How to search for Dark Energy and Large Extradimensions of Spacetime at the ILL

- A review of the qBOUNCE experiment -

Tobias JENKE

Public Talk of 103rd Scientific Council of the Institut Laue-Langevin

06/11/2020

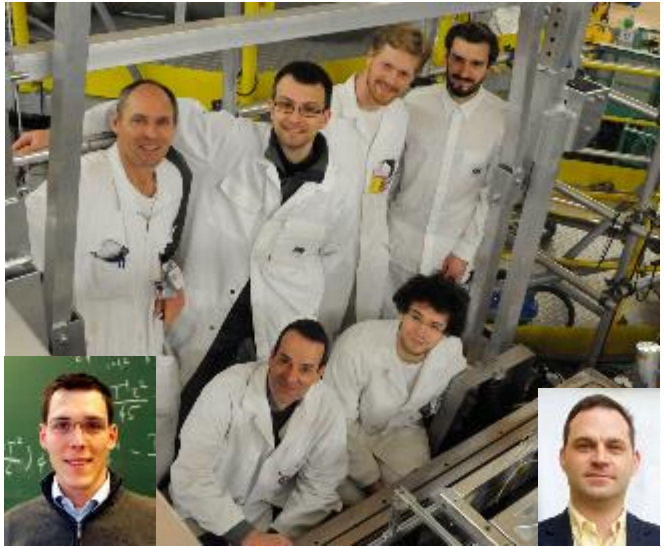
qBounce

- Team Members:
  - Experimentalists: H. Abele (PI), J. Bosina, T. Jenke (ILL), J. Micko (ILL), R.I.P. Sedmik, M. Thalhammer
  - Theory support: M. Pitschmann, A. Ivanov
  - ILL support: P. Geltenbort, S. Roccia, T. Brenner

- Collaborations:

Theory:	J. Burgdörfer, S. Rotter (TU Wien)	Localization
	P. Brax (CEA), G. Pignol (LPSC)	Symmetrons
	G. Manfredi (U. Strasbourg)	chirped excitations
Technology:	U. Schmidt, M. Klein, T. Lauer	Detectors, ALPs
	N. Naganawa, K. Mishima	Track Detectors
The « Miracle »	A. Young	

- Alumni:
  - G. Cronenberg, H. Filter, L. Chizhova, T. Rechberger



Outline:

- Intro: Large Extradimensions of Spacetime and Dark Energy
- (Ultracold) Neutrons for Gravity Experiments!
- Recent Results:
    - Observation of a Quantum Bouncing Ball
    - Ramsey Spectroscopy of Gravitationally Bound UCN
    - Limits on the existence of Dark Energy

Dimensions of Space and Time

Meeting

From Wikipedia, the free encyclopedia

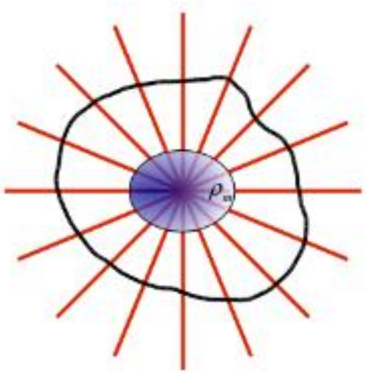
A **meeting** is when two or more people come together to discuss one or more topics, often in a formal or business setting, but meetings also occur in a variety of other environments. Many various types of meetings exist.

Relation between Spatial Dimensions and Gravity

- Imagine you want to organize a MEETING…
    - Three coordinates of space to define the **place**.
    - One time info to define the **time**.

  We live in a 3+1D world.

- Link between number of spatial dimensions and Gravity:



$$\vec{\nabla} \cdot \vec{g} = -4\pi \, G \, \rho_m$$

$$\vec{g} = -\vec{\nabla}\phi$$

$$\Delta\phi = 4\pi \, G \, \rho_m$$

$$\phi(r) = -\frac{G \, m}{r}$$

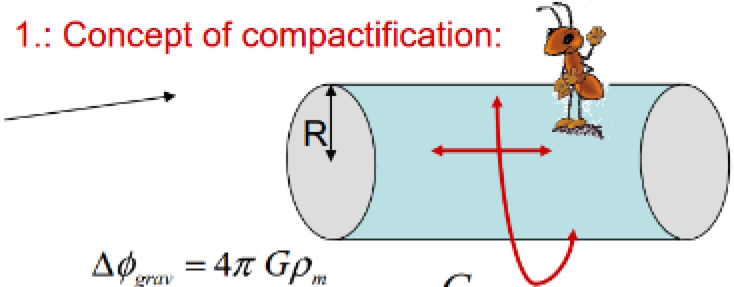
Integral law of Gauss:

$$\int_V \nabla \cdot \vec{A} \, dV = \int_S \vec{A} \cdot d\vec{\sigma} \, .$$

- “We live in three spatial dimensions.” is equivalent to “The gravity potential scales with one over the distance.”

Large Extradimensions of Spacetime

1.: Concept of compactification:



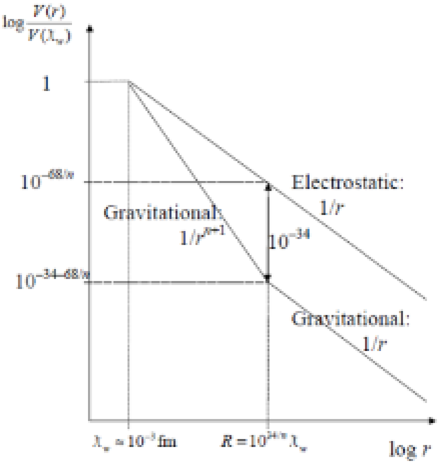
$$\Delta\phi_{grav} = 4\pi G\rho_m$$

$$\phi_{grav} \sim \frac{G_n}{r^{n-2}}$$

Are we sure that we live in a 3+1-dimensional world?

- Gravity is VERY weak….
  The weak force is 10 000 000 000 000 000 000 000 000 000 times stronger than the gravitational force.
- General Relativity is a classical field theory, the Standard Model of Particle Physics is a quantum field theory….

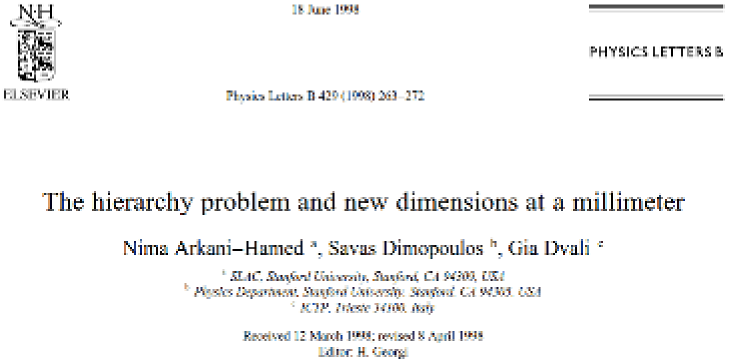
- Possible Solutions:
  - (Compactified) Extradimensions of Space-Time



$$V_{grav}(r) = -G\frac{mM}{r}, \text{ for } r >> R.$$

$$V_{grav}(r) = -G^*\frac{mM}{r^{n+1}}, \text{ for } r << R$$

$R \approx 0.1$ m for $n = 2$;
$R \approx 0.2$ μm for $n = 3$;
$R \approx 0.3$ nm for $n = 4$;
$R \approx 0.5$ pm for $n = 6$, i.e., for $4 + n = 10$ dimensions.


ELSEVIER
18 June 1998
PHYSICS LETTERS B
Physics Letters B 429 (1998) 263–272

The hierarchy problem and new dimensions at a millimeter

Nima Arkani–Hamed [a], Savas Dimopoulos [b], Gia Dvali [c]
[a] SLAC, Stanford University, Stanford, CA 94309, USA
[b] Physics Department, Stanford University, Stanford, CA 94305, USA
[c] ICTP, Trieste 34100, Italy

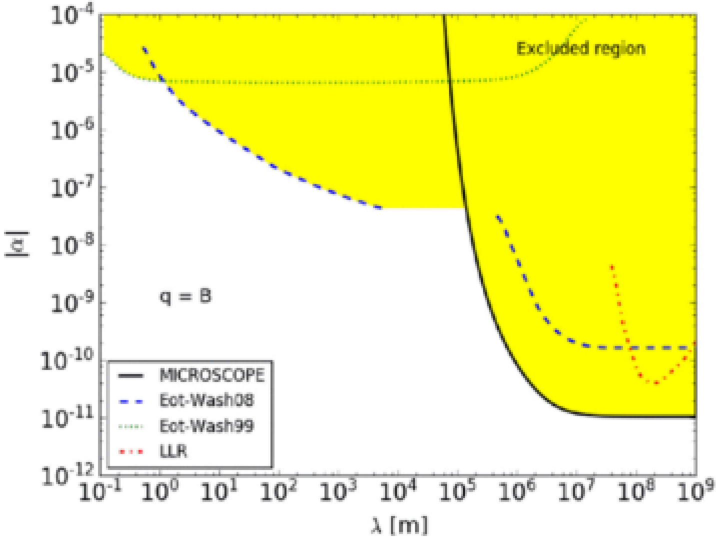
Received 12 March 1998; revised 8 April 1998
Editor: H. Georgi

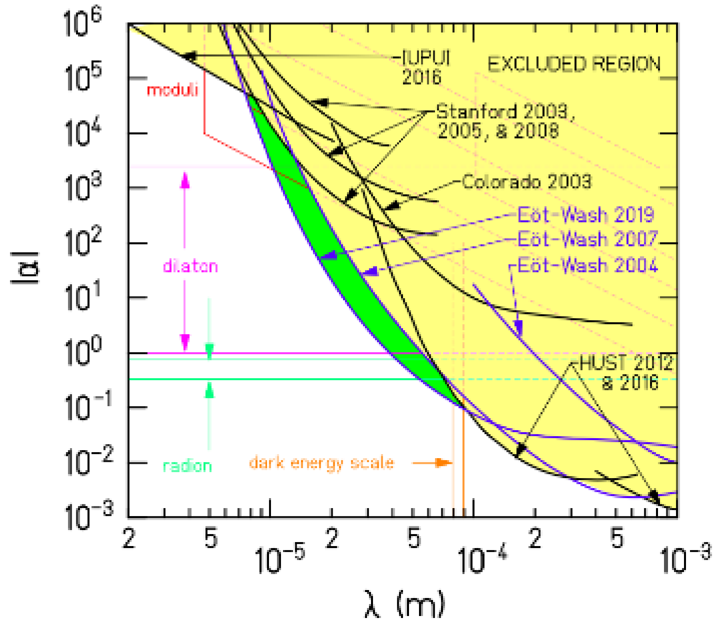
[1] ADD, Phys. Lett. B 429, 263 (1998).
[2] Dubbers, Schmidt: Rev. Mod. Phys. 83, 1111 (2011).

Consequence: Gravity Experiments at Short Distances!

Are we sure that we live in a 3+1-dimensional world?

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





[1] J. Bergé et al., Phys. Rev. Lett. 120, 141101 (2018).
[2] J. G. Lee et al., Phys. Rev. Lett. 124, 101101 (2020).

The expanding Universe

Postulated and Observed in the 1920s

1912 | 1922 | 1927 | 1929

Vesto SLIPHER:
Distant Galaxies are redshifted!

Alexander FRIEDMAN:
Theoretical basis for expanding Universe

Georges LEMAÎTRE:
Independently develops equations for exp. Universe and postulates linear relationship between distance to galaxies and recessional velocity

Edwin HUBBLE:
observes and confirms Lemaitres postulates

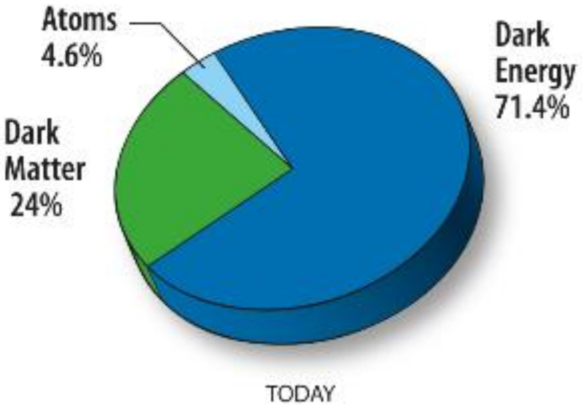
Friedmann-equations

Hubble-Lemaître-law

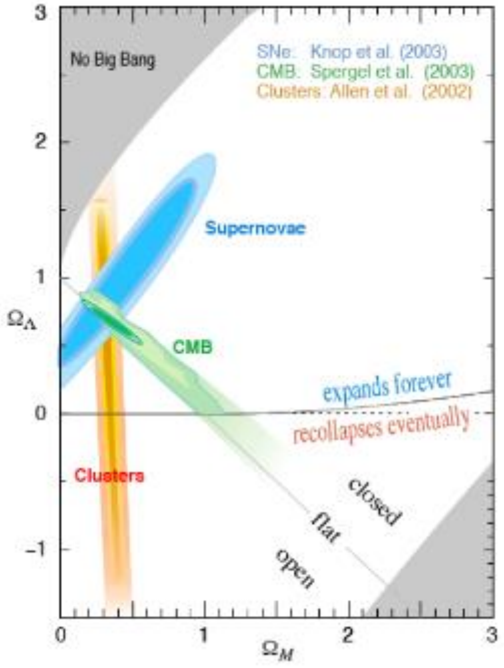
A surprising Discovery in 1998

Yet another mystery in Cosmology

- Naive expectation: The expansion is always decelerating because of the gravitational attraction of matter in the Universe.
- Observations show the opposite…



"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



- How to Explain the origin of Dark Energy?
    - Cosmological Constant?
    - New Fields?
    - Modified Gravity?

[1] P. Touboul et. al, PRL 119, 231101 (2017).

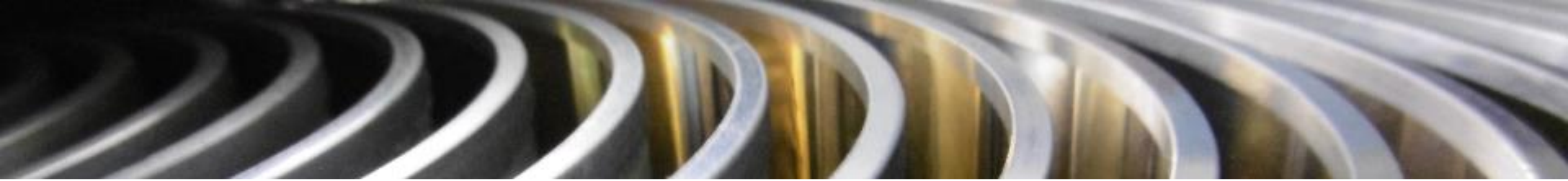
Example of a „New Field“: Chameleon Dark Energy

Basic Principles

- Idea: Dark Energy could be realized in nature in terms of a scalar field with a coupling to matter...
- Problem: The resulting long-ranged force is experimentally excluded.
- 2nd try:
  Introduce a scalar field with a self-interaction and a coupling to matter, resulting in a screening mechanism:

$$V_{\mathrm{eff}}(\phi) = V(\phi) + \rho e^{\beta\phi/M} \qquad V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n}$$

- Effective mass depends on the mass density around
  - High density -> high mass -> low range -> tiny force
  - Low density -> effective mass has the size of the current Hubble parameter
    -> interaction range of kilo-parsecs.
    Universe expands -> effect gets enhanced -> acceleration!
- Obvious Problem: Theory cannot be tested...
- Neutrons as fundamental particles would not be affected by the screening and gravity experiments with neutrons can test it [1].



Conclusion:
(Ultracold) Neutrons
for Gravity Experiments!

Neutrons & Gravity Experiments

Key elements for high accuracy-experiments

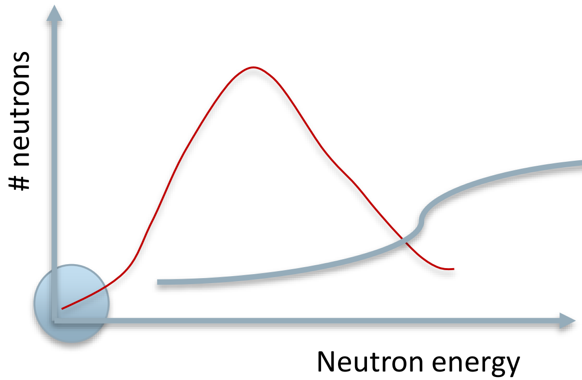
- Neutrons are **massive** particles.
- Neutrons are **electrically neutral**.
- Neutrons only possess a **tiny electric polarizability**.
- Neutrons are sufficiently **long-lived** to carry out experiments.

n $\qquad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.0086649159 \pm 0.0000000005$ u
Mass $m = 939.565413 \pm 0.000006$ MeV [a]
$(m_n - m_{\bar{n}})/\ m_n = (9 \pm 6) \times 10^{-5}$
$m_n - m_p = 1.2933321 \pm 0.0000005$ MeV
$= 0.00138844919(45)$ u
Mean life $\tau = 879.4 \pm 0.6$ s $\quad (S = 1.6)$
$c\tau = 2.6362 \times 10^8$ km
Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.18 \times 10^{-25}$ e cm, CL = 90%
Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm^2 $\quad (S = 1.3)$
Magnetic radius $\sqrt{\langle r_M^2 \rangle} = 0.864^{+0.009}_{-0.008}$ fm
Electric polarizability $\alpha = (11.8 \pm 1.1) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (3.7 \pm 1.2) \times 10^{-4}$ fm^3
Charge $q = (-0.2 \pm 0.8) \times 10^{-21}$ e
Mean $n\bar{n}$-oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free n)
Mean $n\bar{n}$-oscillation time $> 2.7 \times 10^8$ s, CL = 90% [g] (bound n)
Mean nn'-oscillation time > 448 s, CL = 90% [h]

Ultracold Neutrons (UCN)

A thought experiment



very low energy
= large wavelength
= total reflection under all angles

Precise calculation:
neutron optical potential E_F

$$E \propto 10^{-7}\,\mathrm{eV}$$
$$\lambda \propto 1000\ \text{Å}$$
$$\mathrm{v} \propto 5\ \mathrm{m/s}$$
$$T \propto mK$$

The UCN miracle

A practical definition

Ultra-cold neutrons (UCN) are neutrons, that are totally reflected from surfaces of suitable materials under all angles of incidence, hence storable.

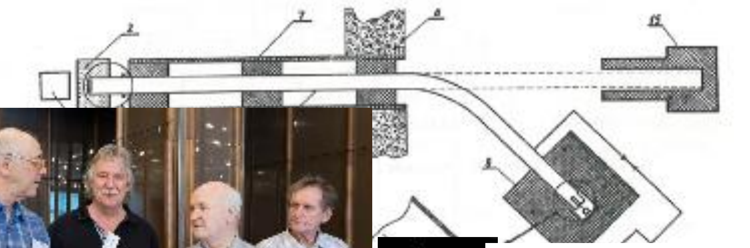
Strong interaction Neutron optical potential	$E_F \propto 100\ \mathrm{neV}$ Inox: 200neV Alu: 54 neV
Gravity $\Delta E = m_n\, g\, \Delta h$	~ 100 neV / Meter
Magnetic field $\Delta E = \mu_n\, B$	~ 60 neV / Tesla

UCN are storable by material traps, gravity and/or magnetic fields!

Storage and observation times of several minutes are feasible.

High precision measurements of the properties of the free neutron (lifetime, electric dipole moment, gravitational levels, …)

UCN discovery (1969)


OBSERVATION OF ULTRACOLD NEUTRONS

V. I. Lushchikov, Yu. N. Pokotilovskii, A. V. Strelkov, and F. L. Shapiro
Joint Institute for Nuclear Research
Submitted 18 November 1968
ZhETF Pis. Red. 9, No. 1, 40 - 45 (5 January 1969)

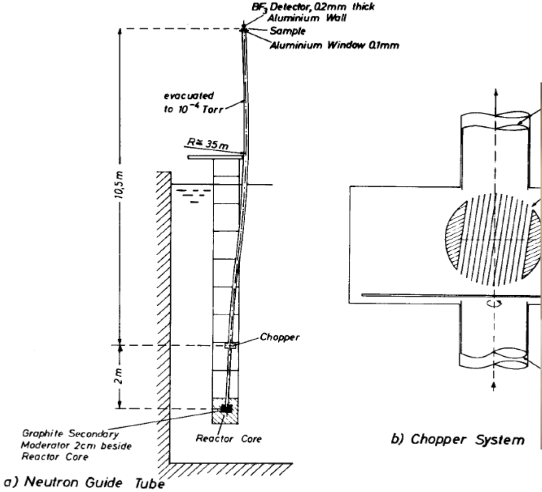
reactor [3] operating at an average power of 6 kW at a flash repetition frequency of one every 5 sec. The flux of thermal neutrons in the polyethylene moderator 3 was 1.6×10^{10} neut/cm^2-sec. This moderator was placed in a standard copper tube of 9.4 cm i.d. and 10.5 m length, the inside surface of which was bright-dipped; a vacuum of 5×10^{-3} mm Hg was maintained in the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers covered with a scin-

F. L. Shapiro

Yu.N. Pokotilovskii, V.I. Lushchikov, A.V. Strelkov

JETP Lett. 9 (1969) 23

… by extracting neutrons from the low energy tail of the distribution in the source


Volume 29B, number 1 PHYSICS LETTERS 31 March 1969

found to obey the 1/v law.

Palmgren [1,2] was the first to perform total cross-section measurements for neutrons as slow as 42 m/s in a "Doppler chopper" where the target moved in the same direction as the neu-

Fig. 1. Vertical beam tube for very slow neutrons.

A. Steyerl

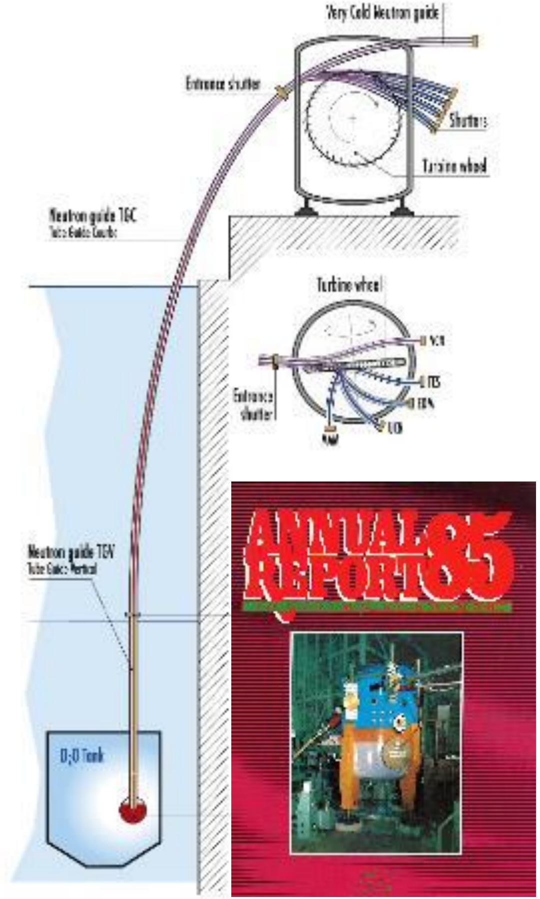
Phys. Lett. 29B (1969) 33

Ultracold and Very Cold Neutron Facility PF2

« The workhorse of UCN physics since 1985 »

• Name of the instrument:	PF2 („physique fondamentale 2“)
• Type of instrument:	source of ultracold neutrons (UCN)
• Age:	born in 1985 (35 years old)
	Scheduled instrument since 1994 replacing PN5
• Adress:	ILL5, level D
• Fathers:	Albert STEYERL & Paul AGERON

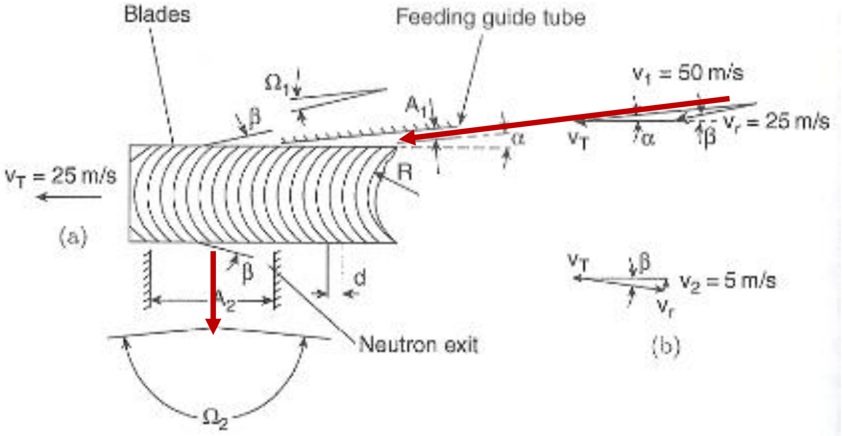
- AS was one Discoverer of UCN in 1969
  [Phys. Lett. 29B (1969) 33]
- A.S. built a device today known as „Steyerl turbine“ at TU München, installed at level D in 1985
- P.A. designed the concept to feed the turbine with neutrons



Principle of the « Neutron Turbine »

« The workhorse of UCN physics since 1985 »

- Principle of a „tennis ball stopped by a receding racket“ [A.S.]



- The PF2 turbine transforms VCN with 50m/s to UCN (5m/s) by roughly 10 reflections.
- The guide section and divergence are increased by a factor of 10.

Principle of the « Neutron Turbine »

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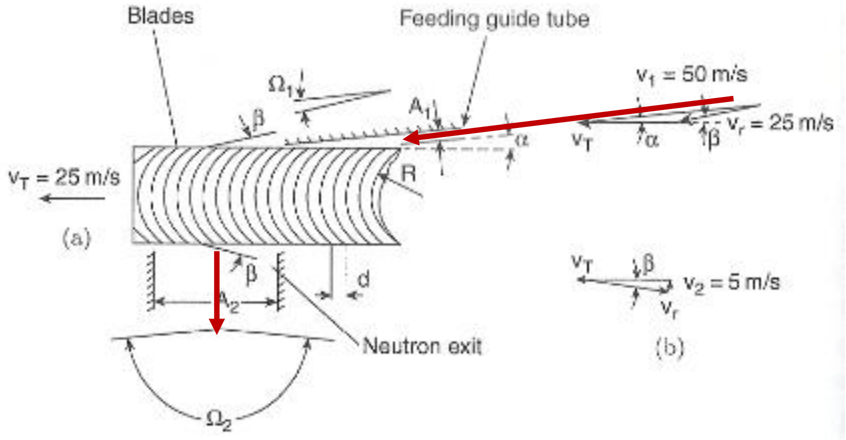

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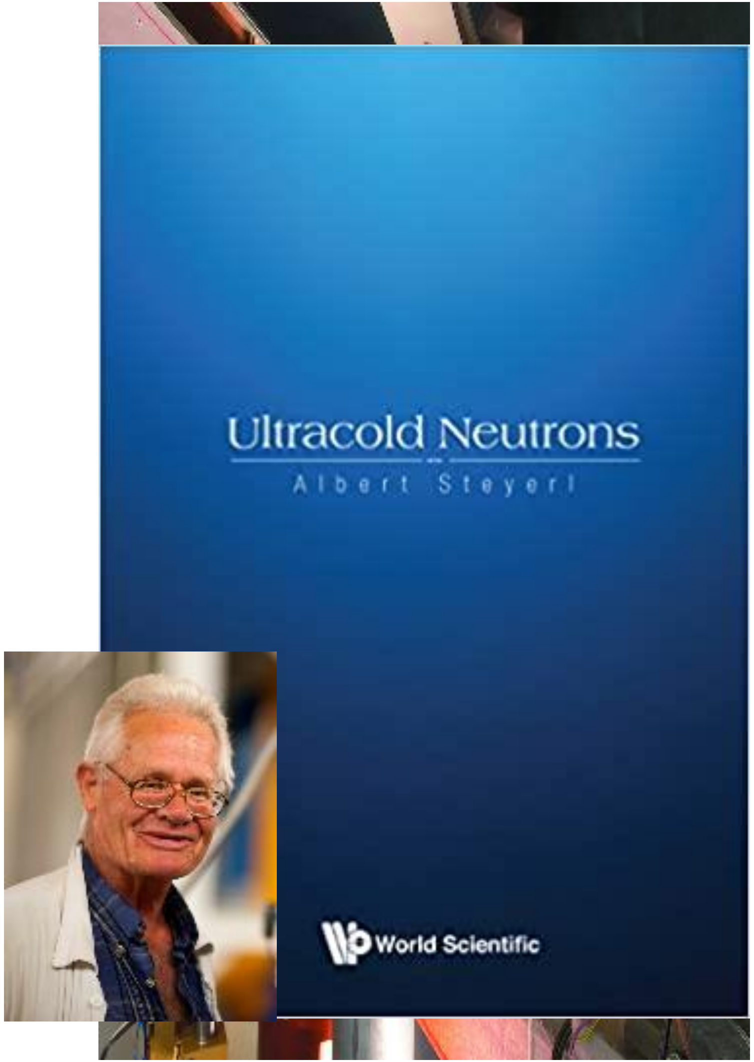


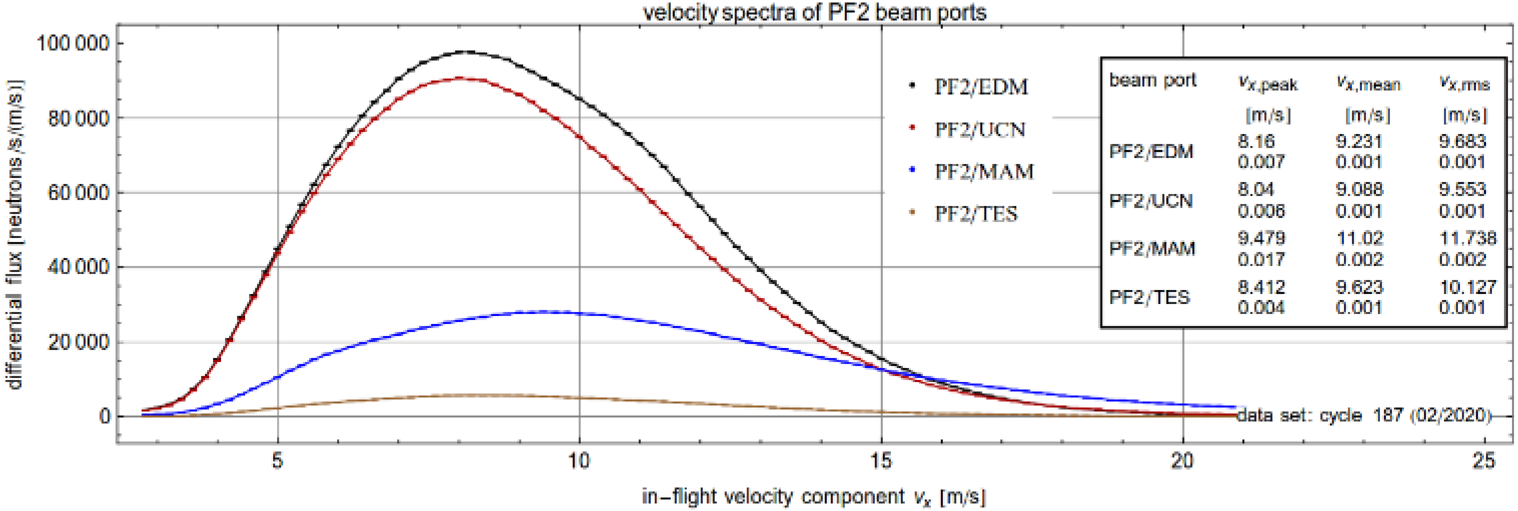
PF2 today: Available UCN flux

…recent data (February 2020)

Total output:

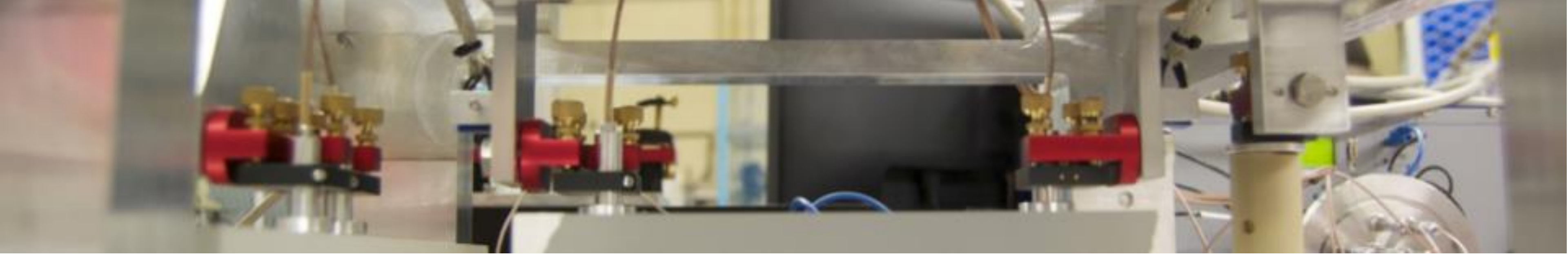
- PF2/EDM: 733.000 cps (no corrections applied) (detector efficiency: 80%)
- PF2/UCN: 89.7% of PF2/EDM
- PF2/MAM: 36.9% of PF2/EDM
- PF2/TES: 05.9% of PF2/EDM

For PF2/EDM, the flux was measured at a distance of 1.5m behind the shutter. All measurements were performed with an Aluminium window (100µm) in place, necessary to separate the vacuum of the turbine from the vacuum of the experiment.



T. Jenke & S. Roccia

thanks to U. Köster (gold foil activation analysis) & M. Jentschel (help with optical calibration of the chopper)



Gravity meets Quantum Mechanics:

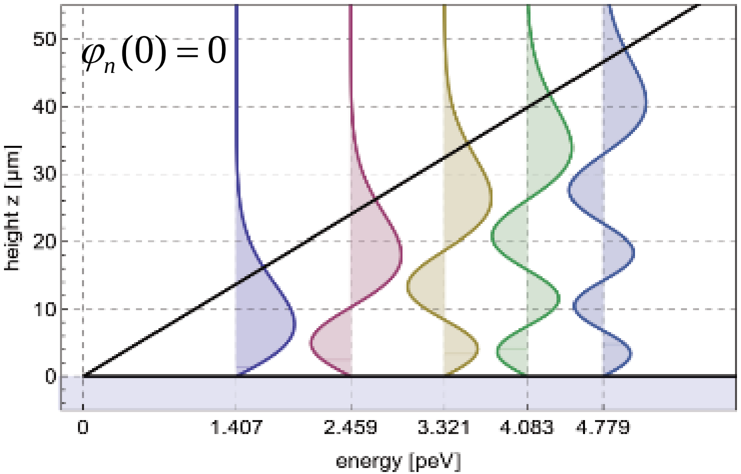
Gravitational Levels

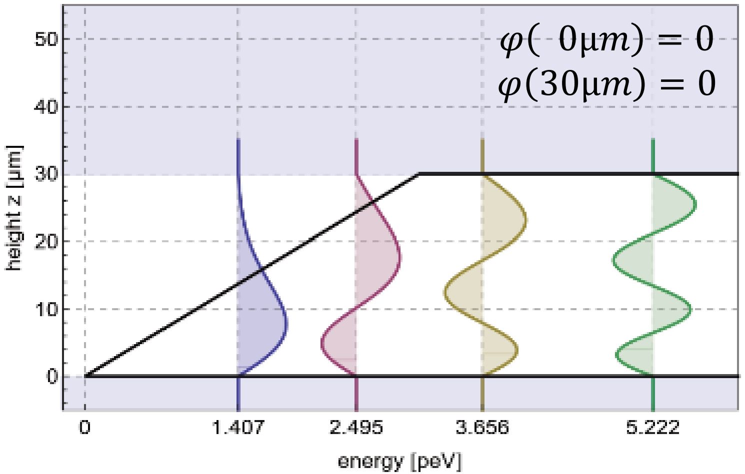
Gravitational Levels of (Ultracold) Neutrons...

A neutron in the gravity field of the Earth

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

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2m_i m_g g}} \approx 5{,}88\mu m \qquad E_0 = m_g g z_0 \approx 0{,}6\,\mathrm{peV} \qquad t_0 = \hbar E_0^{-1} \approx 1{,}1\,\mathrm{ms}$$





The Quantum Bouncer

... theoretically discussed since the beginning of the 1970s ...

- (Historical) Motivations:
  - purely academic
  - teaching:
    - Avoid problem of particle in a box
      (“complicated normalization (wavepackets)”)
    - Hydrogen atom too complicated….
    - Better:

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

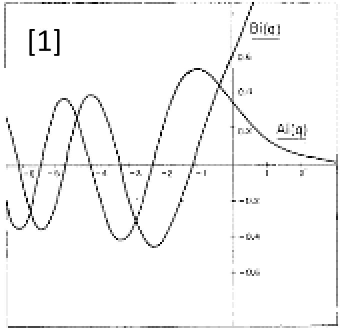


FIG. 2. The Airy functions $Ai(q)$ and $Bi(q)$. From Ref. 6.

Schrödinger Particle in a Gravitational Well

P. W. LANGHOFF
Department of Chemistry
Indiana University
Bloomington, Indiana 47401

(Received 15 January 1971; revised 11 March 1971)

Introductory quantum mechanics textbooks[1] generally include treatments of the one-dimensional Schrödinger equation for motion in a piece-wise constant potential (finite and infinite square wells, double wells, barrier scattering, etc.) and in the familiar harmonic oscillator potential. The pedagogically intermediate case of a potential linear in position arises in the interesting problem of Schrödinger particle dynamics in the uniform gravitational field,[2] in related connection with the equivalence principle,[3] and in simple WKBW-type treatments of the Schrödinger equation based on piece-wise linear approximations to smooth potentials.[4]

The Quantum Bouncer

R. L. GIBBS
Department of Physics
Louisiana Tech University
Ruston, Louisiana 71270

(Received 9 January 1974; revised 1 April 1974)

Examples in one and two dimensions for motion in a uniform gravitational field are considered quantum mechanically. The examples of bouncing in one dimension and sliding down an incline are proposed for use as conceptual aids in an introductory course.

[1] P. W. Langhoff, American Journal of Physics **39**, 954 (1971).
[2] R. L. GIBBS, American Journal of Physics **43**, 25 (1975).

First Proposal for Practical Realization

...from 1978!

- Discovery of Ultracold Neutrons in 1969
- Idea: separate quantum states by lowering a carefully designed and placed absorbing mirror ("absorber")

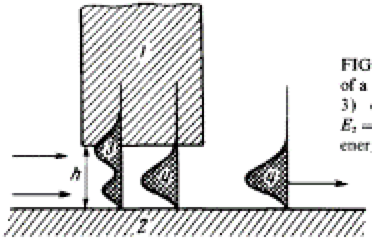


FIG. 2. "Flow" of UCN over a horizontal surface in the case of a gravitational potential. 1) absorber, 2) reflecting surface, 3) density of UCN with vetical-motion energy $E_2 = 2.45\times10^{-12}$ eV. 4) Density of UCN with vertical-motion energy $E_1 = 1.4\times10^{-12}$. Height of slit $h \simeq 20$ μm.

- predictions:
  - transmission of 10^{-3} of the total available flux
  - lifetime: 5000s

- 2^{nd} idea: magnify gravitational bound quantum states by inhom. magnetic fields:

$$F = mg \pm \mu \frac{\partial B}{\partial z}$$

- Predictions:
  - Lifetime: 20s
  - Level width: 3×10^{-17} eV

Quantum effects occurring when ultracold neutrons are stored on a plane

V. I. Luschikov and A. I. Frank

Joint Institute for Nuclear Research

(Submitted 12 September 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 9, 607–609 (5 November 1978)

The problem of storing ultracold neutrons (UCN) on a plane in the presence of a gravitational field is considered. The energy of the vertical motion is then quantized, and the wave functions of the first states are localized in space. The energy and linear dimensional constants of the problems are $\epsilon = 0.6\times10^{-12}$ eV and $\lambda = 0.3\times10^{-3}$ cm. A method is proposed for experimentally separating neutrons situated on the first energy level. Attention is called to the fact that an inhomogeneous magnetic field can be used to vary the values of ϵ and λ in a rather wide range.

PACS numbers: 28.20. — v, 14.20.Cg

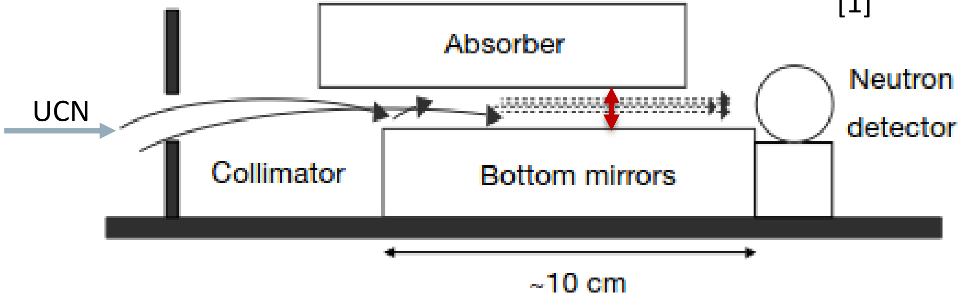
V.I. Luschikov and A. I. Frank, JETP Lett., Vol.28(9) (1978).

Discovery of Gravitational Levels

Integral flow-through-mode

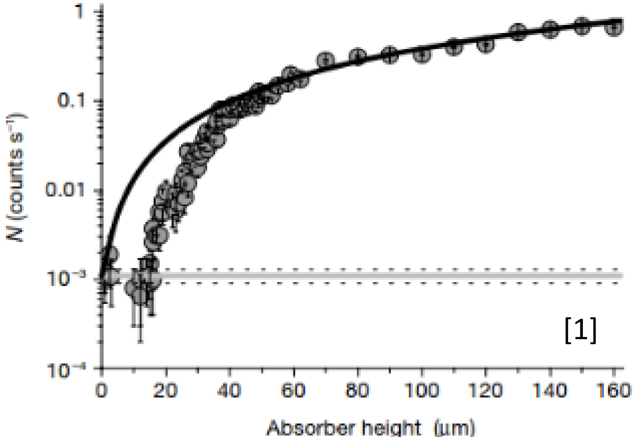
- Experimental series at PF2/UCN between 1999 and 2005
- Principle:

[1]

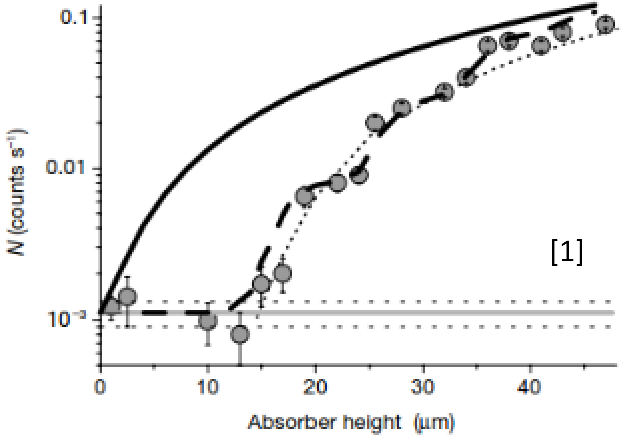


- Class. Expectation:

$$T \propto h^{3/2}$$

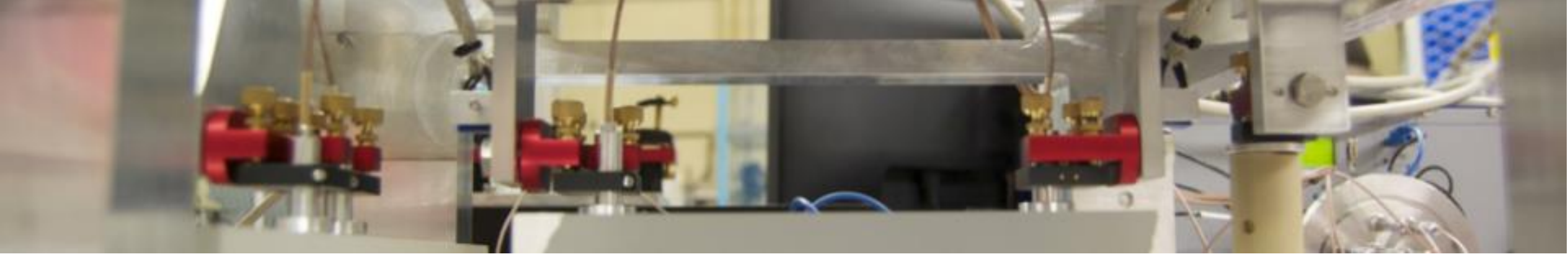


[1]



[1]

[1] V.V. Nesvizhevsky et al., Nature 415, p297 (2002).



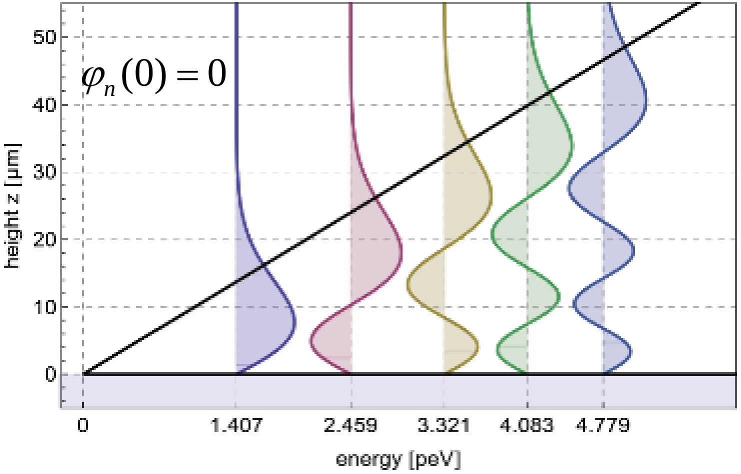
Snapshots of a falling wave packet

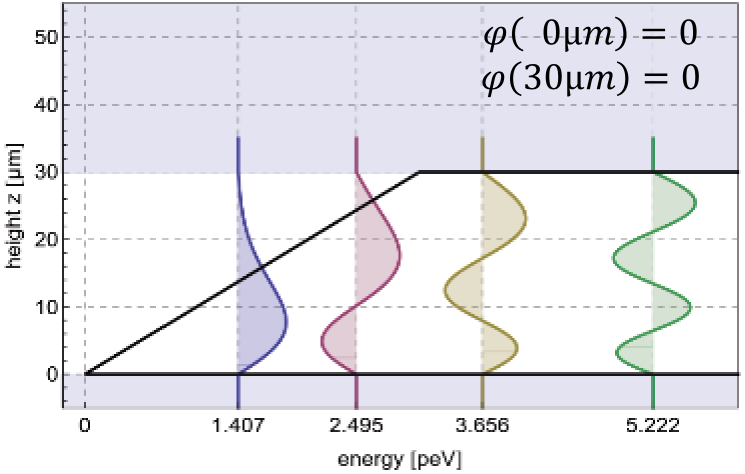
Gravitational Levels...

A neutron in the gravity field of the Earth

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

$z_0 = \sqrt[3]{\frac{\hbar^2}{2m_i m_g g}} \approx 5{,}88\mu m$ $\qquad E_0 = m_g g z_0 \approx 0{,}6\,\mathrm{peV}$ $\qquad t_0 = \hbar E_0^{-1} \approx 1{,}1\,\mathrm{ms}$





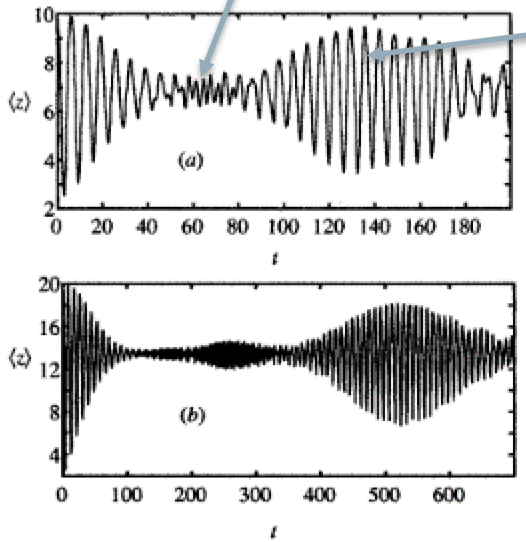
A Quantum-Bouncing Ball

The dynamics...

- The dynamics of the Quantum Bouncer surprises...

Collapse of the wave function

Revival of the Wave function



A quantum bouncing ball

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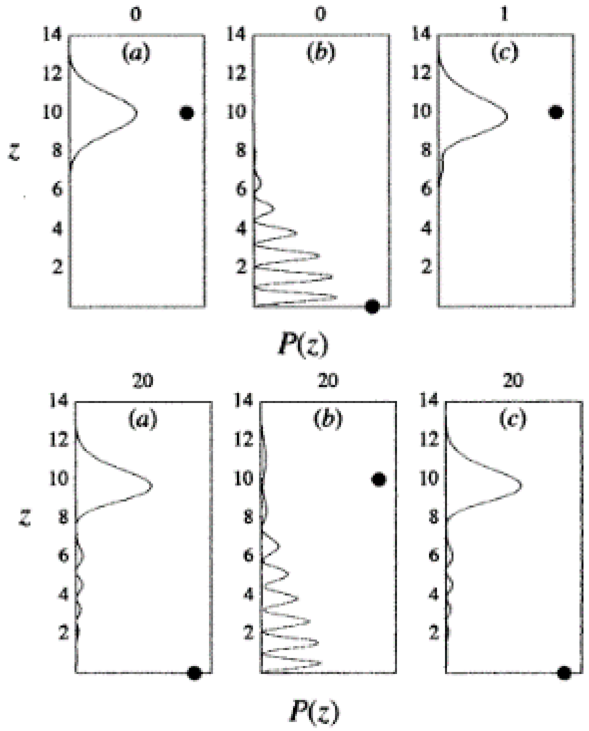
University of Arkansas, Fayetteville, Arkansas 72701

(Received 3 August 1998; accepted 21 January 1999)

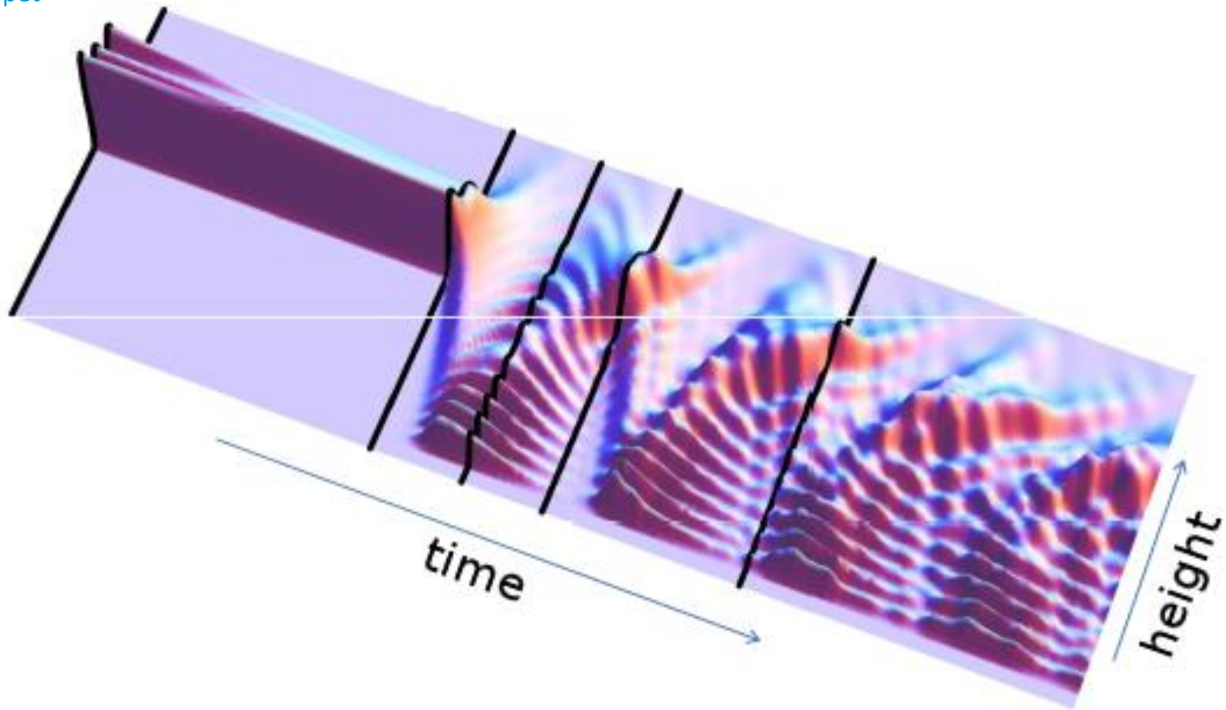
The dynamics of a quantum wave packet bouncing on a hard surface under the influence of gravity are studied. This is a system that might be realized experimentally with cold atoms dropped onto an "atomic mirror." The classical limit is discussed and interesting departures from classical behavior are pointed out and explained. © *1999 American Association of Physics Teachers.*



J. Gea-Banacloche, Am. J. Phys. 67(9) (1999).

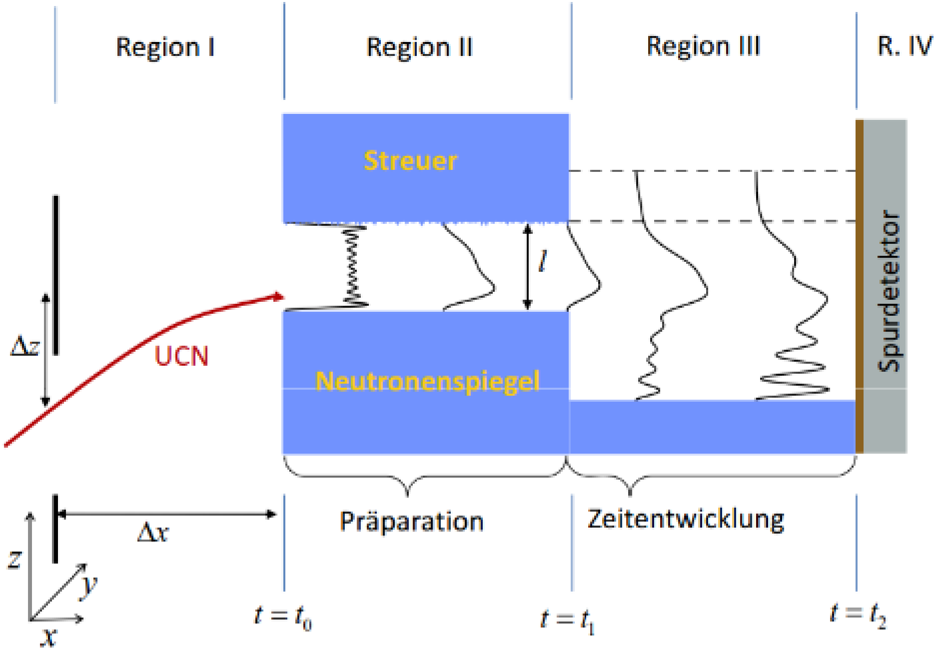
Time Evolution of a Quantum Bouncing Ball

The Quantum Carpet



Time Evolution of a Quantum Bouncing Ball

Exp. Realized in 2014

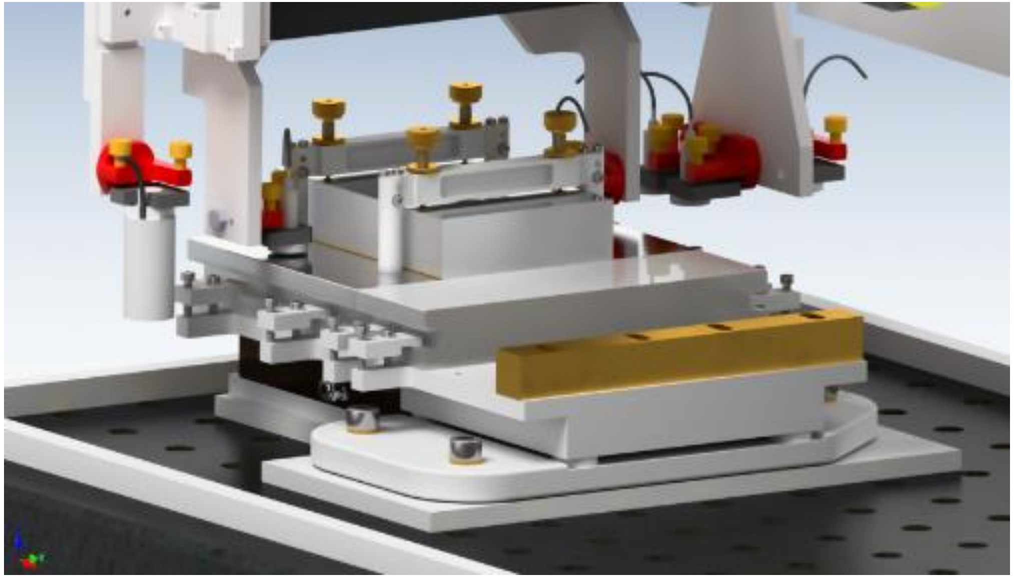


$$|\Psi(z,\tau)|^2 = \left|\sum_m d_m(\tau_0) e^{-i\omega_m \tau} \psi_m(z)\right|^2$$

$$d_m(\tau_0) = \sum_n c_n(\tau_0) e^{-i\phi_n} \langle \psi_m(z) | \varphi_n(z) \rangle \, e^{-i\omega_n \tau_0}$$

Time Evolution of a Quantum Bouncing Ball

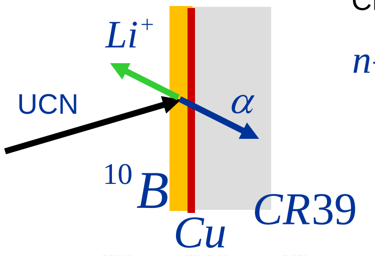
Exp. Realized in 2014



$$|\Psi(z,\tau)|^2 = \left|\sum_m d_m(\tau_0)e^{-i\omega_m\tau}\psi_m(z)\right|^2$$

$$d_m(\tau_0) = \sum_n c_n(\tau_0)e^{-i\phi_n}\langle\psi_m(z)|\varphi_n(z)\rangle\, e^{-i\omega_n\tau_0}$$

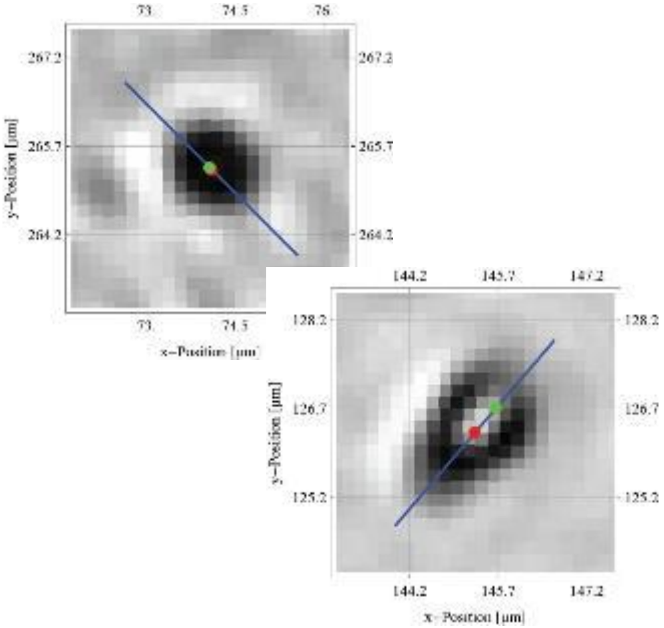
CR39 track detectors with Boron-10 converter

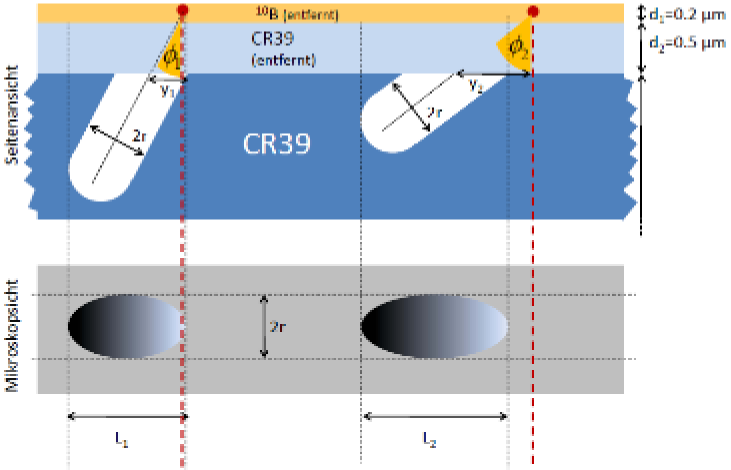


CR39-plastics with neutron converter (200nm ^{10}B)

$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha \quad \rightarrow \quad {}^{7}Li + \alpha + \gamma(0.48\,\mathrm{MeV}) + 2.31\,\mathrm{MeV} \quad 94\%$$

$$\rightarrow {}^{7}Li + \alpha + 2.79\,\mathrm{MeV} \quad 6\%$$

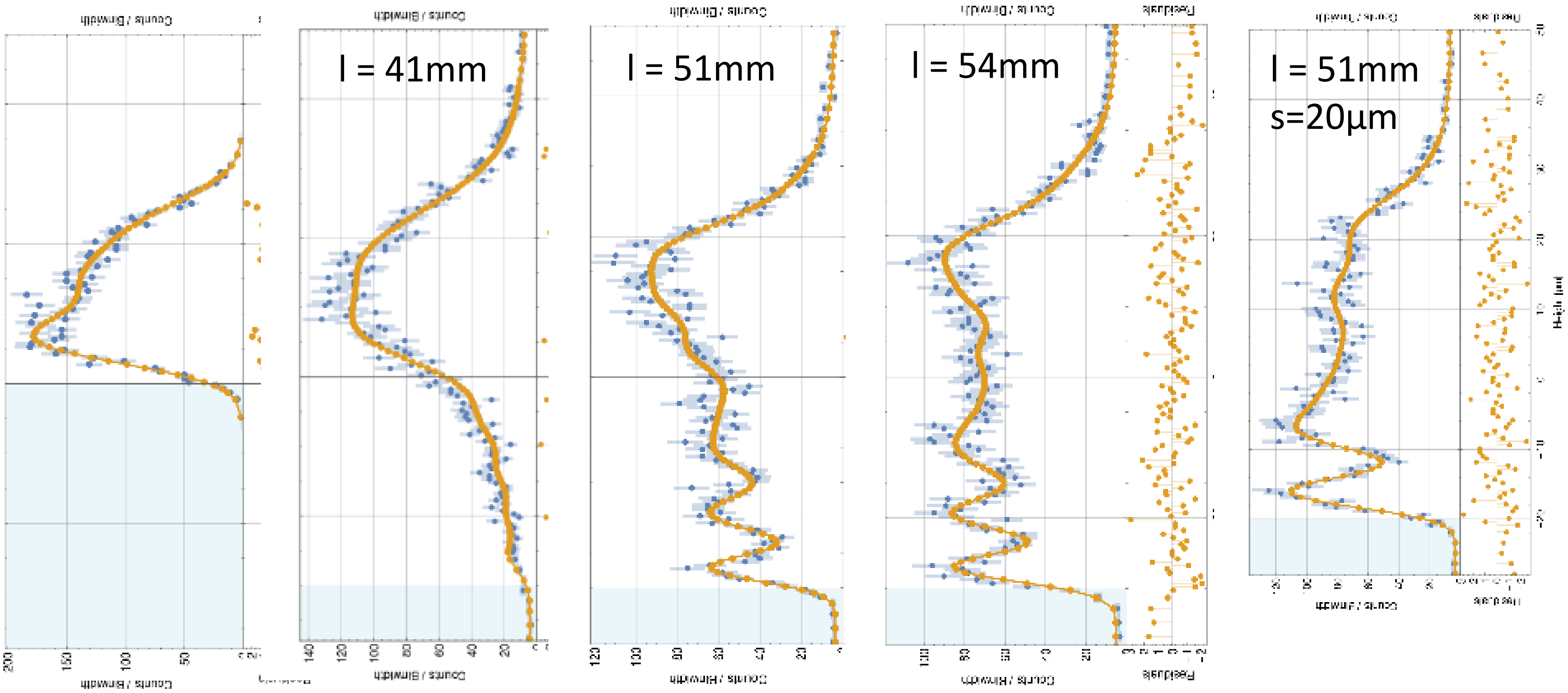




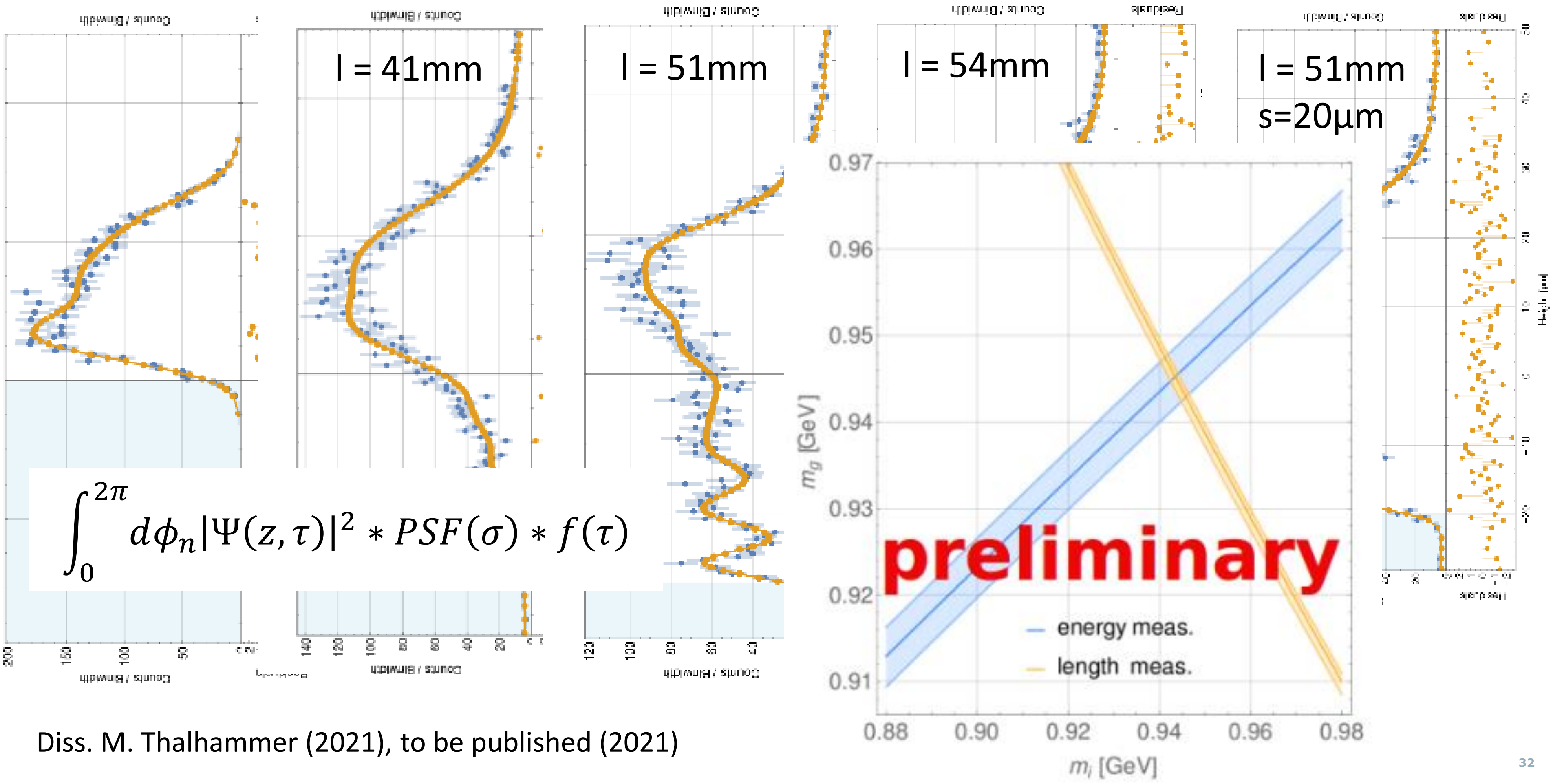
spatial resolution: 1,5..2,0μm

^{10}B efficiency: ≈ 91%

detector efficiency: ≈ 62%

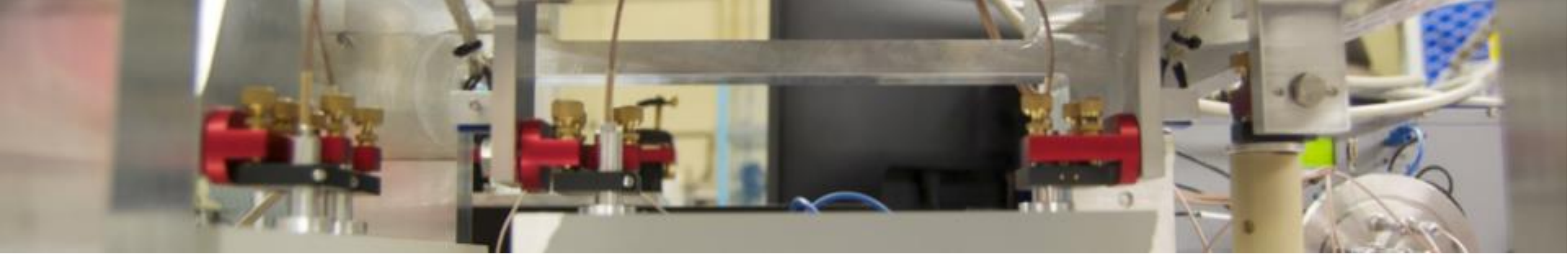


Diss. M. Thalhammer (2021), to be published (2021)



$$\int_0^{2\pi} d\phi_n |\Psi(z,\tau)|^2 * PSF(\sigma) * f(\tau)$$

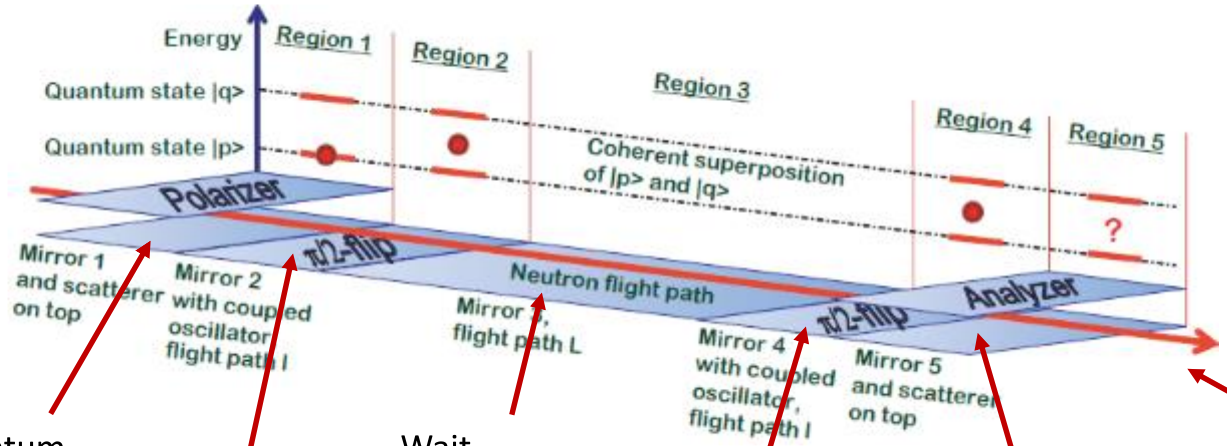
Diss. M. Thalhammer (2021), to be published (2021)



Ramsey Spectroscopy of Gravitational Levels

Measurement Principle

An adaption of Ramsey's method of separated oscillating fields



Prepare a quantum state $|p\rangle$

Create a coherent superposition

$$c_p|p\rangle + c_q|q\rangle$$

by an oscillating boundary condition

Wait...
(Time evolution)

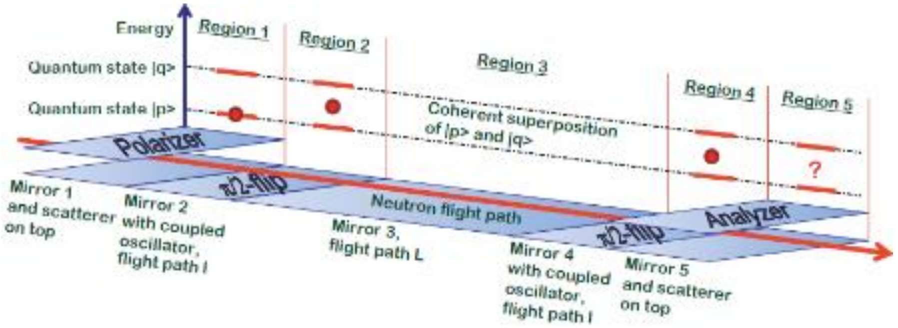
Repeat step 2

Analyze wrt. $|p\rangle$
(filter out the rest)

Count

Measurement Principle

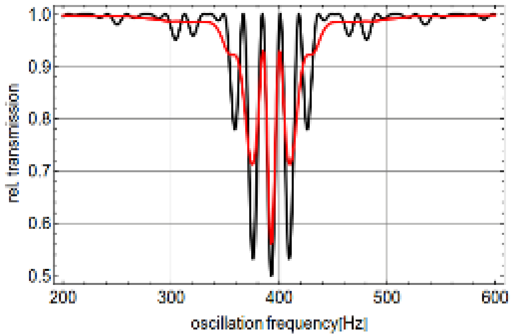
An adaption of Ramsey's method of separated oscillating fields



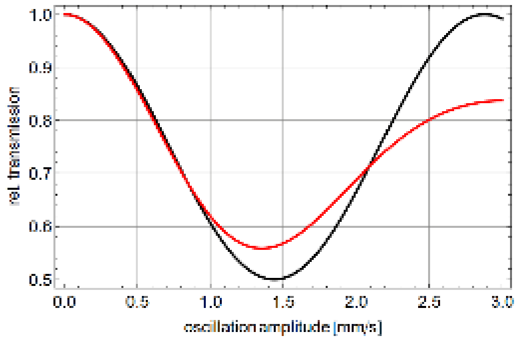
Advantages:

- Less oscillation amplitude needed
- Increase in Flux (due to insensitivity to TOF)
- Better sensitivity (as it is longer)
- Scalable (if one can afford the mirrors)

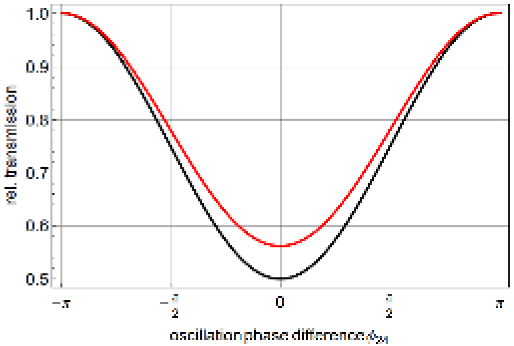
Transmission vs.
Oscillation Frequency



Transmission vs.
Oscillation Strength

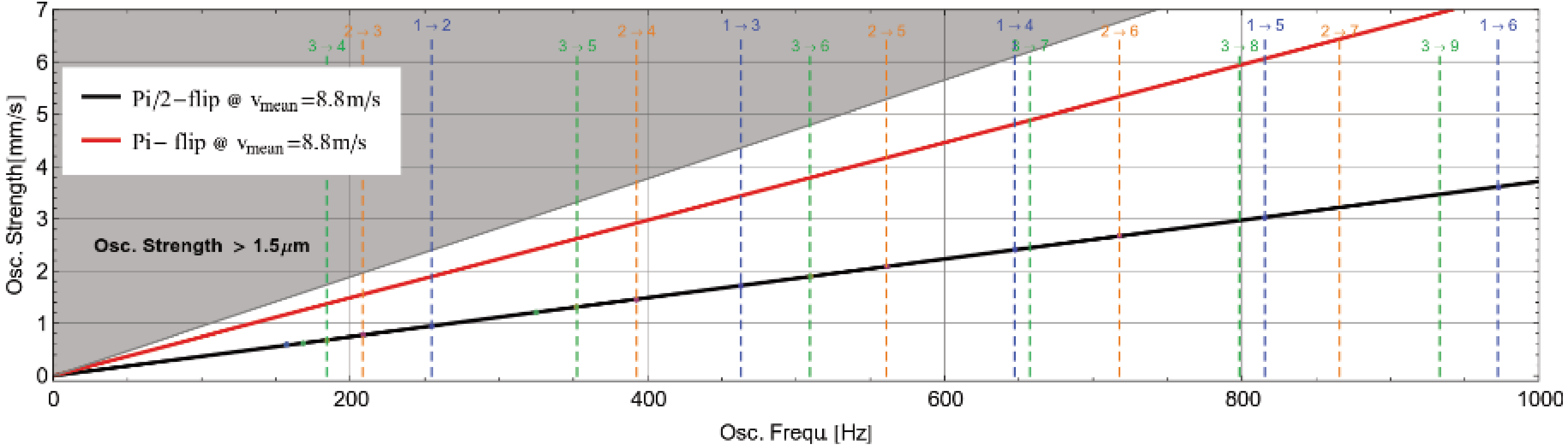


Transmission vs.
Rel. Phase



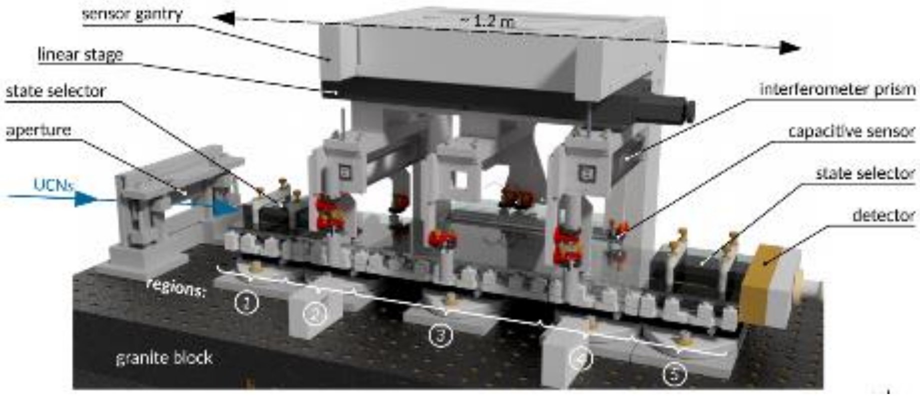
Resonances that can be addressed

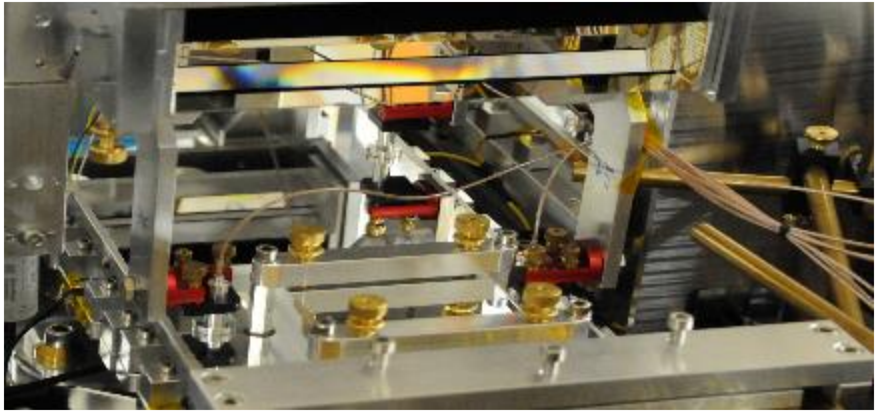
The energy eigenvalues are discrete and non-equidistant...

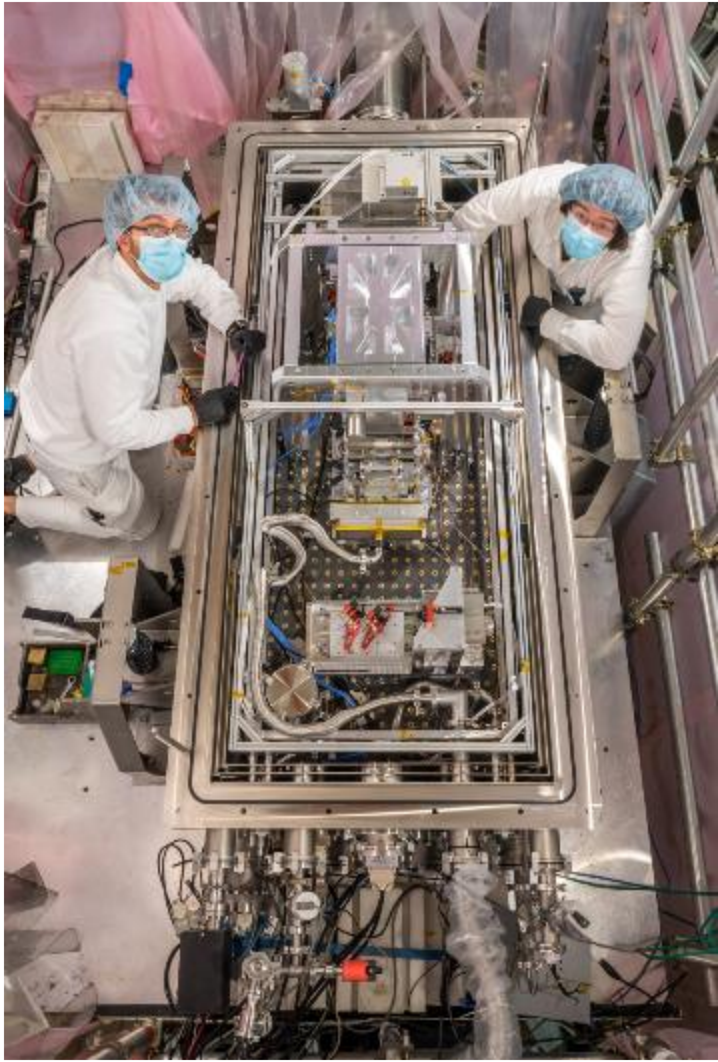


Some Impressions

The energy eigenvalues are discrete and non-equidistant...



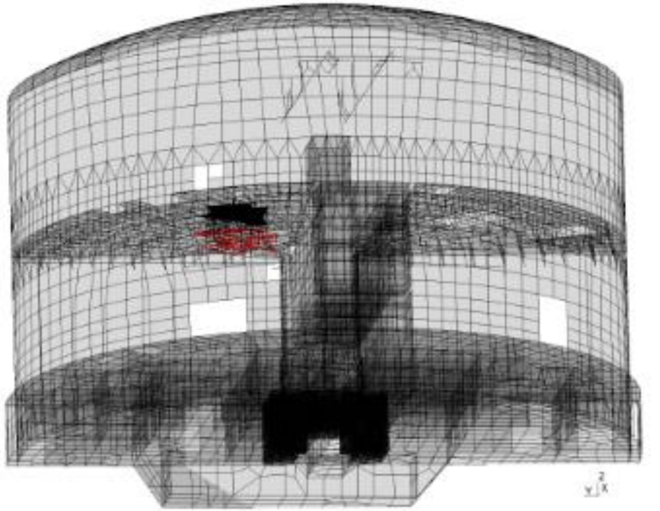


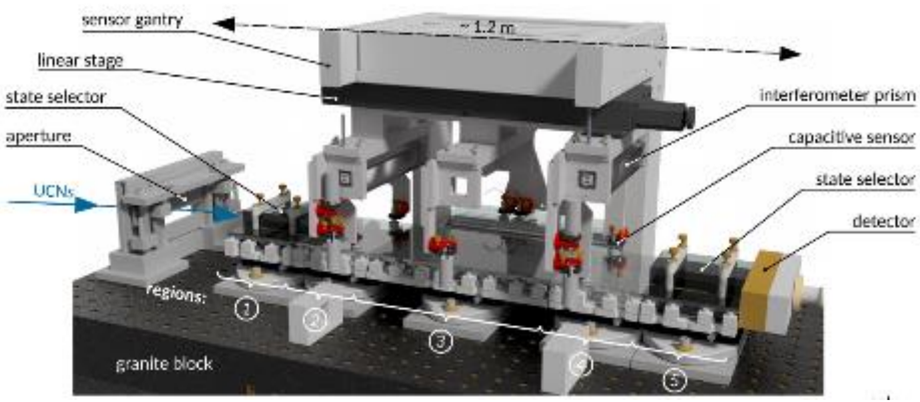


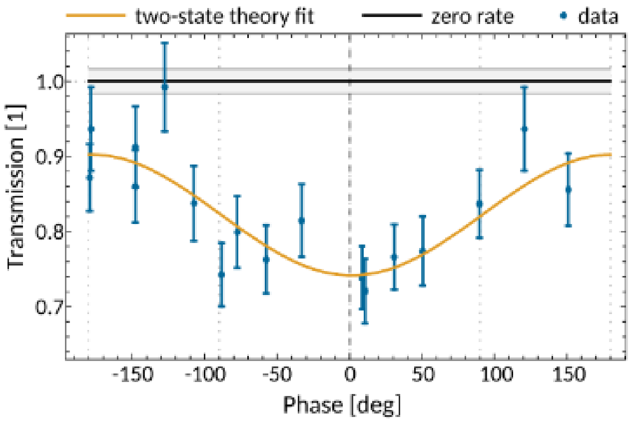
Commissioning of the spectrometer

A long way to go…

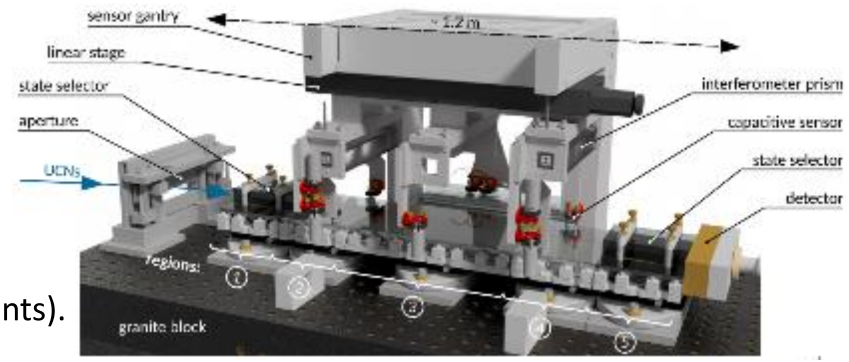
- The spectrometer arrived in 2016.
- Earthquake Reinforcement of Platform and Experiment.
- Beamguide Design (metal guides -> glass guides -> new metal guides).
- TOF analysis of the PF2/UCN guide
- Careful Beam monitor commissioning.
- New design of velocity collimating blades.
- New external control of vibrations, based on six laser beams.
- Enhanced design for step control.





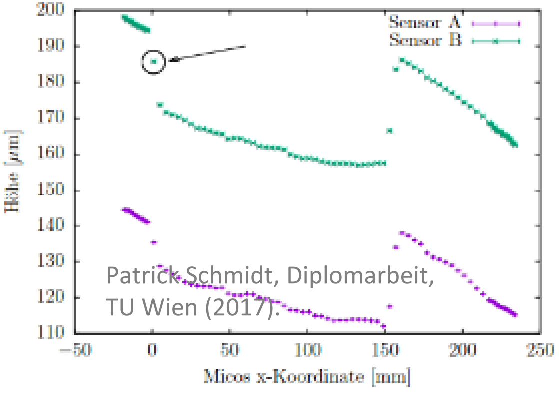


Challenges (2017-2019)

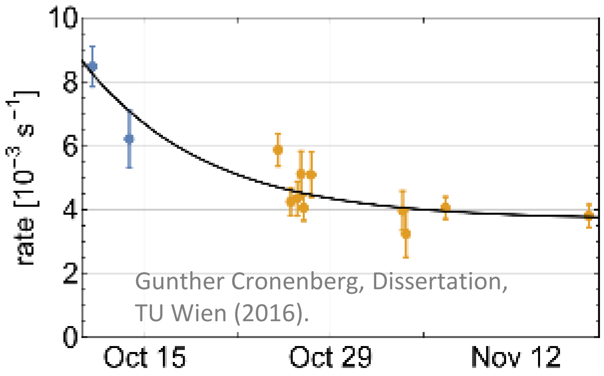


Commissioning of a Ramsey-type spectrometer

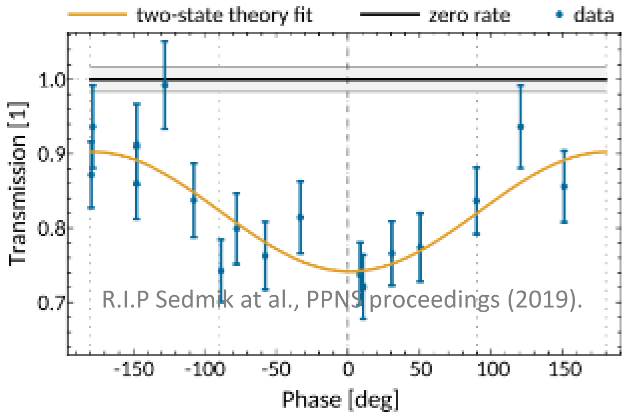
- The rate is lower than expected (from calculations).
- The contrast is lower than expected (from previous measurements). The rate does not reach the "zero rate" for 180° phase shifts.
- The rate is dropping with time.
- The system to measure steps is performing much worse than in 2014.
- Internal resonances of the assembly have an impact on the measurement of the induced oscillations.
- The experiment control is (too!) complex…



Patrick Schmidt, Diplomarbeit, TU Wien (2017).



Gunther Cronenberg, Dissertation, TU Wien (2016).



R.I.P Sedmik at al., PPNS proceedings (2019).

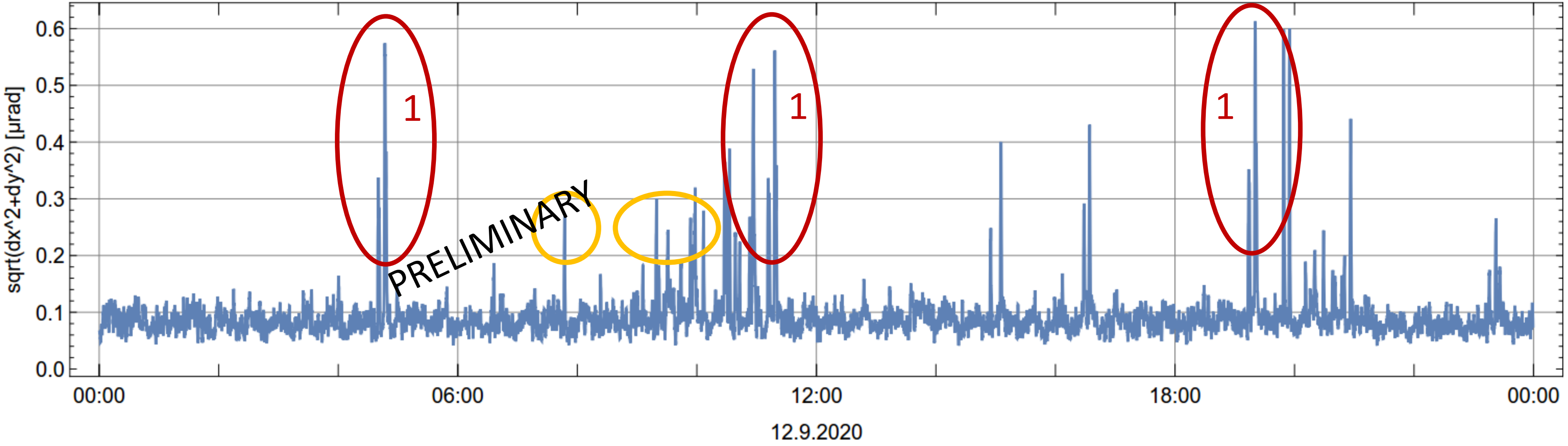
Solutions

Commissioning of a Ramsey-type spectrometer

- The rate is lower than expected (from calculations).
  Solved partially by a modified beamguide design, polished vacuum separation foils…
- The contrast is lower than expected (from previous measurements).
  The rate does not reach the "zero rate" for 180° phase shifts.
  Re-iterate the setup of state preparation and analysis, exchange rough mirrors, vibrate correctly.
- The rate is dropping with time.
  Avoid B4C-rubber in vacuum.
- The system to measure steps is performing much worse than in 2014.
  Modernization of electric power supply at PF2 in 2019, change of sensors to shorter cables.
- Internal resonances of the assembly have an impact on the measurement of the induced oscillations.
  Measure the resonances, loosen screws, tighten others…
- The experiment control is (too!) complex…
  Confinement in Spring 2020

Stability of the setup regarding inclination changes

The power of active control...



1: step control moving

2: SAS at level D (15m away) opening and closing....

Jakob MICKO, PhD thesis (2021).

(Preliminary) Results August/September 2020

Welcome to transition 1->6

PRELIMINARY

- Preliminary Results:
  - Zero rate: 35 mcps
  - Effective Rate @ pi/2-flip: 21 mcps
  - Usable Rate: 17 mcps

(Preliminary) Results August/September 2020

The energy eigenvalues are discrete and non-equidistant...

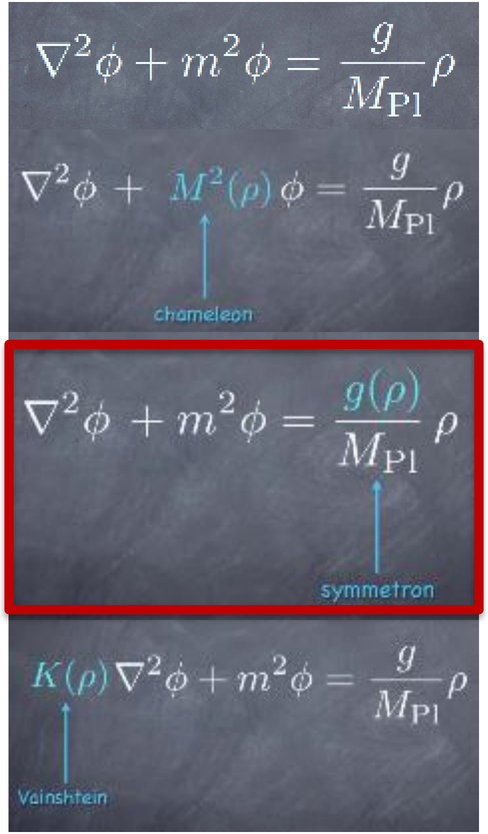
PRELIMINARY

- Preliminary Results:
  - Width of the innermost Ramsey fringe: 8.5 Hz
  - Current Sensitivity: ${}^{\delta\nu}/_{\nu} = 2.5 \cdot 10^{-4}/\sqrt{day}$
    $\delta E = 8 \cdot 10^{-16} eV/\sqrt{day}$

PRELIMINARY

Jakob MICKO, PhD thesis (2021).

Symmetron Dark Energy

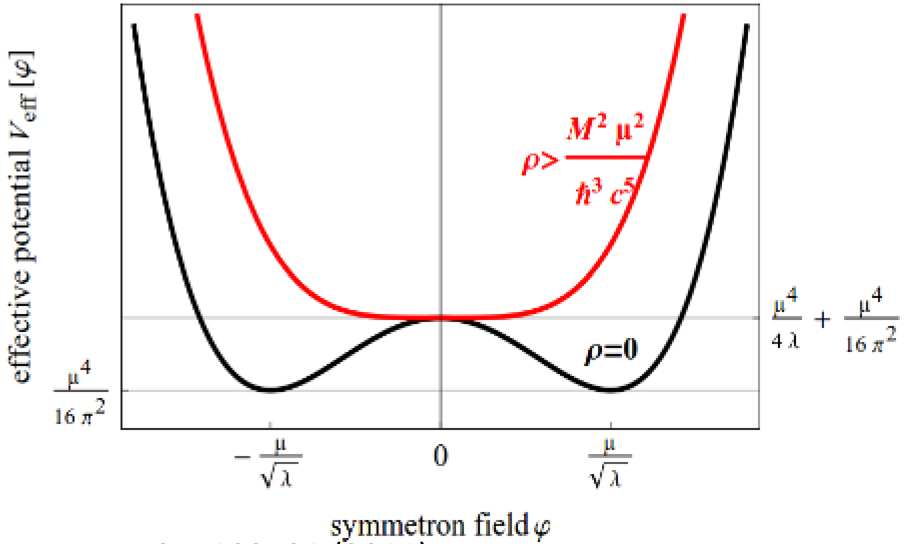


From: Justin Khoury

$$\mathcal{V}_0(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \frac{\mu^4}{4\lambda} \qquad \mathcal{V}_{eff}(\varphi) \sim \mathcal{V}_0(\varphi) + \frac{\varrho}{2M^2}\varphi^2 + \frac{\mu^4}{16\pi^2}$$

3 free parameters:

- mass μ
- self-interaction λ
- Coupling M



K. Hinterbichler et al., Phys. Rev. D 84, 103521 (2011).

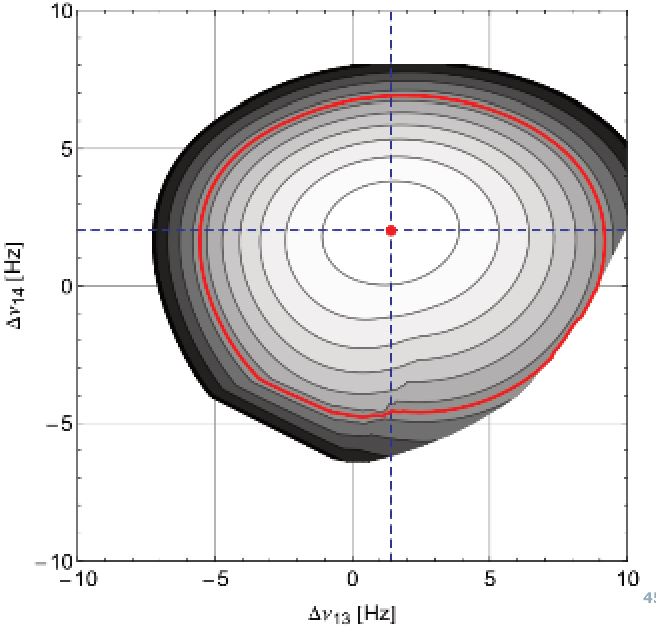
Symmetron Dark Energy

The situation today...

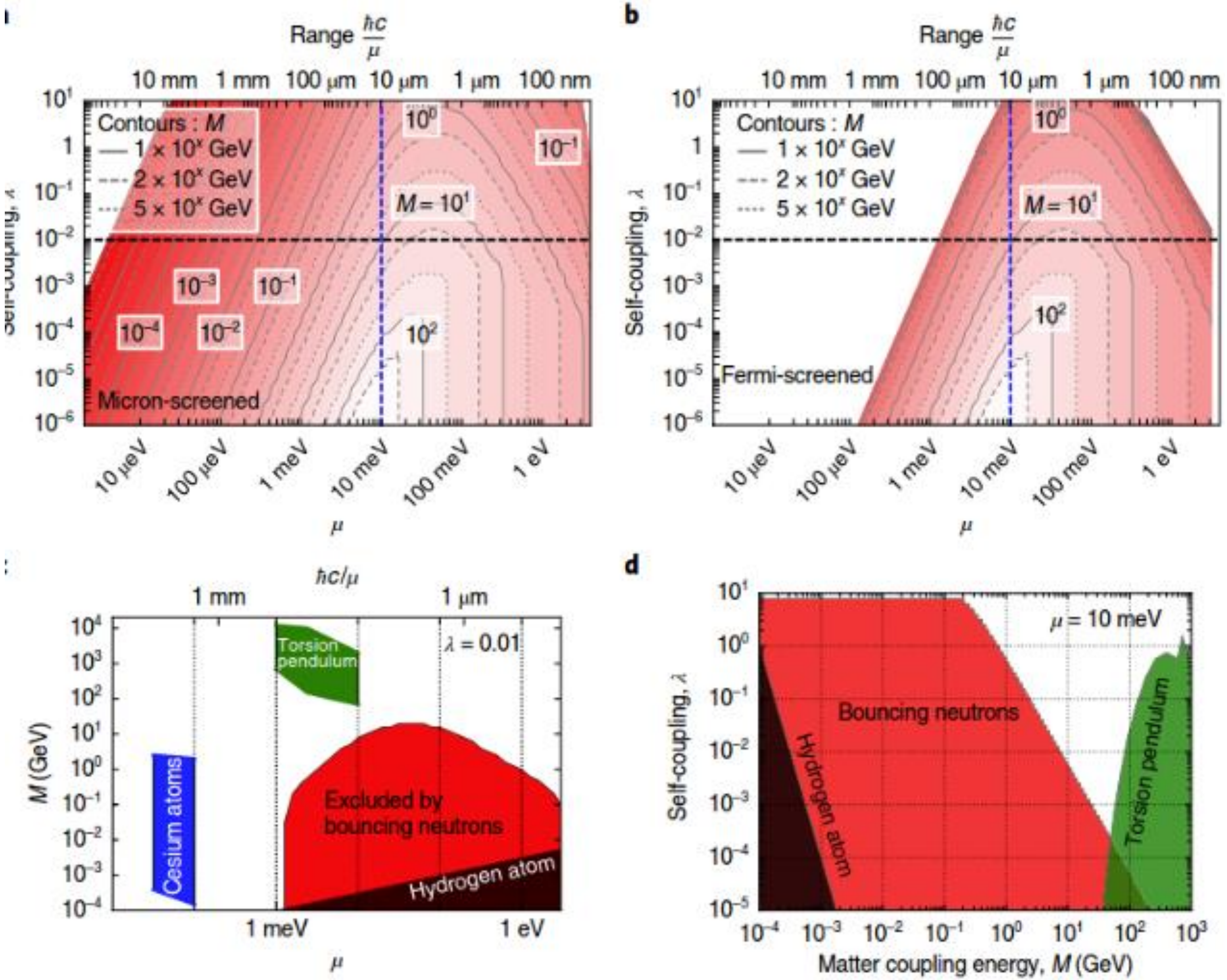
- Two resonances were measured (ν_{13} and ν_{14}) using Rabi spectroscopy.
- Statistical and systematic errors were determined.
- The result is compared to the Newtonian prediction.
- Result of this particular data set: Agreement
- Data Analysis is repeated taking into account the hypothetical potential of Symmetron Dark Energy, adding symmetron mass μ, self-interaction λ, and coupling M as additional free parameters

$$V(z) = mgz + \frac{mc^2}{2M^2}\varphi^2(z)$$

$$\varphi(z) = \varphi_V \tanh\left(\frac{\mu_{\text{eff}} z}{\sqrt{2}} + \tanh^{-1} k\right)$$



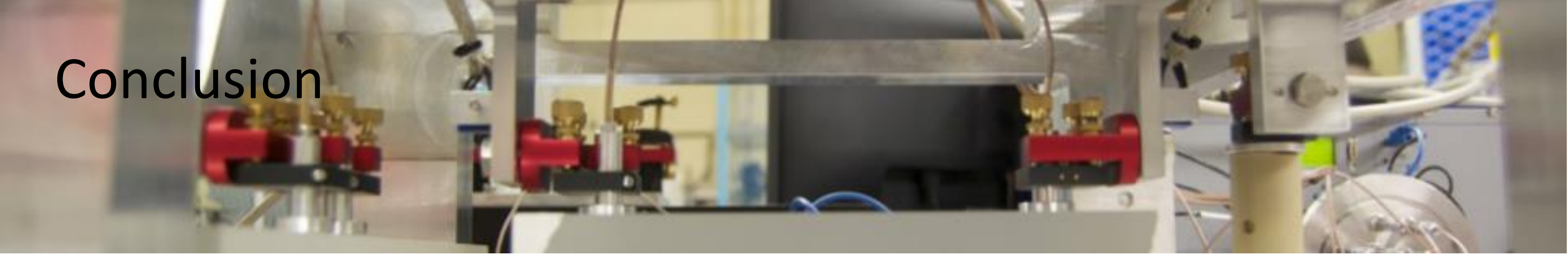
Exclusion Plots



Full χ^2 −analysis with three additional fit parameters (symmetron mass μ, self-interaction λ, coupling M)

The results open a question on how to properly treat the mass density in the quantum range!

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



Conclusion

- Neutrons are excellent probes to test gravity at short distances.
- Neutrons can contribute to answer fundamental questions on…
    - the existence of large extradimensions of spacetime
    - the origin of Dark Energy
    - the weak equivalence principle in the quantum regime
    - …
- Experiments with Ultracold Neutrons take some time…

Thank you for your attention!