NEWS

from the Institut Laue-Langevin (ILL), Grenoble

and especially from its

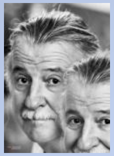
Ultra-Cold Neutron (UCN)

and

Very Cold Neutron (VCN) installation PF2

PF2 team

Thomas Brenner, <u>Peter Geltenbort</u> and Sergey Ivanov

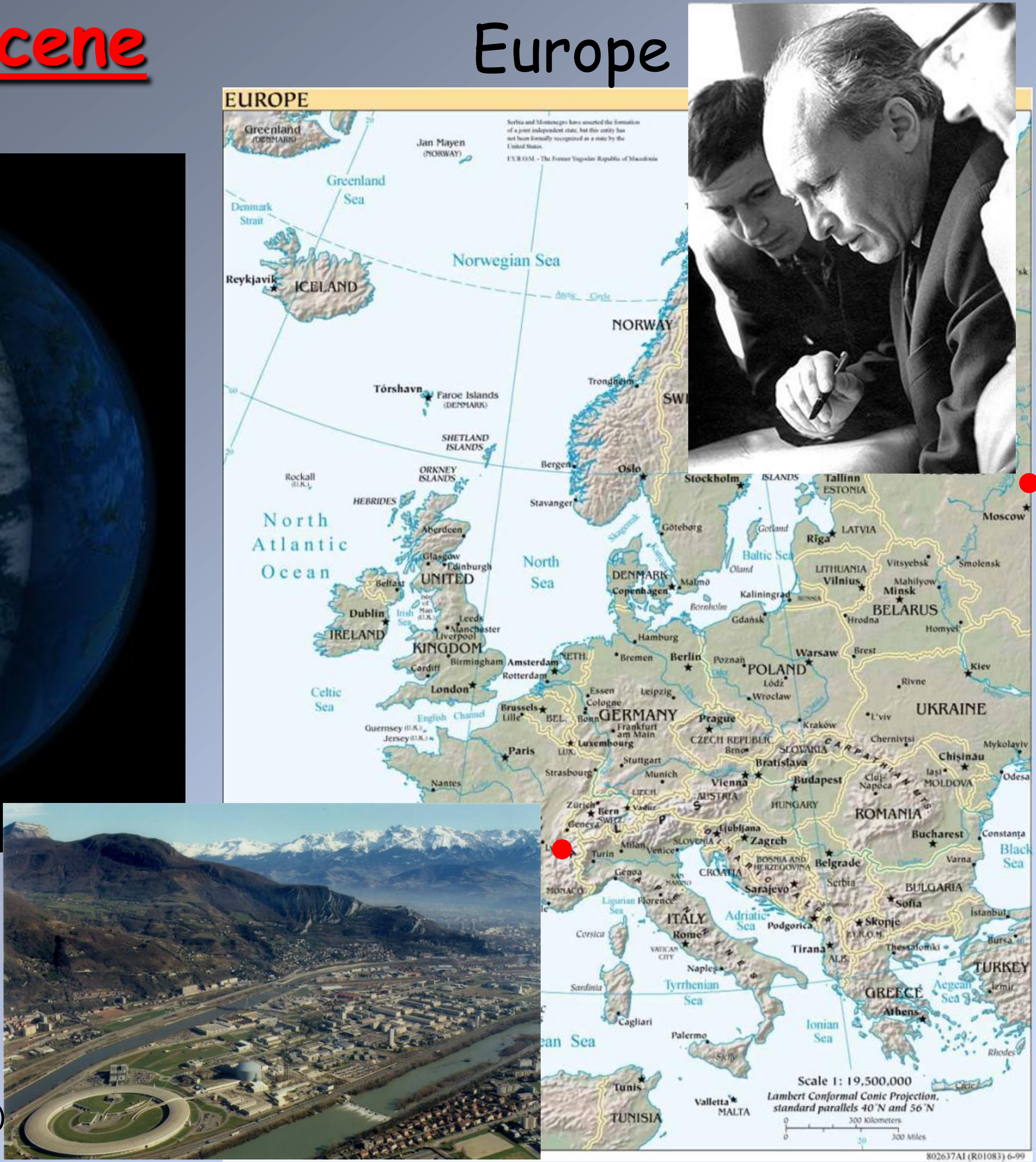


Very Hot (fission) Neutrons — Ultracold Neutrons

10^{7} eV → 10^{-7} eV

Setting the scene

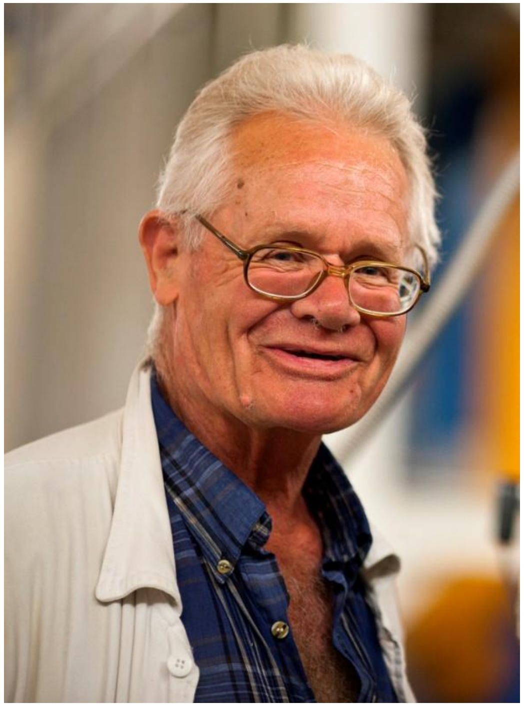
Europe



Earth

door to door (~3200 km): 12 hours
..... or at least 30 hours by car (google map)

ALL UCN discoverers in the Audience



A. Steyerl
Phys. Lett. 29B (1969) 33

Yu.N. Pokotilovskii V.I. Lushchikov A.V. Strelkov
JETP Lett. 9 (1969) 23

… this paper is open for discussion

Everything started 50 years ago

- Proposed in 1964 (Grenoble had knowledge + inclination)
- Laboratory agreed upon in 1967 by France and Germany
  - Neél and Maier-Leibnitz

Traité de l'Elyssé 22.01.1963

Ideas become concrete

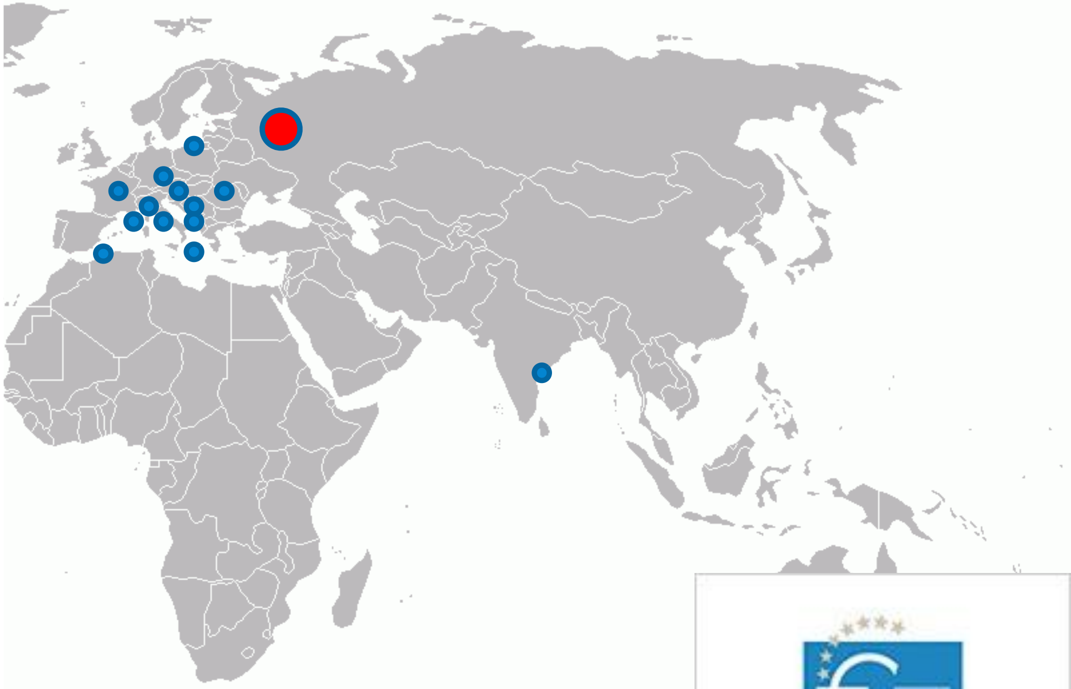
- Reactor first critical in 1971
- Operational for researchers (user service) in 1972 – 58 MW
- UK joined in 1973

…and new partner countries

An annual budget of close to 100 M€ (6 BRUB)
A capital investment of about 2 B€ (120 BRUB)

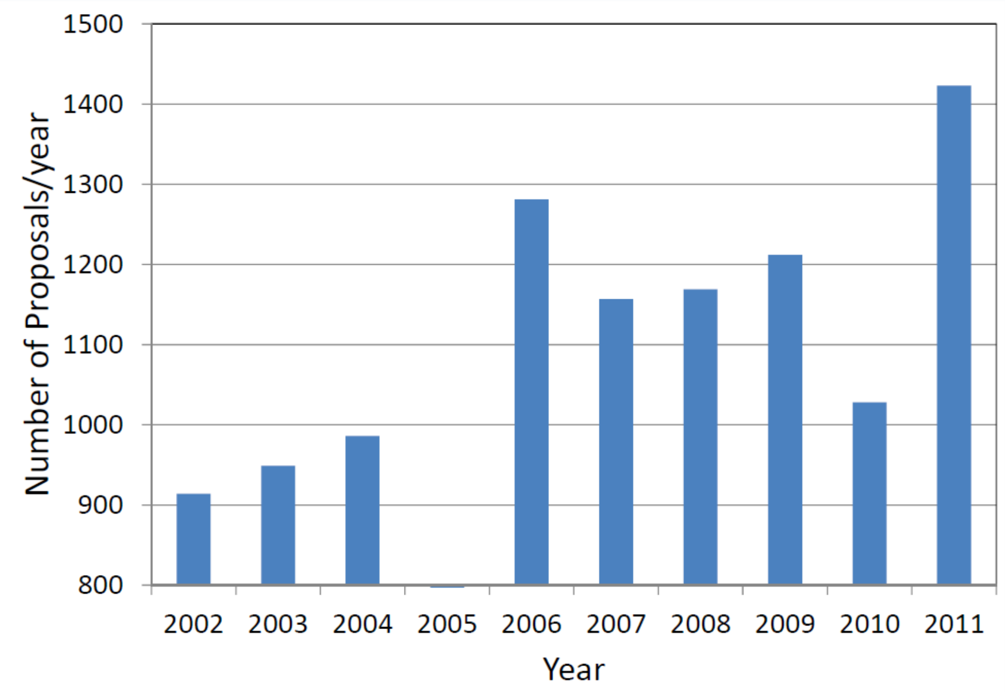
- France, Germany, UK
- Scientific Partners

- Spain	1987
- Switzerland	1988
- Austria	1990
- Russia	1996
- Italy	1997
- Czech Rep	1999
- Sweden, Hungary	2005
- Belgium, Poland	2006
- Slovakia, Denm'k	2009
- India	2011



and hopefully again Russia in the not too far future ….

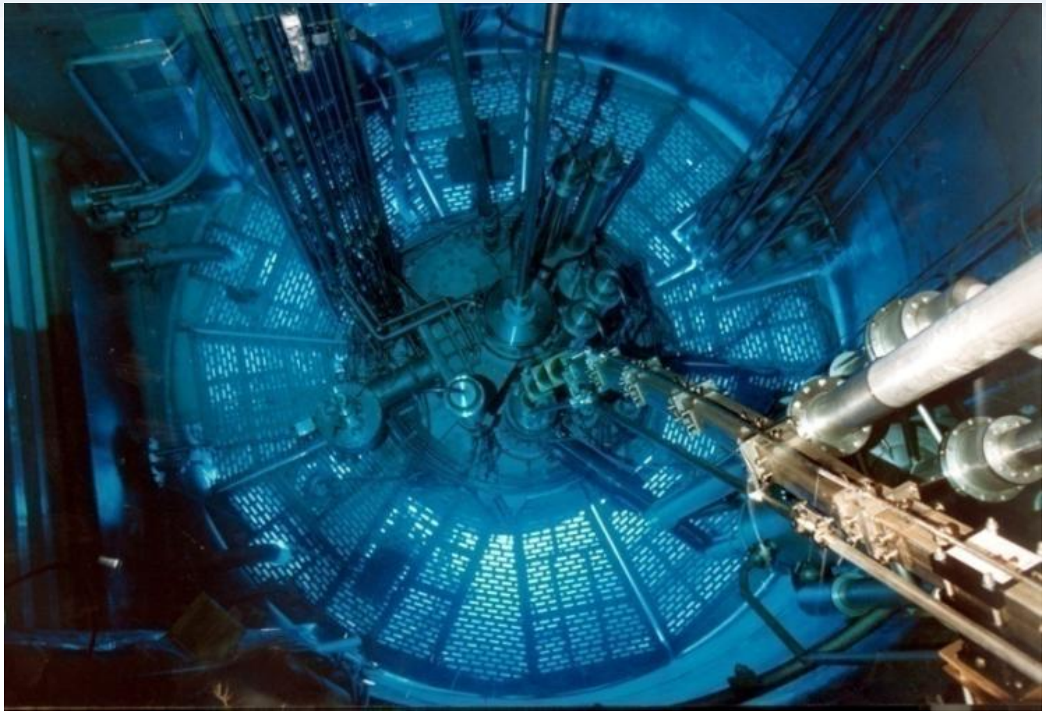
ILL today



- 500 staff
- 4500 users
- 1400 proposals in 2011
- 2000 user visits in 2011
- 800 experimental sessions
- 200 reactor days (> 99% beam)
- 27 (+10) neutron instruments for users (+CRGs)
- 600 refereed scientific publications

Reactor operating schedule...

• 2013-2014	11 months shutdown to perform essential engineering work [post Fukushima]
• Nevertheless...	3 cycles in 2013 and 2.5 in 2014
• 2015-	'Business as usual' with 4 cycles

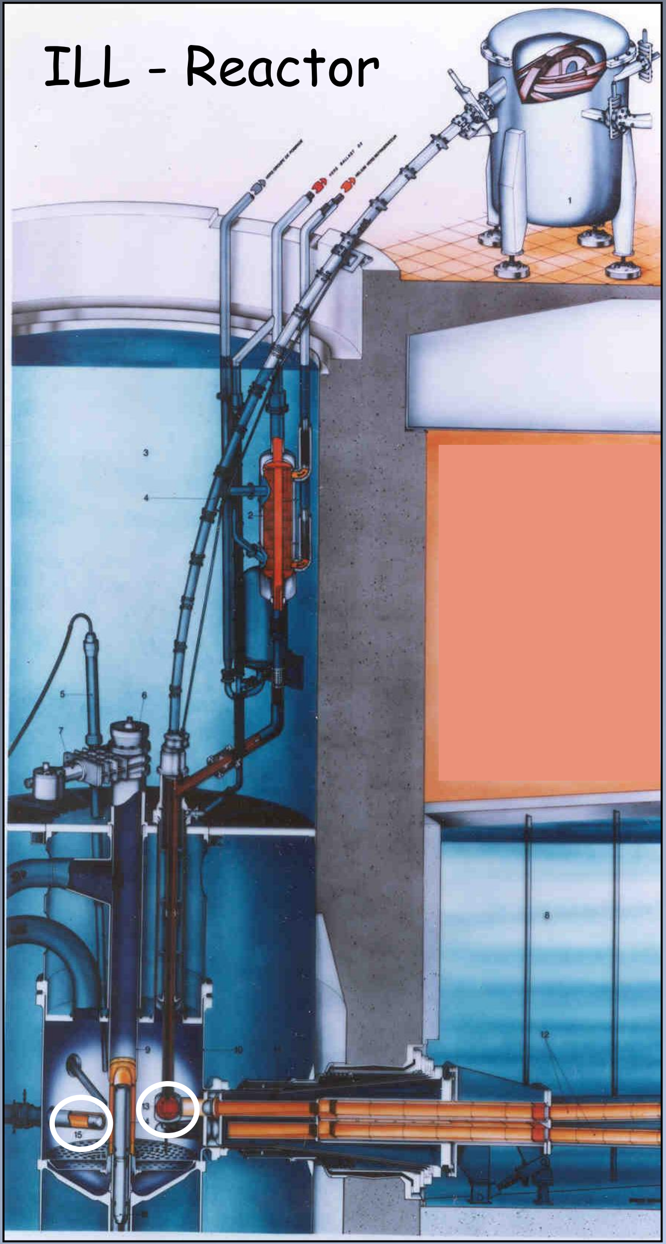


... but

post Fukushima work
also at other nuclear
installations in France required

amongst them
ILL's **fuel element producer!**

Neutron sources at the ILL



ILL - Reactor

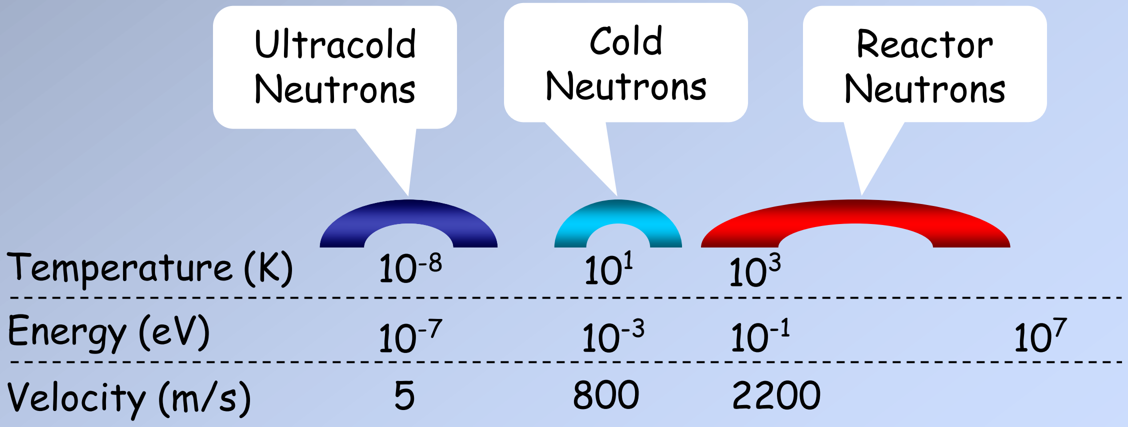
Fuel (chain reaction): $^{235}U(n_{th},f)$ → fission neutrons

Moderator: D_2O at 300K → thermal neutrons

Hot source: 10 dm^3 of graphite at 2400 K

Cold source (horizontal): 6 dm^3 of liquid D_2 at 25 K

Cold source (vertical): 20 dm^3 of liquid D_2 at 25 K



Ultracold Neutrons

Cold Neutrons

Reactor Neutrons

Temperature (K)	10^{-8}	10^{1}	10^{3}	
Energy (eV)	10^{-7}	10^{-3}	10^{-1}	10^{7}
Velocity (m/s)	5	800	2200	

RHF fuel element

Properties of UCN

Ultracold neutrons, that is, neutrons whose energy is so low that they can be contained for long periods of time in material and magnetic bottles

E_{kin} (~ 5 ms^{-1}) = 100 neV (**10^{-7} eV**)

λ_{UCN} ~ 1000 Å

T_{UCN} ~ 2 mK

UCN are totally reflected from suitable materials at *any* angle of incidence, hence **storable**!

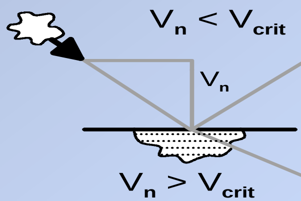
Long storage and observation times possible (up to several minutes)!

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

Interaction with matter:
UCN see a *Fermi-Potential* E_F

E_F ~ **10^{-7} eV** for many materials, e.g.

- beryllium 252 neV
- stainless steel 200 neV



UCN are furthermore storable by gravity and/or magnetic fields

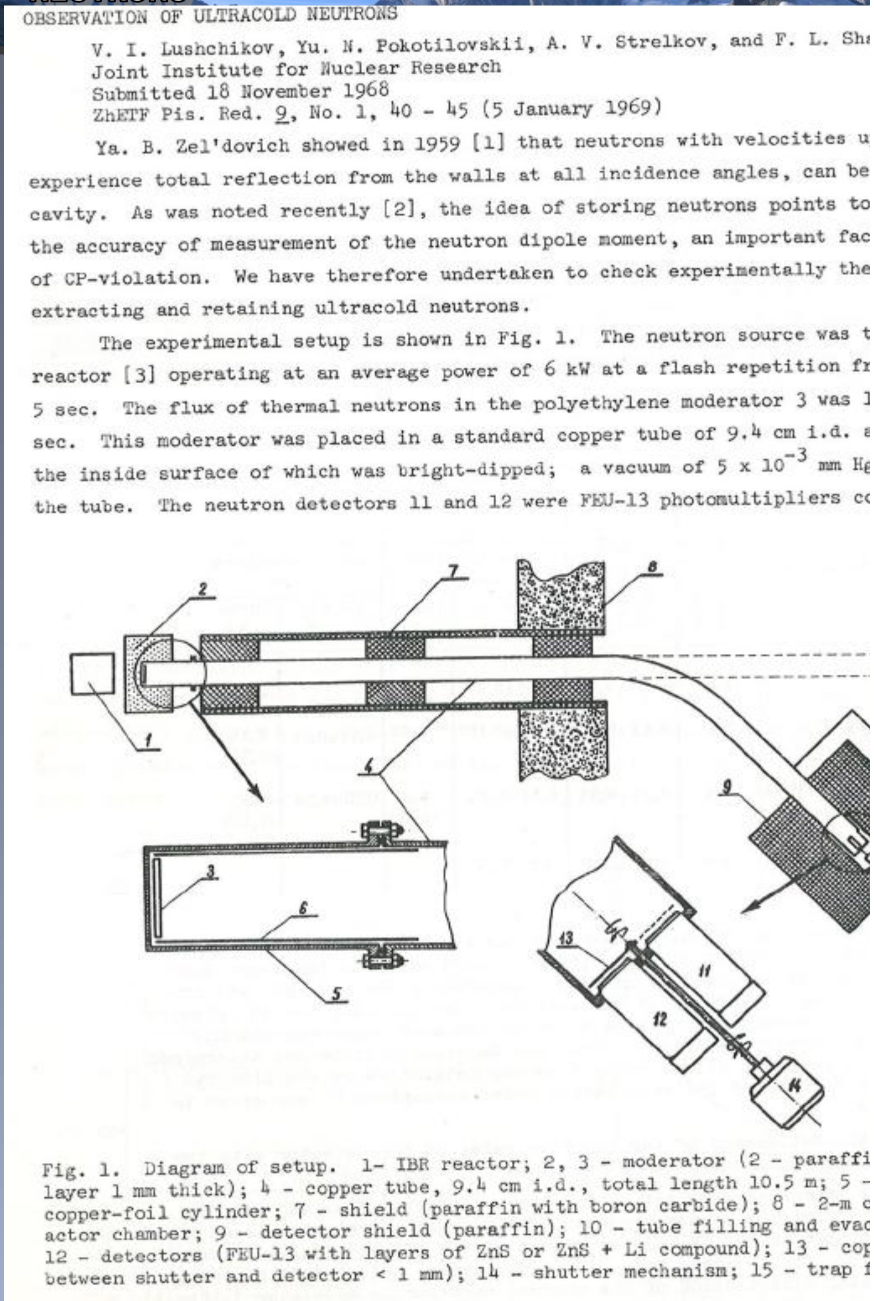
Fermi potential	~ **10^{-7} eV**
Gravity $\Delta E = m_n g \Delta h$	~ **10^{-7} eV** / Meter
Magnetic field $\Delta E = \mu_n B$	~ **10^{-7} eV** / Tesla

Some KEYSTONES in early UCN RESEARCH

1932	Chadwick	discovers the NEUTRON
1936	Fermi	realizes that COHERENT SCATTERING of slow neutrons leads to an EFFECTIVE INTERACTION POTENTIAL V with $V > 0$ (or index of refraction < 1) for most materials
~1940	Fermi	realizes TOTAL REFLECTION for neutrons with $E\cdot\sin^2\Theta <= V$ or $\sin\Theta <= \sin\Theta_c = (V/E)^{\frac{1}{2}}$
1946/47	Fermi & collaborators	demonstrate TOTAL REFLECTION (basis for n guides) led to speculations: if $E \leq V$ then STORABLE
1959	Zel'dovich	put it into print, estimates absorption times and densities (~$50\,\mathrm{cm}^{-3}$!)
1961	Vladimirski	suggests vertical extraction
1963	Doroshkevich	suggests berillyium and estimates the loss rates (as a function of temperatrure) due to wall vibrations $\leq 10^{-7}\,\mathrm{s}^{-1}$
1966	Steyerl	proposes a neutron turbine for $10^{-8} \leq E \leq 10^{-9}\,\mathrm{eV}$
1968	Shapiro	proposes to measure neutron EDM with UCN
1969	Shapiro et al., Steyerl	independently extract and measure UCN
1974	Steyerl	realizes "his" turbine

“Iron Curtain”

UCN discovery (independently on both sides of the Iron Curtain)



OBSERVATION OF ULTRACOLD NEUTRONS

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

Ya. B. Zel'dovich showed in 1959 [1] that neutrons with velocities u
experience total reflection from the walls at all incidence angles, can be
cavity. As was noted recently [2], the idea of storing neutrons points to
the accuracy of measurement of the neutron dipole moment, an important fac
of CP-violation. We have therefore undertaken to check experimentally the
extracting and retaining ultracold neutrons.

The experimental setup is shown in Fig. 1. The neutron source was t
reactor [3] operating at an average power of 6 kW at a flash repetition fr
5 sec. The flux of thermal neutrons in the polyethylene moderator 3 was 1
sec. This moderator was placed in a standard copper tube of 9.4 cm i.d. a
the inside surface of which was bright-dipped; a vacuum of 5 x 10^{-3} mm Hg
the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers co

Fig. 1. Diagram of setup. 1- IBR reactor; 2, 3 - moderator (2 - paraffi
layer 1 mm thick); 4 - copper tube, 9.4 cm i.d., total length 10.5 m; 5 -
copper-foil cylinder; 7 - shield (paraffin with boron carbide); 8 - 2-m c
actor chamber; 9 - detector shield (paraffin); 10 - tube filling and evac
12 - detectors (FEU-13 with layers of ZnS or ZnS + Li compound); 13 - cop
between shutter and detector < 1 mm); 14 - shutter mechanism; 15 - trap f

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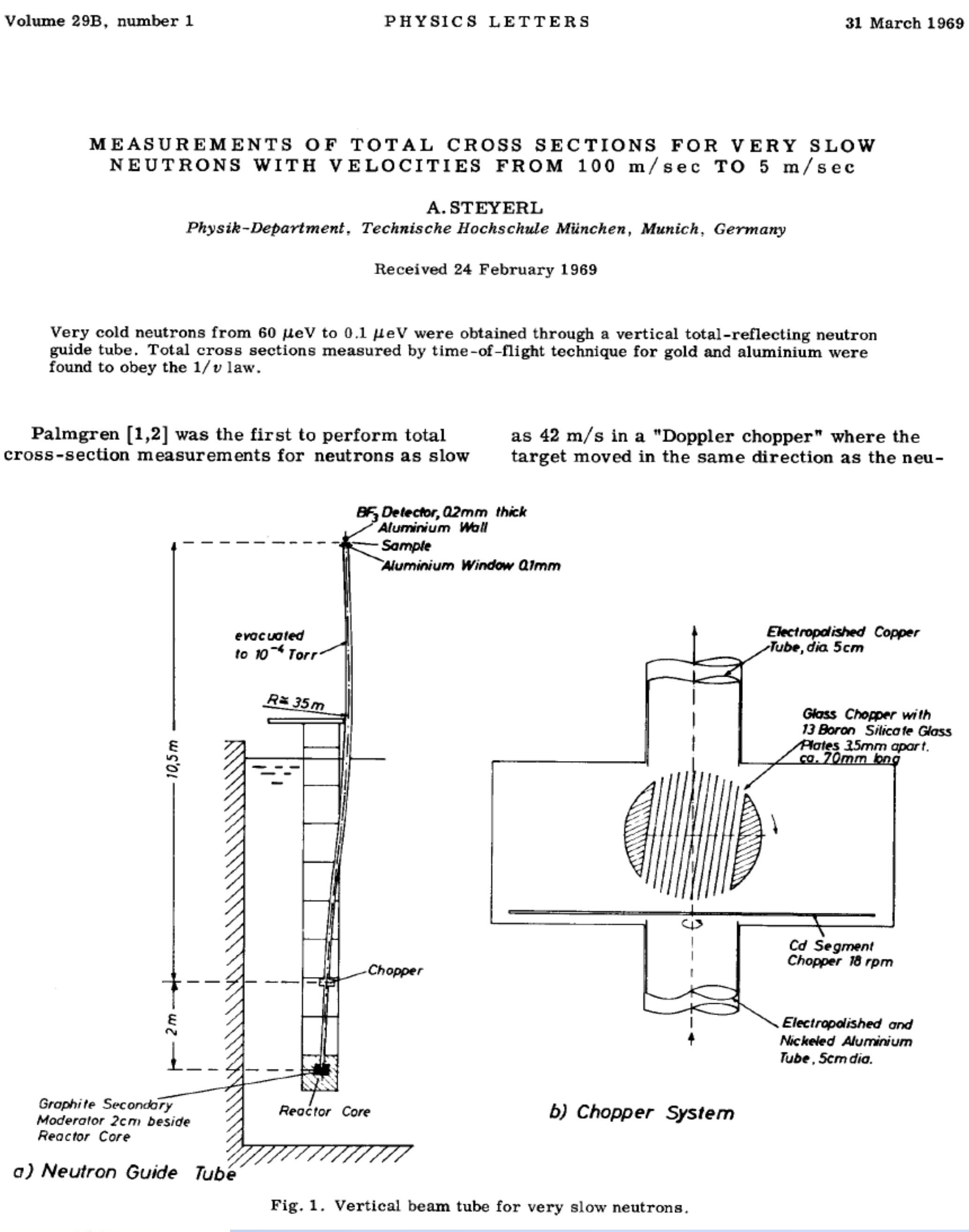


Volume 29B, number 1 PHYSICS LETTERS 31 March 1969

MEASUREMENTS OF TOTAL CROSS SECTIONS FOR VERY SLOW NEUTRONS WITH VELOCITIES FROM 100 m/sec TO 5 m/sec

A. STEYERL
Physik-Department, Technische Hochschule München, Munich, Germany

Received 24 February 1969

Very cold neutrons from 60 μeV to 0.1 μeV were obtained through a vertical total-reflecting neutron guide tube. Total cross sections measured by time-of-flight technique for gold and aluminium were 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-

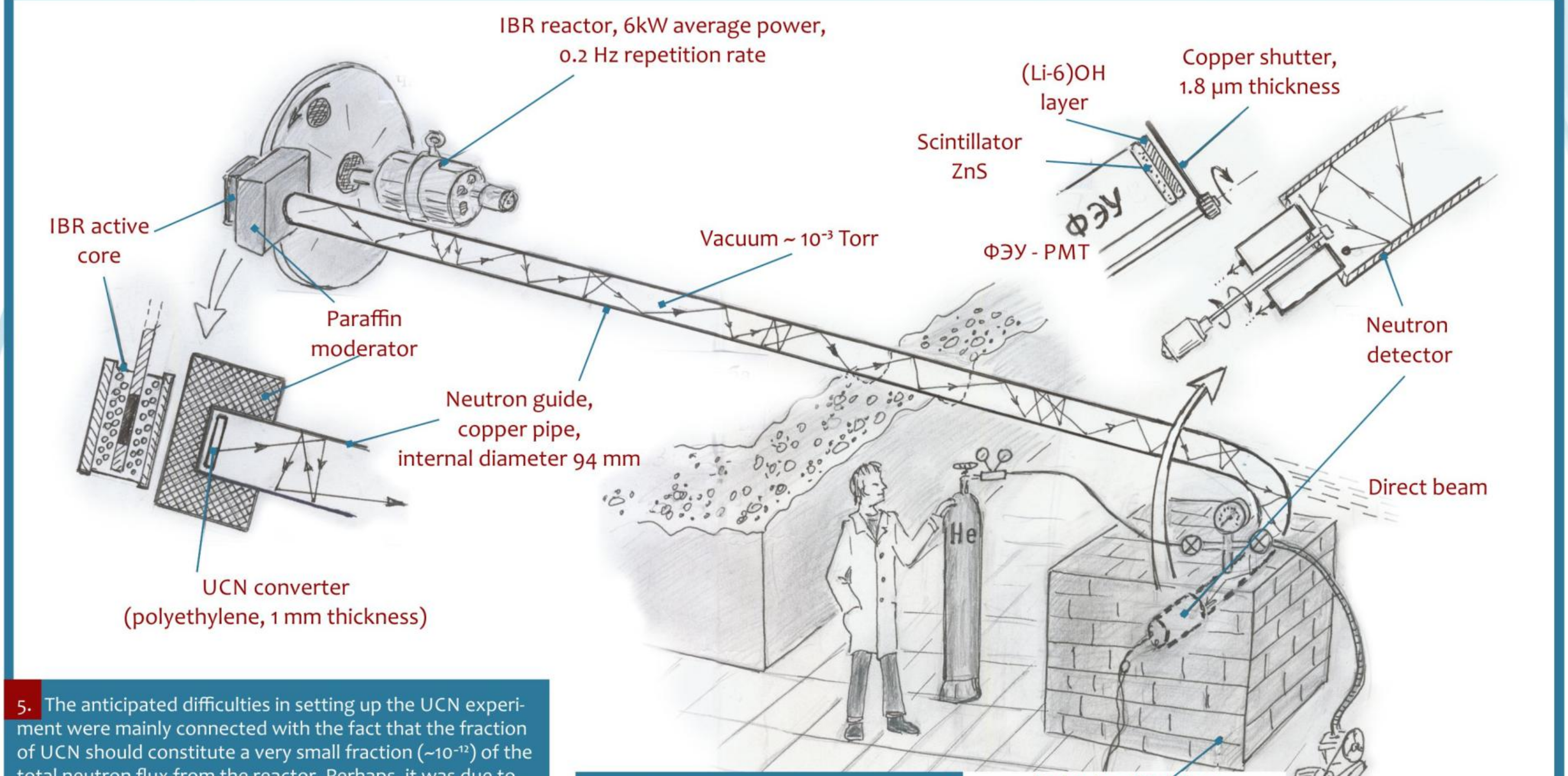
Fig. 1. Vertical beam tube for very slow neutrons.

nomenon of "bottle with neutrons" as a funny and useless.

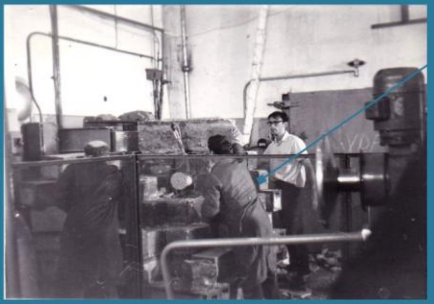
order to significantly increase the sensitivity of the experiment searching for the neutron EDM.

how UCN were “really” discovered in Dubna

drawing courtesy of A. Strelkov



5. The anticipated difficulties in setting up the UCN experiment were mainly connected with the fact that the fraction of UCN should constitute a very small fraction (~10^{-12}) of the total neutron flux from the reactor. Perhaps, it was due to disbelief in the success of the UCN experiment by the eminent physicists working at powerful reactors that prevented them from accepting Shapiro's proposal. Thus, Shapiro was left no other option but to set up the UCN experiment at a low-power IBR reactor in Dubna, where the UCN flux was expected to be a thousand times lower than at a typical stationary reactor. Besides, the approaching date of the IBR shutdown for reconstruction determined the pace of the experiment. Despite the “holiday season” (July-August) Shapiro managed to bring together a group of participants that, under his leadership, in one month built a set-up and ran an experiment, in which for the first time they observed a phenomenon of slow neutron retention caused by successive multiple reflections of neutrons from

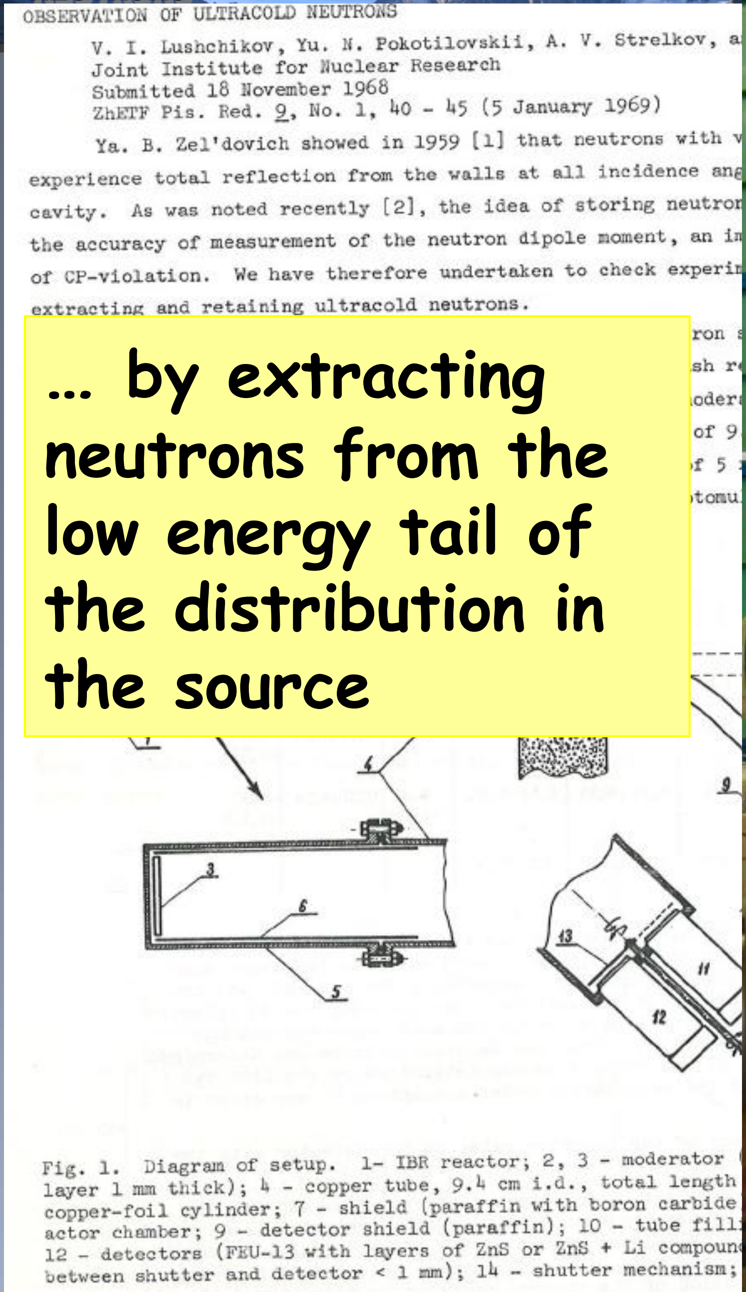


Lushchikov V.I., Negovelov S.I. , Pokotilovski Yu.N.

6. The following experimental results proved the observation of UCN:

1. The detector counting rate decreased by 3 times, when it was closed with a thin shutter made of the same material as the vessel walls. The shutter is almost transparent to neutrons with velocities slightly exceeding the boundary speed of the shutter. However, it should totally reflect the neutrons with velocities

UCN discovery



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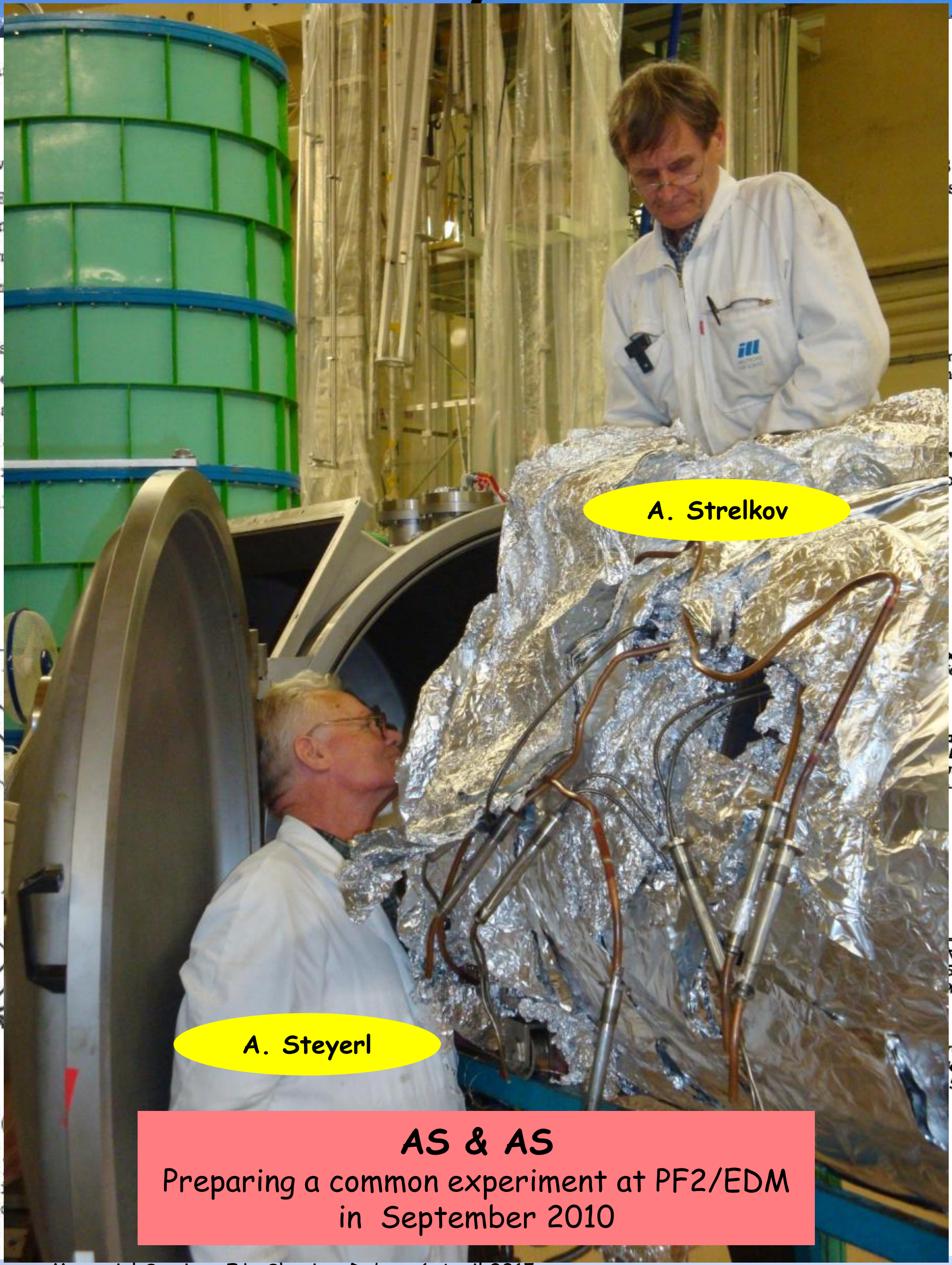
... by extracting neutrons from the low energy tail of the distribution in the source



A. Strelkov

A. Steyerl

AS & AS
Preparing a common experiment at PF2/EDM
in September 2010

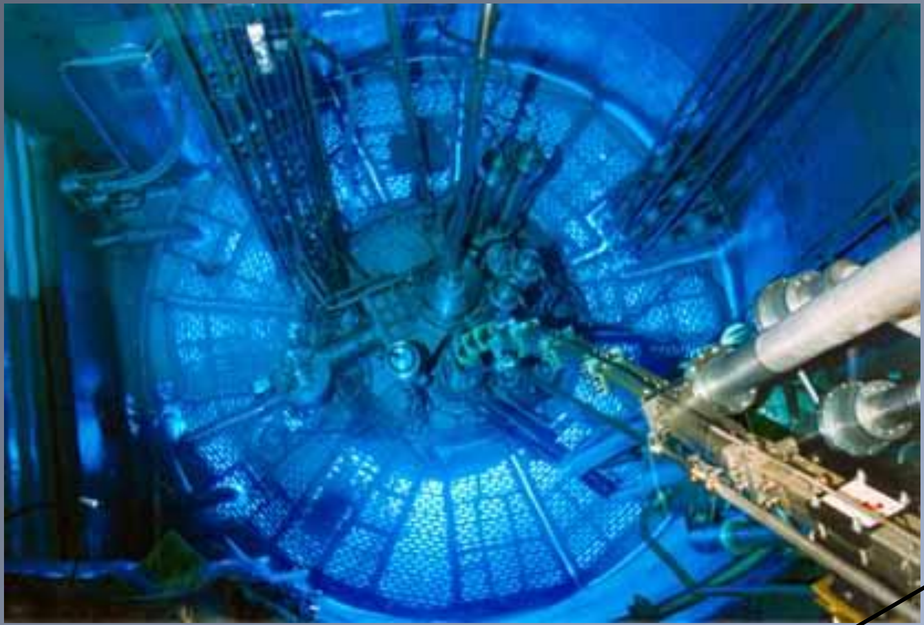
31 March 1969

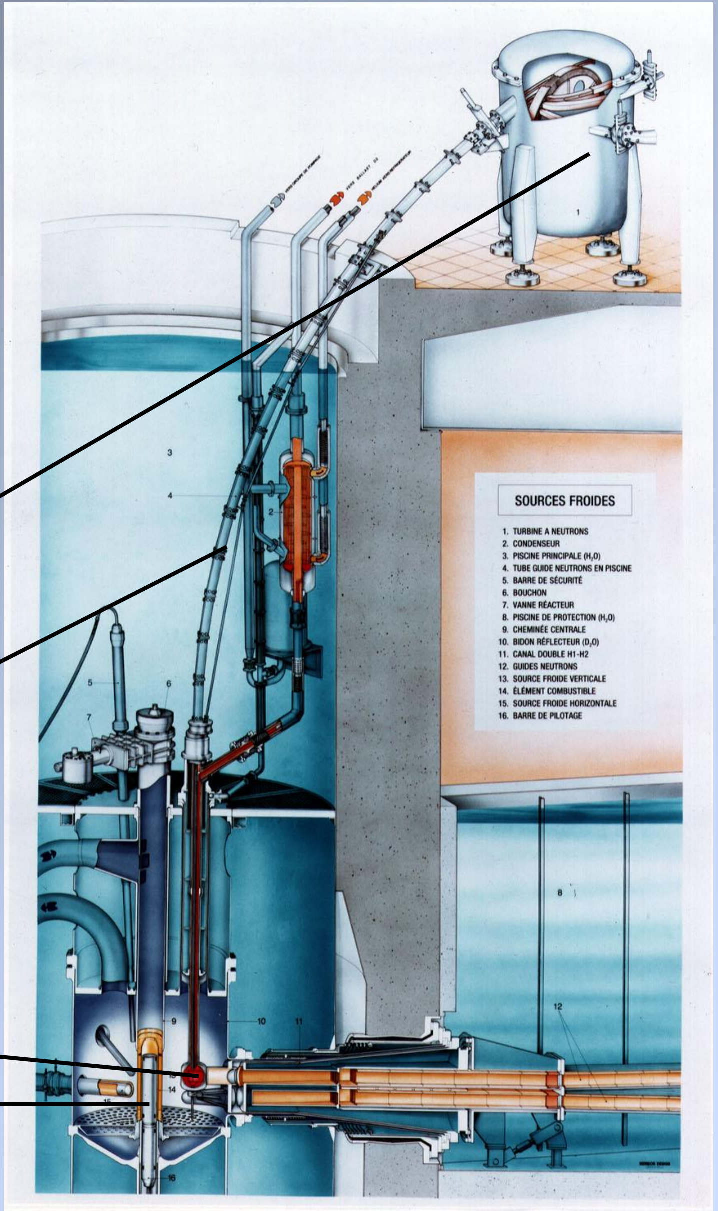
LOW
sec

neutron
were

where the
n as the neu-

The UCN/VCN facility PF2





Neutron turbine
A. Steyerl (TUM - 1985)

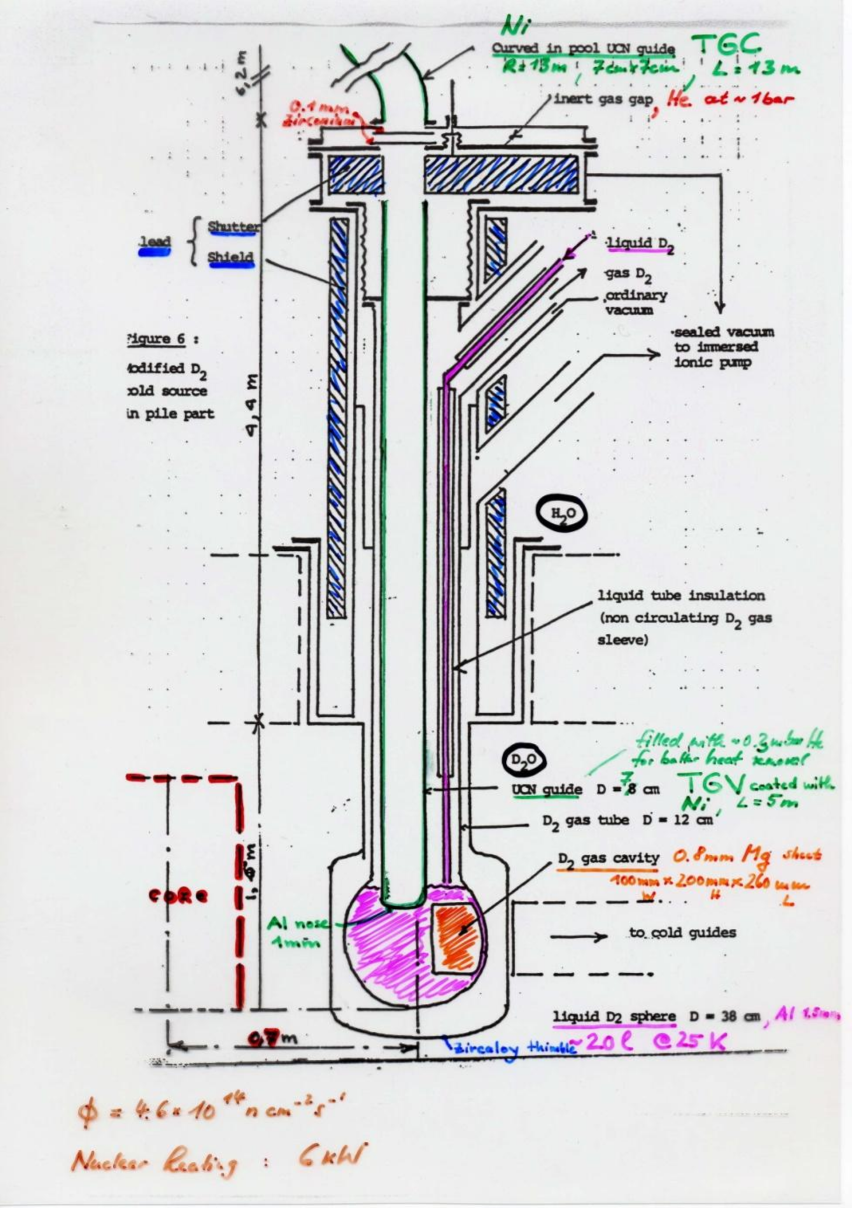
Vertical guide tube

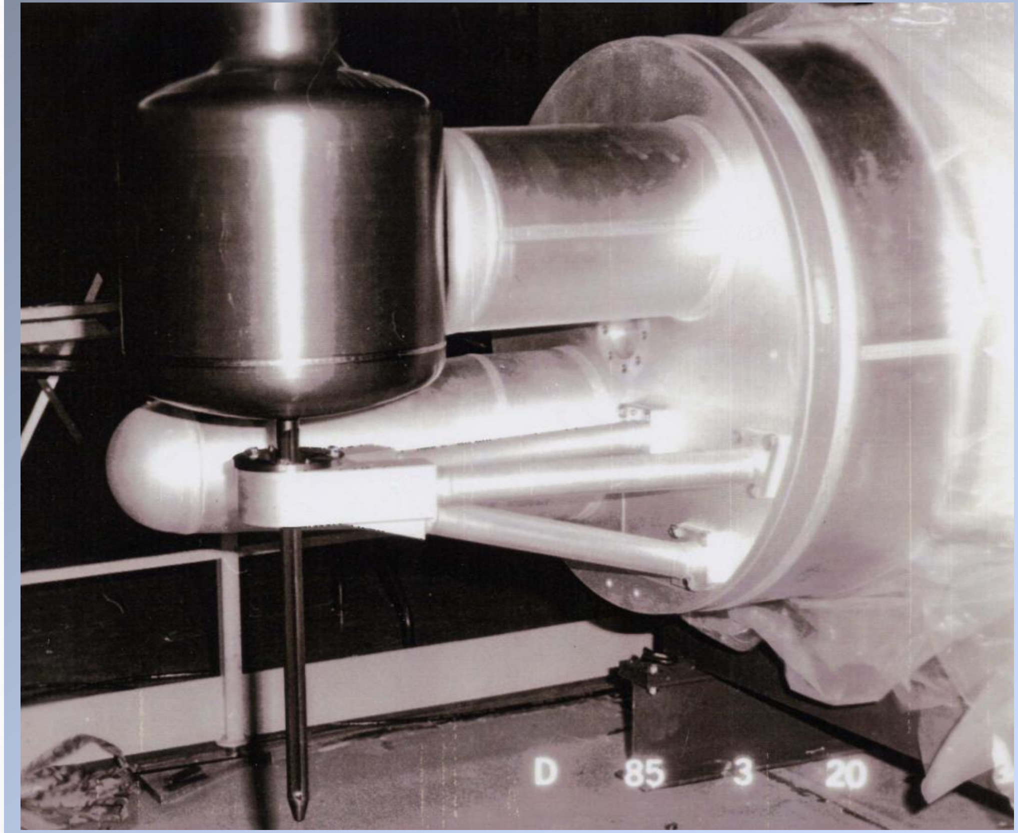
Cold source

Reactor core

A. Steyerl et al., Phys. Lett. A116 (1986) 347

The Vertical Cold Source (VCS)





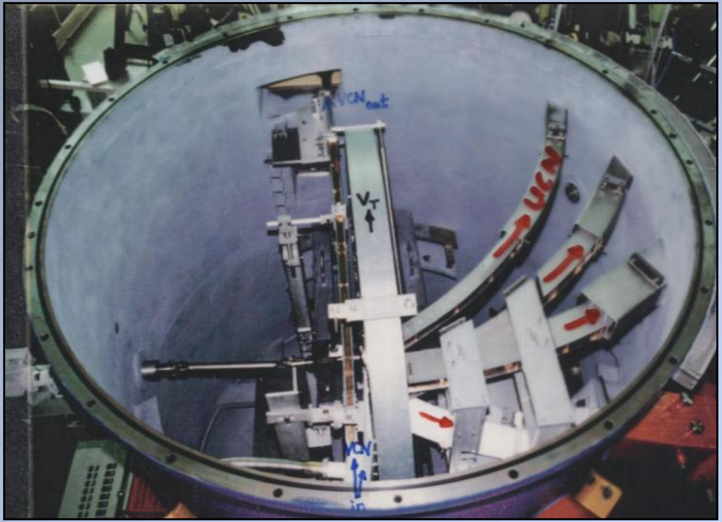
P. Ageron, NIMA284 (1989) 197 (1986) 347

Generating Ultracold Neutrons (UCN)

“Steyerl turbine”

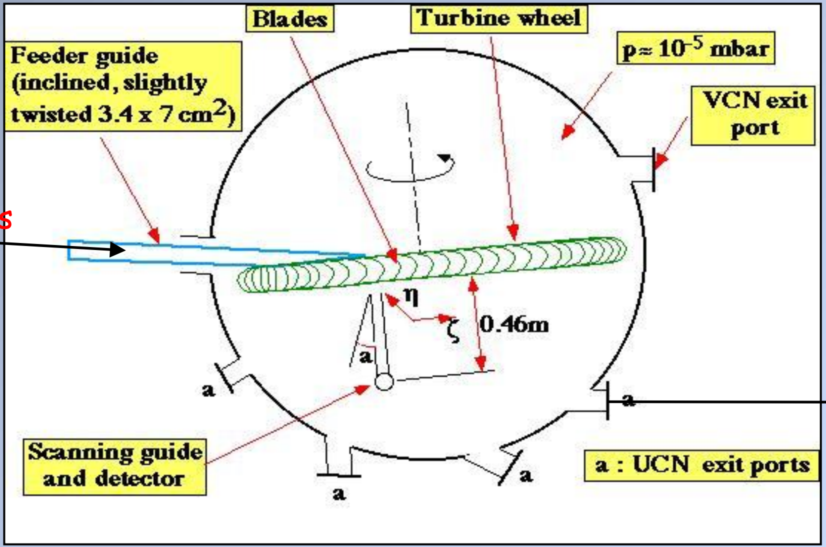
Doppler shifting device

Steyerl turbine
at FRM-I (Munich)

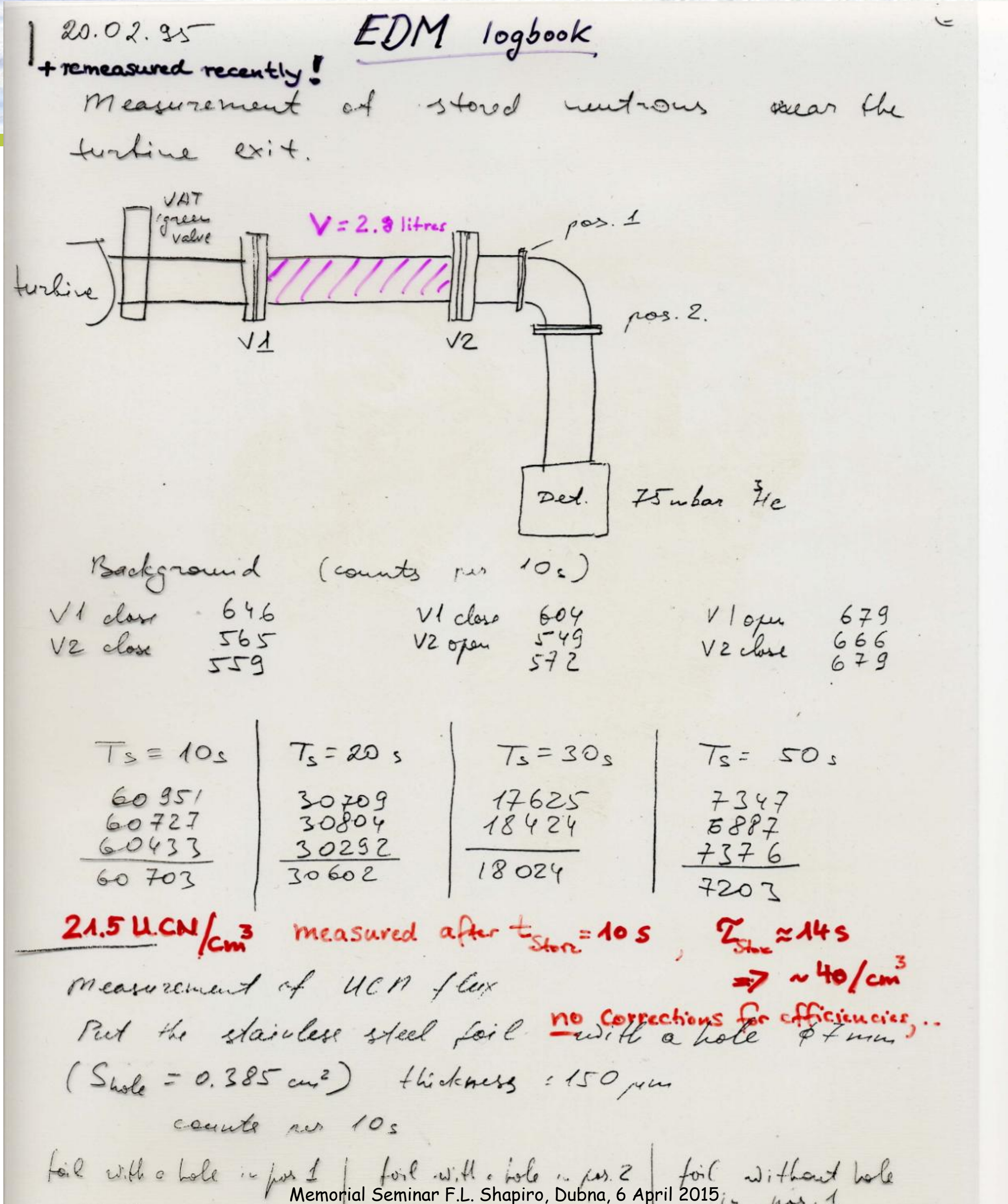


Steyerl turbine (2nd generation)
at PF2 / ILL
10 years later

Very cold neutrons



Ultracold neutrons



20.02.95

+ remeasured recently!

EDM logbook

Measurement of stored neutrons near the turbine exit.

Background (counts per 10s)

V1 close V2 close	646 565 559	V1 close V2 open	604 549 572	V1 open V2 close	679 666 679

$T_s = 10s$	$T_s = 20s$	$T_s = 30s$	$T_s = 50s$
60951	30709	17625	7347
60727	30804	18424	5887
60433	30292		7376
60703	30602	18024	7203

21.5 UCN/cm³ measured after $t_{Store} = 10\,s$, $\tau_{Store} \approx 14\,s$

$\Rightarrow \sim 40/cm^3$

no corrections for efficiencies, ..

Measurement of UCN flux

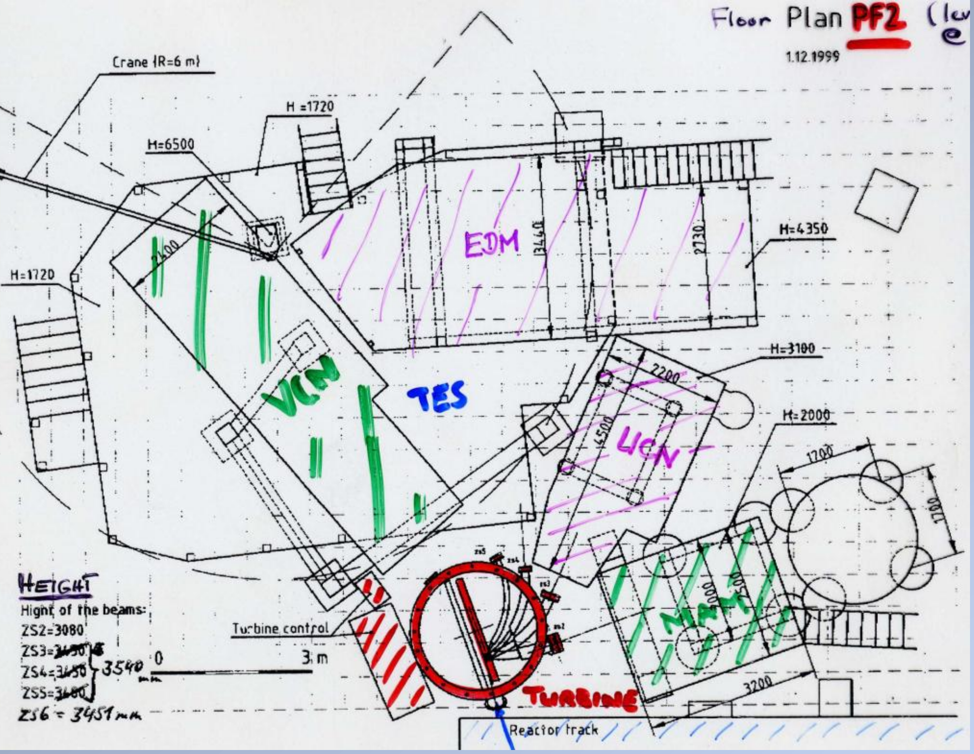
Put the stainless steel foil with a hole ϕ7mm

($S_{hole} = 0.385\,cm^2$) thickness : 150 μm

counts per 10s

foil with a hole in pos 1 | foil with a hole in pos. 2 | foil without hole

The PF2 beam facility



PF2: **P**hysique **F**ondamentale **2**

2nd installation for fundamental physics

4 positions for Ultracold Neutrons (UCN)

- *MAM*
- *EDM*
- *UCN*

was :

$v = 5\ \mathrm{ms}^{-1}$

$\rho = \sim 50\ \mathrm{cm}^{-3}$ (at the experiment)

is :

$v <= 7\ \mathrm{ms}^{-1}$

$\rho = \sim 20\ \mathrm{cm}^{-3}$ (at the experiment)

- *TES*

1 position for Very Cold Neutrons (VCN)

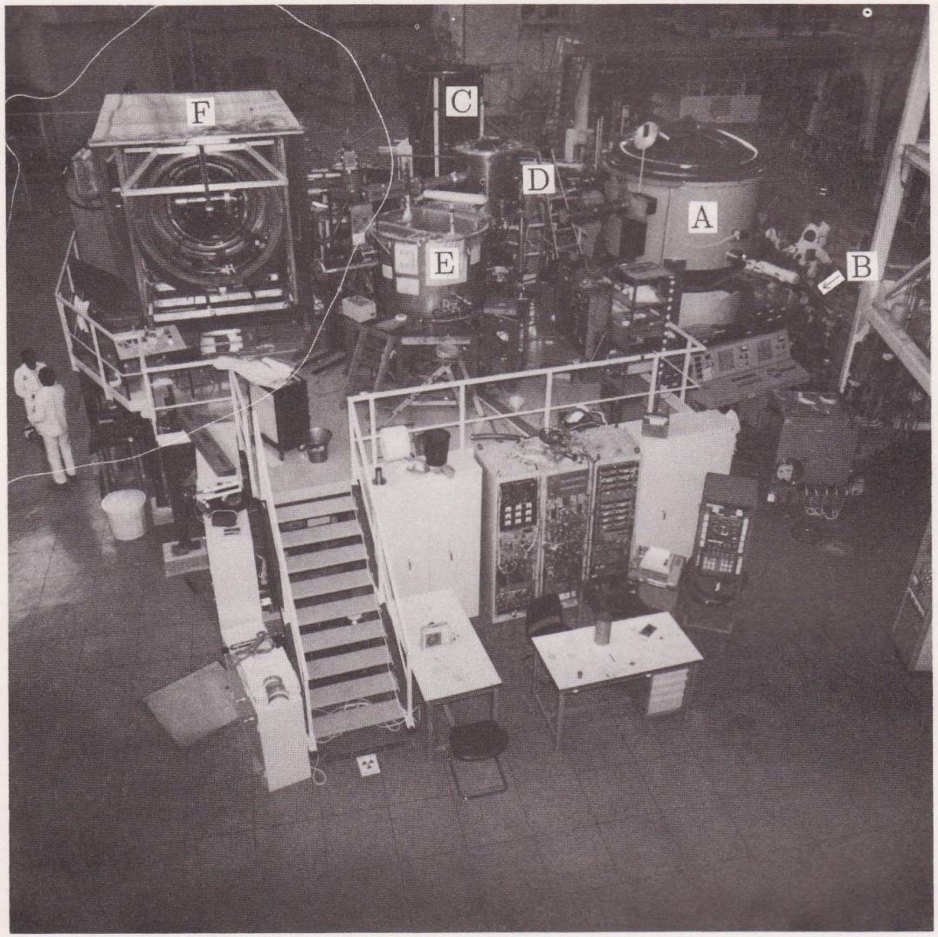
- *VCN beam*

$v = 50\ \mathrm{ms}^{-1}$

$\Phi = 10^{8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

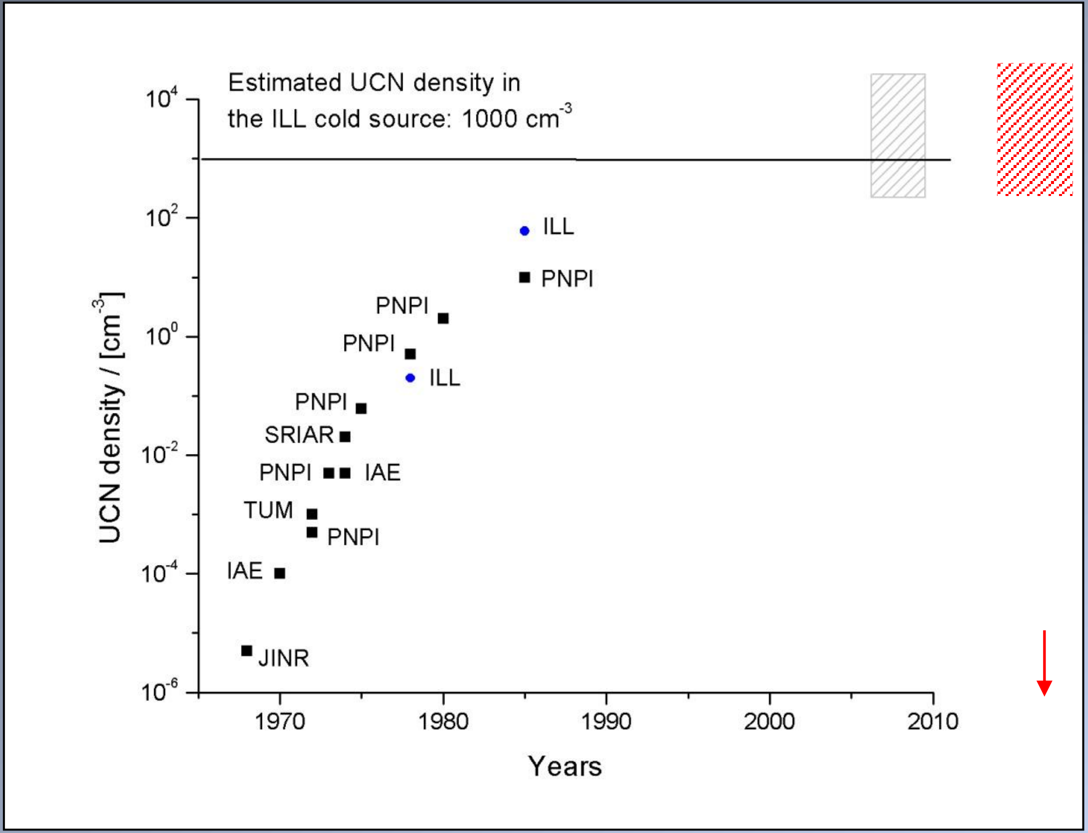
W. Drexel, Neutron News 1 (1990) 23

Level D (now PF2) at the end of the 80s and today



The ultra-cold neutron (UCN) platform at the Institut Laue-Langevin, Grenoble.
Neutrons produced in the reactor core at a lower level enter the neutron turbine (A) through the curved guide tube (B). After reflection from the moving turbine blades, the neutrons (now slowed to UCN energies) can be distributed to various experimental installations: (C) UCN microscope; (D) fluid walled bottle for measurement of the neutron lifetime; (E) apparatus for a neutron lifetime measurement using magnetic storage; (F) the electric dipole moment experiment is seen with one end of the five-layer magnetic shield removed.

UCN facilities – Status and Future



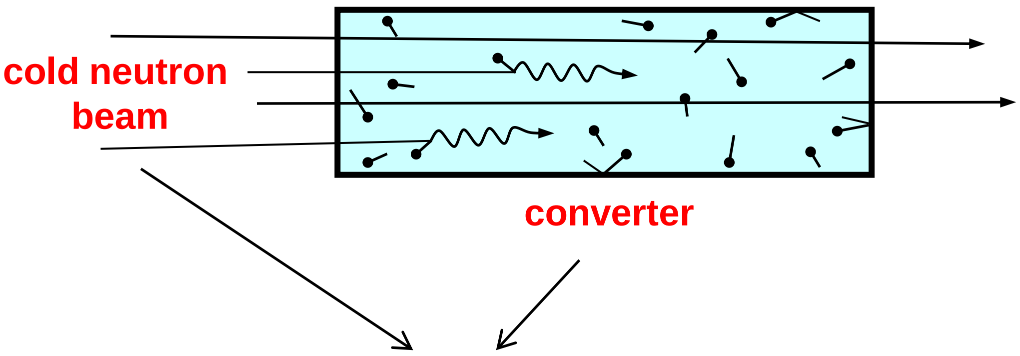
More and stronger UCN facilities in the future worldwide

- **PSI (CH)**
- **Mainz / Munich (D)**
- **ILL (F)**
- **LANL / NIST / SNS / NCSU (USA)**
- **RCNP (J) then TRIUMF (Canada)**
  JPARC (J)
- **PNPI (RUS)**

UCN production in superfluid helium

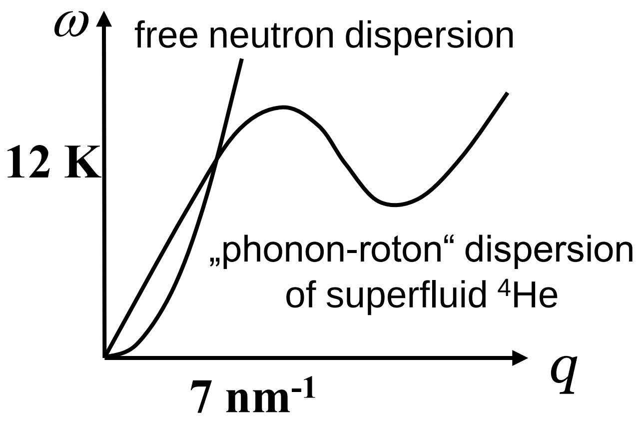
R. Golub, J.M. Pendlebury, PL **53A** (1975) 133

$\sigma_{capture}(^4He) = 0$



cold neutron beam

converter



$$\rho_{UCN} = P\tau$$

$$\tau^{-1} = \tau^{-1}_{decay} + \tau^{-1}_{upscattering} + \tau^{-1}_{capture} + \tau^{-1}_{wall\ losses}$$

- $\tau \approx 800$ s (upscattering @0.5 K and decay)
- $P = 28$ cm^{-3}s^{-1} from 0.9nm flux $\Phi^* = 5.7\times10^9$/cm²snm in direct beam H172

$\rho_{UCN} \rightarrow 10^4$ cm^{-3} possible at cold-neutron guide

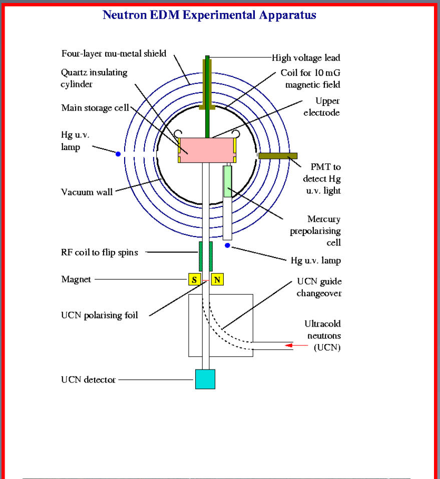
Comparison PF2 - SuperSUN

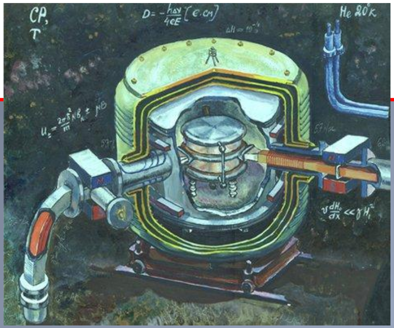
	PF2	SuperSUN
UCN density [cm^{-3}]	**20**	**> 1000**
Total UCN flux [s^{-1}]	**5×10^{5}**	**≤ 5×10^{5}**

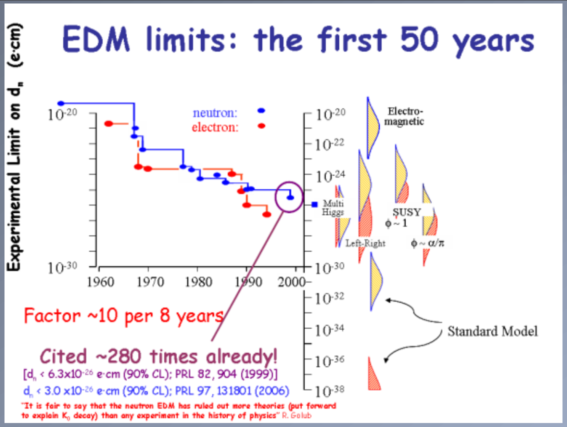
- PF2 stays world-best high-current UCN source, if not outperformed by new sources elsewhere

- SuperSUN will serve experiments using UCN in storage mode with small-to-medium size storage vessels (e.g. nEDM, neutron decay, gravitational levels)

Flagship experiments at PF2







EDM limits: the first 50 years

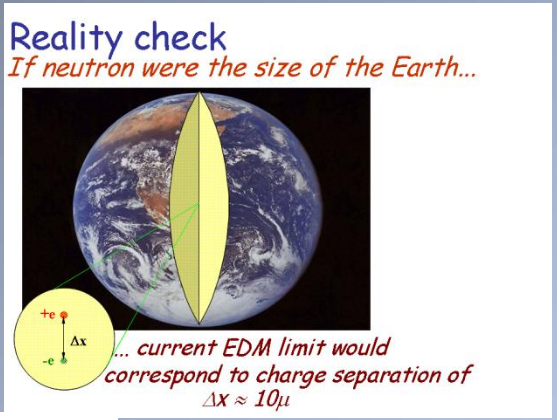
Factor ~10 per 8 years

Cited ~280 times already!

[$d_n < 6.3 \times 10^{-26}$ e·cm (90% CL); PRL 82, 904 (1999)]

$d_n < 3.0 \times 10^{-26}$ e·cm (90% CL); PRL 97, 131801 (2006)

"It is fair to say that the neutron EDM has ruled out more theories (put forward to explain K_0 decay) than any experiment in the history of physics" R. Golub

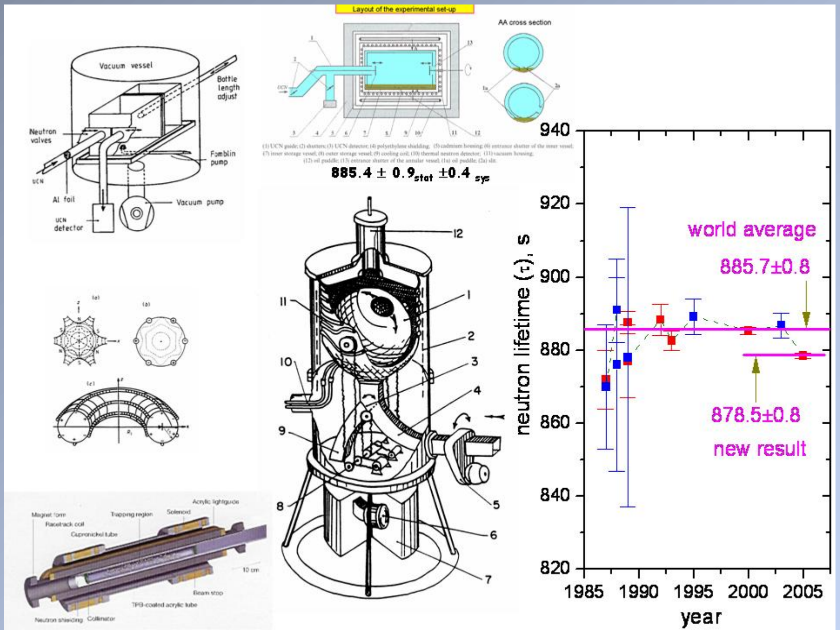


Reality check

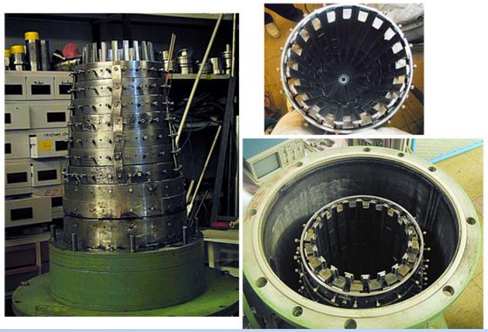
If neutron were the size of the Earth...

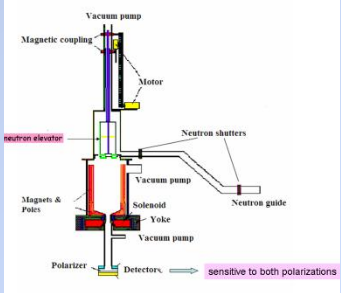
... current EDM limit would correspond to charge separation of

$\Delta x \approx 10\mu$



UCN storage trap made of permanent magnets





Discovery of the ground state

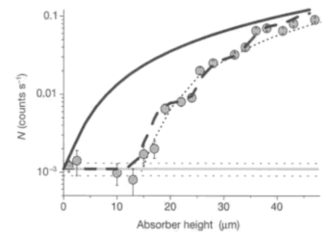
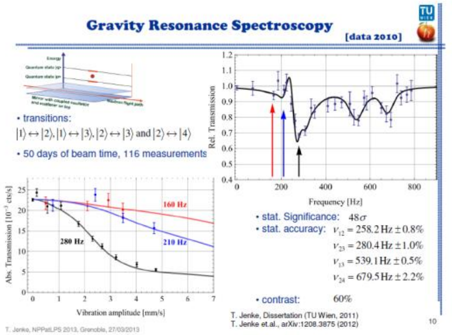


Figure 4 The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 μm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental data. The solid curve is again the full classical treatment. The dotted line is a truncated fit in which it is assumed that only the lowest quantum state—which leads to the first step—exists.

V.V. Nesvizhevsky et al.,
Nature **415** (2002) 297;
Phys Rev **D67** (2003) 102002



Gravity Resonance Spectroscopy [data 2010]

- transitions:
$|1\rangle \leftrightarrow |2\rangle, |1\rangle \leftrightarrow |3\rangle, |2\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |4\rangle$
- 50 days of beam time, 116 measurements

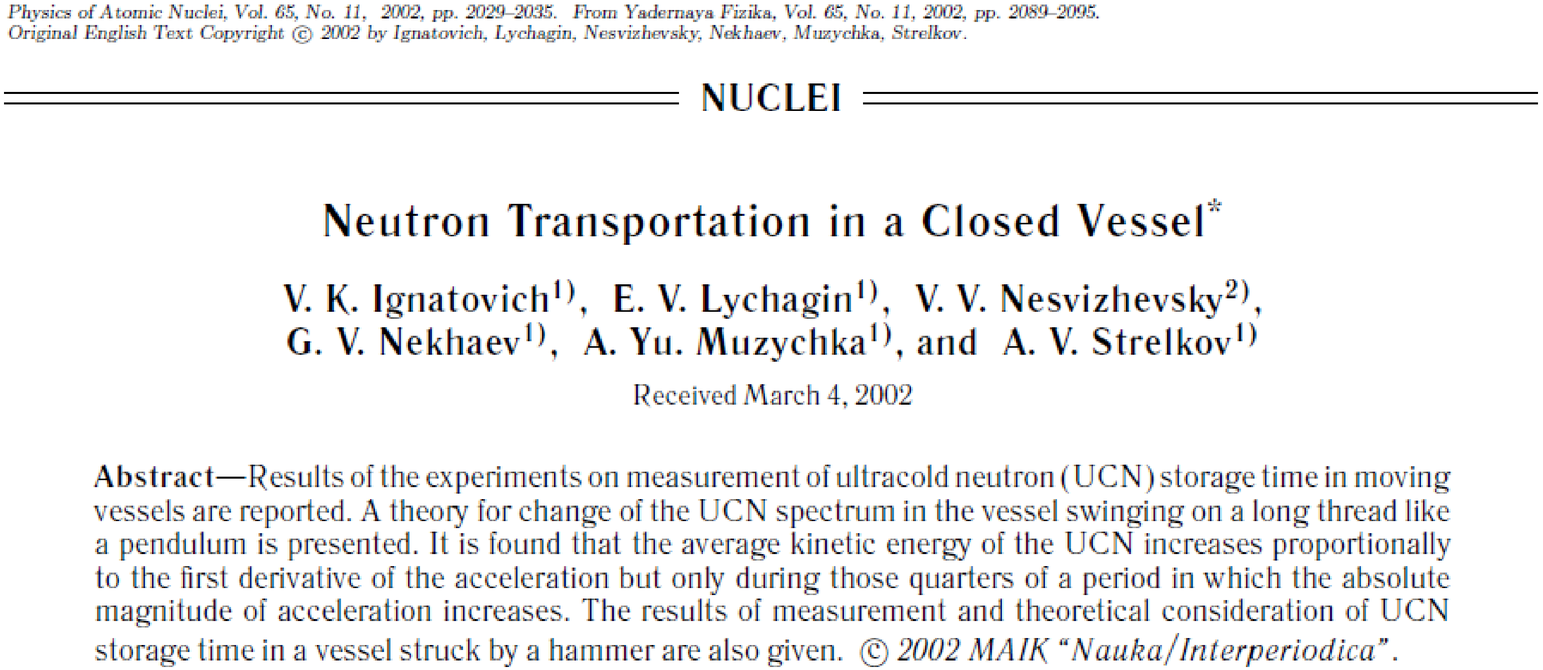
- stat. Significance: 48σ
- stat. accuracy: $\nu_{12} = 258.2\,\text{Hz} \pm 0.8\%$
$\nu_{23} = 280.4\,\text{Hz} \pm 1.0\%$
$\nu_{13} = 539.1\,\text{Hz} \pm 0.5\%$
$\nu_{24} = 679.5\,\text{Hz} \pm 2.2\%$
- contrast: 60%

T. Jenke, Dissertation (TU Wien, 2011)
T. Jenke et.al., arXiv:1208.3875 (2012)

T. Jenke, NPPatLPS 2013, Grenoble, 27/03/2013

10

… based on publ. in 1999 on “Dynamical converter at pulsed sources” (A. Stoica’s talk)



Physics of Atomic Nuclei, Vol. 65, No. 11, 2002, pp. 2029–2035. From Yadernaya Fizika, Vol. 65, No. 11, 2002, pp. 2089–2095.
Original English Text Copyright © 2002 by Ignatovich, Lychagin, Nesvizhevsky, Nekhaev, Muzychka, Strelkov.

NUCLEI

Neutron Transportation in a Closed Vessel*

V. K. Ignatovich(1), E. V. Lychagin(1), V. V. Nesvizhevsky(2),
G. V. Nekhaev(1), A. Yu. Muzychka(1), and A. V. Strelkov(1)

Received March 4, 2002

Abstract—Results of the experiments on measurement of ultracold neutron (UCN) storage time in moving vessels are reported. A theory for change of the UCN spectrum in the vessel swinging on a long thread like a pendulum is presented. It is found that the average kinetic energy of the UCN increases proportionally to the first derivative of the acceleration but only during those quarters of a period in which the absolute magnitude of acceleration increases. The results of measurement and theoretical consideration of UCN storage time in a vessel struck by a hammer are also given. © *2002 MAIK “Nauka/Interperiodica”*.

This is a toy science, and we dedicate it to the
jubilee of the very serious scientist Yu.G. Abov.
We hope that he will enjoy it.

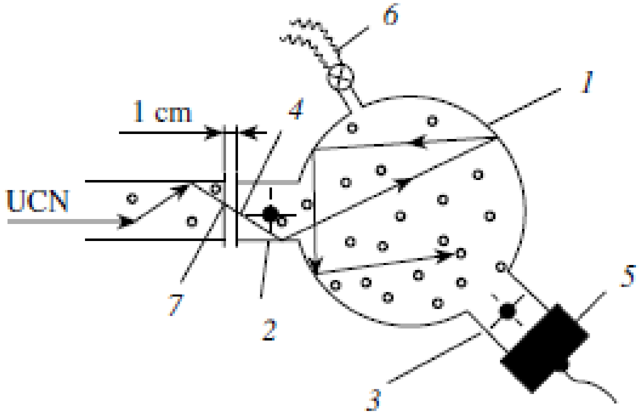
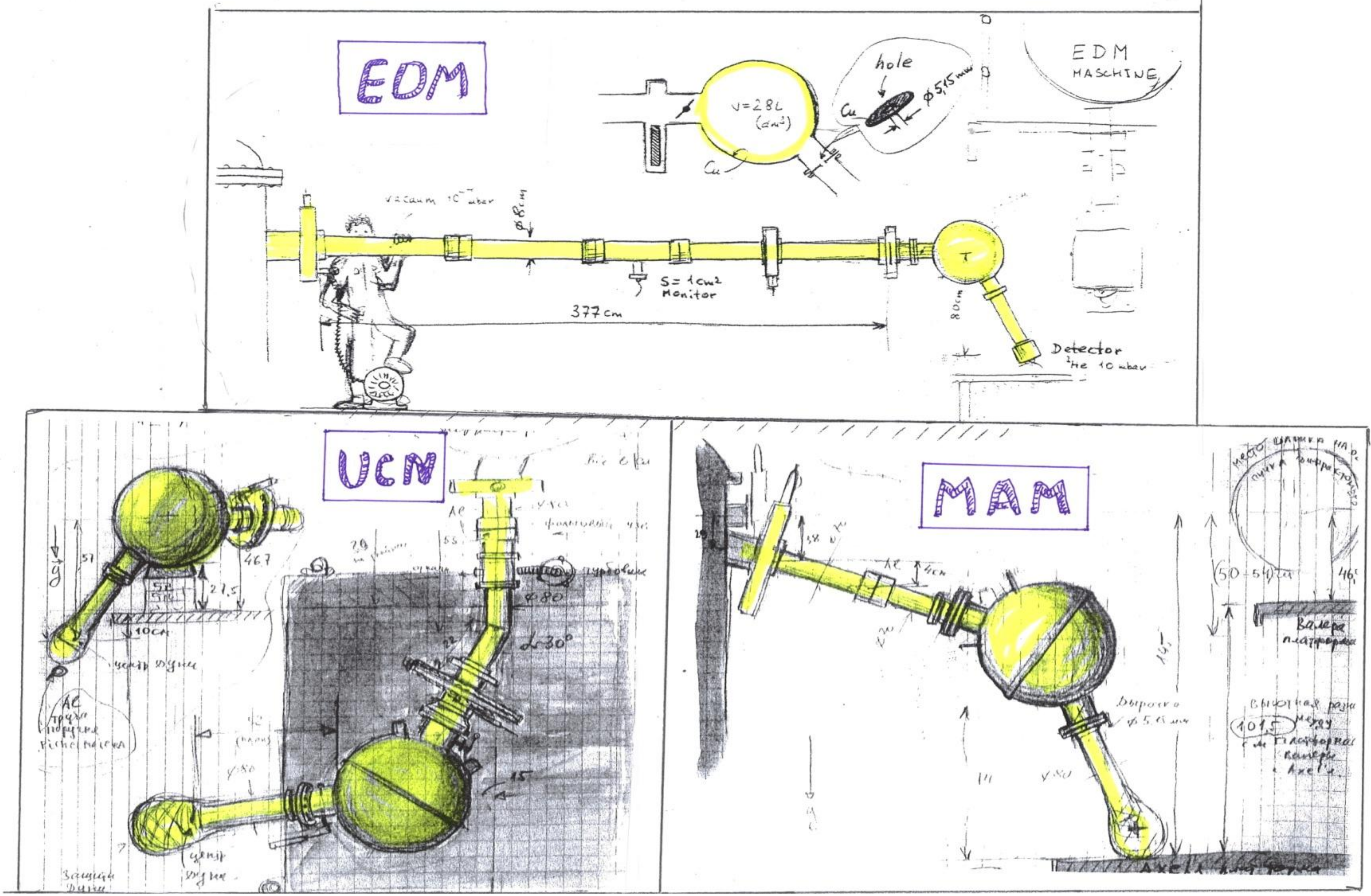


Fig. 1. Scheme of the experiment: (1) container, (2) entrance, (3) exit, (4) entrance window, (5) detector, (6) vacuum tube, and (7) Al foil.

Neutron Transport (Cu sphere as UCN container)

drawing (log book on UCN flux measurements at different beam positions of PF2) **courtesy of A. Strelkov**



Neutron Transport (Results)

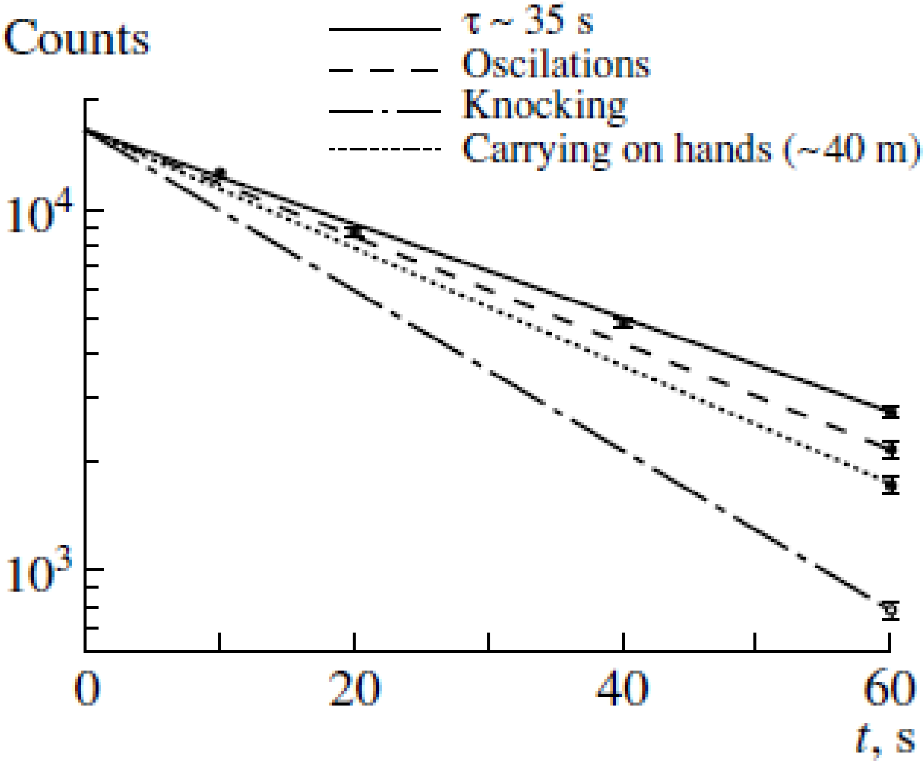


Fig. 2. Storage curve in the stationary vessel and the number of neutrons surviving in the bottle after 60 s, when the bottle was carried, oscillated, or struck with hammer twice per second.

Movie “Emptying an UCN bottle”

P. Geltenbort (courtesy of M. Makela et al., LANL)


WHAT WOULD MACGYVER DO?

Yuri Panin

NRC KI Moscow

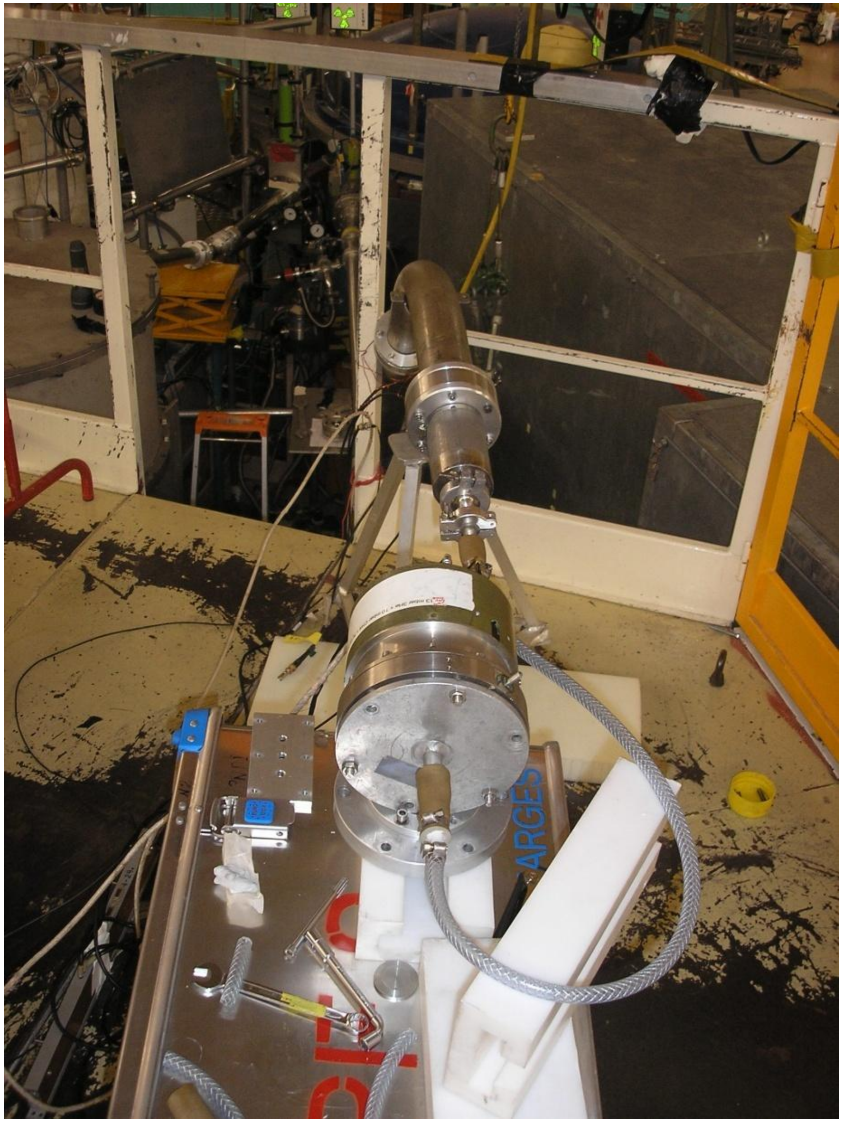
NRC KI team

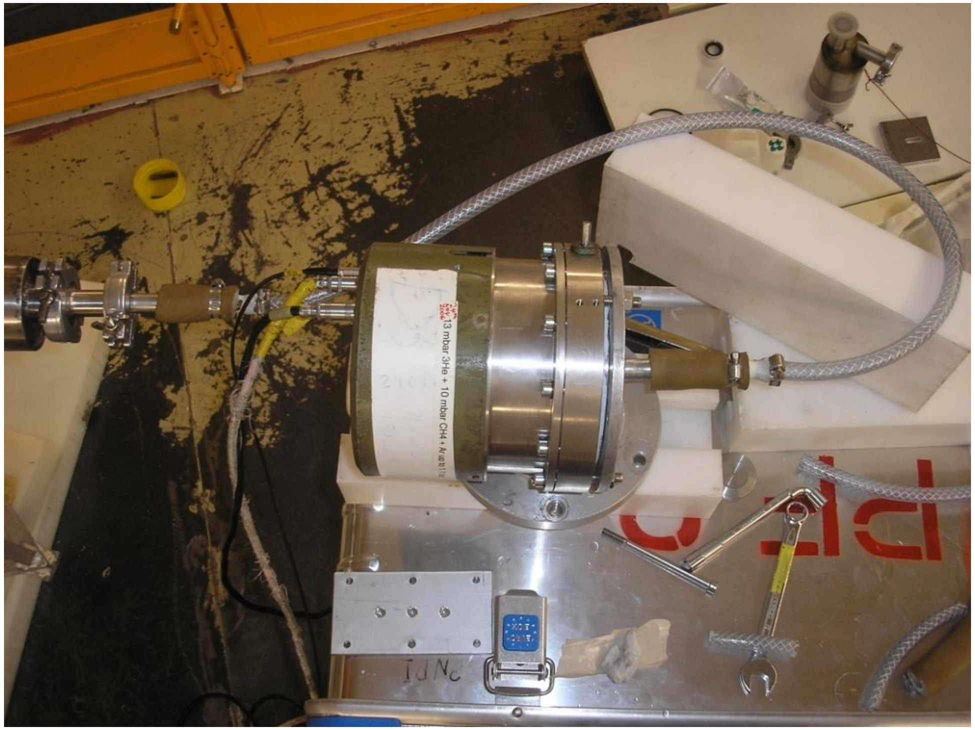
Yuri Panin, Lev Bondarenko, Vasilii Morozov

UCN are always good for a surprise!

Transmission through flexible water hose

Yu. Panin et al., RRC KI Moscow





Surprising result
(80 cm hose with 8 mm inner diameter)

transmission around 85%

FLEXIBLE NEUTRON GUIDE MADE OF POLYVINYL CHLORIDE PLASTIC TO TRANSPORT ULTRACOLD AND VERY COLD NEUTRONS

V. Morozov[a], Yu. Panin[a], P. Geltenbort[b], L. Bondarenko[a],
V.V. Nesvizhevsky[b], A. Strepetov[a], D. Chuvilin[a]

[a]Kurchatov Inst., 53, Kurchatov sqr., Moscow, Russia, R-123182
[b]ILL, 6 rue Jules Horowitz, Grenoble, France, F-38046

Abstract

We present experimental results on transport of ultracold neutrons (UCN) through flexible tubes with the length of up to 3 m and the internal diameter of 6-8 mm made of polyvinyl chloride plastic. Shiny surface of internal walls of such tubes provide high transmission of UCN even if the tube is curved to arbitrary direction. The transmission increases up to 85% if the internal tube surface is covered with layer of liquid fluorine polymer. We discuss an option to use such tubes for building portable sources of UCN and thermal neutrons as well as for capture therapy using low energy neutrons.

Russian PATENT

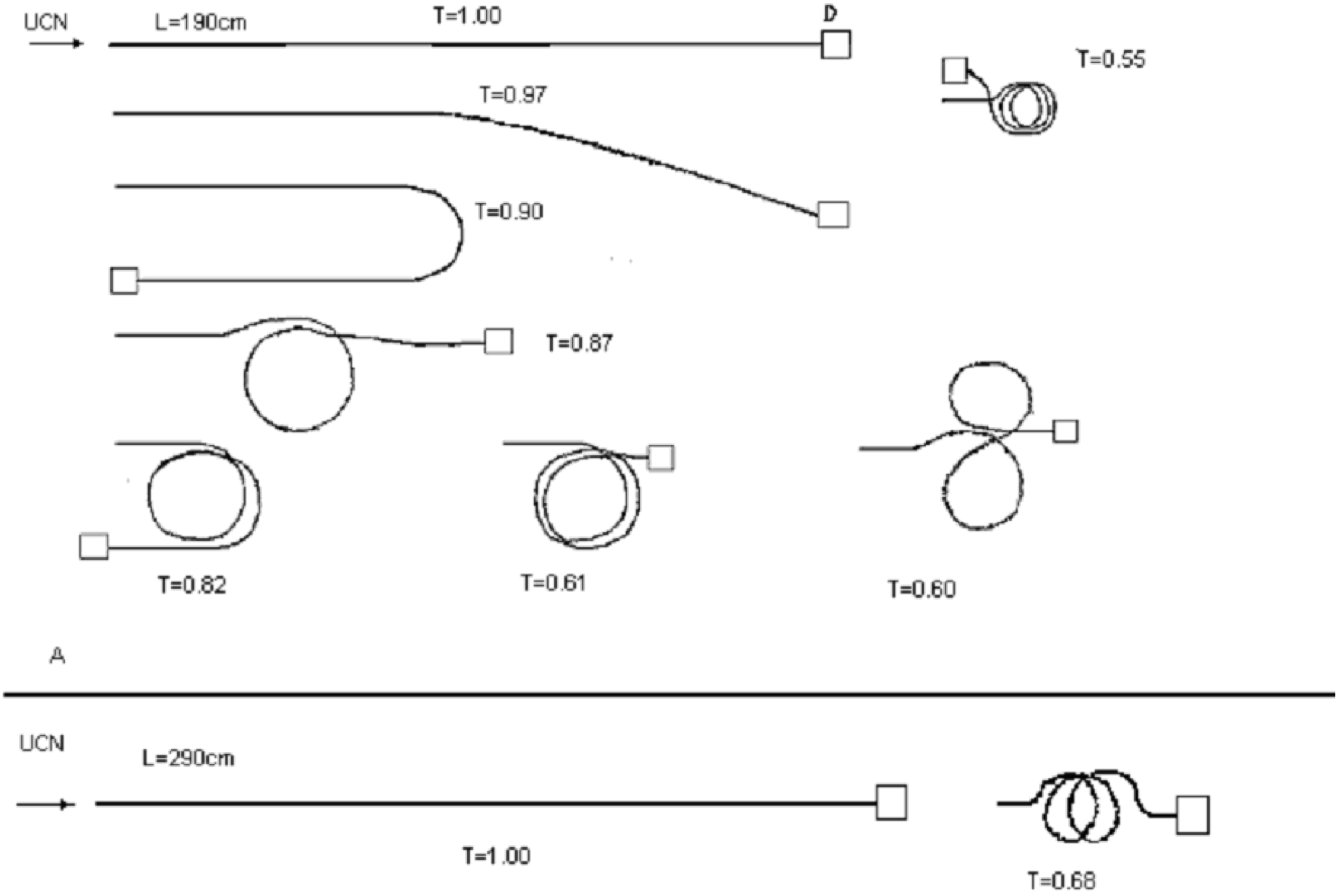
PolyVinyl Chloride or PVC $(CH_2\text{-}CHCl)_n$

S.S. Arzumanov et al., Crystal. Rep. 56 (2011) 1197

density: 1.4 g/cm^3; molecular weight: 30000 – 100000 amu

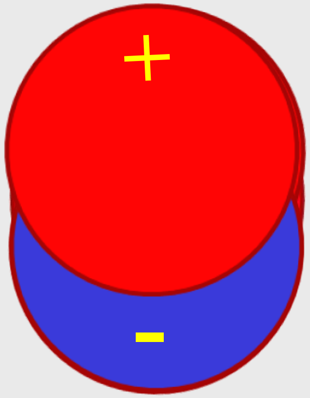
coherent scattering lengths for hydrogen, carbon and chlorine: b_H = -3,74 fm, b_C = 6,65 fm, b_{Cl}= 9,58 fm
Fermi potential: 39.7 neV; critical velocity: 2.8 m/s

Relative Transmission Probability of “fancy guides”



<u>Top view:</u>

- The tube length equals L=190 cm.
- The tube length equals L=290 cm; the tube is coated inside with thin layer of Fluorine polymer.

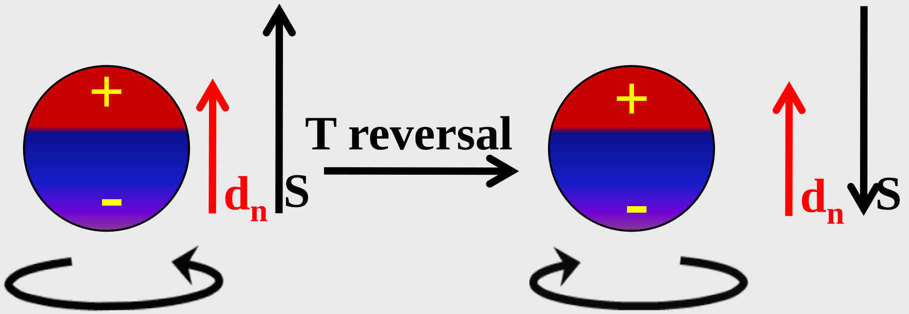


Electric Dipole Moment:

neutron is electrically neutral

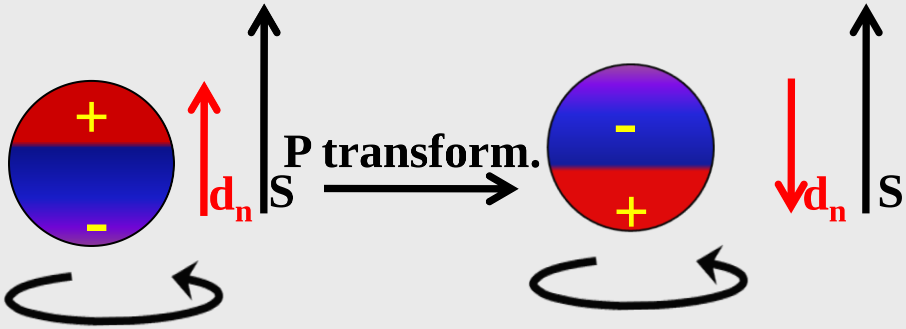
If average positions of positive and negative charges do not coincide:

EDM d_n



electric dipole moment d_n

spin S



P & T violation

CPT conservation ➔ CP violation

CP violation in Standard Model generates very small neutron EDM
Beyond the Standard Model contributions tend to be much bigger

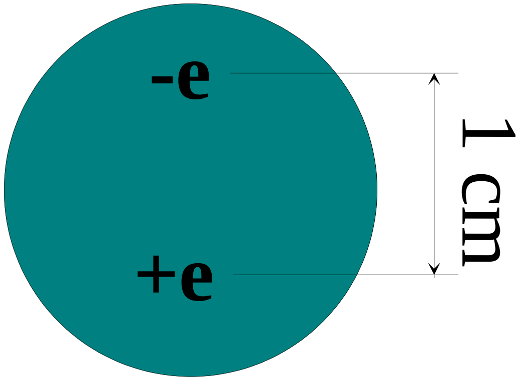
neutron a very good system to look for CP violation beyond the Standard Model

The neutron EDM: exp. vs theory

Progress at ~ order of magnitude per decade

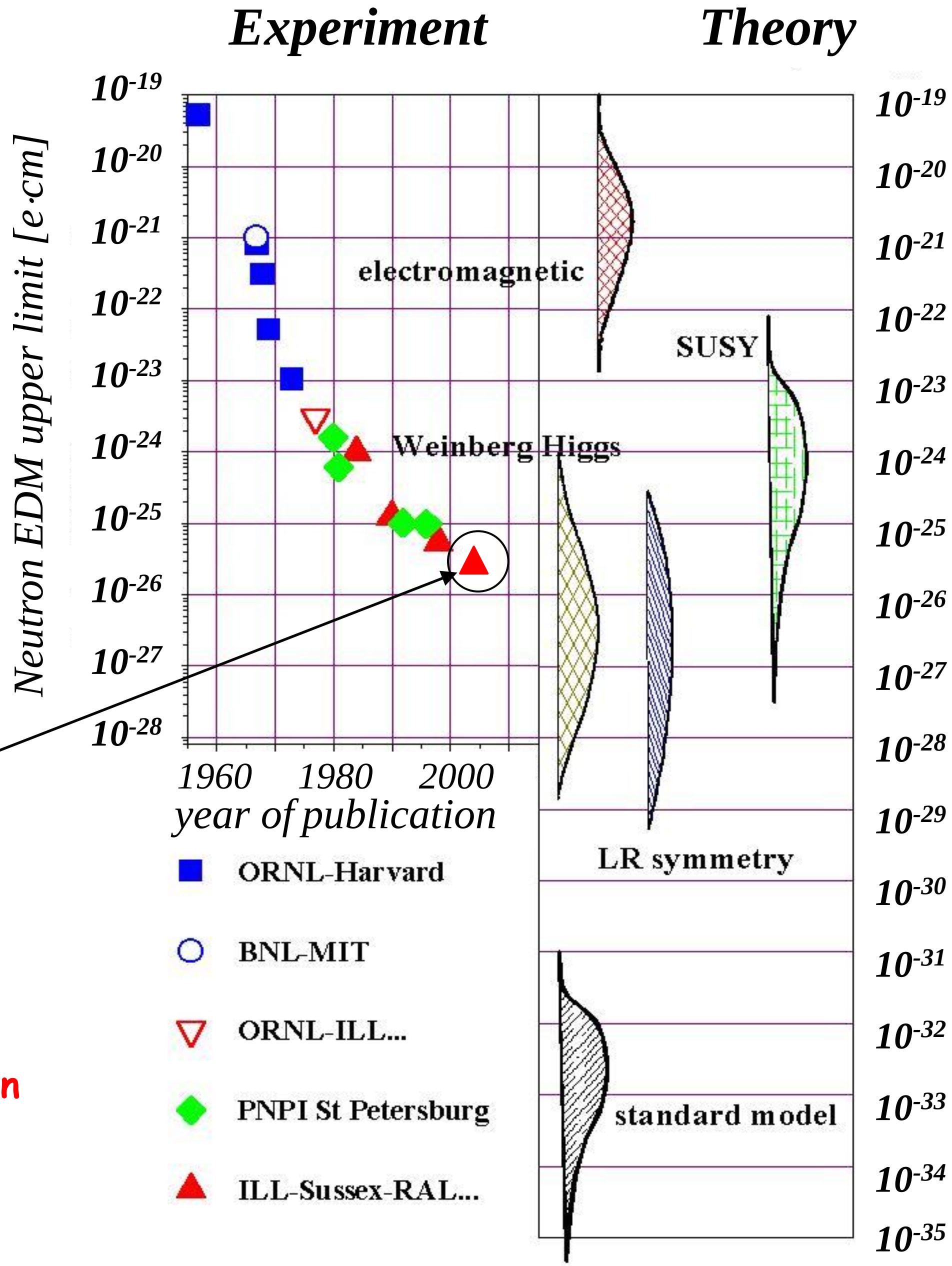
Standard Model out of reach

Severe constraints on *e.g.* Super Symmetry

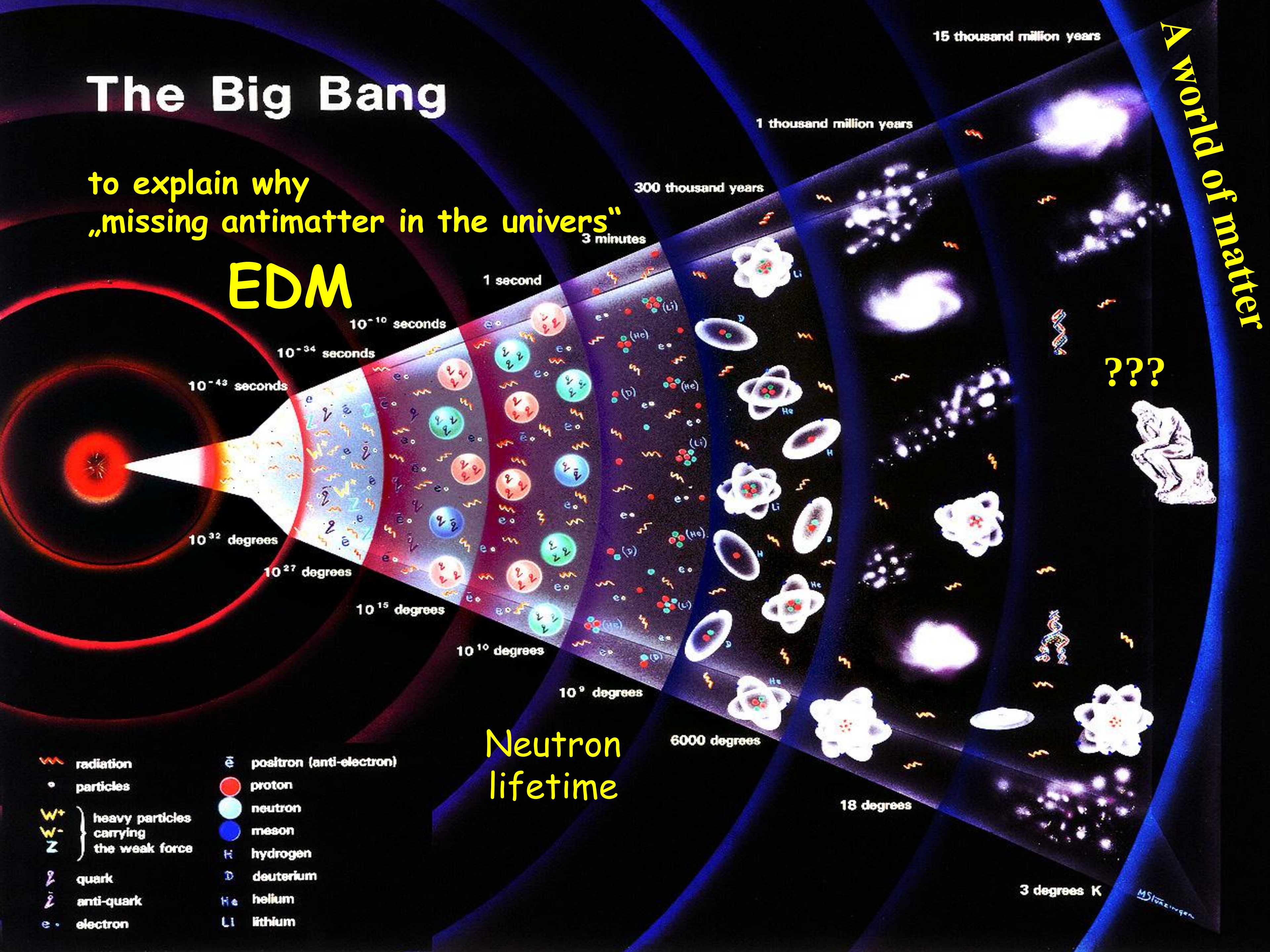


$d_n = 1\ e{\cdot}\mathrm{cm}$

$|d_n| < 3 \times 10^{-26}\ e{\cdot}\mathrm{cm}$



"It is fair to say that the neutron EDM has ruled out more theories (put forward to explain K_0 decay) than any experiment in the history of physics" R. Golub



to explain why
„missing antimatter in the univers"

EDM

Neutron lifetime

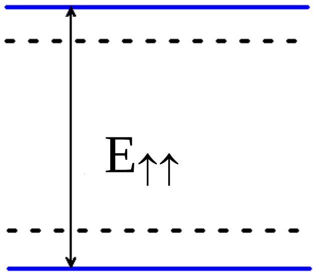
A world of matter

???

Experiments:

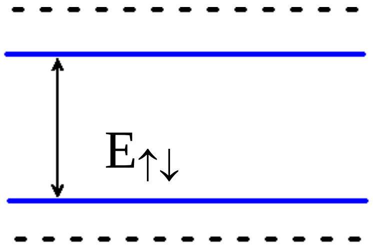
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

Compare the precession frequency for parallel fields:



$$\nu_{\uparrow\uparrow} = E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$

to the precession frequency for anti-parallel fields



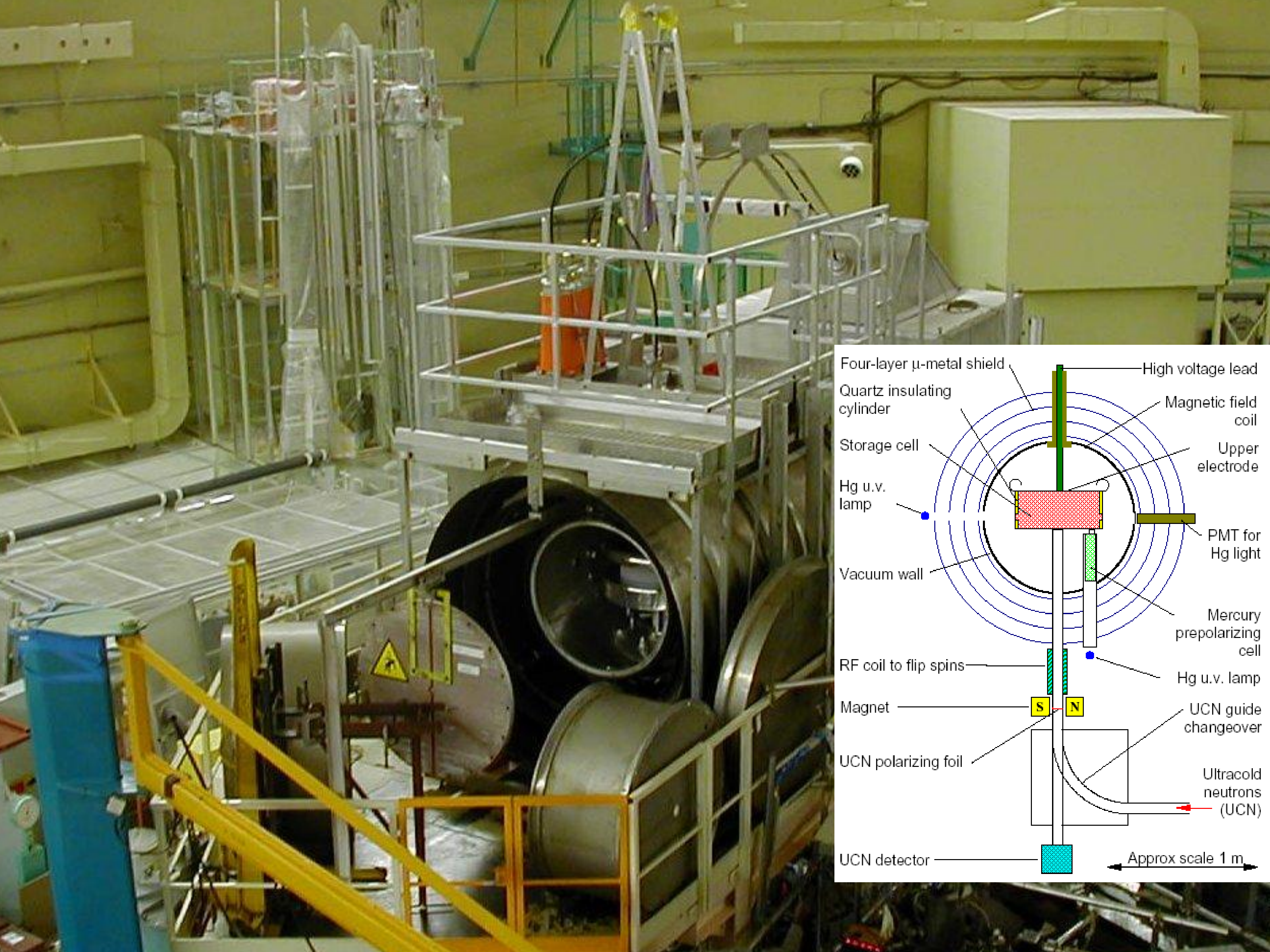
$$\nu_{\uparrow\downarrow} = E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

Need to measure change in Larmor precession frequency to a very high degree : < 1μHz

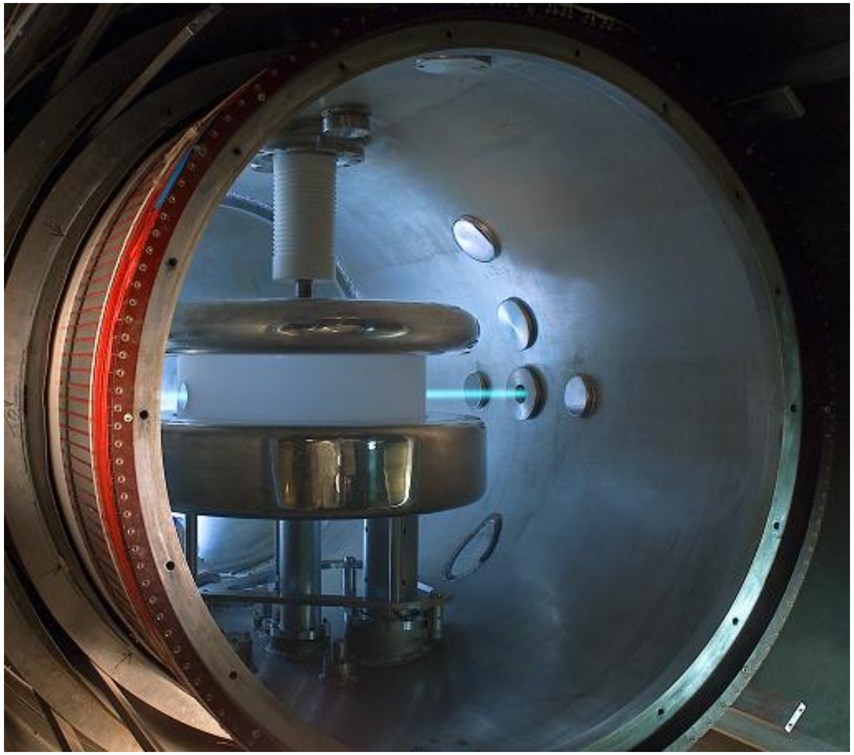
< 1 turn per month!

The difference is proportional to d_n and E:

$$\mathbf{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}) = 4\mathit{E}\,\mathit{d_n}}$$


Four-layer μ-metal shield
Quartz insulating cylinder
Storage cell
Hg u.v. lamp
Vacuum wall
RF coil to flip spins
Magnet
UCN polarizing foil
UCN detector
High voltage lead
Magnetic field coil
Upper electrode
PMT for Hg light
Mercury prepolarizing cell
Hg u.v. lamp
UCN guide changeover
Ultracold neutrons (UCN)
S
N
Approx scale 1 m

Room Temperature Results



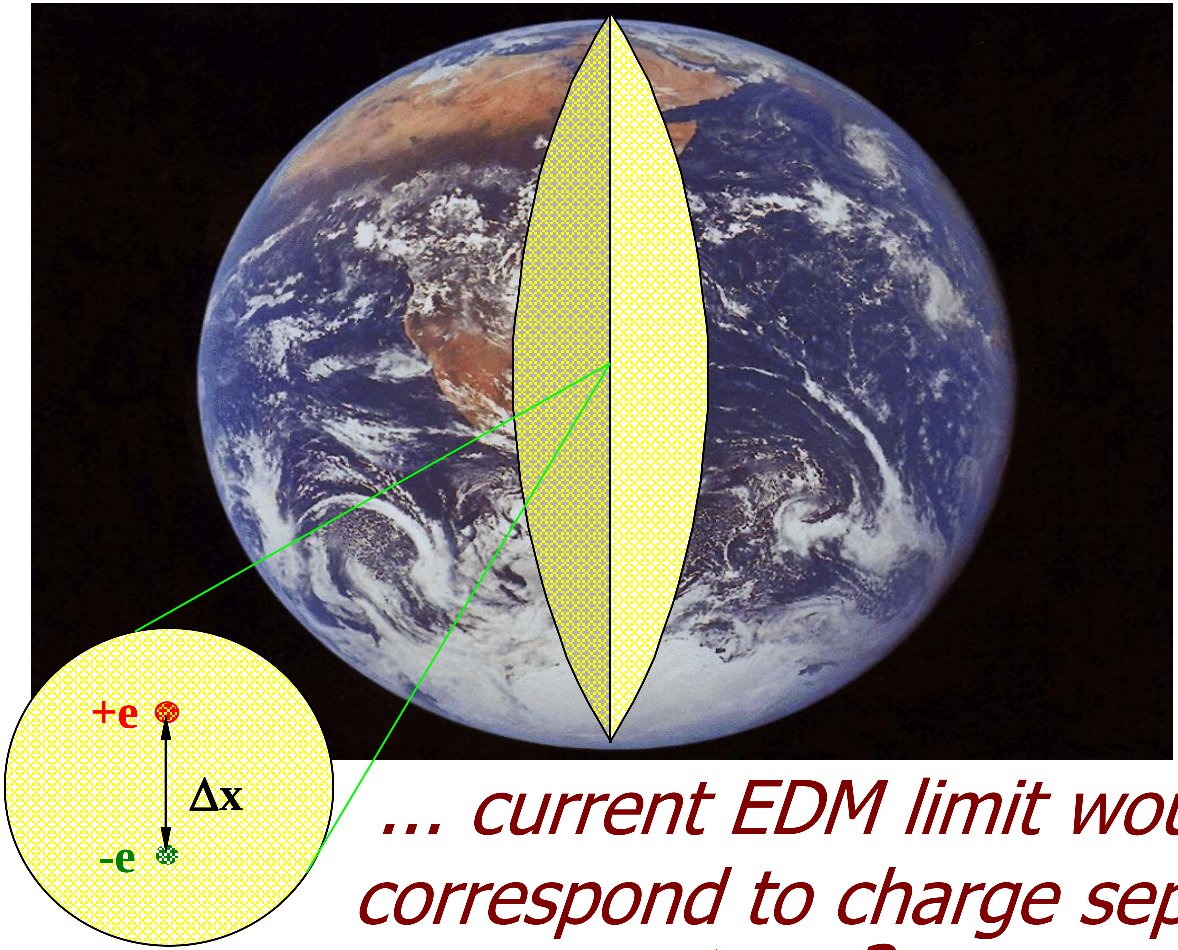
Room temperature neutron EDM result:

C.A. Baker et al., Phys. Rev. Lett. **97,** 131801 (2006) or hep-ex/0602020

$|d_n| < 2.9\times10^{-26}$ e.cm (90% C.L.)

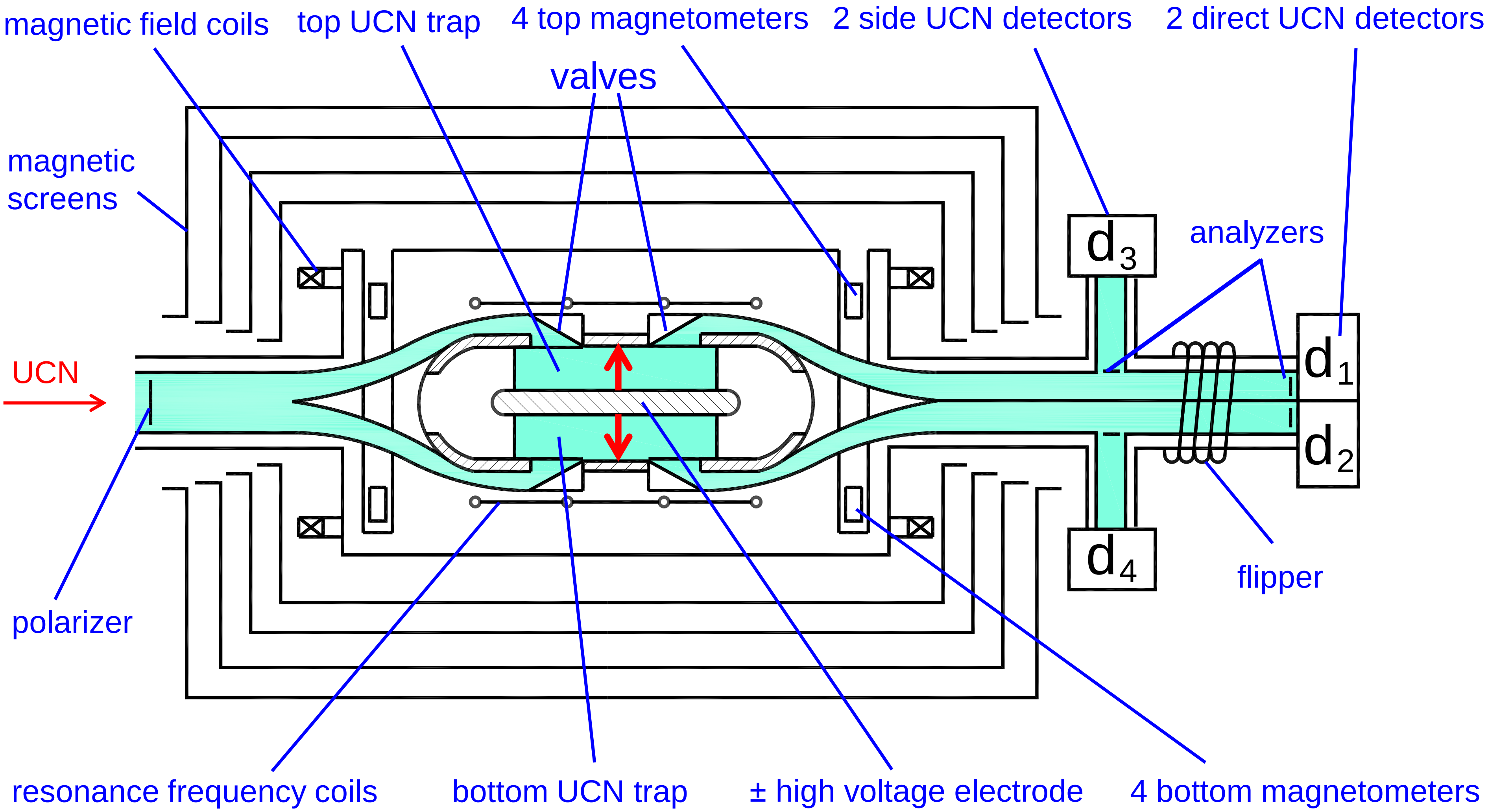
Reality check

If neutron were the size of the Earth...

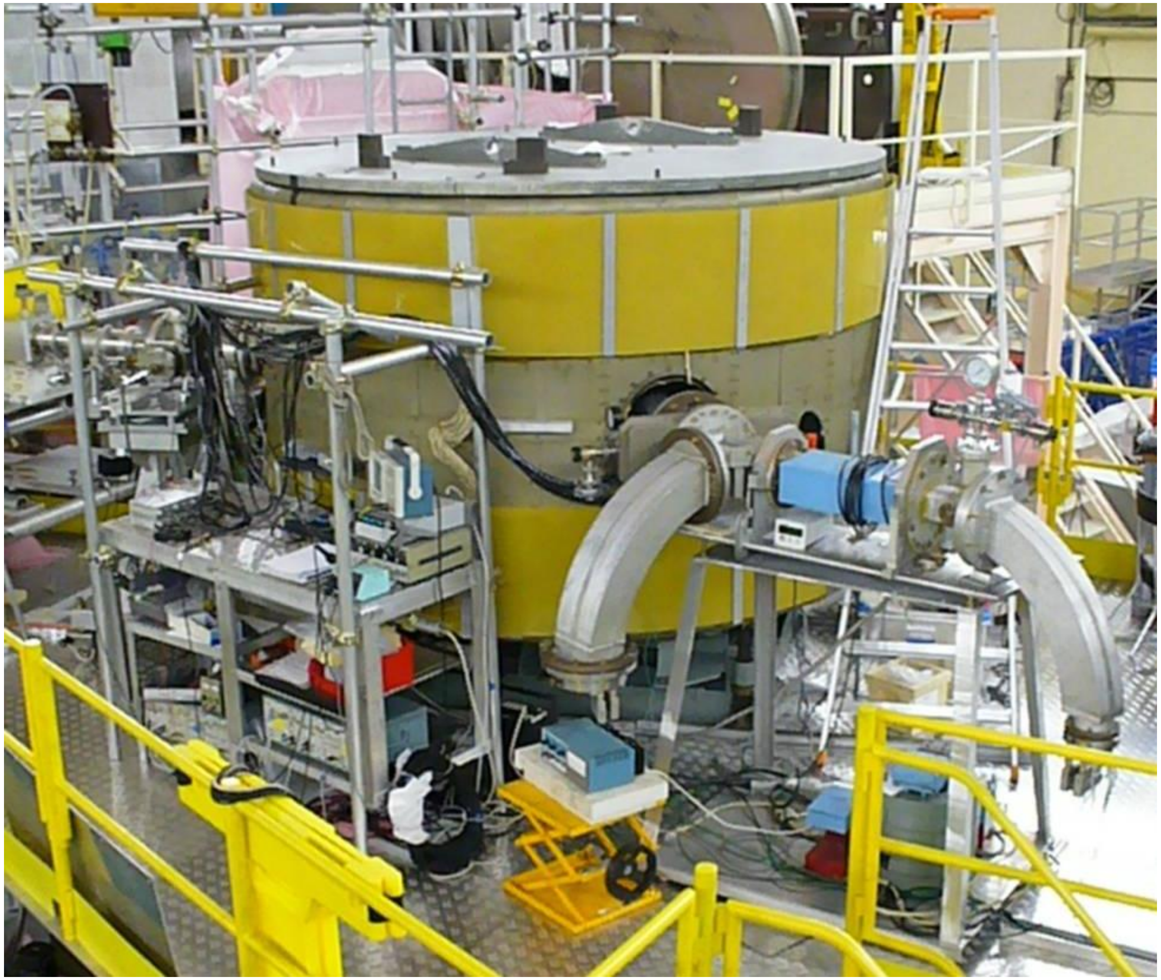


... current EDM limit would correspond to charge separation of $\Delta x \approx 3\mu$

Scheme of PNP double chamber nEDM spectrometer at PF2



PNPI double-chamber nEDM spectrometer at PF2/MAM

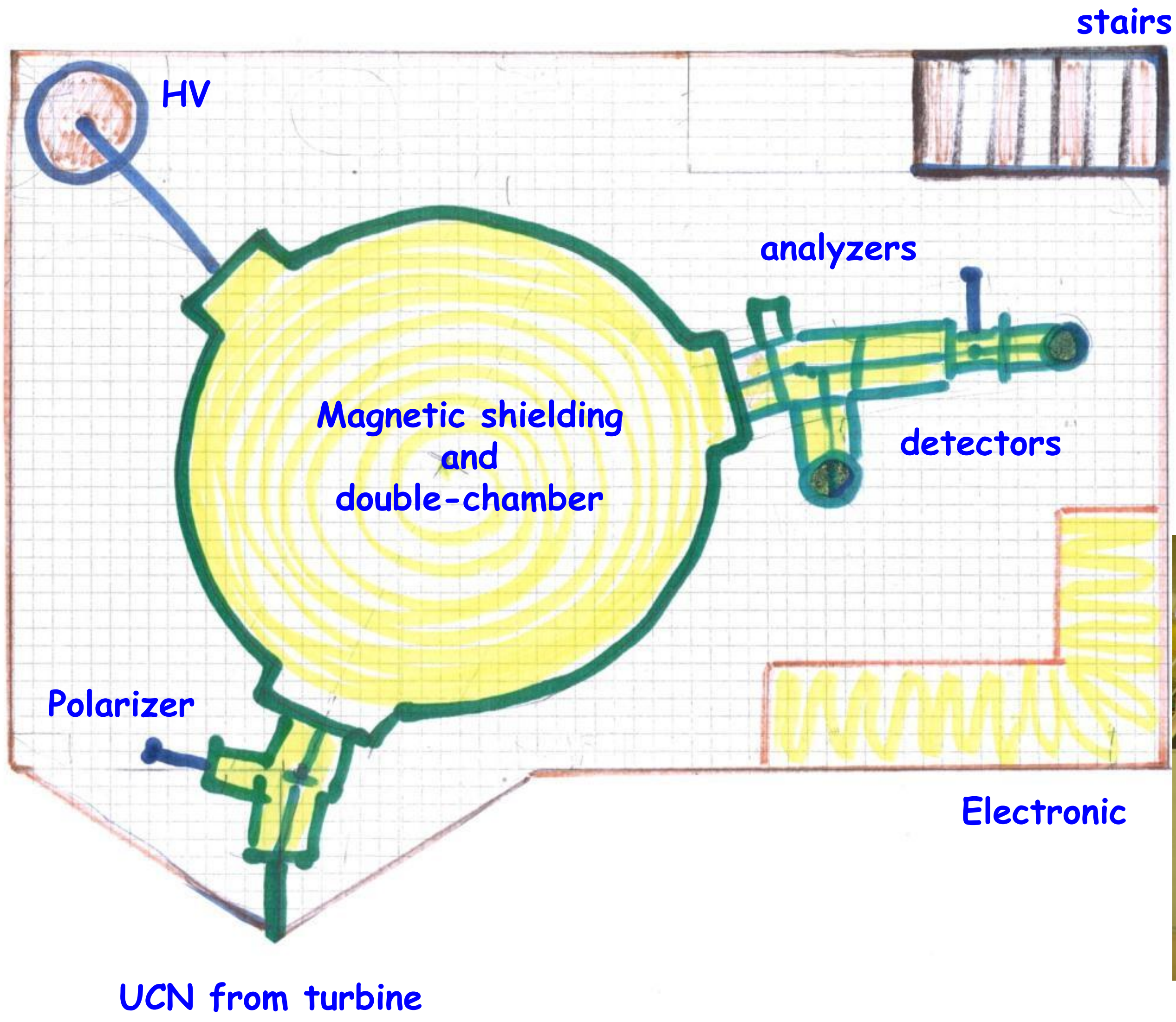


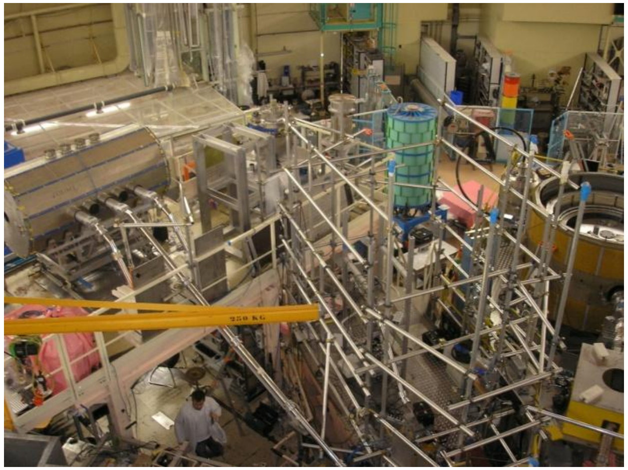
$$/nEDM/ \leq 5.5 \cdot 10^{-26} e \cdot cm$$ **at 90% confidence level**

A.P. Serebrov et al., Pis'ma v ZhETF 99 (2014) 7

Move from PF2/MAM to PF2/EDM platform

expected gain factor in UCN density : 3 to 4

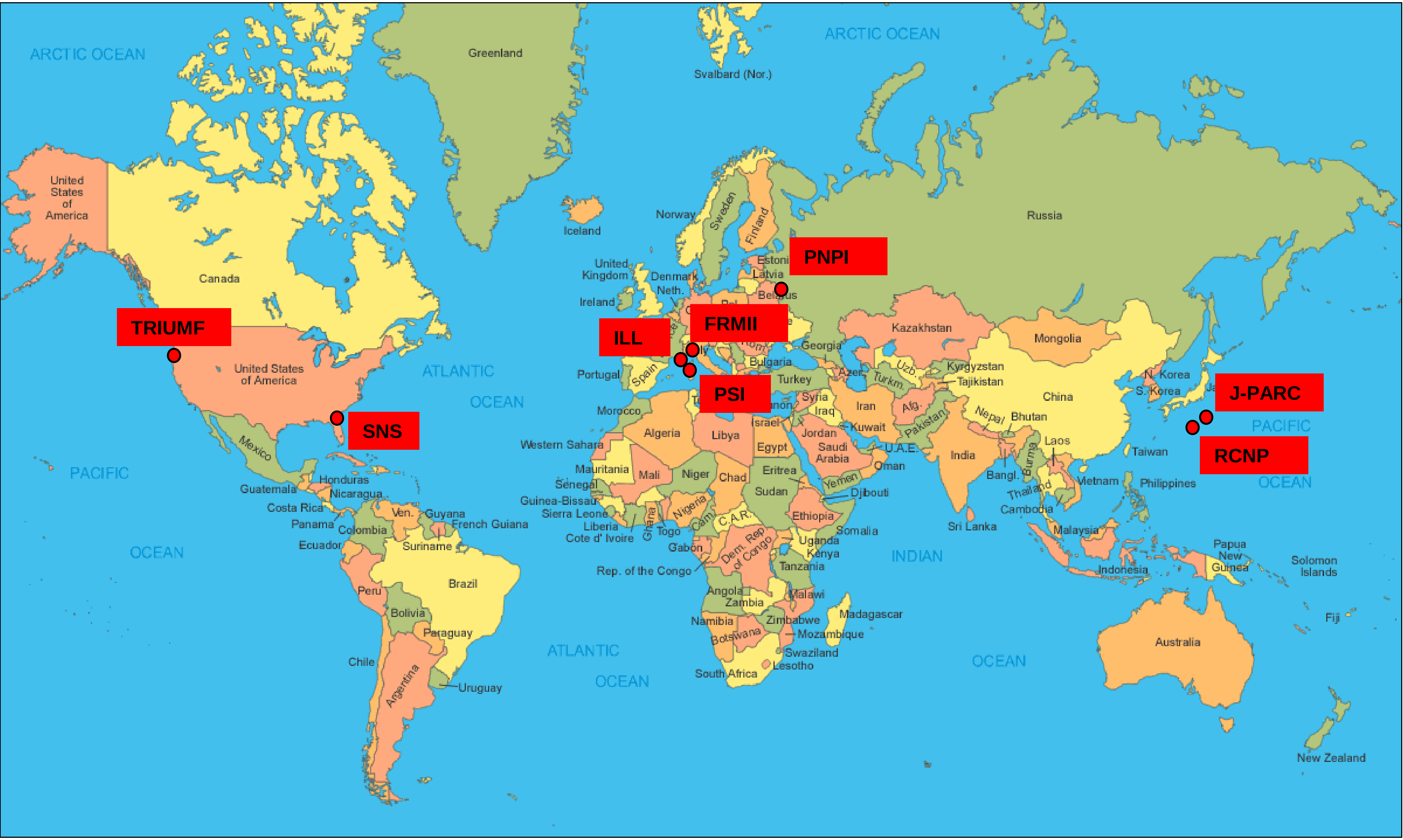




Top view

Side view

Worldwide nEDM Searches



Search for Neutron – Mirror Neutron Oscillations using storage of Ultracold Neutrons

PNPI/IPTI/ILL collaboration: A. Serebrov et al., E. Alexandrov et al., P. Geltenbort, O. Zimmer

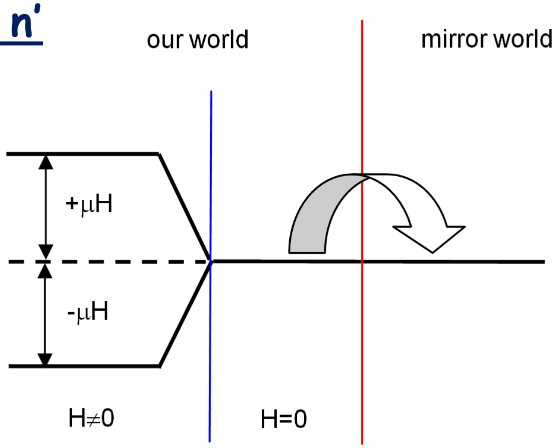
Hypothesis: There is a "mirror world" of partners of the known particles with

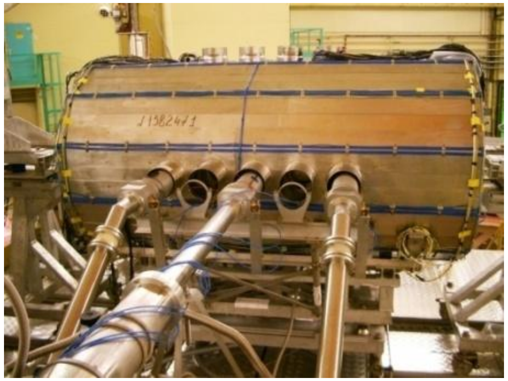
- same fundamental interactions with opposite handedness
  → natural explanation of parity violation
- no interactions with our world, apart gravity and mixing of neutral particles
  → mirror matter is a viable dark-matter candidate

Z. Berezhiani, A.D. Dolgov and R.N. Mohapatra, Phys. Lett. B **375**, 26 (1996)

Test: Search transition of neutron n to mirror neutron n'

- Situation 2006: $\tau_{osc} \geq 1$ s
- A magnetic field suppresses nn' mixing
  → Look for difference of UCN storage time without (<20 nT) and with field (2 μT)



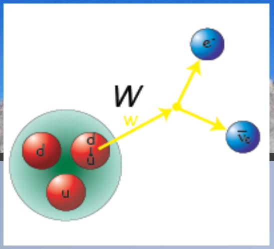


Result with PNPI EDM-setup at PF2:

τ_{osc} (90% C.L.) ≥ 414 s

A..P. Serebrov et al., Phys. Lett. B663 (2008) 181

The free neutron lifetime: $\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ (+782 keV)



$$\frac{1}{\tau_\mathrm{n}} \propto G_\mathrm{F}^2,\ V_\mathrm{ud}^2,\ \lambda^2 \qquad \lambda = \frac{g_\mathrm{A}}{g_\mathrm{V}}$$

$$n \to p + e^- + \bar{\nu}_e + \gamma \qquad BR(15keV) \approx 3 \times 10^{-3}$$

$$n \to H^\circ + \bar{\nu}_e \qquad BR \approx 4 \times 10^{-6}$$

Together with measurements of *asymmetry coefficients* in neutron decay

Extraction of g_V, g_A and V_ud

Test of *Conserved Vector Current* (CVC: 'g_V' = 1)

Test of *Unitary of CKM* matrix ($V_\mathrm{ud}^2 + V_\mathrm{us}^2 + V_\mathrm{ub}^2 = 1$)

Weak interaction theory

Neutrino physics

Cosmology

Solar pp-process:

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \mathrm{e}^+ + \nu_\mathrm{e} \qquad \sigma \propto g_\mathrm{A}^2$$

Big bang:

Primordial elements' abundances

Neutrino induced reactions:

$$\bar{\nu}_\mu + \mathrm{p} \rightarrow \mu^+ + \mathrm{n}$$

$$\nu_\mu + \mathrm{n} \rightarrow \mu^- + \mathrm{p}$$

Neutrino detectors:

$$\mathrm{p} + \bar{\nu}_\mathrm{e} \rightarrow \mathrm{n} + \mathrm{e}^+$$

$$\sigma \propto \frac{1}{\tau_\mathrm{n}}$$

Important input parameter for tests of the Standard Model of the weak interaction

Necessary to understand matter abundance in the Universe

Necessary to calibrate Neutrino Detectors and to predict event rates

Big-Bang Nucleosynthesis (BNN) crucial in constraining cosmological models

Essentially the only probe of physics in the early universe (~1 – 10^4 s; “radiation dominated epoch”)

Single unknown parameter for standard BBN is baryon-to-photon ratio during the nucleosynthesis epoch. All light abundances are a simple function of this parameter.

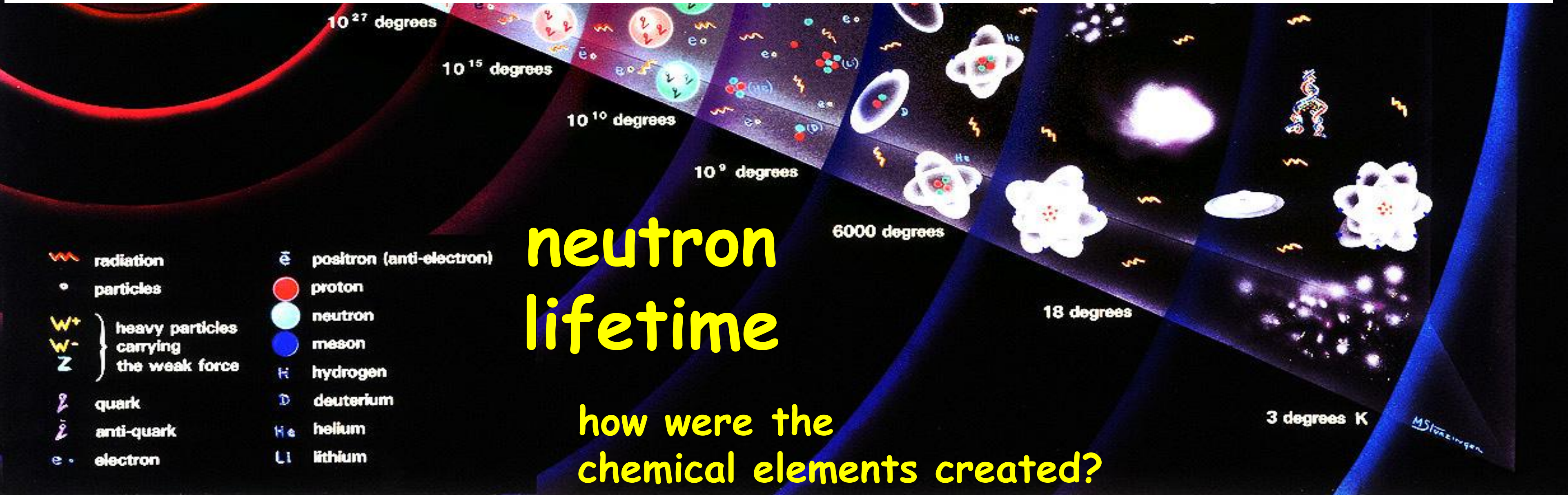
Those yields are particularly sensitive to the neutron lifetime τ_n which affects BBN in 2 ways:

i) τ_n enters in weak reaction rate which ceases at freeze –out temperature T_F, then n/p ratio fixed except for neutron decay

ii) Neutron decay between weak freeze-out (t~1s) and nucleosynthesis (t~200s)

These effects imply that **the shorter the neutron lifetime, the lower the predicted helium abundance**

See “BBN with a new neutron lifetime”, G.J. Mathews et al, Phys. Rev. D71, 021302(R) (2005)



neutron lifetime

how were the chemical elements created?

Measurements of the neutron lifetime τ_n

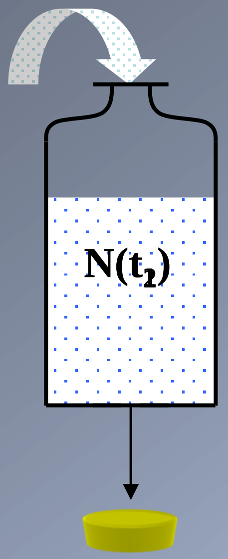
exponential decay law: $N = N_0 e^{-\Lambda t}$

or, ultimately, measure the exponential decay directly

Storage experiments with UCN

"counting the surviving neutrons"

“UCN bottle”



$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \underbrace{\frac{1}{\tau_{\text{wall}}}} + \underbrace{\frac{1}{\tau_{\text{leak}}} + \frac{1}{\tau_{\text{vacuum}}} + \ldots}$$

→ 0 (experiment)

$$\frac{1}{\tau_{\text{wall}}} = \mu \cdot v_{\text{eff}}$$ → 0 (extrapolation)

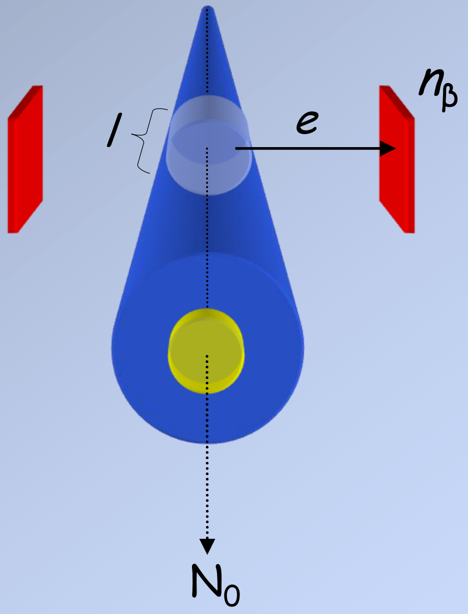
→

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta}$$

Two relative measurements

Beam experiments with cold neutrons

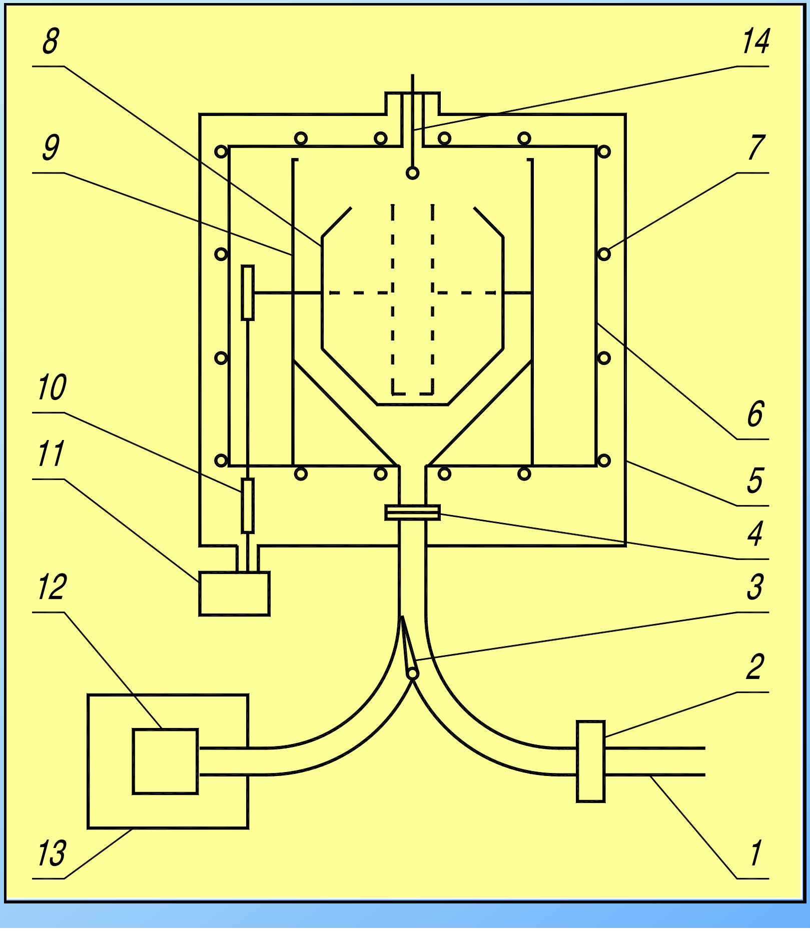
"counting the dead neutrons"



$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

Two absolute measurements

Scheme of “Gravitrap”,
the gravitational UCN storage system



UCN traps are made from copper:

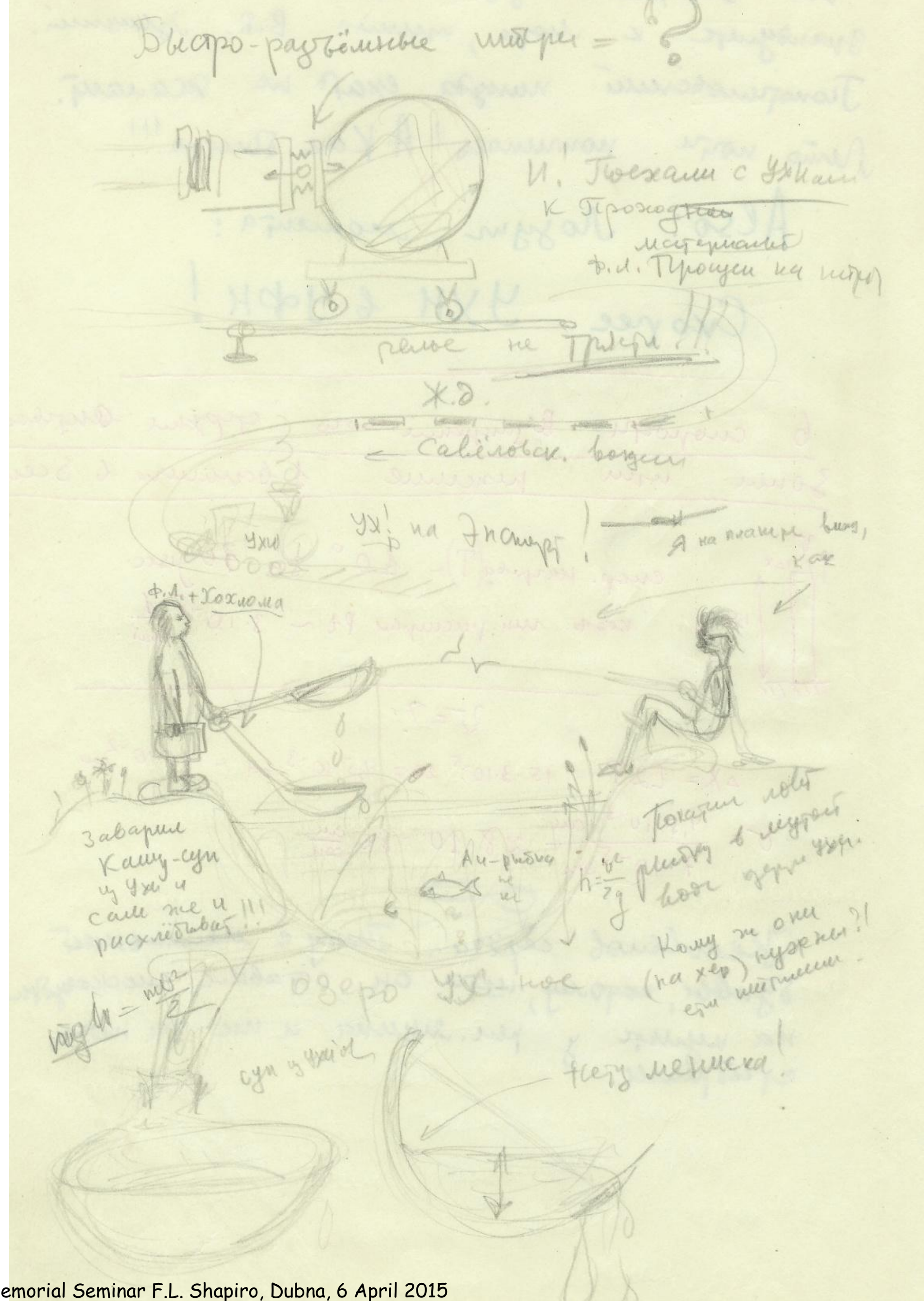
1. quasi-spherical (cylinder + 2 truncated cones) trap, inner
2. narrow (14 cm) cylindrical trap, inner surface - sputtered
3. wide (50 cm) cylindrical trap, inner surface - sputtered tita

KOVSH

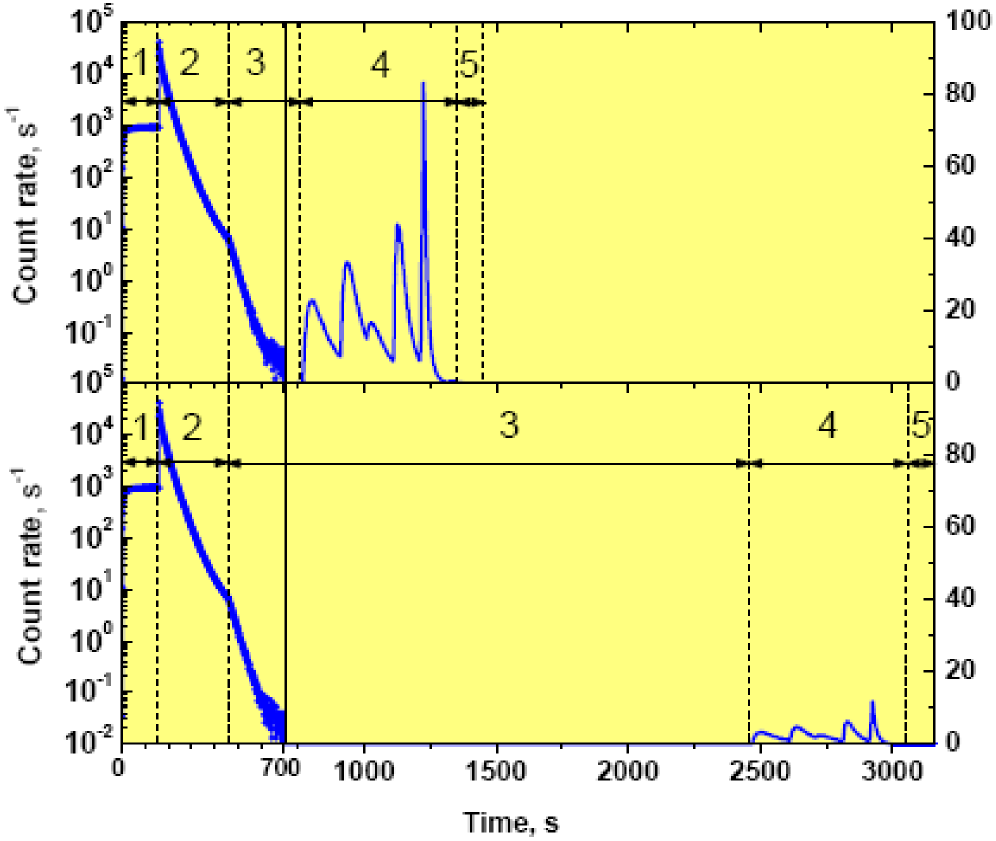
or

“spooning ultracold neutrons”

© A. Strelkov, August 1968



Typical measuring cycle



1. filling 160 s (time of trap rotation (35 s) to monitoring position is included);
2. monitoring 300 s;
3. holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included);
4. emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5 s, 24.5 s) to each position is included);
5. measurement of background 100 s.

$$N(t_2) = N(t_1) \cdot \exp\left(-\frac{t - t_1}{\tau_{st}}\right)$$

$$\tau_{st} = \frac{t_2 - t_1}{ln\left(N(t_1)/N(t_2)\right)}$$

$(878.5 \pm 0.7_{stat.} \pm 0.3_{syst.})$ s

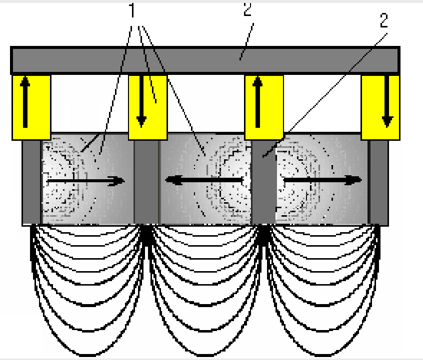
A.P. Serebrov et al., Phys. Lett. B605 (2005) 72

General principle and design

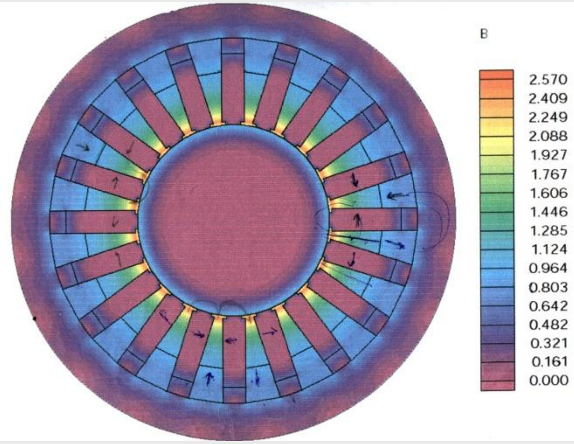
- For μ_n = -60.3 neV/T, a 2T field generates a 120 neV barrier.
- Force due to field gradient, $F = -\mu\,(dB/dz)$, repels only one spin state.
- Use permanent magnets.

- **Step 1: 1D confinement**

  1 – permanent magnets
  2 – magnetic poles

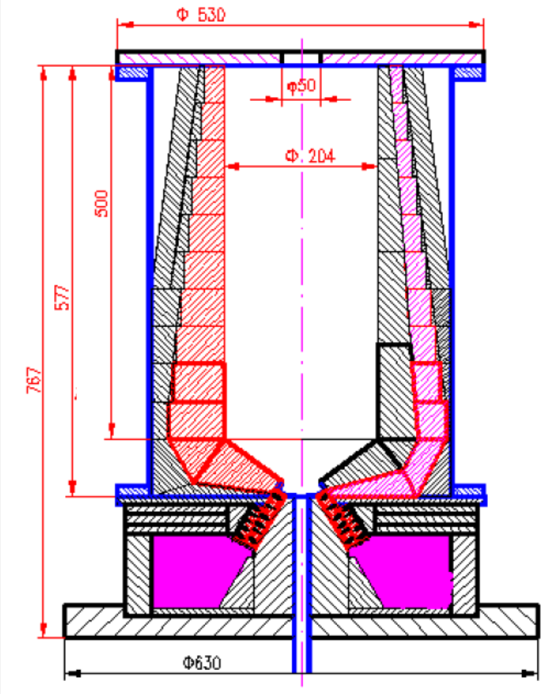


- **Step 2: 2D confinement**



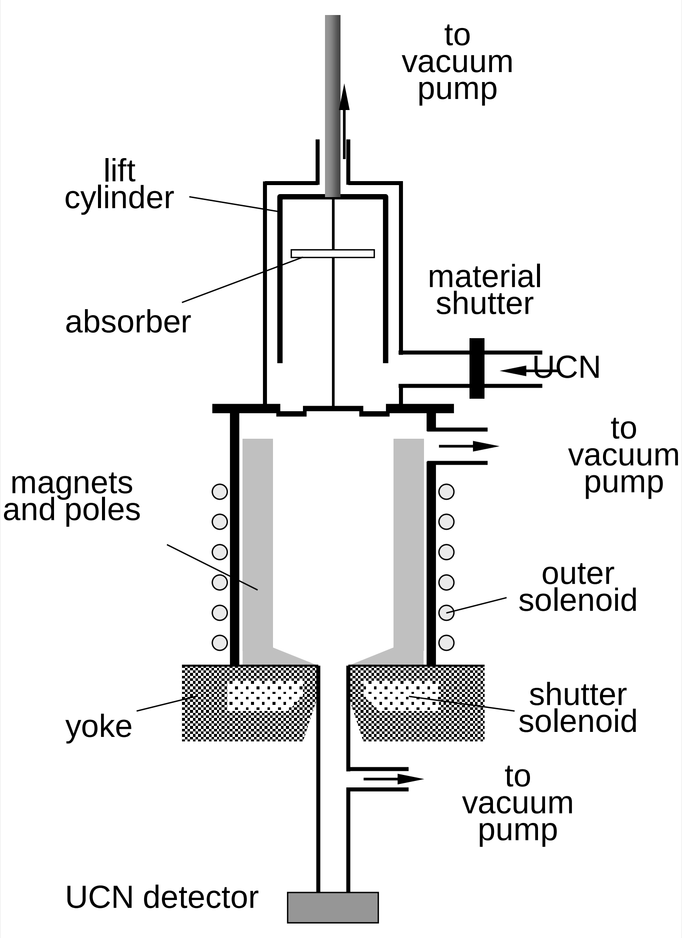
- **Step 3: 3D confinement**

  - top (gravity)
  - bottom (magnetic shutter)



Setup for neutron lifetime measurement

main elements:lift, trap, solenoid, shutter, detector

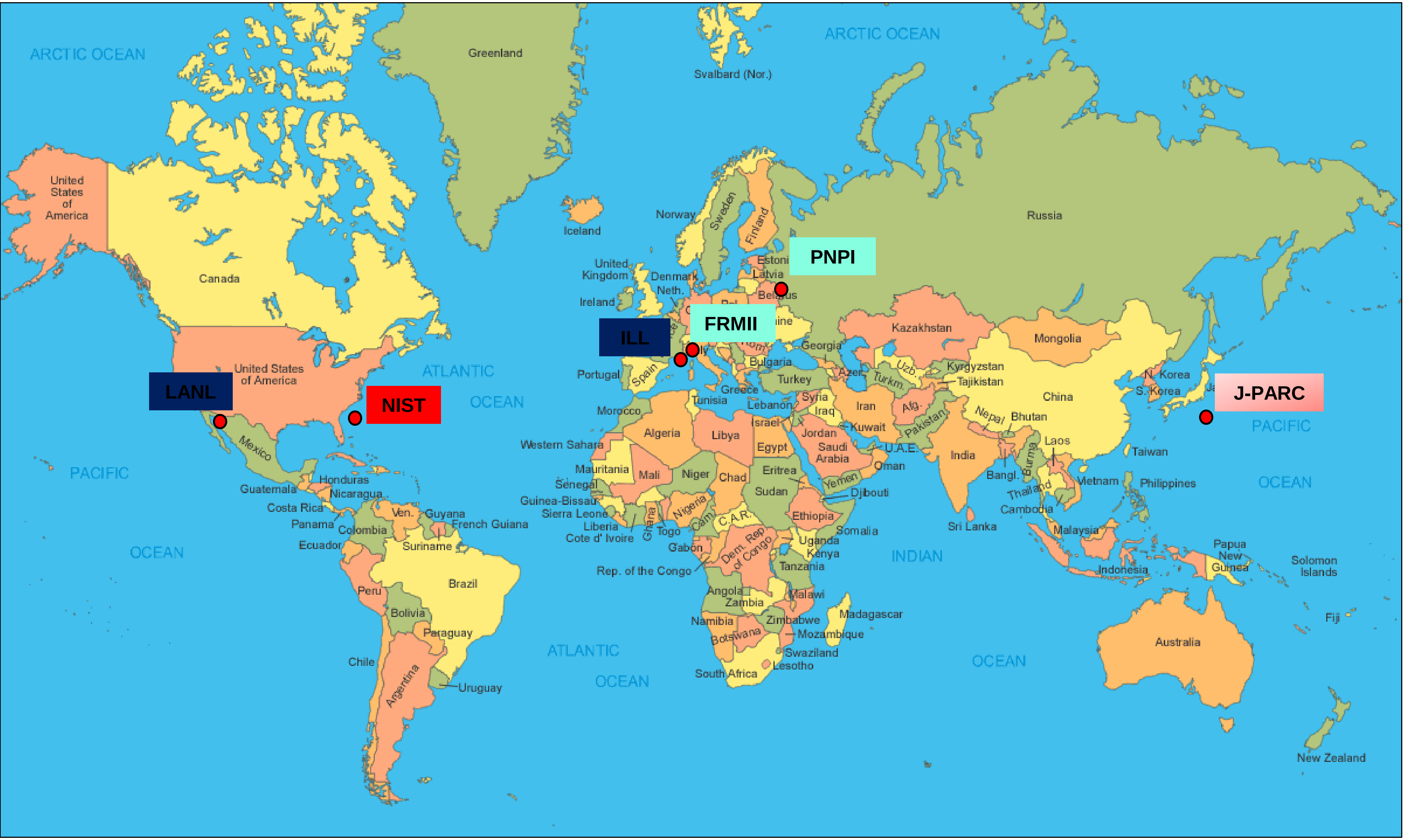


Lift: Fomblin coated Al cylinder + PE disk

(878.3 ± 1.9) s

V.F. Ezhov et al., arXiv:1412.7434 (2014)

Worldwide nLifetime Searches



qBounce (H. Abele and his team)

Motivation

- qBounce: quantized gravity bound states of ultra-cold neutrons

- Test of Newton’s gravity potential at small distances (microns)
- Detection of new forces
- Tests for chameleons, axions

$$V(r) = -G\frac{m_i m_j}{r}(1 - a e^{-r/l})$$

Arkani-Hamed et al.: Physical Review D 59, 086004 (1999)

Neutrons in the gravity field

- Schrödinger eq. with linearized gravity potential

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

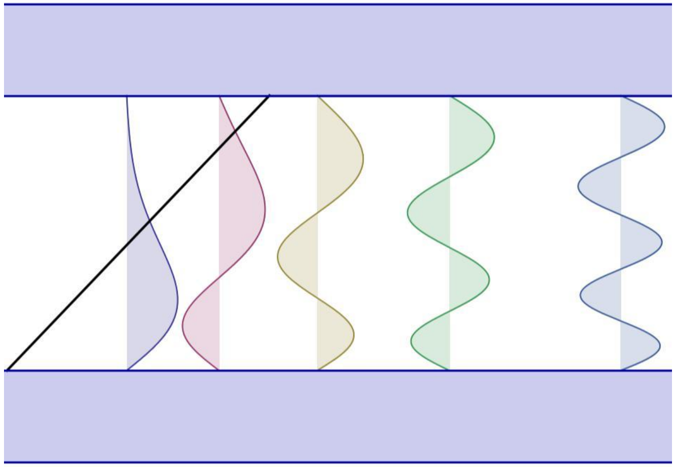
bc: $\varphi_n(0)=0, \quad \varphi_n(l)=0$

$$\varphi_n(z)=a_n Ai\left(\frac{z}{z_0}-\frac{E_n}{E_0}\right)+b_n Bi\left(\frac{z}{z_0}-\frac{E_n}{E_0}\right)$$

- bound, discrete states
- Non-equidistant energy levels

state	energy
1	1.41 peV
2	2.56 peV
3	3.98 peV

Slit width l=27 µm

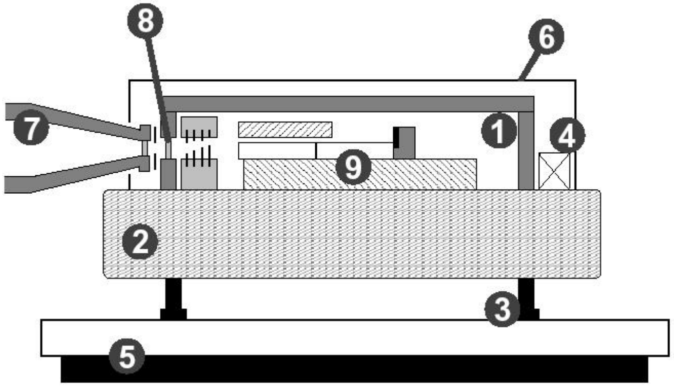


A bit of “history”

The First Realisation 1998 – 2005

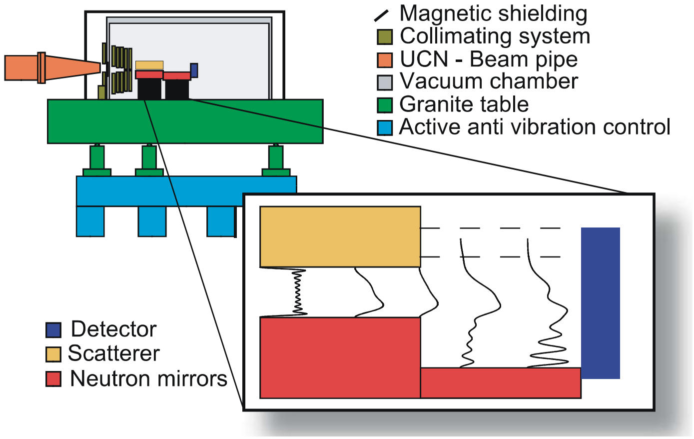
- Institut Laue-Langevin,
- Physikalisches Institut, University of Heidelberg,
- Petersburg Nuclear Physics Institute, St. Petersburg
- Joint Institute for Nuclear Research, Dubna

Theory by Frank A., Luschikov V. 1978 (Neutrons)
Wallis et al. 1992 (Atoms)
Experiment by Nesvizhevsky V. et al. 2002 (Neutrons)



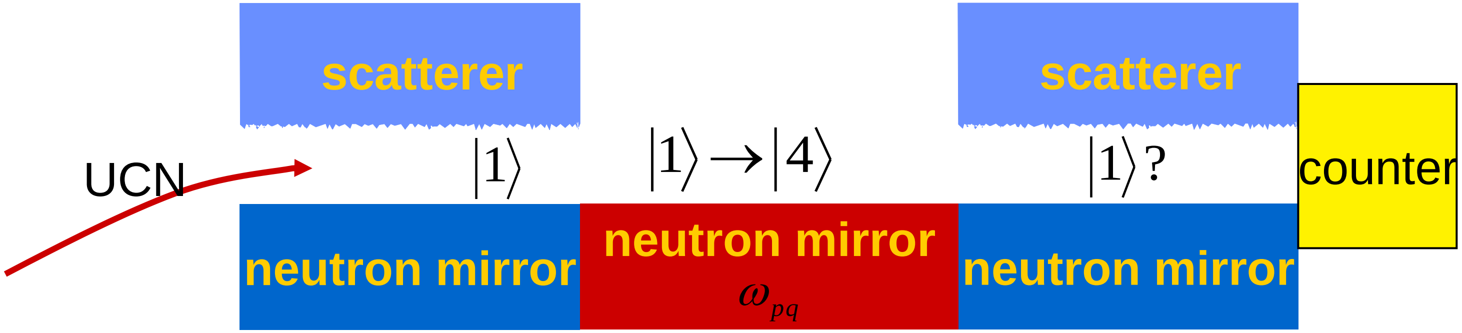
*q*Bounce since 2007

- Quantum bouncer

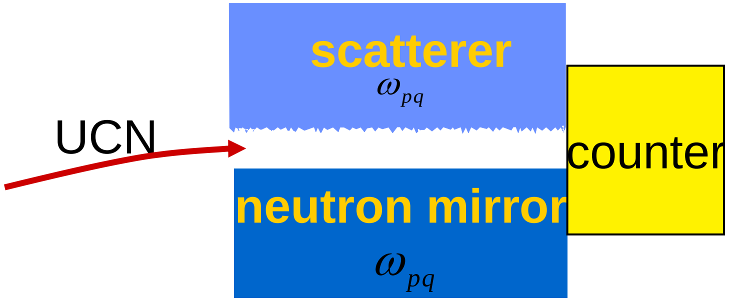


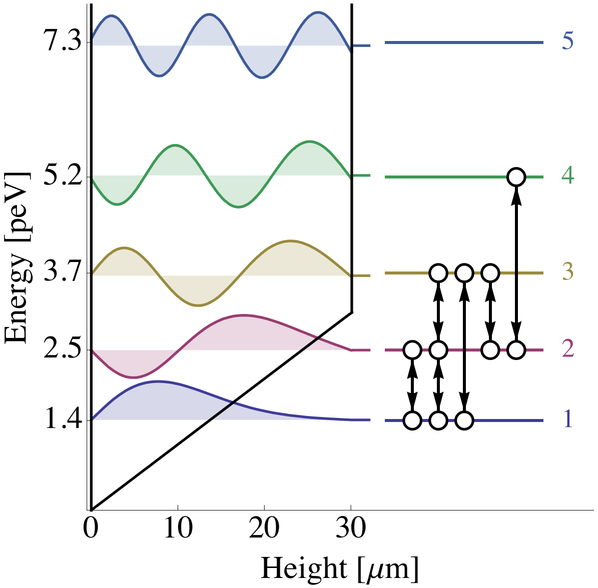
Gravity Resonance Spectroscopy

- **Rabi** (2012)



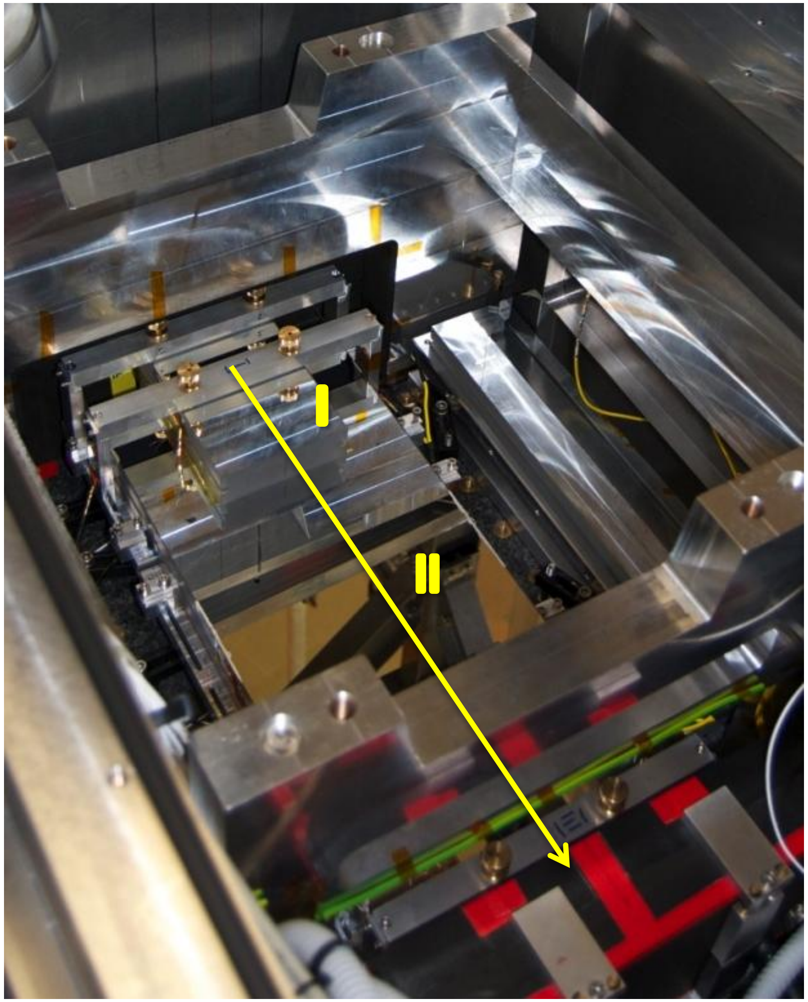
- First realisation (2009,2010)

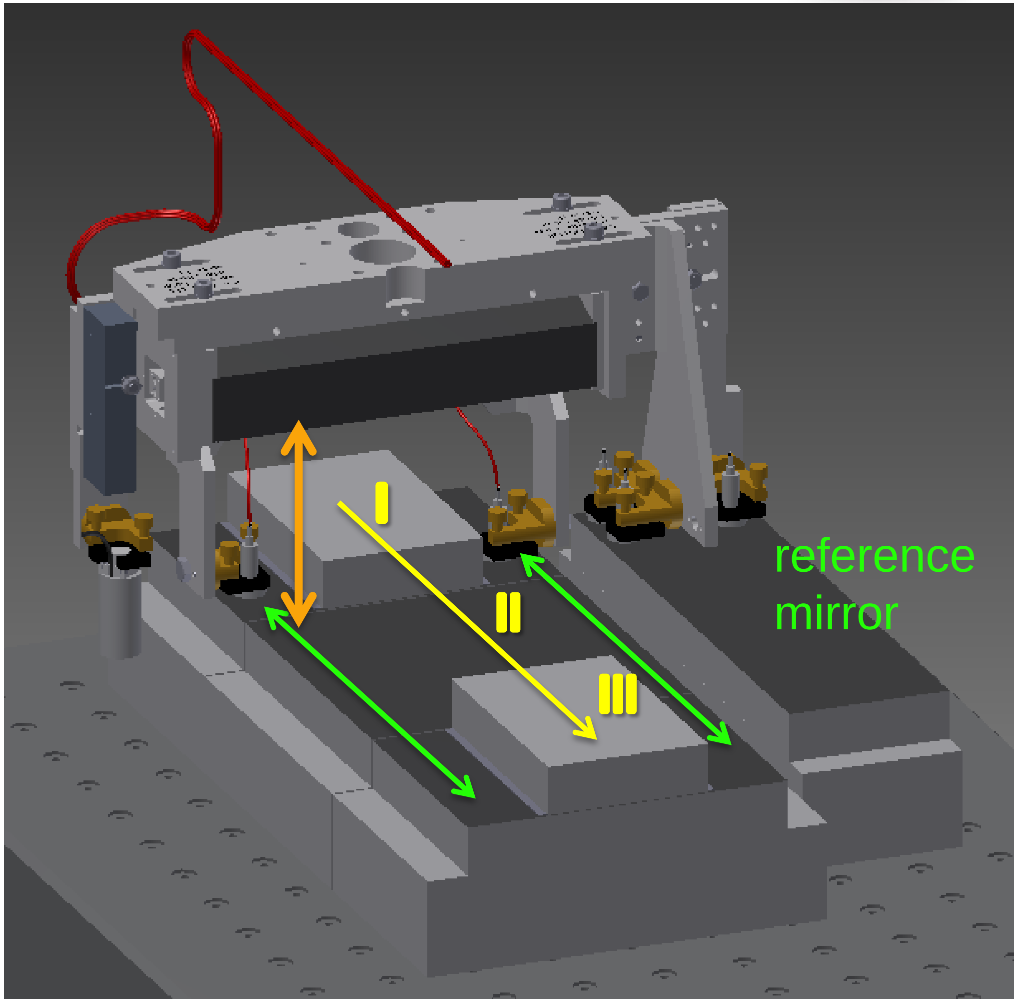




T. Jenke et al.: “Realization of a gravity-resonance-spectroscopy technique”
Nature Physics 7, 468–472 (2011)

Setup





M. Horvath

Results

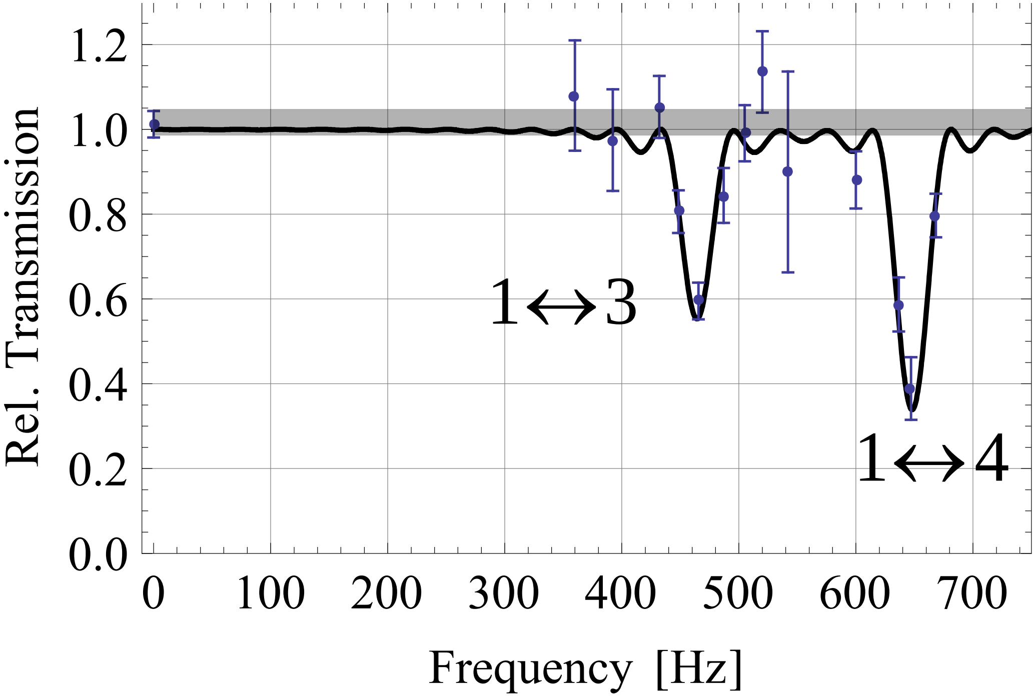
Transitions 1-3 and 1-4 observed

1-3: (46±5)% Intensity drop

1-4: (61±7)%

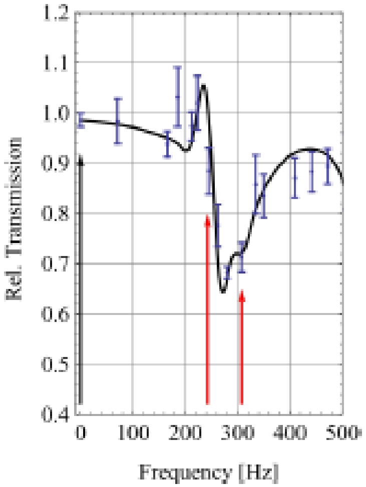
60 measurements

Preliminary, generic fit

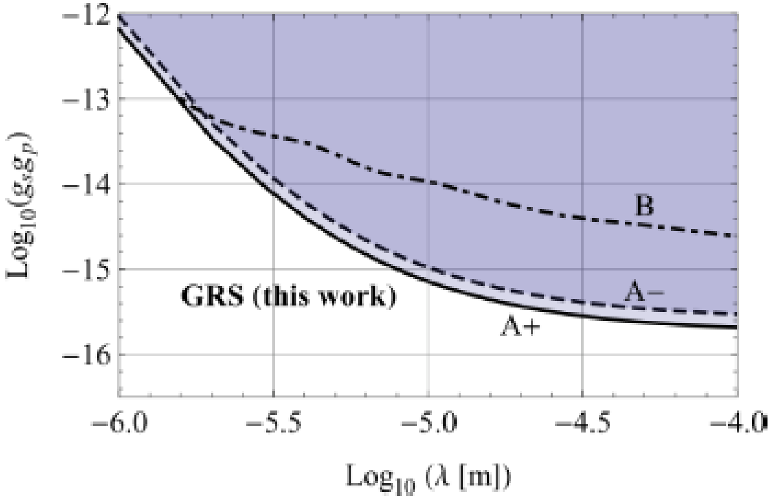

@ 2.1 mm/s

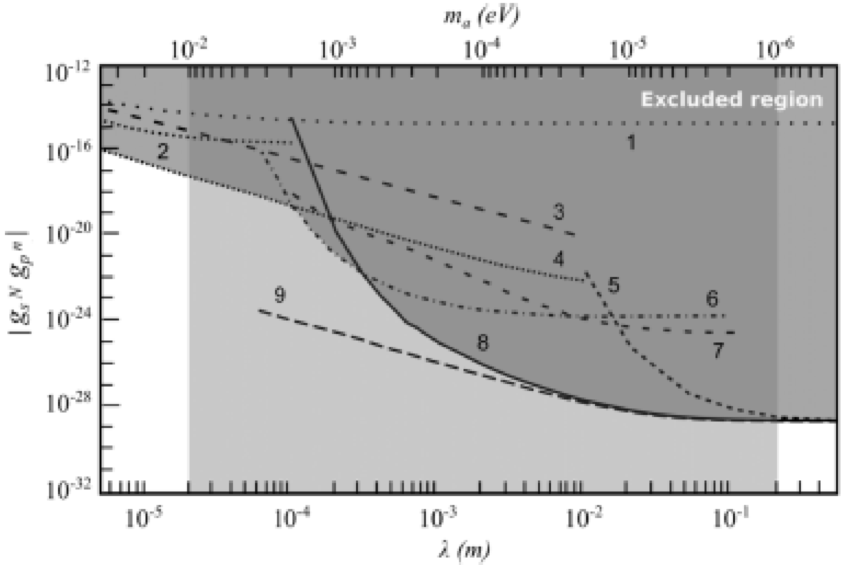
Spin-dependant short-ranged interactions: AXIONS

- exceptional beam time for systematic tests… in 2011
  - mirror setup 2010 untouched
  - installation of guiding field & detector with polarization analysis
  - 1 week of experiment (3 days of beam time, 40% duty cycle)



- results:





T. Jenke, Dissertation (TU Wien, 2011).

T. Jenke et al., PRL 112 (2014)151105

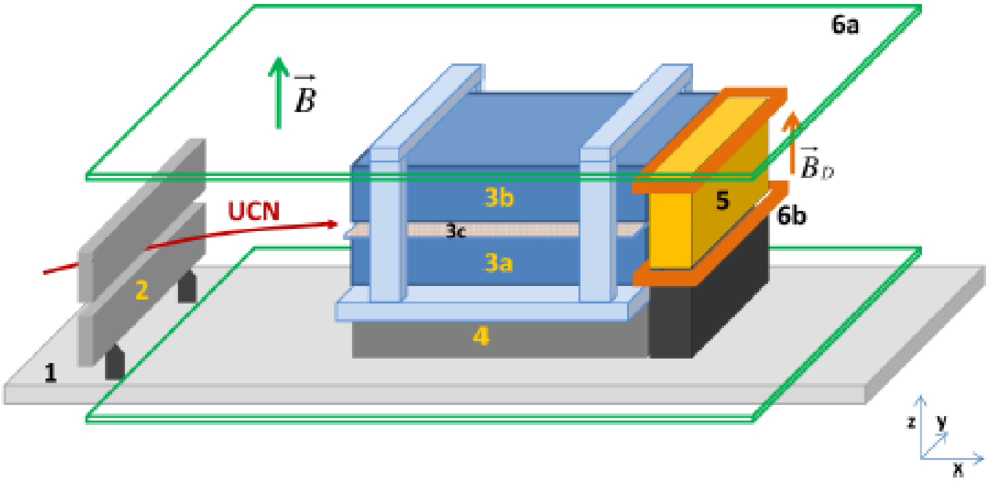
source: K. Tullney et al., PRL111, 100801 (2013).

Spin-dependant short-ranged interactions: AXIONS

- starting point: J.E. Moody, F. Wilczek, PRD30, 131-138 (1984)

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

- realization for the GRS setup of 2010:



- discovery potential [setup 2010]:

$$g_s g_p / \hbar c \geq \frac{3\cdot 10^{-16}}{\sqrt{days}}$$

$$(\lambda = 10\,\mu\text{m}, 68\%\,\text{C.L.})$$

T. Jenke, Dissertation (TU Wien, 2011).

T. Jenke et al., PRL 112 (2014)151105

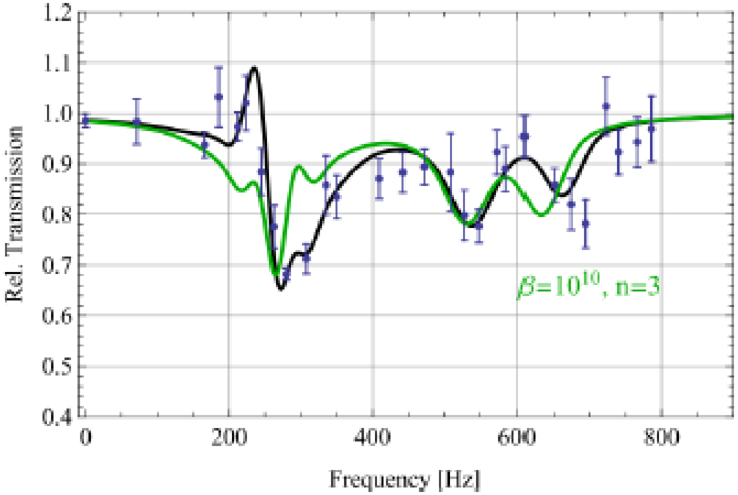
Strongly Coupled Chameleons

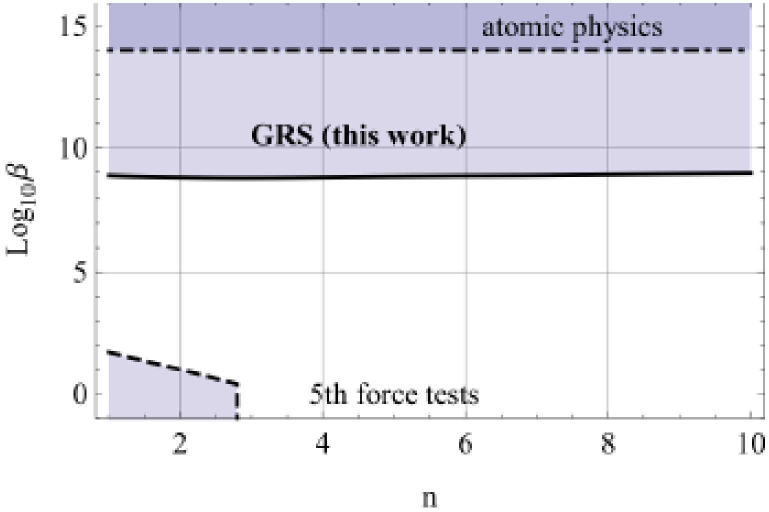
- starting point: P. Brax, G.Pignol, PRL 107, 111301 (2011).
  - UCN are not affected by thin-shell-effect
  - shifts of gravitational levels!
- generalization: A.N. Ivanov et al., PRD 87, 105013 (2013).

$$V_{\mathrm{Chameleon}} = \beta \frac{m}{M'_{\mathrm{Pl}}} \Lambda \left(\frac{n+2}{\sqrt{2}} \frac{\Lambda}{d} \left(\frac{d^2}{4} - z^2 \right) \right)^{\frac{2}{n+2}}$$

- how to? Add potential -> 2 more fit parameters, perform full χ^2 analysis
- result:

$$\beta > 5.8 \times 10^8 \ @ 2 < n < 4 \ (95\% \, \mathrm{C.L.})$$

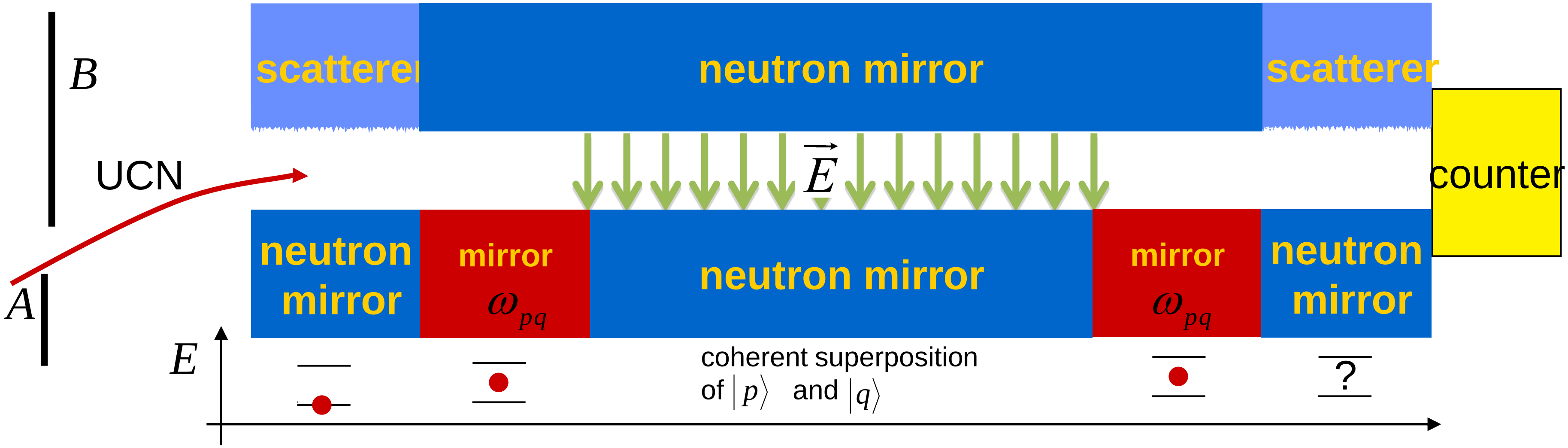




T. Jenke et al., PRL 112 (2014)151105

Outlook:
Probing neutrons neutrality

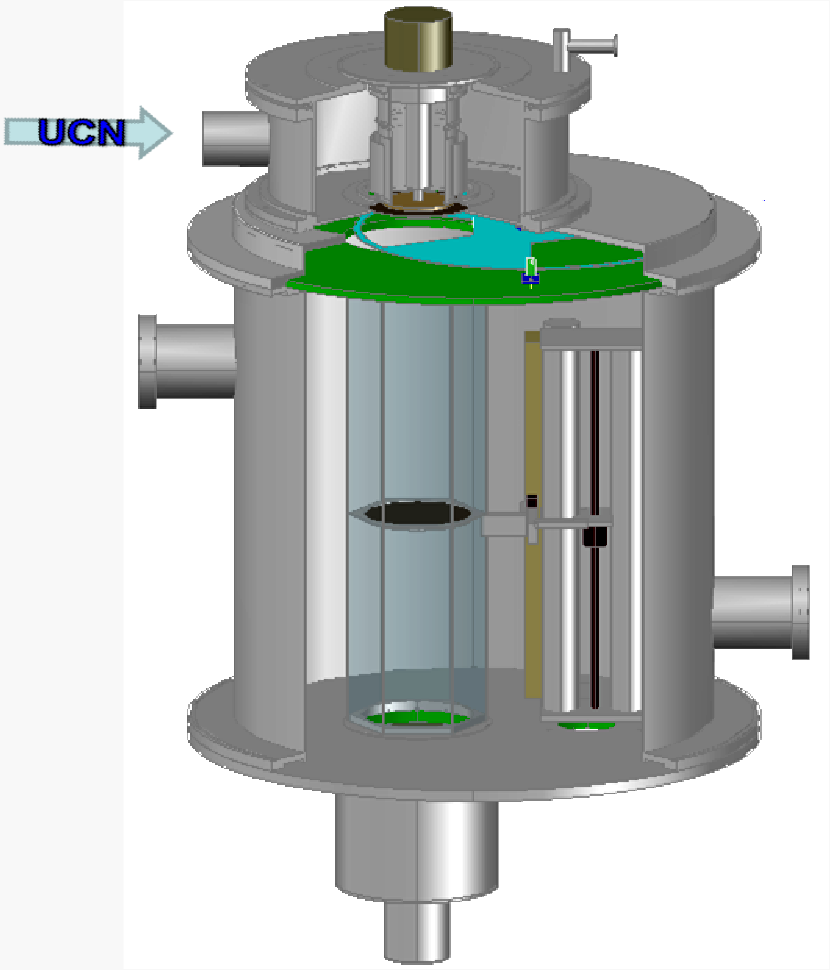
- Electric field modifies detectable phase

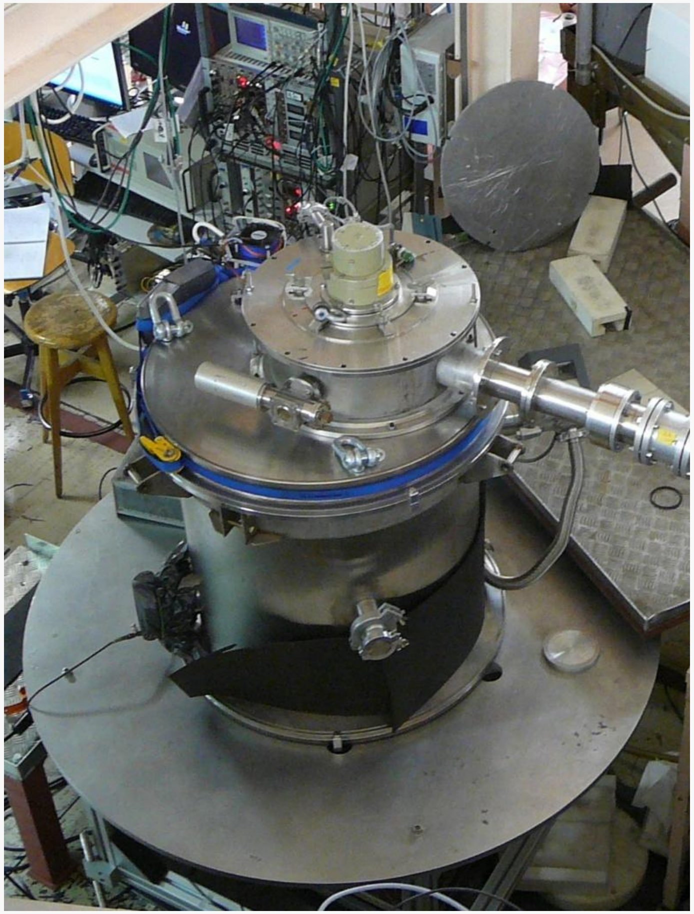


Durstberger-Rennhofer, K. et al. PRD **84, 036004 (2011)**

Gravitational UCN TOF spectrometer

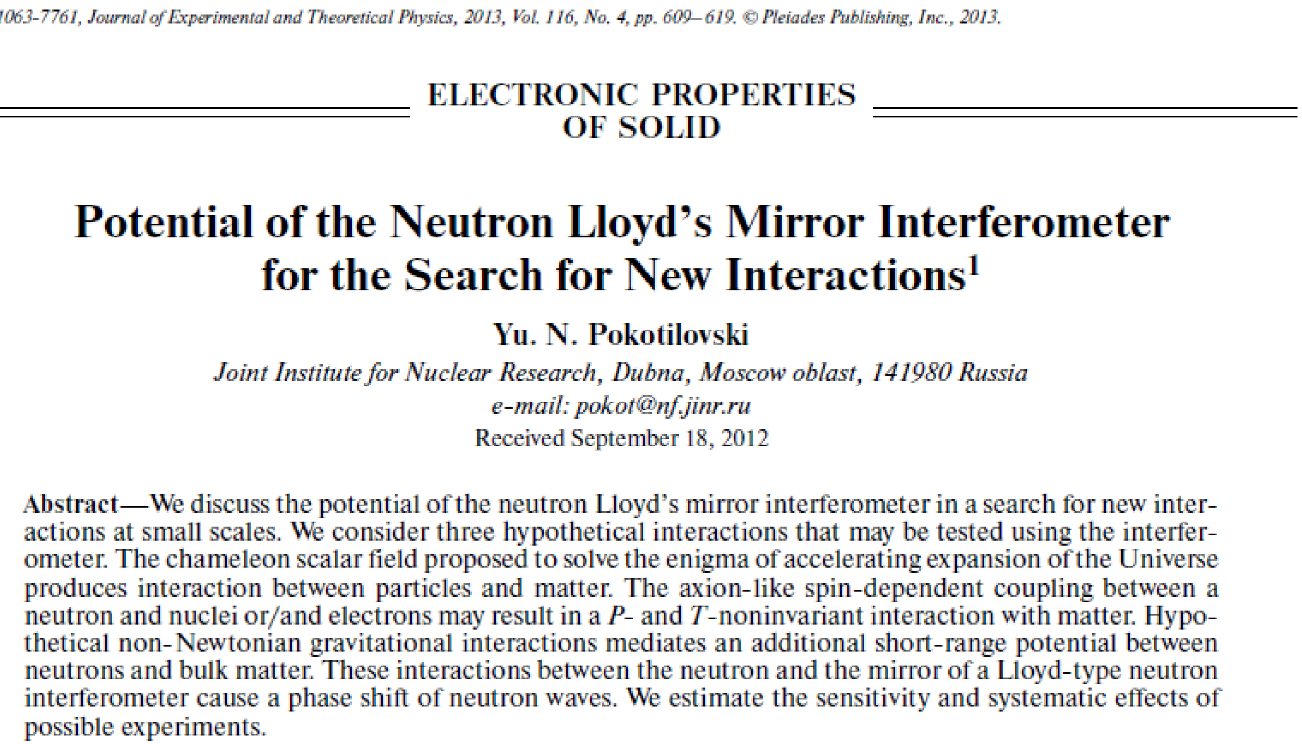
A. Frank and his team





A.I. Frank et al., Journ. Phys. Conf. Ser. 340 (2012) 012042

Lloyd's Interferometer for very cold neutrons
Yu. Pokotilovski
experiment by H. Abele's group



1063-7761, *Journal of Experimental and Theoretical Physics*, 2013, Vol. 116, No. 4, pp. 609–619. © Pleiades Publishing, Inc., 2013.

ELECTRONIC PROPERTIES OF SOLID

Potential of the Neutron Lloyd's Mirror Interferometer for the Search for New Interactions[1]

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Received September 18, 2012

Abstract—We discuss the potential of the neutron Lloyd's mirror interferometer in a search for new interactions at small scales. We consider three hypothetical interactions that may be tested using the interferometer. The chameleon scalar field proposed to solve the enigma of accelerating expansion of the Universe produces interaction between particles and matter. The axion-like spin-dependent coupling between a neutron and nuclei or/and electrons may result in a *P*- and *T*-noninvariant interaction with matter. Hypothetical non-Newtonian gravitational interactions mediates an additional short-range potential between neutrons and bulk matter. These interactions between the neutron and the mirror of a Lloyd-type neutron interferometer cause a phase shift of neutron waves. We estimate the sensitivity and systematic effects of possible experiments.

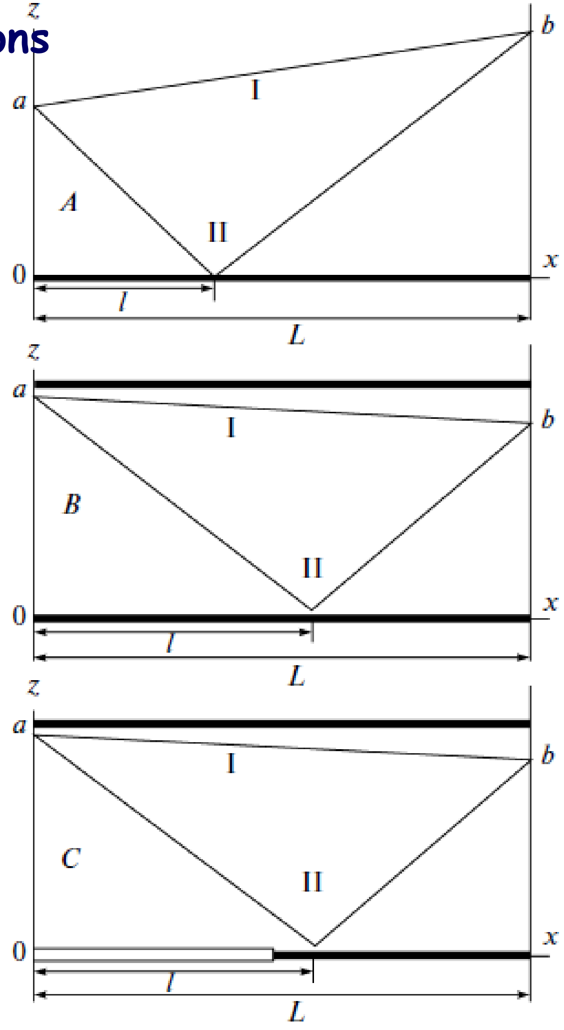

Fig. 1. Three possible configurations of the neutron Lloyd's mirror interferometer: (*A*) the standard Lloyd's mirror geometry; (*B*) interferometer with two mirrors, only the bottom one is reflecting; (*C*) the length of the reflecting mirror is decreased twice to avoid multiple reflections. All planes are vertical, and hence the effect of gravity on interference is reduced. The height of the slit above the reflecting plane is a, L is the distance from the slit to the detector surface, b is the distance of the detector coordinate from the reflecting plane, $l = aL(a + b)$ is the x coordinate of the beam-II reflection point from the mirror.

Recent PF2 highlights in ILL's Annual Reports

Search for mirror dark matter (2007)	
	A. Serebrov et al, Phys. Lett. B **663** (2008) 181
	G. Ban et al., Phys Rev. Lett. **99** (2009) 161603
Optics with accelerated matter (2007)	
	A. Frank et al, Phys. At. Nucl. **71** (2008) 1656
VCN reflection on diamond nanopowder (2008)	
	E. Lychagin et al, Phys. Lett. B **679** (2009) 186
Phase space transformer (2008)	
	S. Mayer et al, Nucl. Instr. Meth. A **608** (2009) 434
Test of Lorentz invariance (2009	
	I. Altarev et al, Phys. Rev. Lett. **103** (2009) 081602
Search for axion-like particles (2009)	
	A. Serebrov et al, JETP Lett. **91** (2010) 6
Gravity resonance spectroscopy (2011)	
	T. Jenke et al., Nature Phys. **7** (2011) 468
Improving our knowledge on dark matter and dark energy using ultracold neutrons (2012)	
	T. Jenke et al., arXiv:1208.3875 and PRL 112 (2014) 151105
Slow-neutron mirrors from holographic nanoparticle polymer composites (2013)	
	J. Klepp et al., Materials 5 (2012) 2788
MONOPOL – a travelling-wave magnetic neutron spin resonator for tailoring polarised neutron beams (2013)	
	E. Jericha et al., to be published
Neutrons constrain dark energy and dark matter scenarios	
	T. Jenke et al., PRL 112 (2014) 151105

UCN (at PF2 of the ILL) in the media

2015

- 19. Januar 2015: Deutschlandfunk / Forschung aktuell - Newton im Neutronen-Check

2014

- 5 June 2014 - The Huffington Post: Bouncing Neutrons Aid Search For Dark Matter, Dark Energy
- 15 May 2014 - The Hindu: No chameleons in dark energy?
- 13 May 2014 - The Huffington Post: Neutron Decay Mystery Baffles Physicists
- 7 Mai 2014 - Ziarul evenimentul (Romania) : Neuronii, cheia descoperirii unui mare mister! Vezi despre ce este vorba!
- 30 April 2014 - Space.com: Dark Matter and Dark Energy Mysteries: Do Neutrons Hold the Key?
- 23. April 2014 - Pro-Physik: Neutronen-Suche nach Dunkler Energie
- 18 April 2014 - Nature news - Bouncing neutrons probe dark energy on a table-top
- 17. April 2014 - derStandard.at - Suche nach der Dunklen Energie im Labor
- 16 April 2014 - Physics, viewpoint: Neutrons Knock at the Cosmic Door
- 16 April 2014 - International Science Times: The Use Of Neutrons To Understand The Mystery of Dark Energy
- 9 March 2014 - The Metro: getting the drop on quantum gravity more details in http://cosmonline.facultimedia.com/blog/2014/03/09/getti

2013

- 4 December 2013 - Physics World: Mystery of neutron-lifetime discrepancy deepens
- 25. August 2013 - Die Welt: Wie eisgekühlte Neutronen die Forschung verändern
- June 2013 - Physics World: Cool things to do with neutrons
- April 2013 - Laboratory News: The humble hero: general relativity, string theory, even the origins of the universe, why the neutron holds the a

2012

- 30 November 2012 - New Scientist, Instant expert: neutron science (A. Harrison; large section on fundamental physics with slow neutrons)
- 6 octobre 2012 - Le Monde : Des neutrons toujours perçants (ILL in general, particle physics with very slow neutron mentioned)

2011

- 7. Oktober 2011 - Deutschlandfunk : Kernteilchen unter der Lupe
- September 2011 - Physics World, blog - Big science at very low energies
- 8 September 2011 - Physics World - Ultracold neutrons probe the particle-physics frontier
- August 2011 - BBC Focus - What's inside a nuclear reactor + podcast
- 31. Mai 2011 - Frankfurter Rundschau / Berliner Zeitung : Der Schwerkraft auf der Spur
- 5 mai 2011 - Pour la science : La gravité mesurée à l'échelle quantique
- 5 mai 2011 - Futura sciences : Des faisceaux de neutrons ultra-froids pour tester la gravitation
- 21 April 2011 - scienceblogs.com : Bouncing Neutrons for Fun and Science - "Realization of a gravity-resonance-spectroscopy technique"
- 18 April 2011 - Physics and Physicists blog : Neutron Gravitational Quantum States Probed
- 18 April 2011 - BBC news online: Neutrons could test Newton's gravity and string theory
- 18 April 2011 - http://science.orf.at/stories/1681588/
- 17 April 2011 - All that matters, the Joerg Heber's blog : Gravity weighs in on spectroscopy

http://derstandard.at/1302745487356/Tricks-der-Quantenphysik-Neue-Methode-misst-Gravitation-auch-in-kleinsten-Dimensionen

http://www.sciencedaily.com/releases/2011/04/110418083349.htm

http://www.scientificcomputing.com/news-probing-the-laws-of-gravity-a-gravity-resonance-m-041811.aspx

http://www.physorg.com/news/2011-04-probing-laws-gravity-resonance-method.html

http://www.nature.com/nphys/journal/vaop/ncurrent/full/nphys1990.html

I hope I could convince you that

since their discovery in 1968 here in Dubna and simultaneously and independently in Garching


ultracold neutrons


– due to the fact that they are storable –

continue to be

a fancy and **powerful tool in fundamental physics**





Thank you, merci beaucoup and besten Dank for your attention!