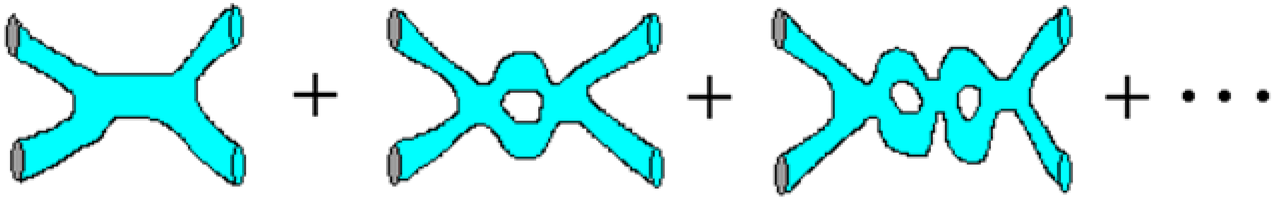
ATOMINSTITUT

Gravity Tests with Quantum Objects

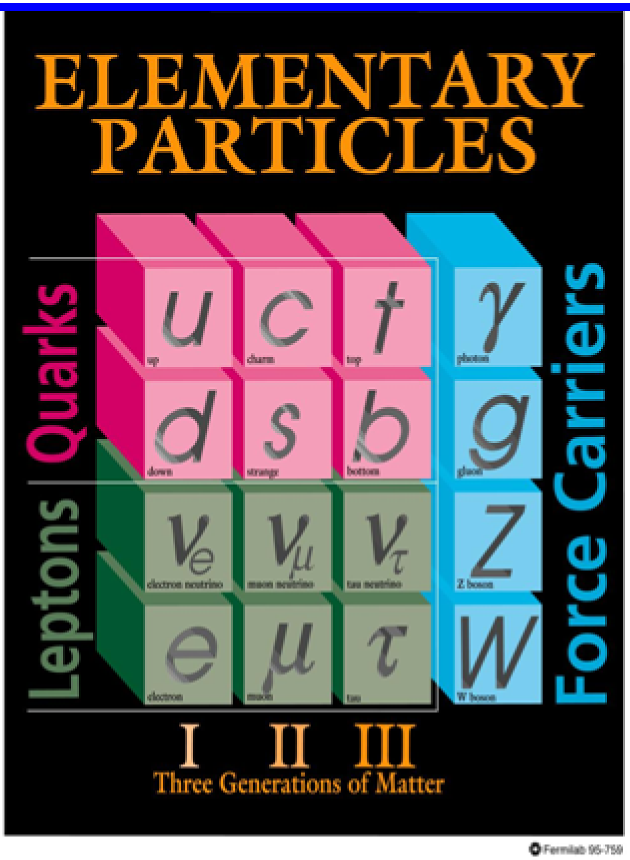
Hartmut Abele
Summer School on Fundamental Neutron Physics 2009



Hartmut Abele, Vienna University of Technology

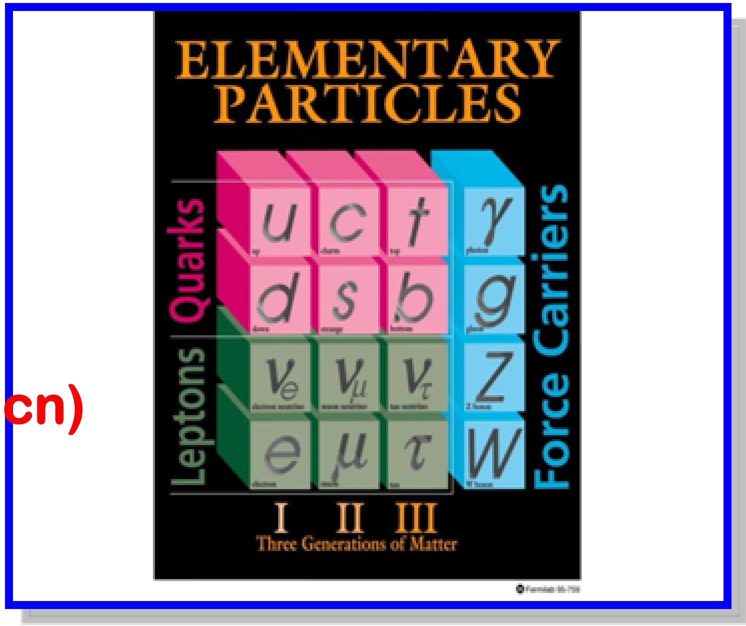
Impressions about gravity

- Gravity is weak



… gravity is missing

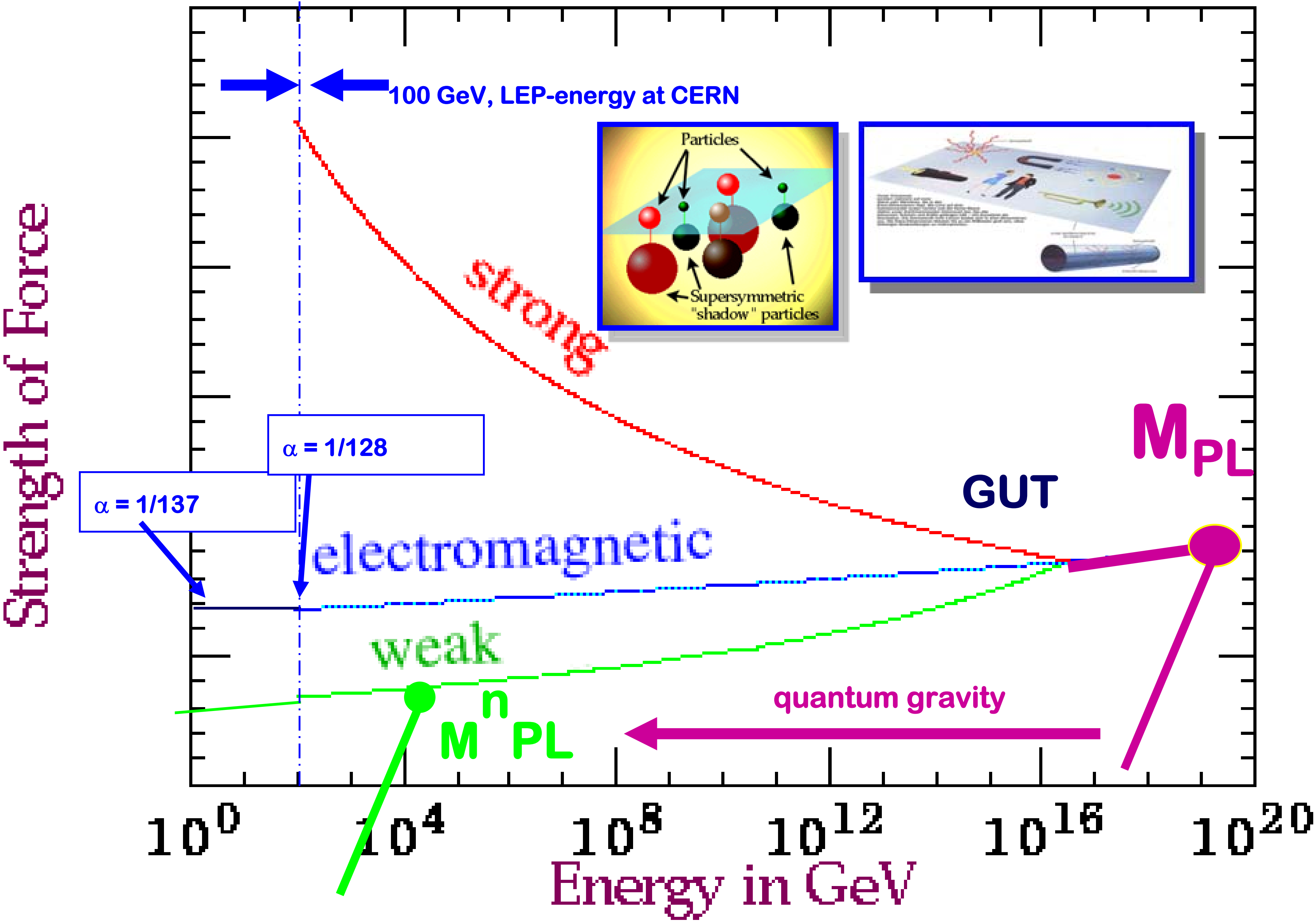
... But incomplete!



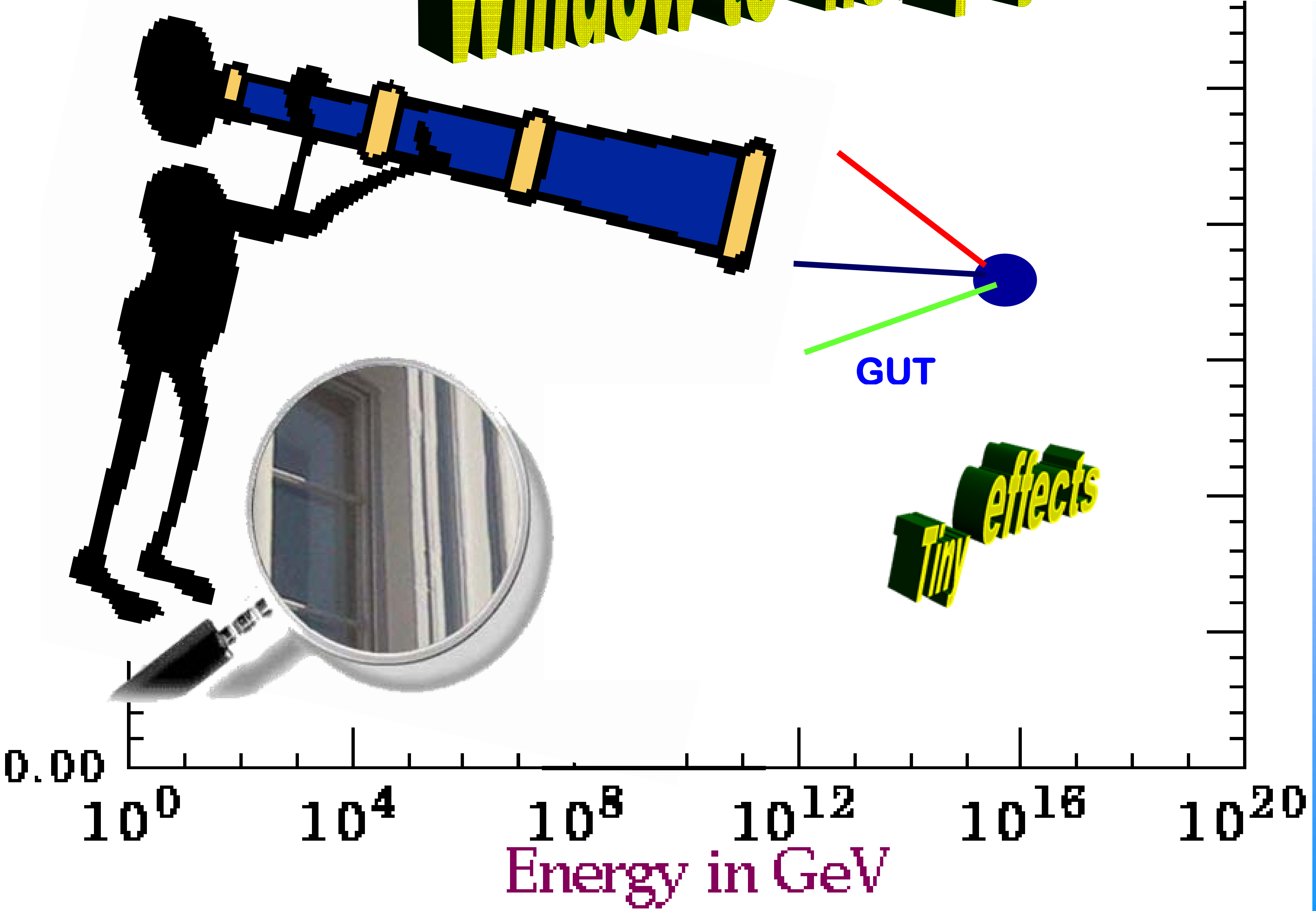
- **Unsolved problems**
  - 3 particle families (A, B, C, cn)
  - 12 masses (n mass: NIST + ILL)
  - 4 Phases of Quark mixing (A, B, C, cn, ucn)
  - 4 Phases Lepton mixing
  - Parity violation (A B, cn, ucn)
  - Gravitation (ucn)
  - CP-Violation and Baryon-Asymmetry of the universe (D, R, cn, ucn)
  - Dark energy, mass density of the universe (A, ucn,cn)
- **Question: Does a universal solution to all these problems exist?**
- **If the answer is yes: ...**

… where shall we search?

Forces Merge at High Energies



Window to "new physics"



Reasons for new interest

- New experimental devices
  - Ultrastable cavities
  - Lasers
  - Frequency comb
  - SQUIDs
  - Space experiments (GP-B, MICROSCOPE, ACES, SUMO, PARCS, RACE, STEP, OPTIS)
  - New space related techniques (drag free, grav. sensors)
- Violations predicted by quantum gravity
  - Modification of Maxwell equations
  - Modification of Dirac equation
  - Yukawa modification of Newton potental

Motivation for modern gravity tests with neutrons

- Neutral
- Small polarizability

- Very sensitive:
- example search for edm:
- Delta E < 0. 000 000 000 000 000 000 000 eV

- Fazit: at low energies, precision is highest

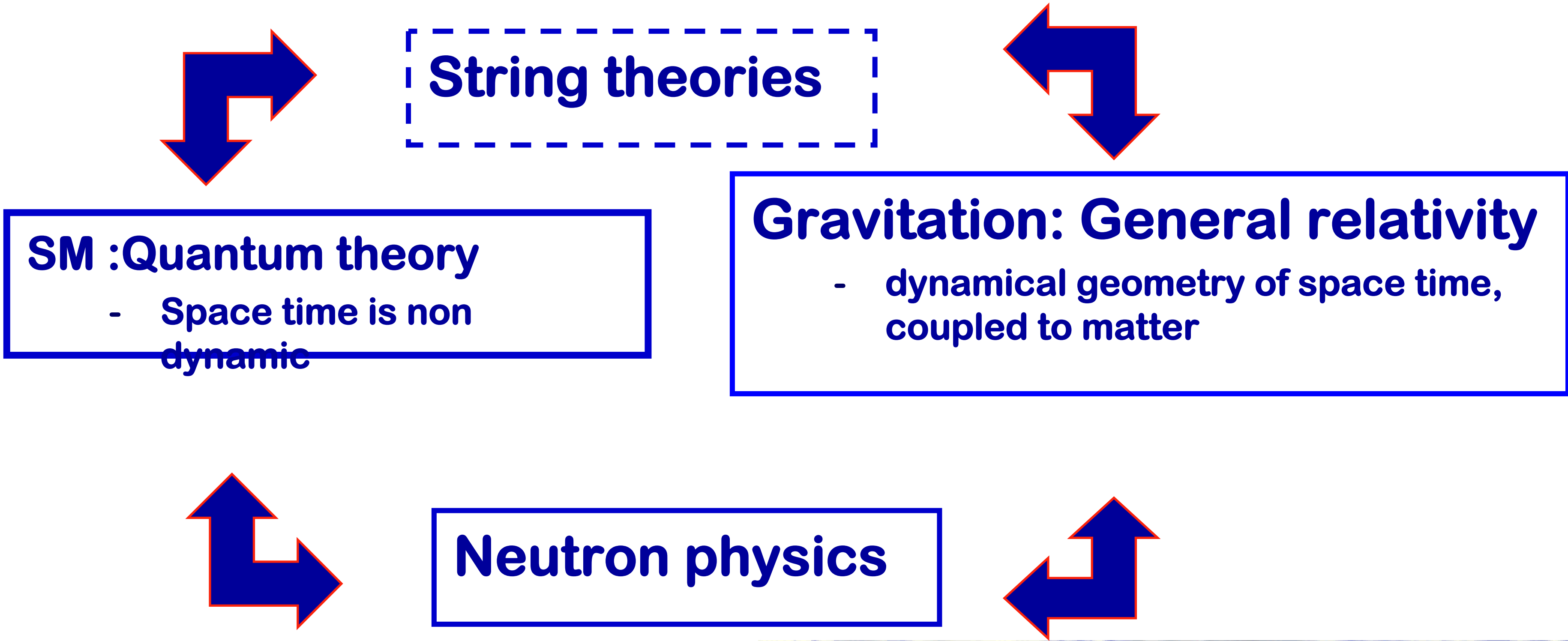
… good statistics

- Neutrons are abundant: 1/7 of the baryonic mass of the universe are neutrons
- New neutron sources

What is the aim?

- To derive the basic law of physics
- based on simple symmetry principles

Two Pillars
left: SM, right: GR



String theories

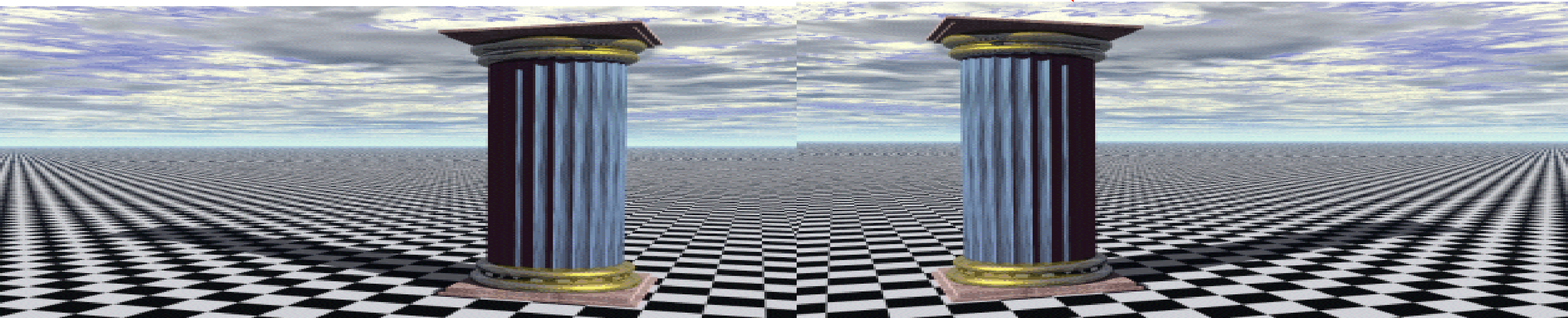
SM :Quantum theory

- Space time is non dynamic

Gravitation: General relativity

- dynamical geometry of space time, coupled to matter

Neutron physics



Standardmodel of Particle Physics

- **Input: Principia:**
  - Gauge principle U(1) x SU(2) x SU(3)
  - Lorentz invariance : x‘ = Lx
  - CPT, ...Invariance

- **Output:**
  - Interactions
  - Equation of motion — Maxwell, Schrödinger, Dirac
  - Existence of — Photons, Gluons, $W^{\pm}$, Z^0 (carriers of interaction)
  - Charge conservation — (Source of interaction)

D. Dubbers 2007

- **Conclusion: SM very successful**
  - e.g. as basis for technology, chemistry, biology, mol.biologie

General Relativity

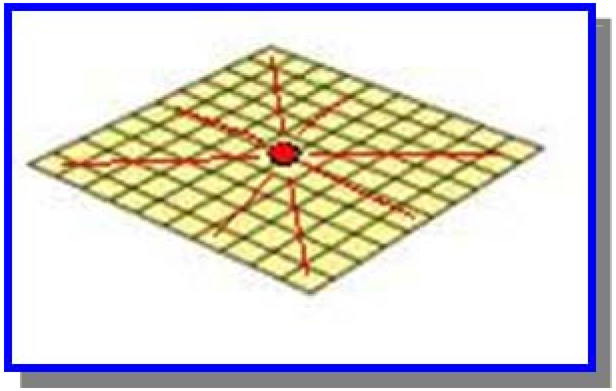
- **Input: Principia:**
  - **Einstein equation**
  - **Geodesic equation**
  - **A metric space**
  - **cosmological constant**

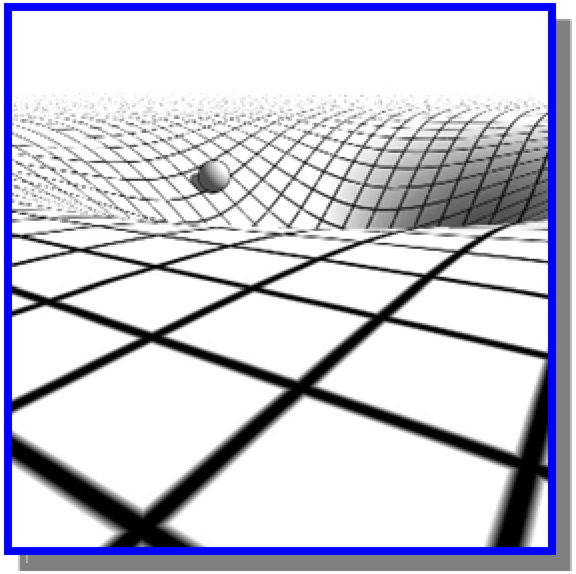
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{d\lambda} \frac{dx^\sigma}{d\lambda} = 0$$

Gravity and Space Time

- SM, Electromagnetism
  - Forces are represented by fields defined on spacetime
- Gravity
  - gravity is inherent in spacetime itself,
  - gravity is a manifestation of the curvature of spacetime





Unification of before disconnected Phenomena:

17th/18th

Celestial Mechanics

Mechanics

Acoustics

Mechanics

19th century

Magnetism

Electricity

Optics

Heat radiation

Elektrodynamics

Mechanics

Themodynamics

Stat. Mechanics

20th century

QM

E.-Dynamics

QED

QED

Weak interaction

QCD

Standardmodell of particles

21th

Particles+

Cosmology

SM

GR

???

General Relativity

- **Input: Principia:**
  - Einstein equation
  - Geodesic equation
  - A metric space
  - cos,mological constant

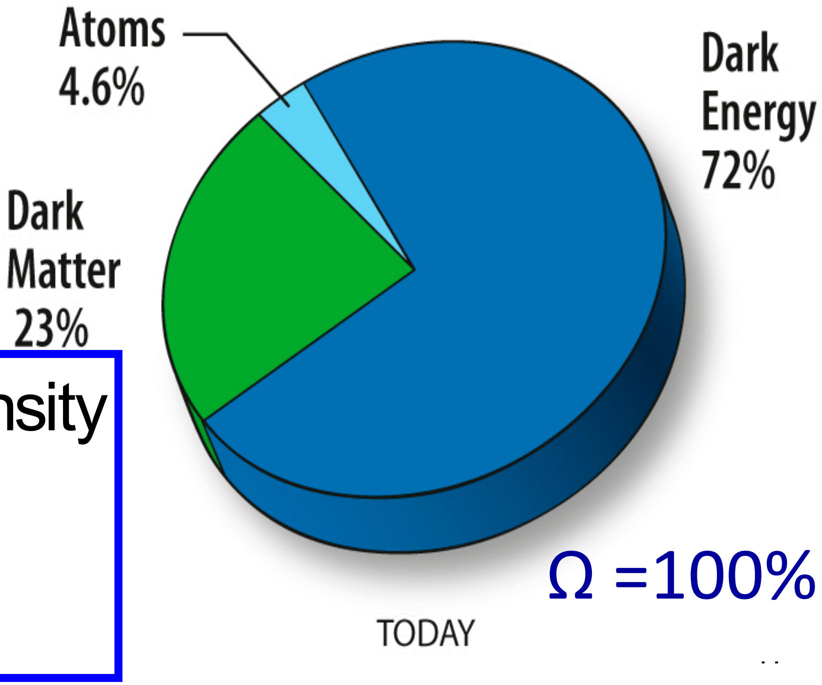
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{d\lambda} \frac{dx^\sigma}{d\lambda} = 0$$

- **Consequences:**
  - From big bang
  - To black holes

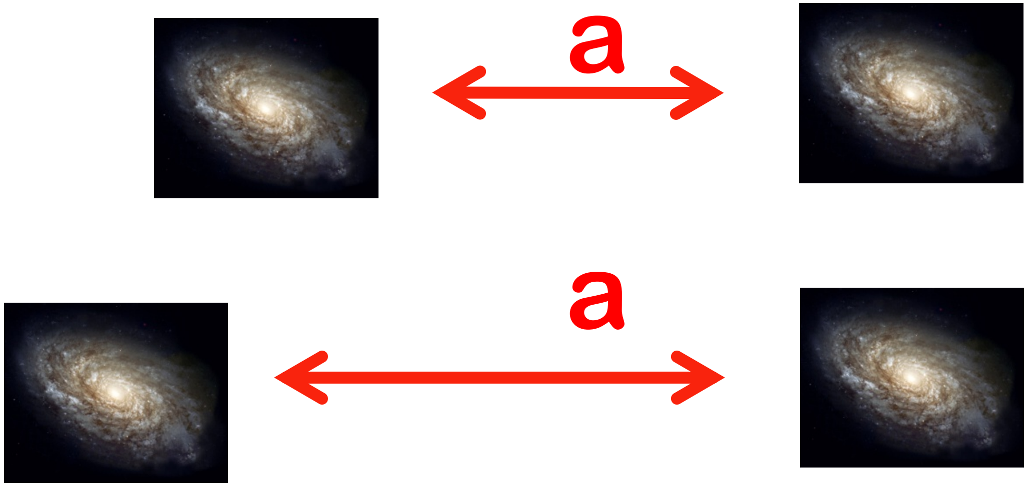
(Expansion rate)^2=Constant×Mass density

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G \times \rho_{\text{Masse}}$$



Ω =100%

Nomenclatura



Distance a

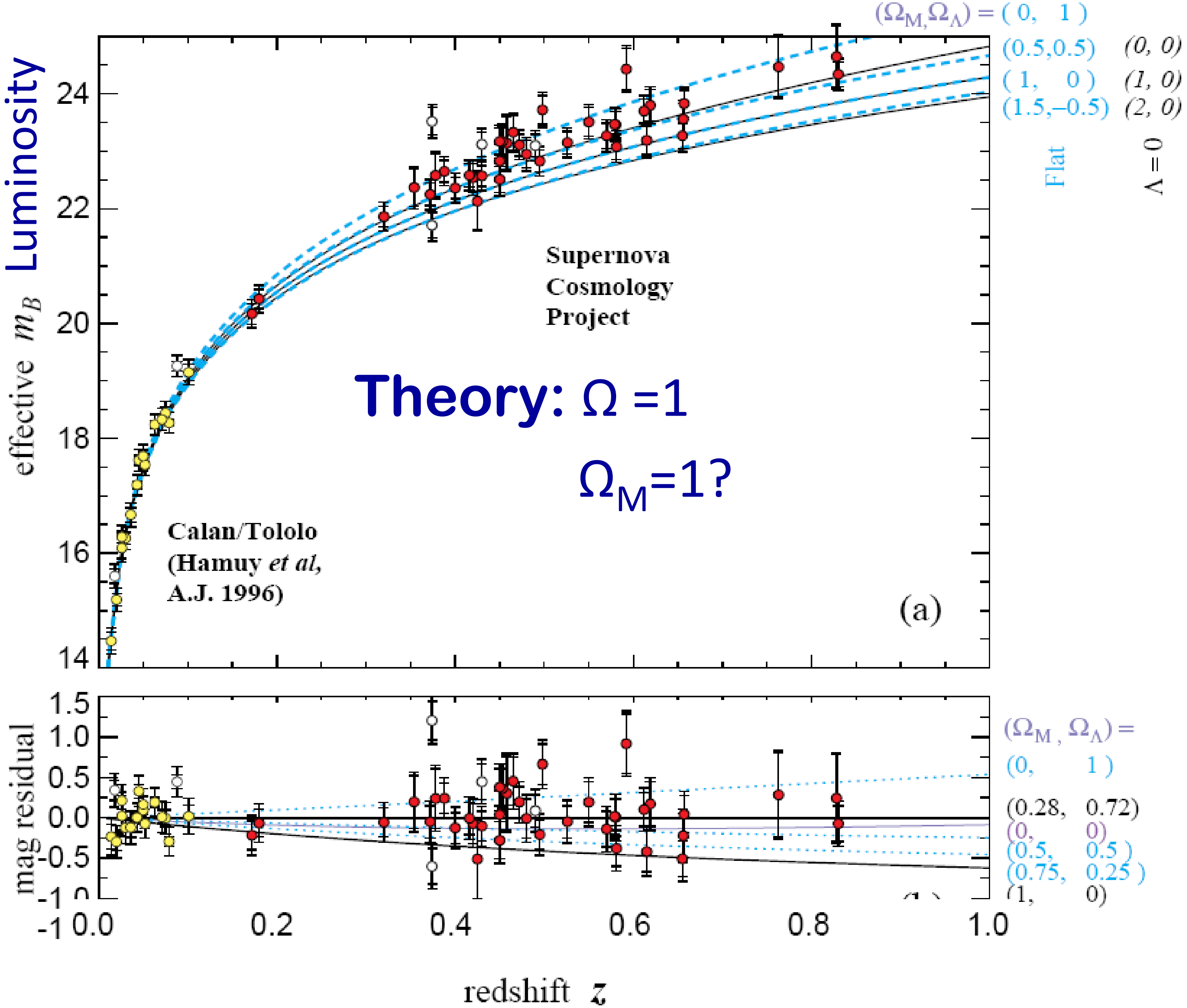
Velocity $\mathrm{v} = \frac{a}{T} = \frac{da}{dT} = \dot{a}$

Acceleration $\ddot{a} = \frac{d\mathrm{v}}{dT} = \dot{v}$

Hubble Constant $H = \frac{\dot{a}}{a}$

Accelerated Universe $\frac{\ddot{a}}{a} > 0$

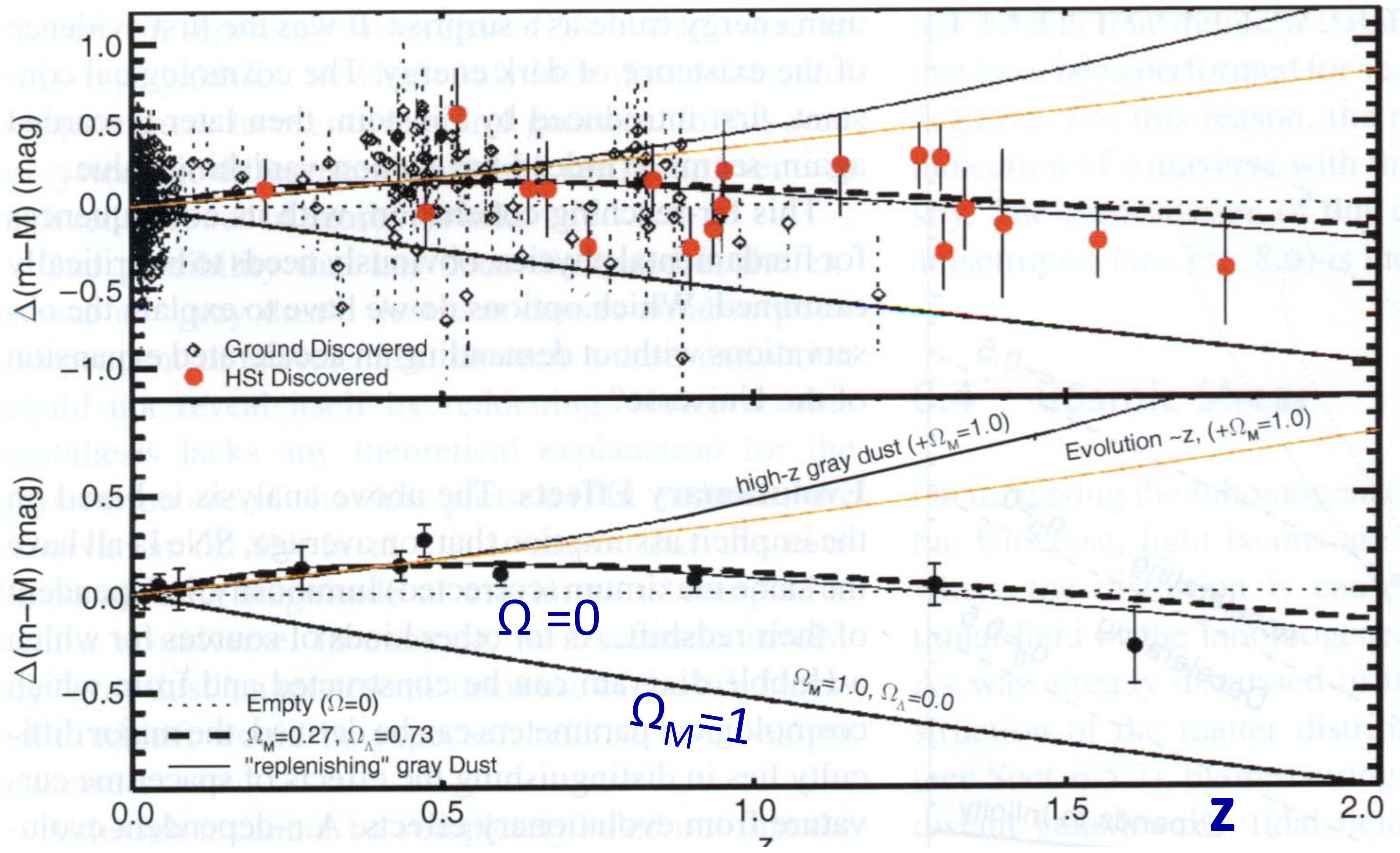
Measurement of Ω and Λ from supernovae



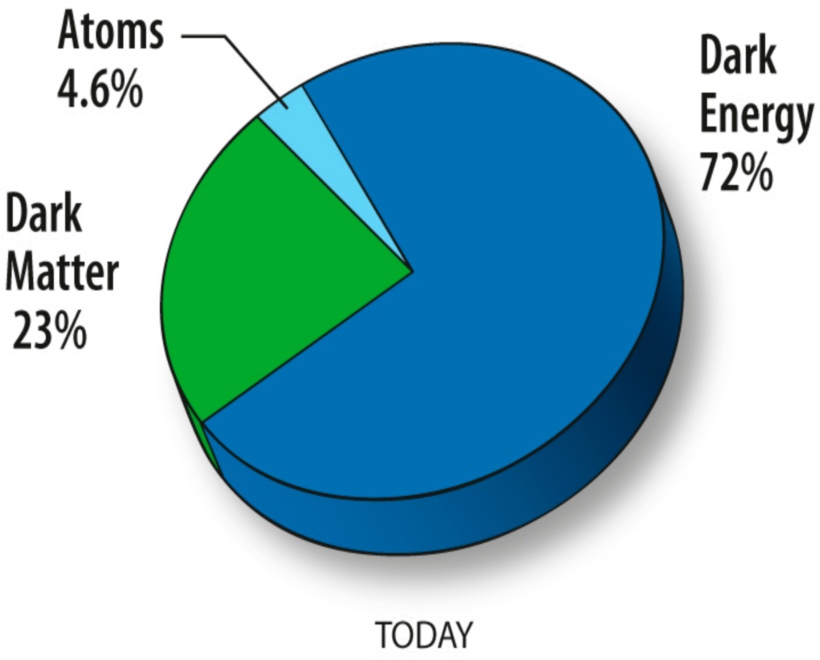
Theory: $\Omega = 1$

$\Omega_M = 1$?

The accelerating expansion



Acceleration of the Universe Friedman DGL



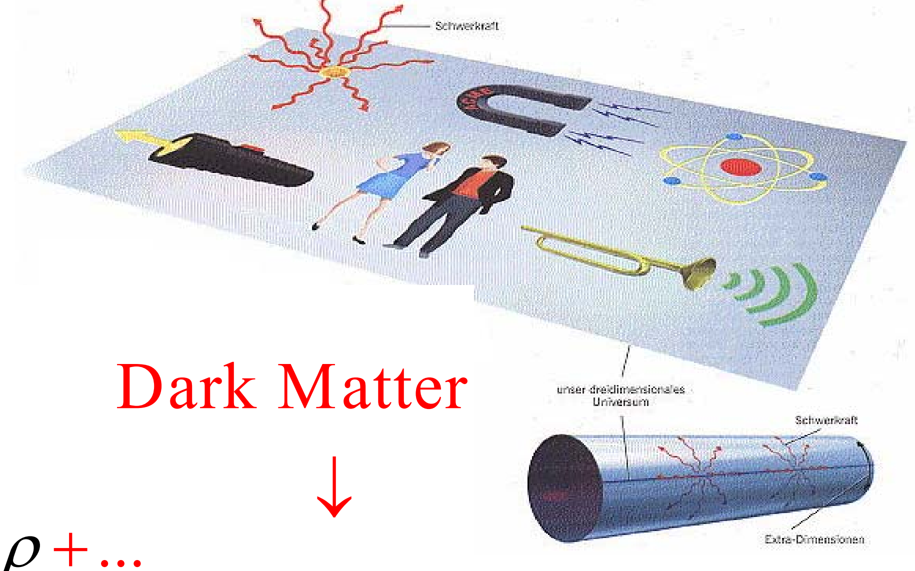
Hubble parameter: $H \equiv \frac{\dot{a}}{a}$

Friedman Eq.: $H^2 = \frac{8\pi}{3} G_N \rho$

$\uparrow$ Gravity $\uparrow$ Energy

accelerated universe: $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3} (\rho - 2\rho_\Lambda)$

Friedman DGL



Hubble parameter: $H \equiv \frac{\dot{a}}{a}$

Dark Matter

↓

Friedman Eq.: $H^2 + \ldots = \frac{8\pi}{3} G_N \rho + \ldots$

Axions

→ 0.2 µm < λ < 2 cm

↑ new Gravity

↑ Vacuum Energy

B&C '05: Cosmological Constant linked to Size of extra dimensions

→ λ ~ 5µm, α < 10^6

accelerated universe: $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho - 2\rho_\Lambda$

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

ADD '99: Repulsive forces
gauge fields in the bulk

→Strength α = 10^6 – 10^9, range λ < 40 µm,

Newton potential + additional terms

α: Strenth

λ: Range

ADD 99: repulsive forces in the bulk

$\alpha = 10^6 - 10^9$

$\lambda < 30\ \mu m$

B&C: Cosmological constant, size of extra dimensions

$\alpha < 10^6$

$\lambda \sim 5\ \mu m$

Axion dark matter

$\alpha <$ ...

$0.2\ \mu m < \lambda < 5\ \mu m$

Neutrons test Newton

- Experiments

Newton used Neutrons for gravity test

- Half of Newton‘s apple is made out of neutrons

- 48% neutrons
- 52 % protons
- $2\mathrm{x}10^{-4}$ electrons

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

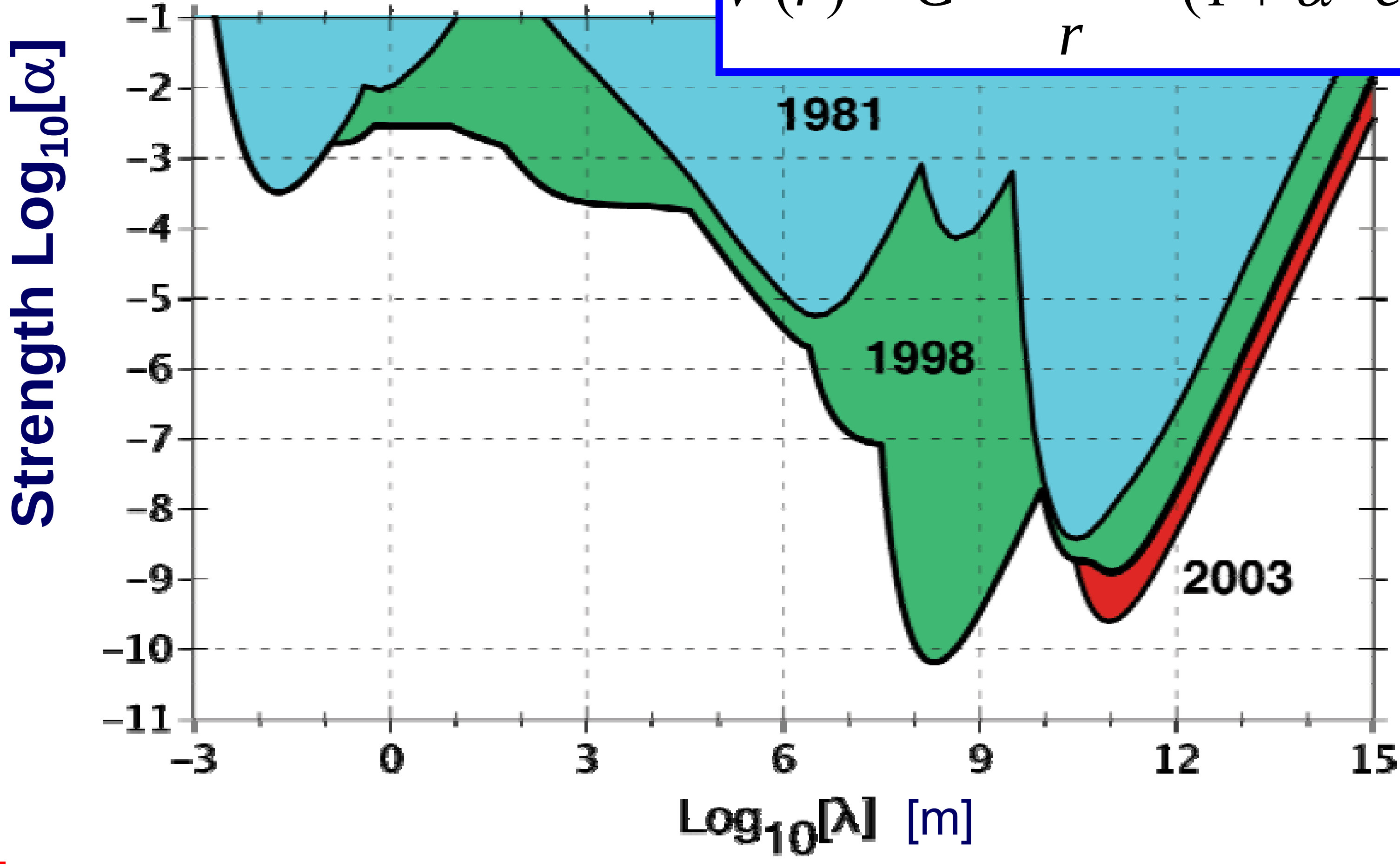
"Nothing yet. ...How about you, Newton?"

Hartmut Abele, Vienna University of Technology

2. Newton's gravitational r^{-2} law

- Newton's law appears to be valid from the millimeter scale up to the galactic scale.

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



Hartm

Reference: Coy, Fischbach, Hellings, Standish & Talmadge (2003)

VOLUME 60, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1988

Tower Gravity Experiment: Evidence for Non-Newtonian Gravity

Donald H. Eckhardt, Christopher Jekeli, Andrew R. Lazarewicz, Anestis J. Romaides,
and Roger W. Sands
Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts 01731

(Received 18 April 1988)

We tested Newton's inverse-square law of gravitation by comparing gravity measured on a 600-m tower with gravity calculated from ground measurements. A significant departure from the law was detected, approaching $(-500 \pm 35) \times 10^{-8}$ m s^{-2} at the top of the tower and suggestive of a rapidly attenuating non-Newtonian attractive force. These results are marginally consistent with a one-term Yukawa-type attractive force, but they are fully consistent with two Yukawa-type forces, attractive and repulsive, and then also with Airy and Cavendish experiments.

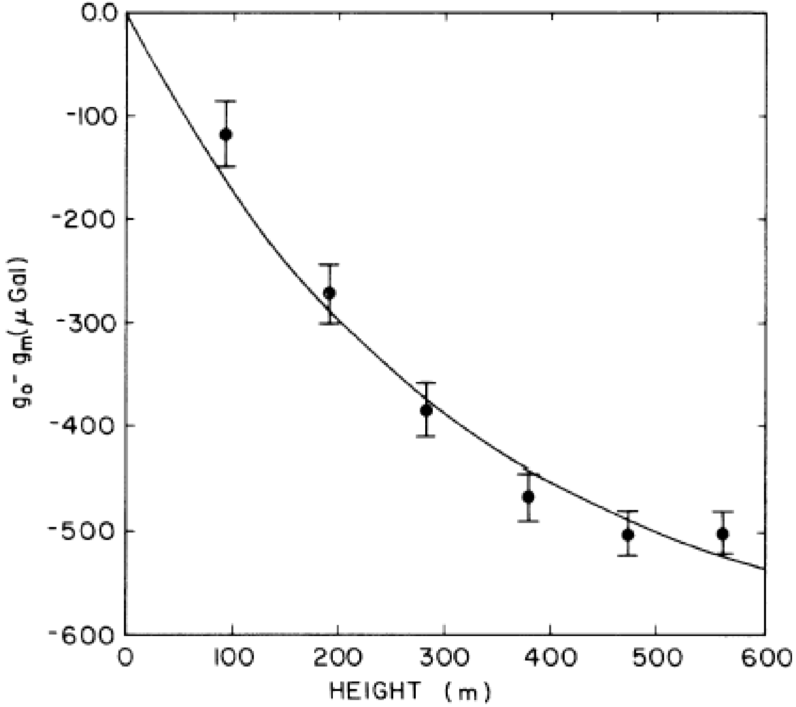
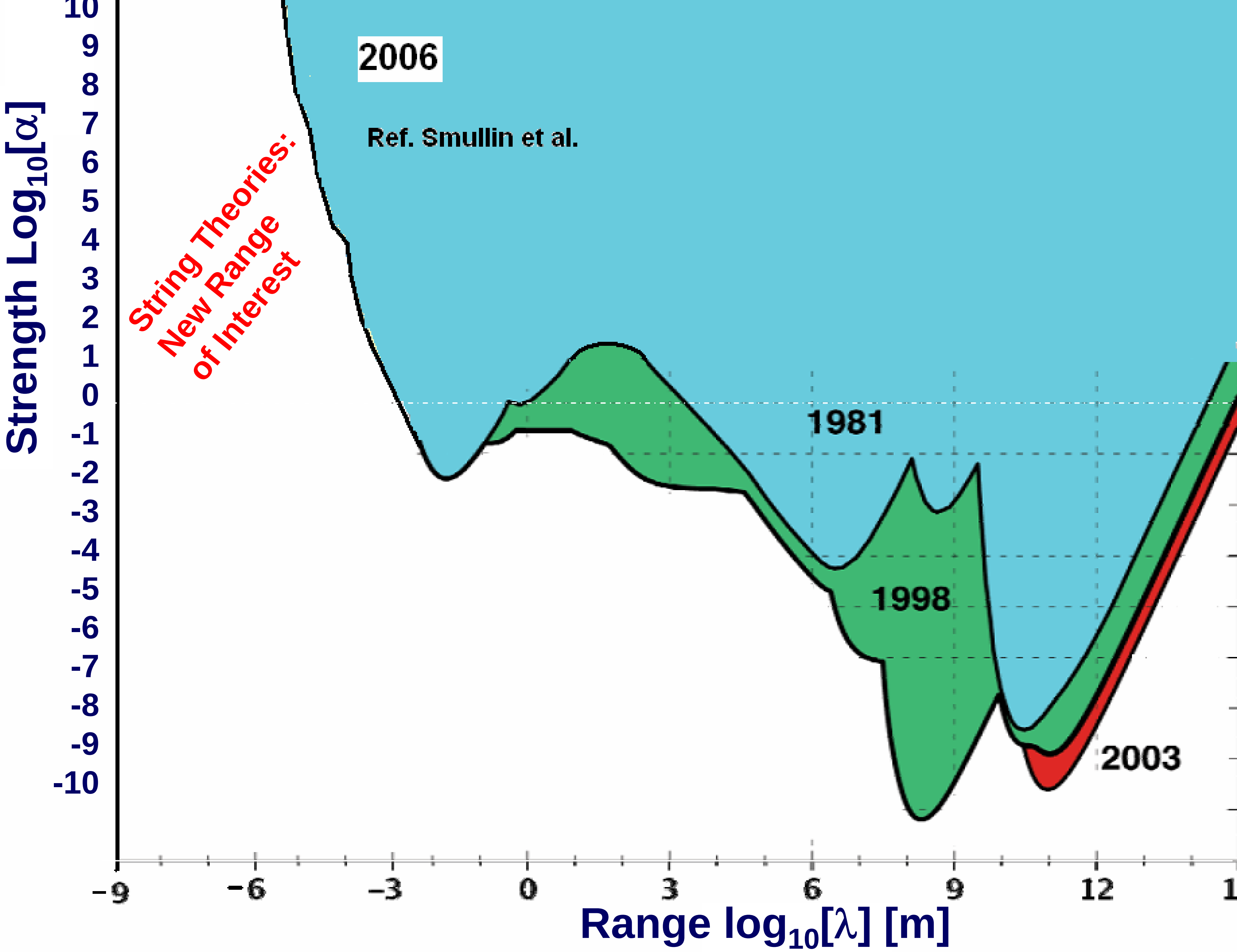


FIG. 1. Scalar Yukawa model fitted to RET experimental results and error bars.

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


2006
Ref. Smullin et al.
String Theories: New Range of Interest
1981
1998
2003
Strength Log$_{10}$[α]
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
−9
−6
−3
0
3
6
9
12
Range log$_{10}$[λ] [m]

Neutrons test Newton

Tool: Ultra-Cold Neutrons

Pragmatic Definition
UCN reflect from surfaces at all angles

Strong Interaction: V ~ 100 neV

Kinetic Energy: 100 neV $50\text{neV} < E < 2.1\mu\text{eV}$
$132\text{nm} > \lambda > 20\text{nm}$
$3\text{m/s} < v < 20\text{m/s}$

Magnetism, Zeeman splitting : 120 neV/T

Energy in the earth‘s gravitational field: $E = mgh$ 100neV/m

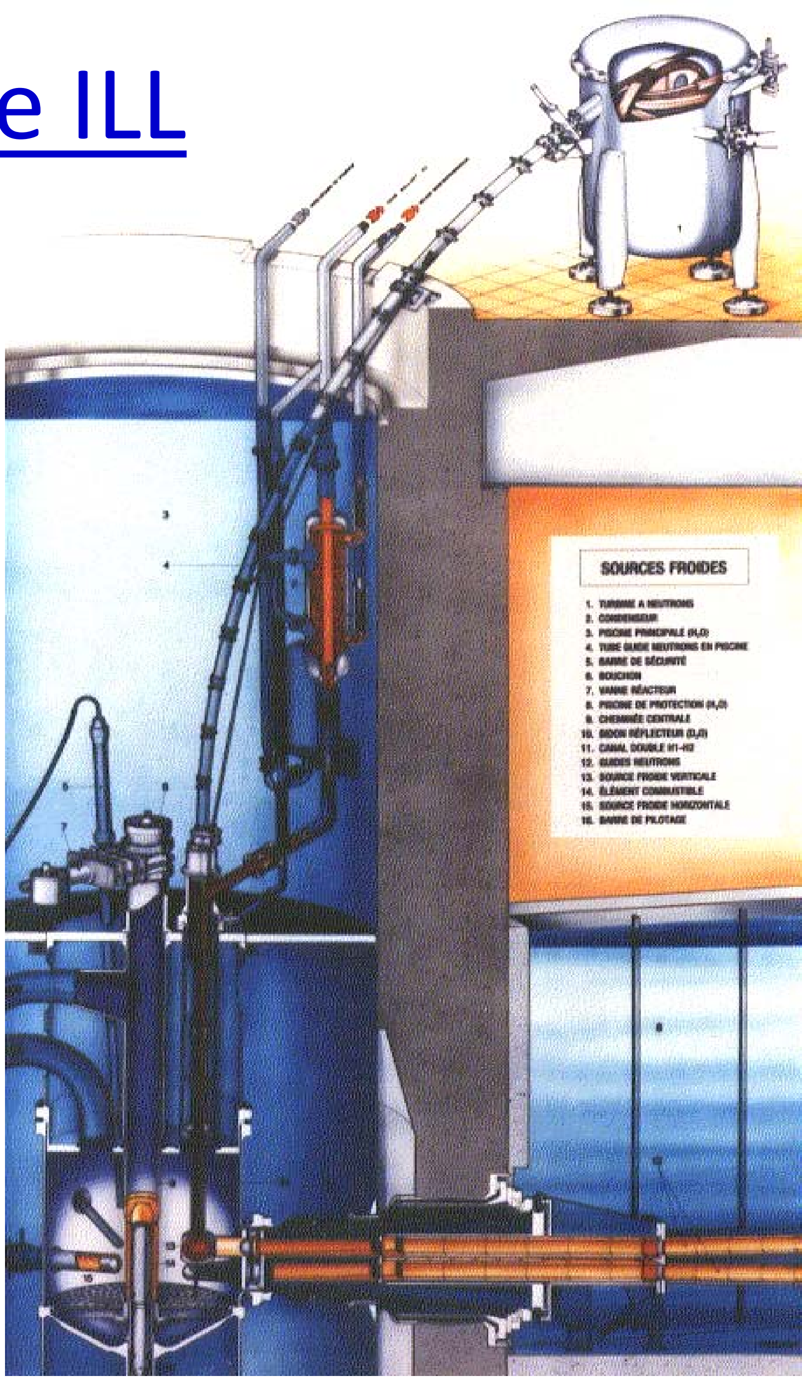

ill
NEUTRONS
FOR SCIENCE
ESRF
ill INSTITUT LAUE-LANGEVIN
EMBL

Neutron Production at the ILL

Fission: 2 MeV

Thermal: 25meV, 300K

Cold: 4 meV, 40K



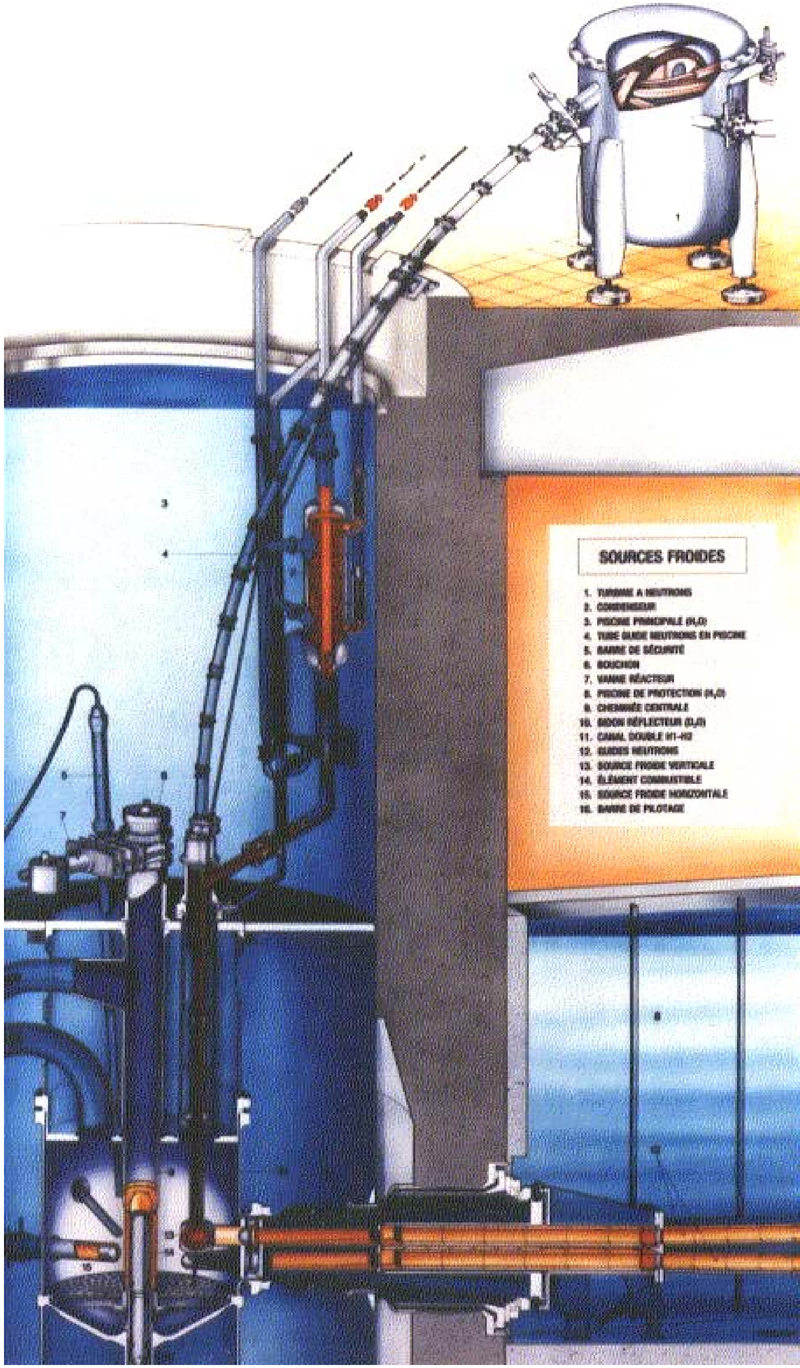
Neutron Production

Fission: 2 MeV

Thermal: 25meV, 300K

Cold: 4 meV, 40K

ultra cold: 100 neV, 1mK



Neutron Production

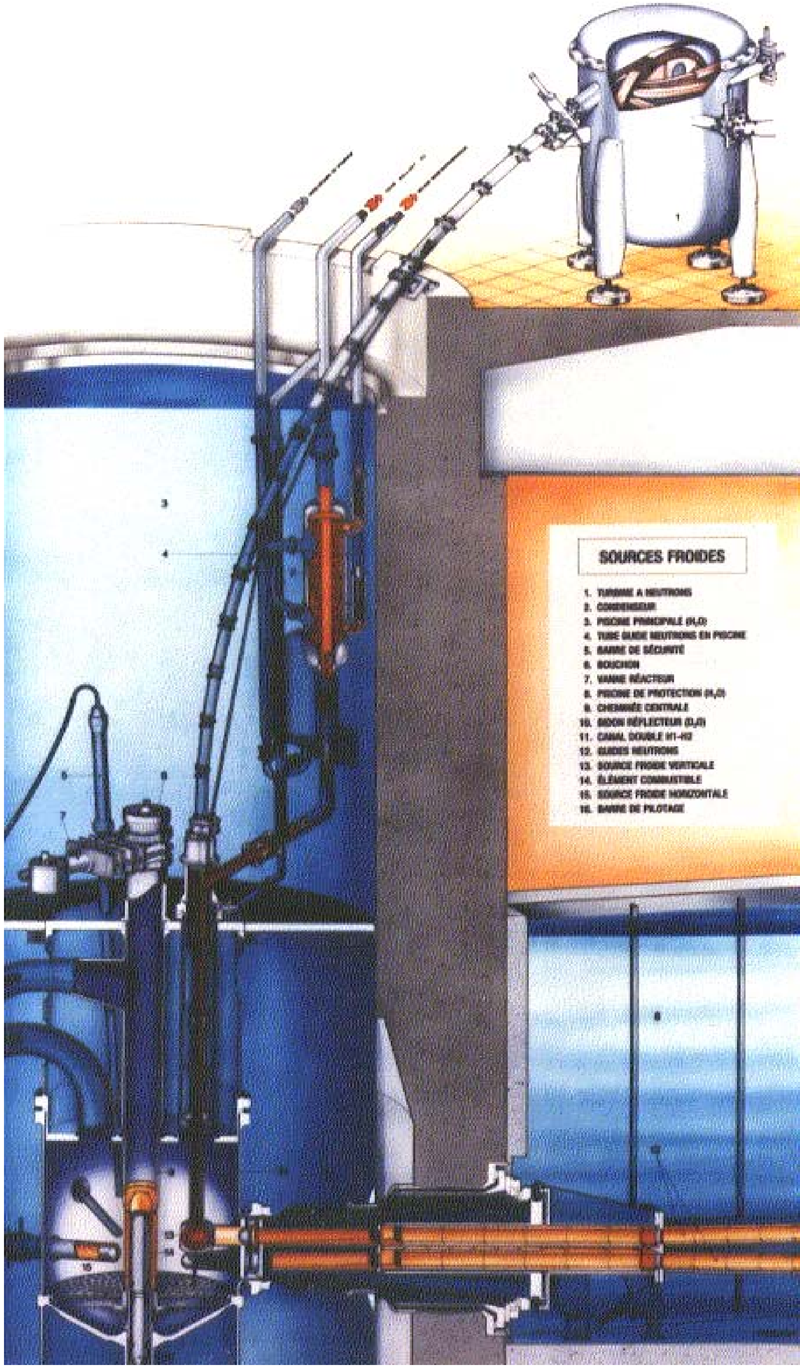
Fission: 2 MeV

Thermal: 25meV, 300K

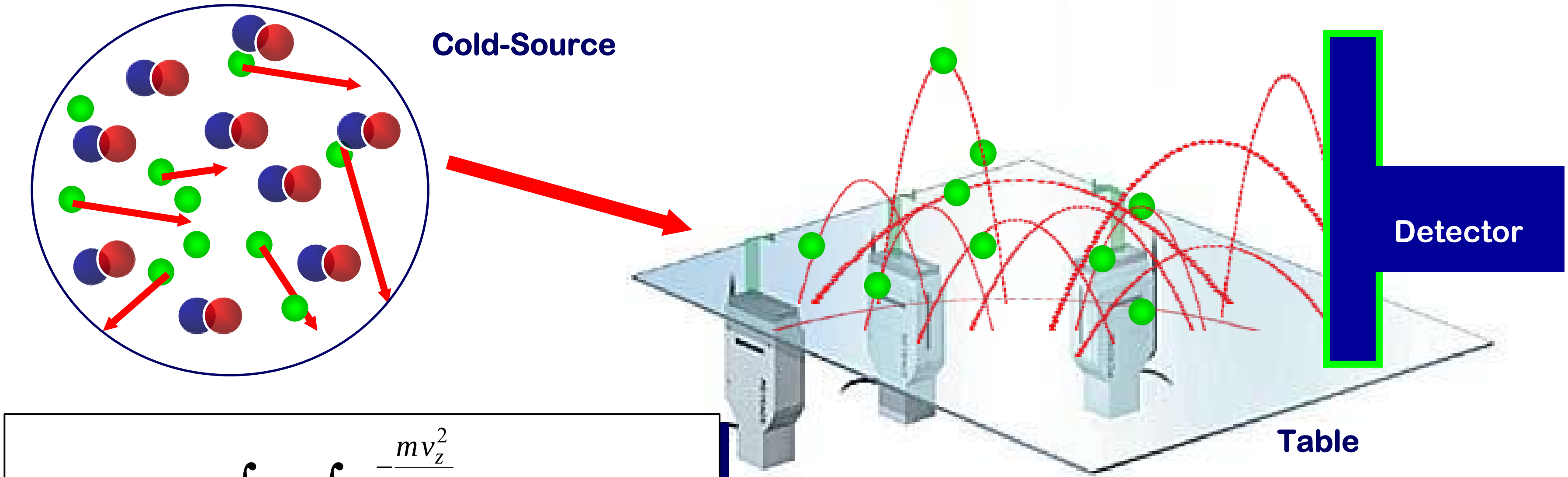
Cold: 4 meV, 40K

ultra cold: 100 neV, 1mK

Gravity Experiment: 1 pico-eV



Classical description



$$T = const \int dh \int e^{-\frac{mv_z^2}{2kT}} dv_z$$

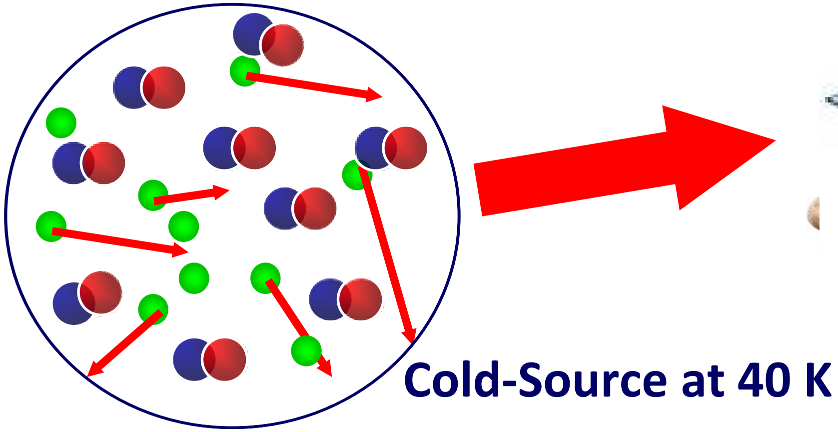
$$\frac{1}{2} m v_z^2 = mgh \Rightarrow \frac{dv_z}{dh} \propto \frac{1}{\sqrt{h}}$$

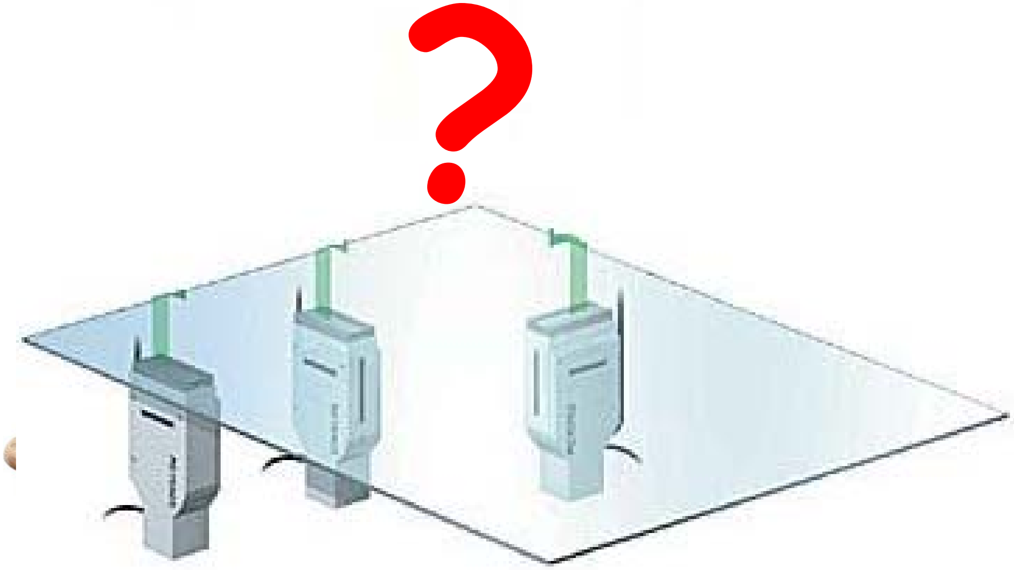
$$\text{40K: replace } e^{-\frac{mv_z^2}{2kT}} \text{ with } 1$$

$$T = const \otimes \int_0^h dh' \int_0^h \frac{dh'}{\sqrt{mgh'}} \Rightarrow$$

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

Quantum Bounce





Energy Conservation: $E = E_{kin} + E_{pot} = p^2 / 2m + mgz$

Heisenberg: $\Delta p \times \Delta z = \frac{\hbar}{2}$

Minimum Energy: $\frac{\partial E}{\partial z} = -\frac{\hbar^2}{4mz^3} + mg = 0$

$$z_0 = \left(\frac{\hbar^2}{2m_n^2 g}\right)^{1/3} = 5.87\,\mu\mathrm{m}$$

Synopsis of Bound Quantum States

Hydrogen Atom

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

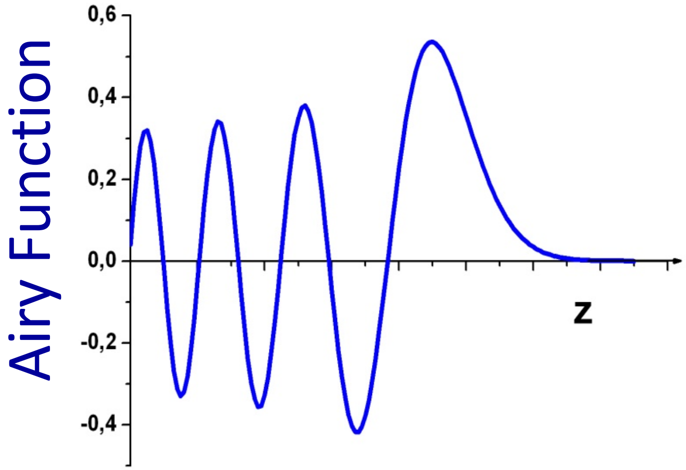
System Neutron & Earth

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

Schrödinger Equation

$$-\frac{\hbar^2}{2m}\nabla\psi + V(z)\psi = E\psi$$

$$V(z) = mgz \quad \text{for} \quad z \geq 0 \quad \text{and} \quad V(z) = \infty \quad \text{for} \quad z < 0$$



- Scale with length scale z_0

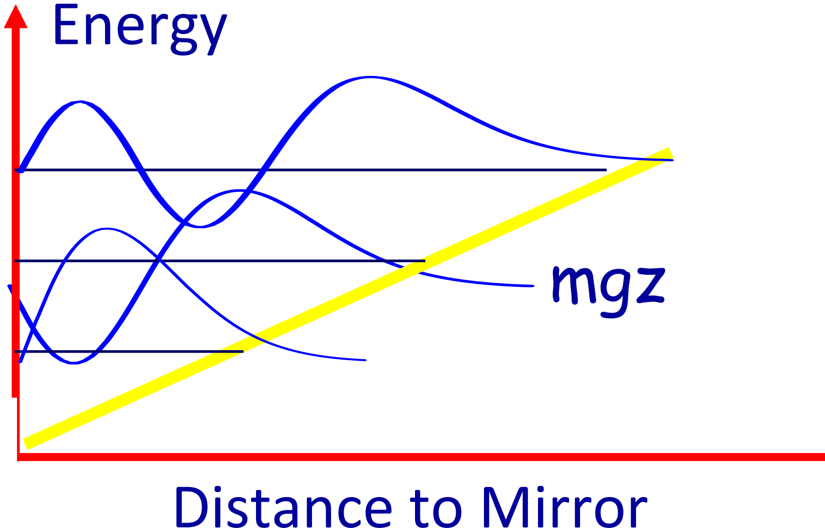
$$\zeta = \frac{z}{z_0}$$

- Shift

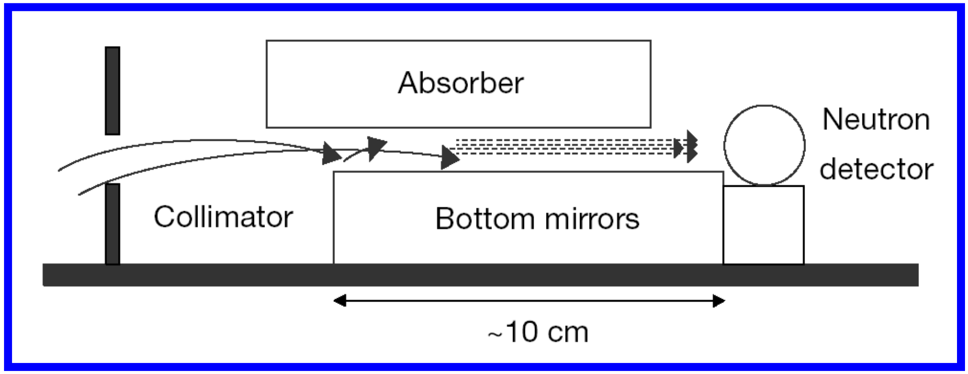
$$\psi_n(\zeta) = Ai(\zeta - \xi_n)$$

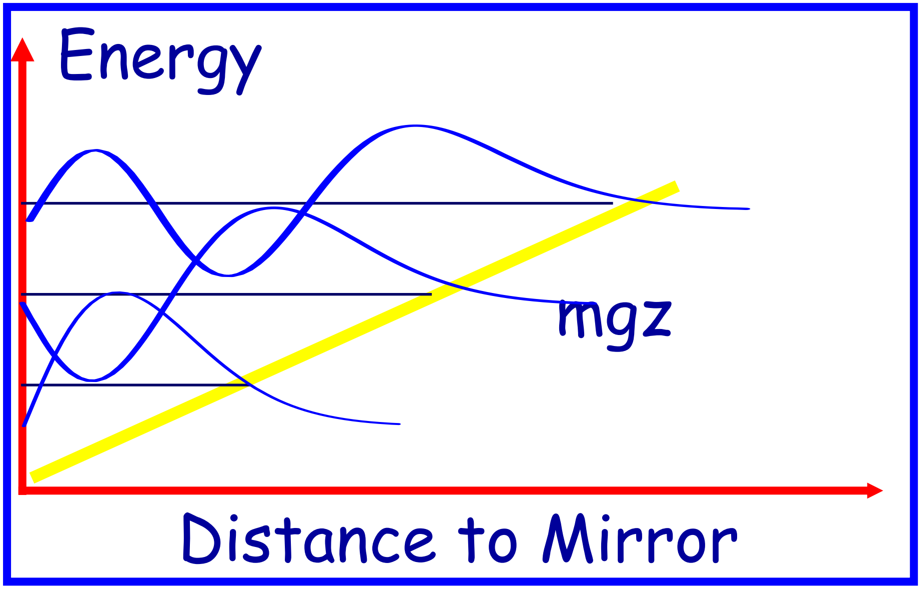
- Turning Points:

$$z_1 = 13.7\mu\text{m}, \; z_2 = 24.1 \; \mu\text{m}$$

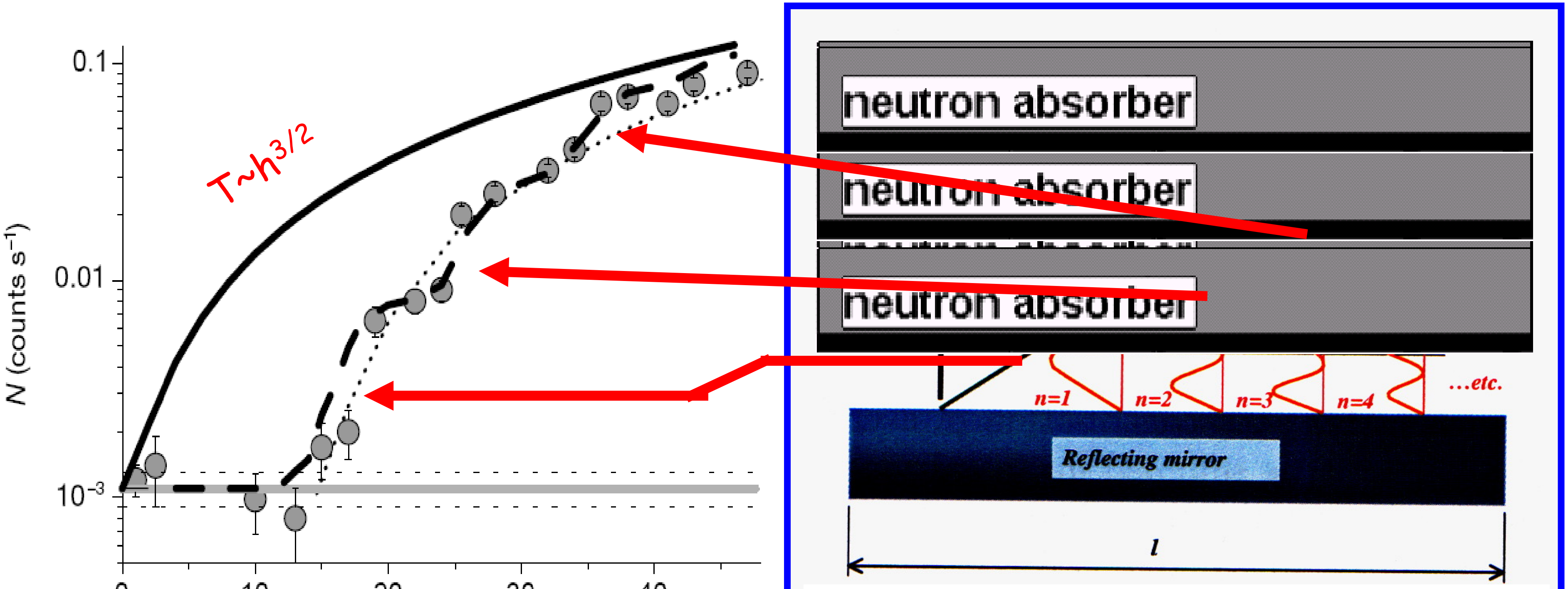


2002: Observation of Bound Quantum States





Neutron mirror:
polished glass plate 10 cm long



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

Trapping UCN‘s in the earth‘s gravitational field

Schrödinger equation:

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

boundary conditions:

$$\varphi_n(0)=0$$

with 2nd mirror at height l

$$\varphi_n(l)=0$$

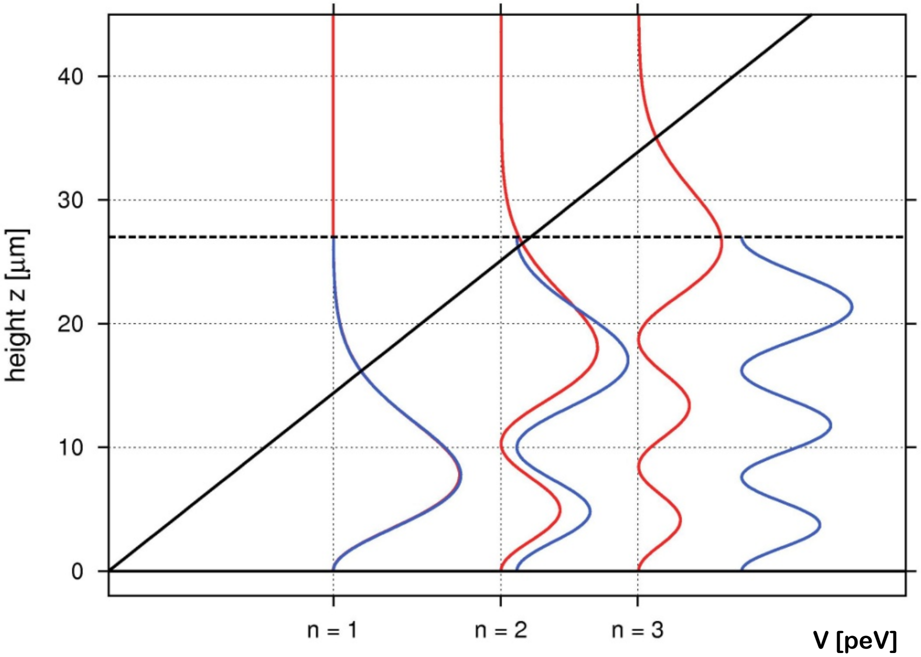
solutions: Airy-functions

scales:

energies: peV

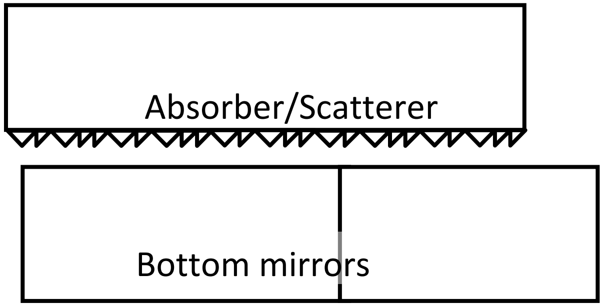
length: μm

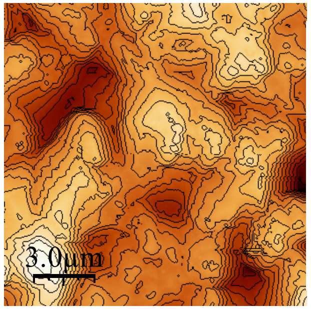
	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	3.97peV



neutron mirror

The absorber

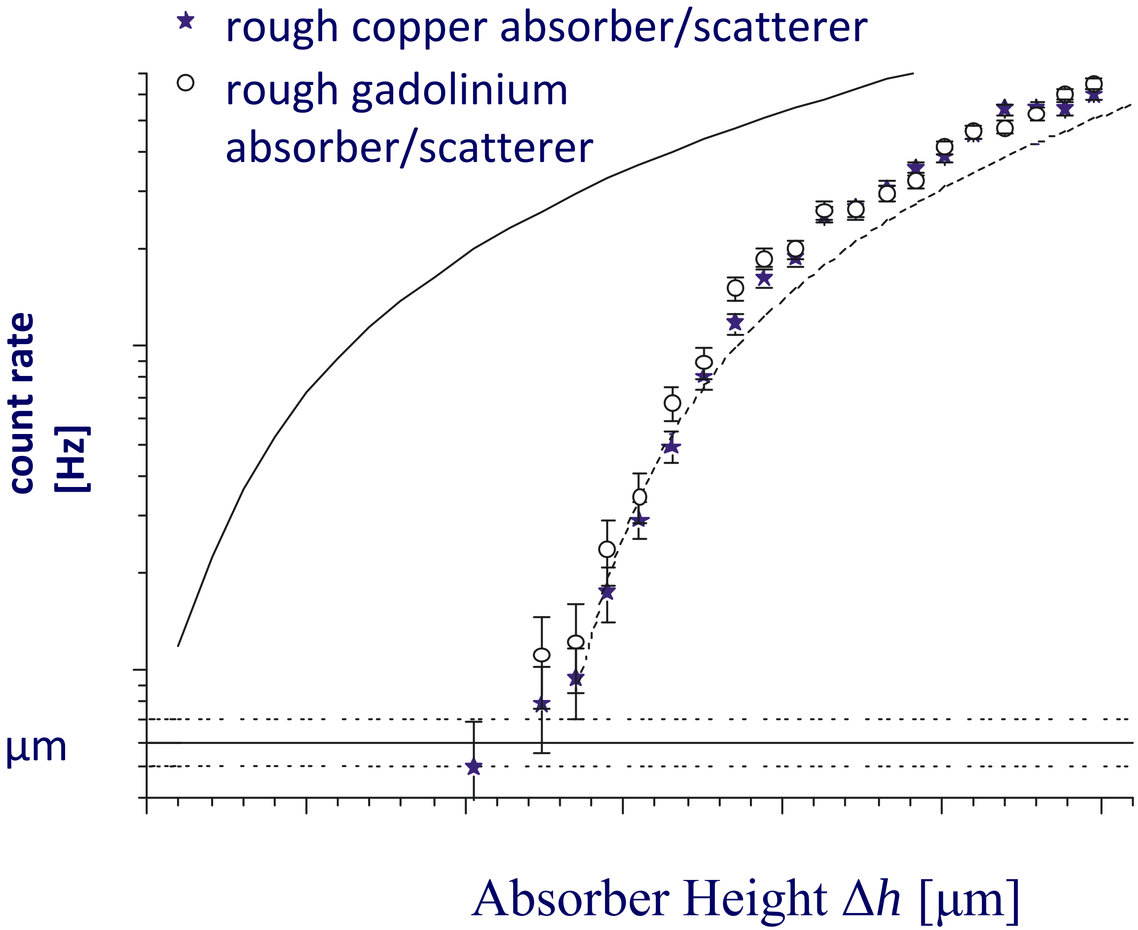




Roughness:

σ = 0,7 µm

Corr. length: 5 µm



- **Loss mechanism**

$$d\langle\psi_n|\psi_n\rangle = -\langle\psi_n|\psi_n\rangle \cdot \Gamma_n(l) \cdot dt$$

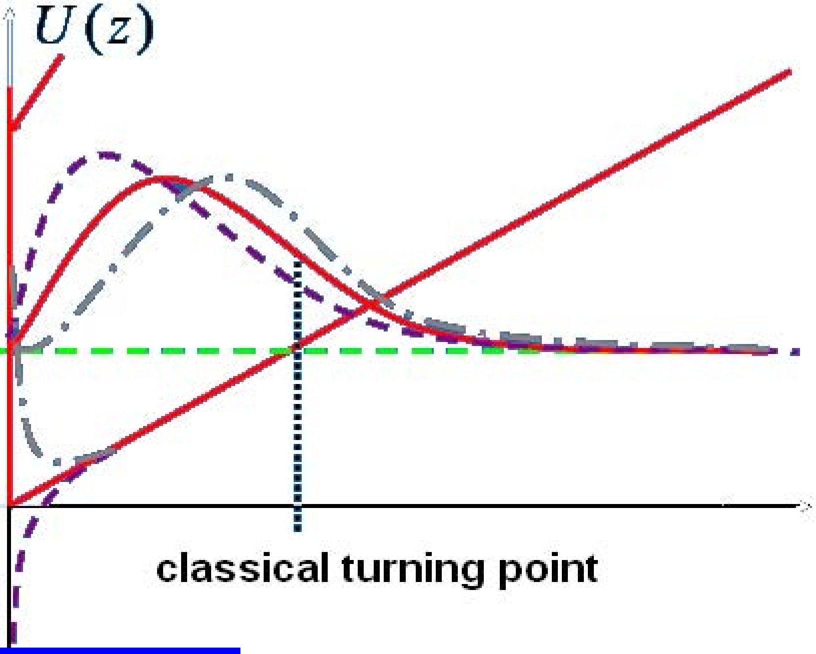
- **Overlapp with absorber**

$$\Gamma_n(l) = \alpha_{\mathrm{loss,n}} \cdot \int_{l-2\sigma}^{l} dz|\psi_n(z)|^2$$

Effect of hypothetical Yukawa-type Forces

arising from higher-dimensional gravity, gauge forces or massive scalar fields

- Yukawa force deforms the wave function
- Changes the energy

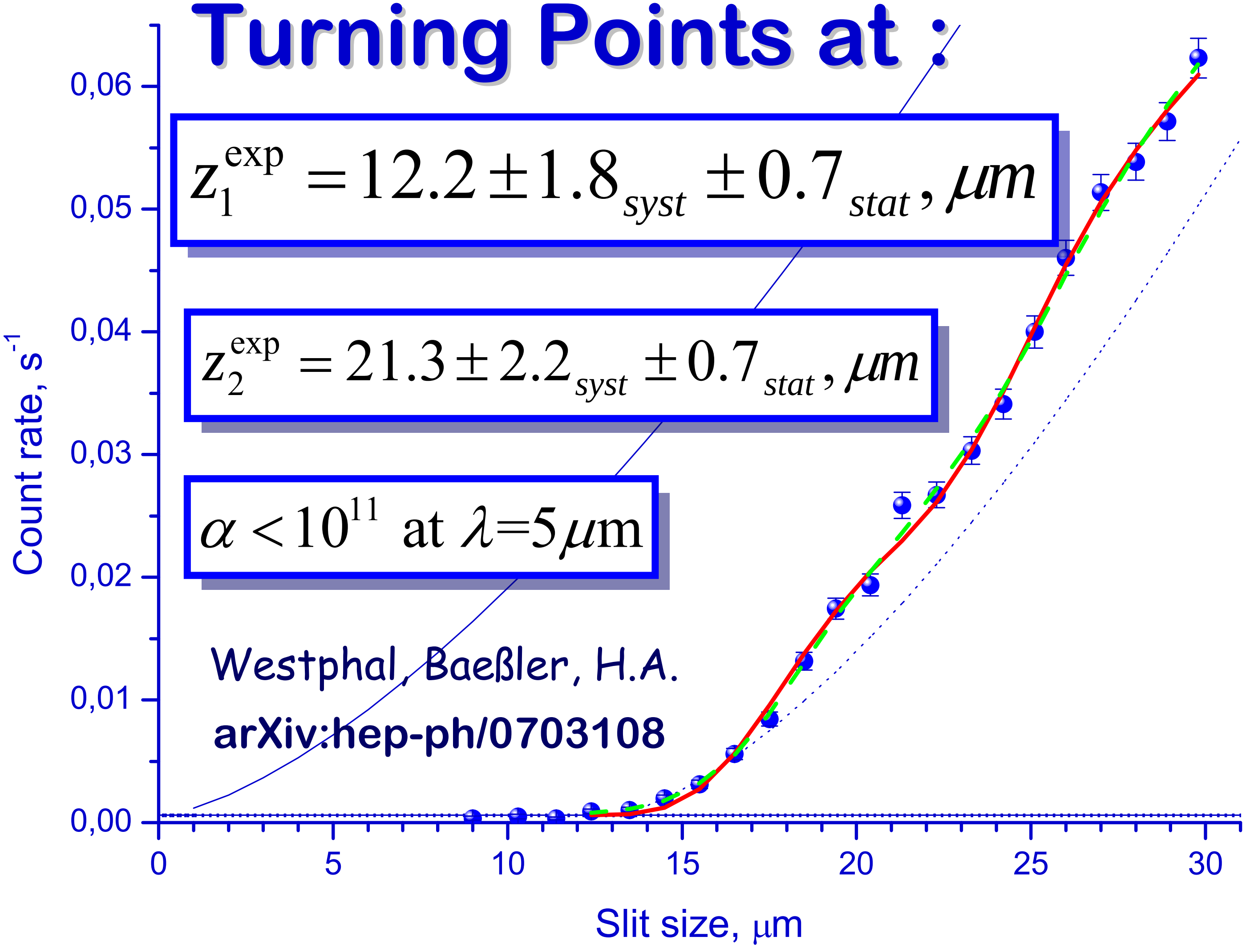


$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

Mirror **Absorber**

$$V(z) = g \cdot z + 2\pi \cdot \alpha \cdot \lambda^2 \cdot G \cdot \rho(e^{-z/\lambda} + e^{-(h-z)/\lambda})$$

2nd Run



Turning Points at :

$$z_1^{\exp} = 12.2 \pm 1.8_{syst} \pm 0.7_{stat}, \mu m$$

$$z_2^{\exp} = 21.3 \pm 2.2_{syst} \pm 0.7_{stat}, \mu m$$

$$\alpha < 10^{11} \text{ at } \lambda = 5 \mu m$$

Westphal, Baeßler, H.A.

arXiv:hep-ph/0703108

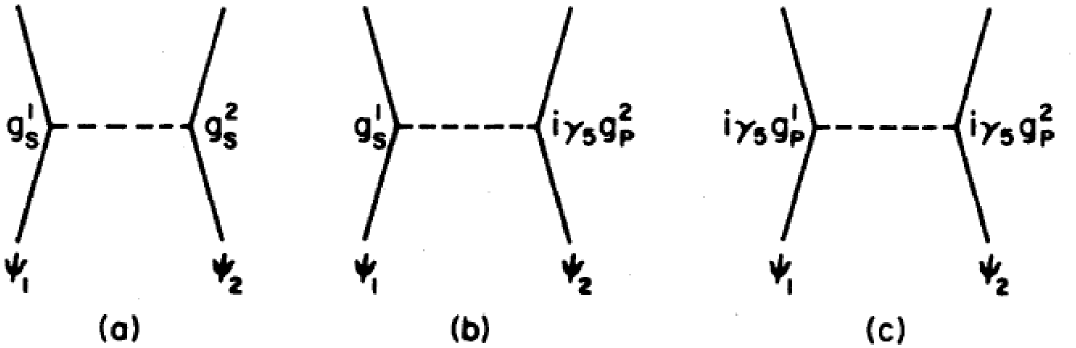
V. Nesvizhevsky et al., EPJ, 2005

2.1 Limits on Axions/CP-Violation

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

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

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



(a) (b) (c)

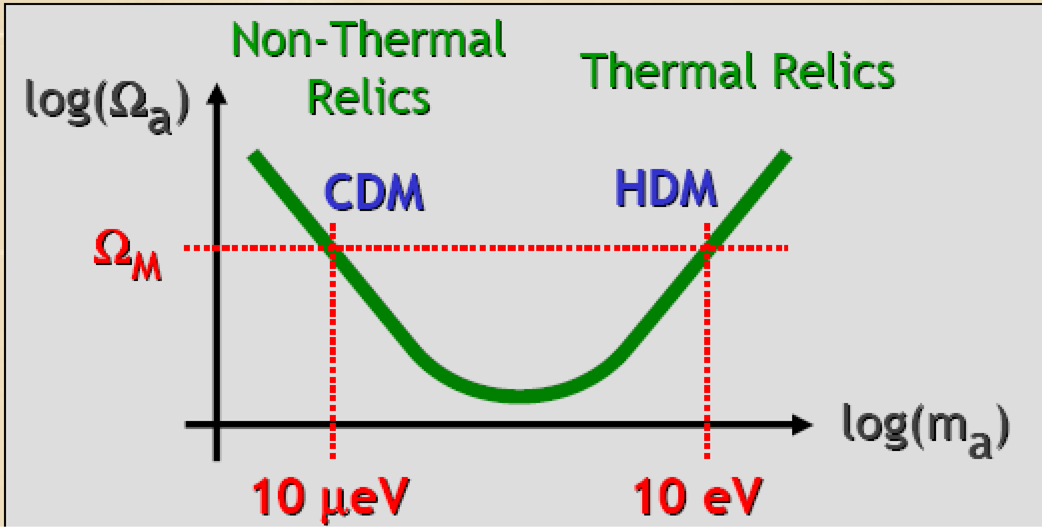
$$V(\vec{r}) = \hbar g_s g_p \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Science week TU Munich 08, Georg Raffelt:

Lee-Weinberg Curve for Neutrinos and Axions

$$\lambda = \frac{\hbar c}{mc^2}$$

Axions



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

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

$$\begin{aligned}\Delta\phi(z) &= -\alpha_a\cdot\frac{\hbar^2\rho_1\lambda}{8m^3}\,e^{-z/\lambda} + \alpha_a\cdot\frac{\hbar^2\rho_2\lambda}{8m^3}\,e^{-(h-z)/\lambda}\\ &= -2\pi\alpha_{\mathrm{eff.}}\cdot\lambda^2\cdot G_4\cdot\left(\rho_1\,e^{-z/\lambda} - \rho_2\,e^{-(h-z)/\lambda}\right)\end{aligned}$$

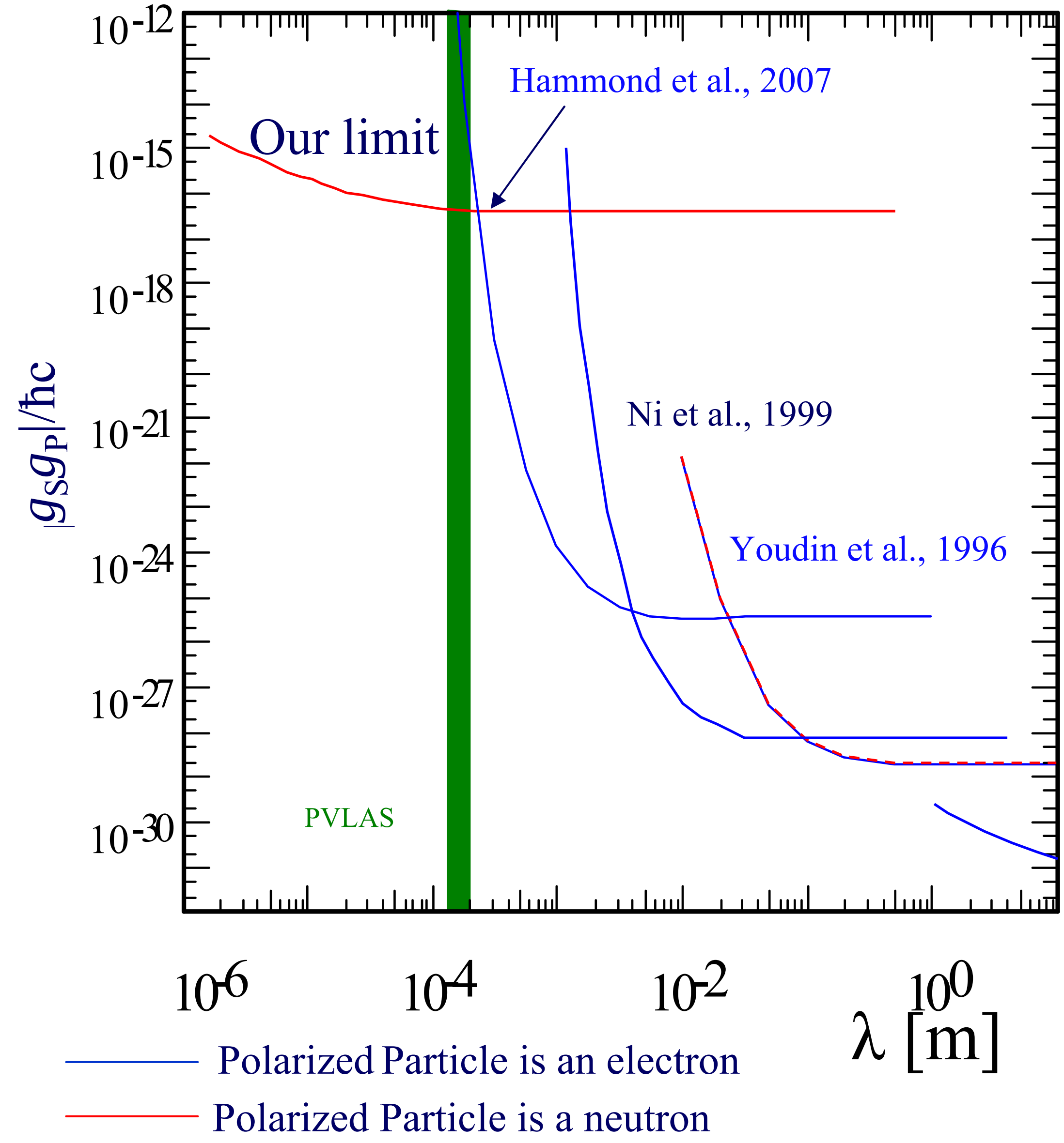
$$\alpha_{\mathrm{eff.}} = \alpha_a\cdot\frac{\hbar^2}{16\pi G_4\cdot m^3}\cdot\lambda^{-1}\quad,\quad \alpha_a := \frac{g_s g_p}{\hbar c}$$

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

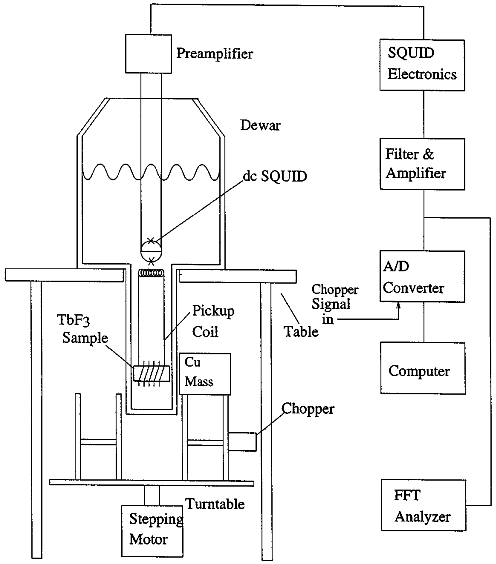
Axion Limits

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

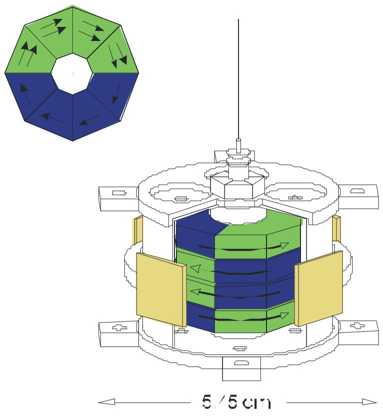
arXiv:hep-ph/0703108



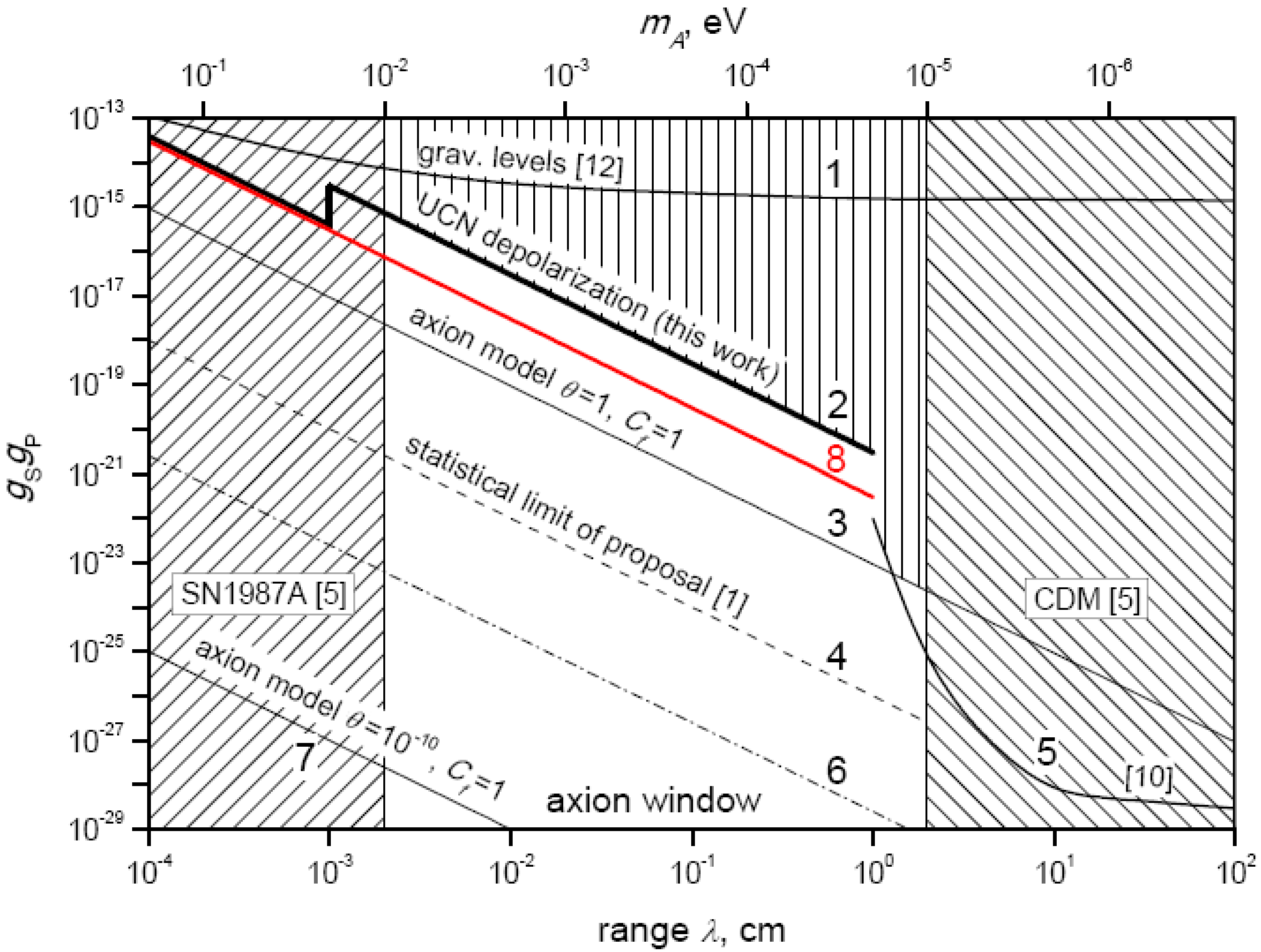
Ni et al., 1999:



Heckel et al., 2006:

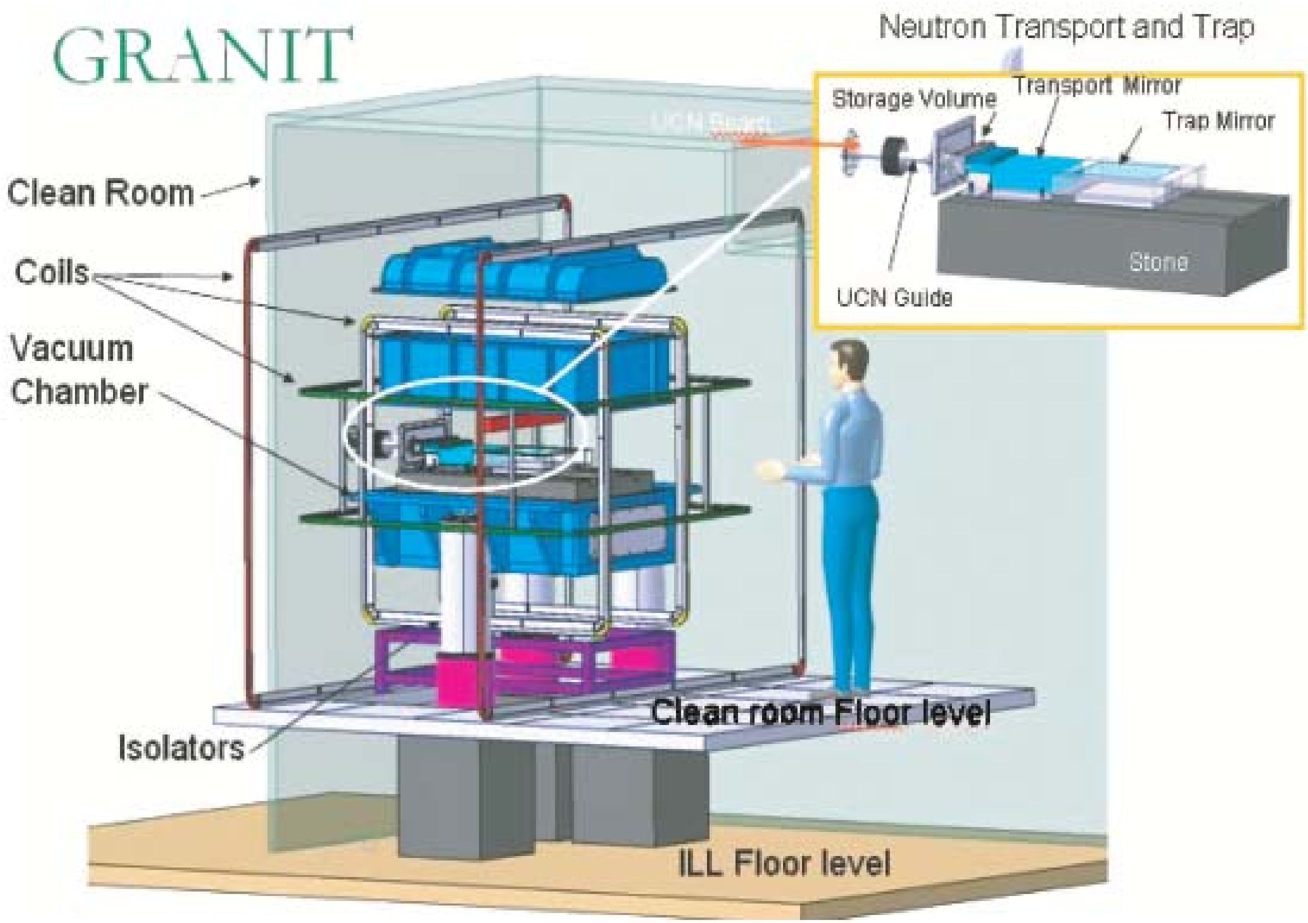


O. Zimmer UCN09

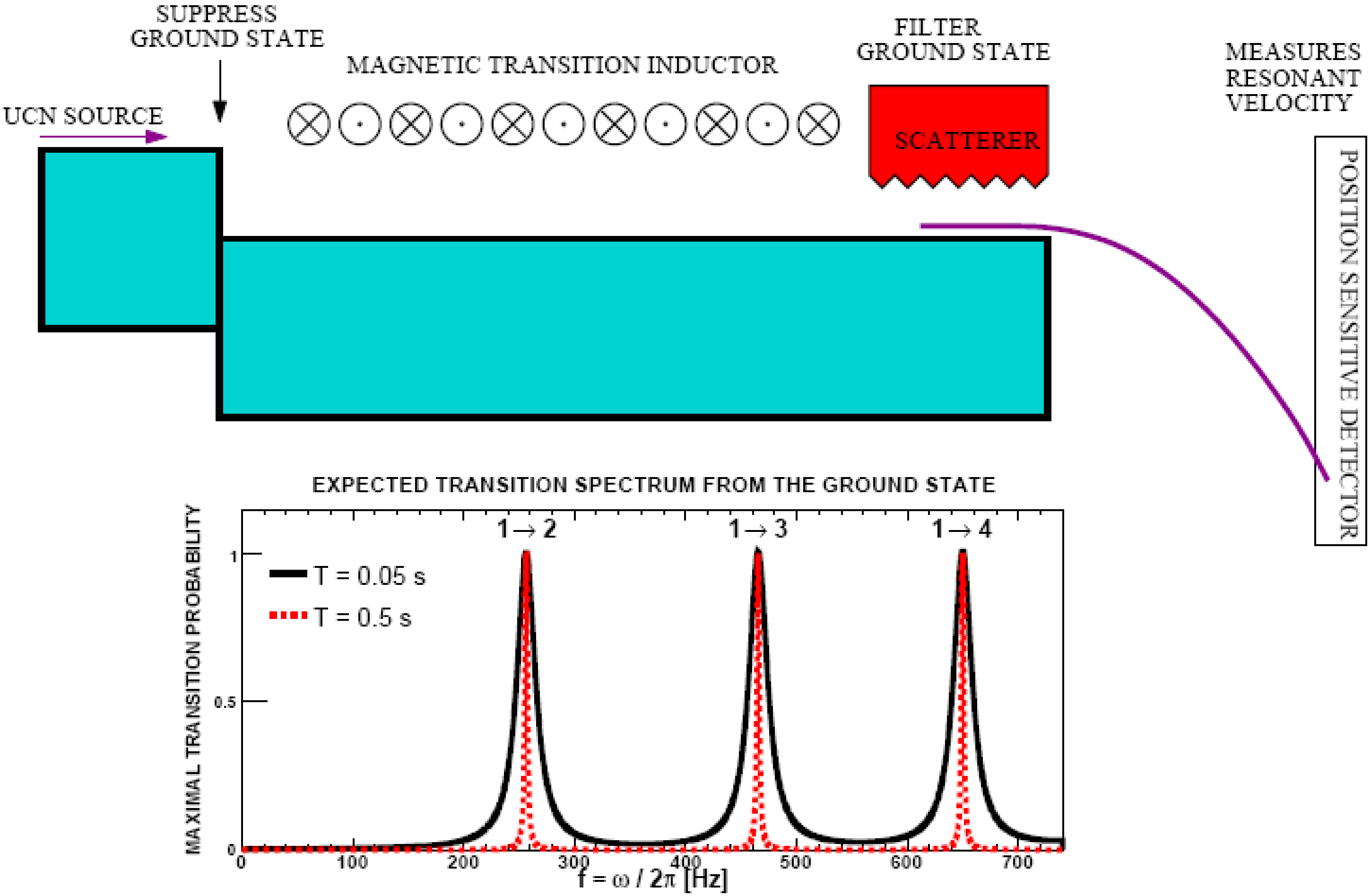


New Projects

1. GRANIT Collaboration



Resonant Transitions

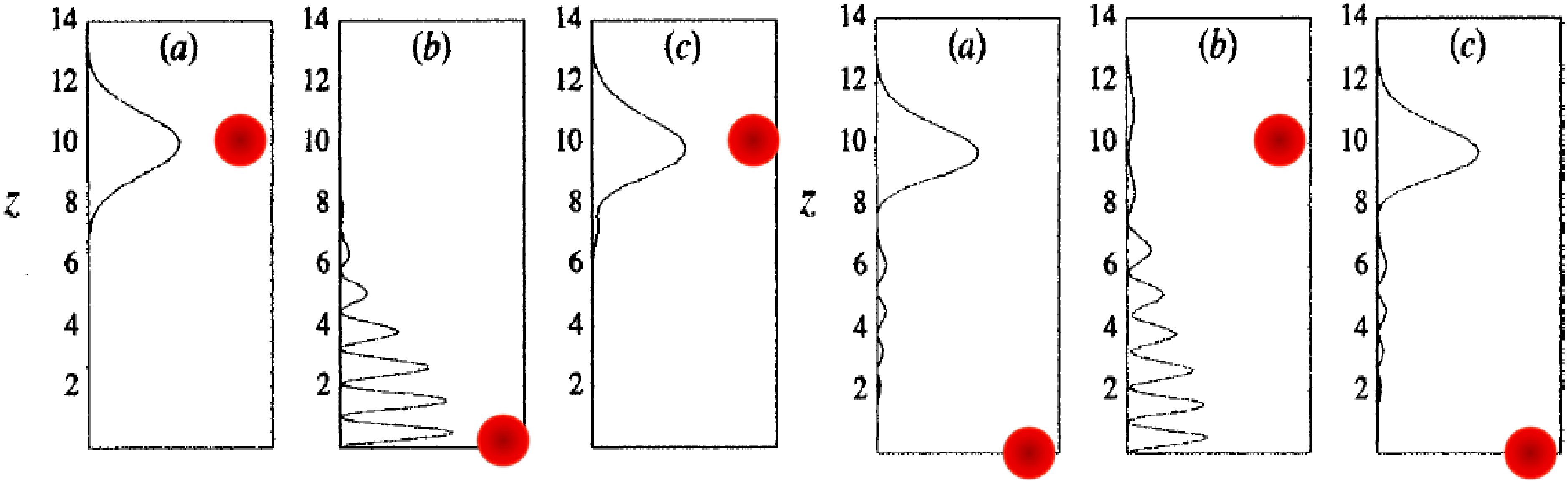


EXPECTED TRANSITION SPECTRUM FROM THE GROUND STATE

2. qBounce

the dynamics of ultra-cold neutrons in the gravity potential

Julio Gea-Banacloche, Am. J. Phys.1999



Quantum interference: sensitivity to fifth forces

Limits

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

$$\Delta\varphi \times \Delta N = 2\pi$$

$$N = 10^6 \rightarrow \Delta\varphi = 10^{-3}$$

$$\varphi = \omega \times t = E \cdot t / \hbar$$

$$\Delta\varphi = \Delta E \cdot t / \hbar$$

$$\Delta E = \Delta\varphi \hbar / T = 0.33\hbar / s = 6 \times 10^{-6}\,\mathrm{peV}$$

- **Count rate: 0.5s^{-1} N = 10^6 after 25 days**
- **Observation time T = 100ms**

Fifth force: $\Delta\varphi$

↓

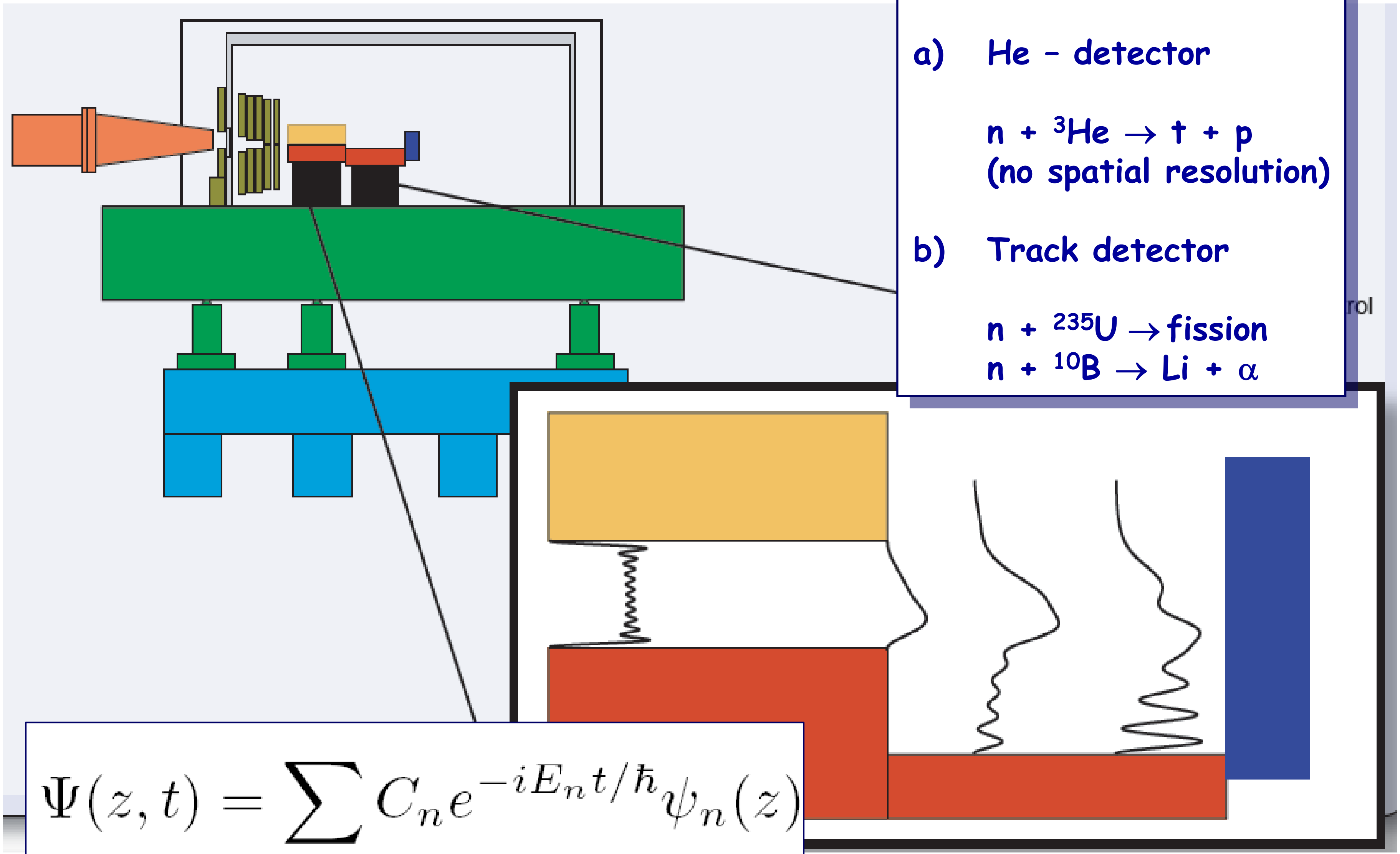
$$N = 10^6$$

$$\Delta E = 6 \times 10^{-6}\,\mathrm{peV}$$

$$\alpha = 3 \times 10^6 \rightarrow 10^5 \rightarrow 10^2$$

$$\Psi(z,t) = \sum C_n e^{-iE_n t/\hbar} \psi_n(z)$$

The Quantum Bouncer



Neutron detection:

a) He – detector

$n + {}^{3}He \rightarrow t + p$
(no spatial resolution)

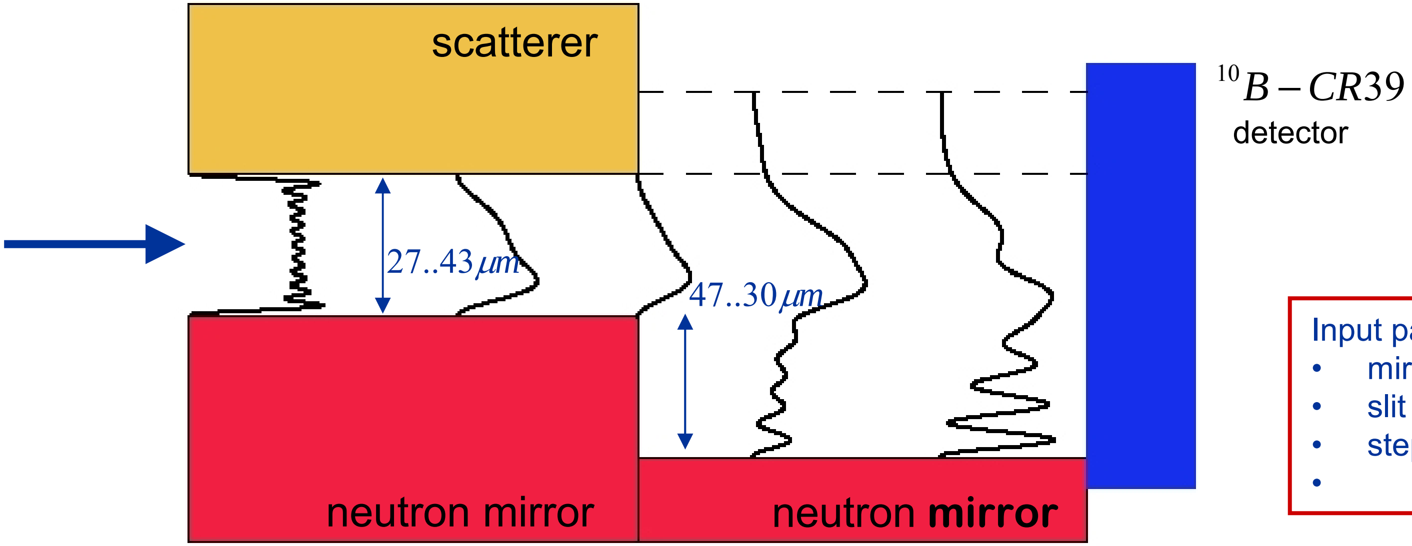
b) Track detector

$n + {}^{235}U \rightarrow$ fission
$n + {}^{10}B \rightarrow Li + \alpha$

$$\Psi(z,t) = \sum C_n e^{-iE_n t/\hbar} \psi_n(z)$$

T. Jenke, Diploma thesis, 2008

Q-Bounce:
The Neutron Mirror Setup



Input parameters:
- mirror lengths
- slit size
- step size
-

$f(v_x)$

Preparation:

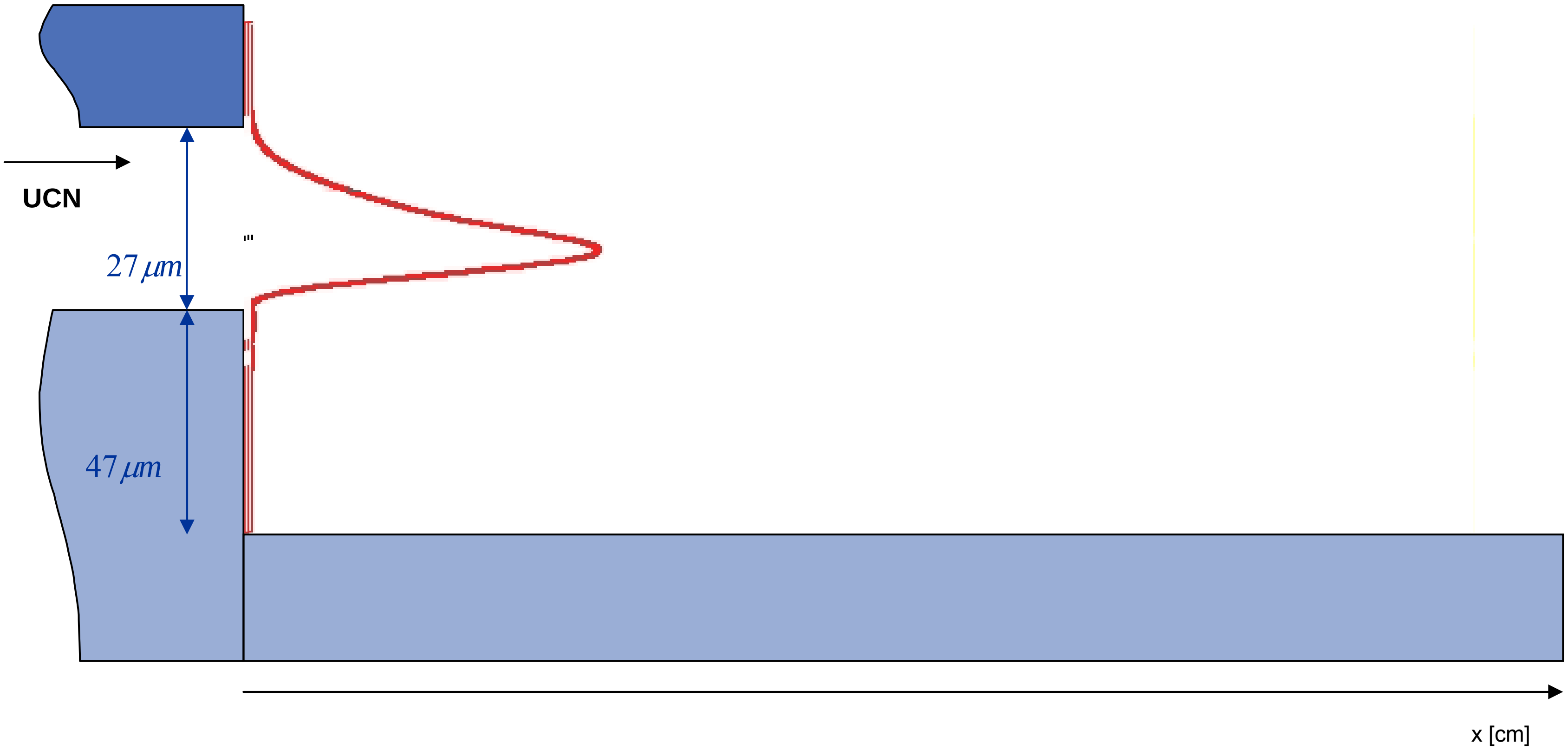
$$\sum_n \left| c_n \varphi_n e^{-iE_n t/\hbar} \right|^2$$

Time evolution:

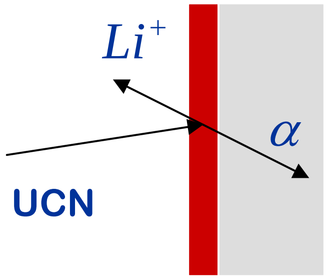
$$\left| \sum_m d_m \phi_m e^{-iE_m (t-t_0)/\hbar} \right|^2$$

Q-Bounce:

The Neutron Mirror Setup



High-resolution track detector



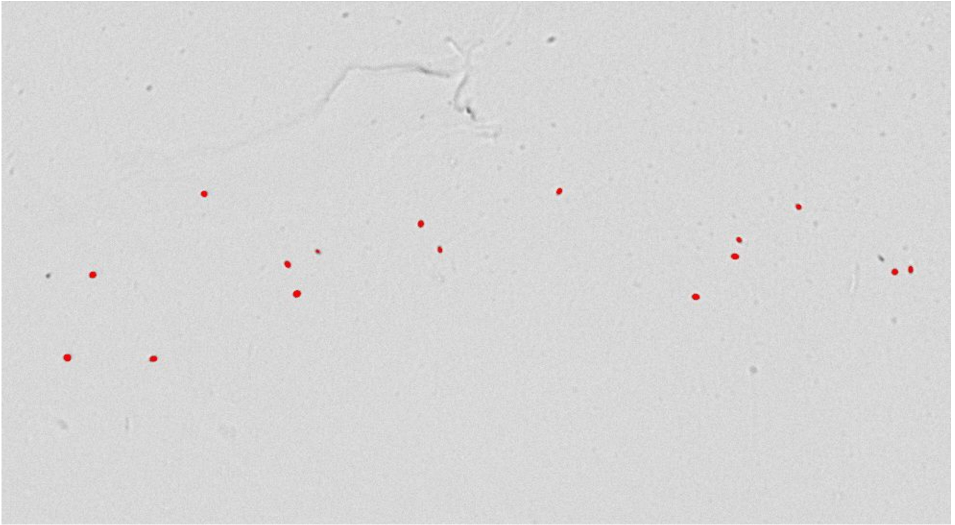
CR39-plastic with 200nm ^{10}B coating

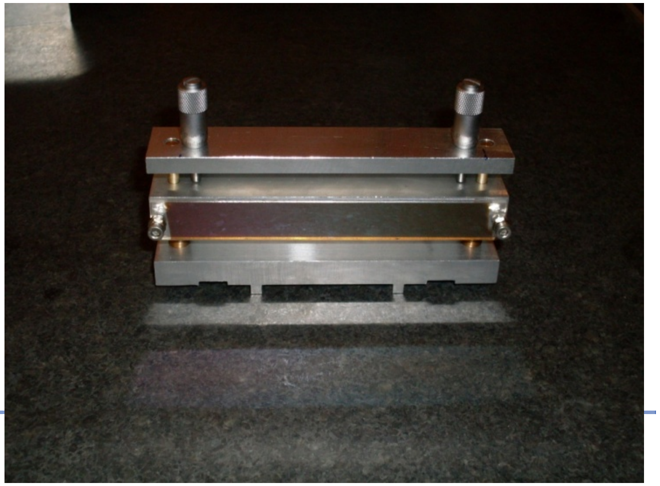
spatial resolution: $< 2\mu m$

^{10}B **efficiency:** $\approx 93\%$

detector efficiency: $\approx 62\%$

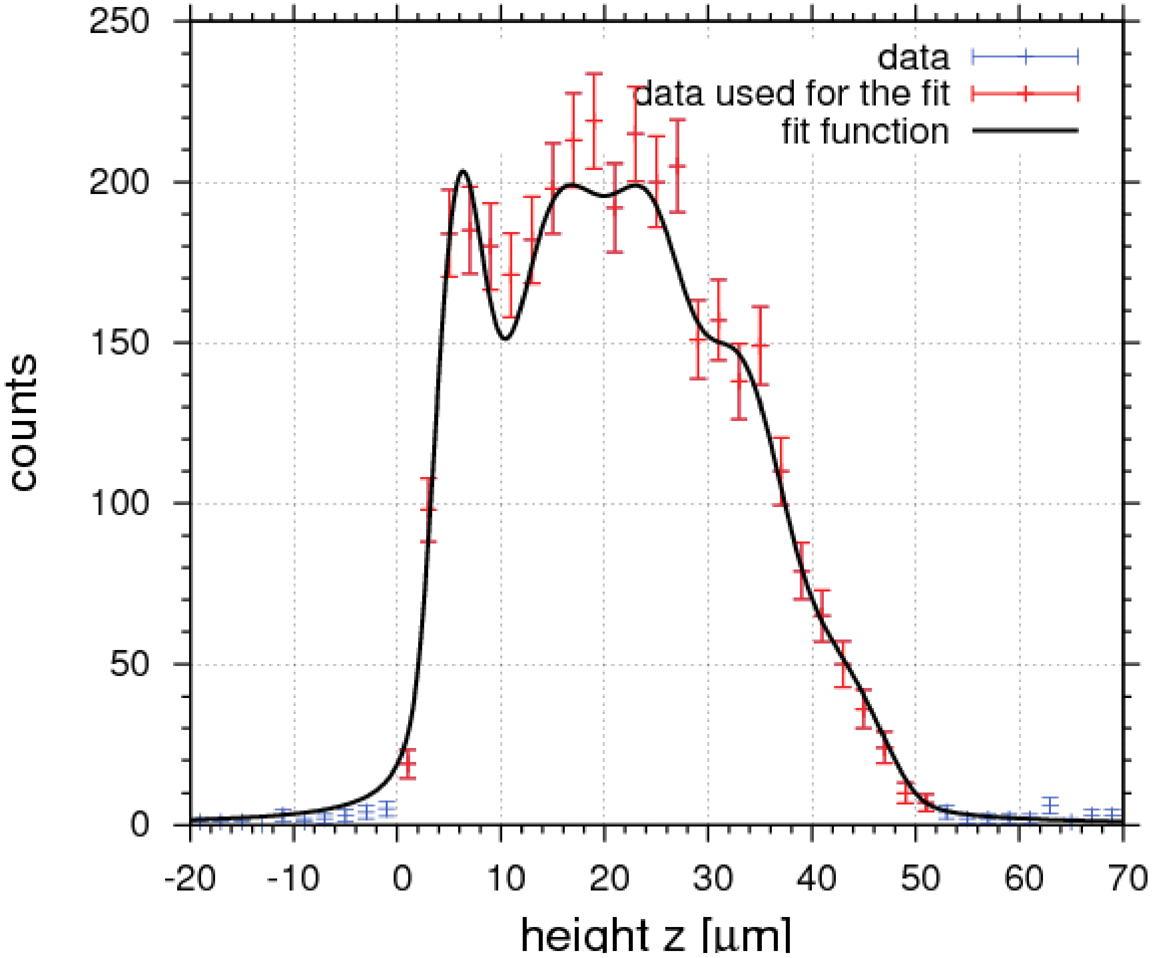
Process:
- Cleaning
- Coating
- Exposure with UCN
- Boron removal
- Etching
- Optical readout
- Data correction
- Data processing

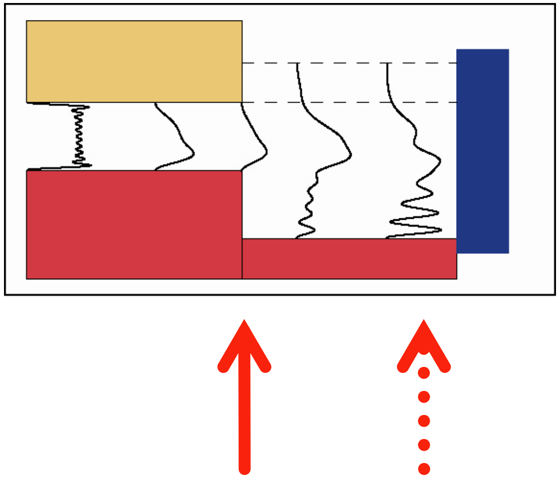




Tobias Jenke, 7th International UCN Workshop, St. Petersburg, 13.06.2009

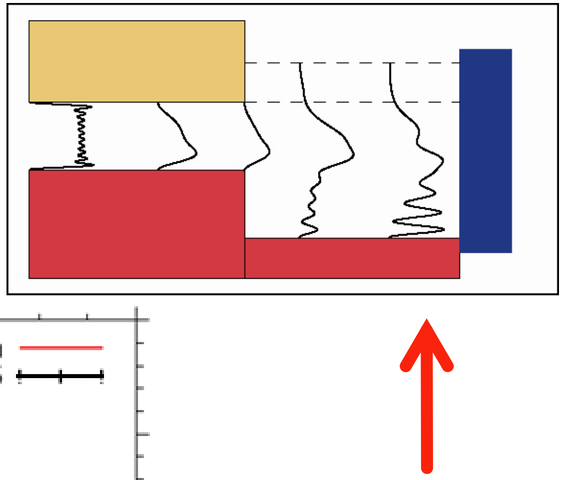
First results

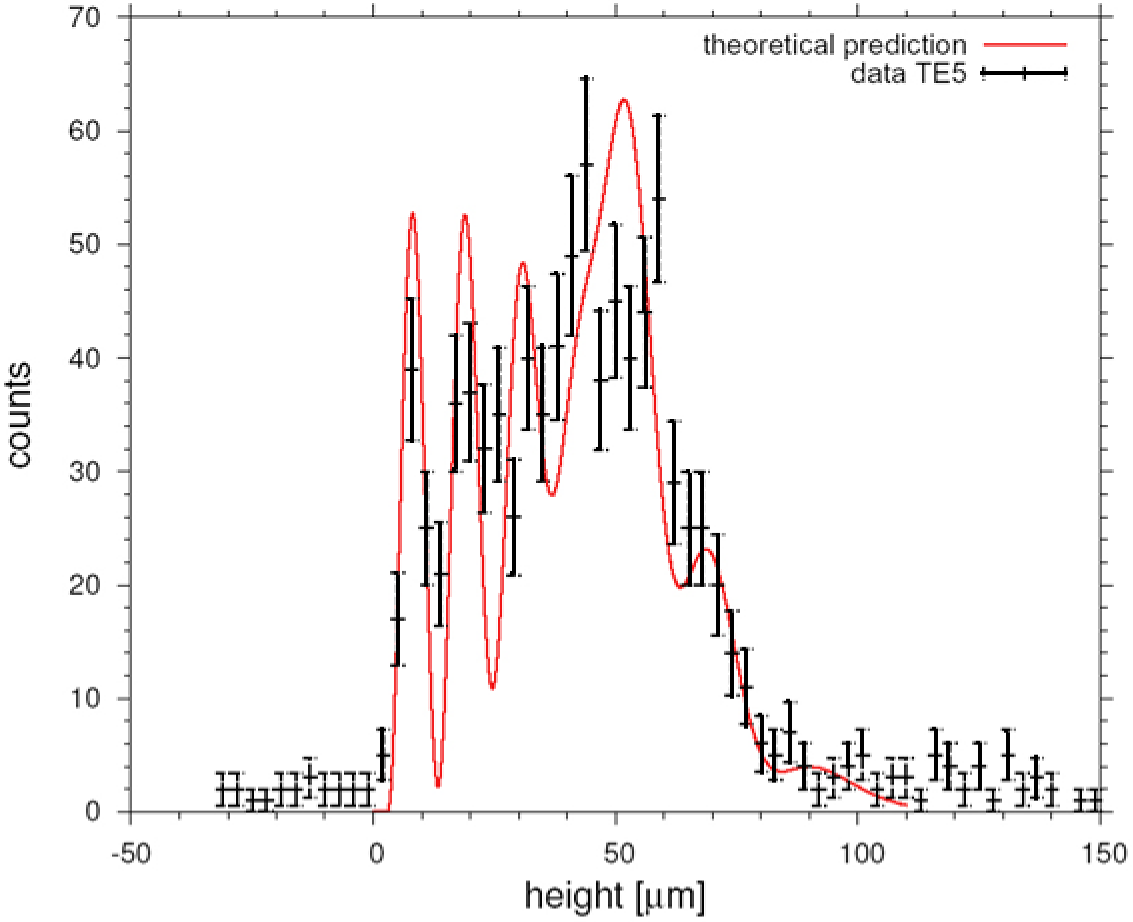




- ~4500 neutrons in total
- distance from step x = 0cm

T. Jenke, 2008




theoretical prediction
data TE5
70
60
50
40
30
20
10
0
counts
-50
0
50
100
150
height [µm]

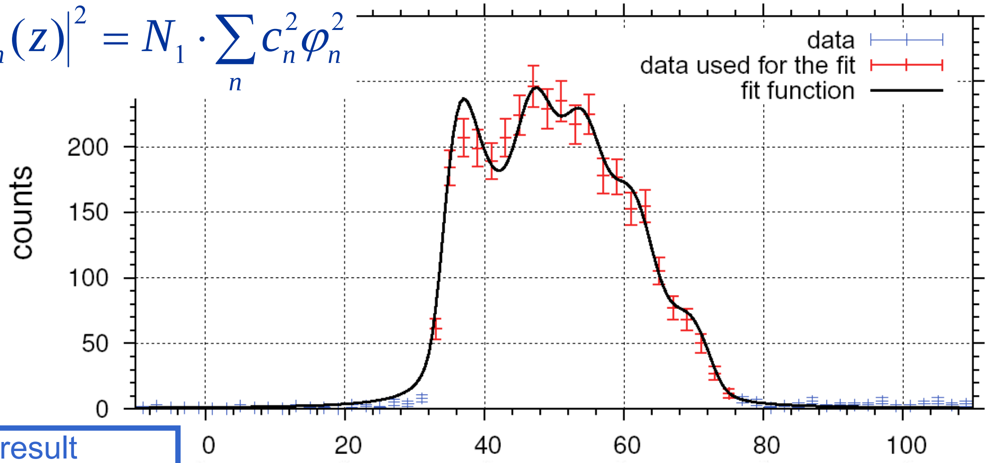
T. Jenke, 2008

Simultaneous fit of TE2 and TE5

setup parametres:

- slit size: $l_1 = 43\,\mu m$
- step size: $l_2 = 30\,\mu m$
- spatial resolution: $\sigma = 2\,\mu m$
- mean evolution time: $\bar{t} = 10.4\ ms$
- stretching: $s_1 = 0.90, s_2 = 0.83$

$$|\psi_{x=10cm}(z)|^2 = N_1 \cdot \sum_n c_n^2 \varphi_n^2$$



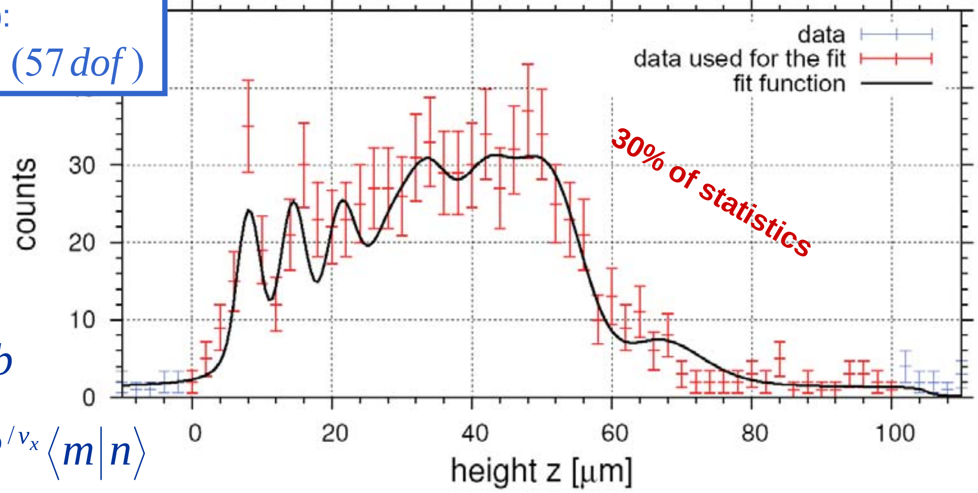
preliminary result (2008/11/19):
$\chi^2_{red} = 1.13\ \ (57\,dof)$

fit parametres:

- 6 coefficients: c_n
- norm N_1 and N_2
- background $b = 1.3\ counts$

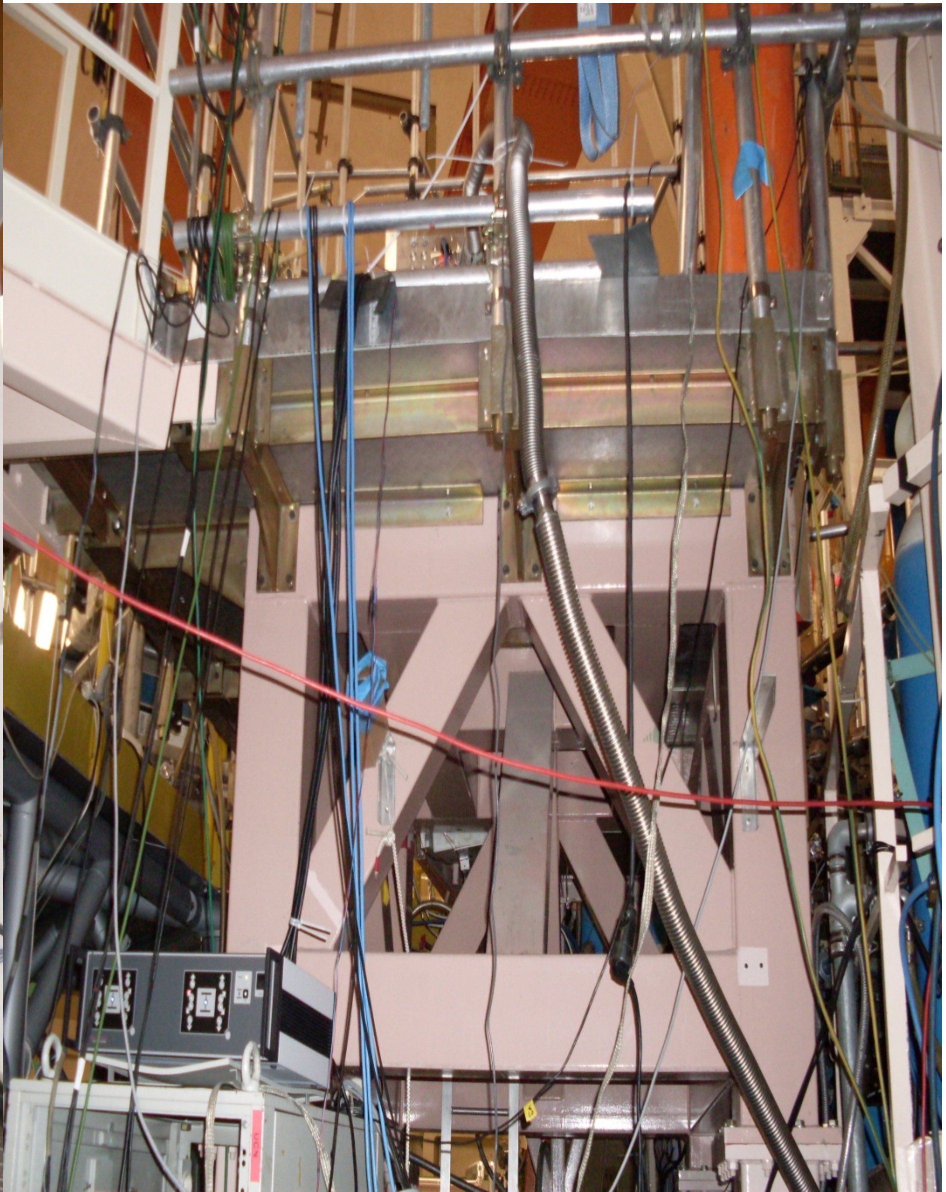
$$|\psi_{x=16cm}(z)|^2 = N_2 \left|\sum_m d_m \phi_m e^{-iE_m/\hbar\cdot(x-x_0)/v_x}\right|^2 + b$$

$$d_m = \sum_n c_n e^{-iE_n/\hbar\cdot x_0/v_x} \langle m|n\rangle$$



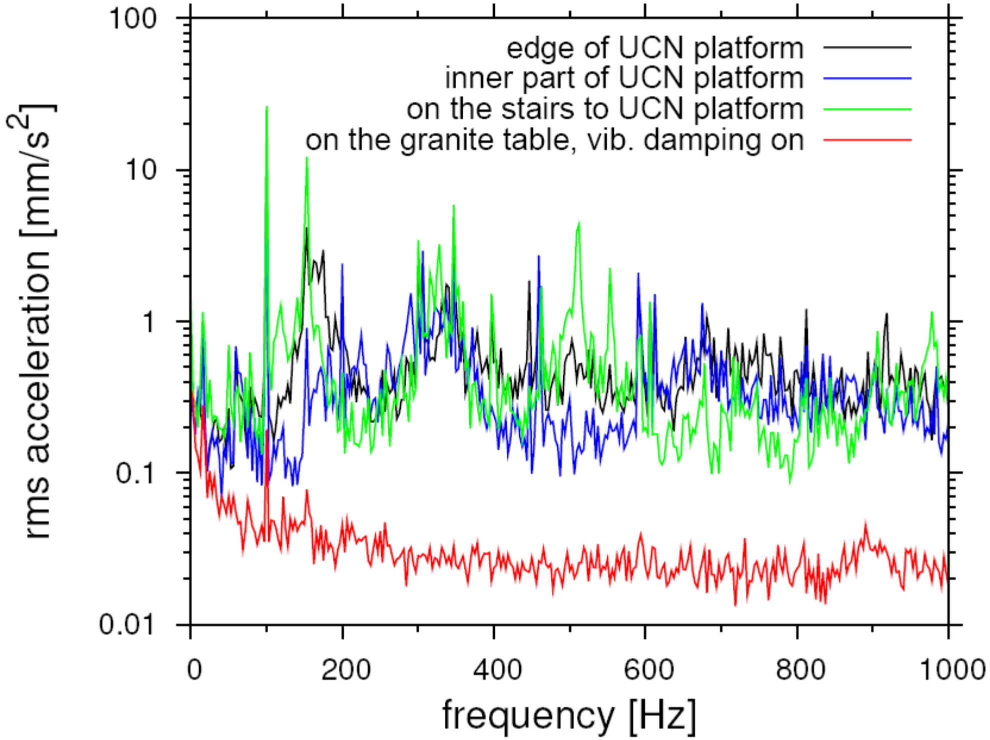
30% of statistics

Simulation T. Jenke

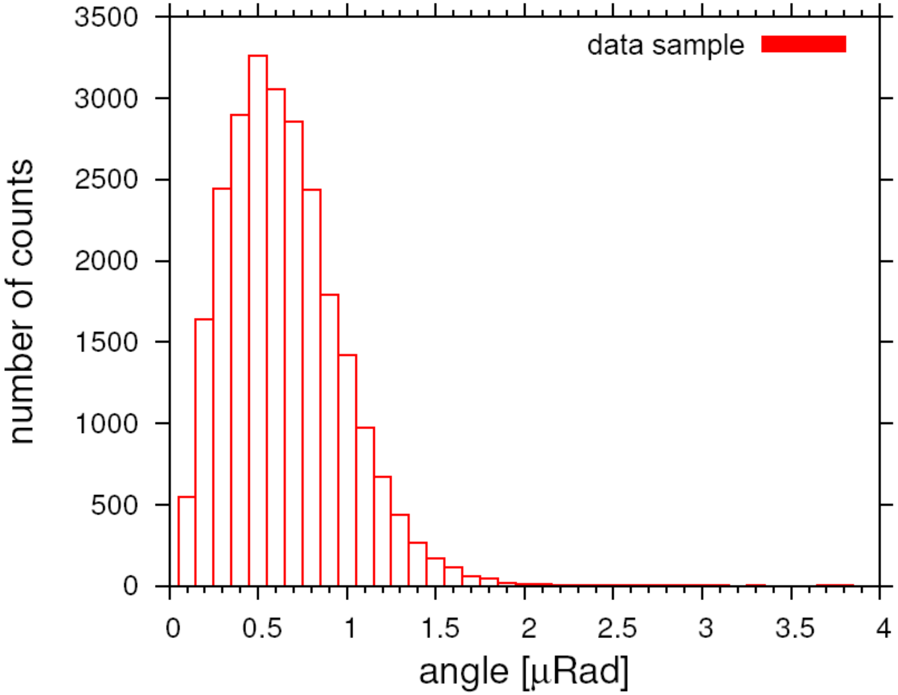


Stability

Vibrations



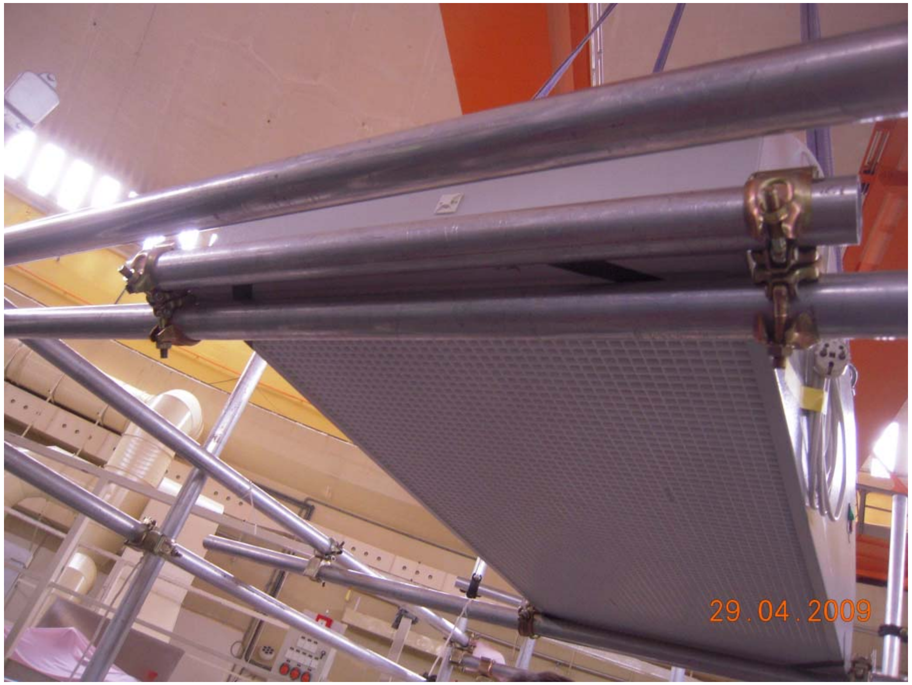
Inclinometers



Hartmut Abele, Technische Universität München

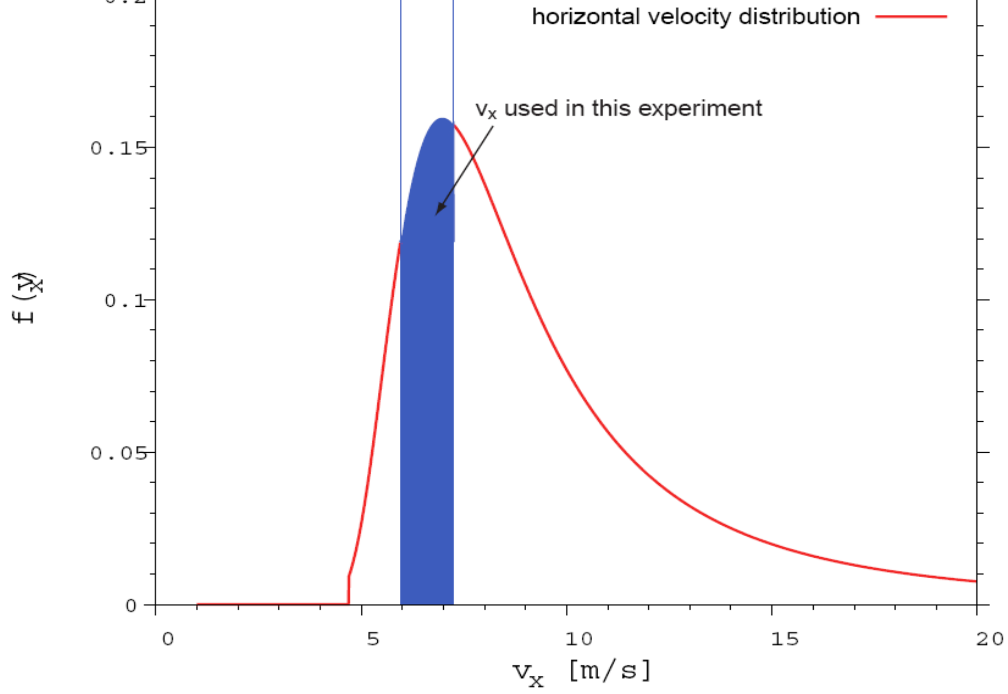
D. Stadler, Diploma thesis, 2009

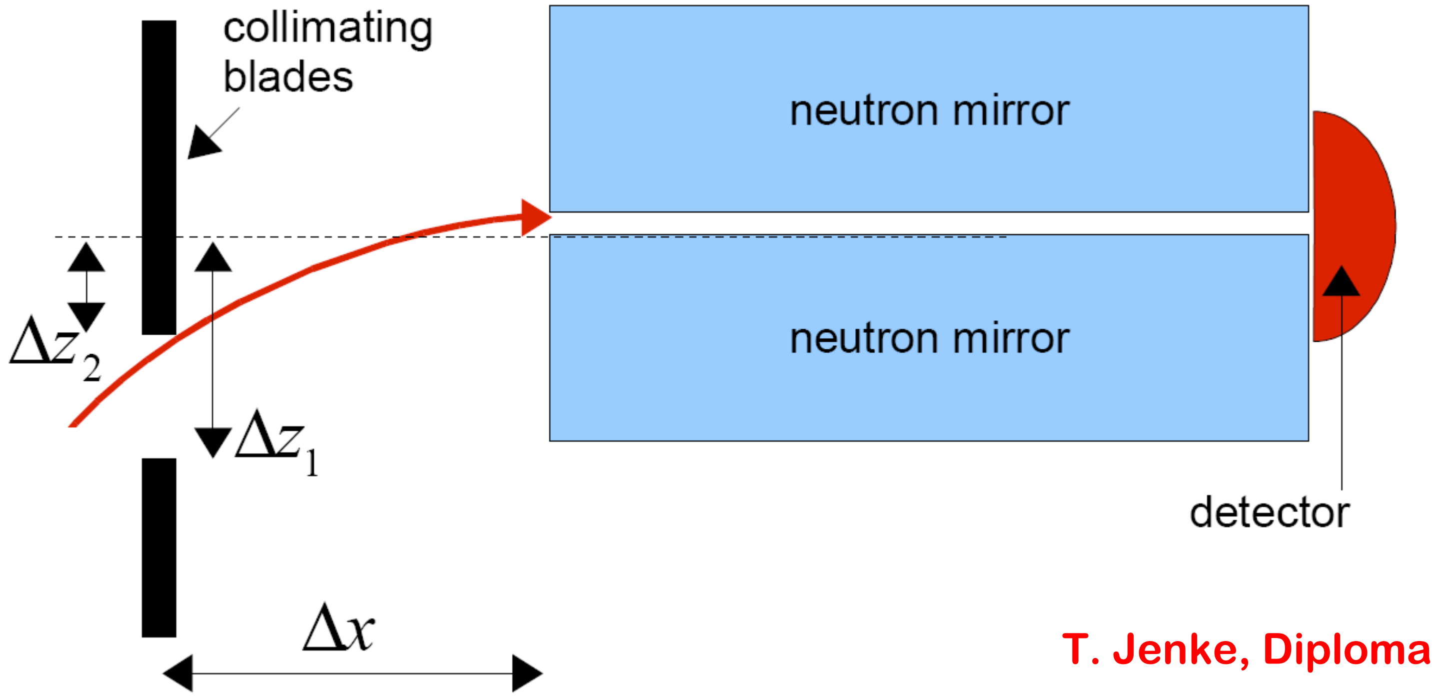
Setup



Horizontal velocity

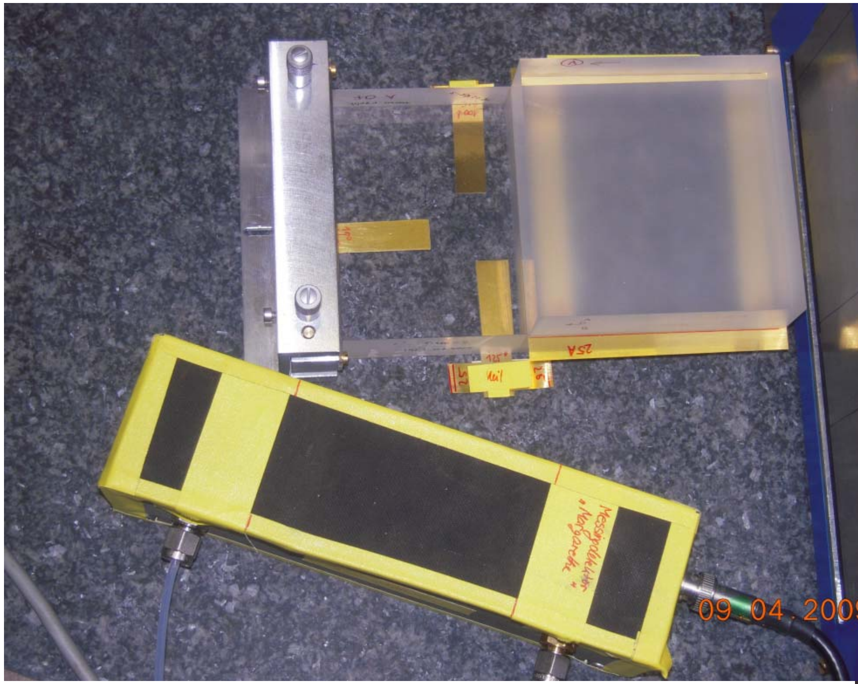
- $6\ \text{m/s} < v_x < 7.2\ \text{m/s}$



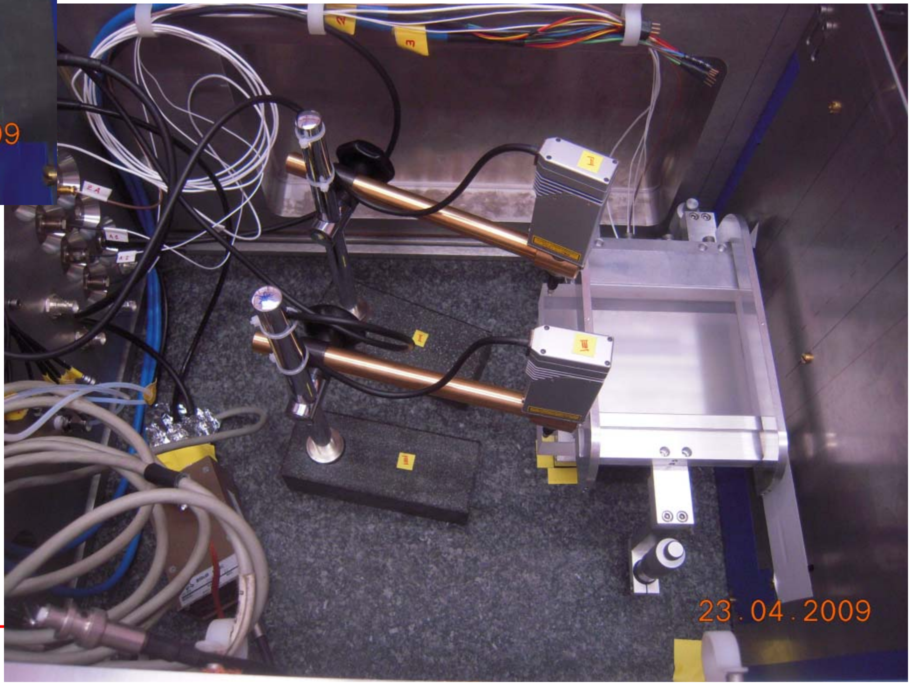


T. Jenke, Diploma thesis, 2008

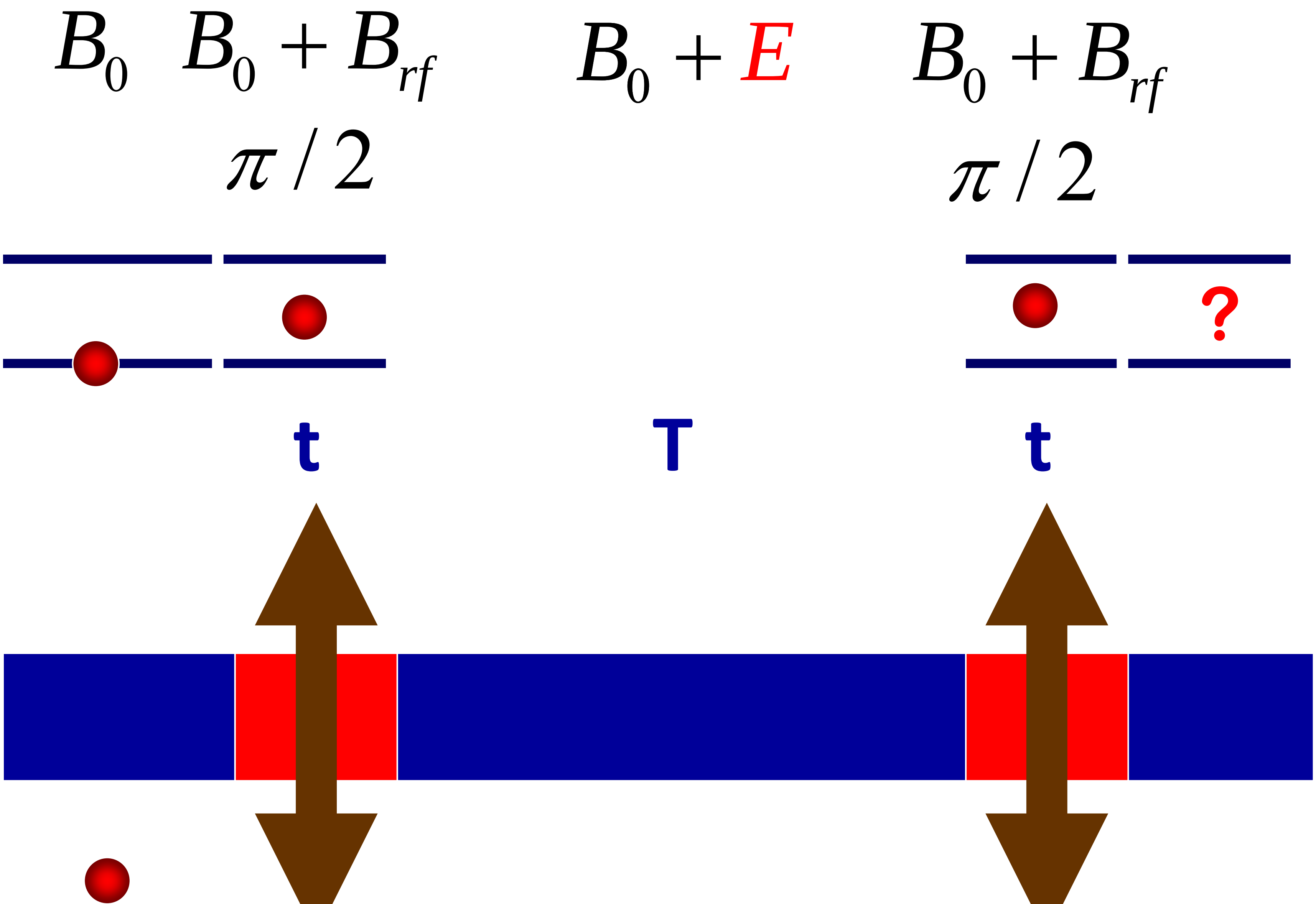
Setup



- **Mirror system**
- **Micrometer screws**
- **Linear gauges 0.1µm**
- **Inclinometers 0.1 µrad**



EDM: Ramsey‘s Method of Oscillating Fields

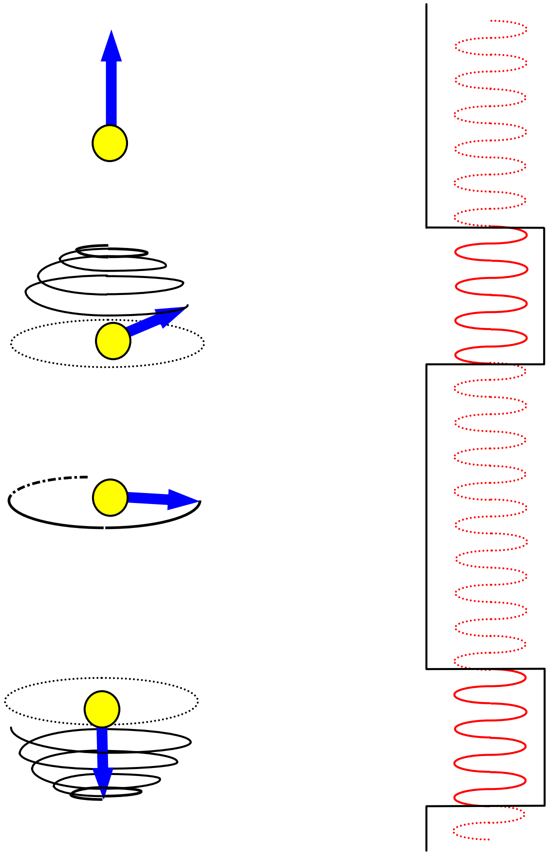


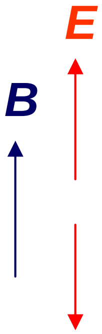
B_0 $\quad B_0 + B_{rf}$ $\quad B_0 + E$ $\quad B_0 + B_{rf}$

$\pi / 2$ $\quad \pi / 2$

Measurement principle

Ramsey method of Separated Oscillating Fields

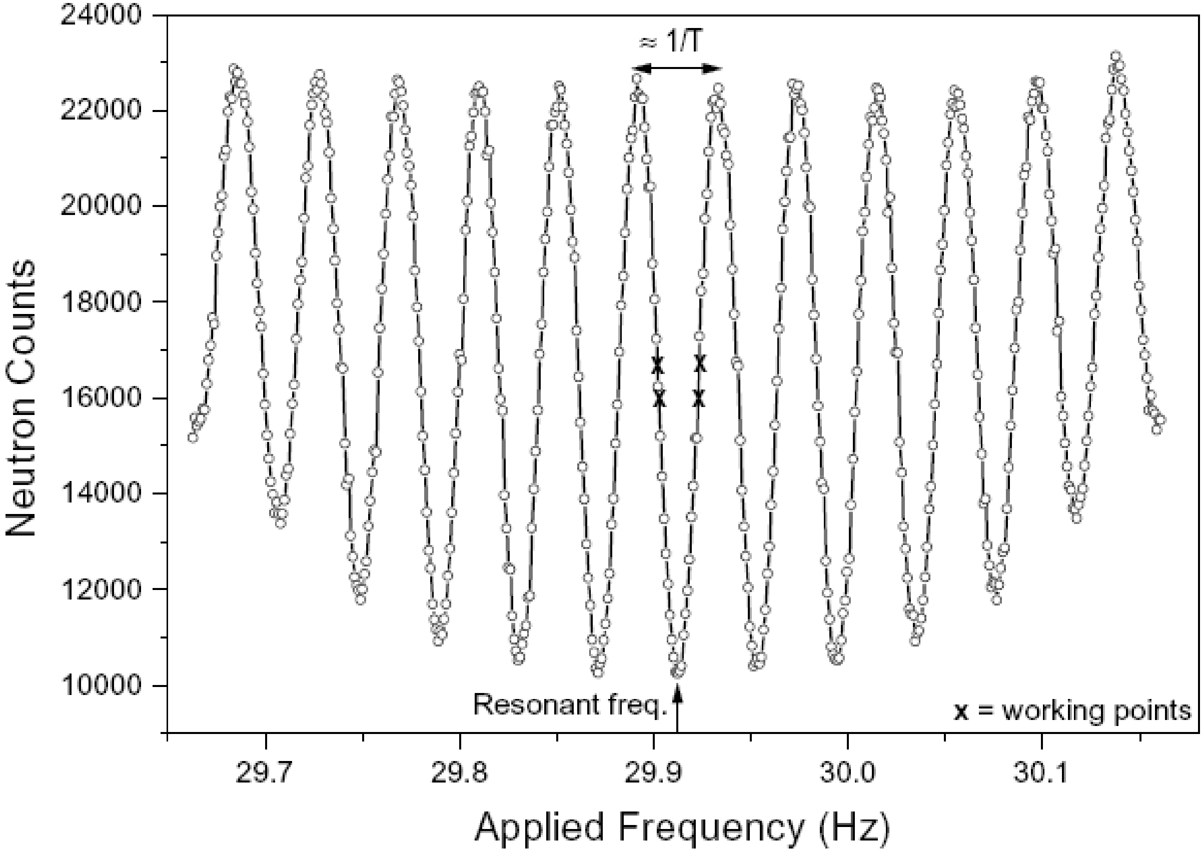




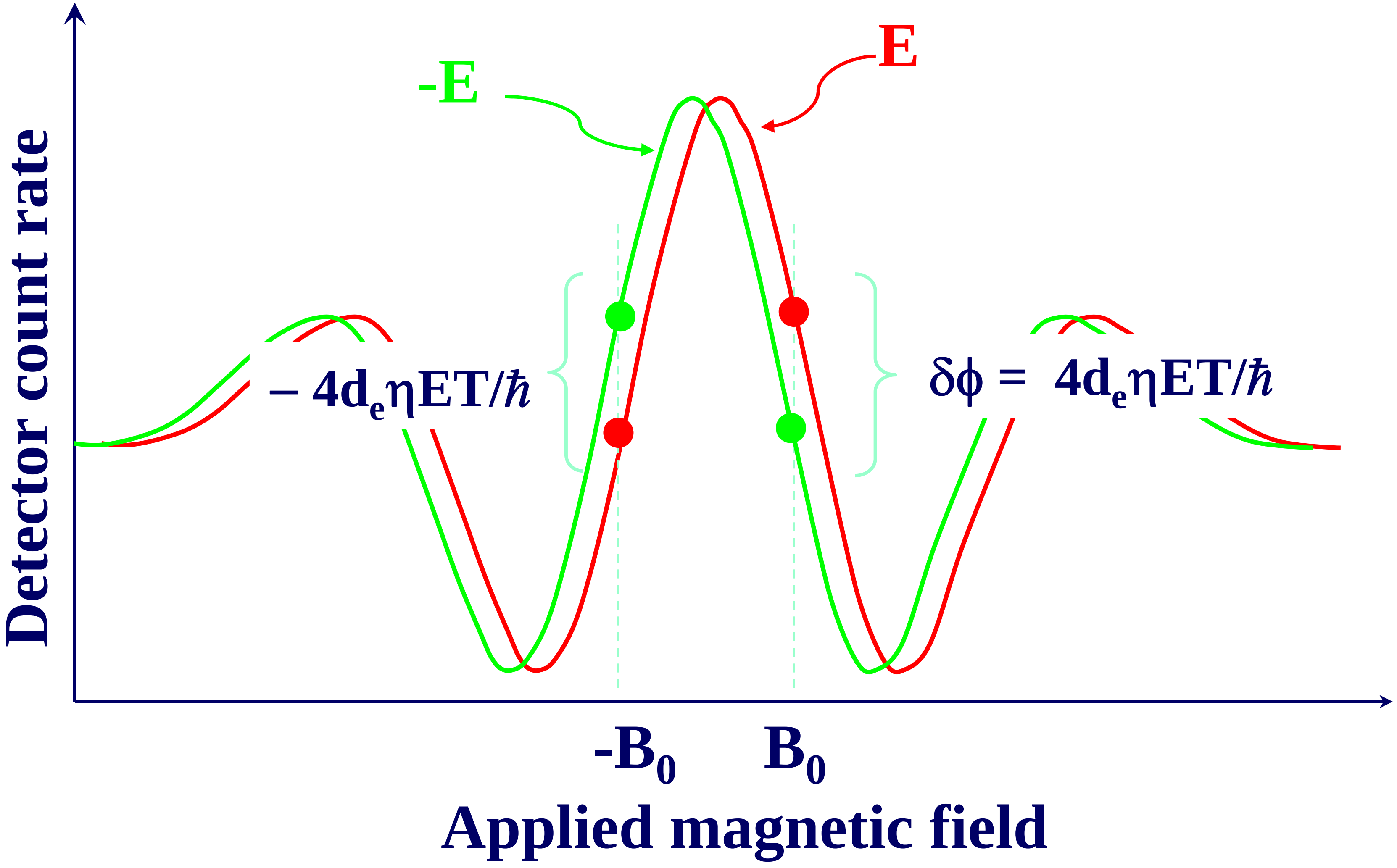
prepare a sample of polarized neutrons

- make a $\pi/2$ spin flip (“start clock”)
- allow free spin precession in parallel ***B*** and ***E*** static fields
- make a $\pi/2$ spin flip (“stop clock”)
- analyze direction of neutron spin
- look at energy (frequency) shift under field inversion:

$$\Delta\varepsilon = h\,|\Delta\nu| = 4Ed_n$$


24000
22000
20000
18000
16000
14000
12000
10000
Neutron Counts
29.7
29.8
29.9
30.0
30.1
Applied Frequency (Hz)
≈ 1/T
Resonant freq.
x = working points

Measuring the edm



$-\,4d_e\eta ET/\hbar$

$\delta\phi = 4d_e\eta ET/\hbar$

Sensitivity

EDM-Phase shift: $\Delta\varphi = \Delta\omega \cdot t$

Heisenberg: $\Delta\varphi \times \Delta N = 1$

Energy of dipole: $E = \vec{d}_n \cdot \vec{E}_{el}$

and $E = h\nu$

$\rightarrow$

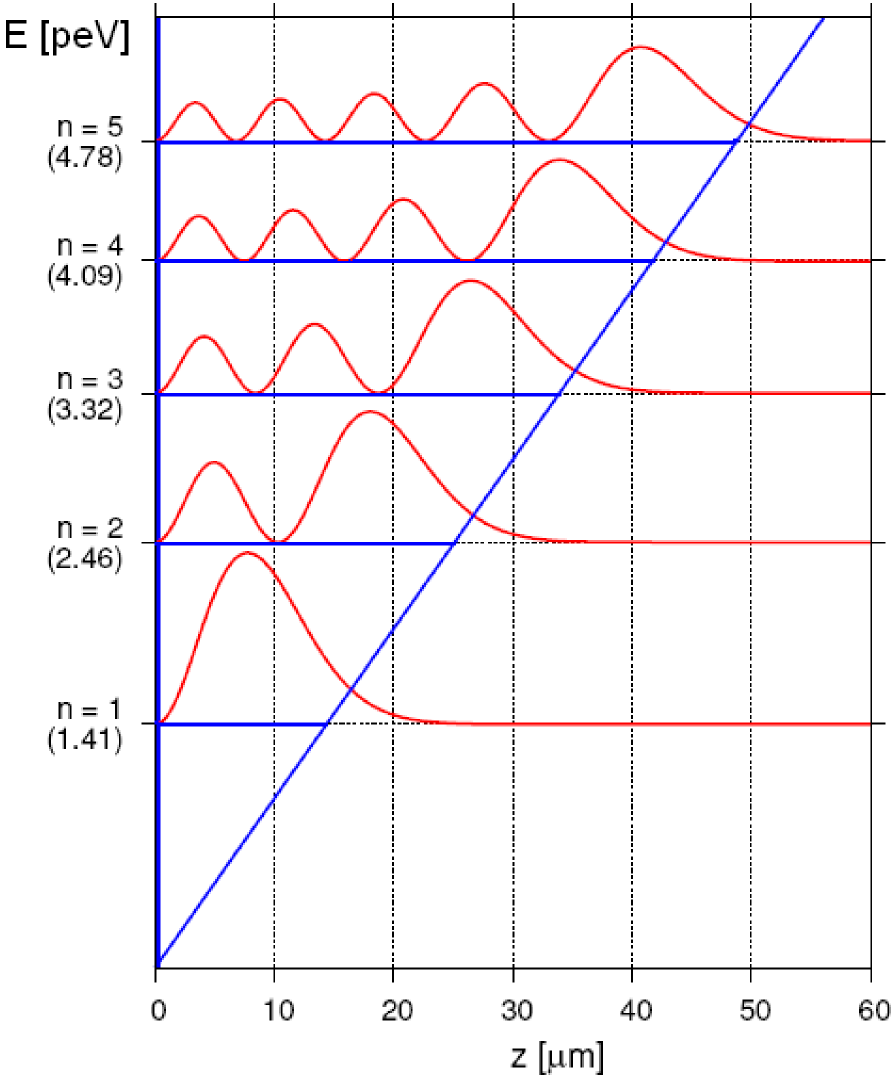
EDM-Phase shift: $\Delta\omega \cdot t = \frac{1}{\sqrt{N}}$

$$d_n = \frac{\hbar}{E_{el} \cdot t \cdot \sqrt{N} \cdot 2\alpha}$$

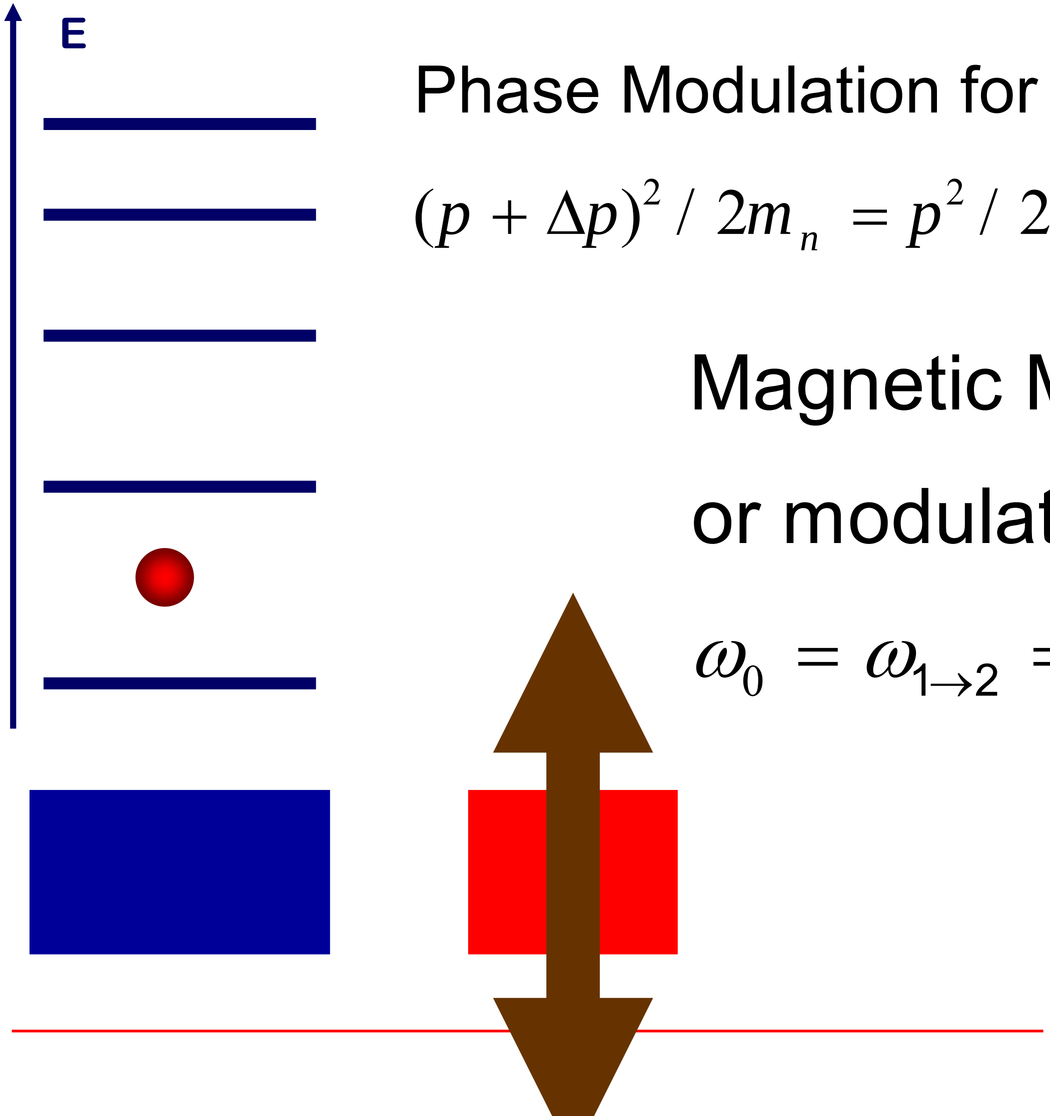
- **N = 18000**
- **t=130 s**
- **E_{el}=11kV/cm**
- **alpha = 0.85 (P = 92%)**
- **$d_n < 1.5 \times 10^{-24}$ ecm**

Application of Ramsey‘s Method to a 2 state system in the gravity potential coupled to a resonator

How can we generalize Ramsey‘s method?



Ramsey‘s Method for Neutrons
2 state system (gravity potential) coupled to a resonator



Phase Modulation for Momentum Transfer Δp

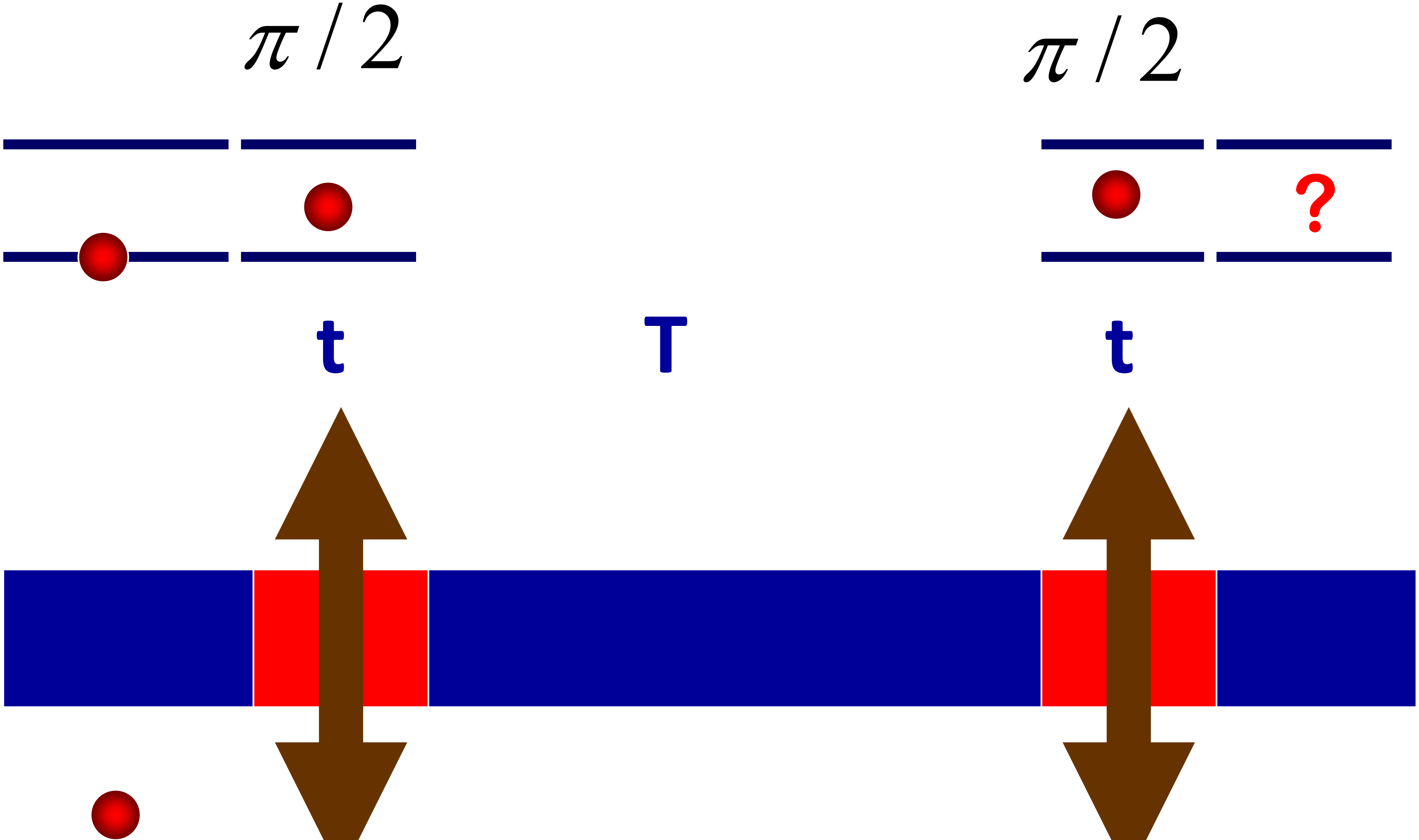
$(p + \Delta p)^2 / 2m_n = p^2 / 2m_n + h\nu$ (Felber, Gähler)

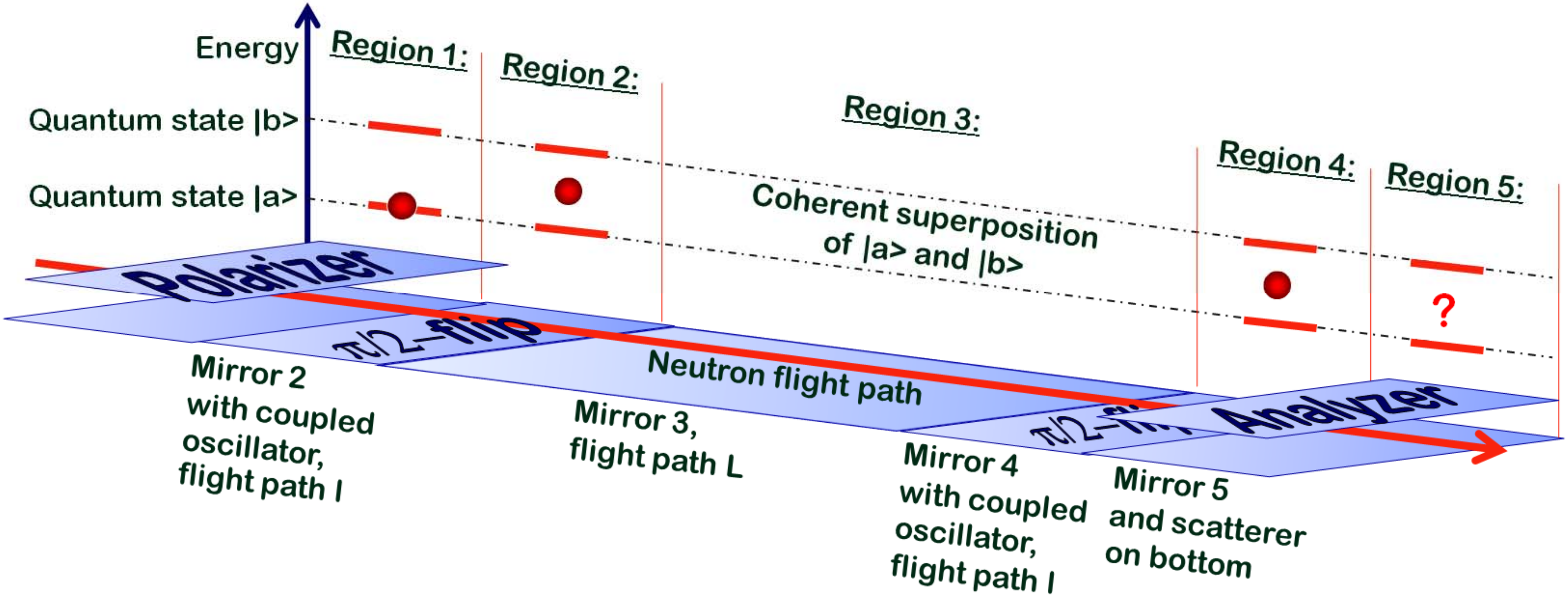
Magnetic Modulation: $\vec{F} = \vec{\mu} \cdot \vec{\nabla}\vec{B}$

or modulated mirror

$\omega_0 = \omega_{1\to 2} = 2\pi \cdot 256$ Hz

An application of Ramsey‘s Method to a system of quantum states in the gravity potential coupled to a resonator.





Energy

Quantum state |b>

Quantum state |a>

Region 1:

Region 2:

Region 3:

Coherent superposition of |a> and |b>

Region 4:

Region 5:

?

Polarizer

π/2–flip

Neutron flight path

π/2–

Analyzer

Mirror 2
with coupled
oscillator,
flight path l

Mirror 3,
flight path L

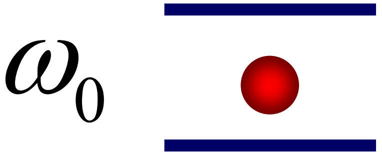
Mirror 4
with coupled
oscillator,
flight path l

Mirror 5
and scatterer
on bottom

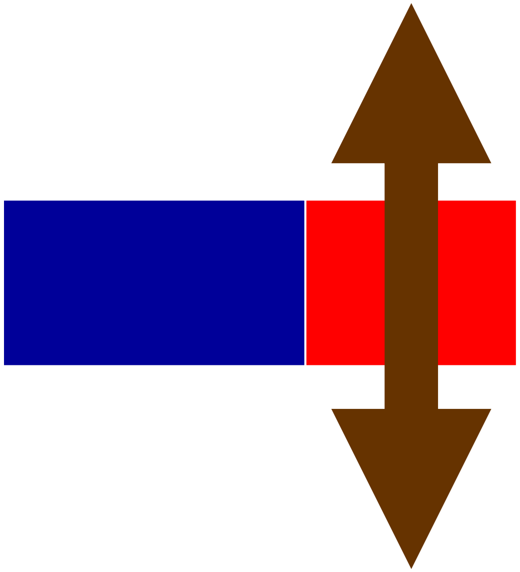
Ramsey‘s Method of Oscillating Fields

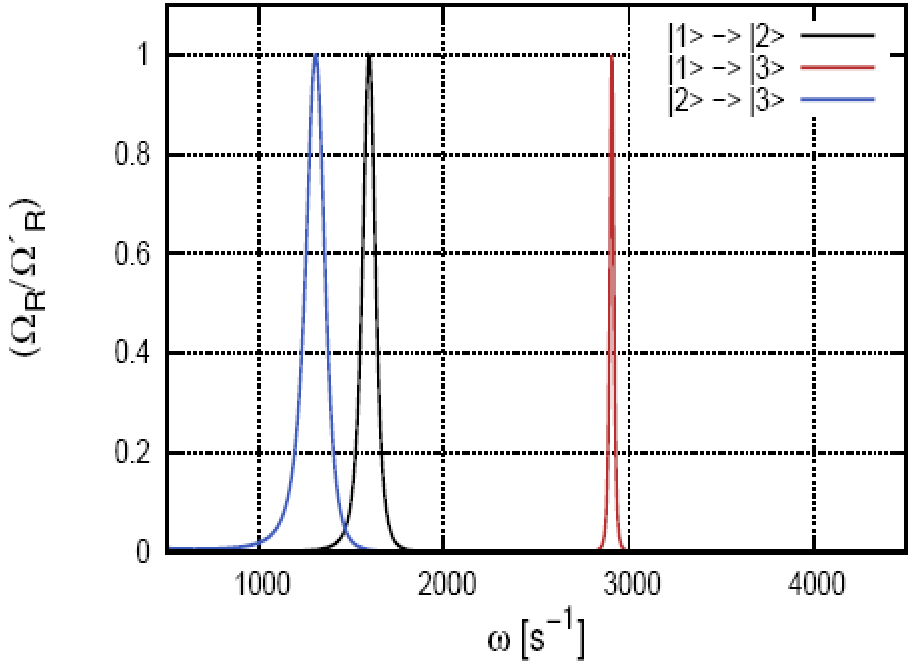
$\pi / 2$

$$H = \begin{pmatrix} \frac{\hbar\omega_0}{2} & \Omega_R e^{i\omega t/2} \\ \Omega_R e^{i\omega t/2} & -\hbar\omega_0 2 \end{pmatrix}$$

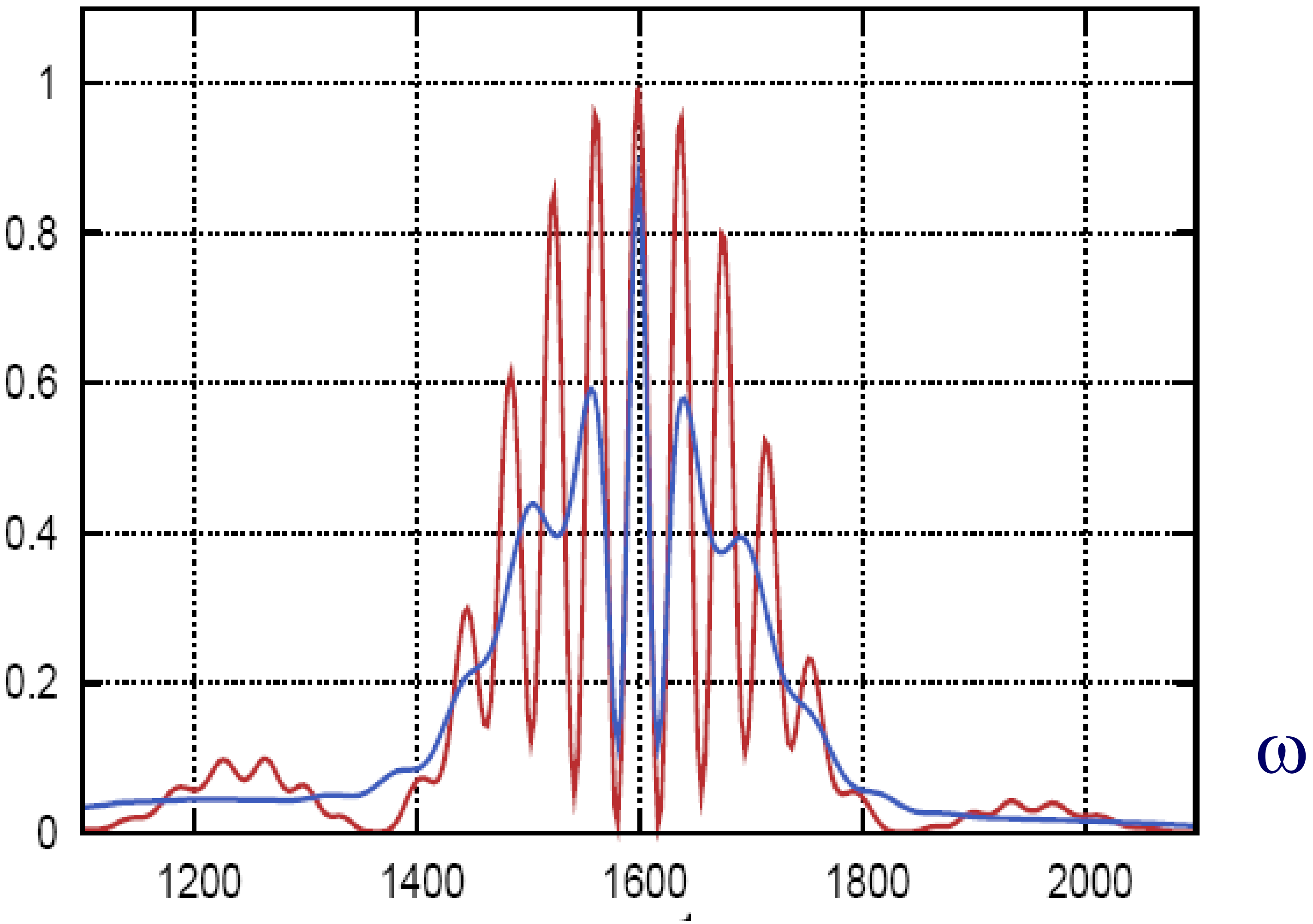


$$\Omega'_R = \sqrt{\Omega_R^2 + (\omega_0 - \omega)^2} = \sqrt{\Omega_R^2 + \delta^2}$$





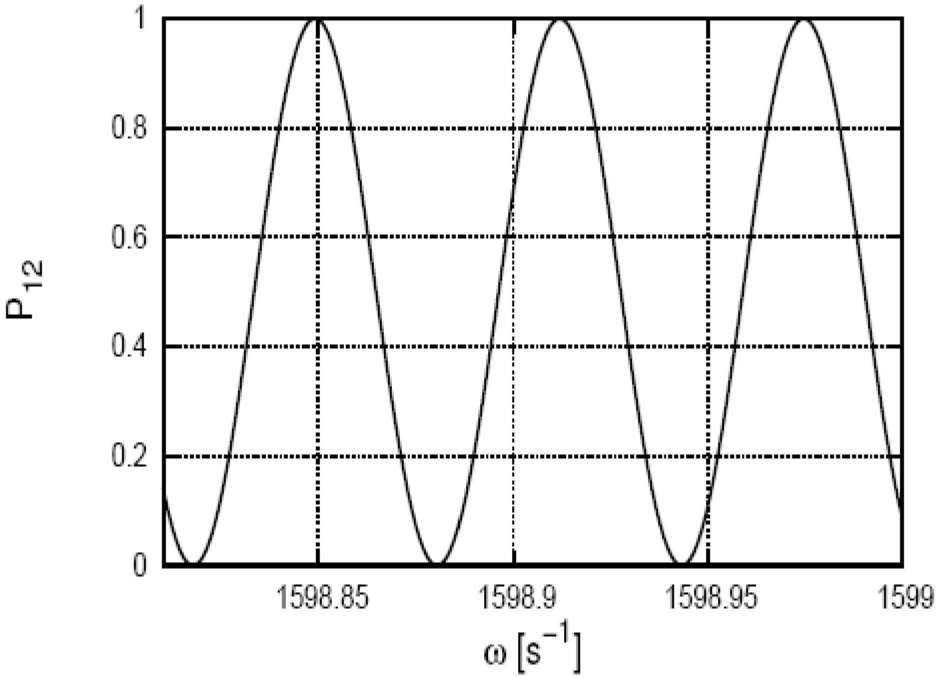
Ramsey-Fringes



5 m/s< v < 7 m/s

3m/s < v < 15 m/s

T = 100 s



Limits

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

$$\Delta\varphi\times\Delta N = 2\pi$$

$$N = 10^6 \rightarrow \Delta\varphi = 10^{-3}$$

$$\varphi = \omega\times t = E\cdot t/\hbar$$

$$\Delta\varphi = \Delta E\cdot t/\hbar$$

$$\Delta E = \Delta\varphi\hbar/T = 0.33\hbar/s = 6\times 10^{-6}\,\text{peV}$$

- **Count rate: 0.1s^{-1} N = 4x10^{5} after 25 days**
- **Observation time T = 130ms**

$$N = 4\times 10^5 : \quad \Delta E = 5\times 10^{-5}\,\text{peV},\ \ \alpha = 3\times 10^7$$

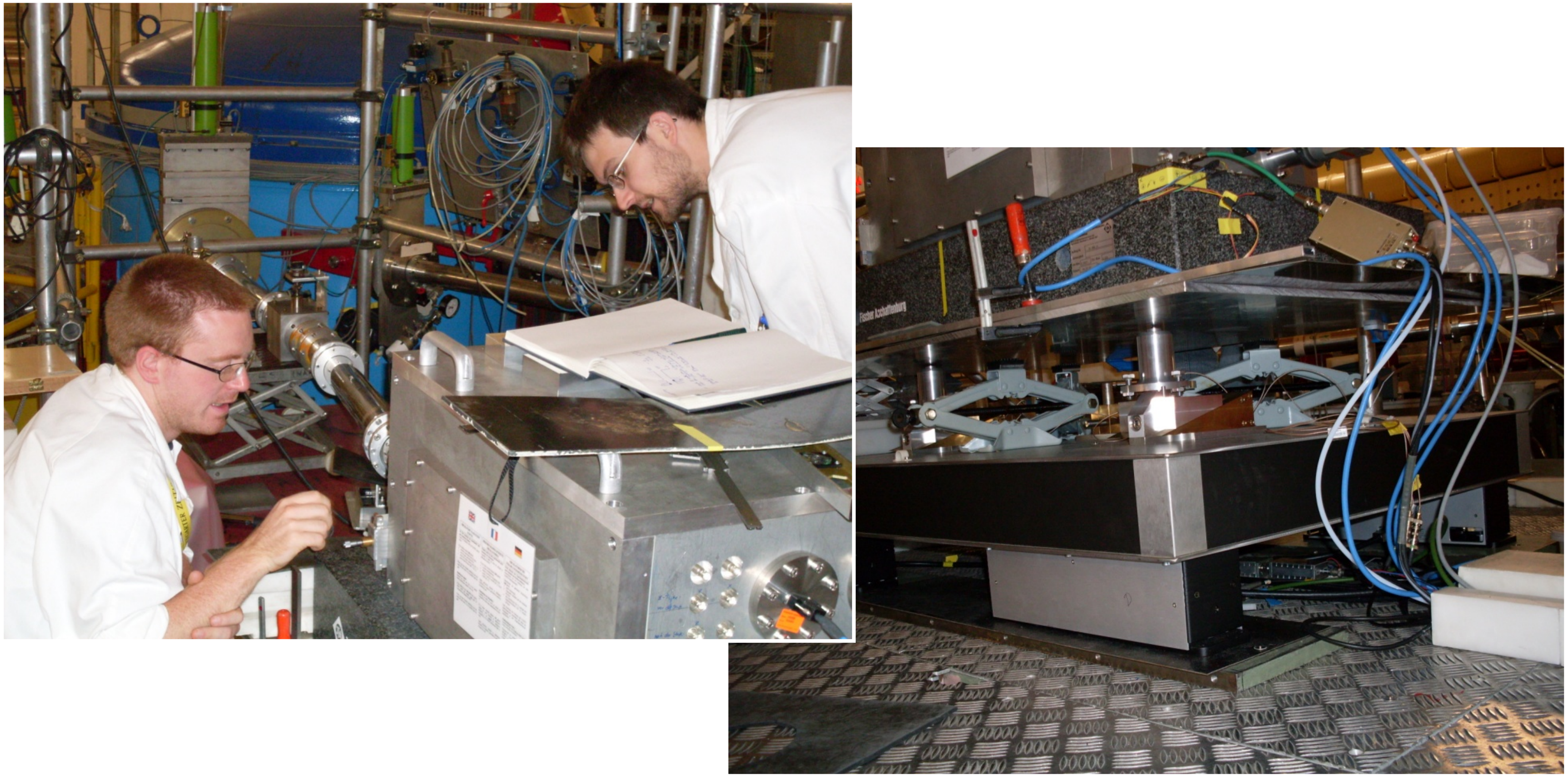
- **Observation time T = 100s – New sources**

$$\alpha = 3\times 10^4$$

$$\alpha = 3\times 10^3, \Delta E = 6\times 10^{-21}\,\text{eV}$$

The Experimental Team:

ATI, Wien: T. Jenke, H. Lemmel, H.A.
TUM: G. Kessler, T. Lins, H. Saul
PI, HD: H. Filter, D. Stadler
ILL: P. Geltenbort



Summary: Galileo in Quantum Land

Observation of quantum states, Nature 2002

Limits on hypothetical fifth forces:

Best axion limits

Development of

spatial resolution detectors (1.5µm)

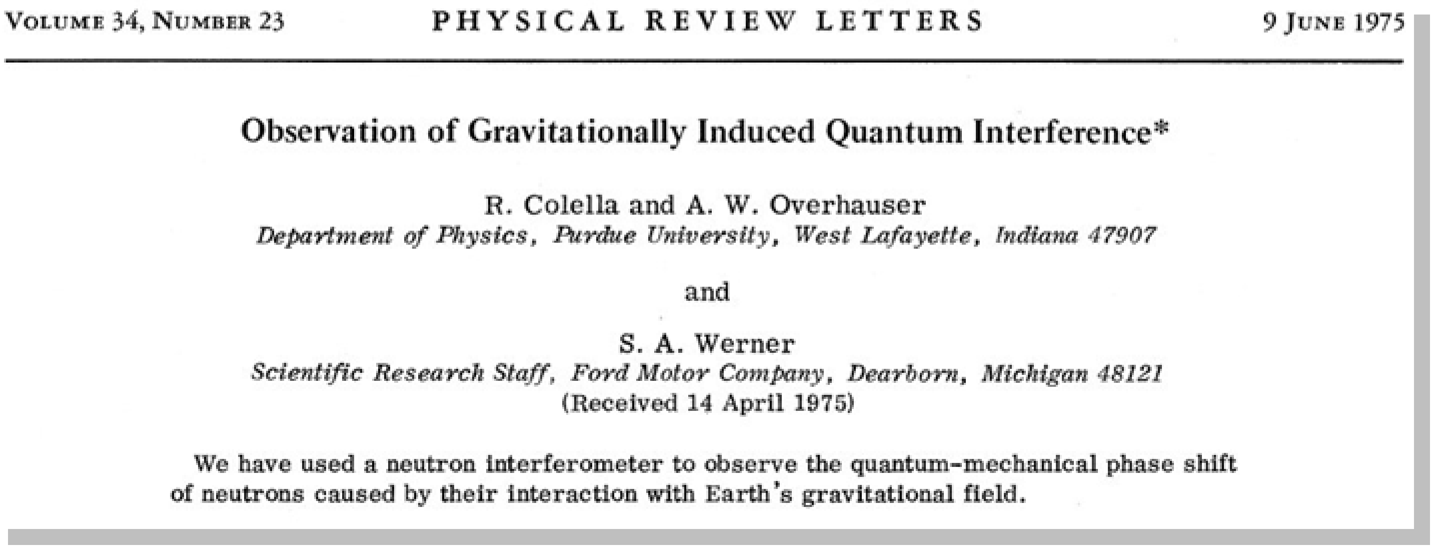
Observation of qBounce

Phase measurements

Neutron Interferometry

- Rauch, Treimann, Bonse:
  - Test of a Single Crystal Neutron Interferometer“, Physics Letters 47 A (1974) 369-371

COW-Experiments



VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

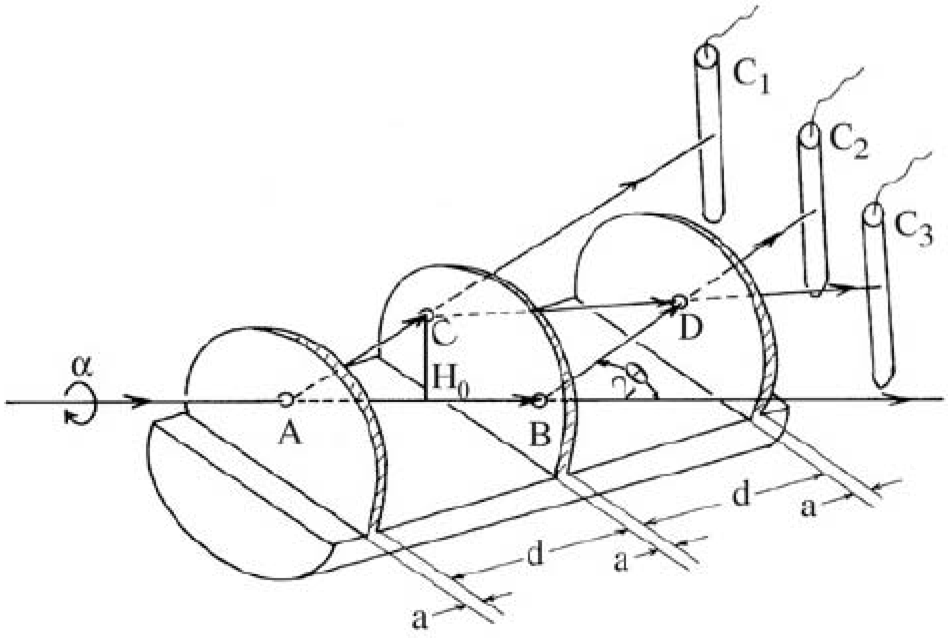
and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121

(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

COW-Experiment



NIST

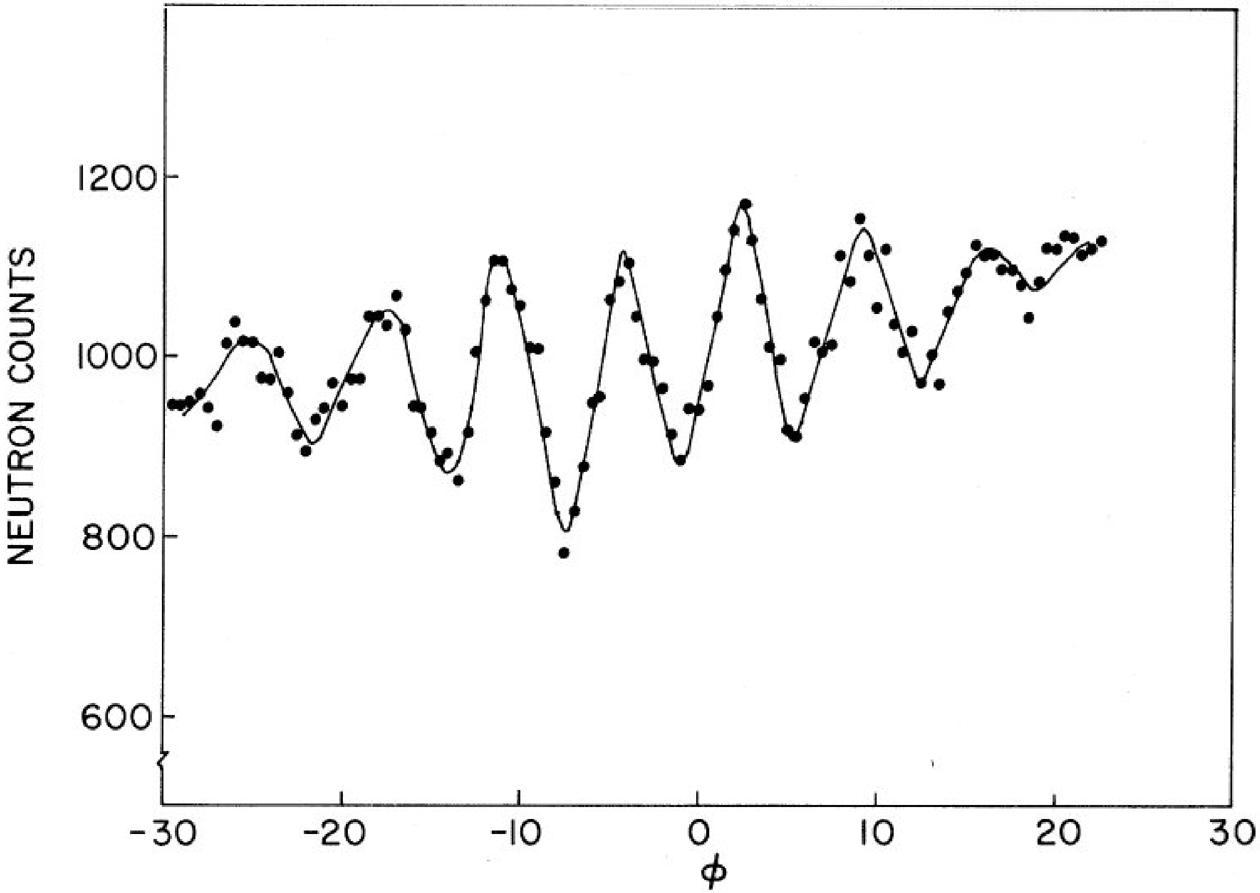
$$\Delta\Phi_{\text{COW}} = \Phi_{ACD} - \Phi_{ABD} = \Delta k S = -q_{\text{COW}} \sin\alpha,$$

$$q_{\text{COW}} = 2\pi\lambda \frac{m_n^2}{h^2} g A_0$$

$$A_0 = H_0 S$$

$$E_0 = \frac{\hbar^2 k_0^2}{2m_n} = \frac{\hbar^2 k^2}{2m_n} + m_n g H(\alpha)$$

COW-Experiment



$$q_{\text{grav}} = g_{\text{COW}}(1+\epsilon)$$

$$\begin{aligned} q_{\text{grav}} &= \left(q^2_{\text{exp}} - q^2_{\text{Sagnac}}\right)^{1/2} - q_{\text{bend}} \\ &= (60.12^2 - 1.45^2)^{1/2} - 1.42 \text{ rad} \\ &= 58.72 \pm 0.03 \text{ rad.} \end{aligned}$$

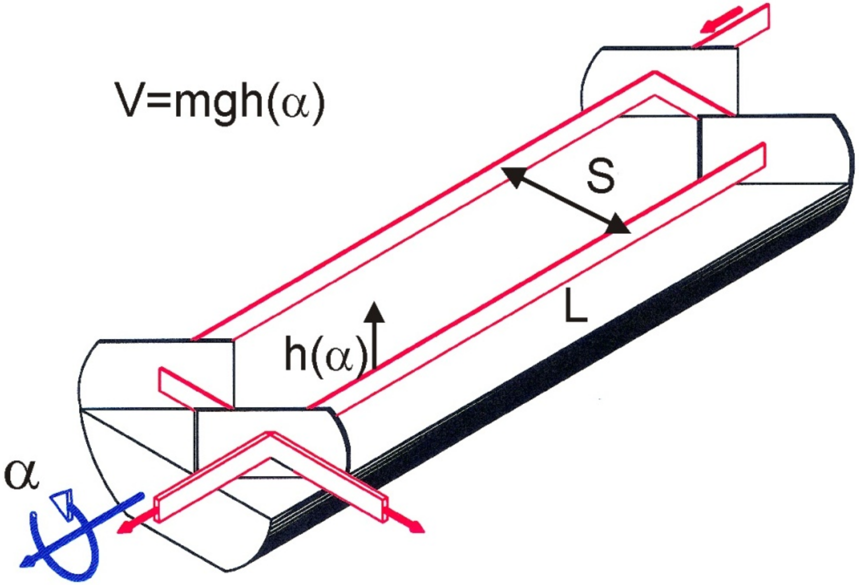
theoretical prediction $q_{\text{grav}} = 59.2 \pm 0.1$ rad

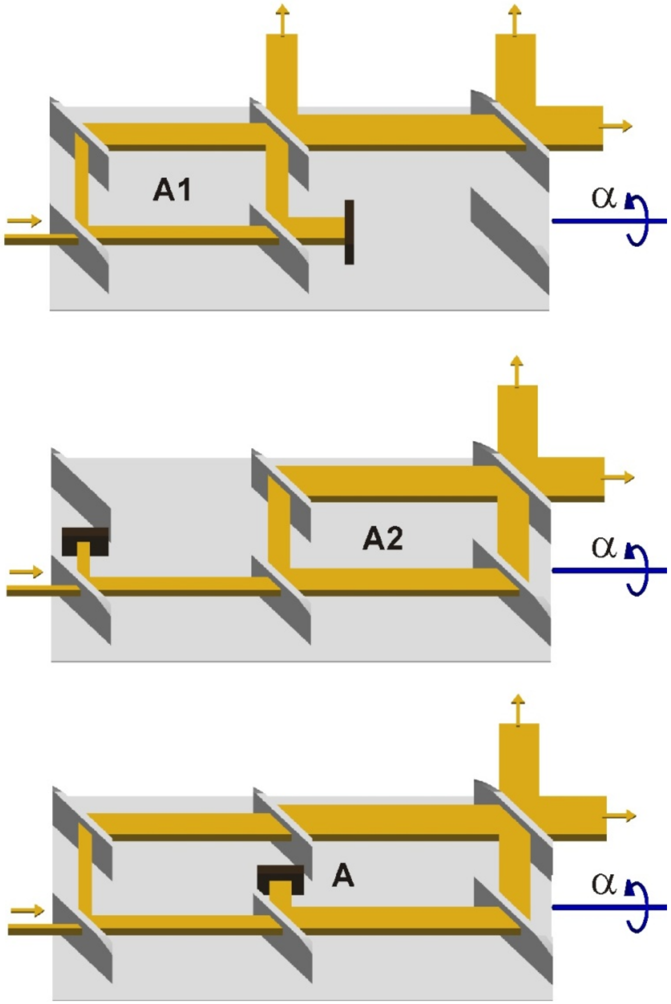
Table 12
History of gravity-induced interference experiments with symmetric (sym.) and skew-symmetric silicon interferometers

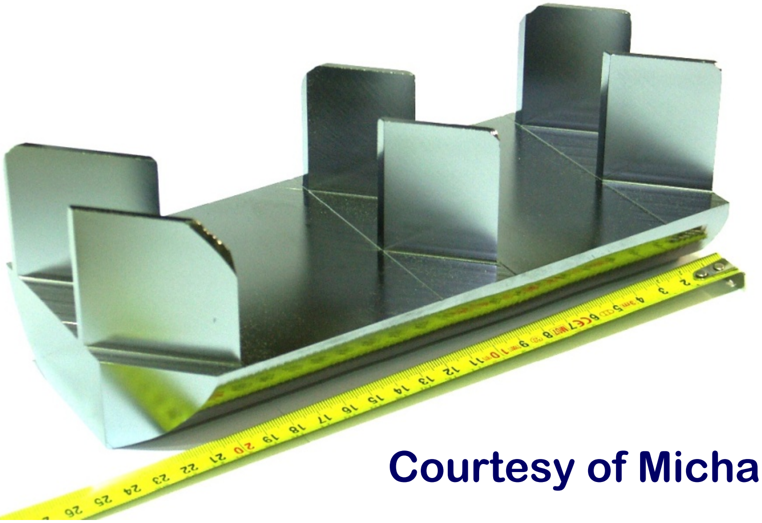
Ref.	Interferometer	λ (nm)	A_0 (cm^2)	Θ_B (deg)	q_{COW} (theory) (rad)	q_{COW} (exp) (rad)	q_{bend} (rad)	Agreement with theory (%)
[380]	Sym.#1	1.445(2)	10.52(2)	22.10(5)	59.8(1)	54.3(2.0)		12
[386]	Sym.#2	1.419(2)	10.152(4)	21.68(1)	56.7(1)	54.2(1)	3.30(5)	4.4
		1.060(2)	7.332(4)	16.02(1)	30.6(1)	28.4(1)	2.48(5)	7.3
[382]	Sym. #2	1.417(1)	10.132(4)	21.65(1)	56.50(5)	56.03(3)	1.41(1)	0.8
[383]	Skew-sym.							
(440)	Full range	1.078(6)	12.016(3)	34.15(1)	50.97(5)	49.45(5)	2.15(4)	3.0
	Rest. range	1.078(6)	12.016(3)	34.15(1)	50.97(5)	50.18(5)	2.03(4)	1.5
(220)	Full range	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	97.58(10)	1.07(2)	3
	Rest. range	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	99.02(10)	1.01(2)	1.5
[383]	Large Sym.							
(440)	Full range	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	223.38(30)	4.02(3)	0.6
(220)	Rest. range	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	221.85(30)	4.15(3)	0.9

The restricted (rest.) range data means that the tilt angle $|\alpha| = 11°$. The two wavelengths of [383] are diffracted by the (220) or (440) lattice planes. The table is based on [21].

New Plans







Courtesy of Michael Zawisky, Vienna University of Technology

Hartmut Abele, Technische Universität München

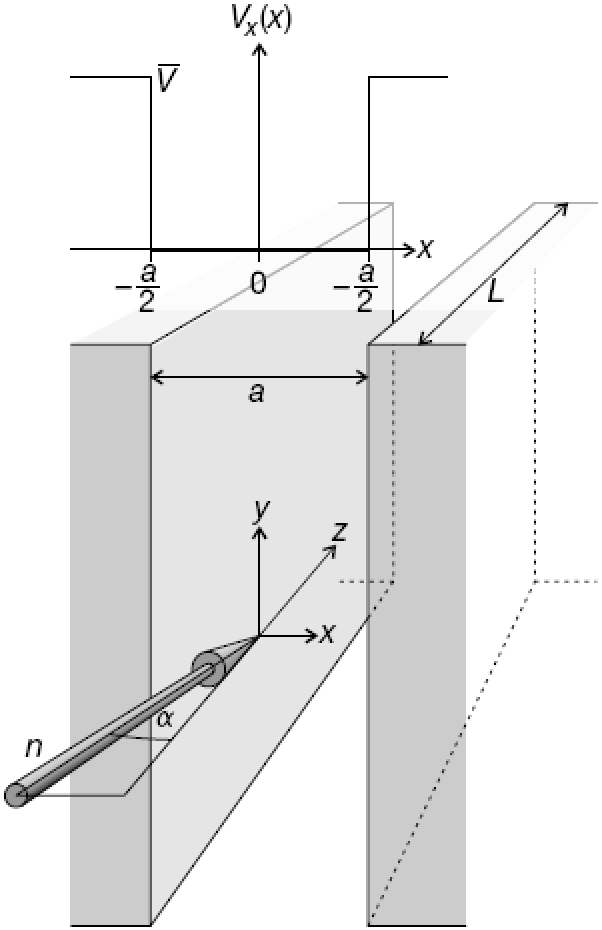
some key features of the new setup at ILL-S18 (France) :

- Larger areas, higher sensitivity (gain factor ≥ 5 at 2.72Å to previous experiments)
- Small rotations reduce bending effects
- Thick base + rotation along an axis of elastic symmetry reduce crystal bending
- Three different areas selectable without changing the setup
- By comparison of the phase shift gained by A1 and A2 diffraction corrections within the crystal lamellas cancel out to first order
- Several harmonics (2.72, 1.36, 0.91Å) available with identical beam geometry
- Narrow wavelength distribution 5×10^{-3}
- Nearly perfect symmetric lattice orientation, no offset in α-rotation and simplification of the dynamical diffraction model

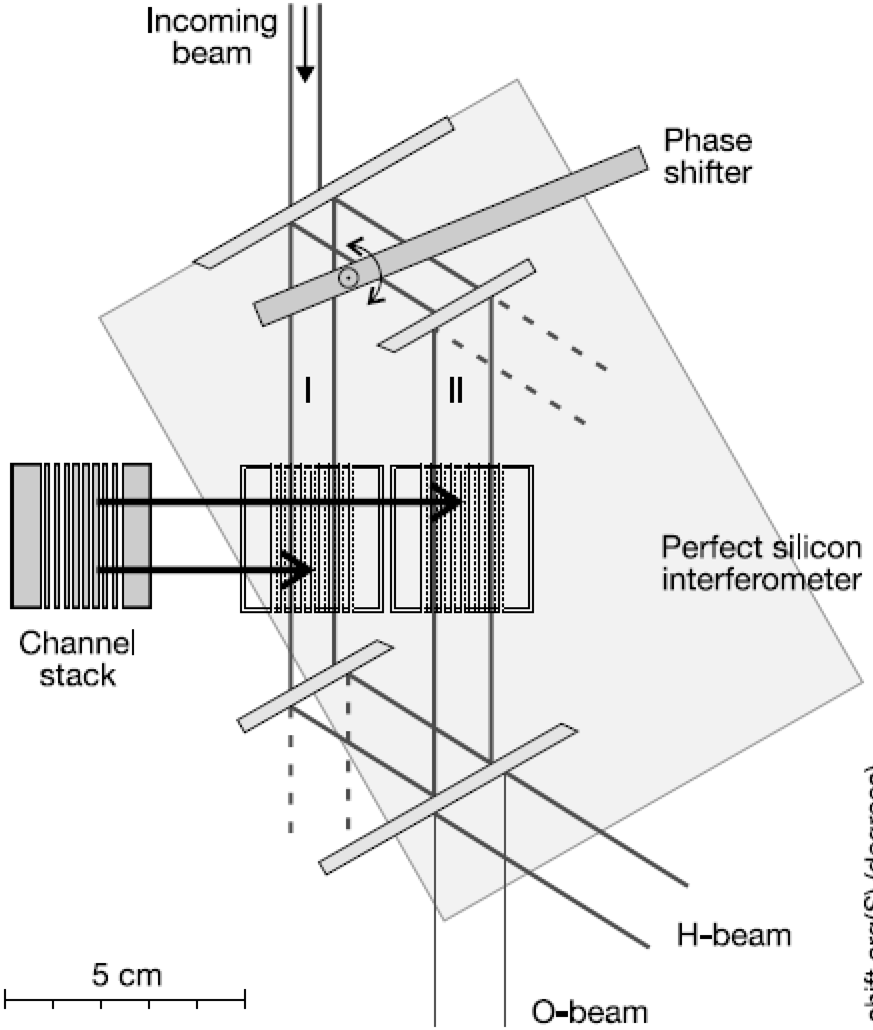
Courtesy Michael Zawisky, Vienna University of Technology

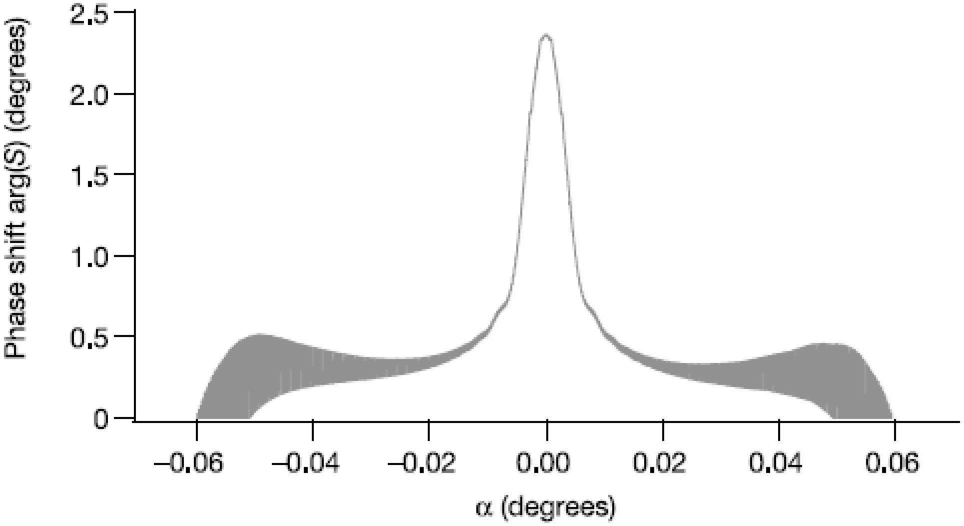
Measurement of a confinement induced neutron phase

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



- **Thermal neutrons**
- **slit size 22µm**

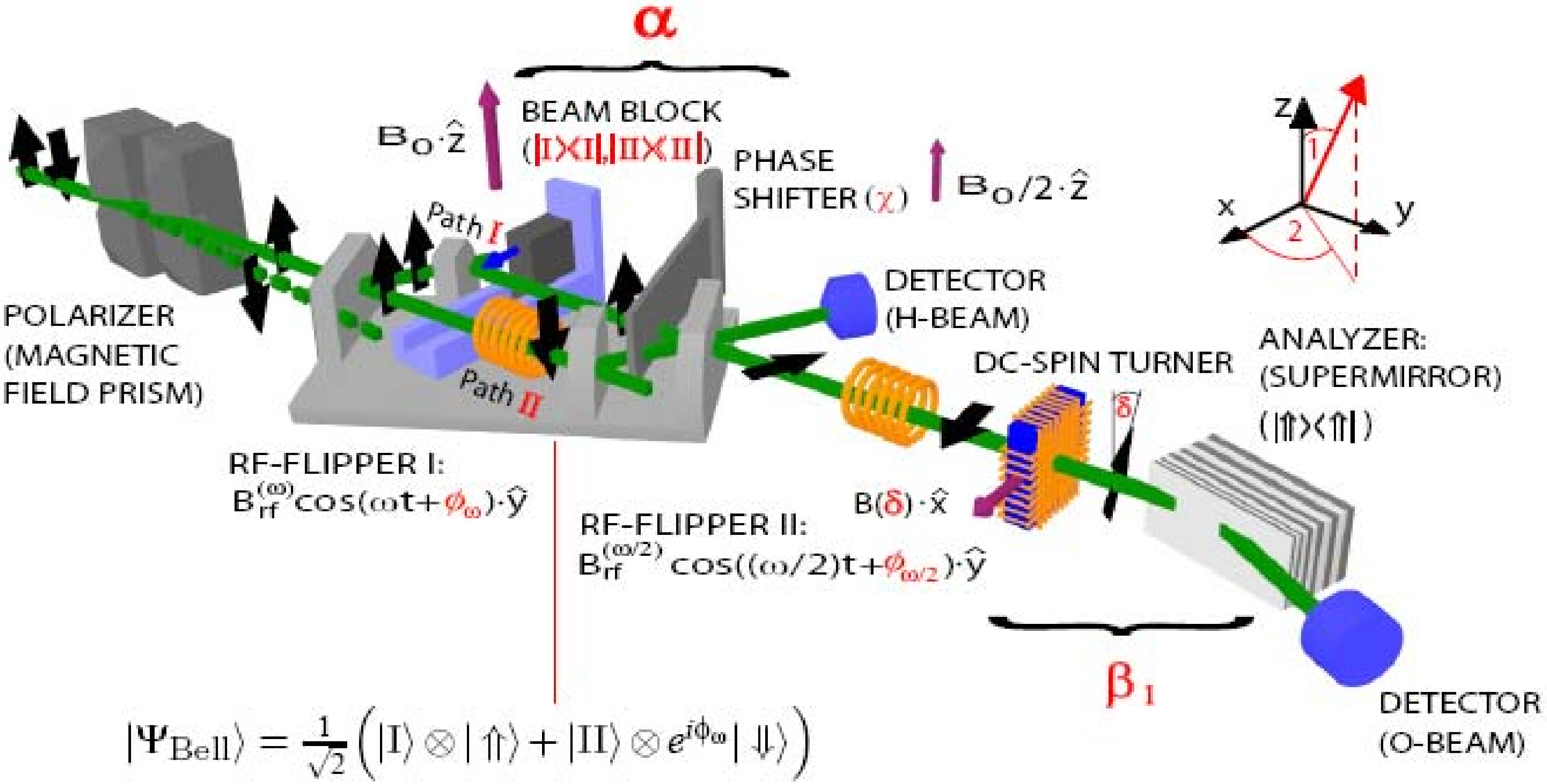

Incoming beam
Phase shifter
I
II
Channel stack
Perfect silicon interferometer
H-beam
O-beam
5 cm


Phase shift arg(S) (degrees)
2.5
2.0
1.5
1.0
0.5
0
–0.06
–0.04
–0.02
0.00
0.02
0.04
0.06
α (degrees)

Y. Hasegawa et al.: Violation of a Bell-like inequality

- by correlating spin and energy degrees of freedom of polarized neutron beams
- classically expected quantity S≤2
- S=2.555±0.005

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\downarrow\rangle \otimes |I\rangle - |\uparrow\rangle \otimes |II\rangle)$$



$$|\Psi_{\text{Bell}}\rangle = \frac{1}{\sqrt{2}}\left(|\text{I}\rangle \otimes |\Uparrow\rangle + |\text{II}\rangle \otimes e^{i\phi_\omega}|\Downarrow\rangle\right)$$

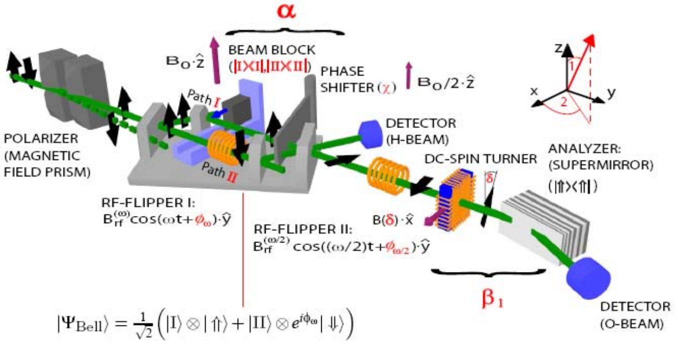
Courtesy of S. Sponar, Vienna University of Technology

Vienna University of Technology

Vienna Impressions

Neutron & Quantum Physics

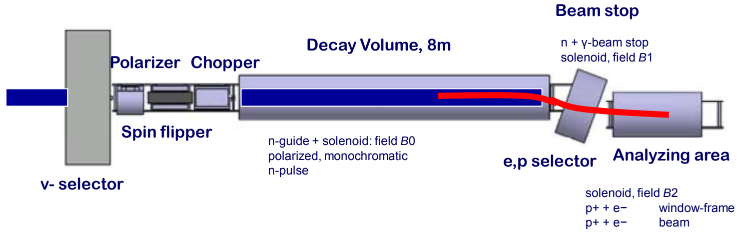
- ## Neutron Interferometry



- ## Gravity tests with neutrons

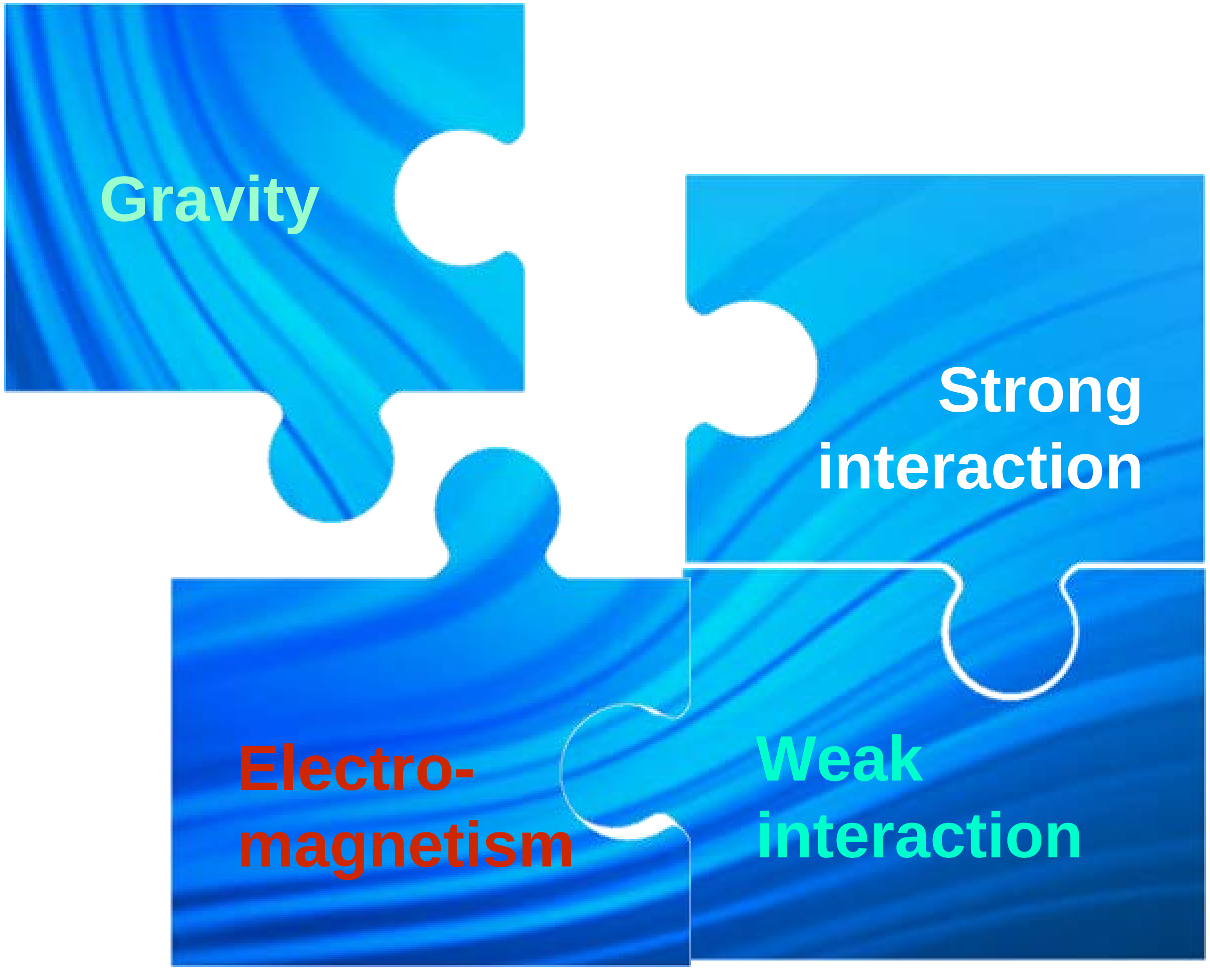
- ## Neutron Alphabet & Beta-decay

PERC:
A clean, bright and versatile source of neutron decay products



- ## Neutron Tomography

Unification of Forces?
Quests in Fundamental Physics



Lämmerzahl, Graduiertentage Heidelberg 2003