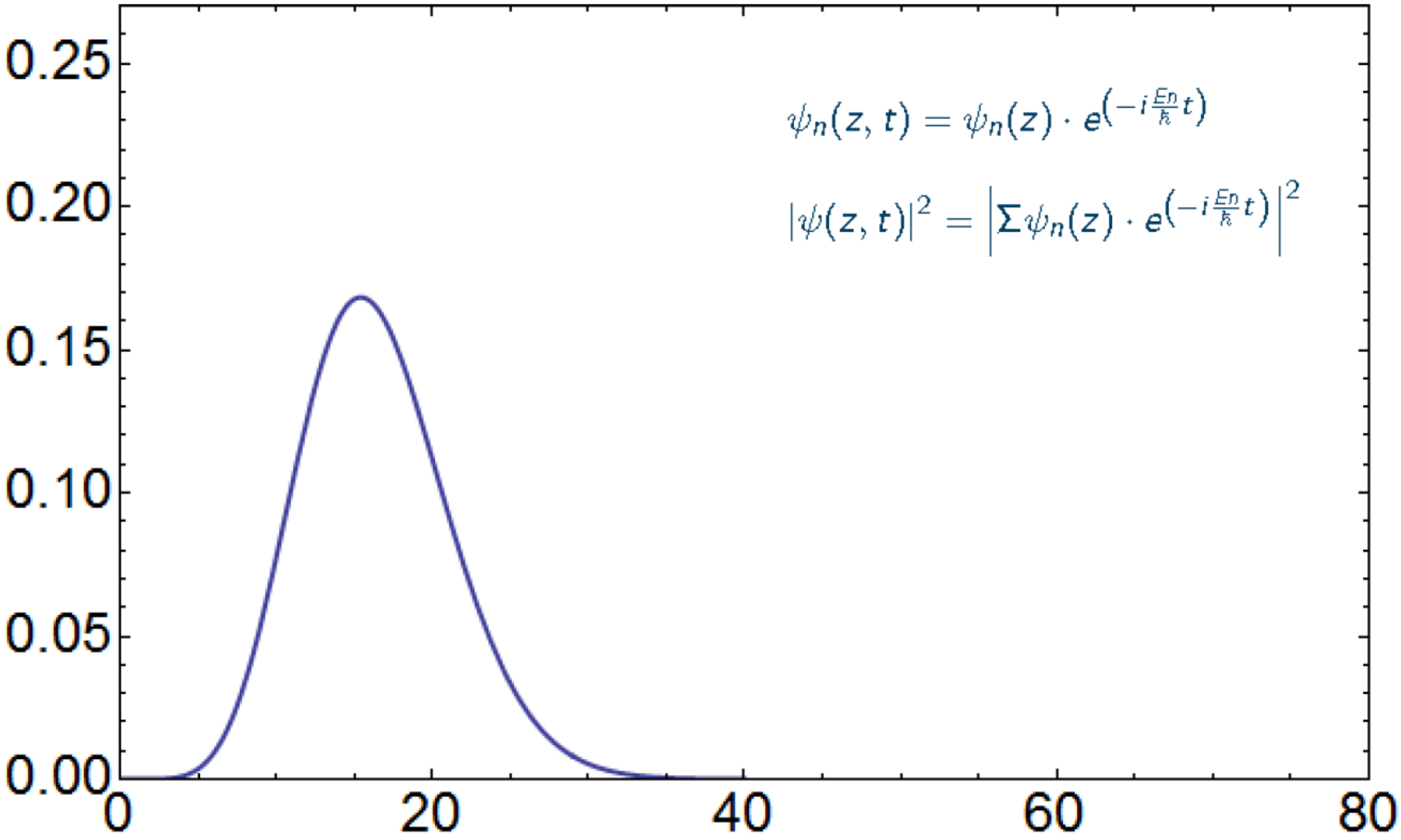
E_0 2peV

ψ, ψ^2

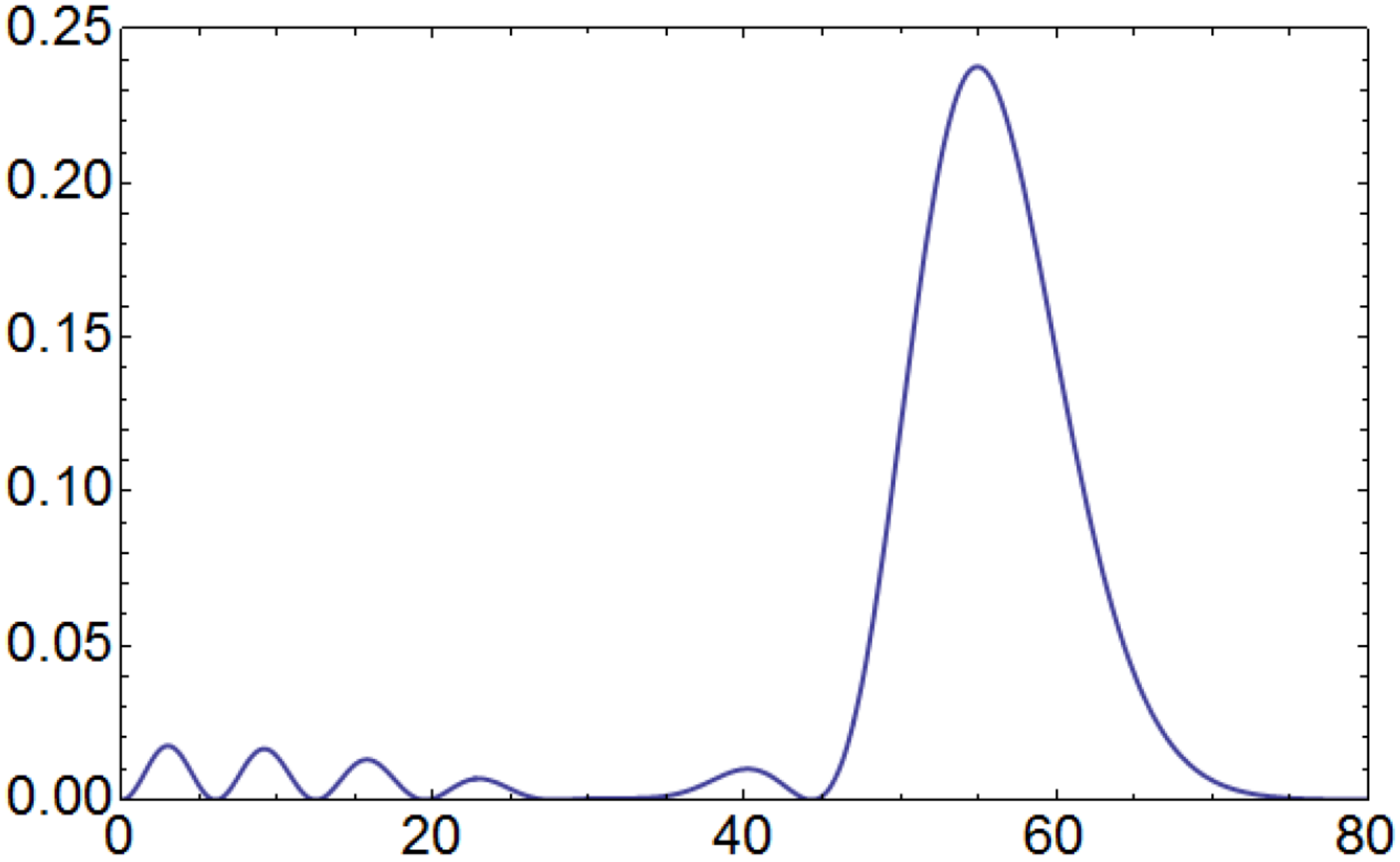




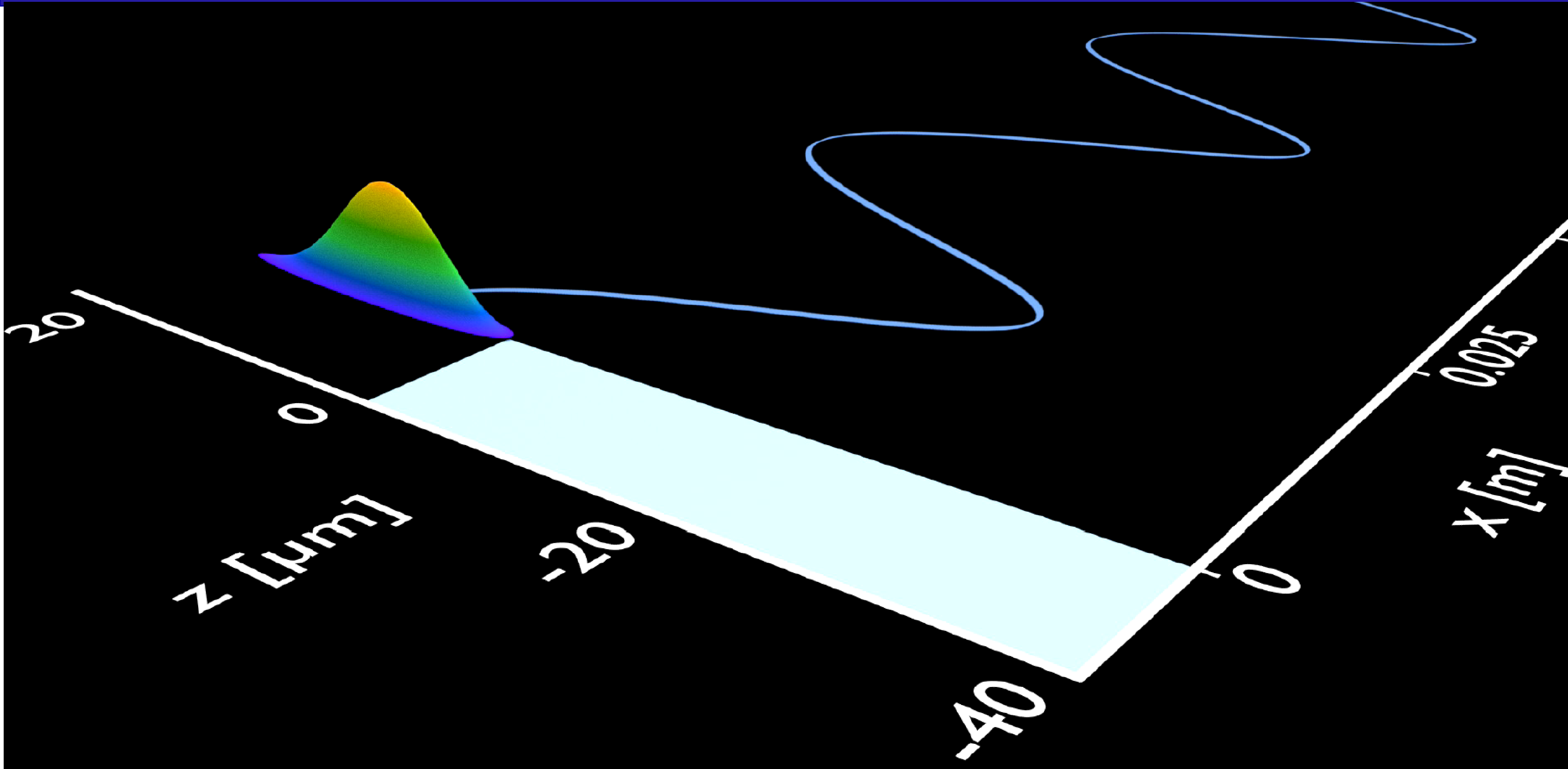
Quantum Interference State 1 & State 2



Quantum Interference State 6, 7 & State 8

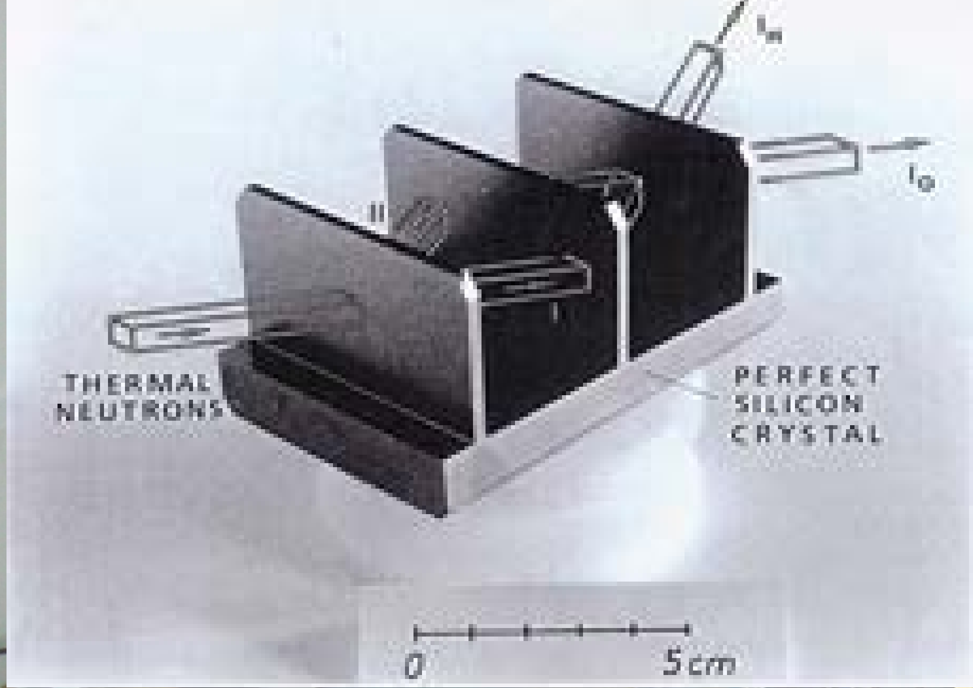


*q*BOUNCE



Martin Thalhammer, Technische Universität Wien

H. Rauch et al., 1974
Quantum Interference as Precision Tool



Study of basic Laws:
4 π Rotation of Spin ½

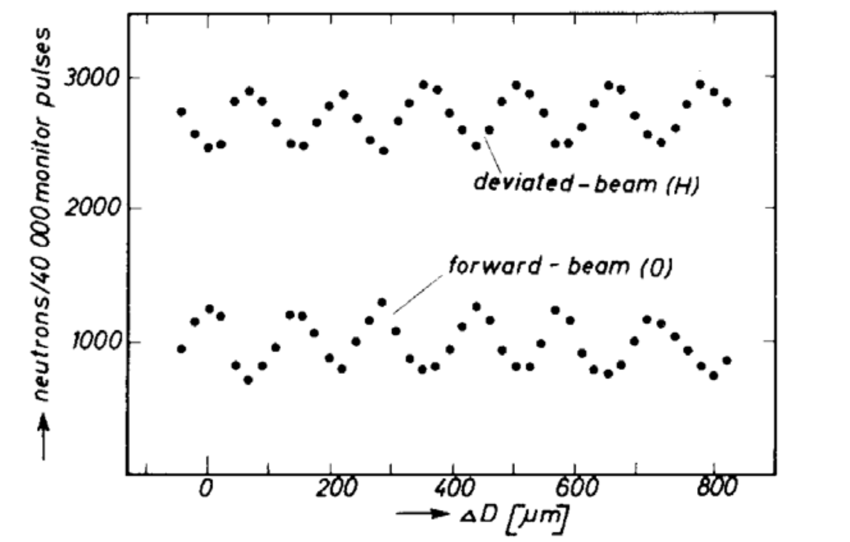
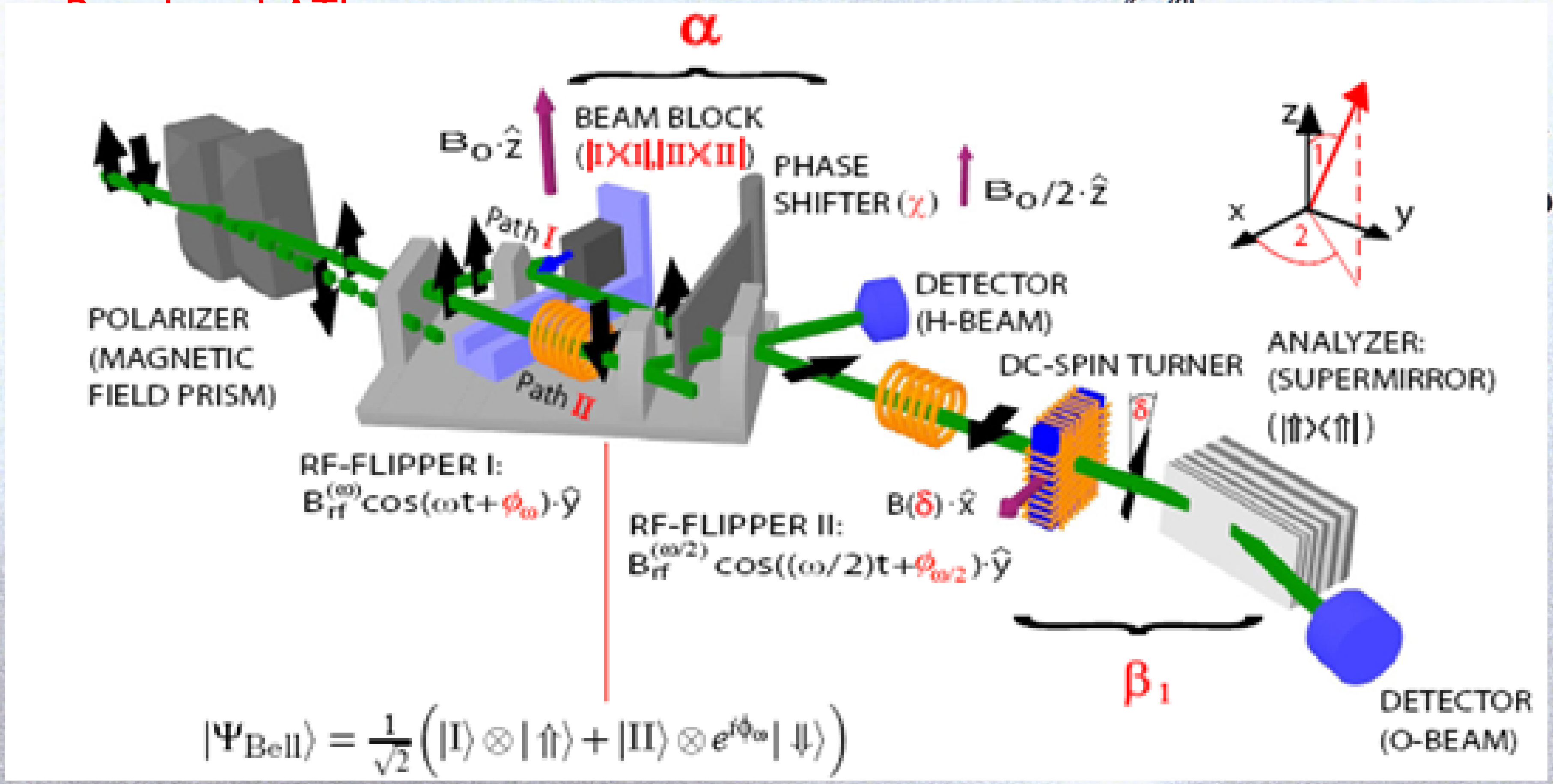


Fig. 2. Measured intensity modulation of the deviated and forward beam as a function of the different optical paths for beam I and II within an Al-sheet. (The statistical error is smaller than the size of the points.)

Atominstitut as EPS Historic Site, May 2019

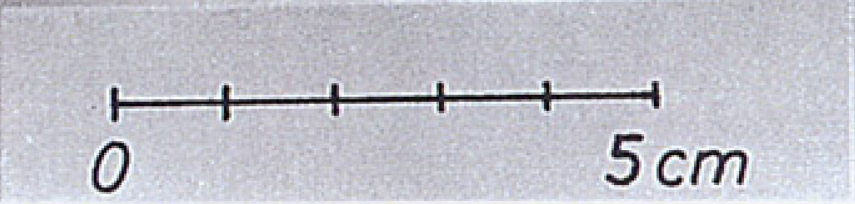
Neutron Interferometer

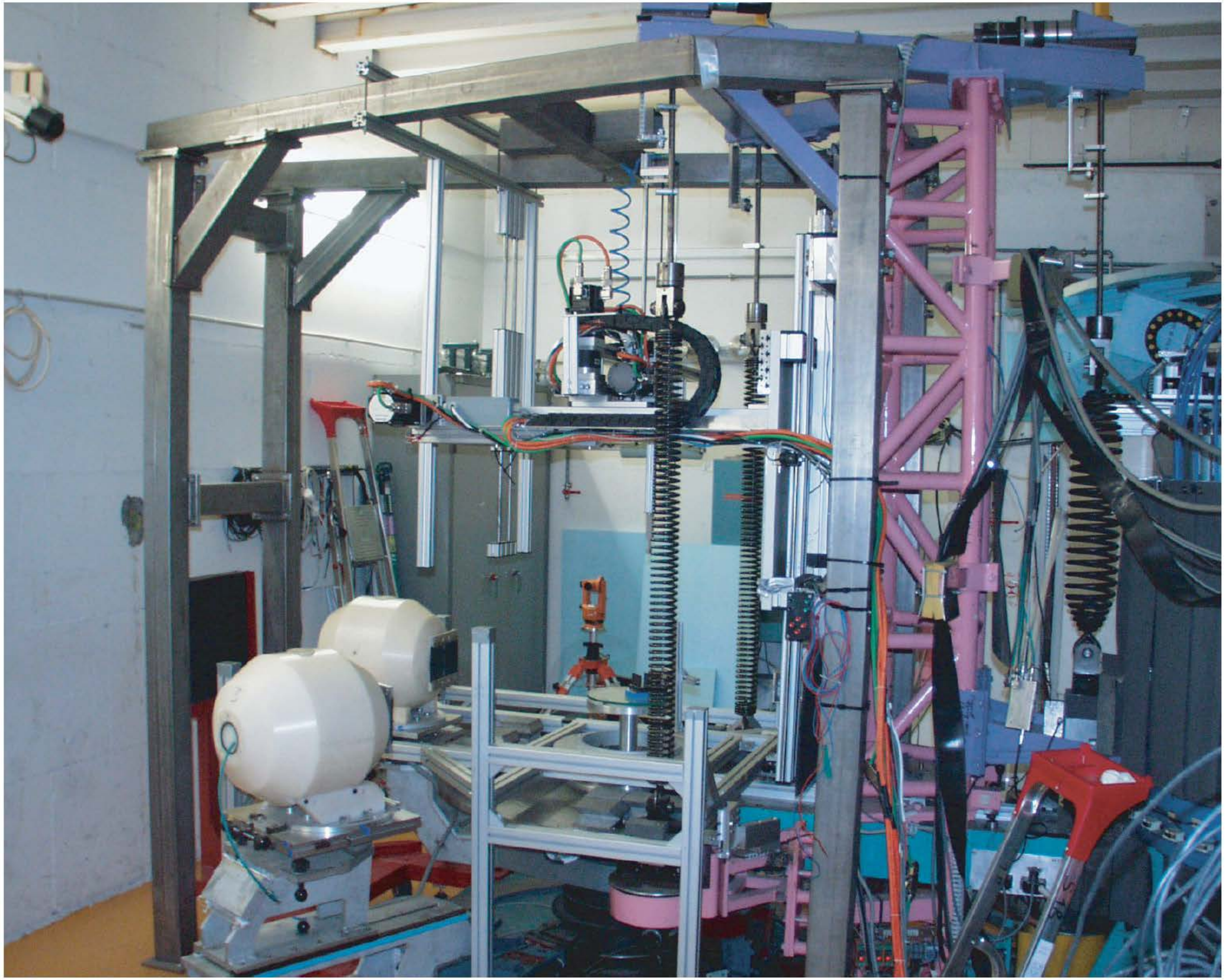
11. Jan. 1974

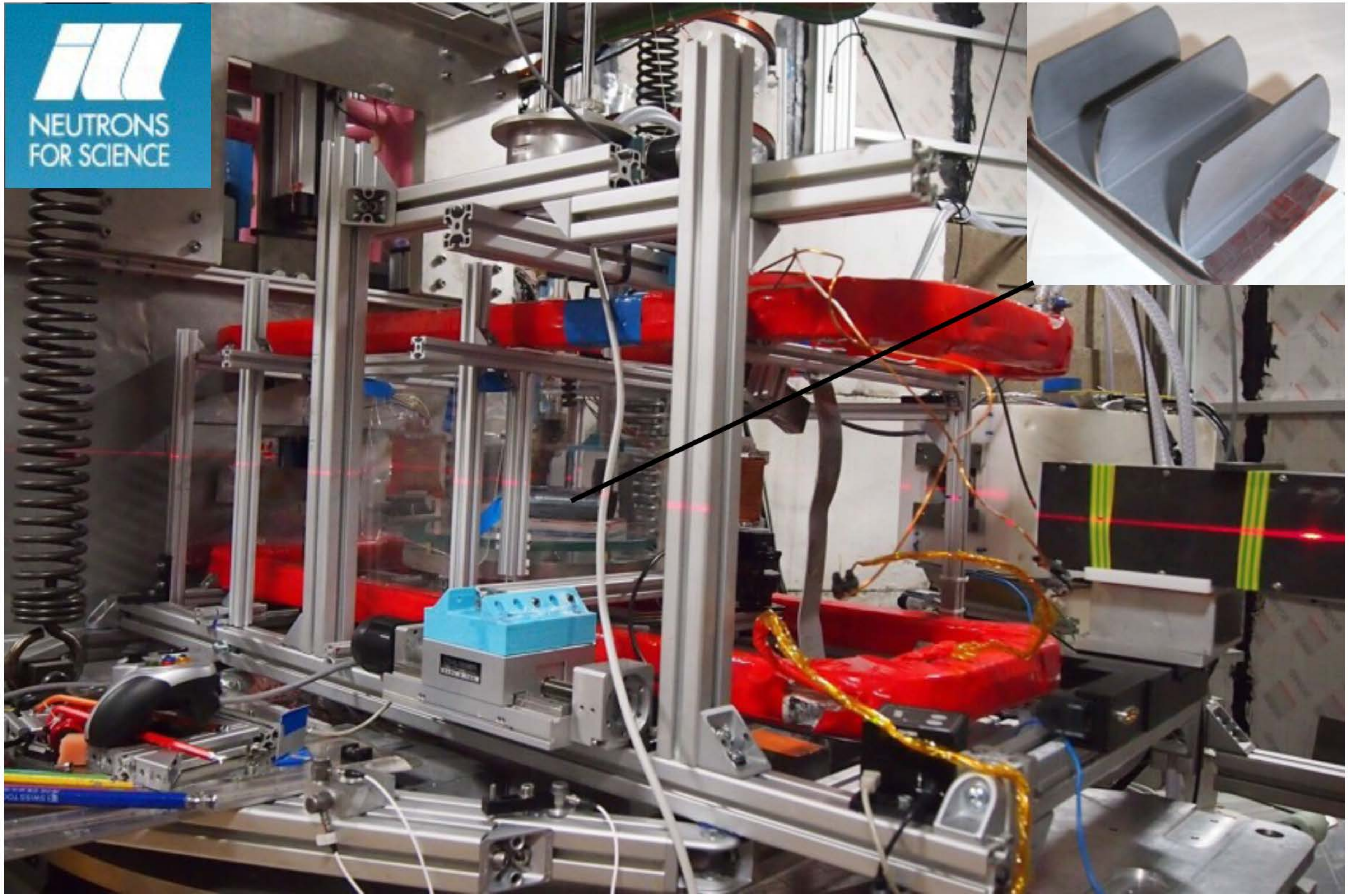


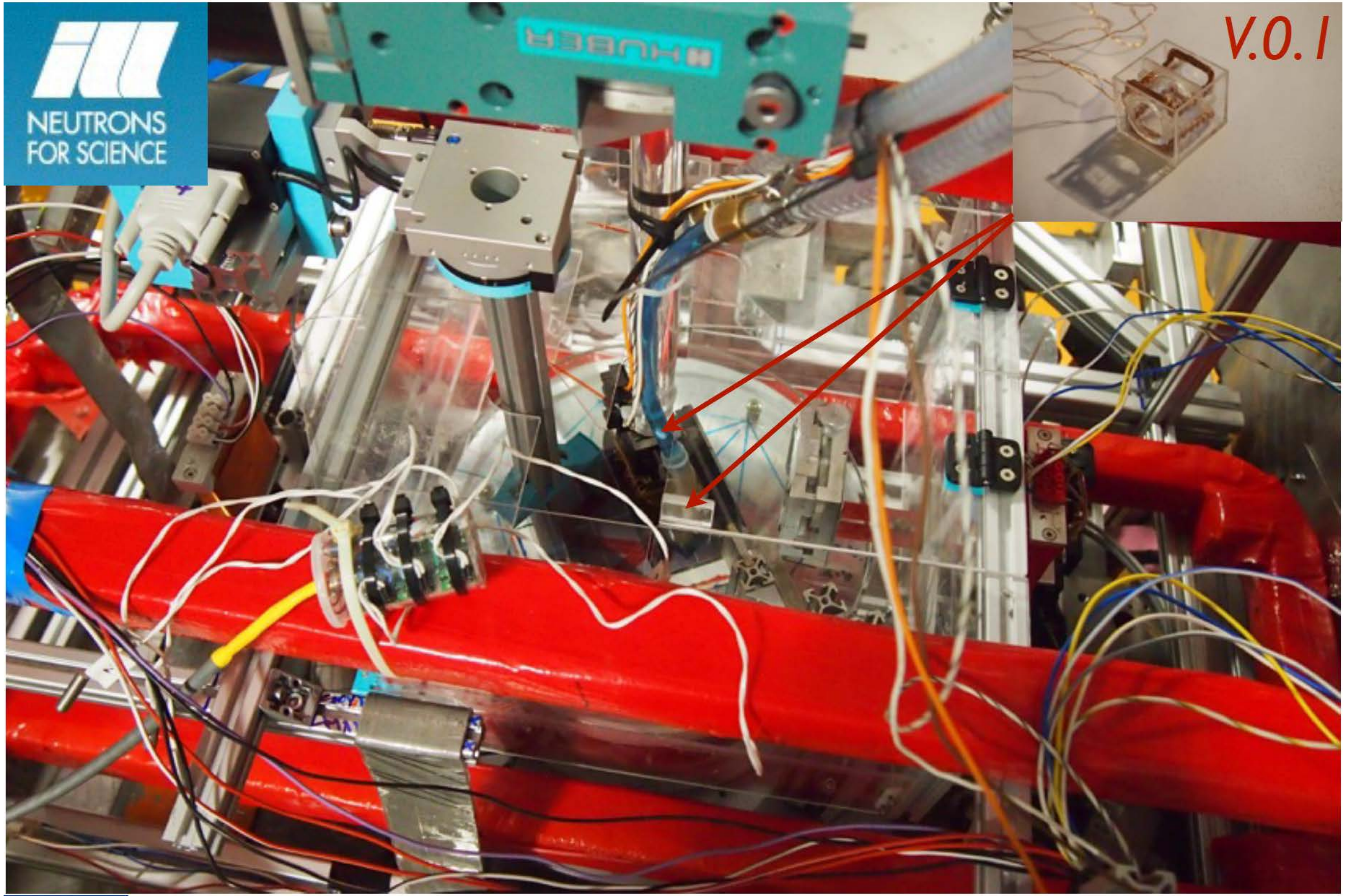
4π Rotation

Rauch
Zeilinger
Badurek



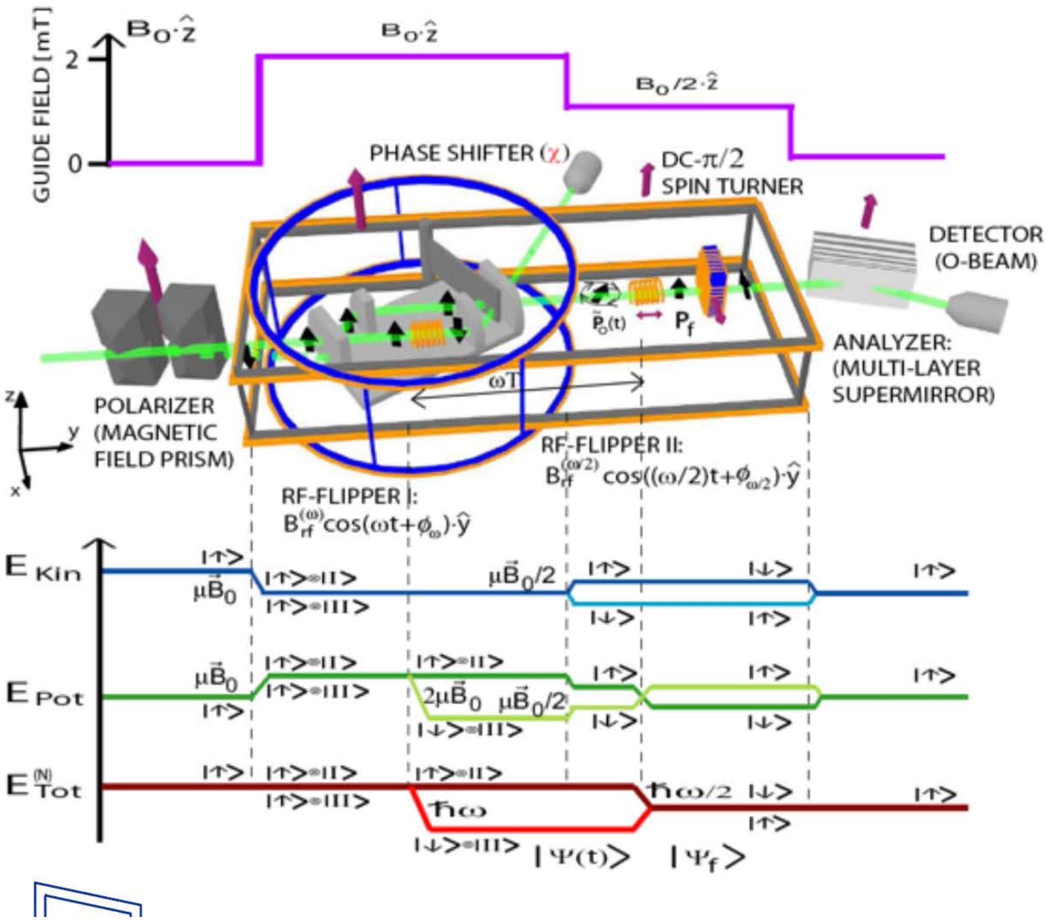


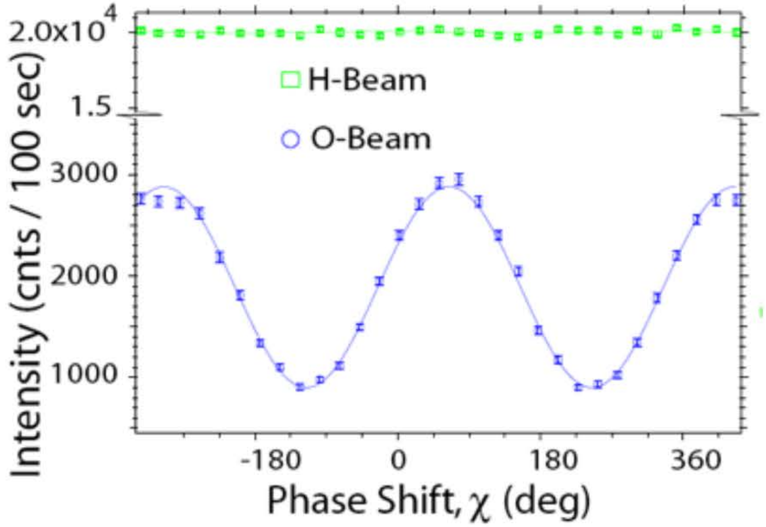

NEUTRONS
FOR SCIENCE


NEUTRONS
FOR SCIENCE
V.0.1

Coherent Energy Manipulation in Neutron Interferometry

$$|\Psi_{\mathrm{Bell}}(t)\rangle = \frac{1}{\sqrt{2}}\Big(|\mathrm{I}\rangle \otimes |\Uparrow\rangle + \mathrm{e}^{i\omega t}\mathrm{e}^{\mathrm{i}\chi}|\mathrm{II}\rangle \otimes |\Downarrow\rangle\Big)$$

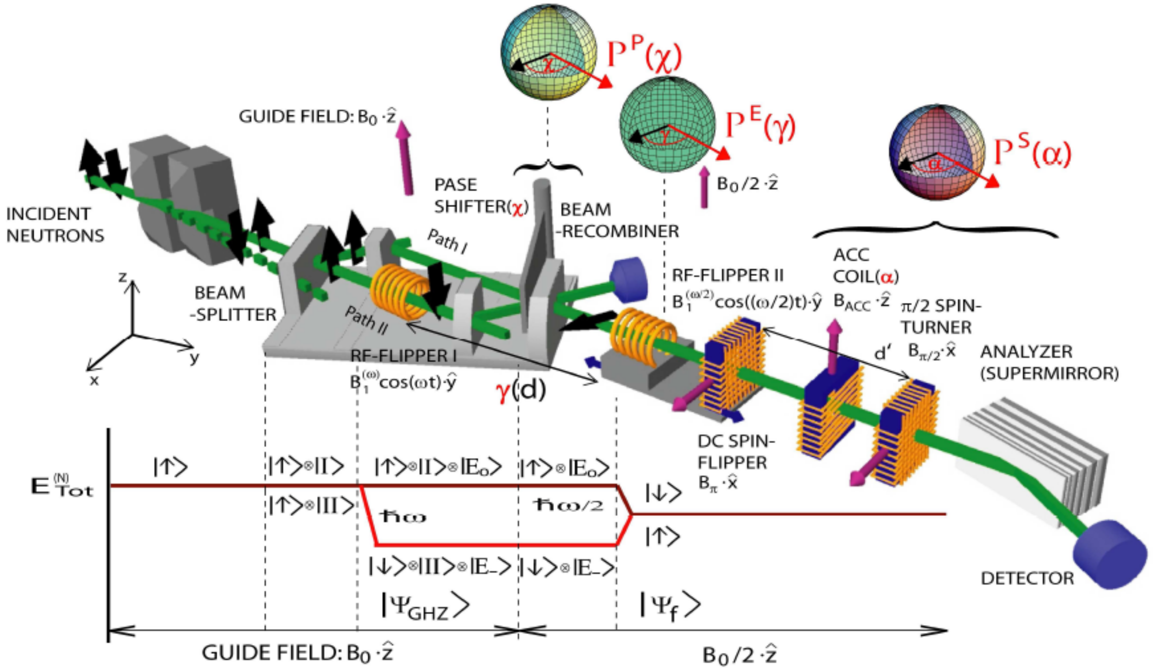




- O-beam: stationary interference fringes (RF(ω/2), spin analysis)
- H-beam: no interference fringes

Greenberger-Horne-Zeilinger (GHZ) states in Neutron Interferometry

$$|\Psi_{\text{GHZ}}\rangle = \frac{1}{\sqrt{2}}\Big(|\text{I}\rangle \otimes |E_0\rangle \otimes |\Uparrow\rangle + |\text{II}\rangle \otimes |E_0 - \hbar\omega\rangle \otimes |\Downarrow\rangle\Big)$$



$$\hat{P}^{\,\text{spin}}(\alpha) = \Pi\Big(\frac{1}{\sqrt{2}}\big(|\Uparrow\rangle + e^{i\alpha}|\Uparrow\rangle\big)\Big)$$

$$\hat{P}^{\,\text{path}}(\chi) = \Pi\Big(\frac{1}{\sqrt{2}}\big(|\text{I}\rangle + e^{i\chi}|\text{II}\rangle\big)\Big)$$

$$\hat{P}^{\,\text{energy}}(\gamma) = \Pi\Big(\frac{1}{\sqrt{2}}\big(|E_0\rangle + e^{i\gamma}|E_0 - \hbar\omega\rangle\big)\Big)$$

$$M = E(\sigma_x^{(S)}\sigma_x^{(P)}\sigma_x^{(E)}) - E(\sigma_x^{(S)}\sigma_y^{(P)}\sigma_y^{(E)}) - E(\sigma_y^{(S)}\sigma_x^{(P)}\sigma_y^{(E)}) - E(\sigma_y^{(S)}\sigma_y^{(P)}\sigma_x^{(E)})$$

$$M_{\text{GHZ,exp}} = 2.558(4) \nleq 2$$

max value according to NCHVTs

Hasegawa *et al.*, *Phys. Rev. A* 81, 032121 (2010). www.neutroninterferometry.com

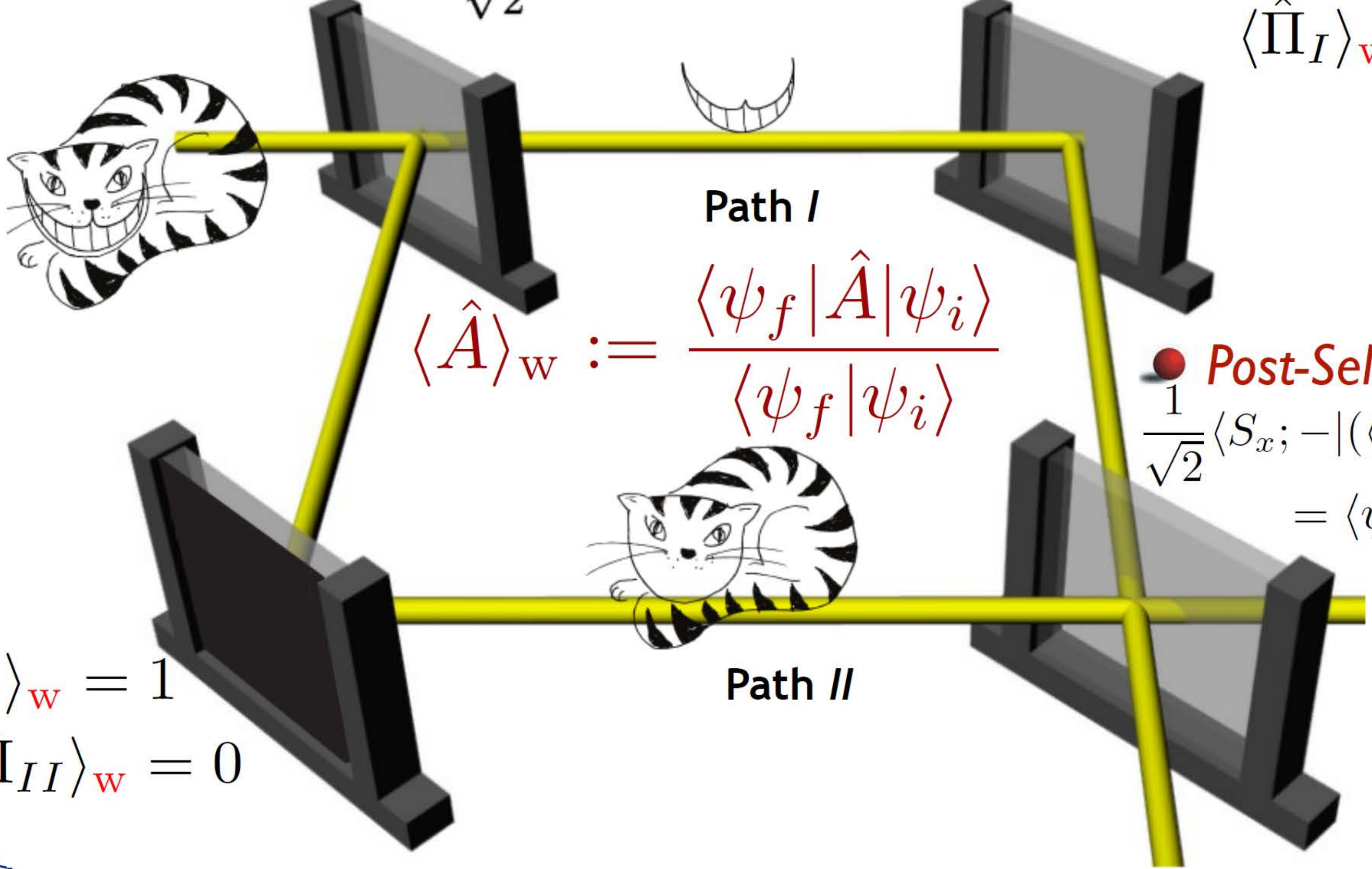
Quantum Cheshire Cat

TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

- *Pre-Selection:* $|\psi_i\rangle = \frac{1}{\sqrt{2}}\left(|S_x;+\rangle\,|I\rangle + |S_x;-\rangle\,|II\rangle\right)$

$$\langle \hat{\sigma}_z^{\mathrm{S}} \hat{\Pi}_I \rangle_{\mathrm{w}} = 1$$

$$\langle \hat{\Pi}_I \rangle_{\mathrm{w}} = 0$$



$$\langle \hat{A} \rangle_{\mathrm{w}} := \frac{\langle \psi_f | \hat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$$

- *Post-Selection:* $\frac{1}{\sqrt{2}}\langle S_x; -|\left(\langle I| + \langle II|\right) = \langle \psi_f|$

$$\langle \hat{\Pi}_{II} \rangle_{\mathrm{w}} = 1$$

$$\langle \hat{\sigma}_z^{\mathrm{S}} \hat{\Pi}_{II} \rangle_{\mathrm{w}} = 0$$

Y. Aharonov, et al,. *New J. Phys.* **15** (2013) 113018, Figure courtesy of Leon Filter.

*q*BOUNCE & ultra-cold neutrons

Energy Eigen States in Gravity Potential

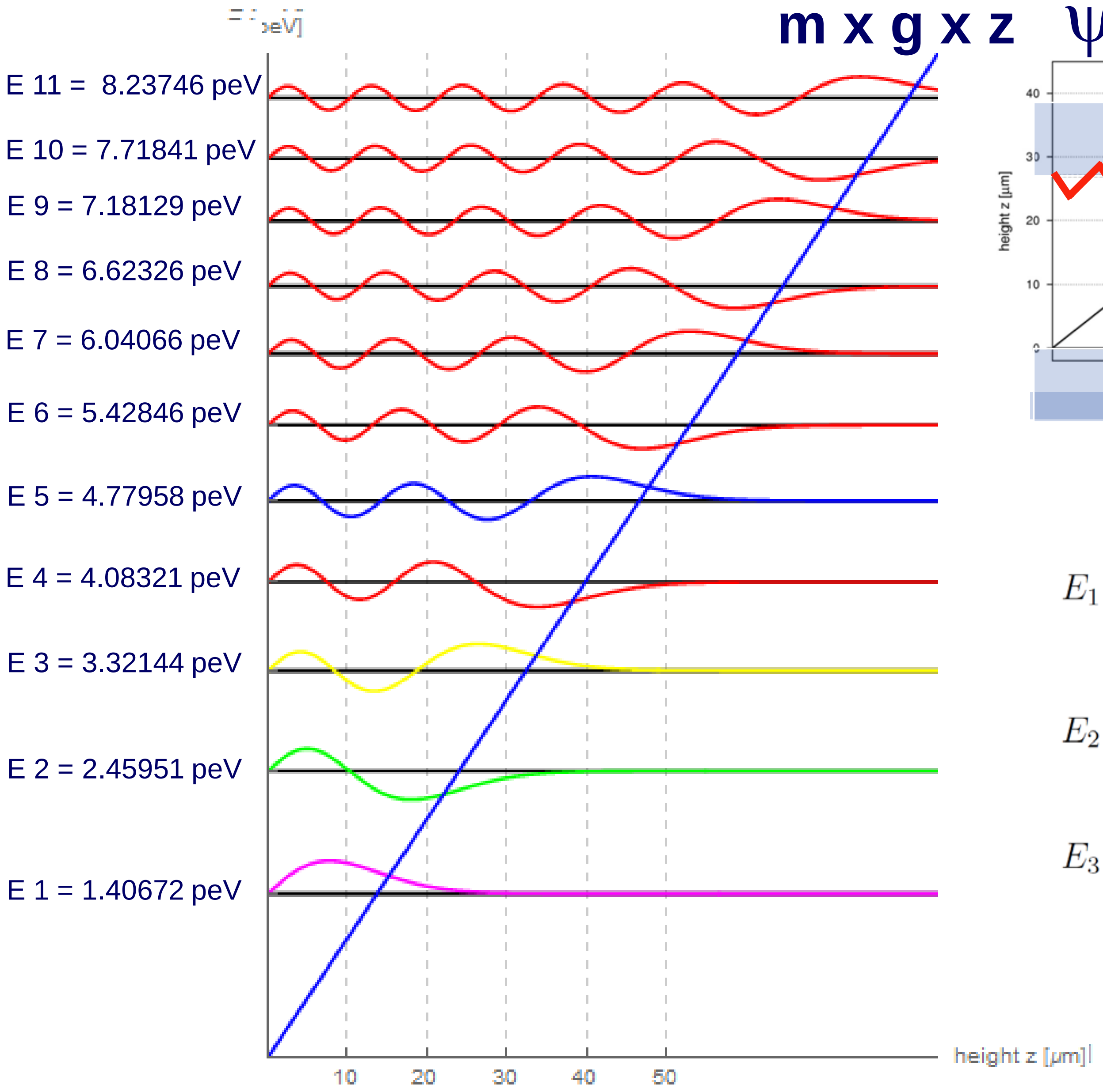
$$\Delta E = \hbar\omega$$

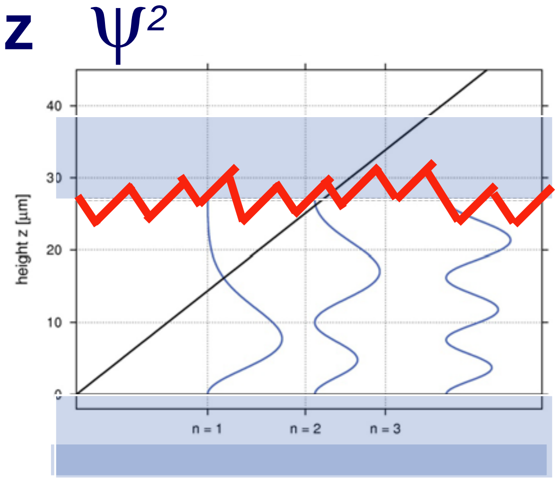
$$|2\rangle \rightarrow |5\rangle$$

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

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

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





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

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

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

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

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

Addressing Quantum States

- State selector: put a neutron in the ground state |1>
- Resonant transition |1> → |x>, |2> → |x>, GRS
- Two mirror system: tune energy levels
- Superposition of quantum states, the phase factor
- Investigation of spacetime & cosmology using the techniques of quantum interference via resonance spectroscopy

A neutron as an ideal object to Test Gravity

- Question: What is the level of sensitivity?

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
  - Ramsey's Spectroscopy Method of Separated Oscillating Field by GRS

- Energy $\Delta E = 4 \times 10^{-18}$ eV, ACME
  - Search for an electric dipole moment, electron (ThO), $d_e < 9 \times 10^{-29}$ ecm
- Energy $\Delta E = 2 \times 10^{-15}$ eV
  - Rabi's Spectroscopy Method by GRS

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

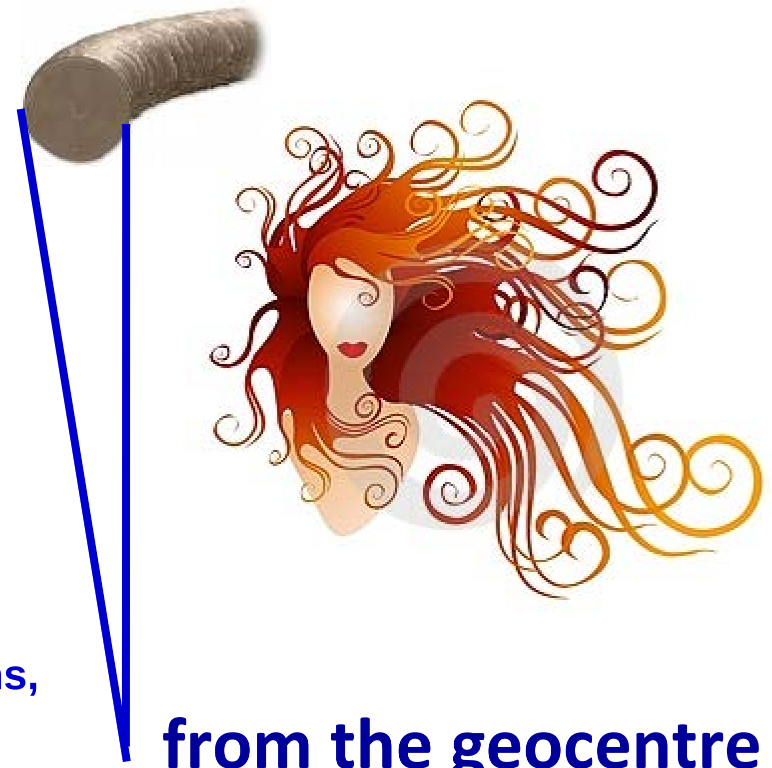
Review Article:
H.A., The neutron. Its properties and basic interactions, Prog. Part. Nucl. Phys. 60 1-81 (2008)

Neutron as an object:
extreme sensitivity and 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**



from the geocentre

See 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

Neutron Beta Decay & High Precision Experiments with PERC

Spokesperson: B. Maerkisch, TU München,Time & Project Manager: E. Jericha, TU Wien

Observables in neutron decay

Decay rate J.D. Jackson et al., PR 106, 517 (1957)

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right) p_e E_e \left(E_0 - E_e\right)^2$$

$$\times\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{\sigma}_n\rangle}{\sigma_n}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

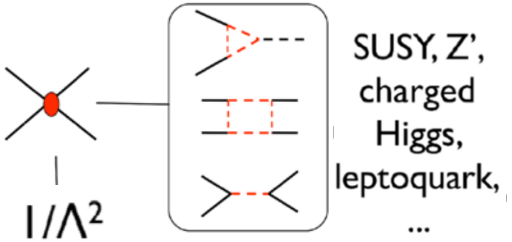
$1/\Lambda^2$

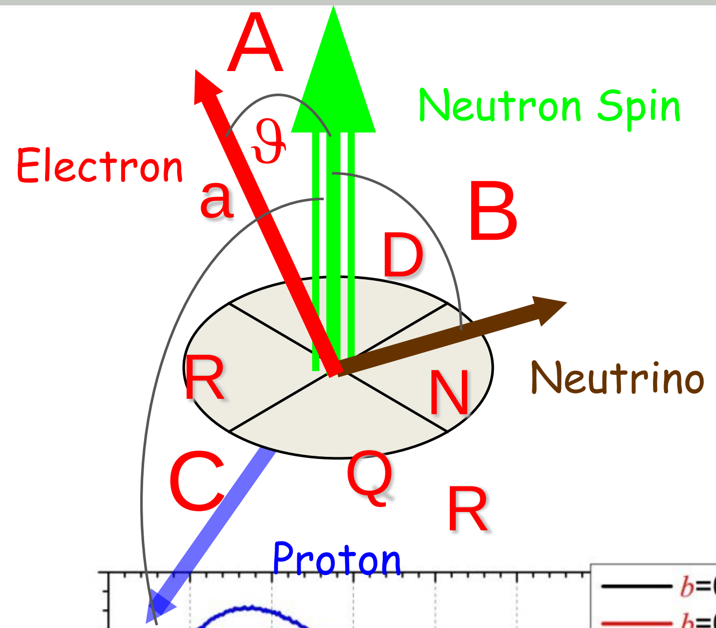
2 unknown parameters: V_{ud}, $\lambda = g_A / g_V$

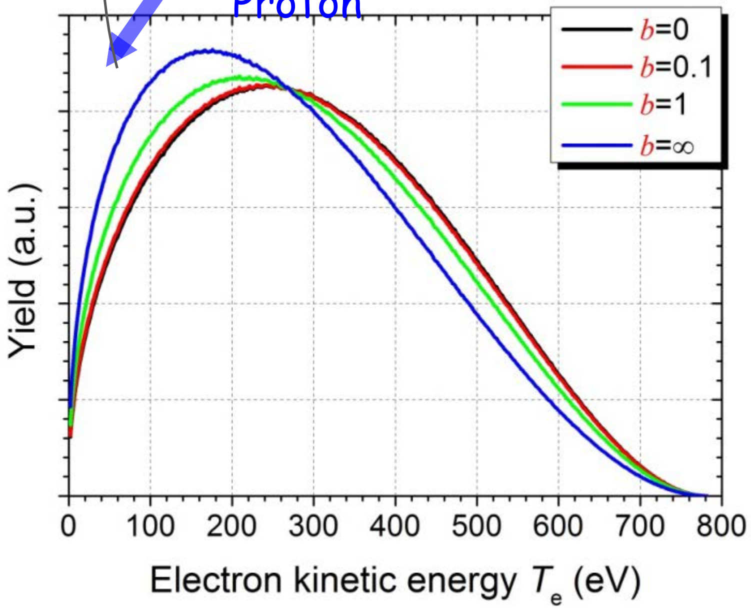
20 or more observables: $\tau_n, a, b, A, B, C, D, \ldots$

$$\tau_n = \frac{4908.7(1.9)\,\mathrm{s}}{|V_{ud}|^2\left(1+3|\lambda|^2\right)}, \quad a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}, \quad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

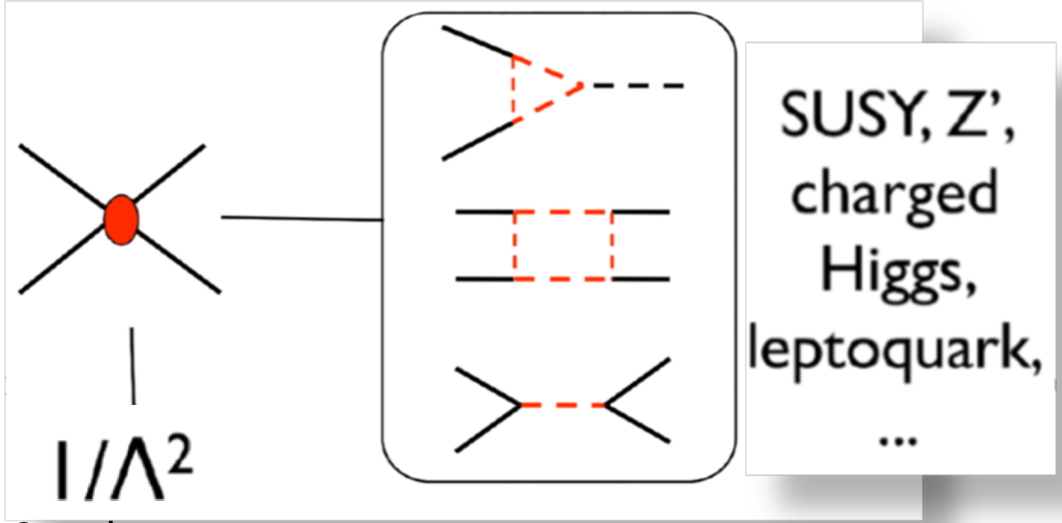
$$b = 2\frac{\mathrm{Re}(g_S + 3\lambda g_T)}{1+3|\lambda|^2}$$







Observables in neutron decay



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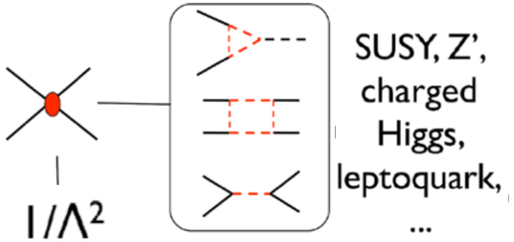

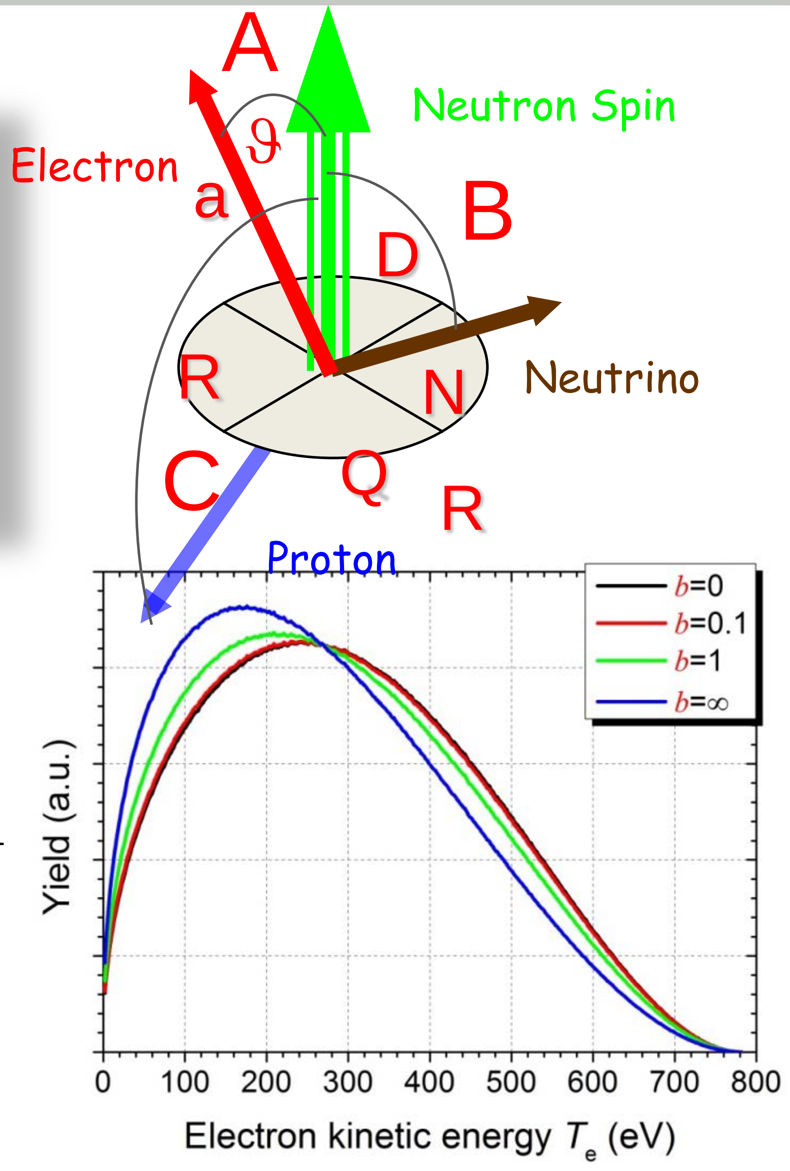

Neutron Beta Decay

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Exotic decay channels are not the cause of the neutron lifetime anomaly

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[b] Physik-Department, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany
[c] Institut Laue-Langevin, 71 avenue des Martyrs, CS 20156, 38042 Grenoble Cedex 9, France
[d] Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Wien, Austria

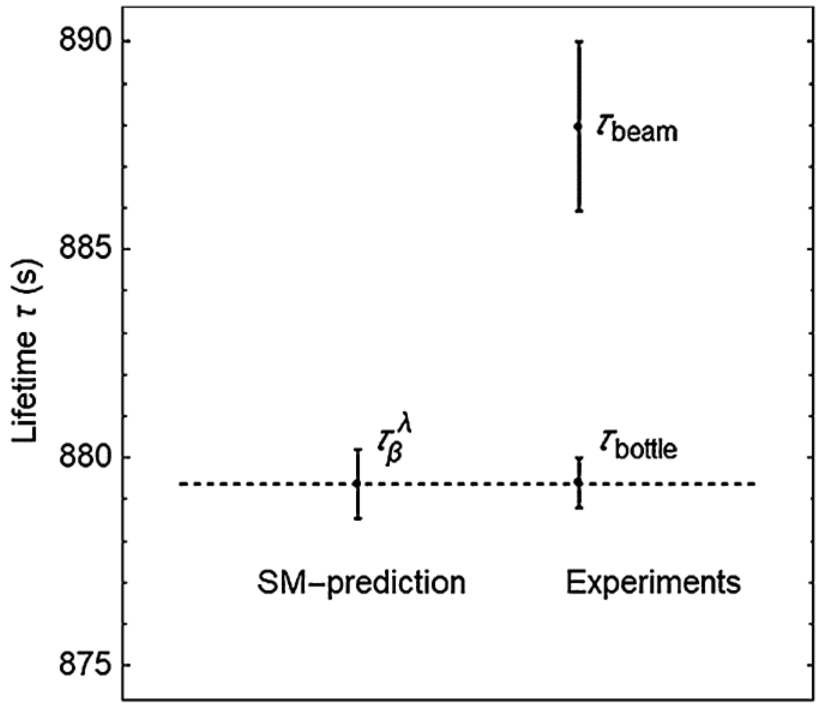

Fig. 2. The standard model expectation for the neutron lifetime τ_β^λ from Eq. (6) coincides with the measured bottle lifetime, and not with the beam lifetime. This finding excludes a dark branch as cause of the neutron anomaly. The dashed line through τ_β^λ is inserted to guide the eye.

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ABSTRACT

Since long neutron lifetimes measured with a beam of cold neutrons are significantly different from lifetimes measured with ultracold neutrons bottled in a trap. It is often speculated that this “neutron anomaly” is due to an exotic dark neutron decay channel of unknown origin. We show that this explanation of the neutron anomaly can be excluded with a high level of confidence when use is made of our new result for the neutron decay β asymmetry. Furthermore, data from neutron decay now compare well with Ft-data derived from nuclear β decays.

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$$\tau_\beta^\lambda = \frac{2}{\ln 2}\frac{\overline{Ft}_{0^+\to 0^+}}{f(1+\delta_R')(1+3\lambda^2)} = \frac{5172.3(1.1)\ \text{s}}{1+3\lambda^2}$$

Editors' Suggestion

Measurement of the Weak Axial-Vector Coupling Constant in the Decay of Free Neutrons Using a Pulsed Cold Neutron Beam

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[1]*Physik-Department, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany*

[2]*Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*

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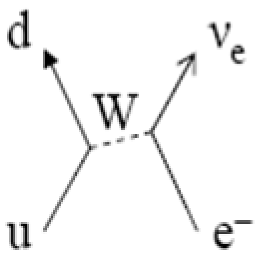
(Received 31 January 2019; published 21 June 2019)

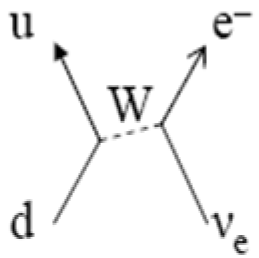
We present a precision measurement of the axial-vector coupling constant g_A in the decay of polarized free neutrons. For the first time, a pulsed cold neutron beam was used for this purpose. By this method, leading sources of systematic uncertainty are suppressed. From the electron spectra we obtain $\lambda = g_A/g_V = -1.27641(45)_{\mathrm{stat}}(33)_{\mathrm{sys}}$, which confirms recent measurements with improved precision. This corresponds to a value of the parity violating beta asymmetry parameter of $A_0 = -0.11985(17)_{\mathrm{stat}}(12)_{\mathrm{sys}}$. We discuss implications on the Cabibbo-Kobayashi-Maskawa matrix element V_{ud} and derive a limit on left-handed tensor interaction.

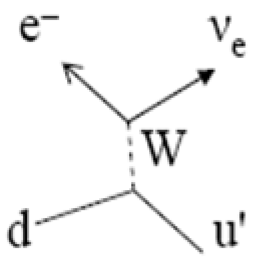
Why ratio $\lambda = g_A / g_V$ from Neutrons?

- Processes with the same Feynman-Diagram

Primordial element formation	$n + e^+ \rightarrow p + \nu'_e$	$\sigma_\nu \sim 1/\tau$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_\nu \sim 1/\tau$
	$n \rightarrow p + e^- + \nu'_e$	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.	







Constraints on the Dark Matter Interpretation $n \to \chi + e^+e^-$ of the Neutron Decay Anomaly with the PERKEO II Experiment

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[2]*Physik-Department ENE, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany*
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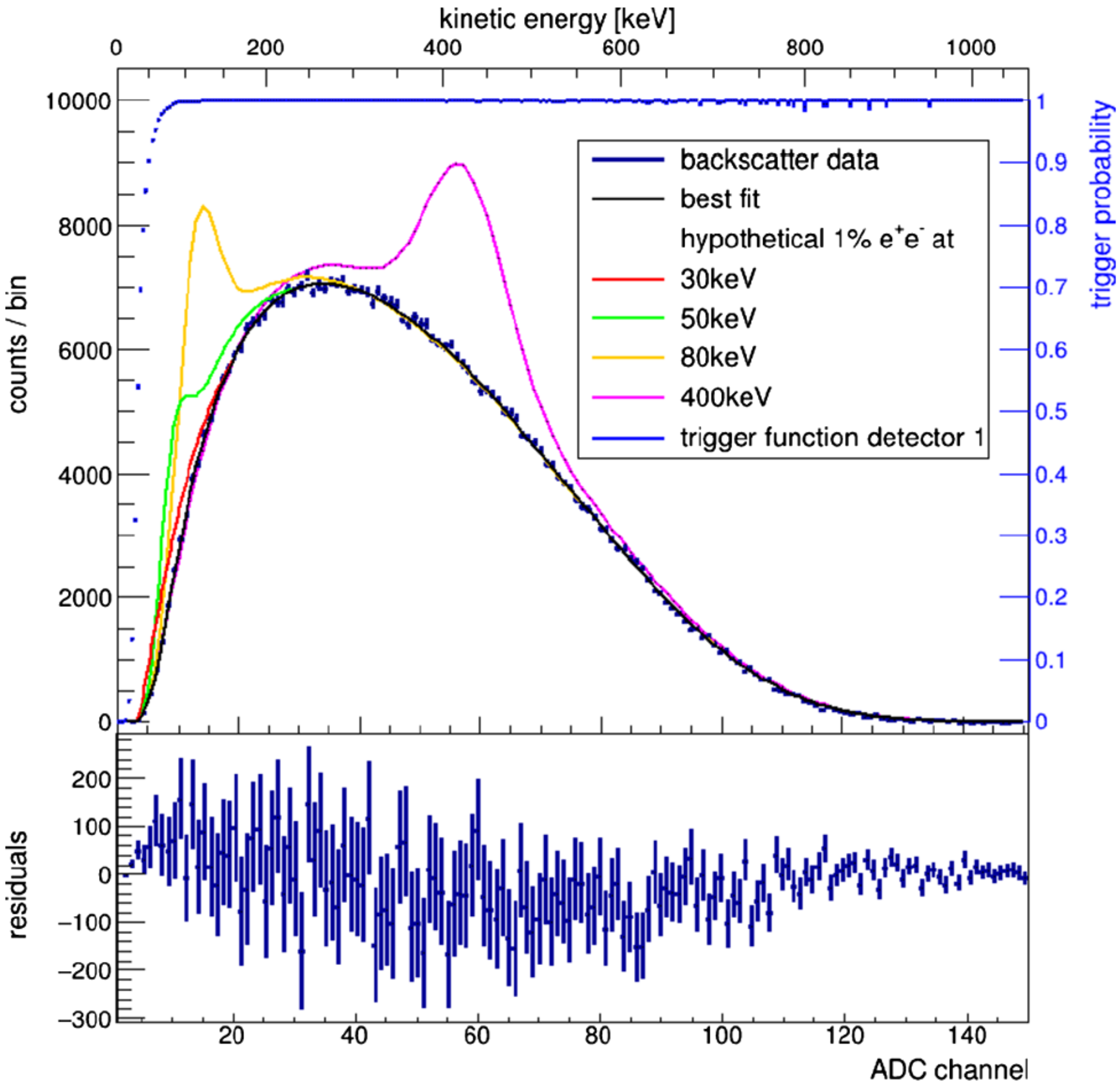
Discrepancies from in-beam- and in-bottle-type experiments measuring the neutron lifetime are on the 4σ standard deviation level. In a recent publication Fornal and Grinstein proposed that the puzzle could be solved if the neutron would decay on the one percent level via a dark decay mode, one possible branch being $n \to \chi + e^+e^-$. With data from the PERKEO II experiment we set limits on the branching fraction and exclude a one percent contribution for 95% of the allowed mass range for the dark matter particle.

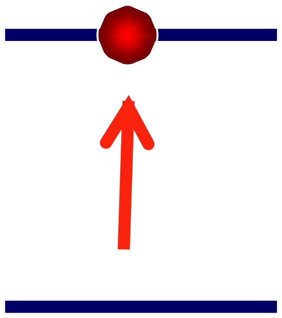
DOI: 10.1103/PhysRevLett.122.222503


kinetic energy [keV]
0
200
400
600
800
1000
10000
8000
6000
4000
2000
0
counts / bin
backscatter data
best fit
hypothetical 1% e⁺e⁻ at
30keV
50keV
80keV
400keV
trigger function detector 1
trigger probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
residuals
200
100
0
−100
−200
−300
20
40
60
80
100
120
140
ADC channel

How can we generalize Ramsey‘s method?

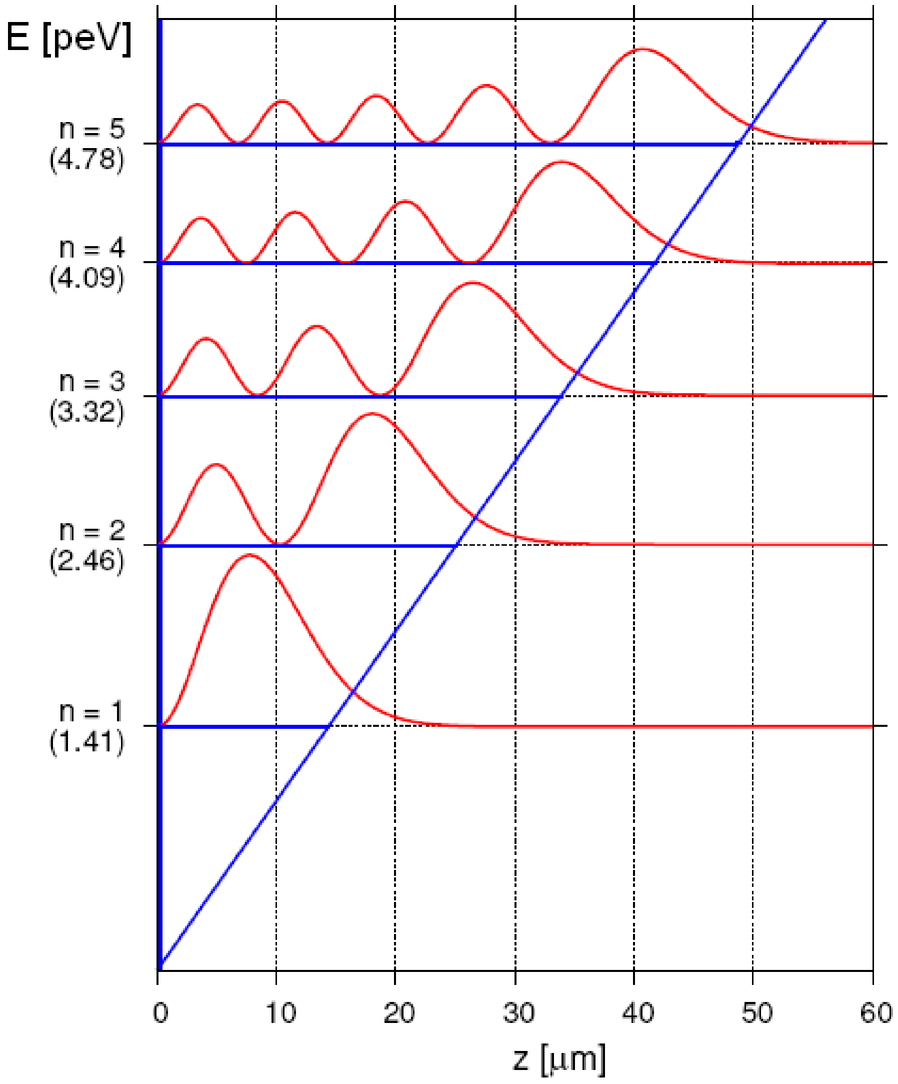
$$\Delta E = \hbar\omega$$

$$\omega = 2\pi \times 395\ \text{Hz}$$



$$E = h\nu$$

*q*Bounce:
Vibrating mirror

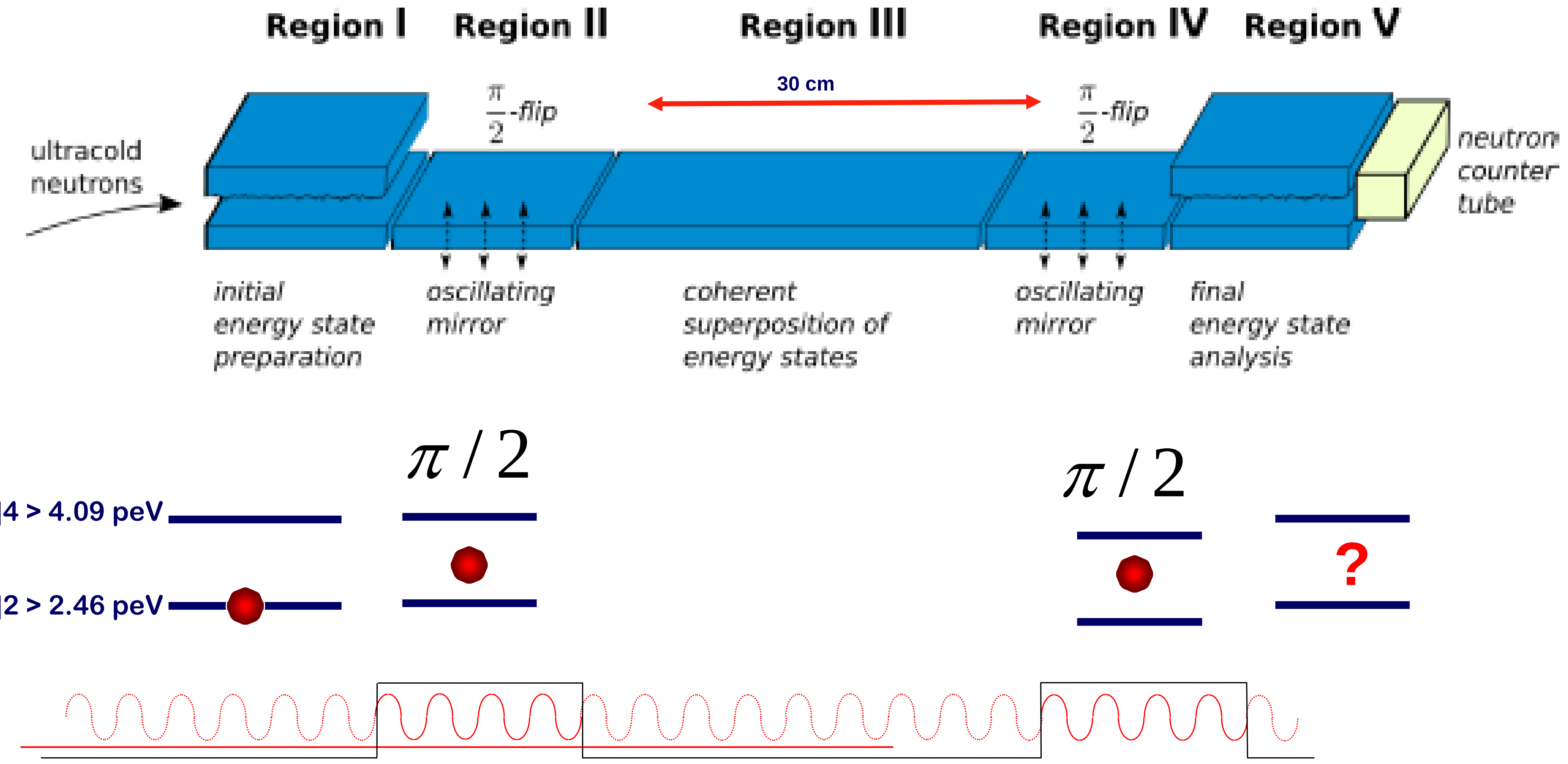


*q*BOUNCE

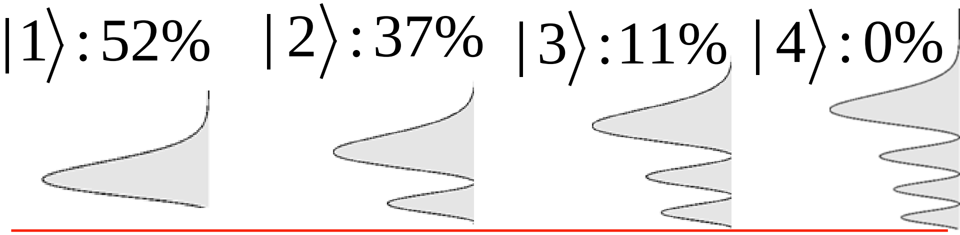
- Back to gravitational quantum states &
- Gravity Resonance Spectroscopy

Ramsey‘s Method for Neutrons

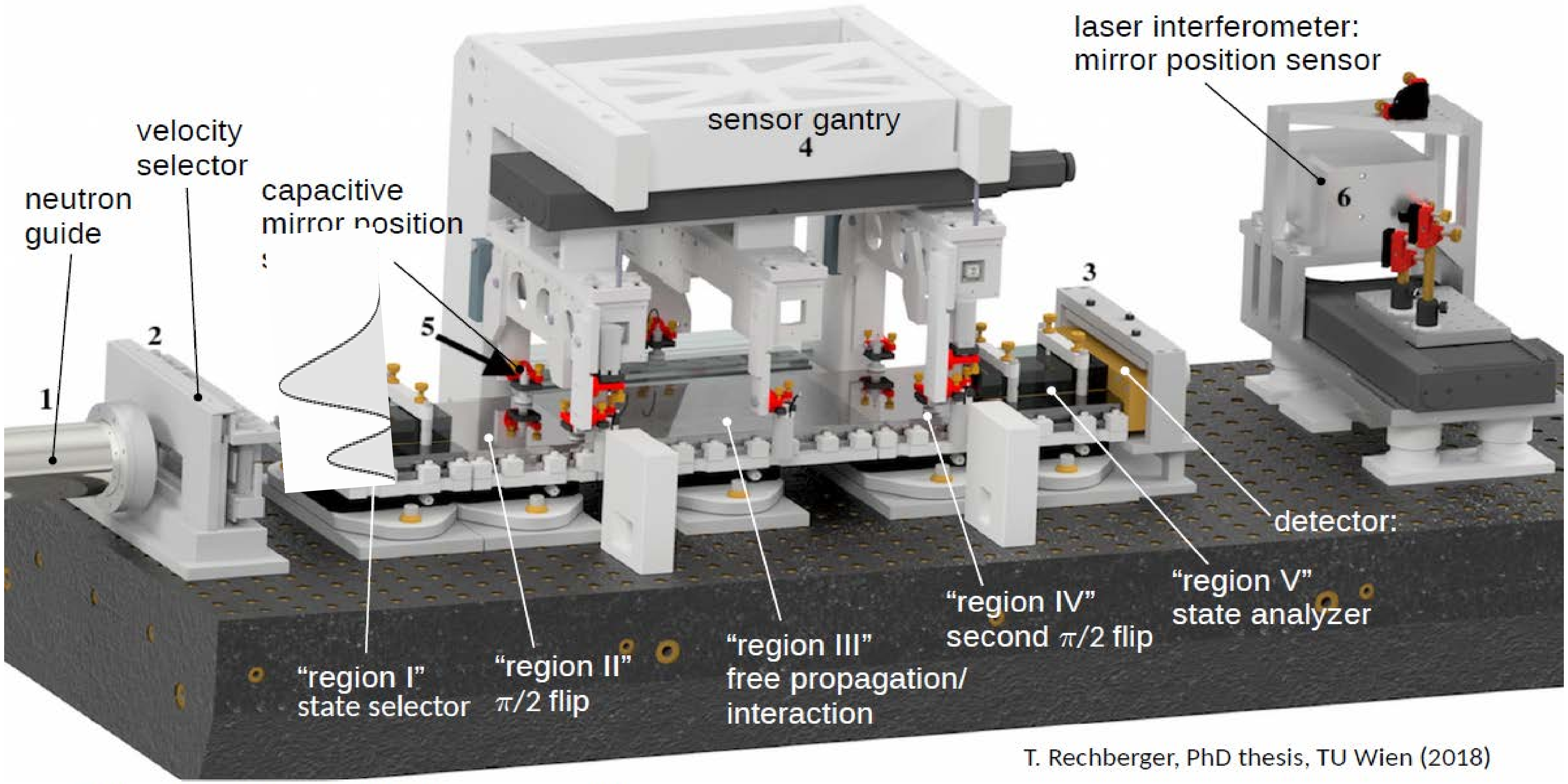
2 state system (gravity potential) coupled to a resonator



Cycle nº 183



Ramsey GRS Implementation



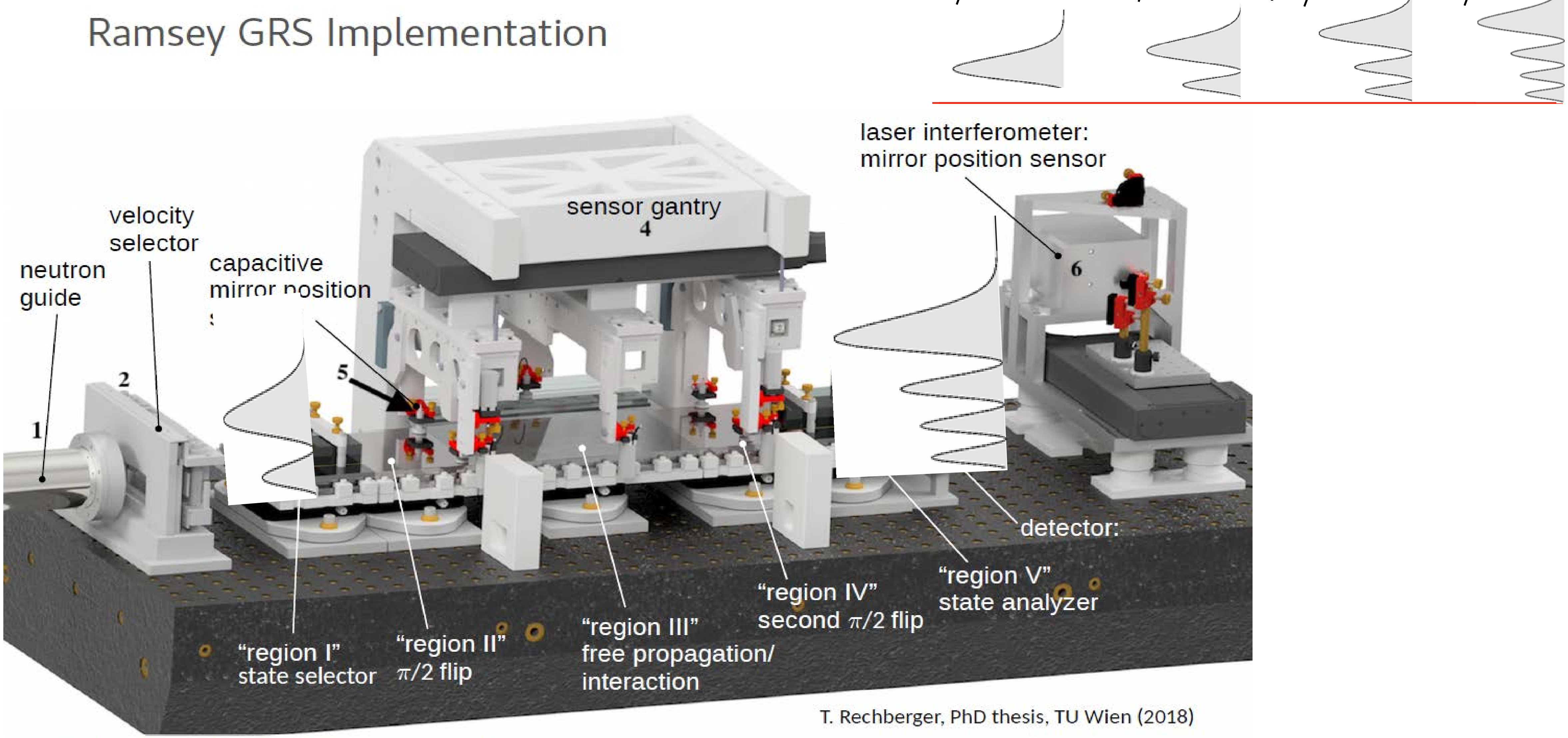
T. Rechberger, PhD thesis, TU Wien (2018)

170 x 90 x 22 cm³ , 850 kg granite table
flatness better than 2 µm

Cycle nº 183

$|1\rangle : 52\%$ $|2\rangle : 37\%$ $|3\rangle : 11\%$ $|4\rangle : 0\%$

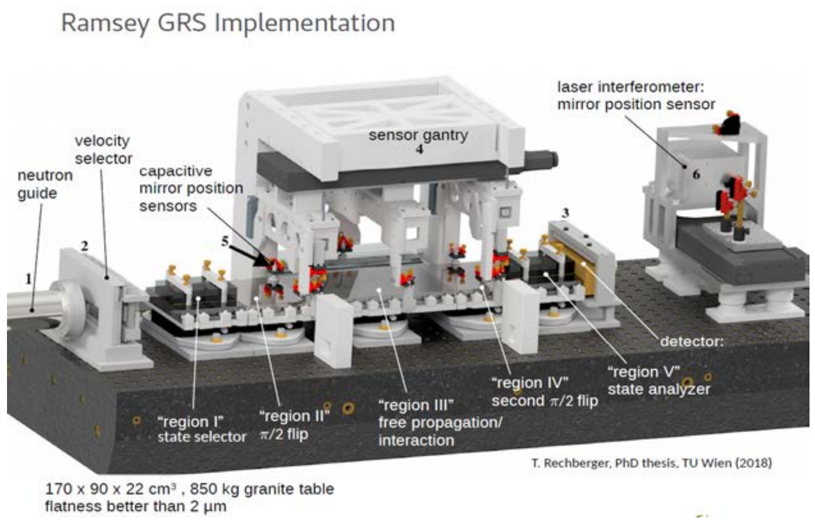
Ramsey GRS Implementation

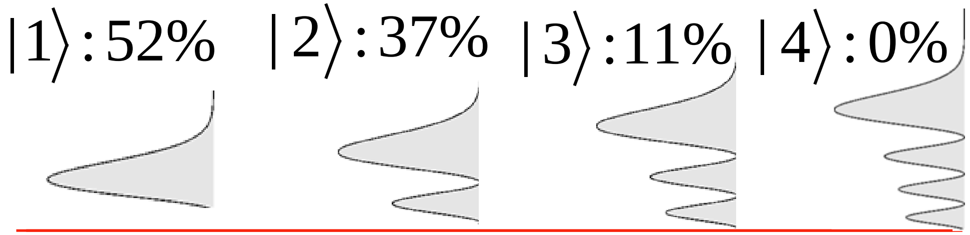


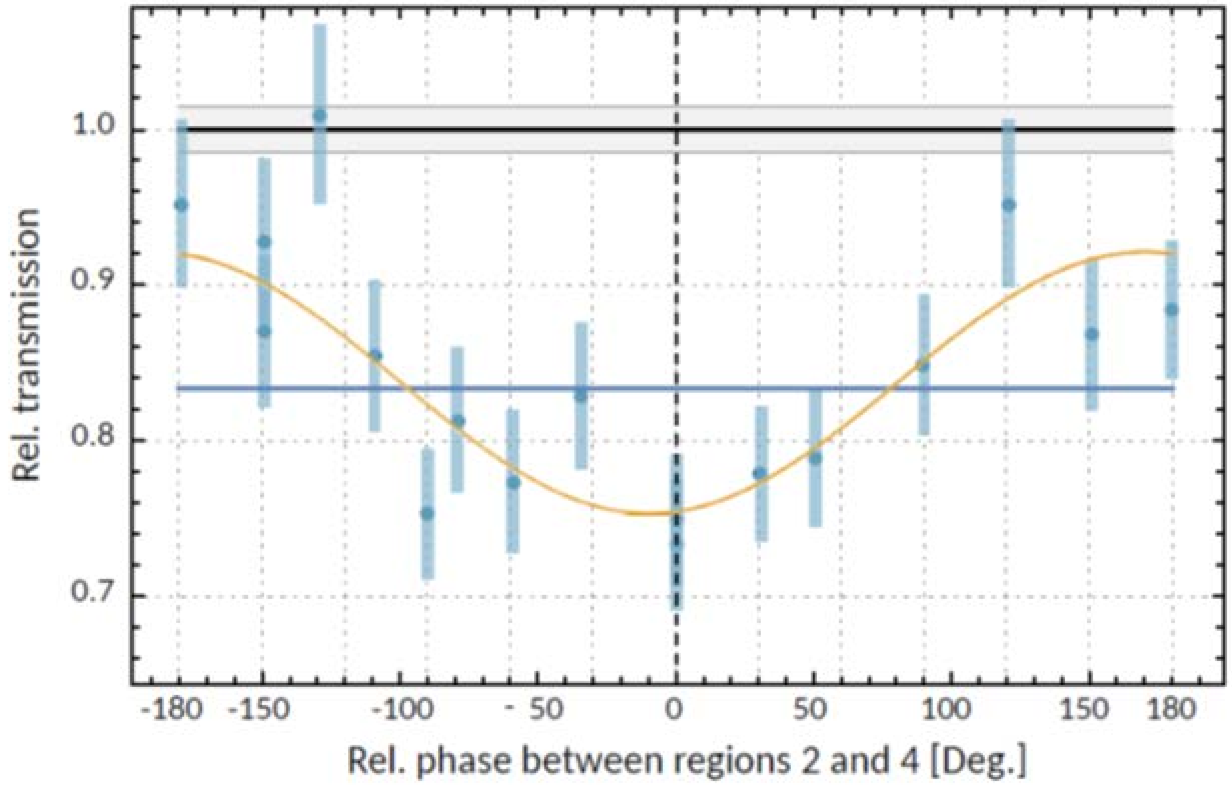
T. Rechberger, PhD thesis, TU Wien (2018)

170 x 90 x 22 cm³ , 850 kg granite table
flatness better than 2 µm

Cycle nº 183, Proof of Principle: Ramsey @ GRS



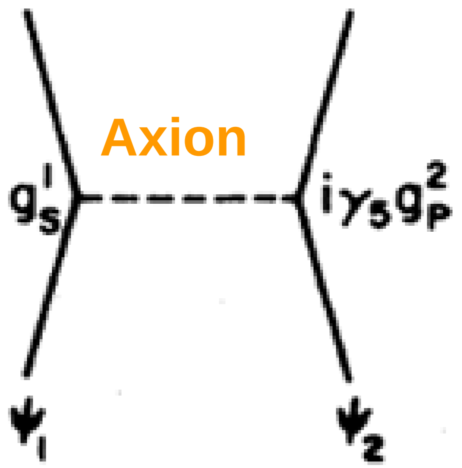




A neutron as an ideal object for Dark Matter Searches

- A neutron
  - is neutral
  - has small polarizability
  - probes small distances on the nm … µm – scale
  - gives access to all gravity-parameters:
    - **mass, distance, energy momentum, …**
  - 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**
  - has a spin
    - **Axions-exchange? Chameleons? Symmetrons?**

Hypothetical New Interaction



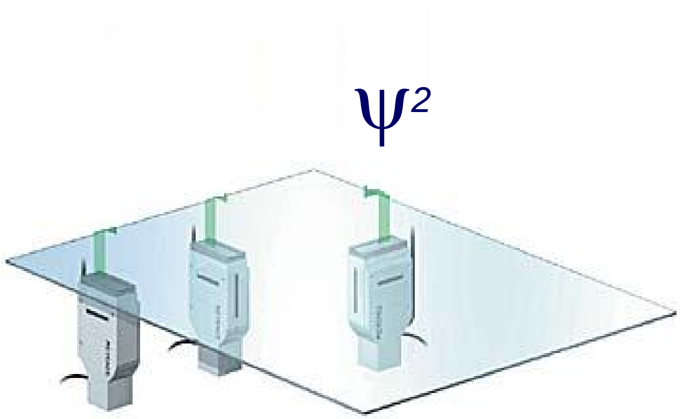
qBOUNCE: Quantum States and the Dark Sector

- Schrödinger Equation

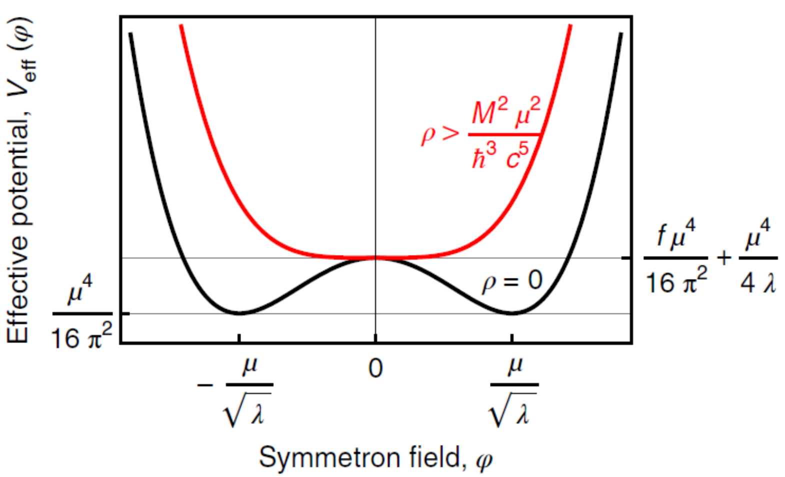
$$DE: -\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz + V(\Phi) = E\psi$$

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

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



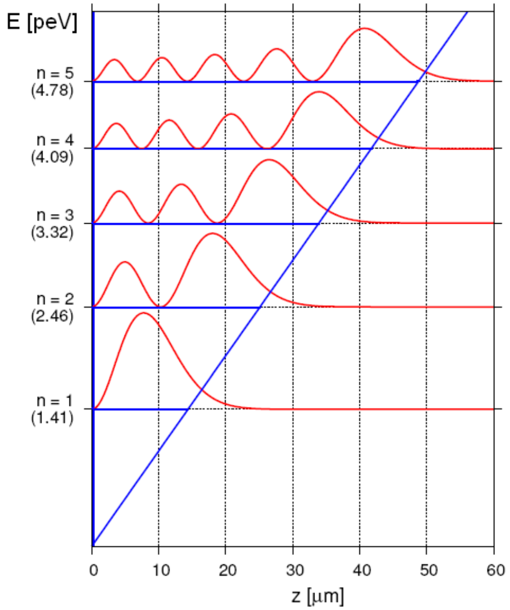
Hypothetical New Interaction



- Characteristic length and energy scale

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

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



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

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

qBOUNCE and Lorentz Violation (LV), mgSME

- Schrödinger Equation

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

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

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

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

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

Gravitational Searches for Lorentz Violation with Ultracold Neutrons

C. A. Escobar[1,*] and A. Martín-Ruiz[2,3,†]

$$H_{\rm NR} = \frac{1}{2}mc^2h_{00} - h_{0k}p^kc - \frac{1}{4m}h_{00}p^2 - \frac{1}{2m}h_{jk}p^jp^k.$$

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

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

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

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

qBOUNCE and Lorentz Violation (LV), mgSME

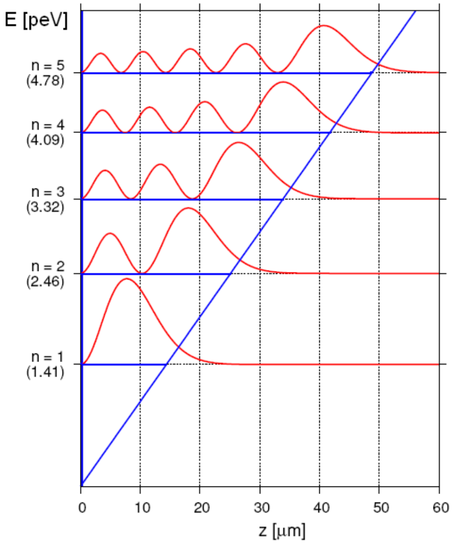
- Ivanov

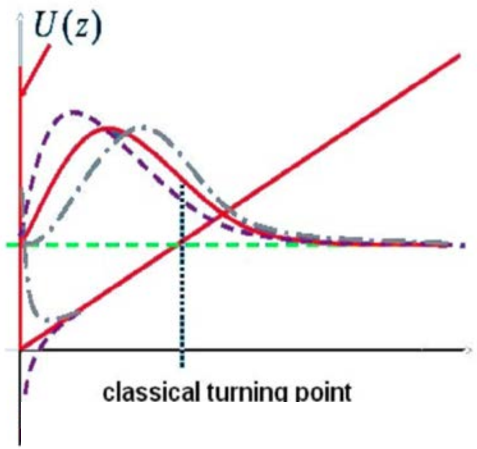
$$i\frac{\partial\psi}{\partial t} = \mathrm{H}\psi \quad , \quad \mathrm{H} = -\frac{1}{2m}\Delta + mgz + \Phi_{\mathrm{nLV}}$$

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

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

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





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

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

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

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

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

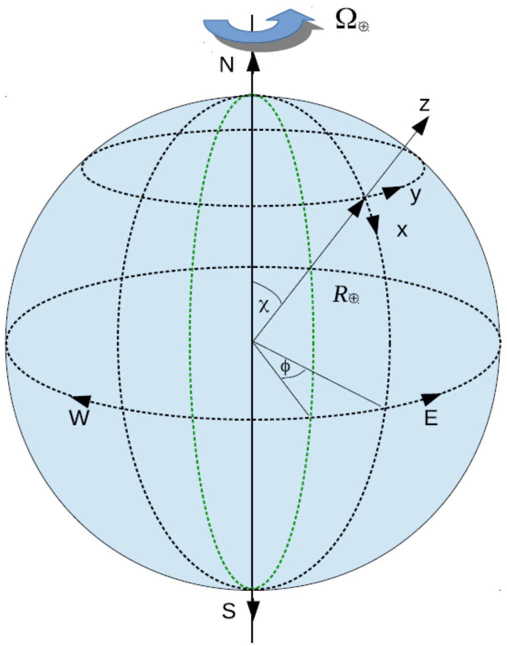
$$\delta\nu_{31} = (2\bar{c}^n_{zz} + \bar{c}^n_{00})\frac{E_3 - E_1}{6\pi\hbar}\,\mathrm{Hz} = 154.341\,(2\bar{c}^n_{zz} + \bar{c}^n_{00})\,\mathrm{Hz},$$

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

*q*BOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- Ivanov

the longitude of the ILL laboratory is $\phi = 5.71667^0$,



local sidereal time $T_\oplus$

$$T_\oplus = T - T_0 \quad , \quad T_0 = \frac{66.25^0 - \phi}{360^0}(23.934\,\mathrm{hr})$$

celestial equatorial time

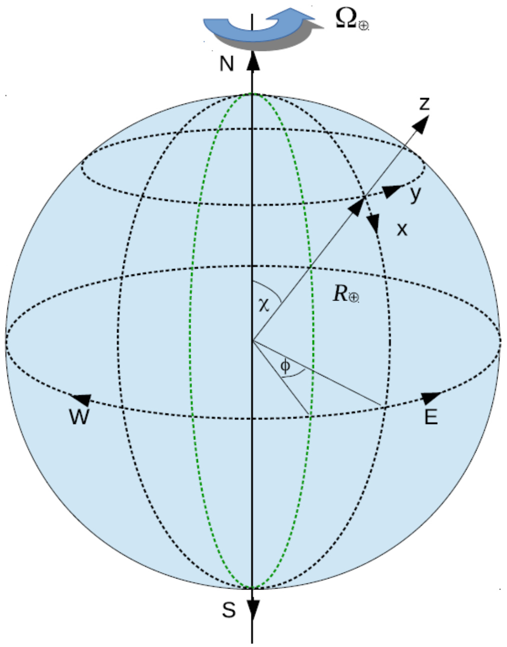
$$R_{jJ}(T_\oplus) = \begin{pmatrix} \cos\chi\cos\Omega_\oplus T_\oplus & \cos\chi\sin\Omega_\oplus T_\oplus & -\sin\chi \\ -\sin\Omega_\oplus T_\oplus & \cos\Omega_\oplus T_\oplus & 0 \\ \sin\chi\cos\Omega_\oplus T_\oplus & \sin\chi\sin\Omega_\oplus T_\oplus & \cos\chi \end{pmatrix}$$

the transition from the canonical Sun–centered frame with coordinates (X, Y, Z) to the laboratory frame

*q*BOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- Ivanov

the longitude of the ILL laboratory is $\phi = 5.71667^0$,



$$
\begin{aligned}
\bar{c}^n_{zz} &= R_{zA}(T_\oplus)R_{zB}(T_\oplus)\bar{c}^n_{AB} = \frac{1}{2}\left[\sin^2\chi(\bar{c}^n_{XX}+\bar{c}^n_{YY}) + 2\cos^2\chi\,\bar{c}^n_{ZZ}\right] + \sin\chi\cos\chi\left[(\bar{c}^n_{XZ}+\bar{c}^n_{ZX})\cos\Omega_\oplus T_\oplus\right.\\
&+ \left.(\bar{c}^n_{YZ}+\bar{c}^n_{ZY})\sin\Omega_\oplus T_\oplus\right] + \frac{1}{2}\sin^2\chi(\bar{c}^n_{XX}-\bar{c}^n_{YY})\cos 2\Omega_\oplus T_\oplus,\\
\bar{d}^n_{0z} &= R_{zJ}(T_\oplus)\bar{d}^n_{0J} = \sin\chi\left(\bar{d}^n_{0X}\cos\Omega_\oplus T_\oplus + \bar{d}^n_{0Y}\sin\Omega_\oplus T_\oplus\right) + \cos\chi\,\bar{d}^n_{0Z},\\
\bar{d}^n_{z0} &= R_{zJ}(T_\oplus)\bar{d}^n_{J0} = \sin\chi\left(\bar{d}^n_{X0}\cos\Omega_\oplus T_\oplus + \bar{d}^n_{Y0}\sin\Omega_\oplus T_\oplus\right) + \cos\chi\,\bar{d}^n_{Z0},\\
\varepsilon_{zxy}\bar{g}^n_{y0z} &= R_{yA}(T_\oplus)R_{zB}(T_\oplus)\bar{g}^n_{A0B} = \frac{1}{2}\sin\chi\left(\bar{g}^n_{Y0X}-\bar{g}^n_{X0Y}\right) + \cos\chi\left(\bar{g}^n_{Y0Z}\cos\Omega_\oplus T_\oplus - \bar{g}^n_{X0Z}\sin\Omega_\oplus T_\oplus\right)\\
&+ \frac{1}{2}\sin\chi\left[\left(\bar{g}^n_{X0Y}+\bar{g}^n_{Y0X}\right)\cos 2\Omega_\oplus T_\oplus - \left(\bar{g}_{X0X}-\bar{g}_{Y0Y}\right)\sin 2\Omega_\oplus T_\oplus\right],\\
\varepsilon_{zxy}\bar{g}^n_{yz0} &= R_{yA}(T_\oplus)R_{zB}(T_\oplus)\bar{g}^n_{AB0} = -\sin\chi\,\bar{g}^n_{XY0} + \cos\chi\left(\bar{g}^n_{YZ0}\cos\Omega_\oplus T_\oplus - \bar{g}^n_{XZ0}\sin\Omega_\oplus T_\oplus\right),\\
\varepsilon_{zyx}\bar{g}^n_{x0z} &= -R_{xA}(T_\oplus)R_{zB}(T_\oplus)\bar{g}^n_{A0B} = -\frac{1}{2}\sin\chi\cos\chi\left(\bar{g}^n_{X0X}+\bar{g}^n_{Y0Y}-2\bar{g}^n_{Z0Z}\right) + \left(\sin^2\chi\bar{g}^n_{Z0X} - \cos^2\chi\,\bar{g}^n_{X0Z}\right)\\
&\times\cos\Omega_\oplus T_\oplus + \left(\sin^2\chi\bar{g}^n_{Z0Y} - \cos^2\chi\bar{g}^n_{Y0Z}\right)\sin\Omega_\oplus T_\oplus - \frac{1}{2}\sin\chi\cos\chi\left[\left(\bar{g}^n_{X0X}-\bar{g}^n_{Y0Y}\right)\cos 2\Omega_\oplus T_\oplus\right.\\
&+ \left.\left(\bar{g}^n_{X0Y}+\bar{g}^n_{Y0X}\right)\sin 2\Omega_\oplus T_\oplus\right],\\
\varepsilon_{zyx}\bar{g}^n_{xz0} &= -R_{xA}(T_\oplus)R_{zB}(T_\oplus)\bar{g}^n_{AB0} = \bar{g}^n_{ZX0}\cos\Omega_\oplus T_\oplus + \bar{g}^n_{ZY0}\sin\Omega_\oplus T_\oplus,\\
\bar{b}^n_j &= R_{jJ}(T_\oplus)\bar{b}^n_J,\\
\bar{d}^n_{j0} &= R_{jJ}(t)\bar{d}^n_{J0},\\
\varepsilon_{jk\ell}\bar{g}^n_{kl0} &= R_{jJ}(T_\oplus)\varepsilon_{JKL}\bar{g}^n_{KL0},\\
\varepsilon_{jk\ell}\bar{H}^n_{k\ell} &= R_{jJ}(T_\oplus)\varepsilon_{JKL}\bar{H}^n_{KL}. \qquad (15)
\end{aligned}
$$

$$\Gamma_\nu = \gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma^5\gamma^\mu + e_\nu + i f_\nu\gamma^5 + \frac{1}{2}g_{\lambda\mu\nu}\sigma^{\lambda\mu}$$

the transition from the canonical Sun–centered frame with coordinates (X, Y, Z) to the laboratory frame

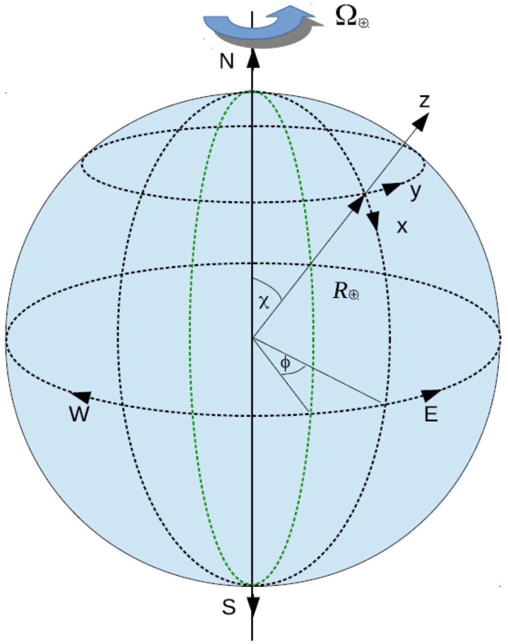
*q*BOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- For the transition of unpolarized UCN

$$\left|\sin^2\chi\,(\bar{c}^n_{XX}+\bar{c}^n_{YY})+2\,\cos^2\chi\,\bar{c}^n_{ZZ}+\bar{c}^n_{00}\right|<2.2\times10^{-3}$$

$$\left|(1+\sin^2\chi)\,\tilde{c}^n_Q+5\,m\,\bar{c}^n_{ZZ}\right|<2.2\times10^{-3}m$$

$$\left|\bar{c}^n_{ZZ}\right|<4.4\times10^{-4}$$



- Transition of polarized UCN

$$\delta\nu_{pq}\;=\;\left\{\left[\sin^2\chi(\bar{c}^n_{XX}+\bar{c}^n_{YY})+2\,\cos^2\chi\,\bar{c}^n_{ZZ}+\bar{c}^n_{00}\right]+\sin\chi(\bar{g}^n_{X0Y}-\bar{g}^n_{Y0X})\langle S_x\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz},$$

$$\delta\nu_{pq}\;=\;\left\{\left[\sin^2\chi(\bar{c}^n_{XX}+\bar{c}^n_{YY})+2\,\cos^2\chi\,\bar{c}^n_{ZZ}+\bar{c}^n_{00}\right]+\sin\chi\cos\chi\,(\bar{g}^n_{X0X}+\bar{g^n}_{Y0Y}-2\,\bar{g^n}_{Z0Z})\,\langle S_y\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz},$$

$$\delta\nu_{pq}\;=\;\left\{\left[\sin^2\chi(\bar{c}^n_{XX}+\bar{c}^n_{YY})+2\,\cos^2\chi\,\bar{c}^n_{ZZ}+\bar{c}^n_{00}\right]-\cos\chi(4\,\bar{d}^n_{0Z}+2\,\bar{d}^n_{Z0})\,\langle S_z\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz}$$

$$\left|\bar{b}^n_Z-m\,(\bar{d}^n_{Z0}-\bar{g}_{XY0})-\bar{H}^n_{XY}\right|<\frac{1}{\cos\chi}\times10^{-24}\,\mathrm{GeV}$$

- Example of numerical analysis:

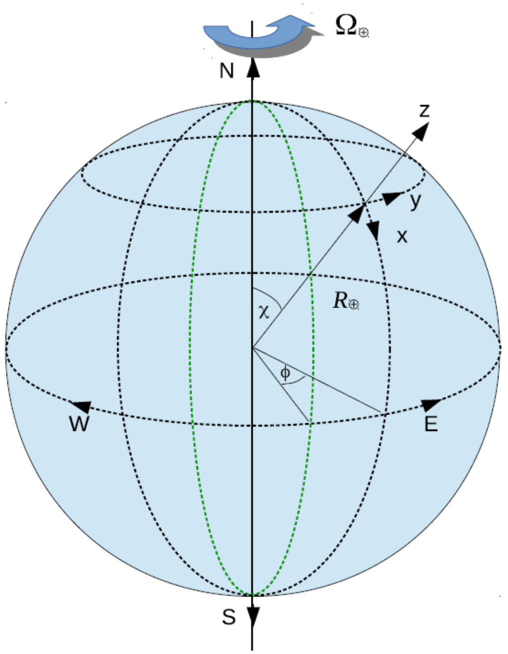
$$\delta\nu_{41}\;=\;229.624\,\{(1+\sin^2\chi)\,\tilde{c}^n_Q+5\,m\,\bar{c}^n_{ZZ}+\sin\chi\,m\,(\bar{g}^n_{X0Y}-\bar{g}^n_{Y0X})\langle S_x\rangle\}\,\mathrm{Hz},$$

$$\delta\nu_{31}\;=\;229.624\,\{[(1+\sin^2\chi)\,\tilde{c}^n_Q+5\,m\,\bar{c}^n_{ZZ}+\sin\chi\cos\chi\,\tilde{g}^n_Q\,\langle S_y\rangle\}\,\mathrm{Hz},$$

qBOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- For the current sensitivity of qBOUNCE we get

$$\left|5\, m\, \bar{c}^n_{ZZ} + \sin\chi\, m\left(\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X}\right)\langle S_x\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV},$$
$$\left|5\, m\, \bar{c}^n_{ZZ} + \sin\chi\cos\chi\, \tilde{g}^n_{Q}\,\langle S_y\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV},$$
$$\left|5\, m\, \bar{c}^n_{ZZ} - \cos\chi\left(4\,\tilde{d}^n_{Z} + 2\,\bar{H}^n_{XY}\right)\langle S_z\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV}$$



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

$$\left|\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X}\right| < 10^{-4},$$
$$\left|\tilde{g}_Q\right| < 1.3\times 10^{-4}\,\mathrm{GeV},$$
$$\left|\tilde{d}^n_Z + \frac{1}{2}\,\bar{H}^n_{XY}\right| < 2.3\times 10^{-5}\,\mathrm{GeV},$$

- Neutron Sector:

Combination	Result
$\lvert\bar{c}^n_{ZZ}\rvert$	$< 4.4\times 10^{-4}$
$\lvert\bar{c}^n_{XX}\rvert$	$< 2.2\times 10^{-4}$
$\lvert\bar{c}^n_{ZZ}\rvert$	$< 2.2\times 10^{-4}$
$\lvert\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X}\rvert$	$< 10^{-4}$
$\lvert\tilde{g}_Q\rvert$	$< 1.3\times 10^{-4}$ GeV
$\lvert\tilde{d}^n_Z + \frac{1}{2} H_{XY}\rvert$	$< 2.3\times 10^{-5}$ GeV
$\lvert\tilde{b}^n_Z\rvert$	$< 1.4\times 10^{-24}$ GeV

nature physics

GRS & Rabi Spectroscopy

Letter | Published: 23 July 2018

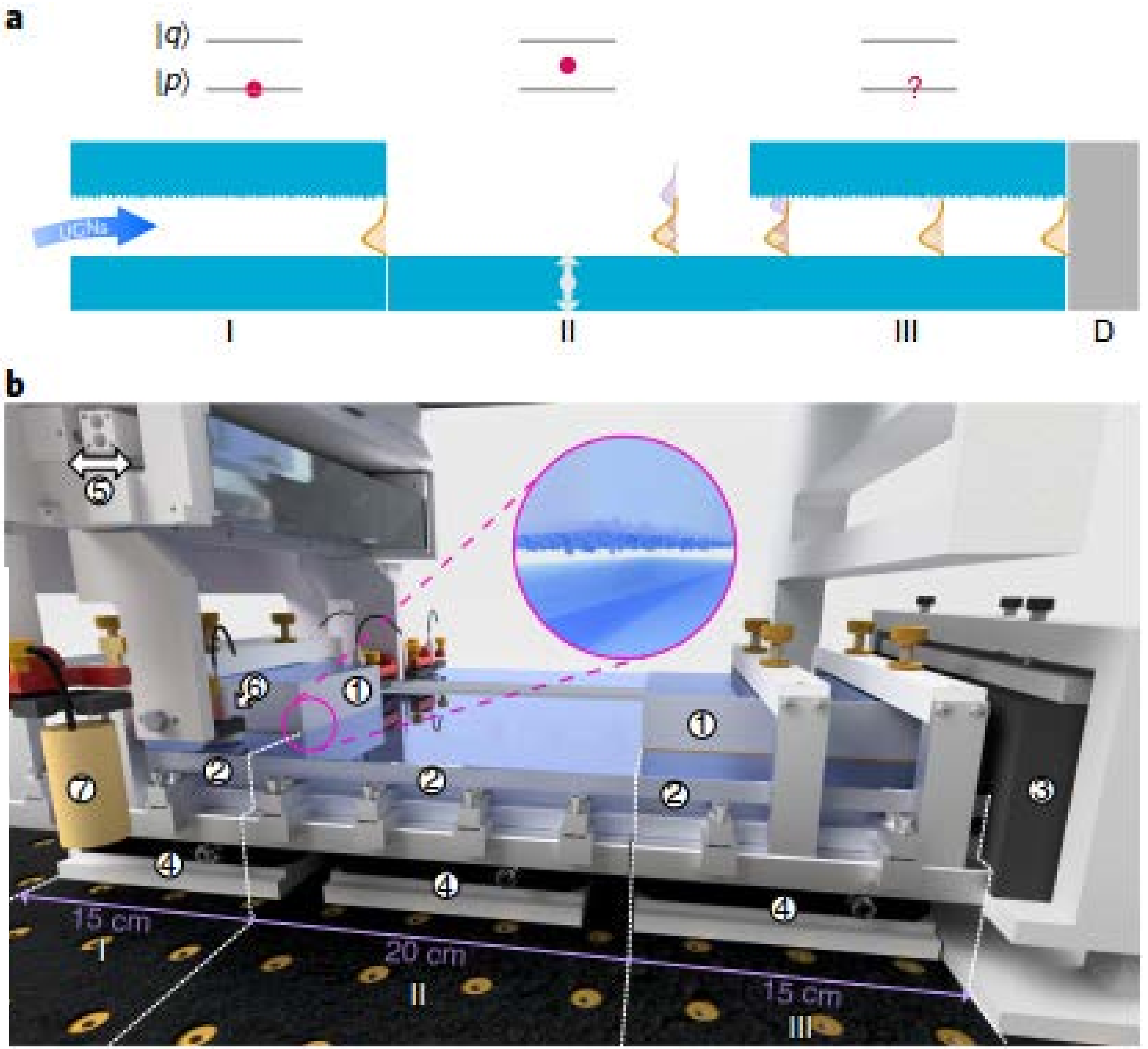
Acoustic Rabi oscillations between gravitational quantum states and impact on symmetron dark energy

Gunther Cronenberg, Philippe Brax, Hanno Filter, Peter Geltenbort, Tobias Jenke, Guillaume Pignol, Mario Pitschmann, Martin Thalhammer & Hartmut Abele

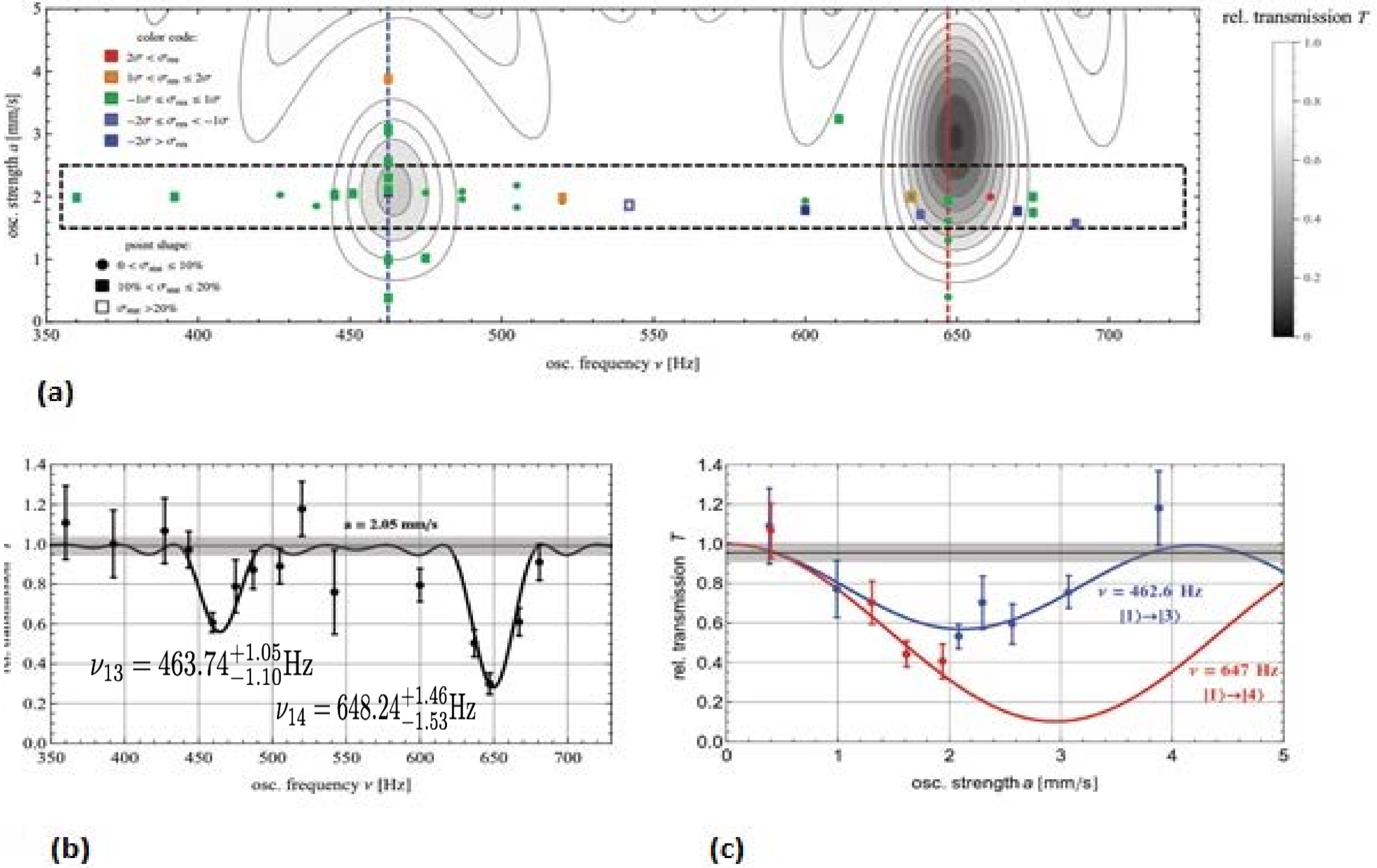
Nature Physics (2018) | Download Citation

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

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



*q*Bounce – *Rabi-* Gravity Resonance Spectroscopy



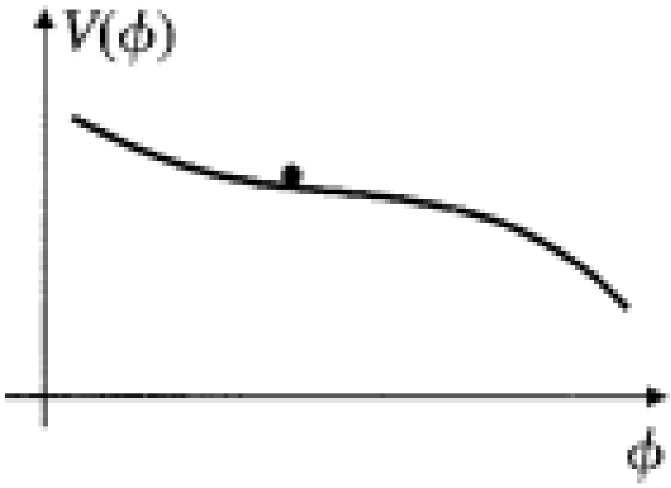
Cronenberg et al., Nature Physics 14, 1022–1026 (2018)

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

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

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



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

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

nature physics

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Bound to pack entropically

CORRELATED OXIDES
Coexisting phase transitions

DARK ENERGY
Neutrons rule out symmetrons

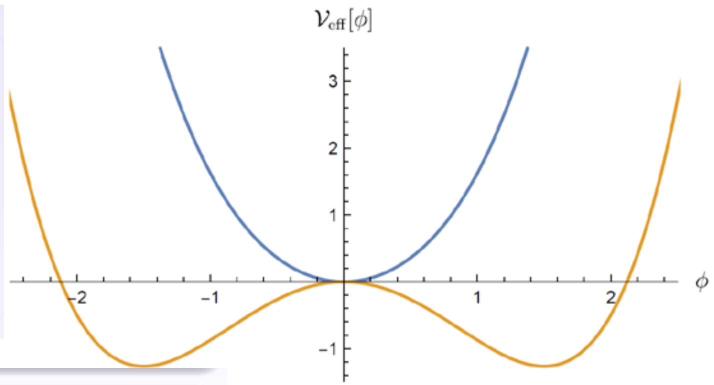
INTERMOLECULAR COULOMBIC DECAY
Going bio

Symmetrons (M. Pitschmann, P. Brax)

Symmetron

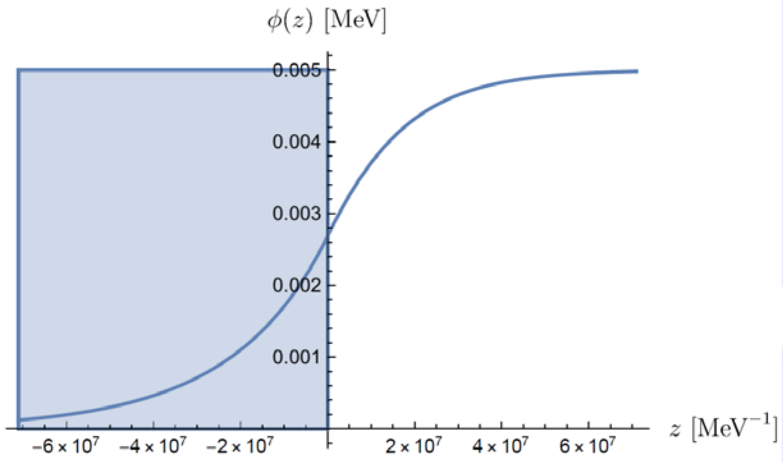
- "Invented" by *K. Hinterbichler & J. Khoury* in 2010[a]
- based on *Spontanous Symmetry Breaking* similar to the *Higgs mechanism* but with a real scalar field ϕ

[a] PRL **104**, 231301 (2010)



2 Phases

1. *Spontanous Symmetry Breaking*: $\frac{\rho}{M^2} < \mu^2$ $\left(\text{"vacuum value"} \ \phi_V = \pm\frac{\mu}{\sqrt{\lambda}}\right)$
2. *Symmetric Phase*: $\frac{\rho}{M^2} \geq \mu^2$ "dense matter"



$\lambda = 10^{-10}$

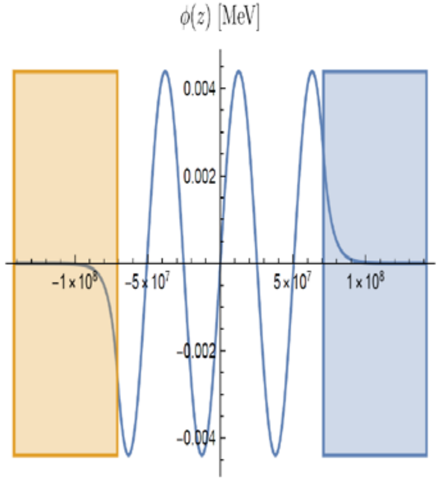
$\mu_{\rm eff} = 5 \times 10^{-8}$ MeV

$M = 5 \times 10^4$ MeV

$k = 0.537$

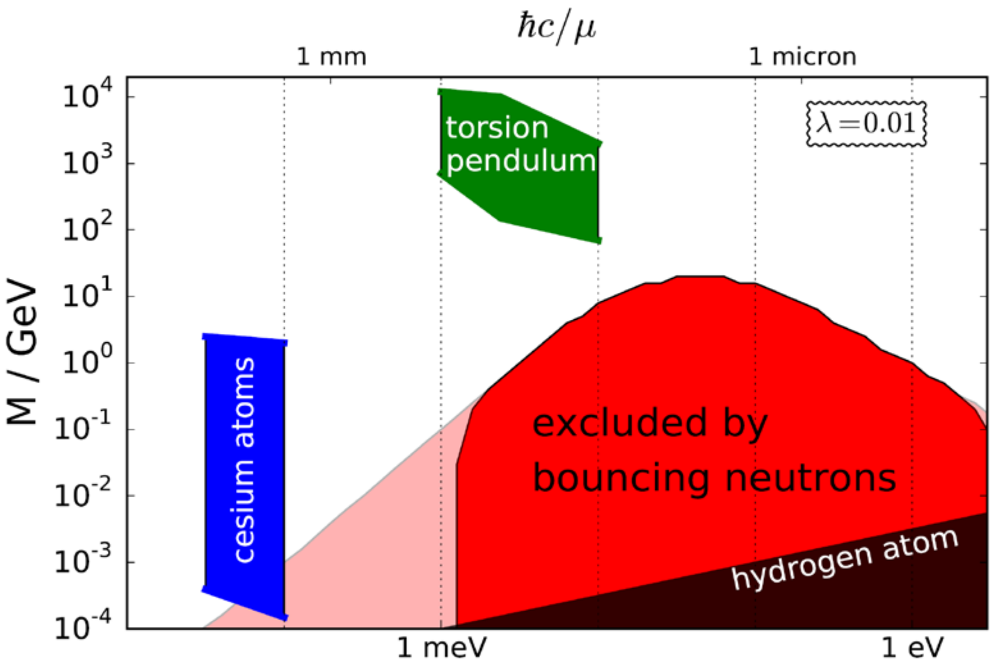
$\rho_M = 1.082 \times 10^{-5}$ MeV^4

$\rho_{\rm eff} = 4.570 \times 10^{-6}$ MeV^4

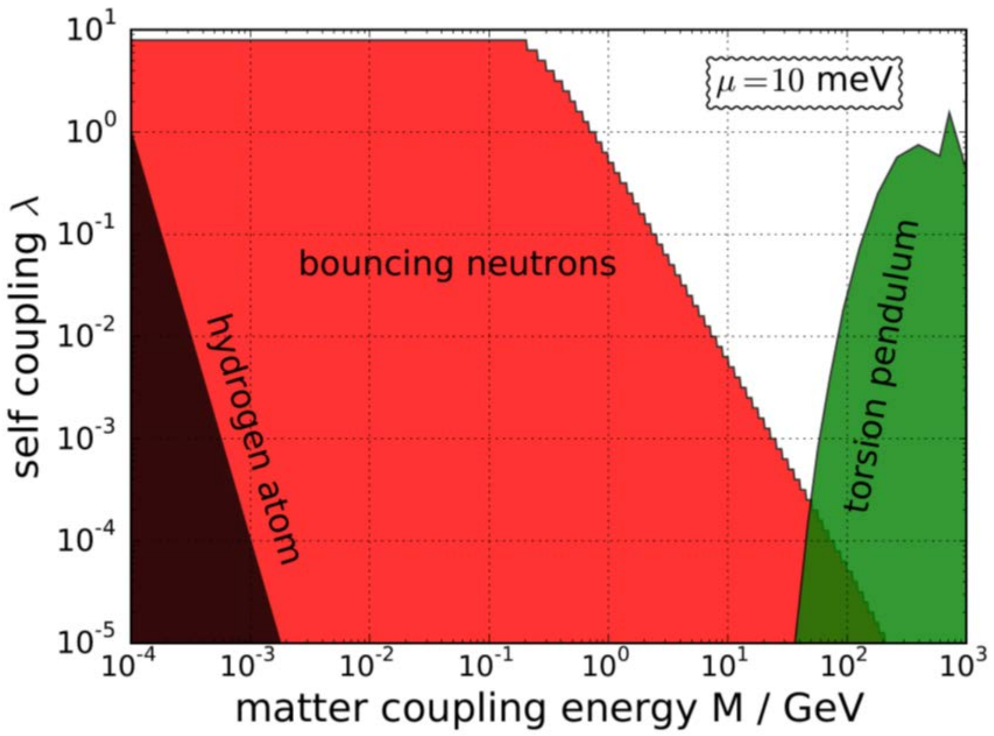


Symmetron Field

- **Mass M vs Range μ**



- **λ vs Mass M**

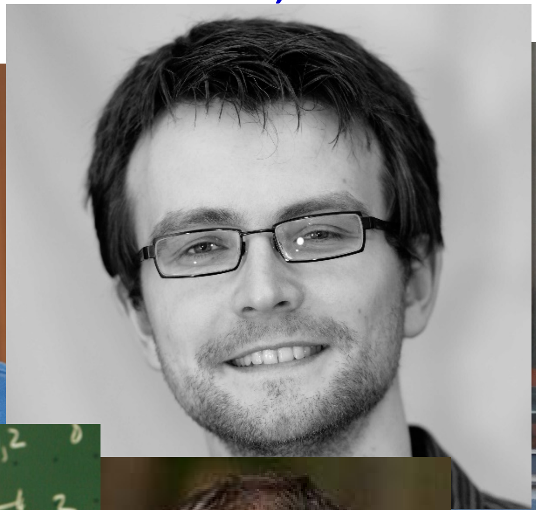
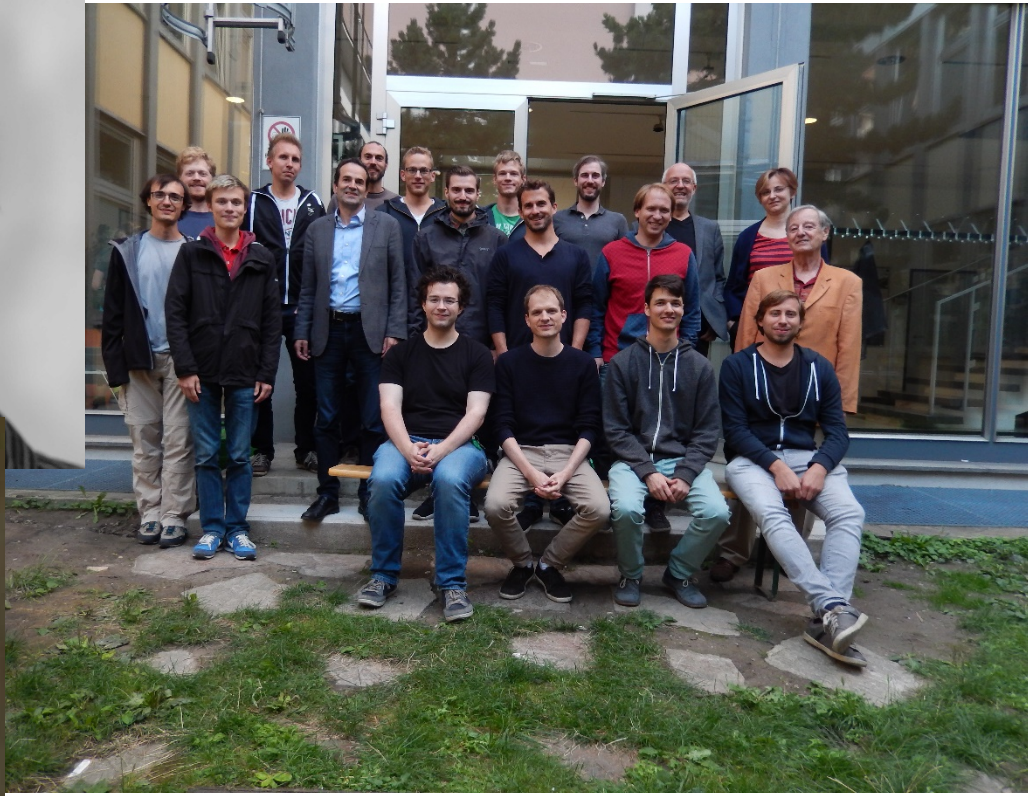


Cronenberg et al., NP 2018

The Team at Atominstitut & ILL

- Gravity tests with quantum objects
  - T. Jenke, G. Cronenberg, J. Bosina, R. Sedmik, J. Micko, H. Filter, P. Geltenbort (ILL), M. Heumesser, H. LemmelM. Thalhammer, T. Rechberger, P. Schmidt, J. Herzinger, M. Pitschmann,
    Collaboration P. Geltenbort, U. Schmidt



free fall at short distances

- ***qBounce*** **-** Quantum Bouncing Ball:
  - Mathematical description with Airy-Functions
- Measurements of Airy-Wave-Functions in the gravity potential of the Earth
  - Fall height: 30µm
  - Mirror, polished glass
- Gravity Resonance Spectroscopy: Proof of Principle
  - Aim: $\Delta E = 10^{-21}$ eV
- Test of Equivalence Principle
- Test Newton‘s Law at short distances
  - Search for hypothetical gravity-like forces, LV, effects of string theories, higher dimensional field theories etc.