High-precision studies in fundamental physics with slow neutrons

Oliver Zimmer

Institut Laue Langevin

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Topics

- The impossible particle and its properties
- Search for an electric dipole moment of the neutron
- Short-range gravity
- Test of Einstein's $E = mc^2$

The neutron before Chadwick

The neutron before Chadwick

“Such an atom would posses striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and ...“

(„Nuclear Constitution of Atoms“, Proc. Royal Soc. 1920)

The neutron before Chadwick

"Such an atom would posses striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and it could not be stored in a closed vessel."

(„Nuclear Constitution of Atoms", Proc. Royal Soc. 1920)

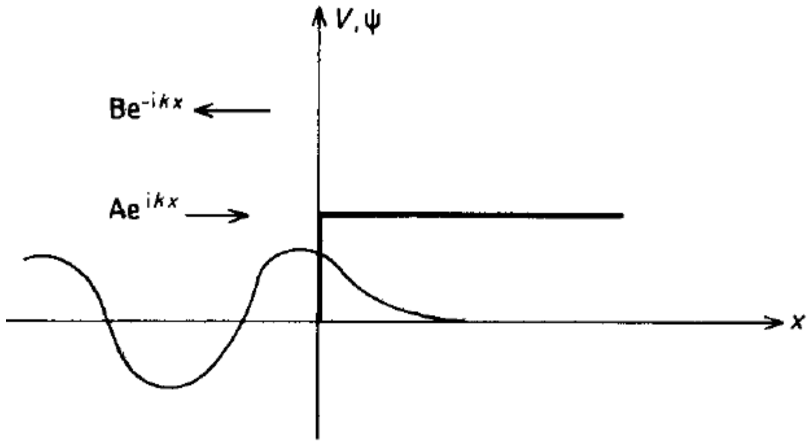
How to store it nevertheless?

Mirror reflection under any angle of incidence

$\rightarrow$ ***UCN can be trapped in "neutron bottles"***

Trapping potential #1:

neutron optical potential $V + iW$



Physical origin:

- neutron scattering by nuclei
- interference of incident and scattered waves
- refractive index:

$$n = \frac{k'}{k} = \sqrt{1 - \frac{V}{E}} \qquad V = \frac{2\pi\hbar^2}{m} N a$$

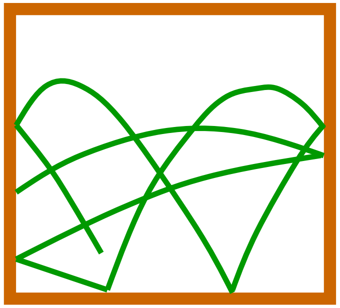
Typical values for *V*:

Be: 252 neV, Al: 54 neV, Ti: -49 neV

Trapping potential #2:

neutron gravity *mgz*

for Δz = 1 m: ΔE = 100 neV

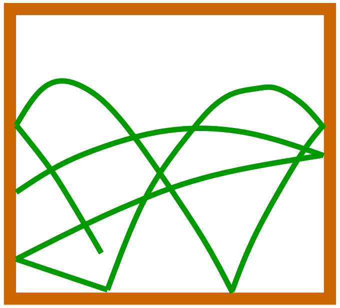


as good for trapping
(if bottle is tall enough):

Trapping potential #2:

neutron gravity *mgz*

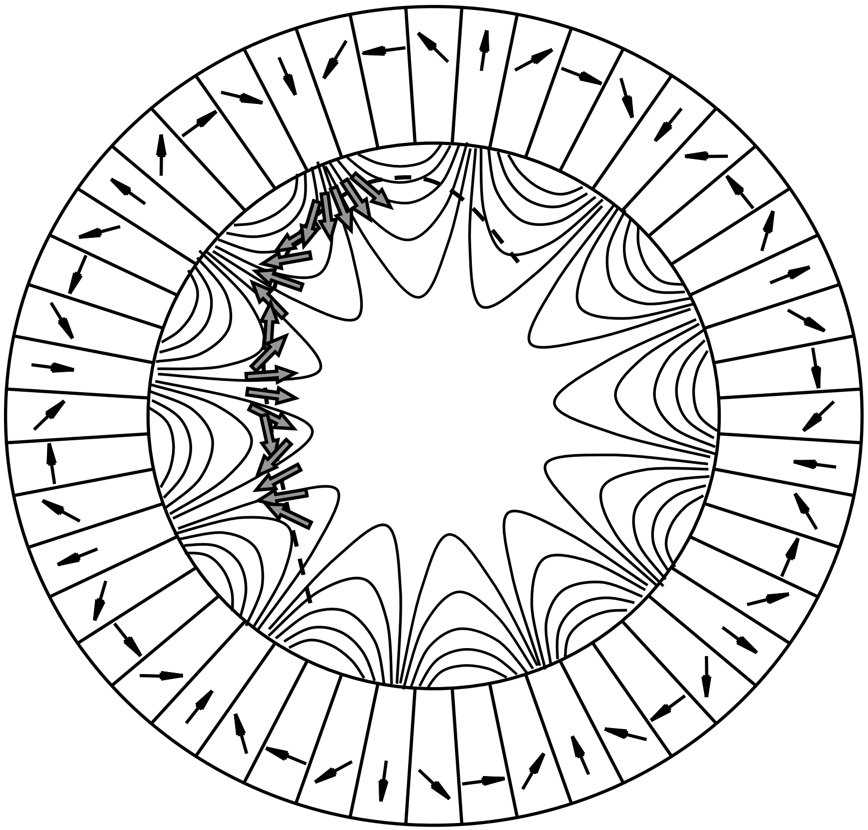
for Δz = 1 m: ΔE = 100 neV



Trapping potential #3:

magnetic interaction ±μB

for ΔB = 1 T: ΔE = ±60 neV



Adiabatic spin transport if

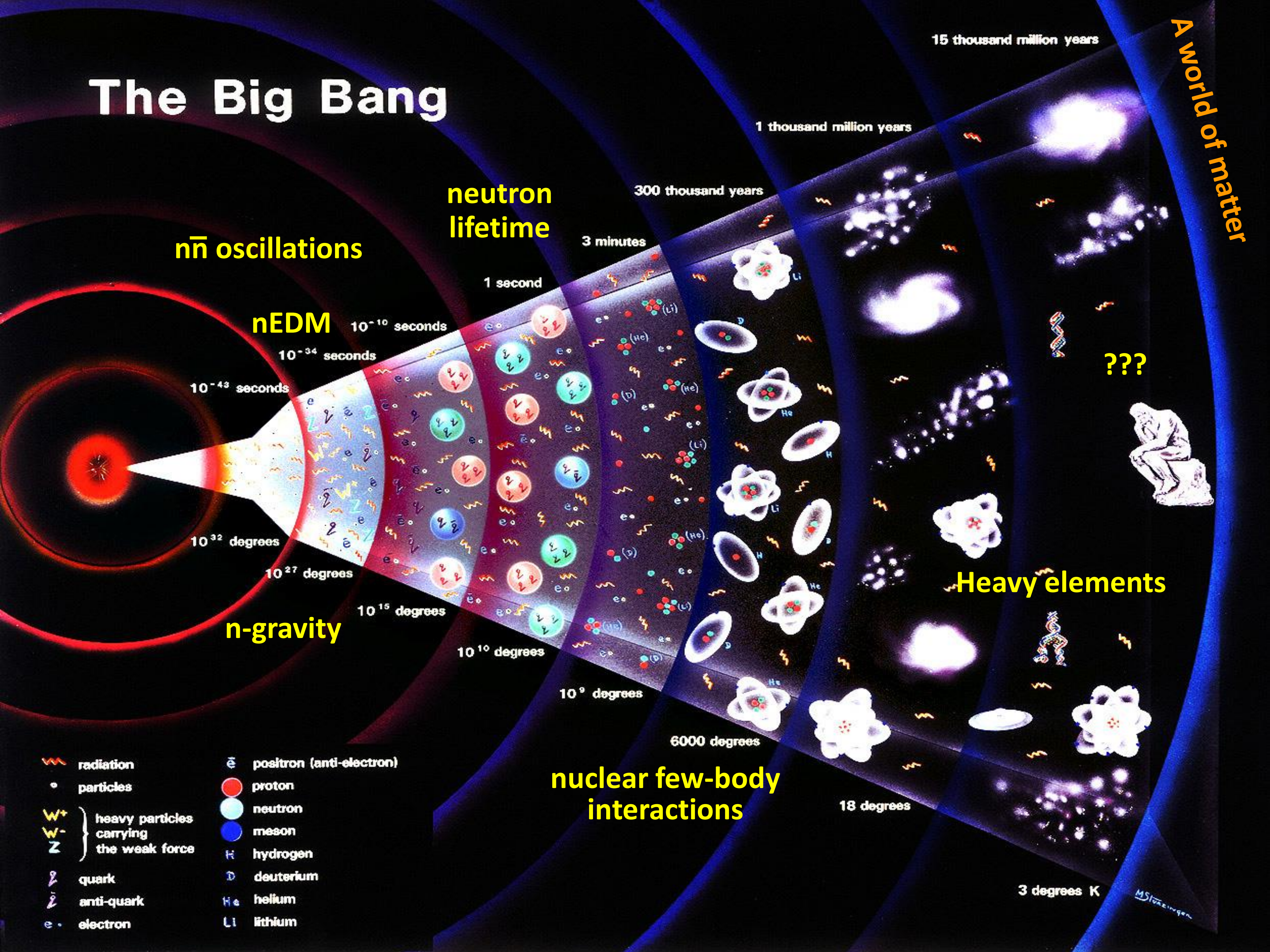
$$\frac{1}{|\boldsymbol{B}|} \cdot \left| \frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t} \right| \ll \frac{\boldsymbol{\mu} \cdot \boldsymbol{B}}{\hbar} = \omega_{\mathrm{L}}$$

→ mT fields sufficient in typical situations

Magnetic gradient fields suppress losses due to wall collisions

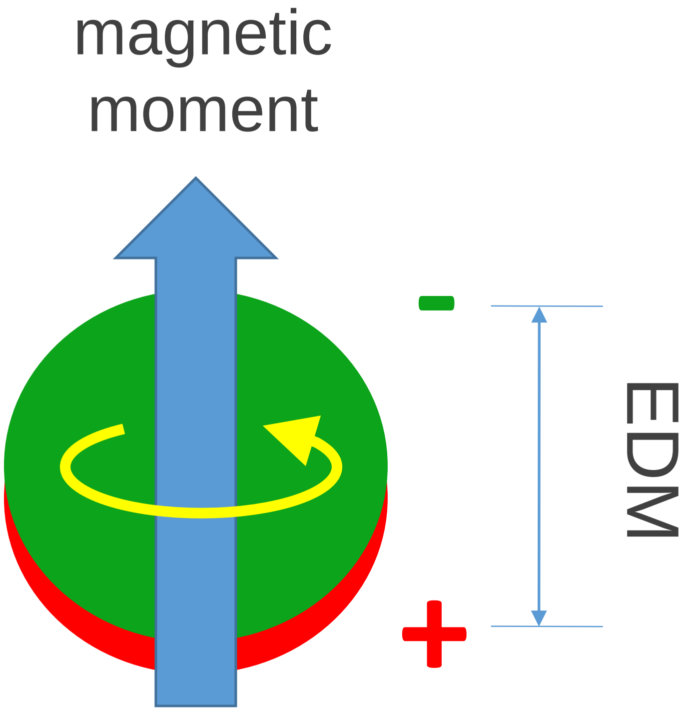
Neutron properties:

Property	Symbol	Value
Spin$^{\text{Parity}}$	s^P	$\frac{1}{2}^+$
Mass (relative to ^{12}C mass standard)	m_n	$1.008\,664\,915\,8(6)$ u
Mass (absolute units)		$939.565\,33(4)$ MeV c^{-2}
Neutron - proton mass difference	$m_\text{n} - m_\text{p}$	$0.001\,388\,448\,9(6)$ u
		$1.293\,331\,8(5)$ MeV c^{-2}
Charge	q_n	$(-0.4 \pm 1.1) \times 10^{-21}\, e$
Mean-square charge radius	$\langle r_\text{n}^2 \rangle$	$-0.116\,1(22)$ fm^2
Electric polarisability	α_n	$(9.8^{+1.9}_{-2.3}) \times 10^{-4}$ fm^3
Magnetic moment	μ_n	$-1.913\,042\,7(5)\ \mu_N$
		$= -6.030\,773\,8(15) \times 10^{-8}$ eV T^{-1}
Electric dipole moment	d_n	$< 2.9 \times 10^{-26}\, e$ cm (90% c.l.)
Mean n$\overline{\text{n}}$-oscillation time of free neutron	$\tau_{\text{n}\overline{\text{n}}}$	$> 8.6 \times 10^7$ s (90% c.l.)
... of bound neutron		$> 1.2 \times 10^8$ s (90% c.l.)
Parameters of β-decay, $\text{n} \rightarrow \text{p} + \text{e}^- + \overline{\nu}_\text{e}$		
Q-value	Q	$0.782\,332\,9(5)$ MeV c^{-2}
Mean life time	τ_n	$885.7(8)$ s
Ratio of weak coupling constants g_A / g_V	λ	$-1.2670\,(30)$
Coefficients of angular correlations:		
neutron spin - electron momentum: $P_\text{n} \cdot p_\text{e}$	A	$-0.1162\,(13)$
momenta of antineutrino and electron: $p_\nu \cdot p_\text{e}$	a	$-0.102\,(5)$
neutron spin - antineutrino momentum	B	$0.983\,(4)$
triple correlation $P_\text{n} \cdot (p_\text{e} \times p_\nu)$	D	$-0.6\,(10) \times 10^{-3}$
Phase angle between V and A weak currents	ϕ_{VA}	$-180.08\,(10)^0$



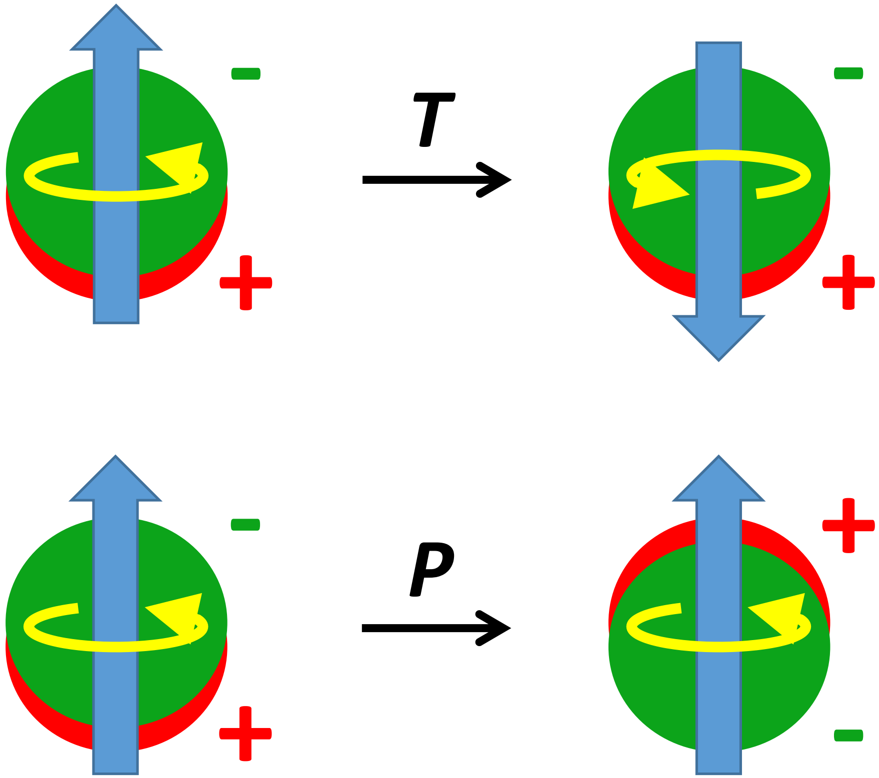
The Big Bang
A world of matter
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
$n\bar{n}$ oscillations
neutron lifetime
nEDM
n-gravity
nuclear few-body interactions
Heavy elements
???
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Search for an electric dipole moment of the neutron



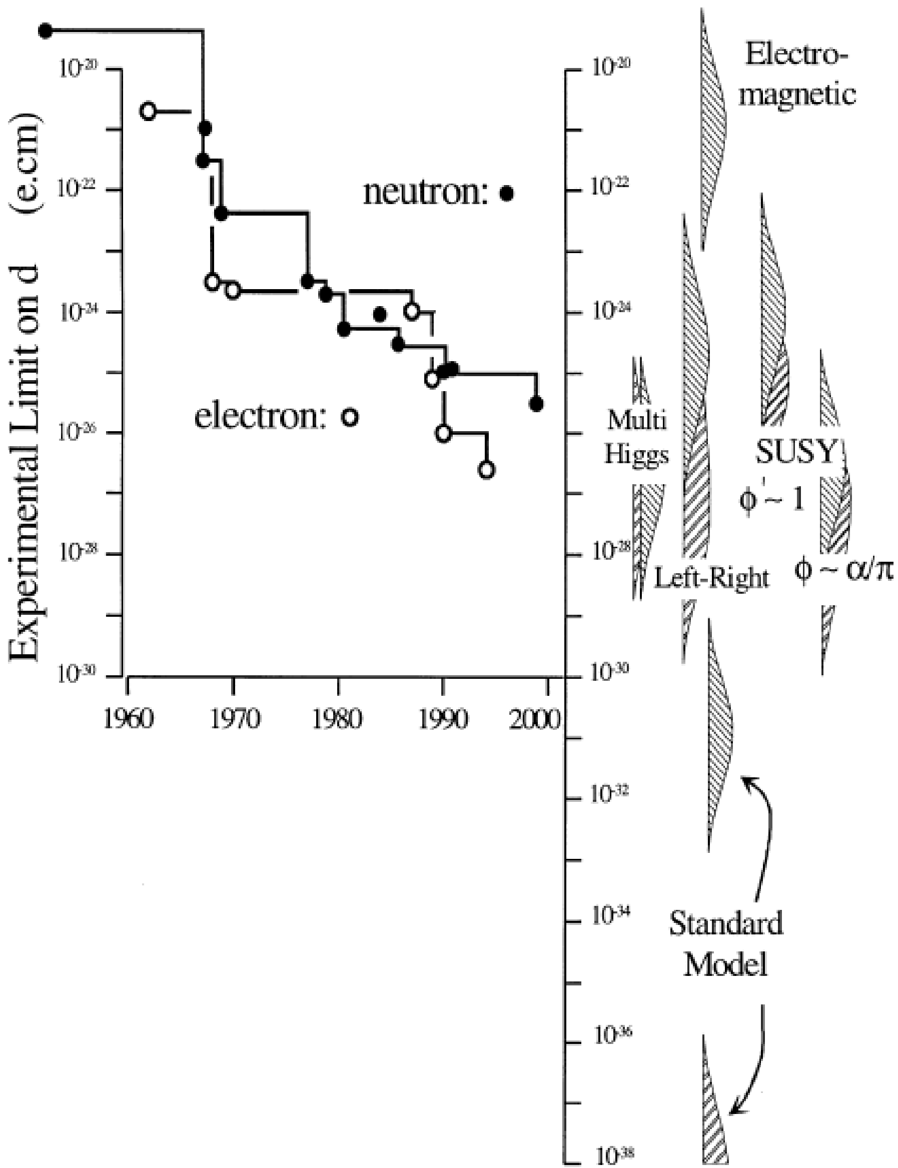
Violation of fundamental symmetries

Purcell and Ramsey, PR 78 (1950) 807

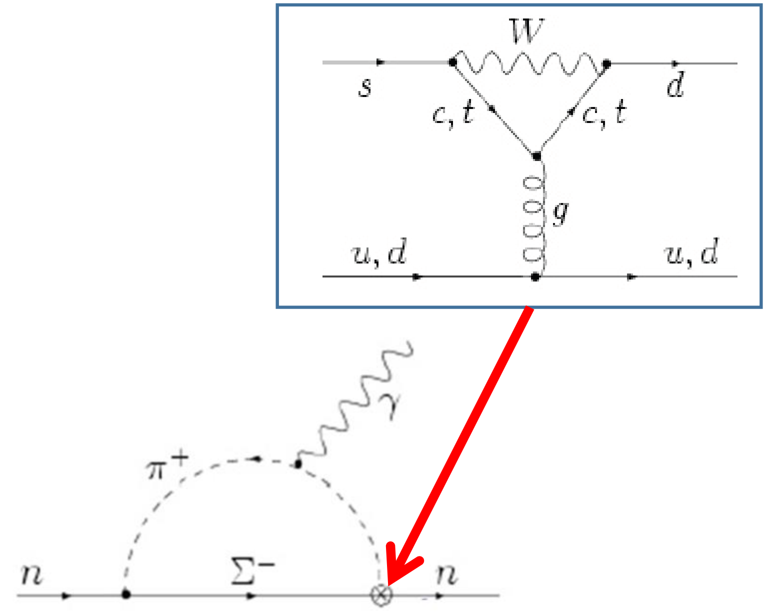


- A non-zero particle EDM violates *T* (time reversal symmetry) and parity *P*
- If we assume *CPT* conservation, also *CP* is violated, which is needed to explain the matter/antimatter asymmetry in the Universe

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$



Pendlebury and Hinds, NIM A 440 (2000) 471



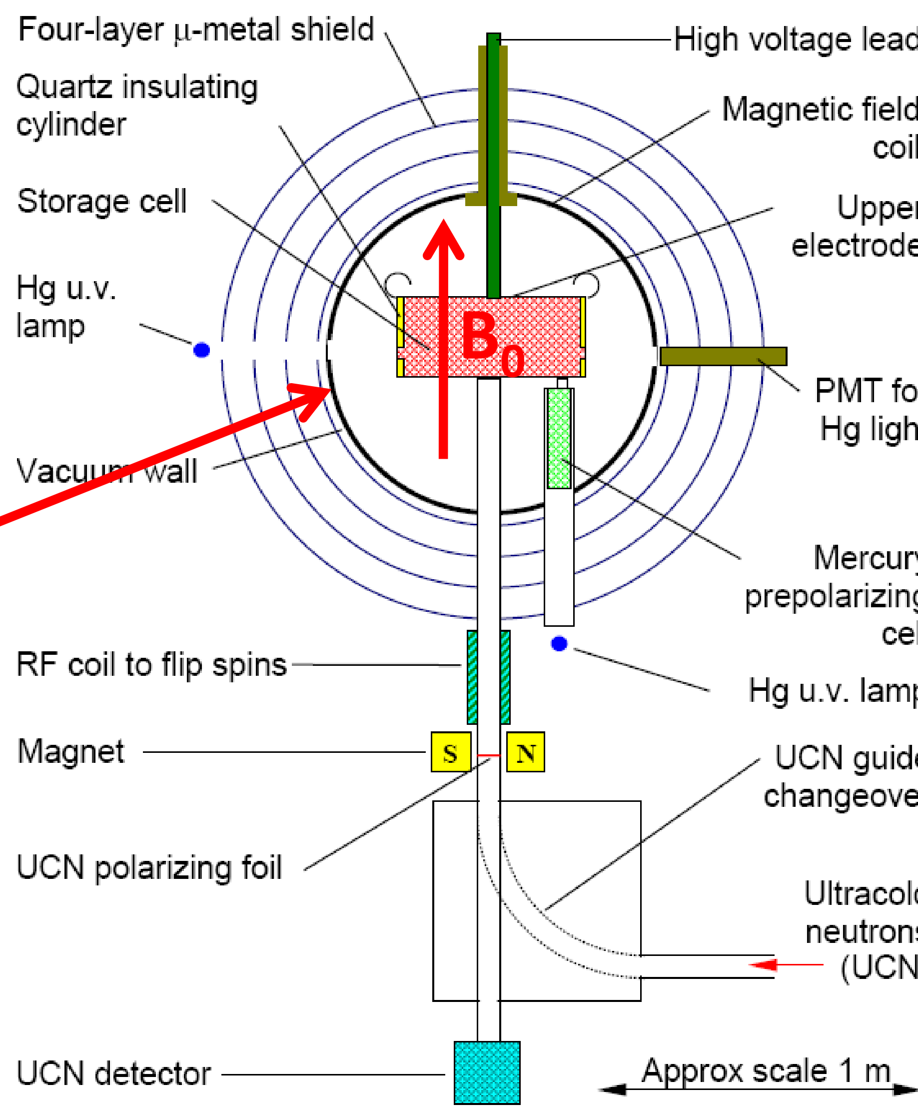
- *CP* violation within the Standard Model (SM) is too weak to explain the matter/antimatter asymmetry in the Universe
- nEDM tiny in the SM (10^{-31} ecm), but large in many beyond-SM theories
- nEDM sensitive probe to search new fundamental forces

How is it measured?

Ultra-cold neutrons (UCN) trapped at 300 K in vacuum

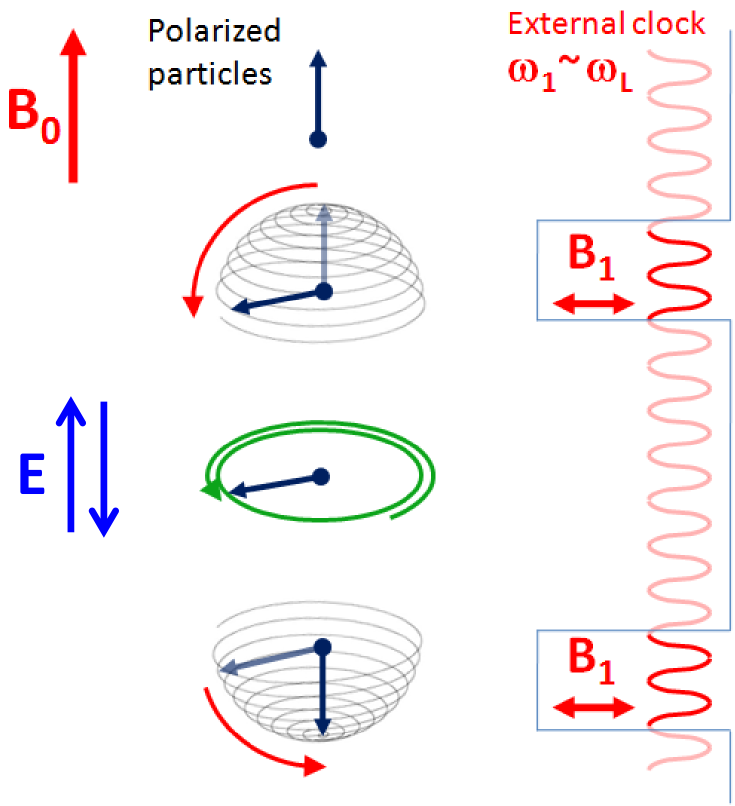
~ 0.5 m

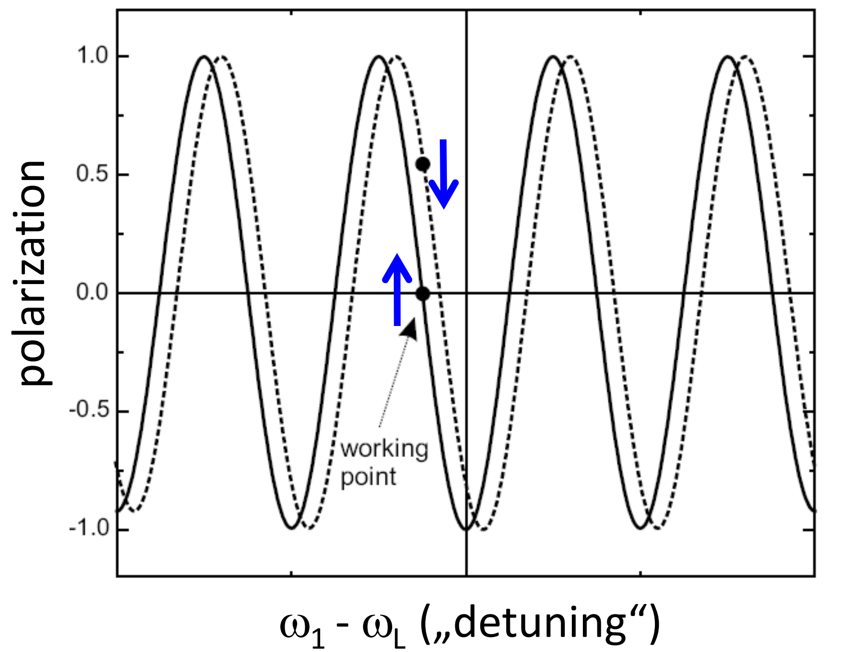
RAL/SUSSEX/ILL experiment:



Ramsey's method

Particle beam or trapped particles
(...spin echo)





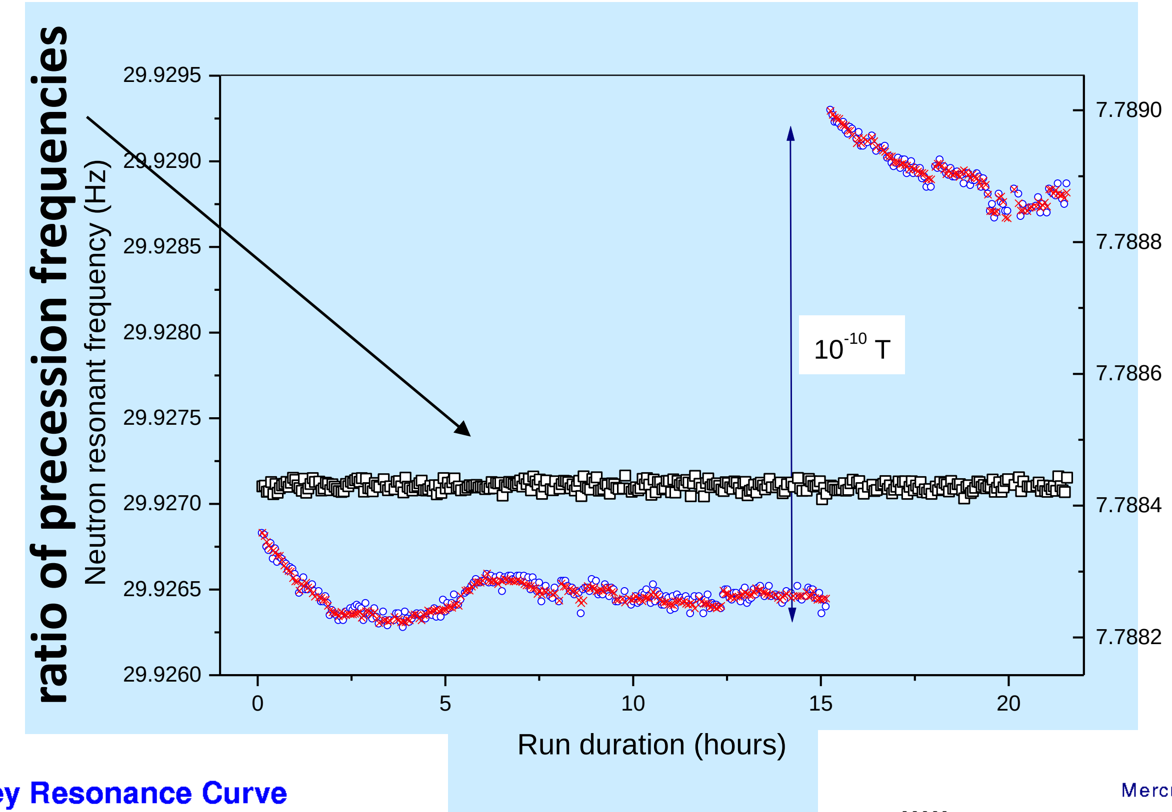
EDM changes frequency:

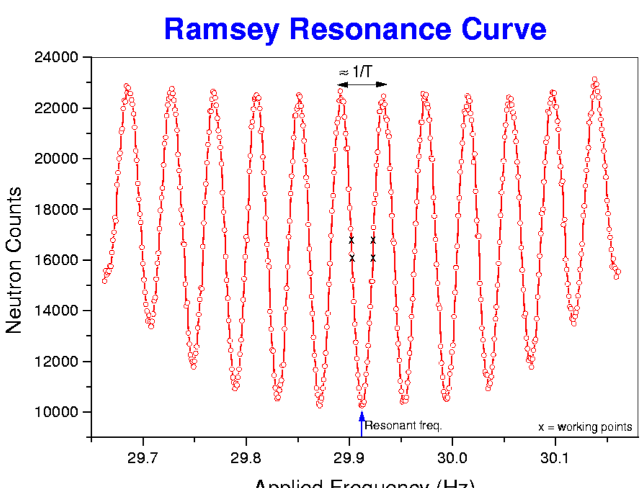
$$\hbar\omega_L \sim \mu_n B \pm d_n E$$

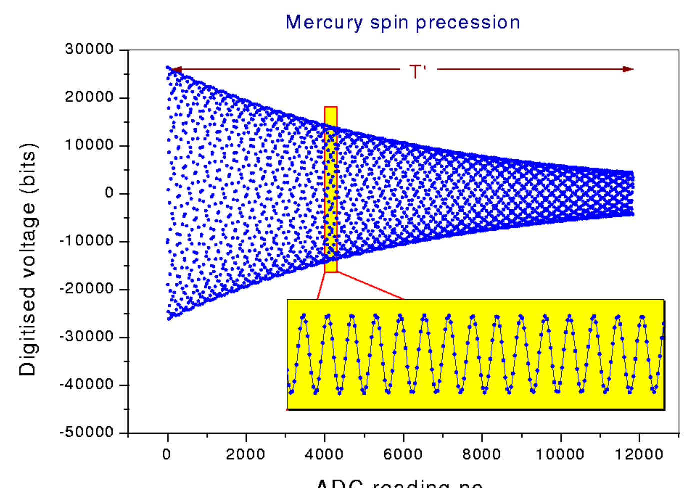
Experimental sensitivity:

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

^{199}Hg co-magnetometer for correction of magnetic field drifts





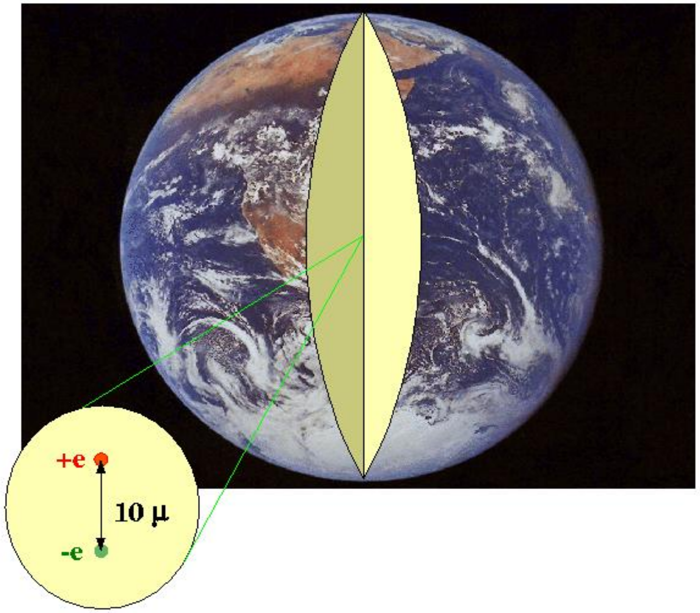


Best result so far (RAL / Sussex / ILL)

$|d_n| < 2.9 \times 10^{-26}$ **e cm** (90% CL)

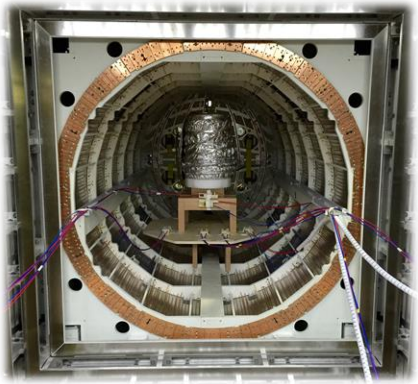
C.A. Baker et al., PRL **63** (2006) 131801

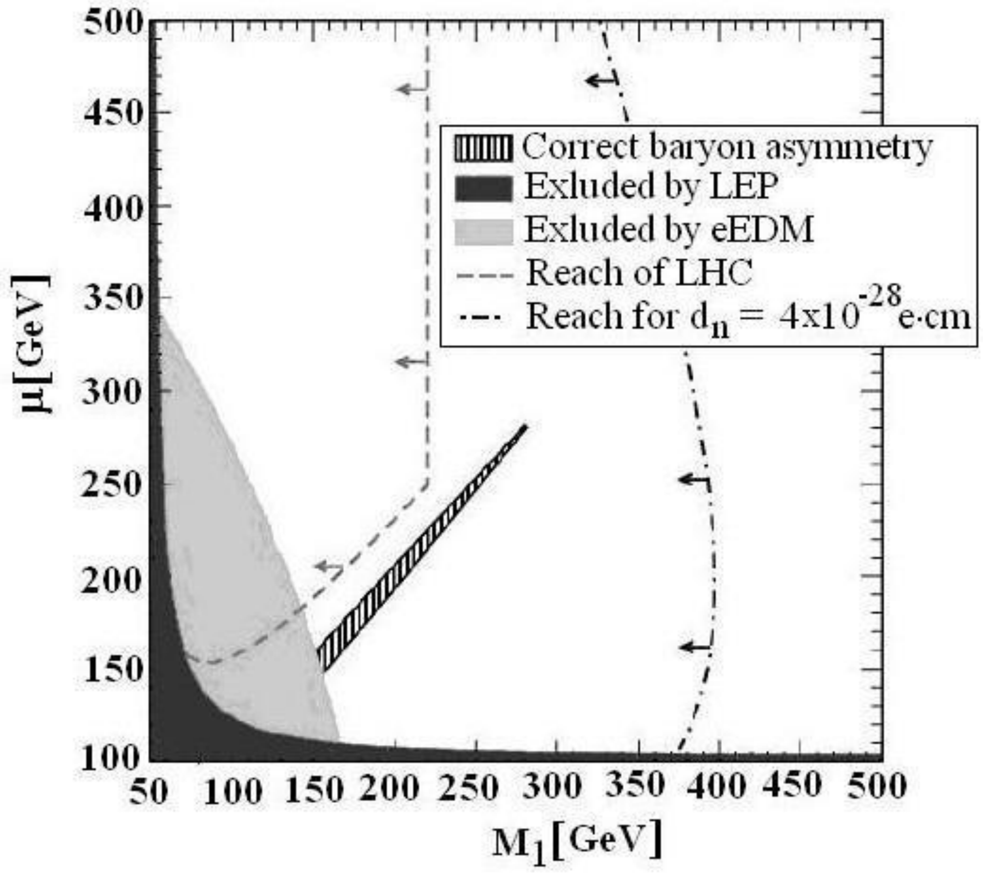
- 10^{-22} eV spin-dependent interaction
- one spin precession per half year



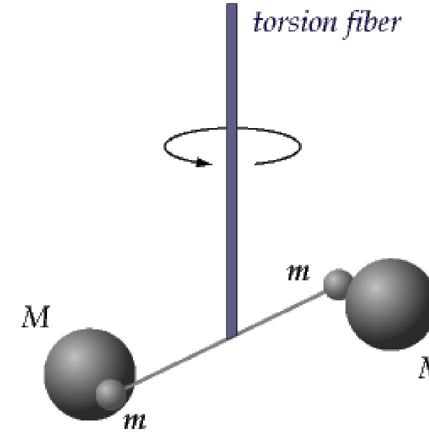
Next steps?

- World-wide effort: projects at PSI, SNS, TRIUMF, TUM, PNPI, ILL
- Accuracy goal: below 10^{-27} ecm
- needs new UCN sources, excellent magnetic shielding…





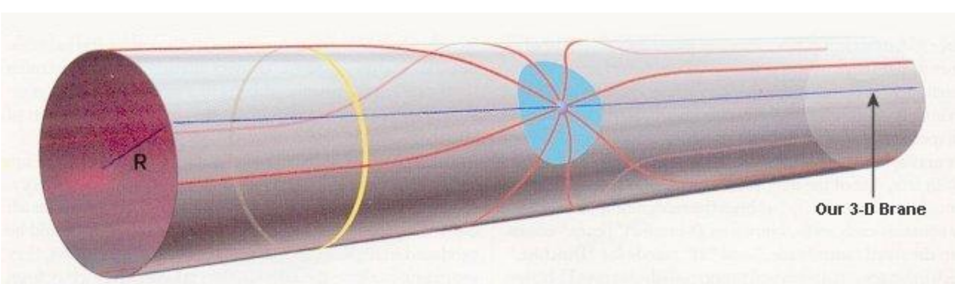
Short-range gravity



Small extra-dimensions:
Explanation why gravity is such a weak force?

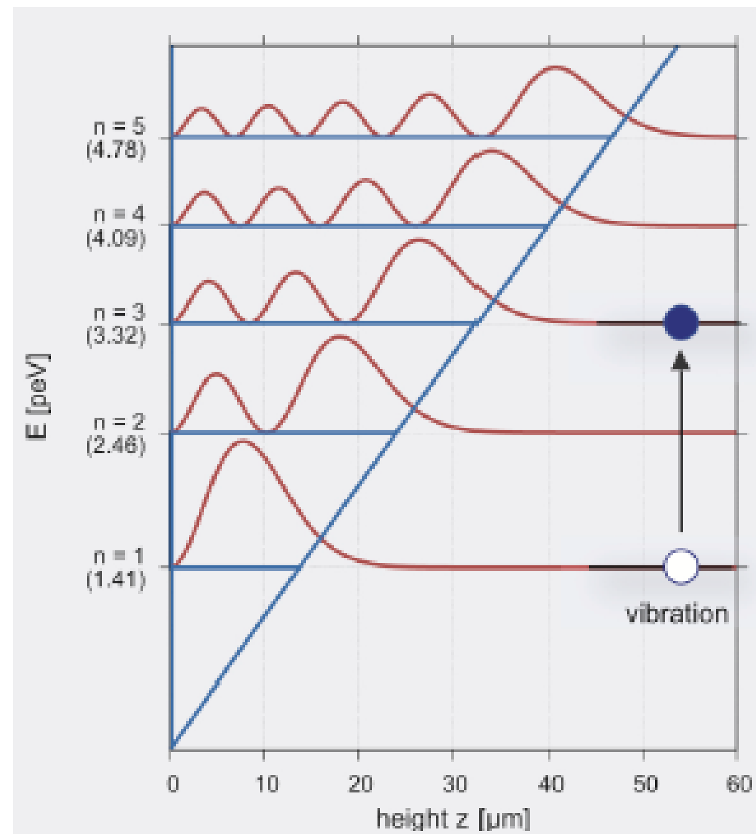
Modification of gravity
with *n* additional dimensions at distances *r* < *R*:

$$F = -G\frac{m_1 m_2}{r^2} \rightarrow -g\frac{m_1 m_2}{r^2}\frac{L^n}{r^n}$$

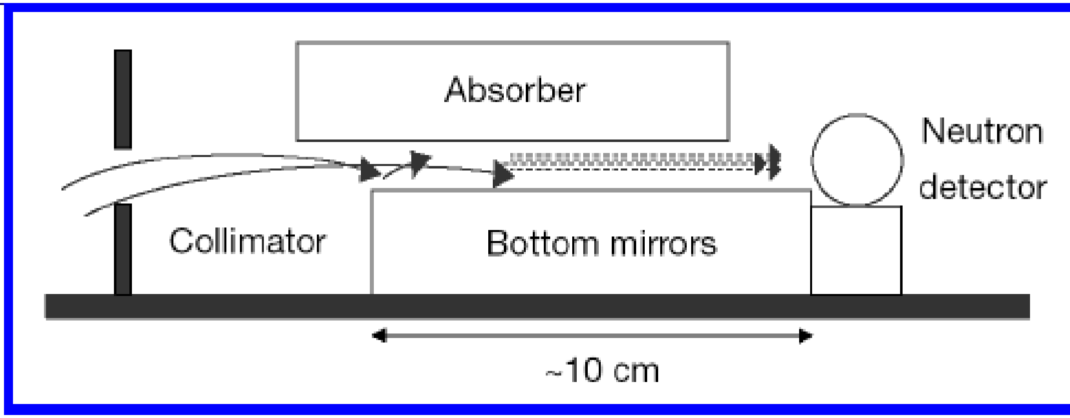


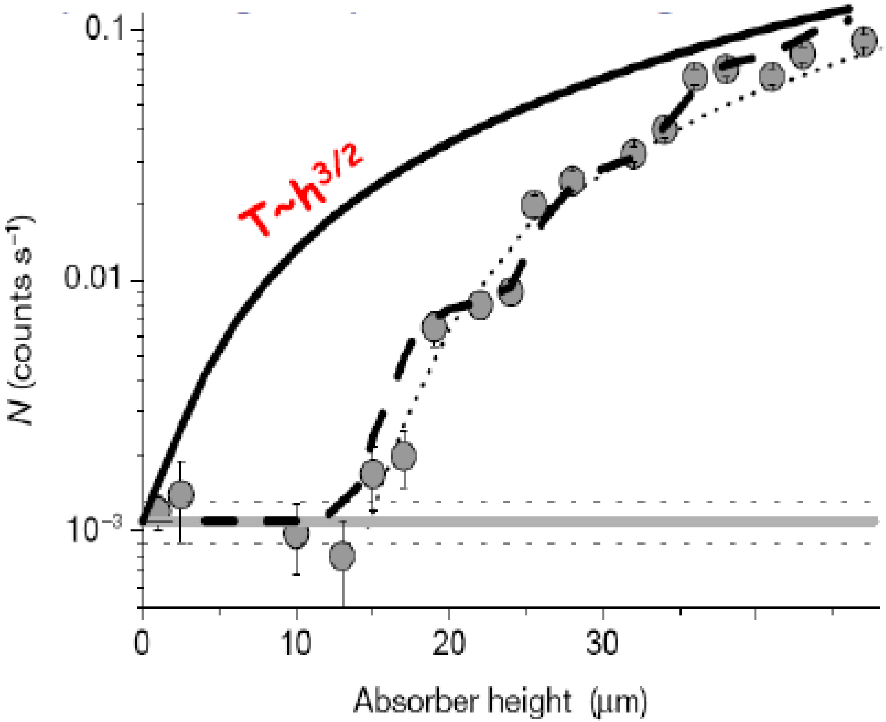
SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

New spectroscopic tool:

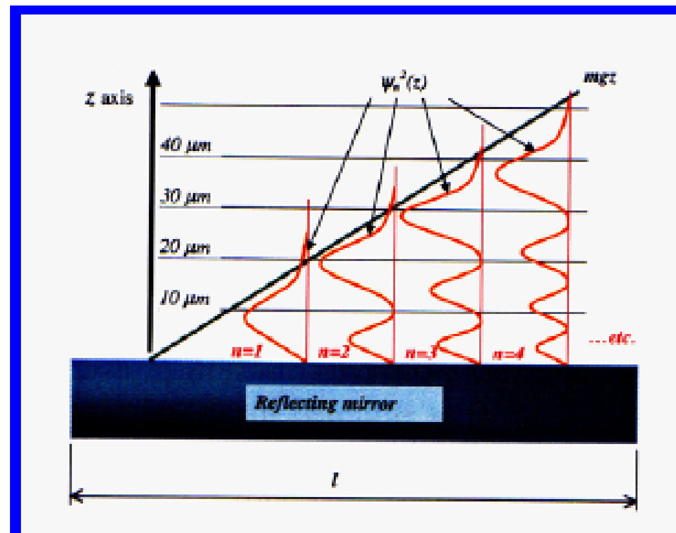


First observations (2002)



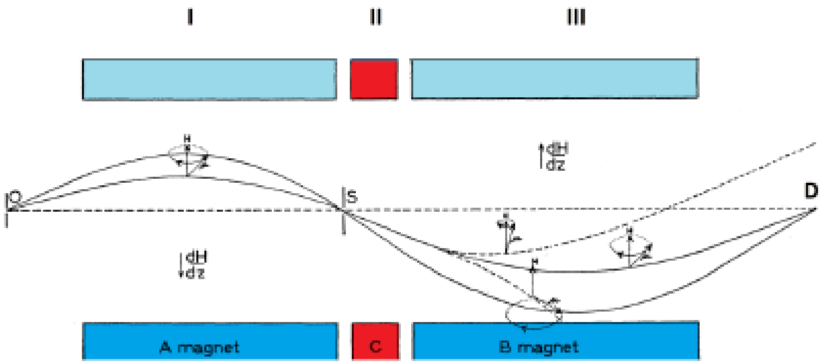


V. Nesvizhevsky et al., Nature **415** (2002) 299



Rabi-type spectroscopy of gravity
*q*Bounce collaboration (H. Abele, T. Jenke...)

NMR Spectroscopy Technique
to *explore magnetic moments*



3 Regions:

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

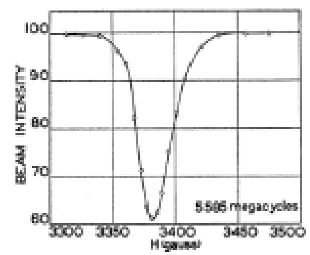
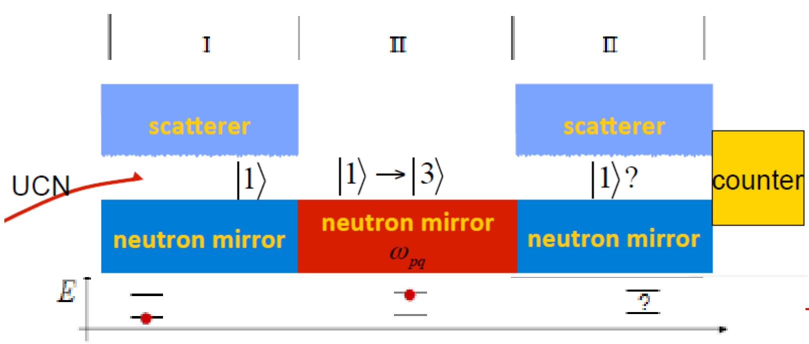


FIG. 4. Resonance curve of the Li^7 nucleus observed in LiCl.

Gravity Resonance Spectroscopy Technique
to *explore gravity*



3 Regions:

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

Most recent results on Gravity Resonance Spectroscopy

Transitions 1-3 and 1-4 observed

1-3: (46±5)% Intensity drop

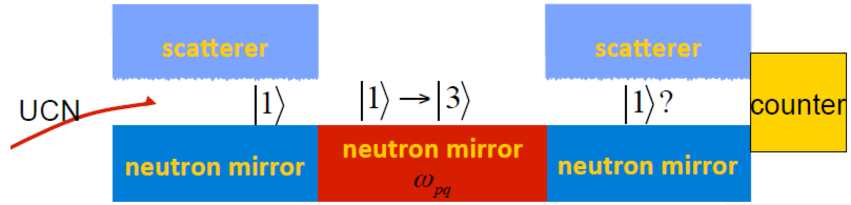
1-4: (61±7)%

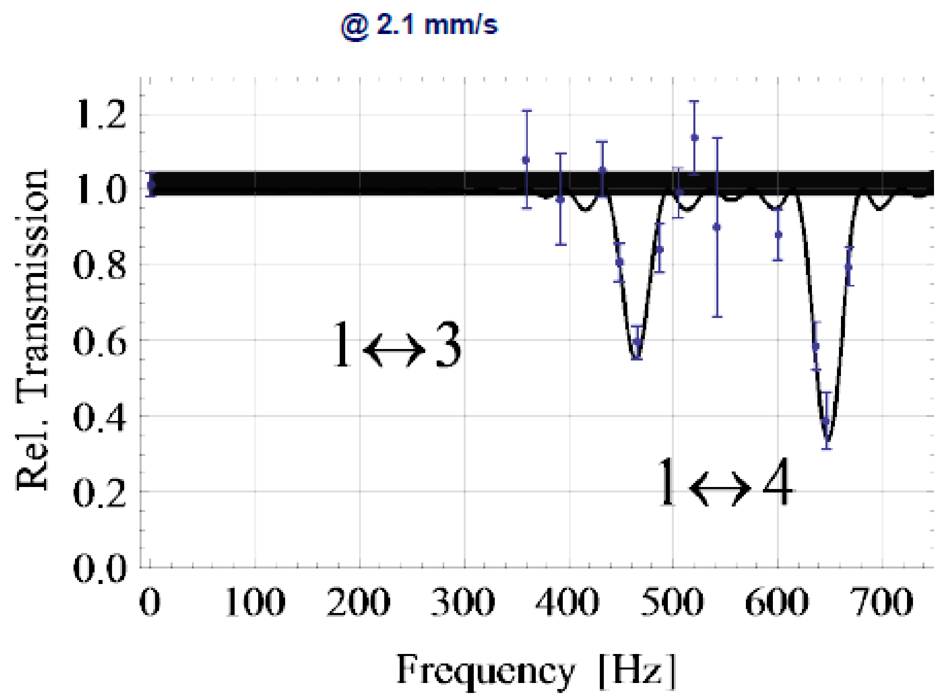
60 measurements

Preliminary,

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

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

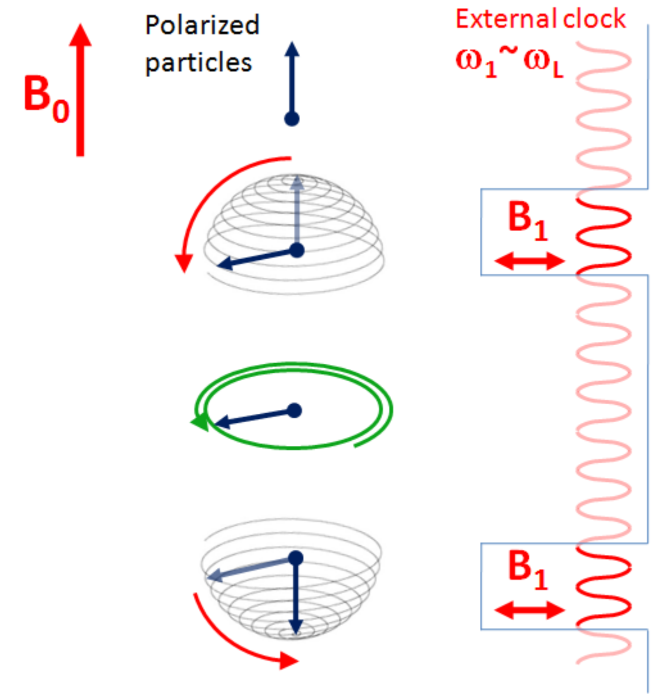




Thesis Cronenberg

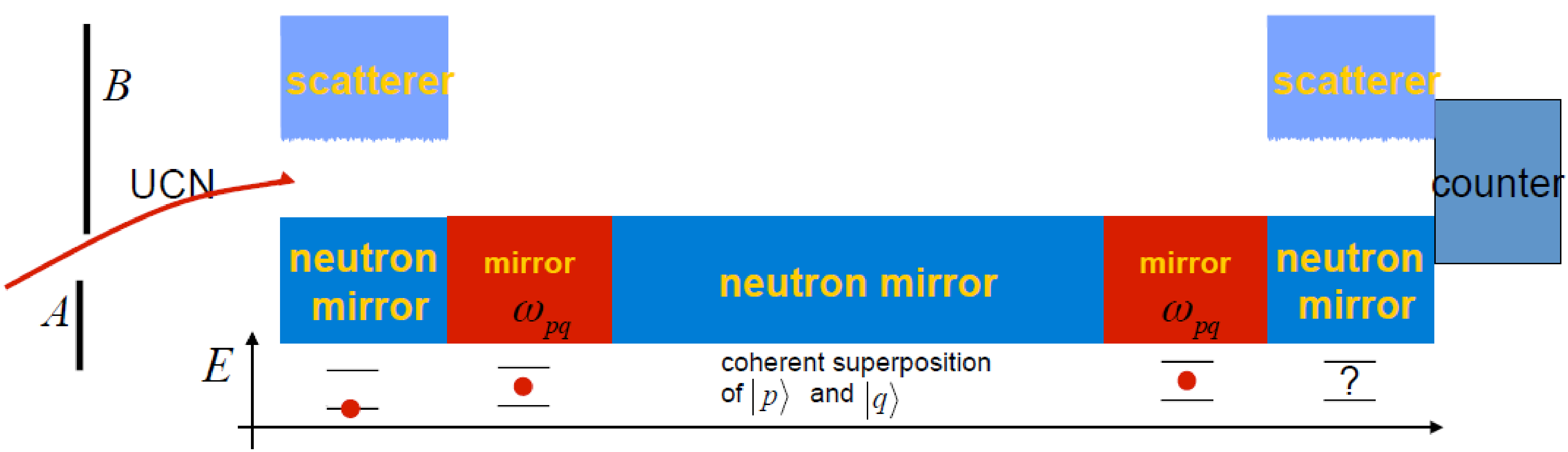
Ramsey spectrometer for gravity states

H. Abele et al., Phys. Rev. D **81** (2010) 065019



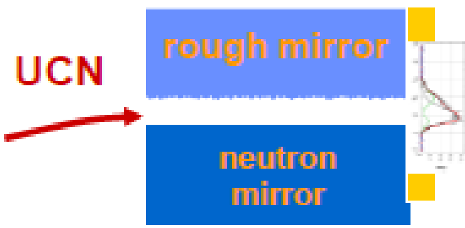
Advantages:

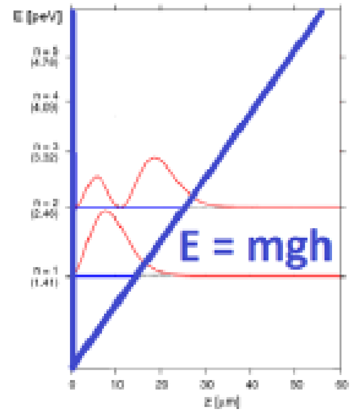
- Long flight path → smaller uncertainty ΔE
- static central mirror for free state evolution

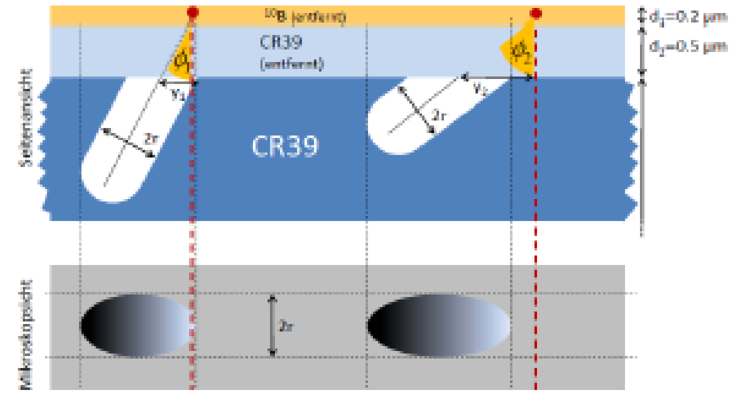


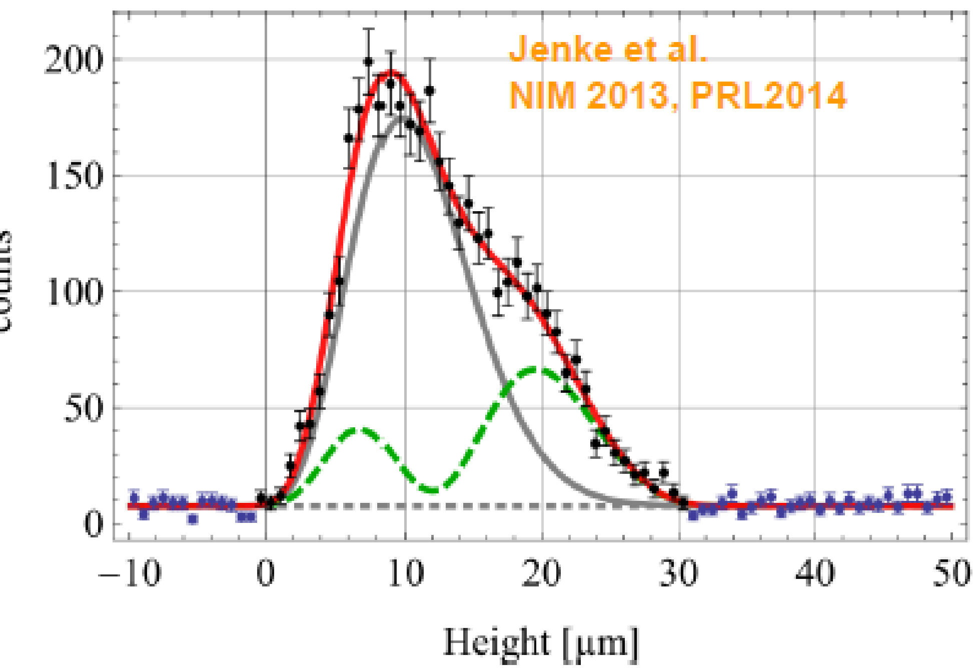
Airy - Quantum States 1 & 2

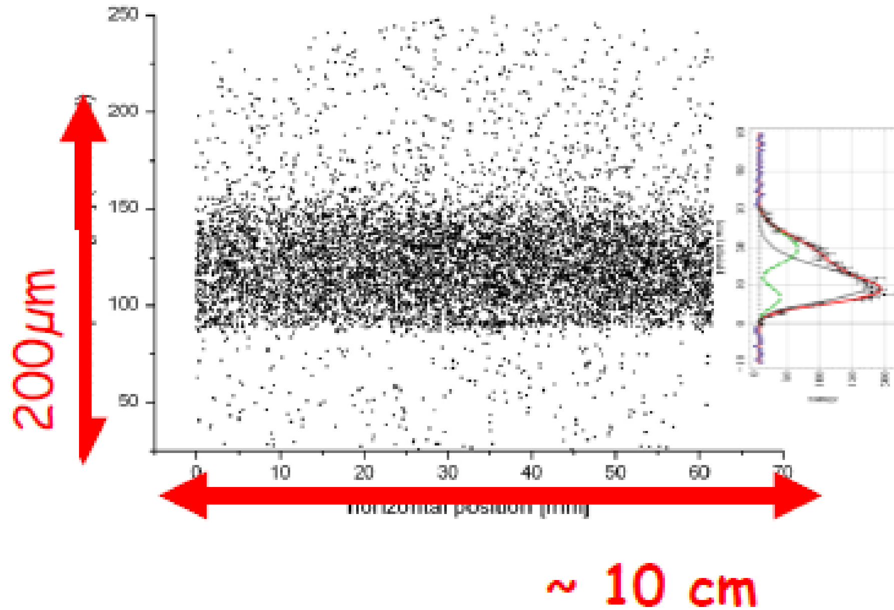
$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$$







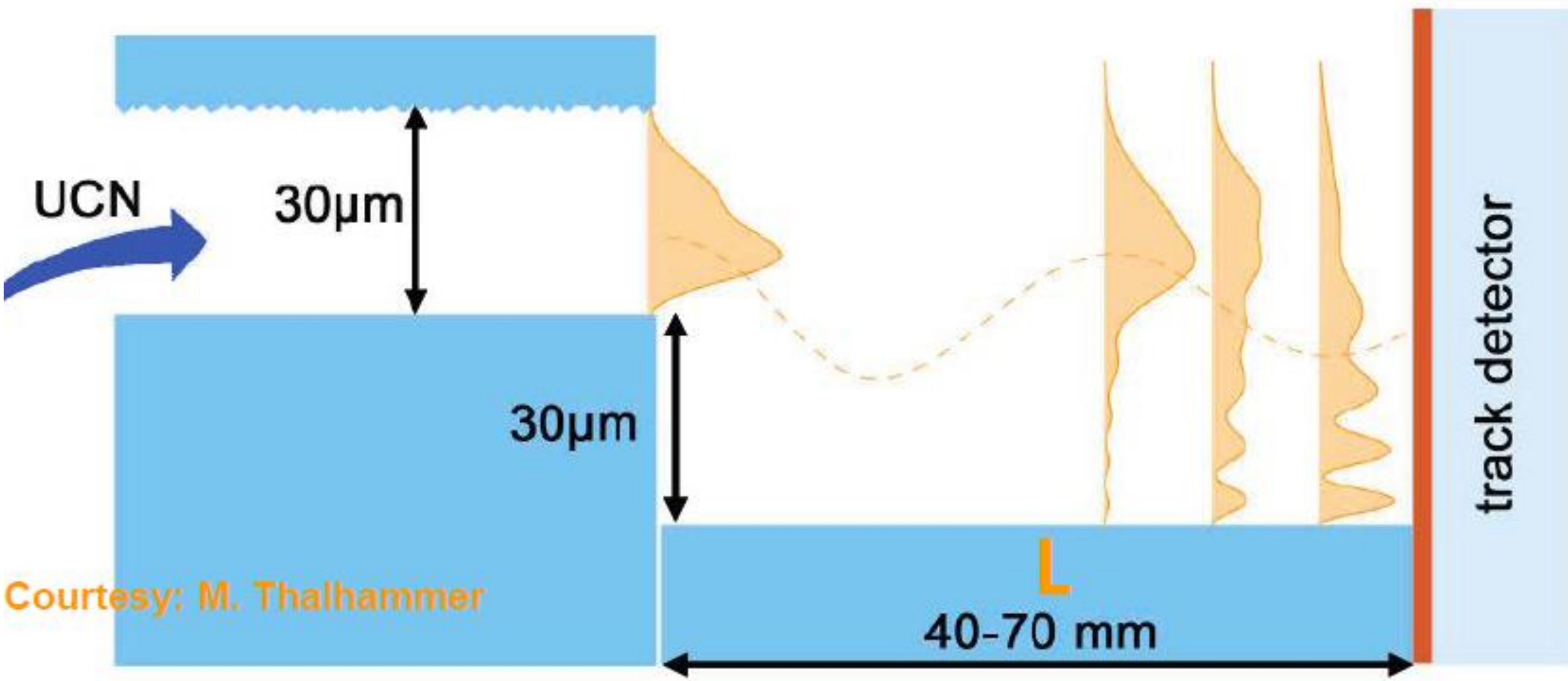




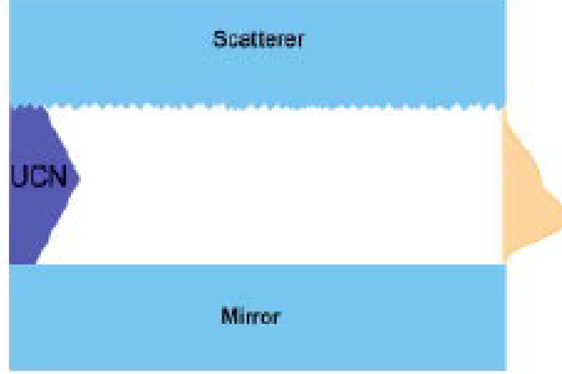
Snapshots of $|\psi|^2$ with 1.5 μm resolution

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

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

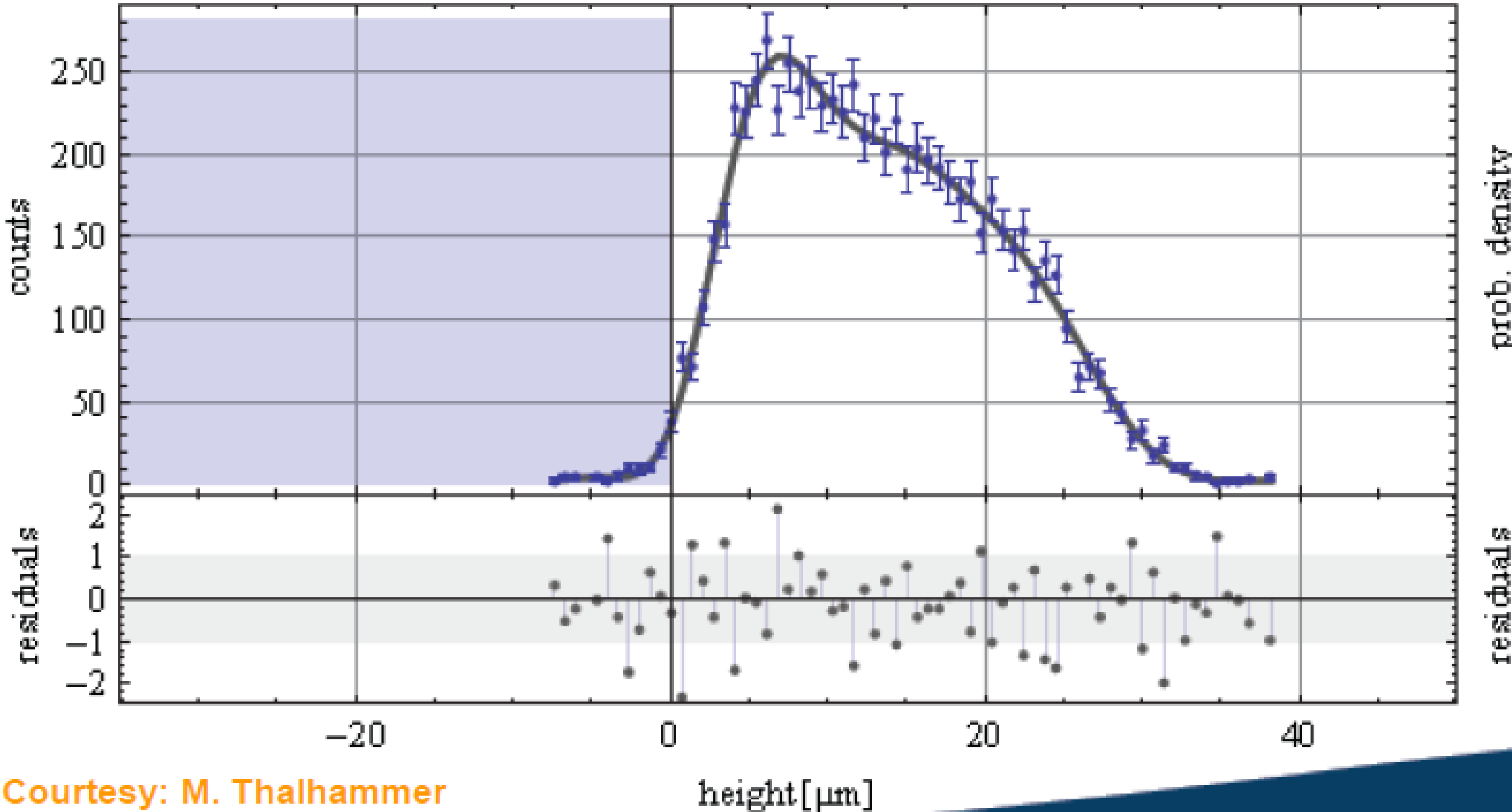


Preparation L = 0



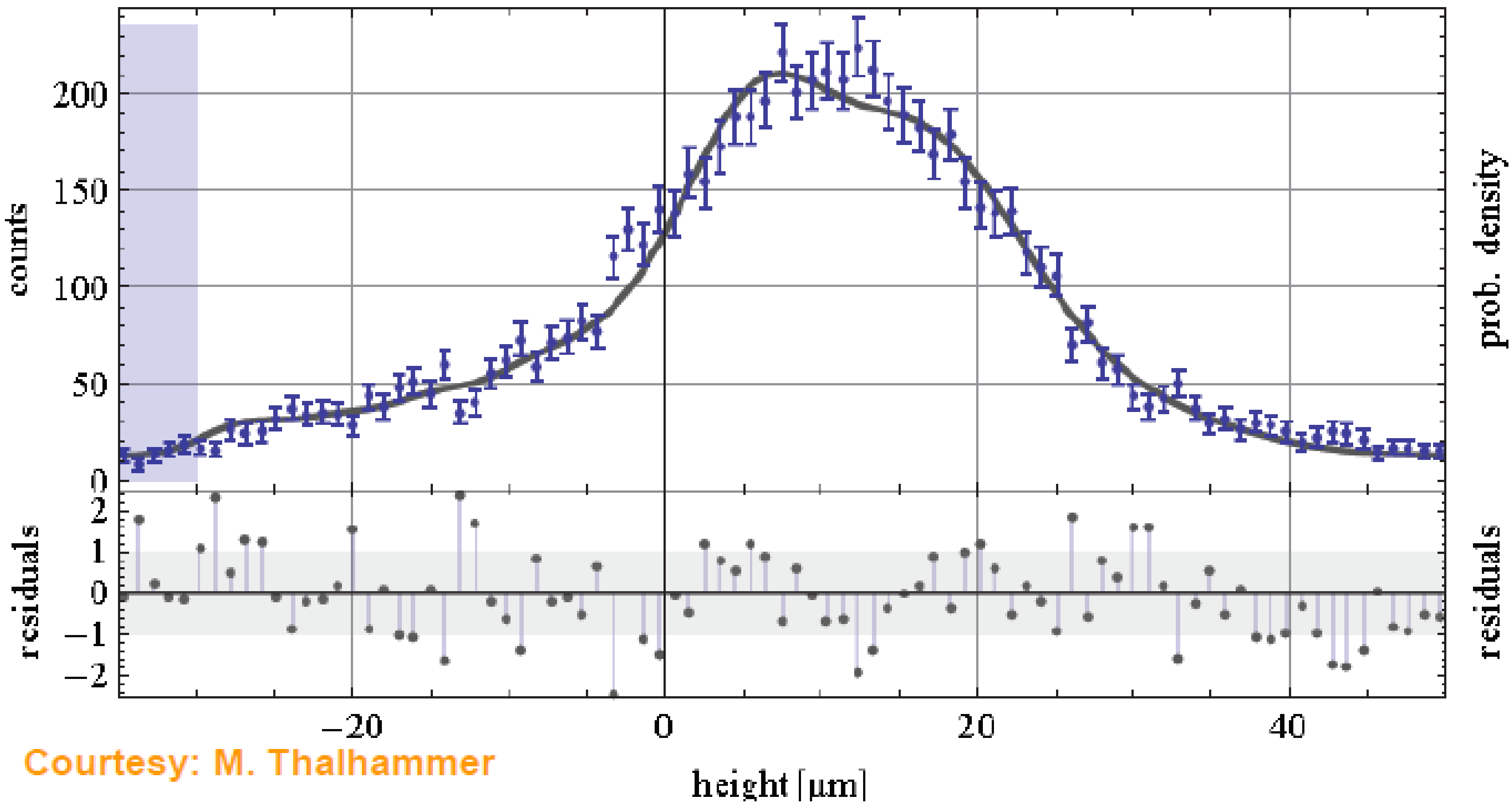
$$|\Psi_I(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

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



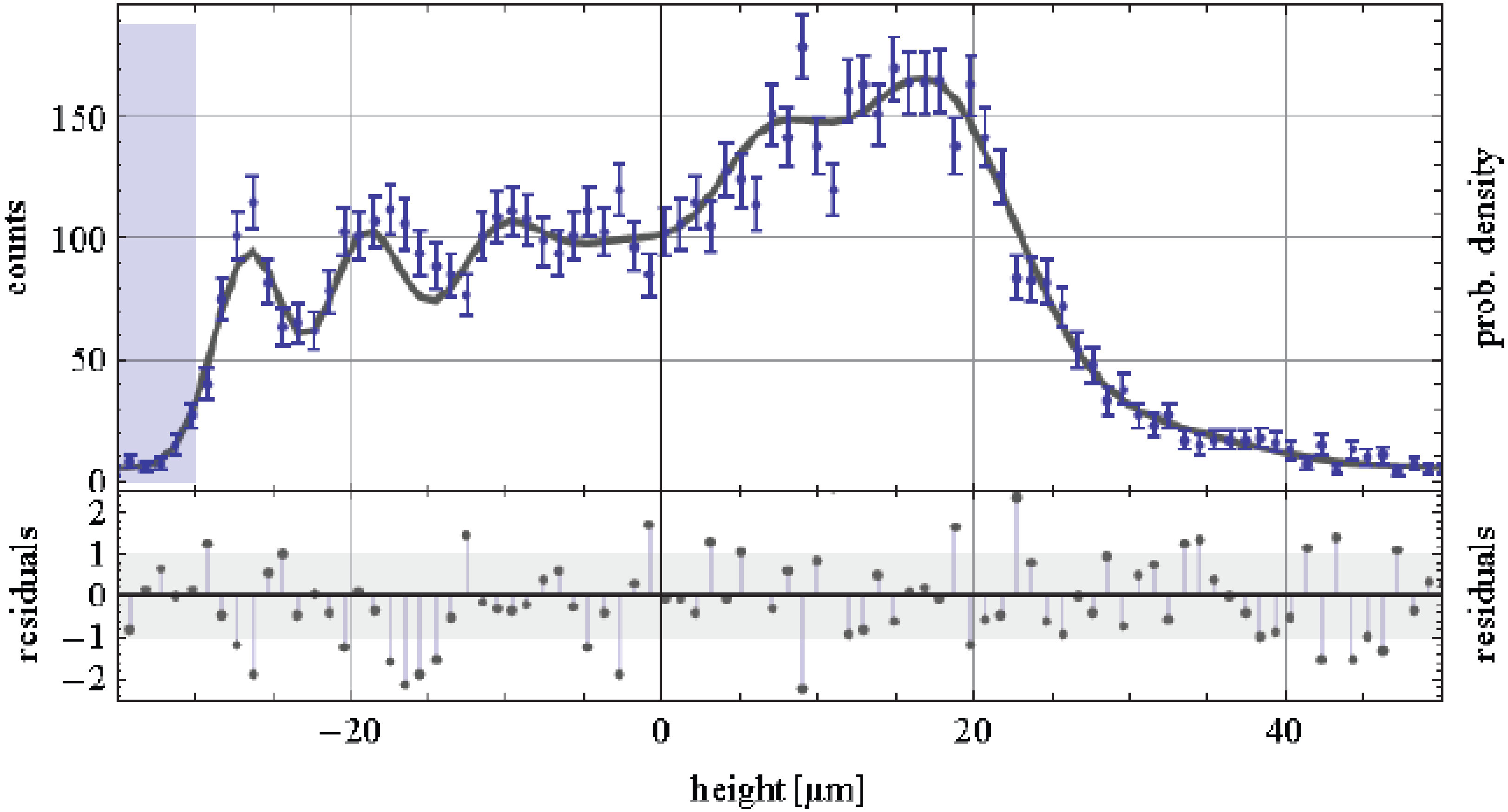
Courtesy: M. Thalhammer

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



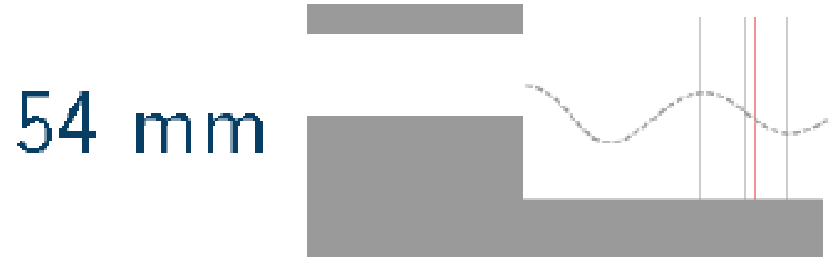
Courtesy: M. Thalhammer

Move downwards, L = 51 mm

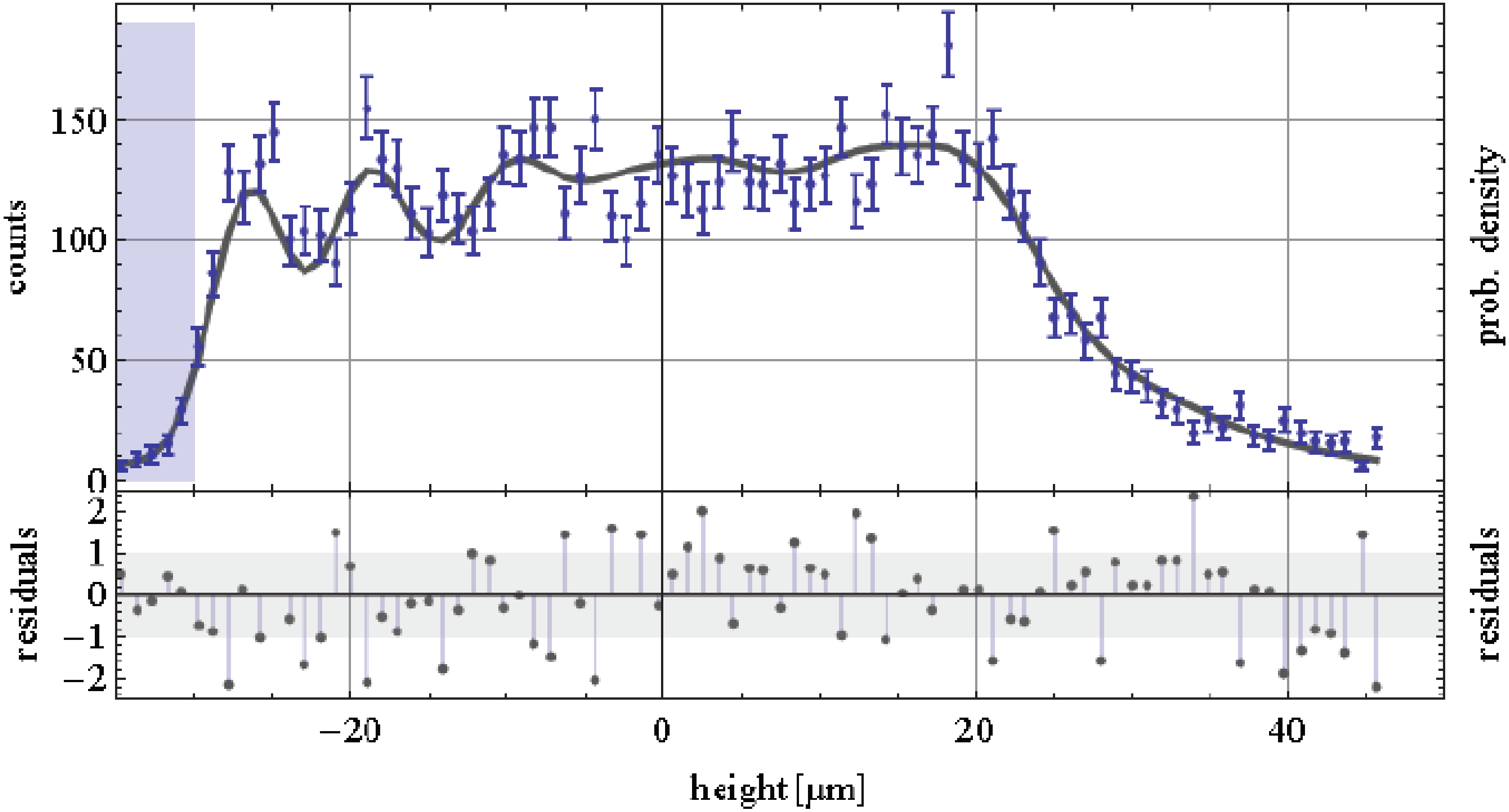


Courtesy: M. Thalhammer

L = 54 mm

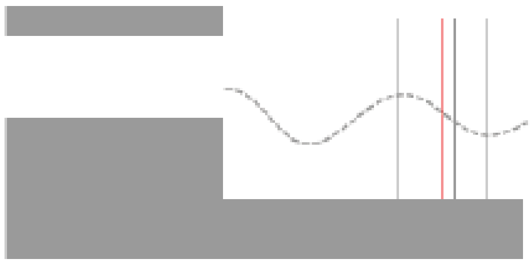


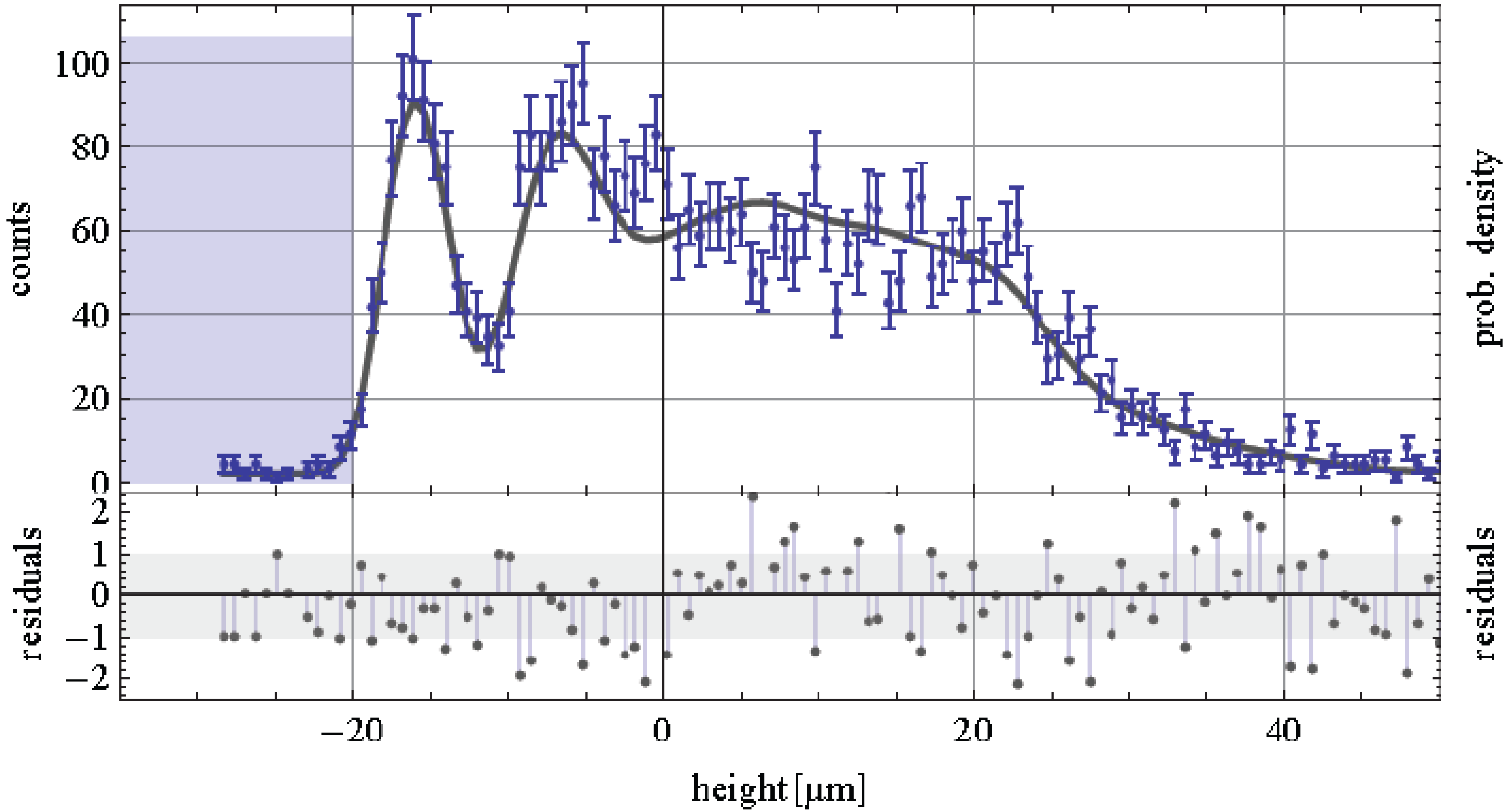
54 mm



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

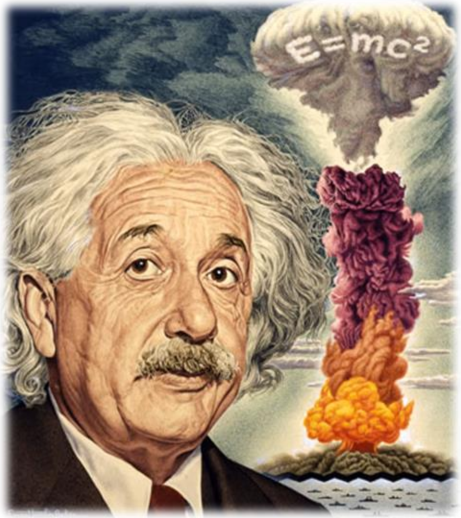
L = 51 mm @ 20 µm





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

$E = mc^2$



How can we test it?

- need process, where mass is converted in energy
- thermal-neutron capture reaction:

$$ {}^{L}\mathrm{X} + {}^{1}\mathrm{n} \rightarrow {}^{L+1}\mathrm{X} + \sum_i \gamma_i $$

thermal energies $\sim 10^{-2}$ eV

excess energy: several 10^{6} eV

total energy uncertainty: $< 10^{-8}$

$$[m(\mathrm{n}) + m({}^{L}\mathrm{X}) - m({}^{L+1}\mathrm{X})]c^2 = \sum_i E(\gamma_i) \quad ?$$

$$E(\gamma) = h\nu = \frac{hc}{\lambda}$$

In terms of mass units A relative to an atomic mass scale $u = 10^{-3}/N_\mathrm{A}$ kg :

$$A(\mathrm{n}) + \underbrace{A({}^{L}\mathrm{X}) - A({}^{L+1}\mathrm{X})}_{\Delta A({}^{L+1}\mathrm{X})} = 10^3 \frac{N_\mathrm{A} h}{c} \sum_i \frac{1}{\lambda_i({}^{L+1}\mathrm{X})}$$

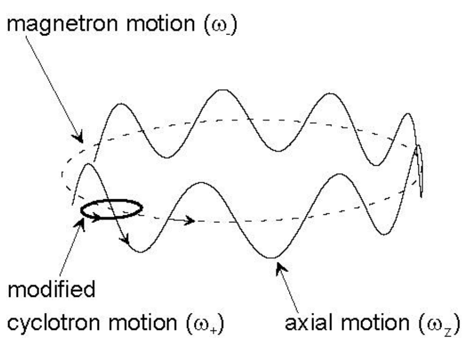
molar Planck constant

$$\underbrace{\Delta A({}^{L+1}\mathrm{X}) - \Delta A({}^{K+1}\mathrm{Y})}_{\text{Penning trap measurements (4 masses)}} = 10^3 \frac{N_\mathrm{A} h}{c} \underbrace{\left[\sum_i \frac{1}{\lambda_i({}^{L+1}\mathrm{X})} - \sum_j \frac{1}{\lambda_j({}^{K+1}\mathrm{Y})} \right]}_{\text{Gamma-ray wavelength measurements (2 nuclides after neutron capture)}}$$

Penning trap measurements (4 masses)

Gamma-ray wavelength measurements
(2 nuclides after neutron capture)

$$\omega = \frac{qB}{m}$$



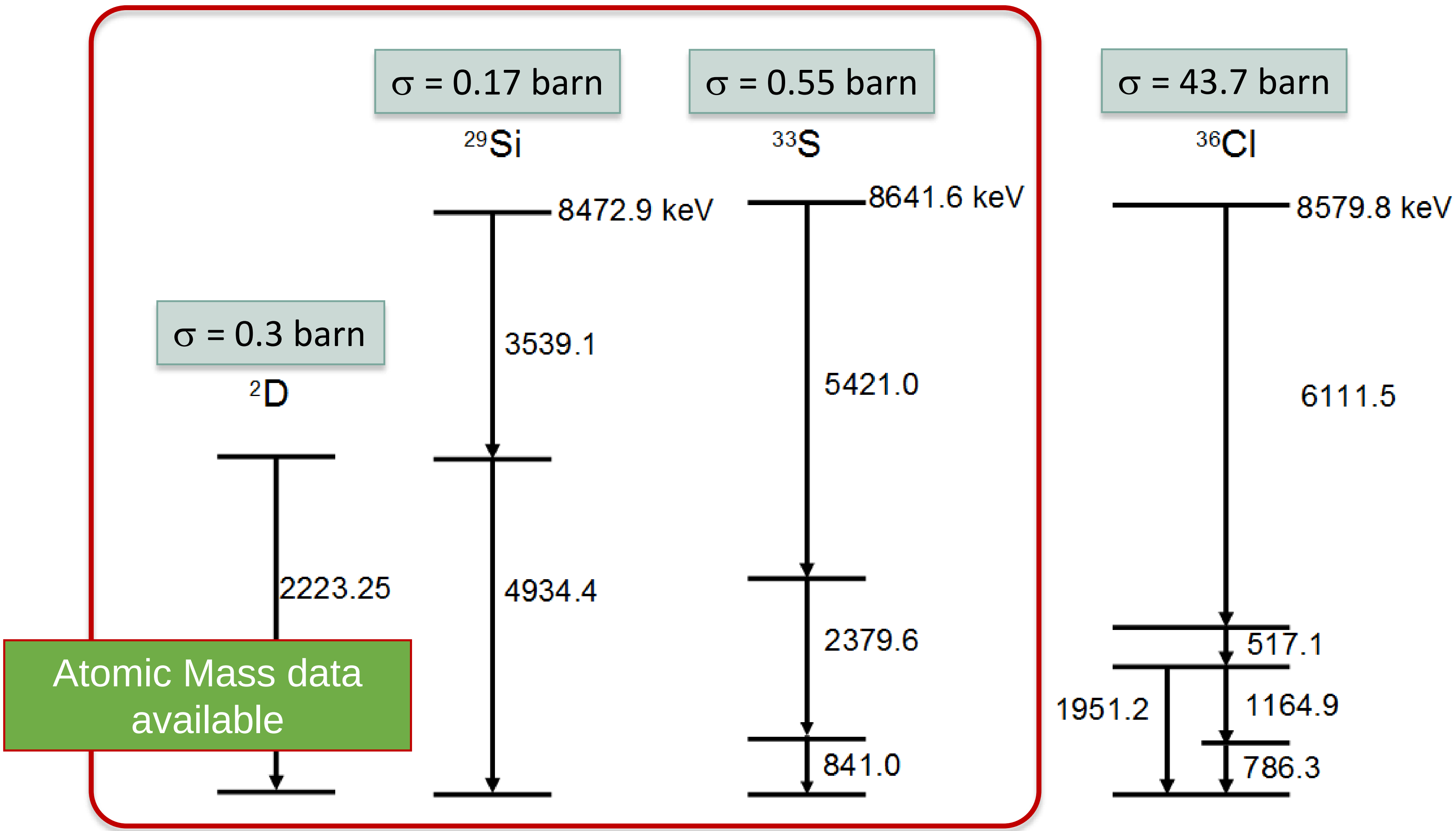
Double crystal monochromator

GAMS

Which isotopes?

Penning Trap: $A(^{L,L+1}X)$ can be measured with 10^{-11} relative uncertainty!

Need mass values for two pairs of stable isotopes



A 10^{-11} relative uncertainty on A requires λ measurements with accuracy 10^{-8}

What is needed to determine gamma energies (or wavelengths) with high accuracy?

is necessary but insufficient

High accuracy $\rightarrow$ use gamma spectroscopy based on **Laue diffraction**

$$n\frac{hc}{E_\gamma} = 2d\sin\theta$$

Bragg's law for photons

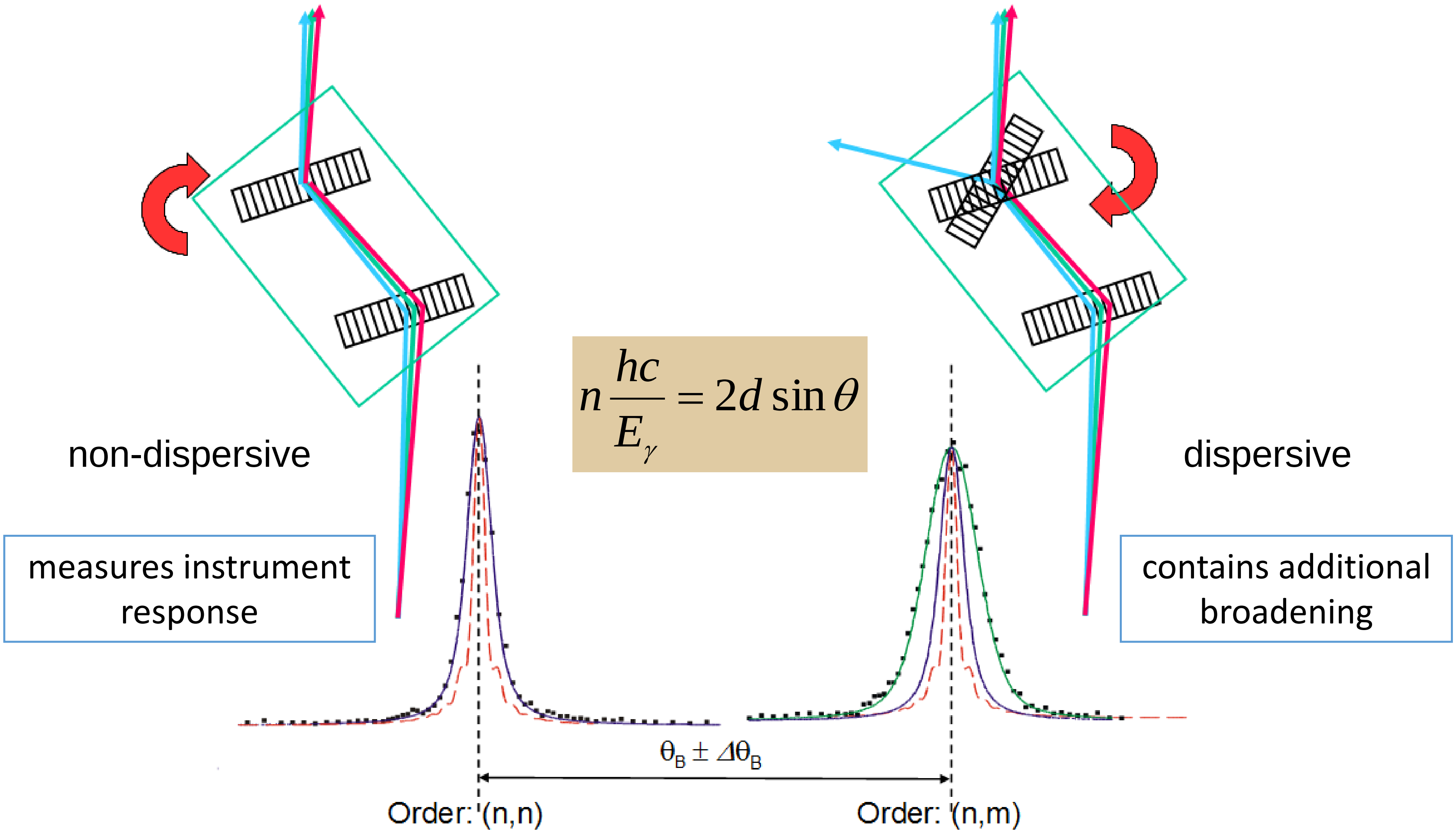
$\Delta d/d < 10^{-8}$

$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)^2 \sim \left(\frac{\Delta\theta}{\theta}\right)^2 + \left(\frac{\Delta d}{d}\right)^2$$

Need absolute measurements of:

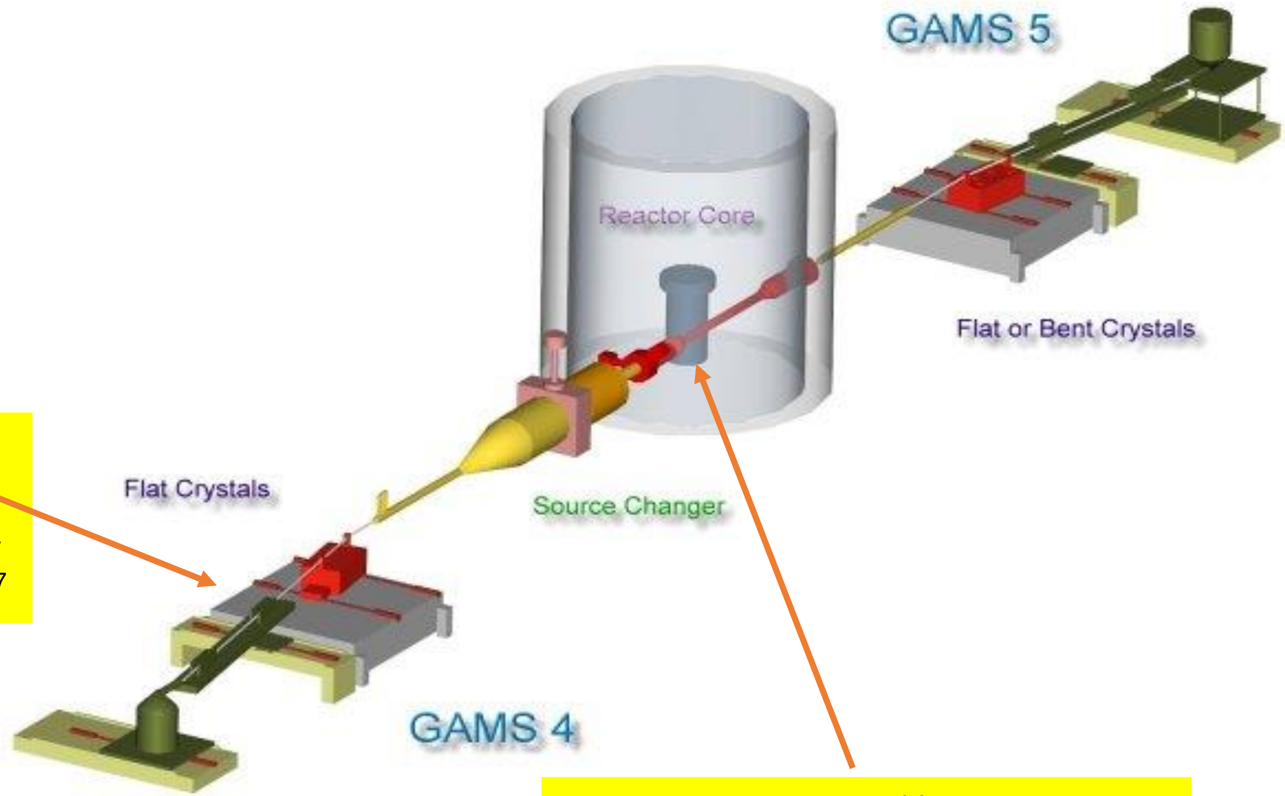
- lattice constant d
- scattering angle θ

Flat double-crystal monochromator spectrometer for gamma rays: **GAMS**



$$n\frac{hc}{E_\gamma} = 2d\sin\theta$$

Implantation of spectrometer

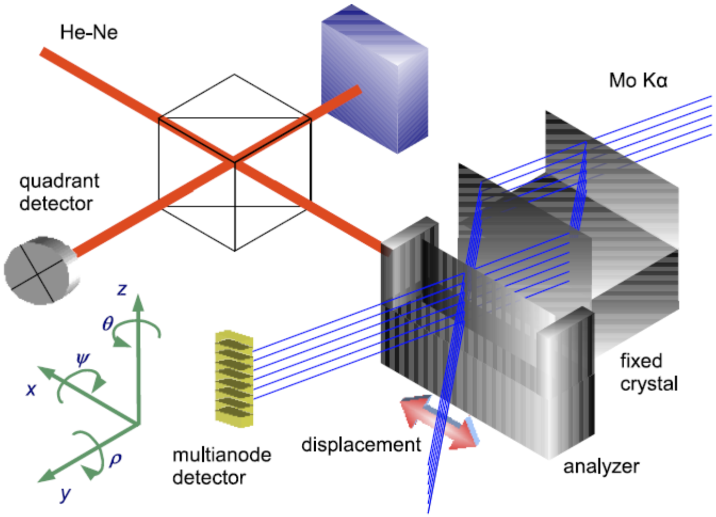


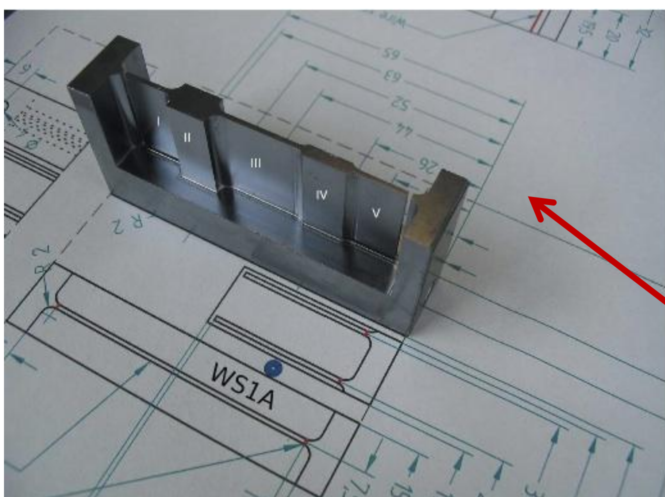
Flat Crystals:

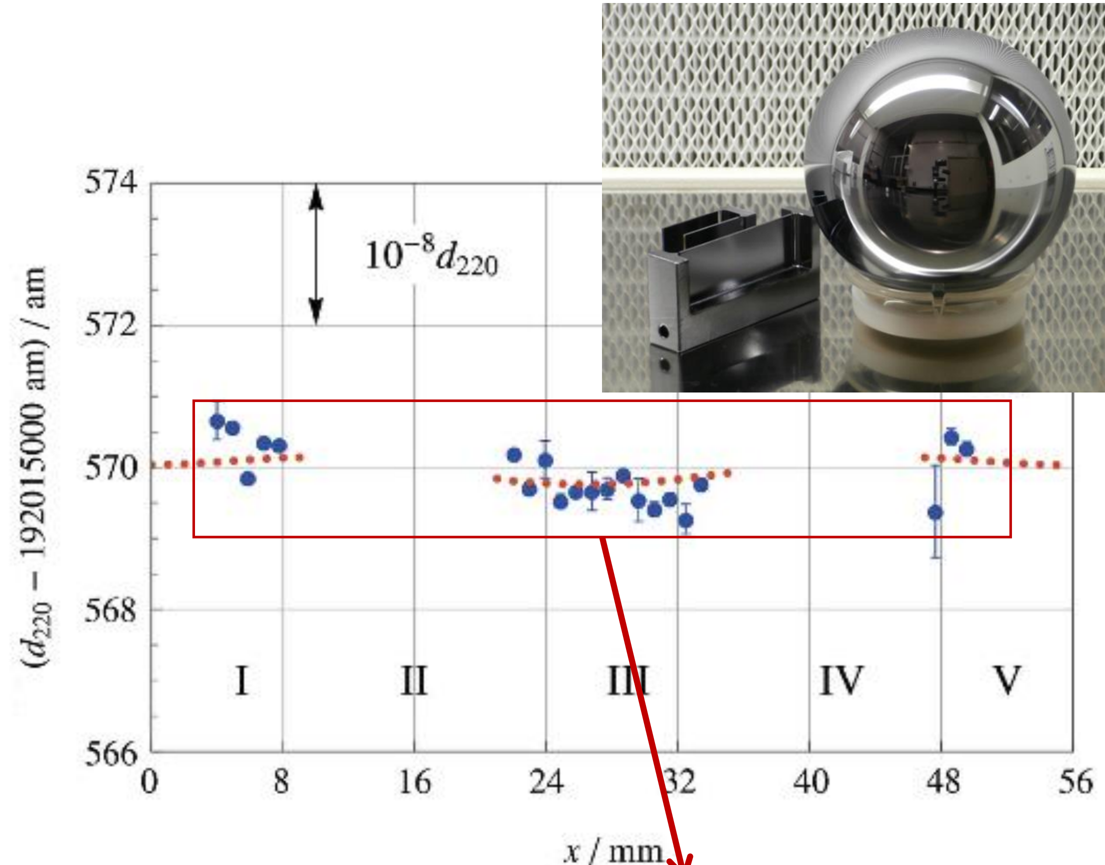
- Resolution: 10^{-6}
- Eff. Solid Angle: 10^{-11}
- absolute Energy: 10^{-7}

Neutron Flux: 5×10^{14}
Targets: 0.1 – 10g
Target change during reactor cycle

$\Delta d/d$: How perfect are GAMS crystals?





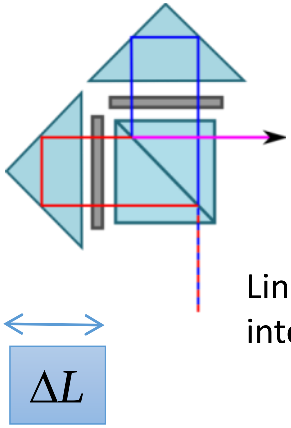


$\Delta d/d < 10^{-8}$, extremely perfect silicon crystals, d known in SI units

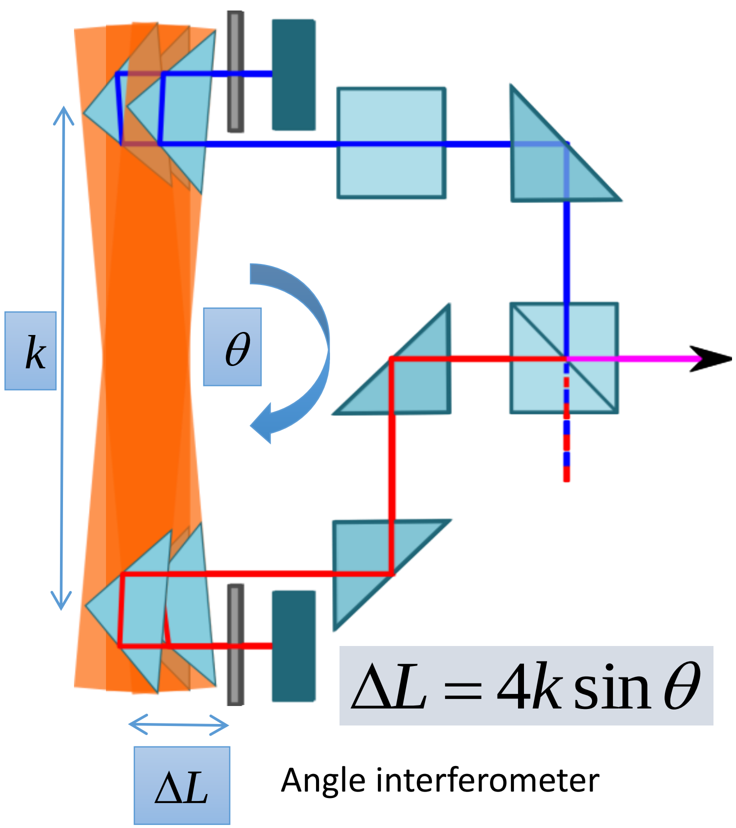
Silicon crystal for GAMS6 from WASO4 reference material

- Fabricated by PTB, Braunschweig, Germany
- Characterized by INRIM, Torino, Italy

Angle interferometer with self-calibration

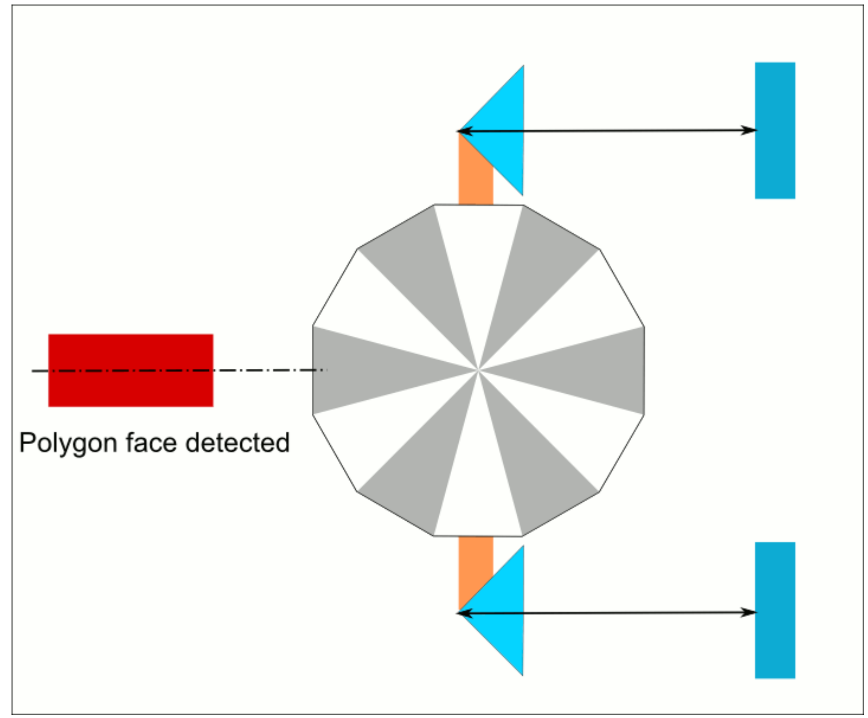


Linear displacement interferometer



$$\Delta L = 4k\sin\theta$$

Angle interferometer



$$2\pi = \sum_{i}^{N} \arcsin\left(\frac{\Delta L_i}{4k}\right)$$

- N ΔL_i are measured
- Equation is solved for k

Result of $E = mc^2$ test using GAMS4

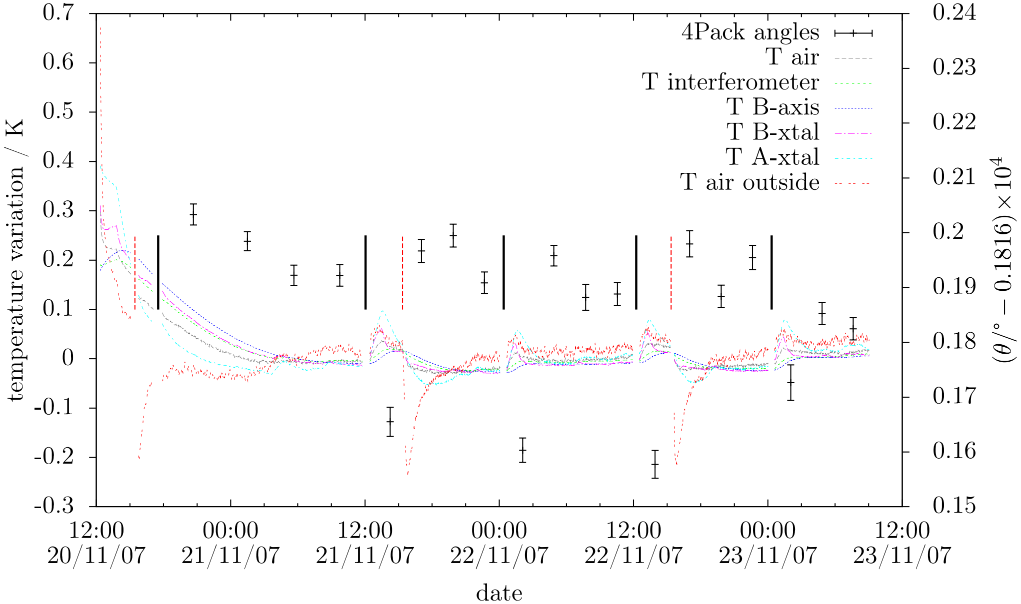
$$E_\gamma - \Delta mc^2 = -(1.2 \pm 4.3) \times 10^{-7}$$

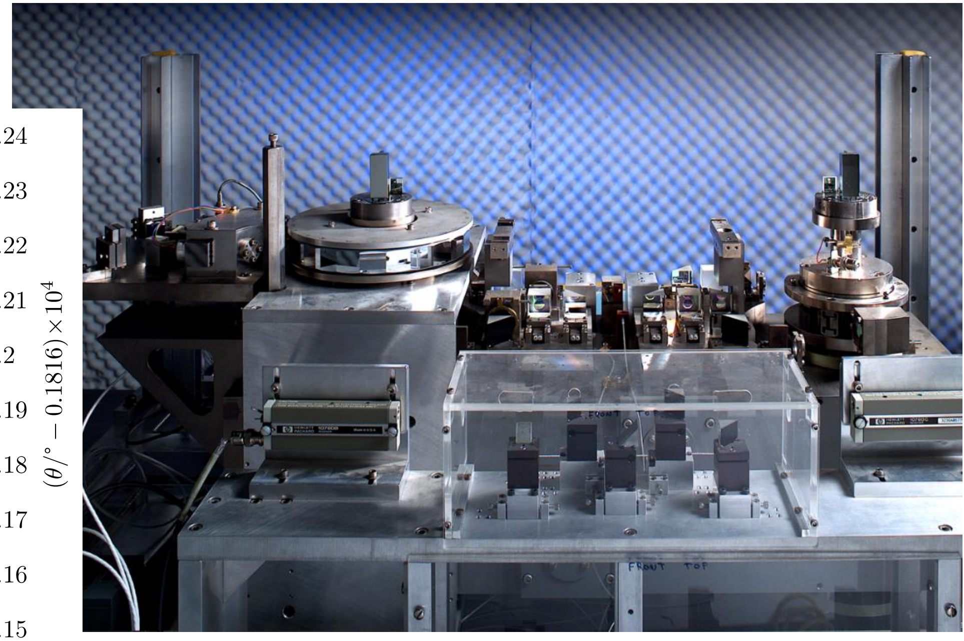
S. Rainville et al., Nature **438** (2005) 1096

^{A+1}X	Δm from Penning trap (u)	Δm from GAMS4 (u)	Rel. Diff. × 10^7
^{29}Si	0.00670861569(47)	0.00670860929(536)	-9.5(8.0)
^{33}S	0.00688901053(50)	0.00688901206(351)	2.2(5.1)
weighted average relative difference			-1.2(4.3)

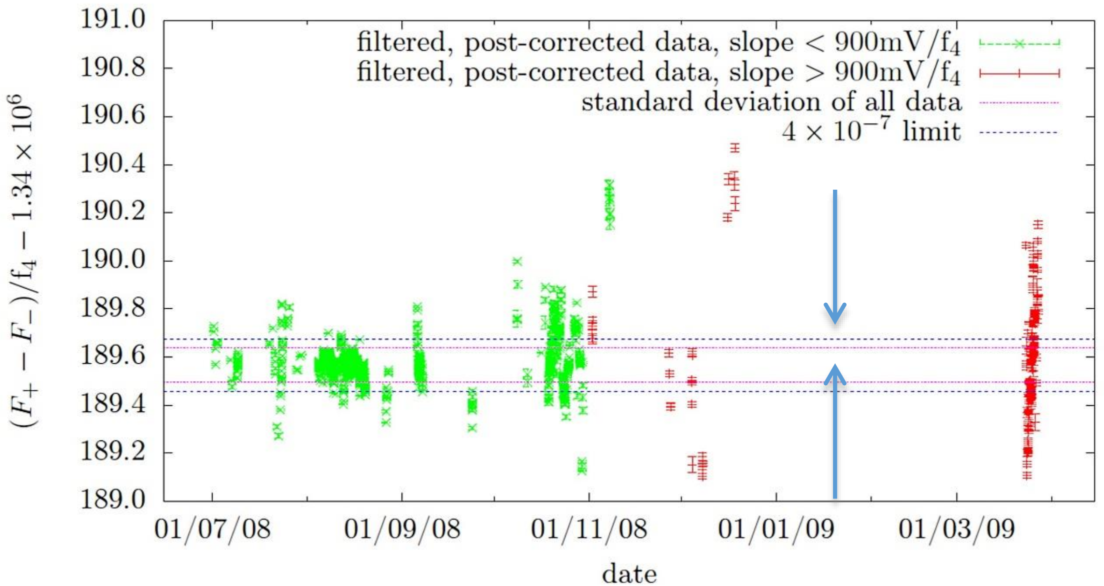
Wavelength measurements are limiting

Accuracy reach of GAMS4





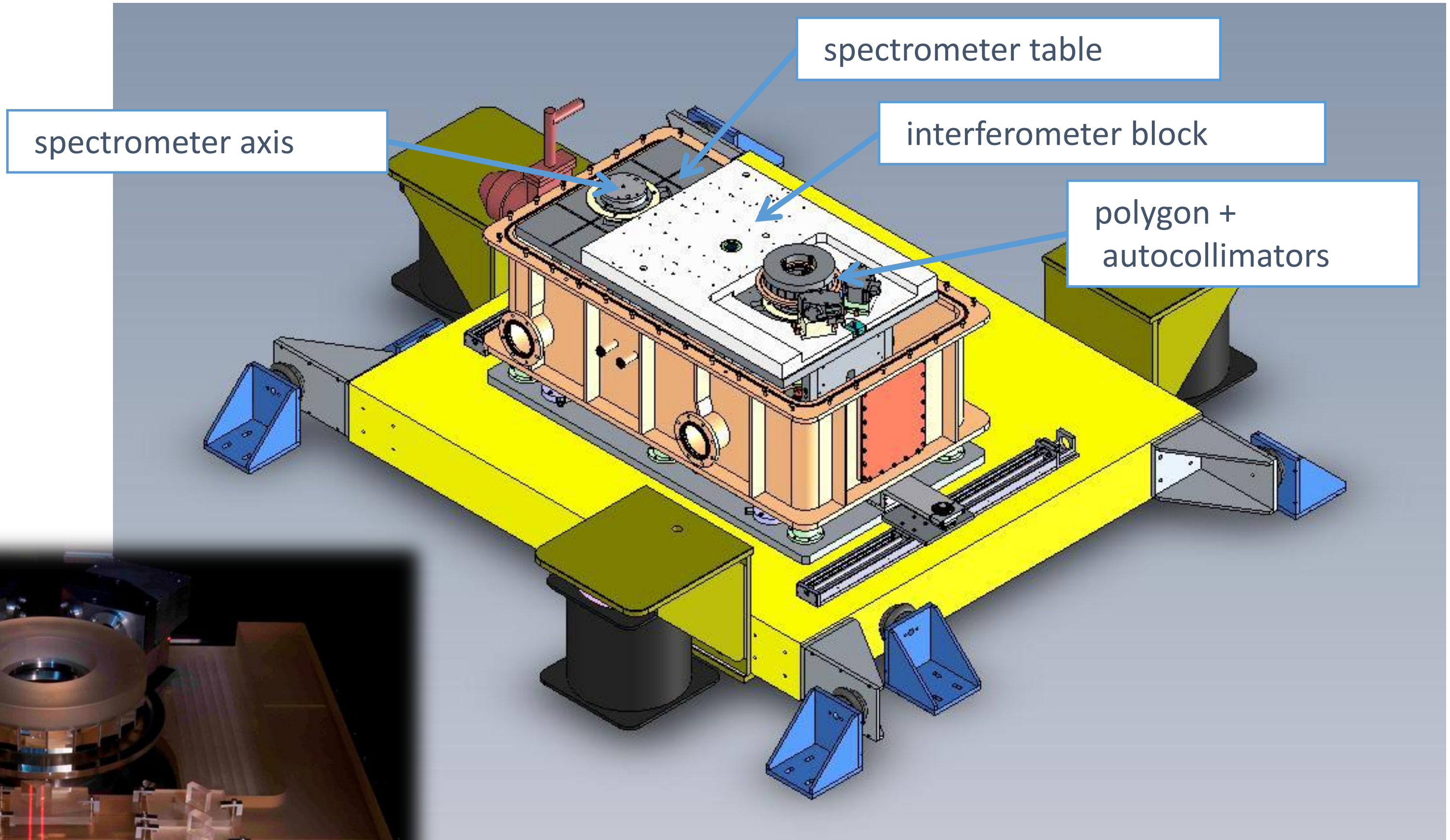
Stability of calibration: 2.1×10^{-7}

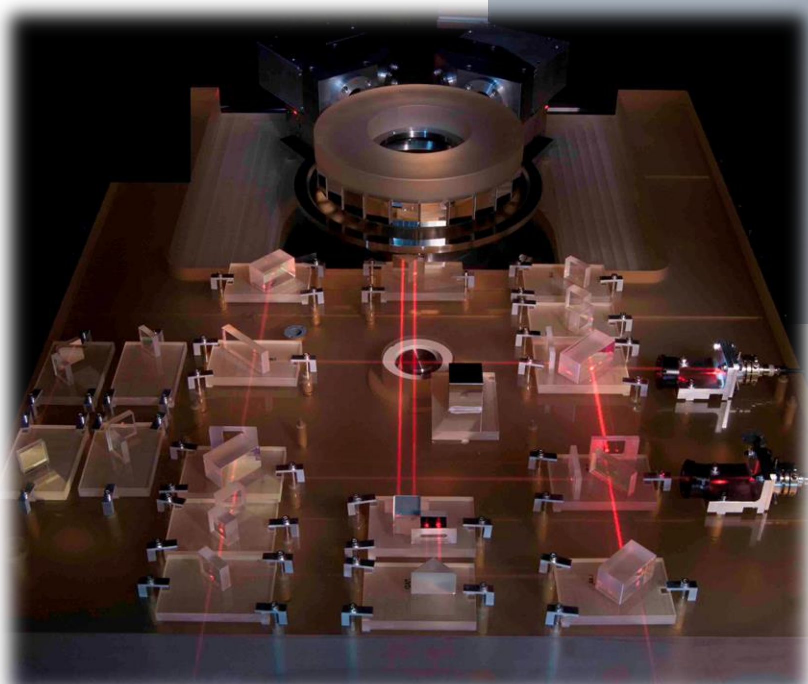


Angle measurement and calibration under atmosphere possible not better than on 10^{-7} level

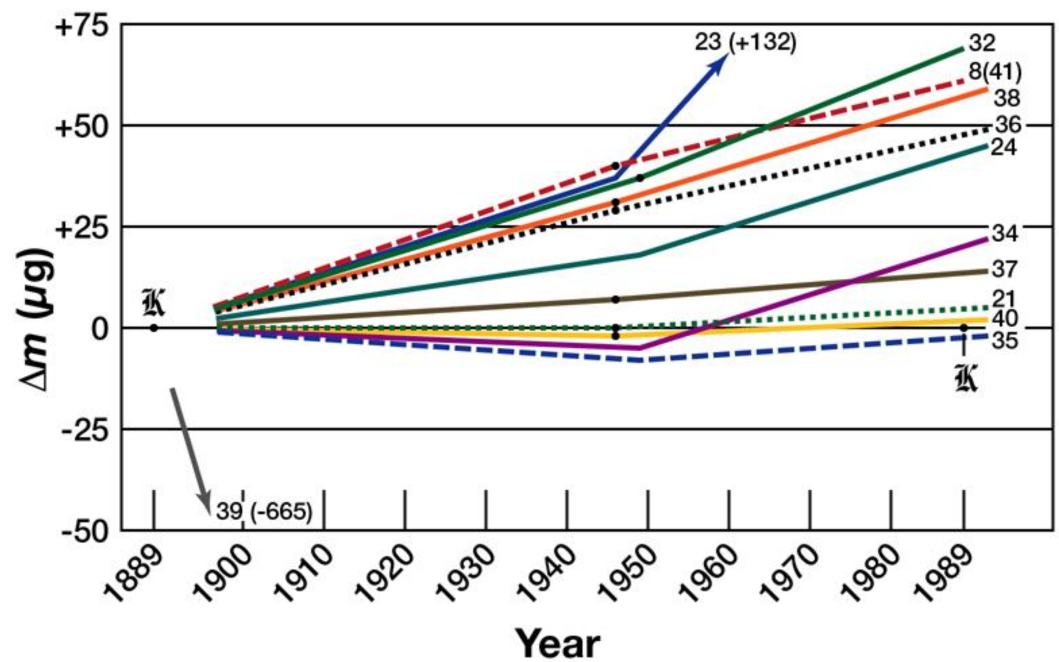
J. Krempel, PhD LMU, 2011

New instrument GAMS6

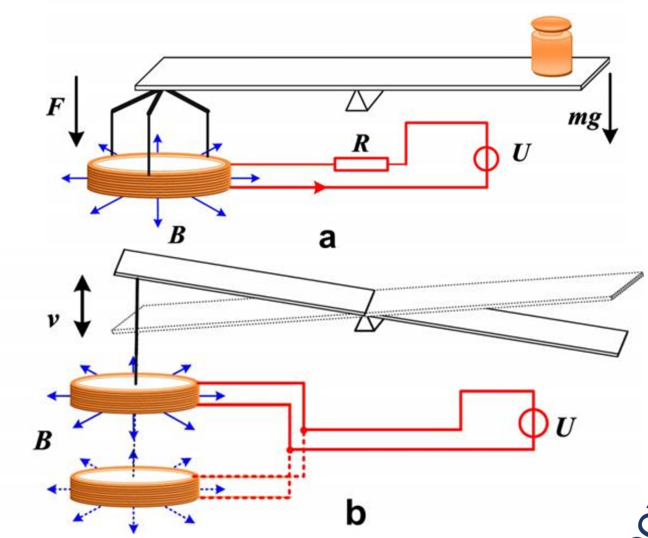




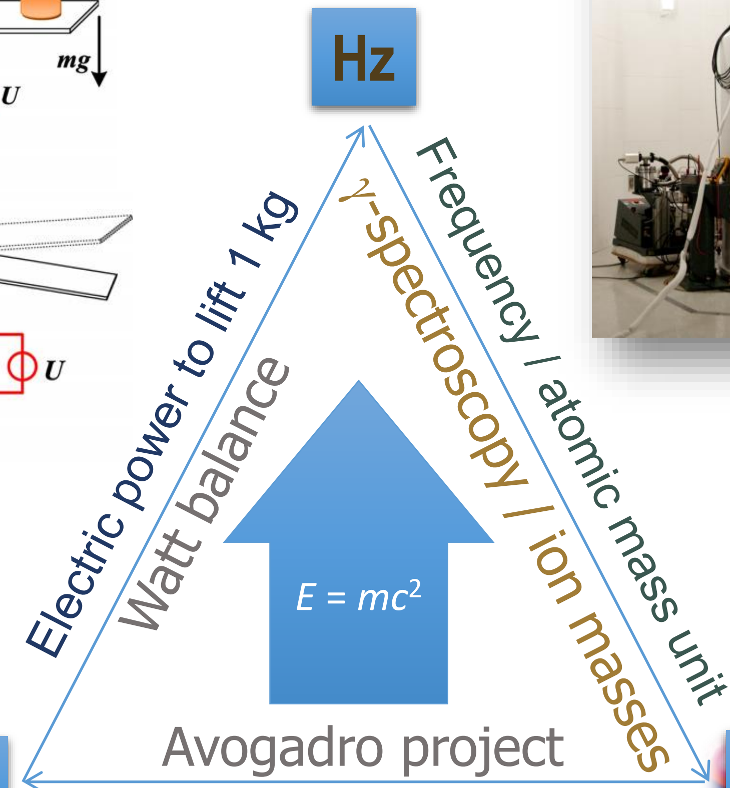
Challenge: redefinition of the kilogram

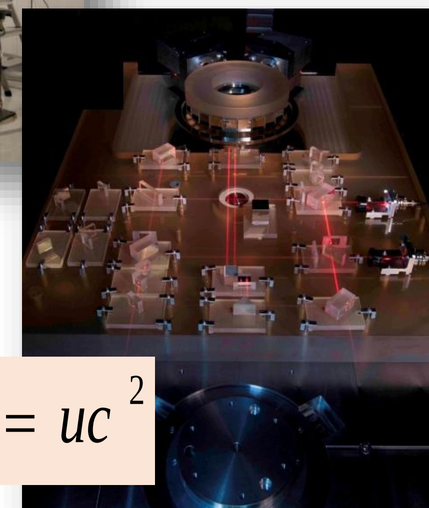


Routes to a new mass unit definition



$$h = \frac{4 m_{kg} g v}{R_{J-90}^2 R_{K-90} (UI)_{90}}$$

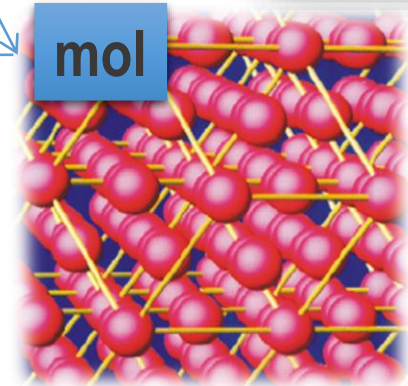




$$N_A h \nu = u c^2$$

Number of atoms in 1 kg

$$m_{kg} = 10^3 \times N_A u$$



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$E = mc^2$

Michael Jentschel
Institut Laue Langevin