# Particle Physics

at the

# high-precision / low-energy frontier

using

# UltraCold Neutrons

at the Institut Laue-Langevin in Grenoble

*Peter Geltenbort*

Very Hot Neutrons

$10^{7}$ eV

Ultracold Neutrons

$10^{-7}$ eV

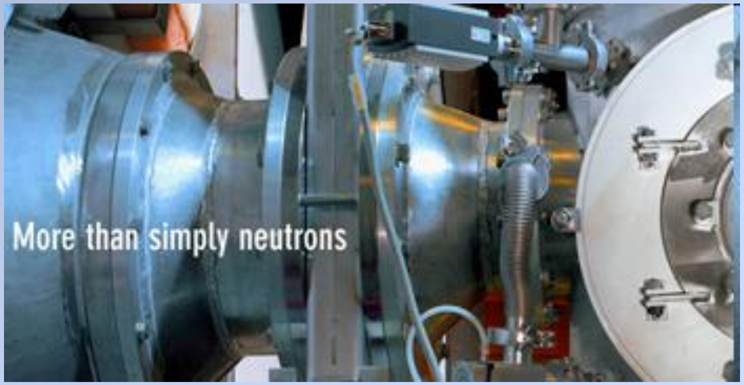
# Setting the scene

Thanks to the organizers for the very warm and generous "registration reception"

# Setting the scene

NEUTRONS FOR SCIENCE®
Institut Laue-Langevin

With its international funding and expertise the Institut Laue-Langevin (ILL) offers scientists and industry the world's leading facility in neutron science and technology. From its Grenoble site in the south-east of France the Institute operates the most intense neutron source on Earth

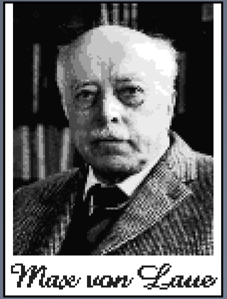


The ILL is firmly committed not only to building high-performance instruments but also to offering the best scientific environment to the user community

NEUTRONS
FOR SCIENCE

# Institut Laue-Langevin (ILL)

## “A neutron factory and an user facility”


Max von Laue

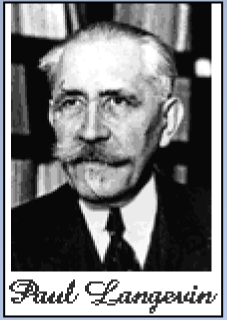
founded 17 January 1967
International Convention (renewal every 10 years)
signed until end 2013

first neutrons in 1971

cold and hot neutrons
sources started operation
in 1972

general refit from 1991 - 94

“earthquake” refit from 2003 - 07


Paul Langevin

*Millennium Programme*
phase M-0 done
phase M-1 running
phase M-2 in planning (141M€ in total)


H. Maier-Leibnitz


L. Neel

**Associates : France, Germany, United Kingdom**

Scientific Member Countries : A, B, CH, CZ, DK, E, H, I, IND, RUS , PL, S, SK

Further “Candidate” Countries: FIN, N, NL, FIN, RO, SLO, …

covers about 95% of European neutron users

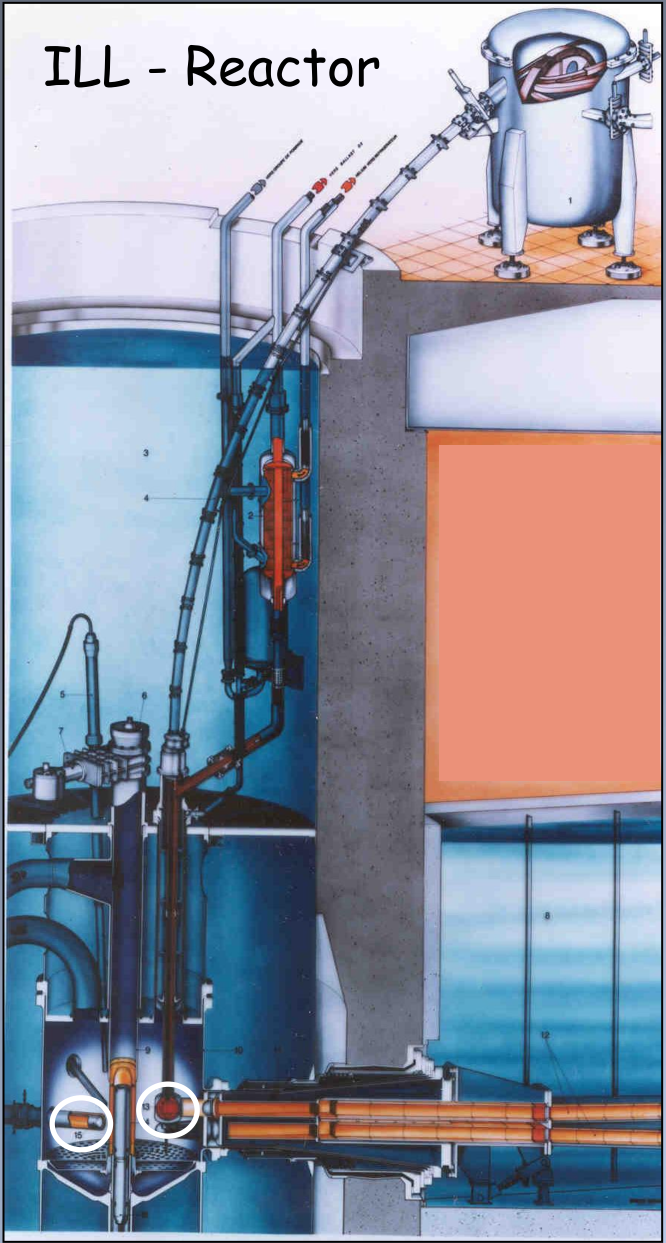
**Experimental Programme in 2010** (3 cycles of 50 days)
- 740 experiments (allocated by subcommittees) on 28 ILL-funded and 10 CRG instruments
- 1056 visitors coming from 35 countries
- 1142 proposals submitted and 670 accepted
- 652 publications by ILL staff and users

### Fields of research

solid-state physics, material science, chemistry, bio- and earth sciences, engineering,
**nuclear and particle (fundamental) physics**

489 staff (66 sci. + 32 PhD stud.); 88.5M€ annual budget

# Neutron source(s) at ILL



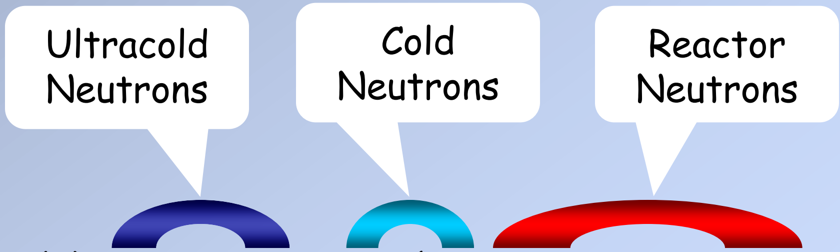
**Fuel** (chain reaction): $^{235}U(n_{th},f)$ → fission neutrons

**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 | |

NEUTRONS FOR SCIENCE

# The Nuclear and Particle Physics group (NPP)

## Nuclear physics

PN1 (LOHENGRIN)
Recoil mass spectrometer for fission fragments

PN3 (GAMS)
Ultra-high resolution gamma ray spectrometer

## Particle physics

PF1B
Facility for cold neutrons

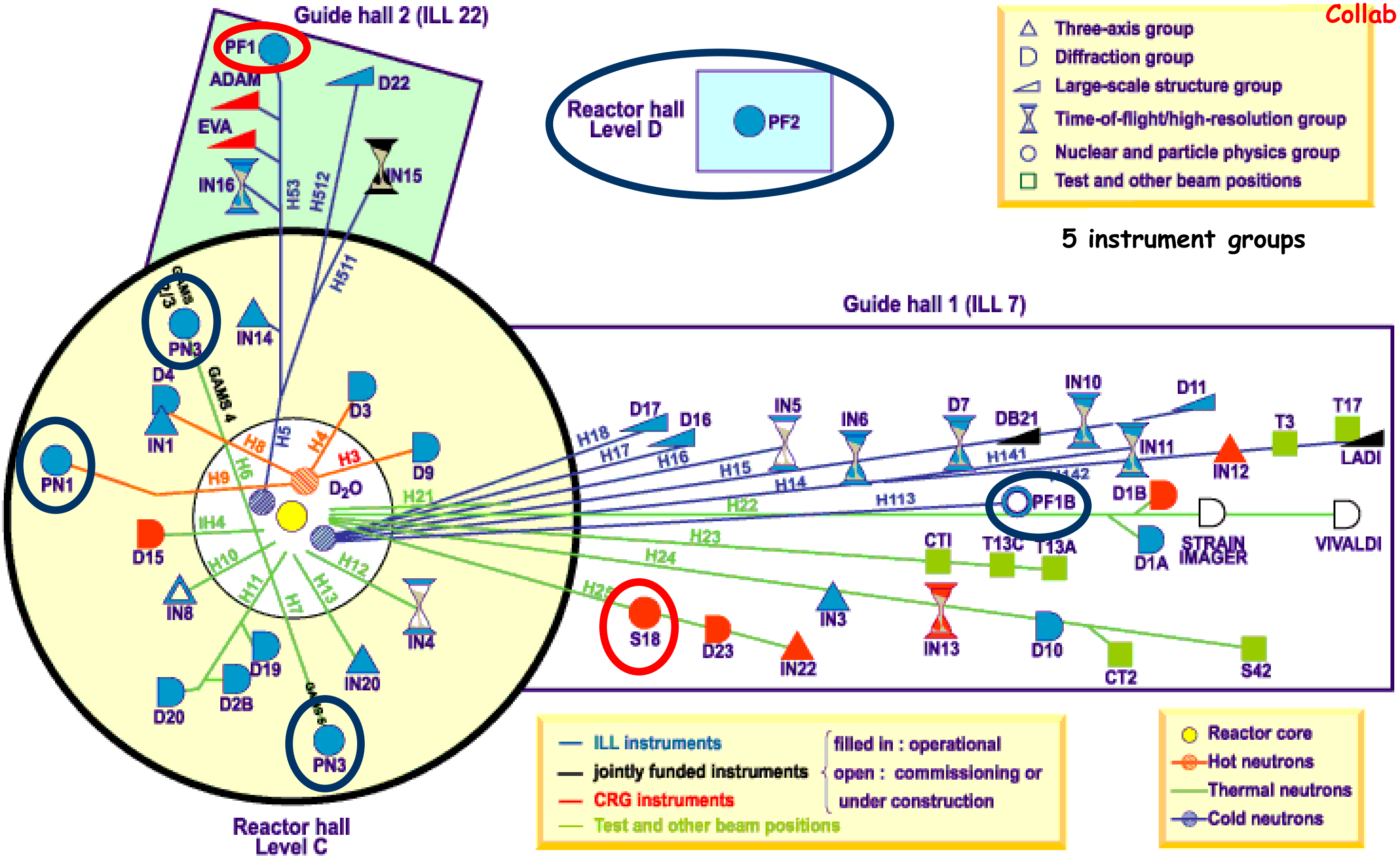
PF2
Facility for ultracold and very cold neutrons

(former PF1)
cryoEDM experiment

S18 - perfect crystal
neutron interferometer

ILL-funded

Collab. Research Group



5 instrument groups

**ESRF**

(6 GeV Synchrotron)

**ILL**

(High Flux Reactor)

# The Nuclear and Particle Physics group (NPP)

## Nuclear physics

**PN1 (LOHENGRIN)**
Recoil mass spectrometer for fission fragments

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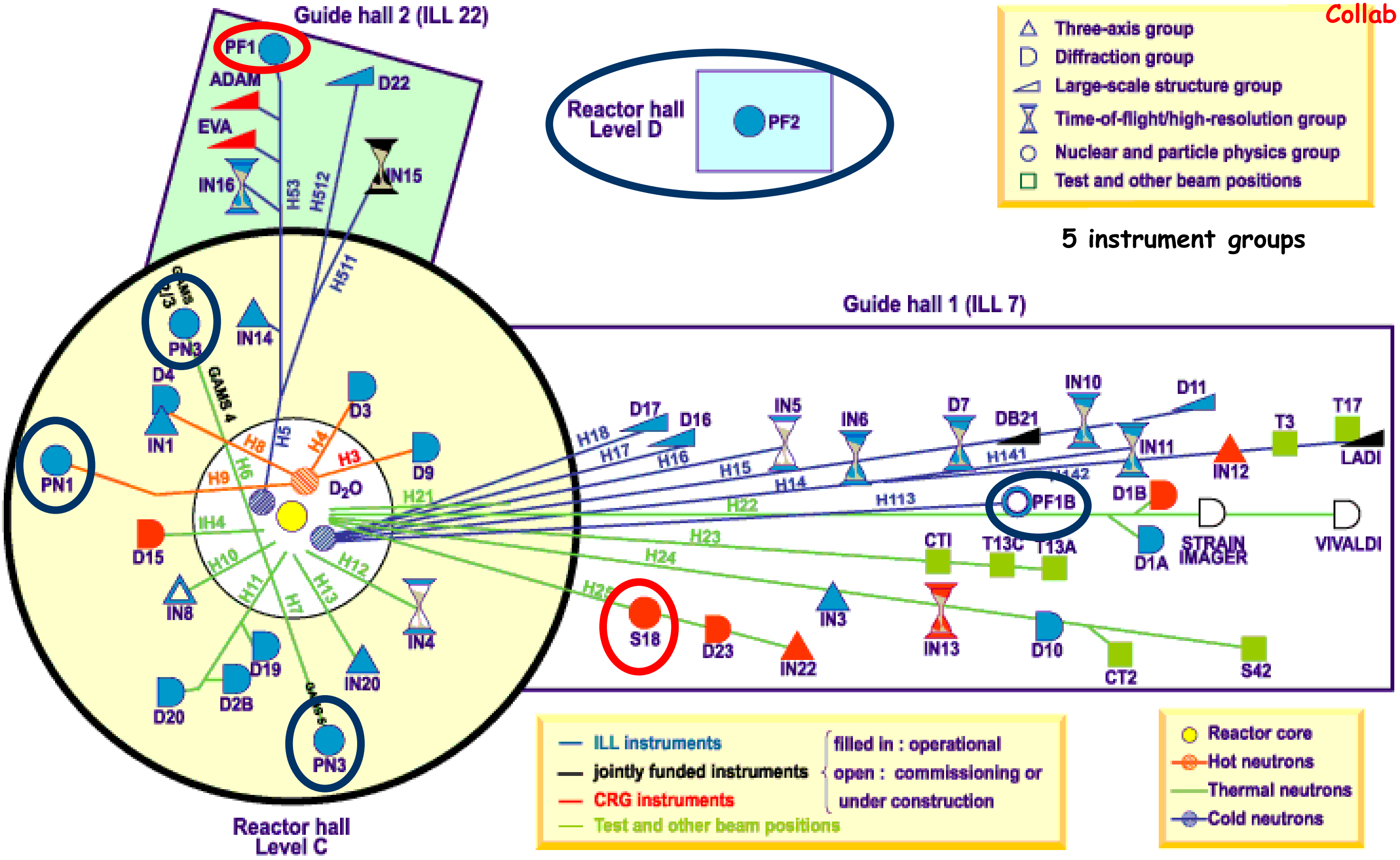
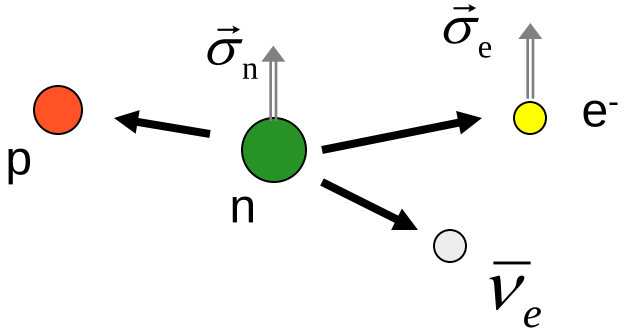


5 instrument groups

# Observables in Neutron Beta Decay

Jackson et al., PR 106, 517 (1957):

Observables in Neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance)



$$dw \propto \rho(E_e)\cdot\left(1+3|\lambda|^2\right)\cdot\left\{1+a\frac{\vec p_e\cdot\vec p_\nu}{E_e E_\nu}+b\frac{m_e}{E_e}\right.$$
$$\left.+\vec\sigma_n\cdot\left(A\frac{\vec p_e}{E_e}+B\frac{\vec p_\nu}{E_\nu}+D\frac{\vec p_e\times\vec p_\nu}{E_e E_\nu}\right)\right\}$$

Fierz interference term $b=0$

Beta-Asymmetry $A=-2\frac{|\lambda|^2+\mathrm{Re}\,\lambda}{1+3|\lambda|^2}$

Neutrino-Electron-Correlation $a=\frac{1-|\lambda|^2}{1+3|\lambda|^2}$

Neutron lifetime $\tau_n^{-1}=\frac{2\pi}{\hbar}G_F^2 V_{ud}^{\ 2}\left(1+3|\lambda|^2\right)\int\rho(E_e)$

# Hot topic questions beyond the SM

- What do we learn from $V_{ud}$ and quark mixing?
- What is the origin of P-violation?
- T-violation?

- Additional forces
- Number of quark generations
- Neutrino helicity
- Search for RHC: W-mass and mixing $\zeta$
- CP-violation

# 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**)

$\lambda_{UCN}$ ~ 1000 Å

$T_{UCN}$ ~ 2 mK

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

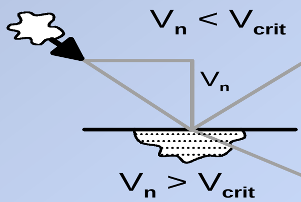
Long storage and observation times possible (up to several minutes)!

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.

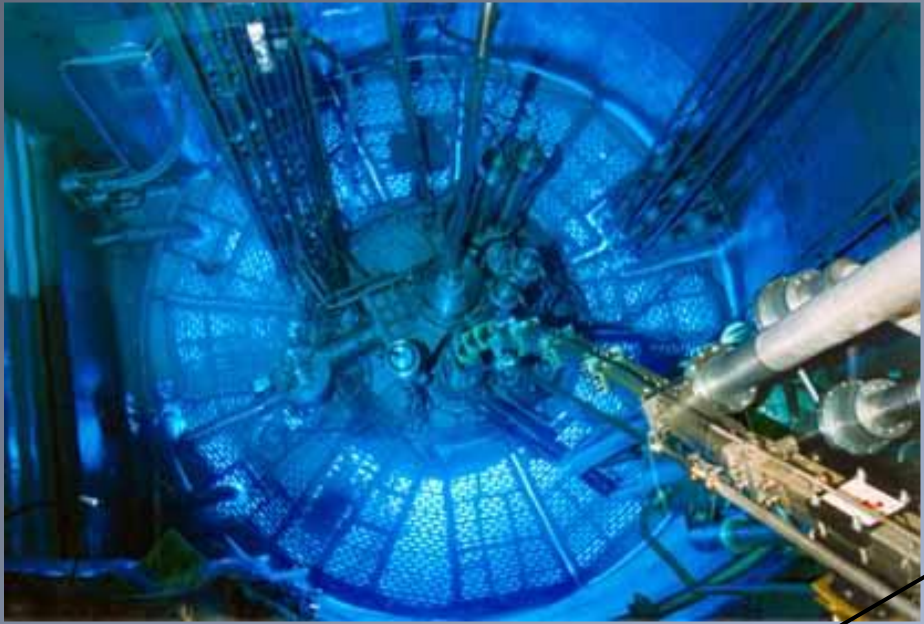
| | |
|---|---|
| - beryllium | 252 neV |
| - stainless steel | 200 neV |

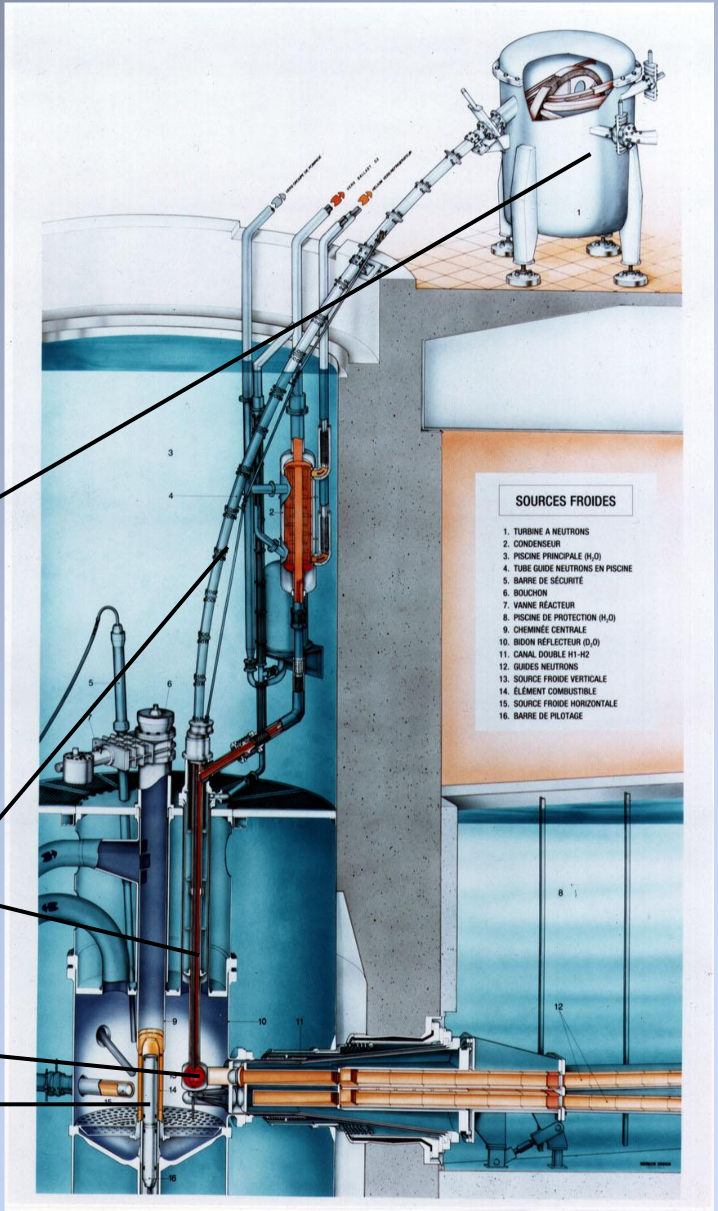


UCN are furthermore storable by gravity and/or magnetic fields

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

# The UCN/VCN facility PF2





Neutron turbine
A. Steyerl (TUM - 1985)

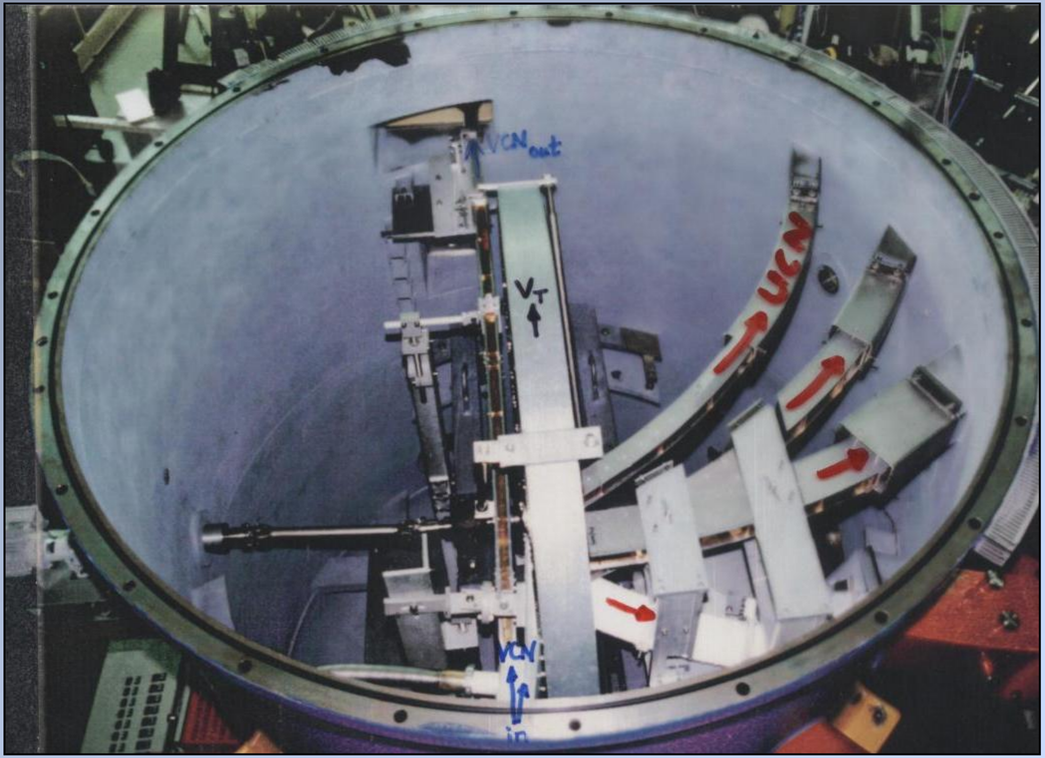
Vertical and curved guide tubes

Cold source

Reactor core

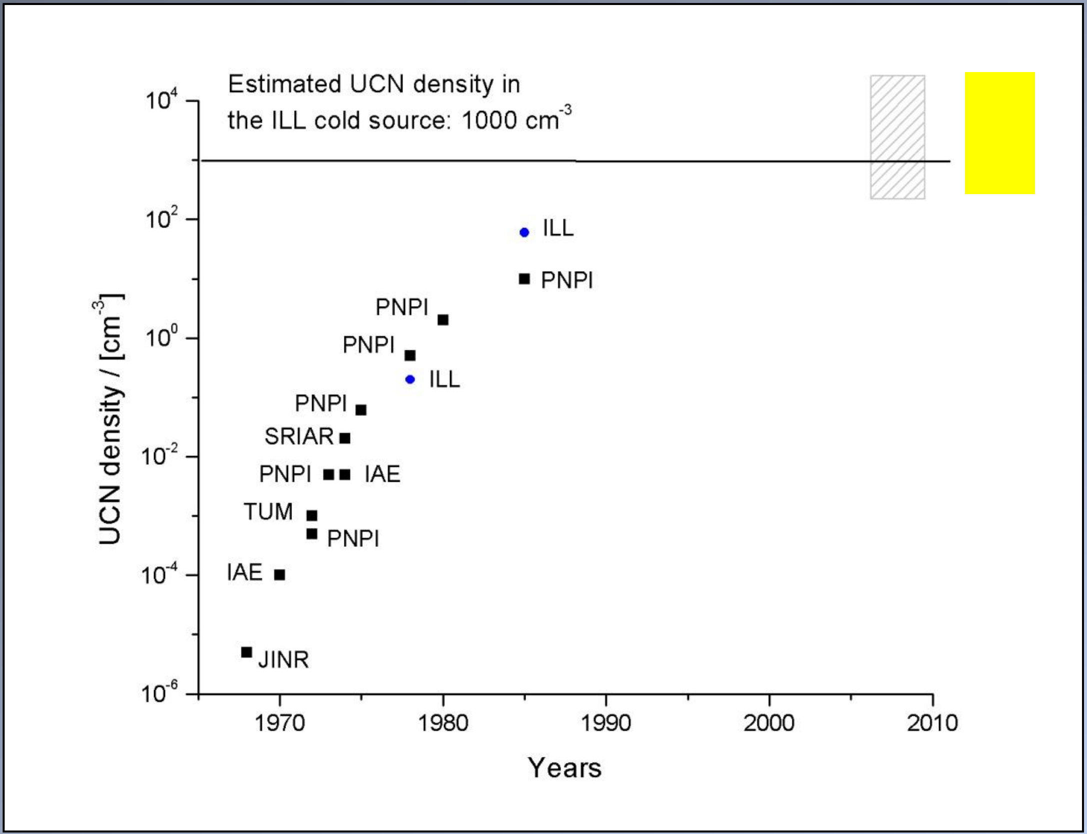
# The Vertical Cold Source (VCS)

Steyerl turbine
at FRM-I (Munich)



Steyerl turbine (2$^{nd}$ generation)
at PF2 / ILL
10 years later

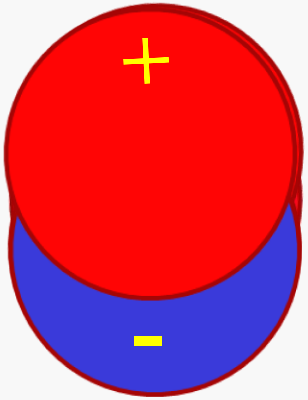
# UCN facilities – Status and Future



More UCN facilities in the future worldwide

- **PSI (CH)**
- **Mainz / Munich (D)**
- **ILL (F)**
- **PNPI (RUS)**
- **LANL / NCSU** *[SNS/ NIST]* **(USA)**
- **RCNP / JPARC (J)**
  later at TRIUMF (CAN)

# EDM  CP violation

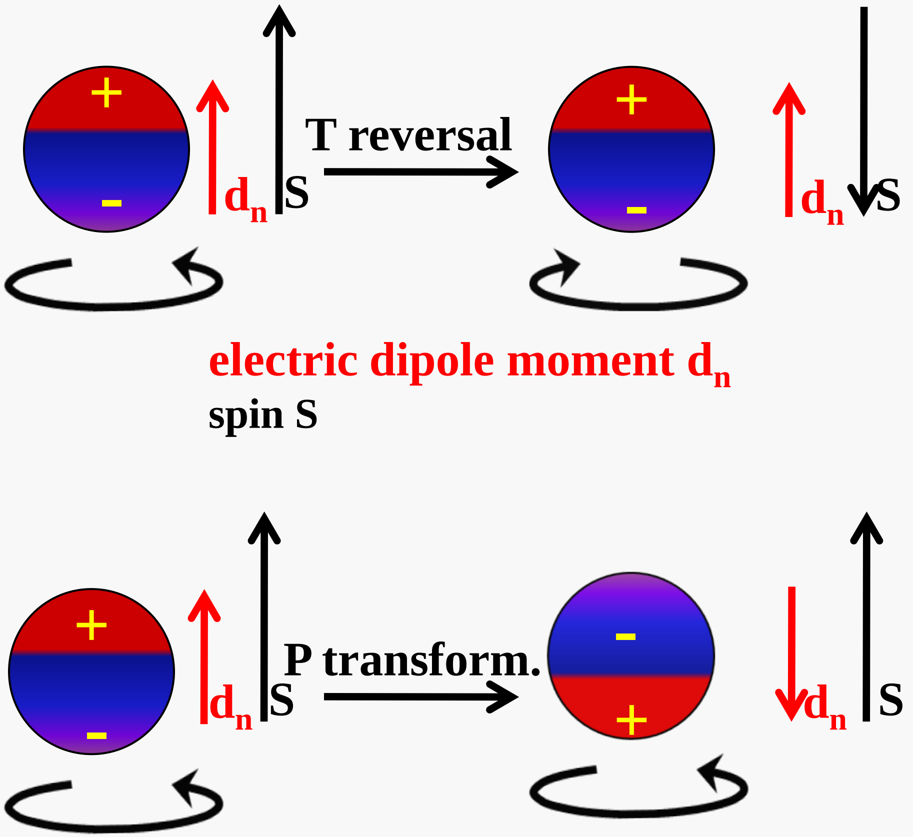


**Electric Dipole Moment:**

**electrically neutral or charged particles**

**If there is a charge distribution:**

**EDM**



electric dipole moment $d_n$

spin S

**P & T violation**

**CPT conservation → CP violation**

# EDM CP violation

The Electric Dipole Moment: $d_n$

$d_n \neq 0 \quad \Rightarrow \quad P$ and $T$ violation

---

*CP* violation observed in K decay, B mesons → $d_n \neq 0$

**CP violation, interest**

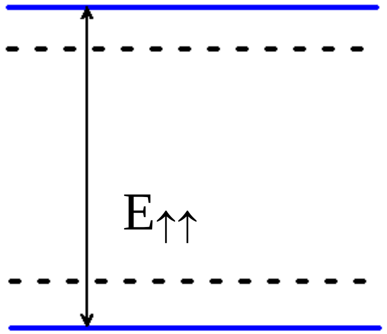
- The study of CP violation is important to:
  - Understanding the fundamental laws of physics
  - Understanding the baryon asymmetry of the cosmos
- EDM is a particularly promising laboratory for CP violation
  - The Standard Model contribution is very small
  - Contributions from new physics tend not to be

# nEDM: spin frequency

Experiments:

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

Compare the precession frequency for parallel fields:

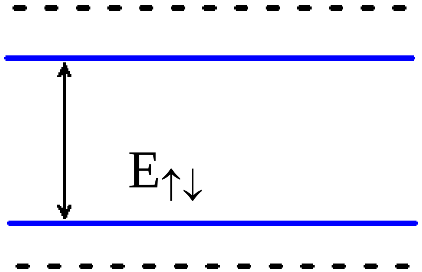


$$\nu_{\uparrow\uparrow} = E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$

The difference is proportional to $d_n$ and $E$:

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

to the precession frequency for anti-parallel fields

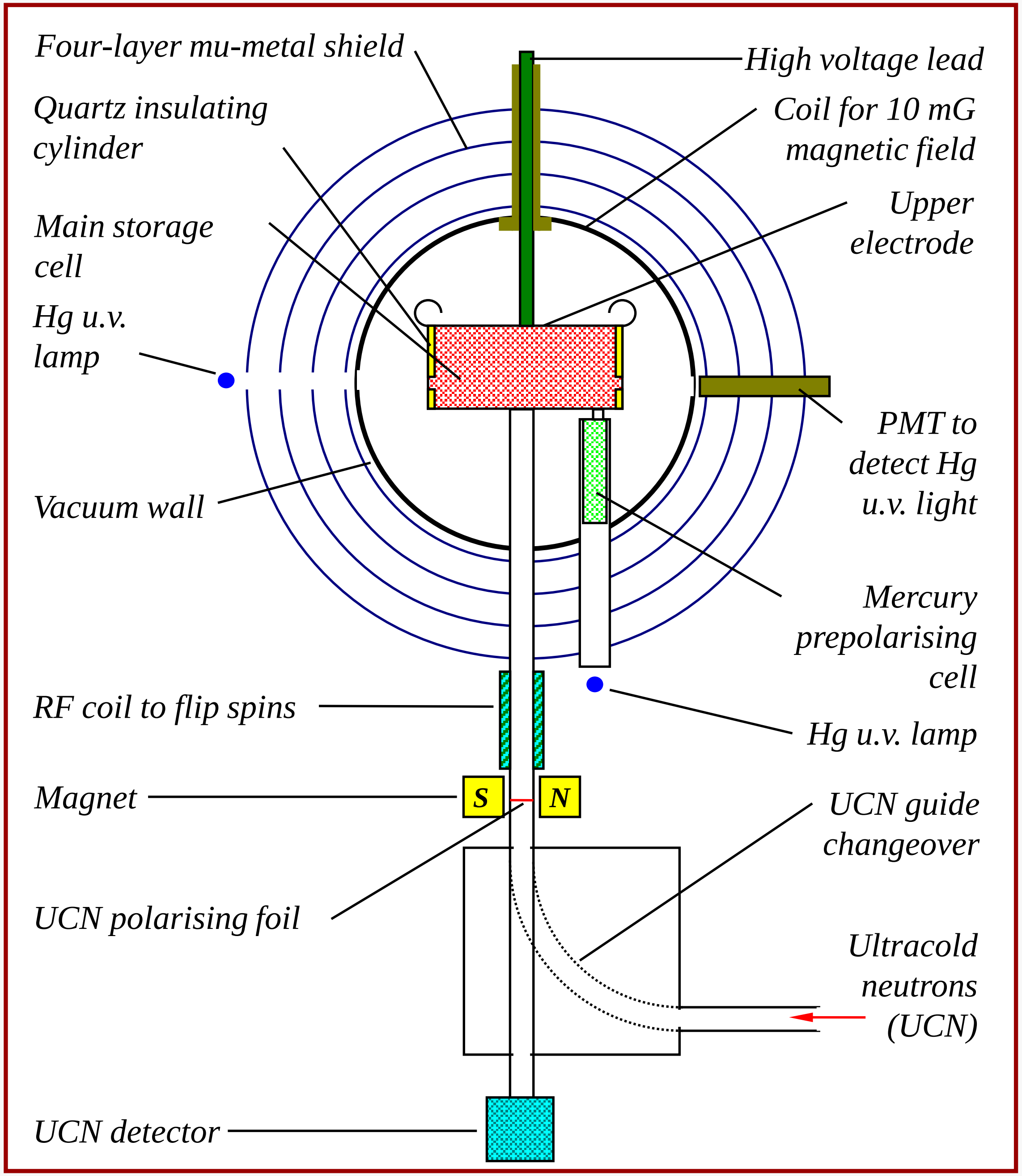


$$\nu_{\uparrow\downarrow} = E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

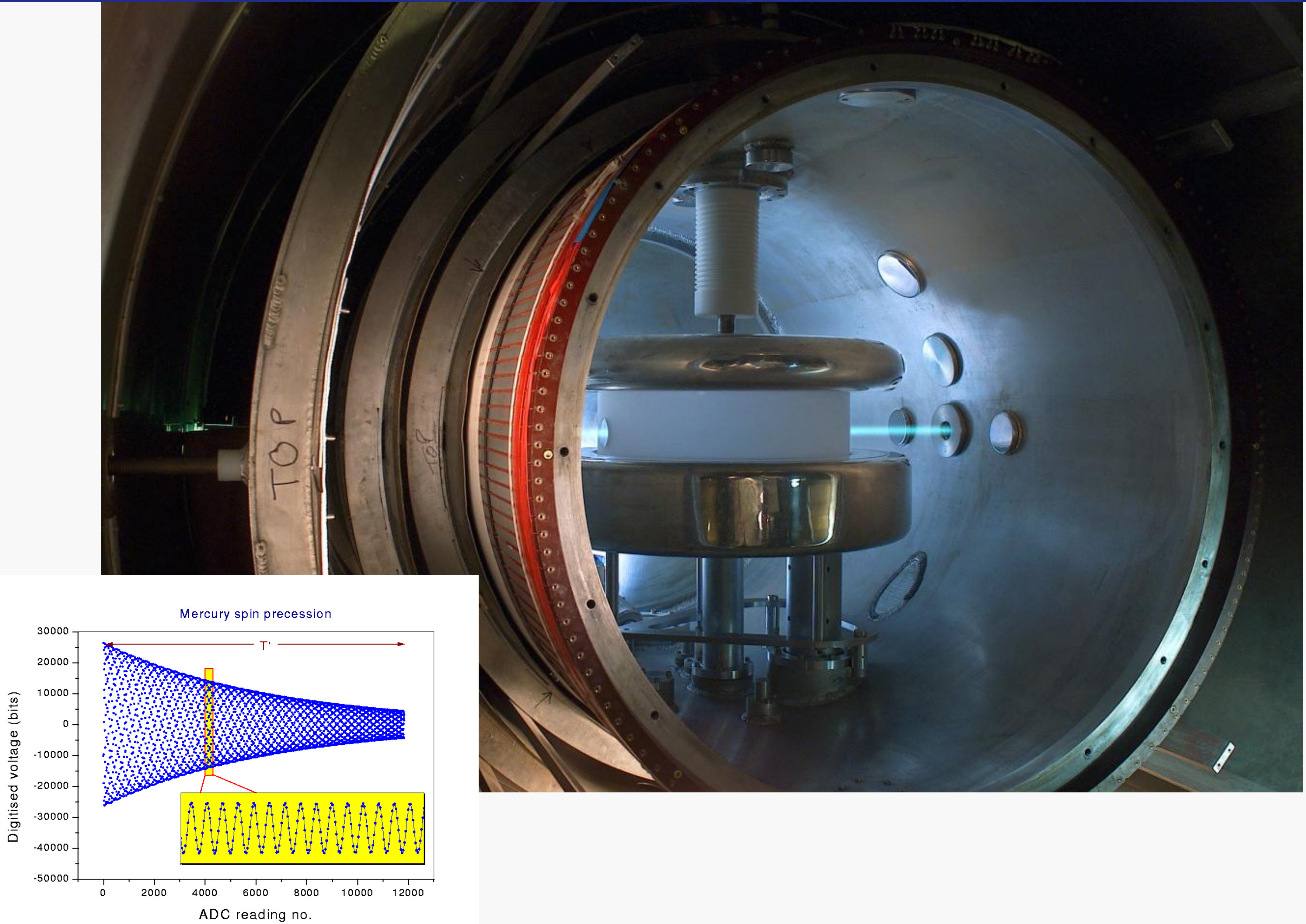
Need to measure change in Larmor precession frequency to a very high degree : < 1μHz

<1 turn per month!

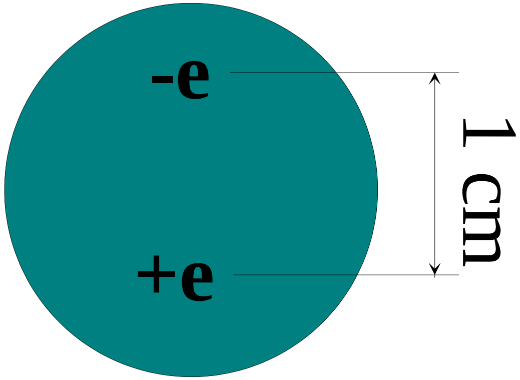
# nEDM: ILL


Four-layer mu-metal shield
High voltage lead
Quartz insulating cylinder
Coil for 10 mG magnetic field
Main storage cell
Upper electrode
Hg u.v. lamp
PMT to detect Hg u.v. light
Vacuum wall
Mercury prepolarising cell
RF coil to flip spins
Hg u.v. lamp
Magnet
S
N
UCN guide changeover
UCN polarising foil
Ultracold neutrons (UCN)
UCN detector

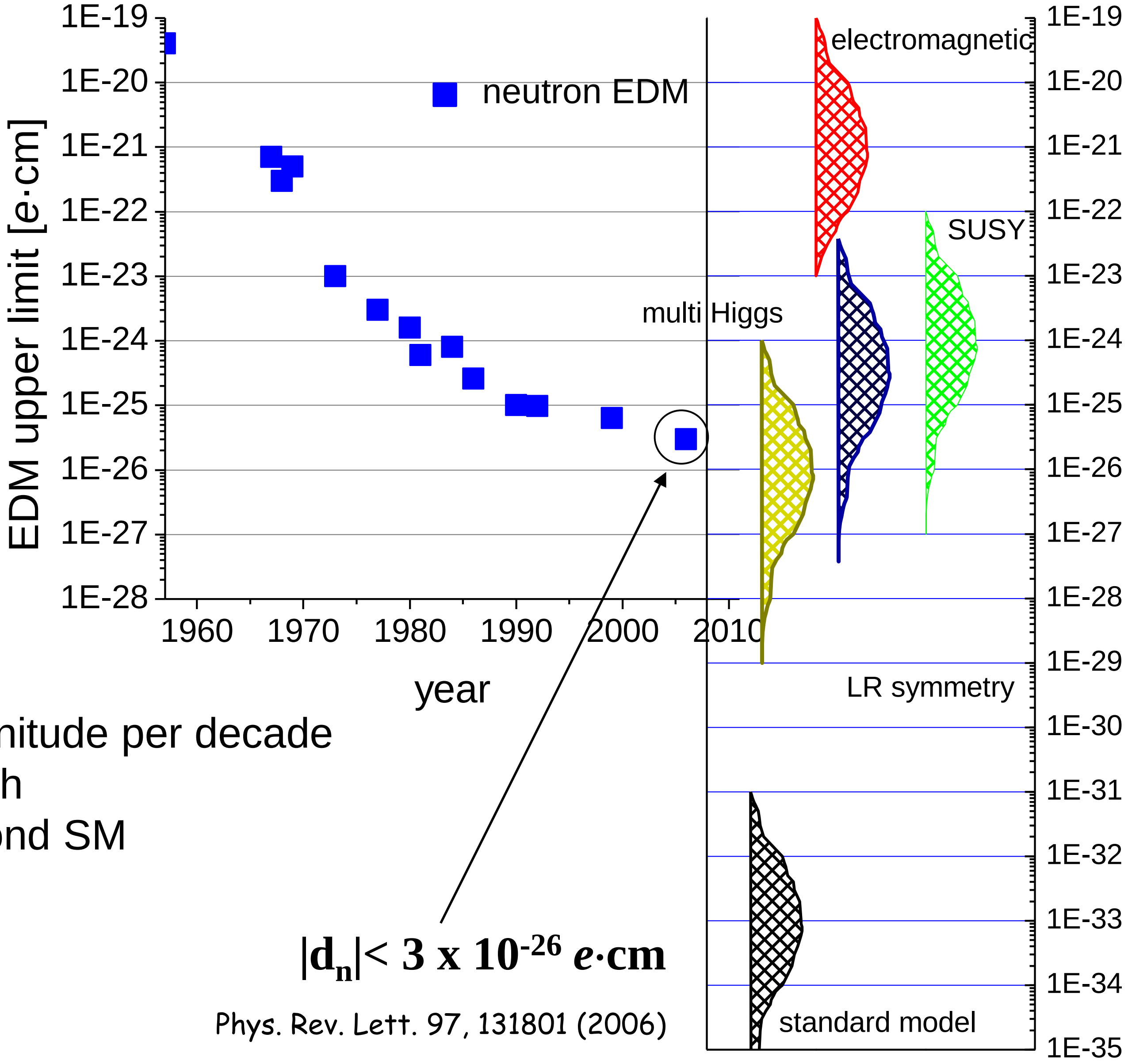
# nEDM: ILL


TOP
Mercury spin precession
T'
Digitised voltage (bits)
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
0
2000
4000
6000
8000
10000
12000
ADC reading no.

# EDM models - experiment



**$d_n = 1\ e\cdot\text{cm}$**



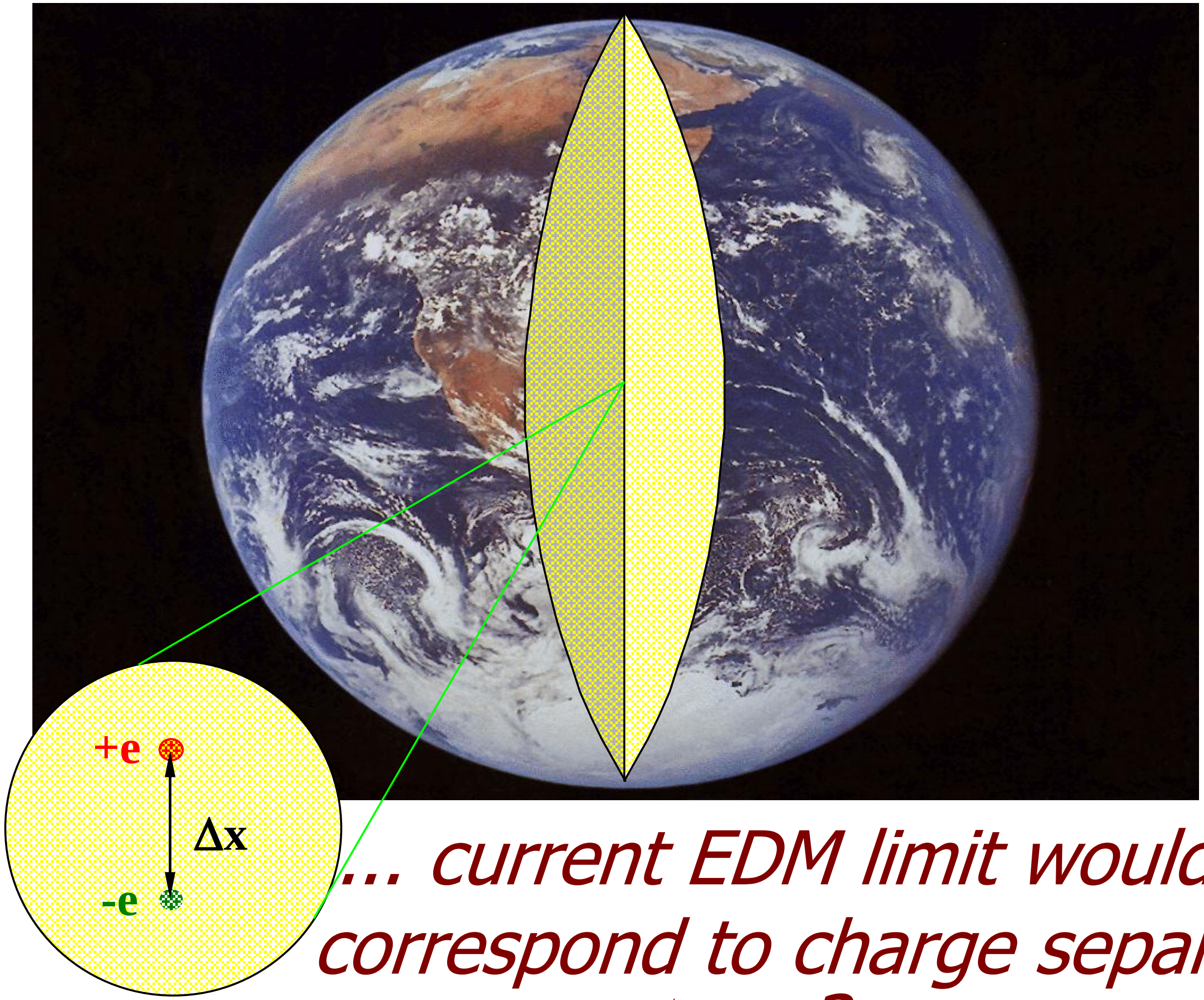
**$|d_n| < 3 \times 10^{-26}\ e\cdot\text{cm}$**

Phys. Rev. Lett. 97, 131801 (2006)

Progress at ~ order of magnitude per decade
Standard Model out of reach
constraints on models beyond SM

# Reality check

*If neutron were the size of the Earth...*



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

# nEDM: cryoEDM

$$\sigma(d_n) = \frac{\hbar}{2ET\alpha\sqrt{N}}$$

new superthermal UCN source

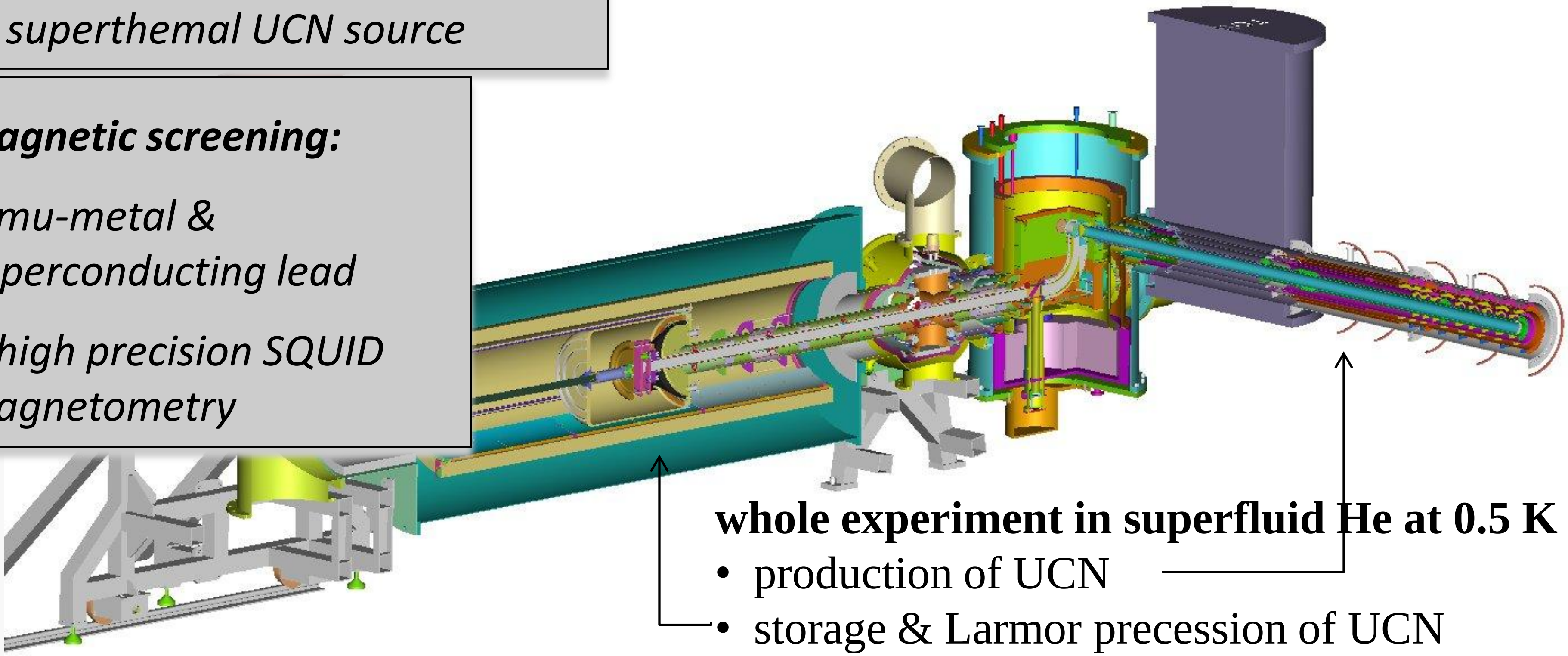
higher electric fields in *l*He

***Ultra-cold neutron source:***

*Strong 9 Å neutron beam coupled to superthemal UCN source*

***magnetic screening:***

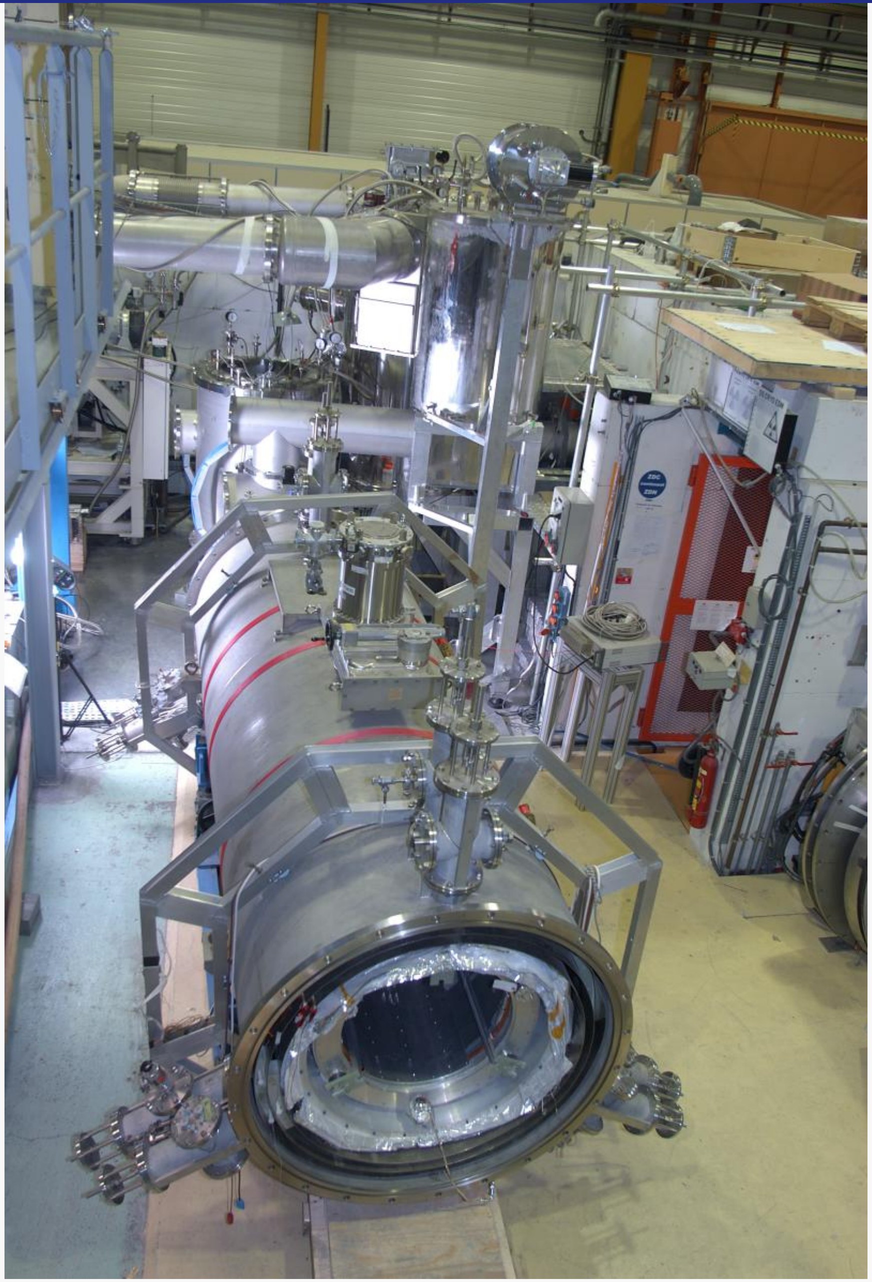
- *mu-metal & superconducting lead*
- *high precision SQUID magnetometry*



**whole experiment in superfluid He at 0.5 K**

- production of UCN
- storage & Larmor precession of UCN
- magnetometry
- detection of UCN

# nEDM: cryoEDM outlook



*Cryogenic apparatus working: base temperature ~ 0.5K*

*UCN production, transfer & storage system working => needs optimising*

*HT applied on system => needs enhancing*

*Magnetic field system operational => will require further improving*

***Experiment runs (commissioning) but most parameters need improvement for order of ~$10^{-27}$ e·cm measurement***

# 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

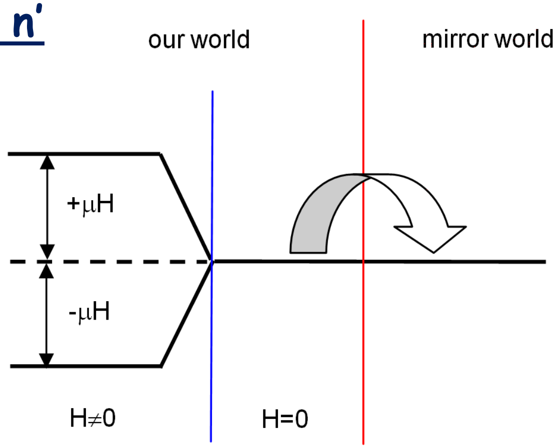
*Hypothesis:* There is a "mirror world" of partners of the known particles with

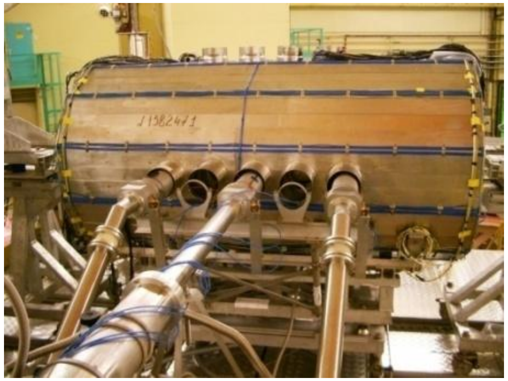
- same fundamental interactions with opposite handedness
  → natural explanation of parity violation
- no interactions with our world, apart gravity and mixing of neutral particles
  → mirror matter is a viable dark-matter candidate

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:

$\tau_{osc}$ (90% C.L.) $\geq$ **414 s**

A. Serebrov et al., arXiv:0706.3600; submitted to PLB

# Search for Macroscopic CP Violating Forces Using a Neutron EDM Spectrometer¶

**A. P. Serebrov[a], O. Zimmer[b], P. Geltenbort[b], A. K. Fomin[a], S. N. Ivanov[a], E. A. Kolomensky[a],**
**I. A. Krasnoshekova[a], M. S. Lasakov[a], V. M. Lobashev[a], A. N. Pirozhkov[a],**
**V. E. Varlamov[a], A. V. Vasiliev[a], O. M. Zherebtsov[a], E. B. Aleksandrov[c],**
**S. P. Dmitriev[c], and N. A. Dovator[c]**

[a] *Petersburg Nuclear Physics Institute, Russian Academy of Sciences, Gatchina, Leningrad region, 188300 Russia*
*e-mail: serebrov@pnpi.spb.ru*
[b] *Institut Laue Langevin, BP 156, 38042 Grenoble, France*
[c] *Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

Received December 8, 2009

The search for CP violating forces between nucleons in the so-called axion window of force ranges λ between $2 \times 10^{-5}$ m and 0.02 m is interesting because only little experimental information is available there. Axion-like particles would induce a pseudo-magnetic field for neutrons close to bulk matter. A laboratory search investigates neutron spin precession close to a heavy mirror using ultracold neutrons in a magnetic resonance spectrometer. From the absence of a shift of the magnetic resonance we established new constraints on the coupling strength of axion-like particles in terms of the product $g_s g_p$ of scalar and pseudo-scalar dimensionless constants, as a function of the force range $\lambda$, $g_s g_p \lambda^2 \leq 2 \times 10^{-21}$ [cm$^2$] (C.L.95%) for $10^{-4}$ cm $< \lambda < 1$ cm. For 0.1 cm $< \lambda < 1$ cm previous limits are improved by 4 to 5 orders of magnitude.

**DOI:** 10.1134/S0021364010010029

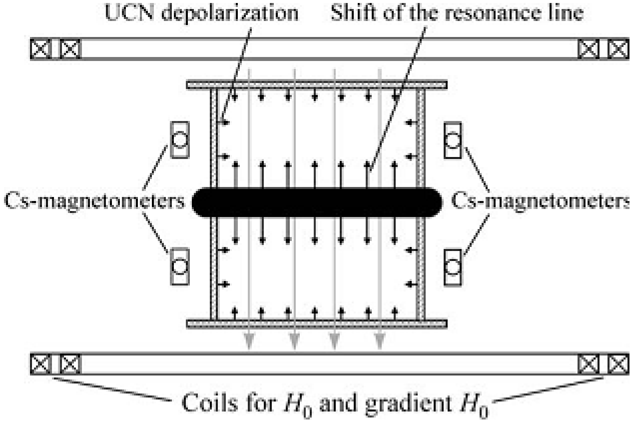


**Fig. 1.** Experimental setup with double storage chamber for UCN, Cs-magnetometers and coils for field setting and correction.

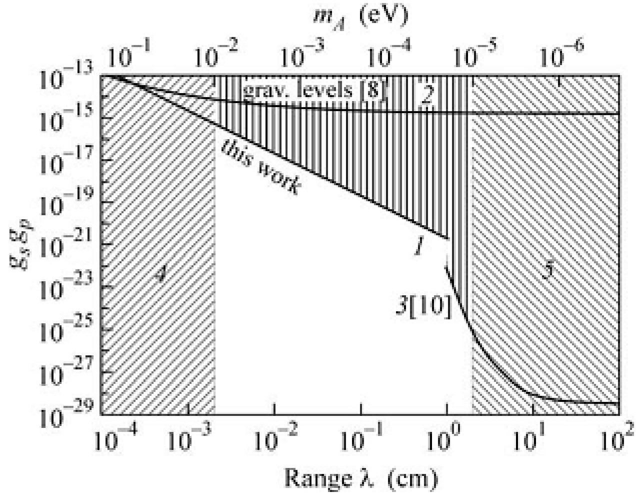
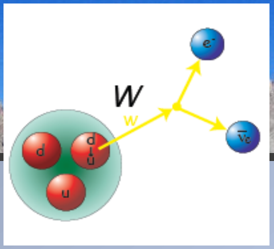


**Fig. 3.** Constraints to the coupling constant product $g_s g_p$ of axion-like particles to nucleons as a function of the range λ of the macroscopic force. On the upper horizontal axis the mass range of the axion-like particle is shown using the relation $\lambda = \hbar/m_A c$. Line *1*: shift of resonance (this work); line *2*: gravitational levels [8]; line *3* [10]; line *4*: astrophysically excluded region of axion mass [3]; line *5*: cosmologically excluded region in model of cold dark matter [3].

# Is our world really isotropic?

**Abstract:** *Physics at the Planck scale could be revealed by looking for tiny violations of fundamental symmetries in low energy experiments. In 2008, we have performed a sensitive test of the isotropy of the Universe using stored Ultra Cold Neutrons, obtaining the first limit on the coupling of a free neutron with a hypothetical cosmic axial field.*

**Figure 1** : The hypothetical cosmic axial field, defining a privileged direction in the universe, is searched for in daily modulation of precision observables.



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

$$\frac{1}{\tau_n} \propto G_F^2,\ V_{ud}^2,\ \lambda^2 \qquad \lambda = \frac{g_A}{g_V}$$

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

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

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 ($V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$)

*Weak interaction theory*

*Neutrino physics*

*Cosmology*

Solar pp-process:

$$p + p \rightarrow d + e^+ + \nu_e \qquad \sigma \propto g_A^2$$

Big bang:

Primordial elements' abundances

Neutrino induced reactions:

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

$$\nu_\mu + n \rightarrow \mu^- + p$$

Neutrino detectors:

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

$$\sigma \propto \frac{1}{\tau_n}$$

**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**

# A “typical” UCN storage experiment at ILL – MamBo I

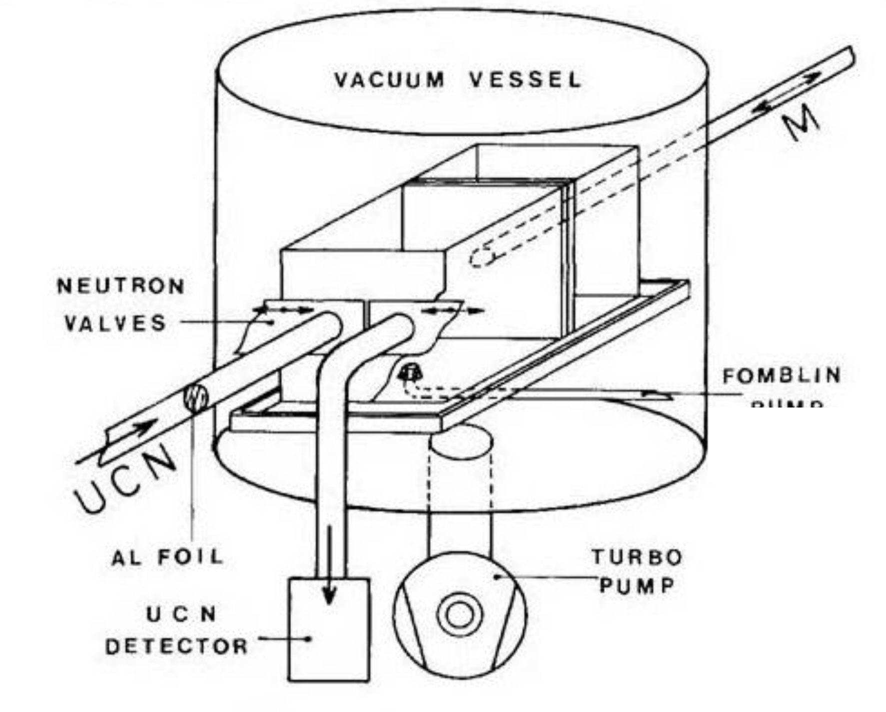


FIG. 1. Sketch of the apparatus.

Glass walls:
H=0.3 m, W=0.4 m
L=0.5m … 0.01 m
(surface *A* and volume *V* sizeable)

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

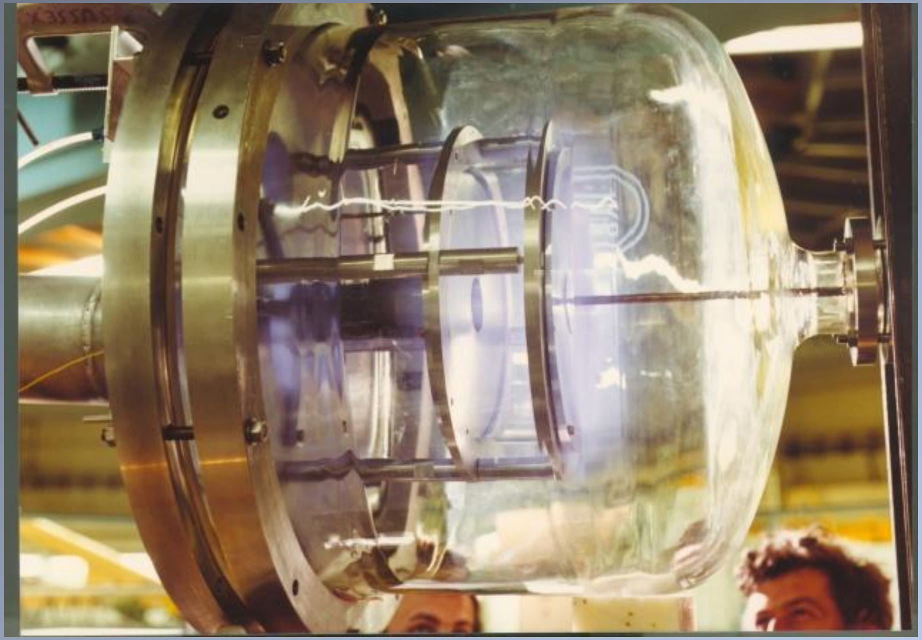
$\tau_{\text{wall}} \rightarrow$ number of wall collisions, i.e. mean free path $\lambda$

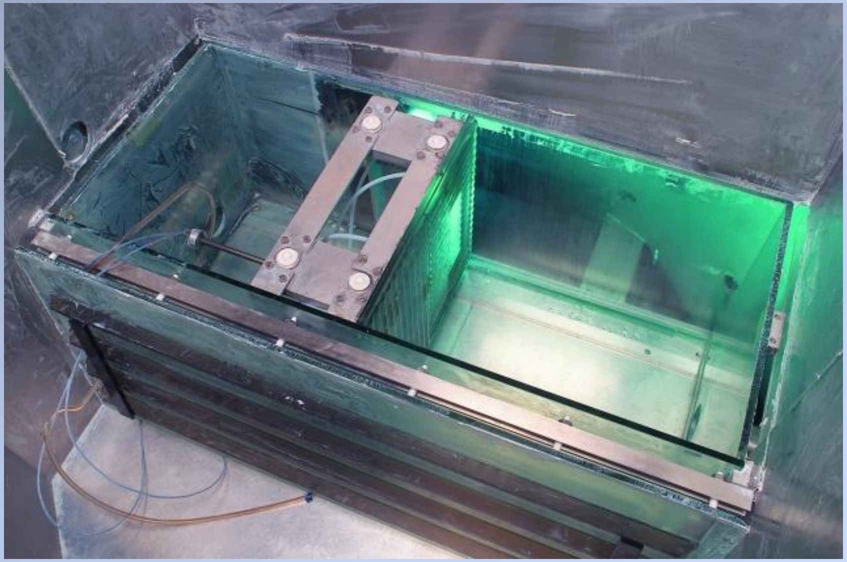
Measure storage lifetime $\tau_m$
-for different
volume to surface ratios *V/A*
- and extrapolate for $V \rightarrow \infty$

$$\frac{1}{\tau_{\text{wall}}} \rightarrow 0$$

## MamBo I

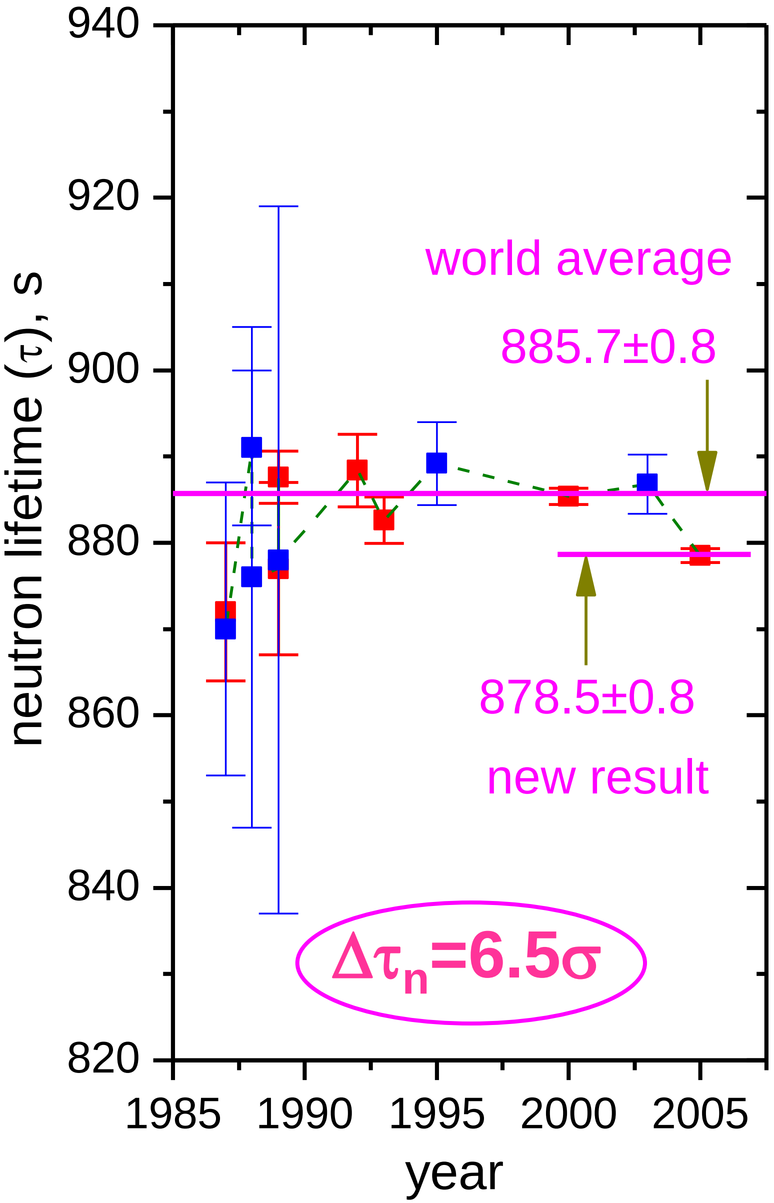
## MamBo II





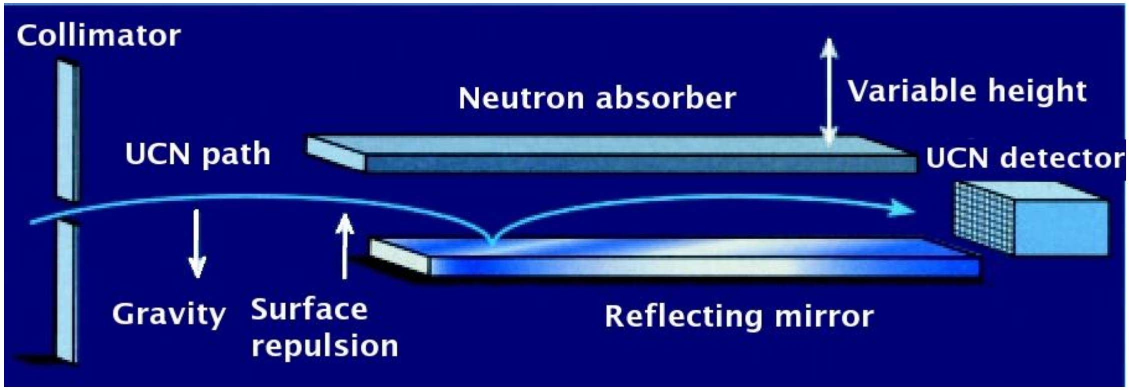
# Neutron lifetime: world average and new result

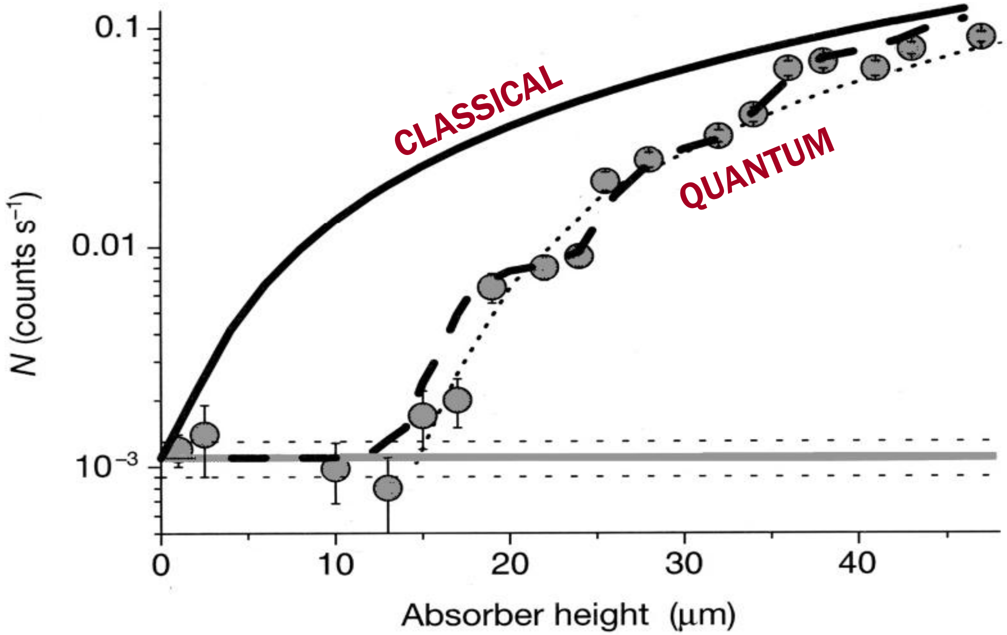
| Lifetime τ[s] | Method | Ref./Year |
|---|---|---|
| 878.5 ± 0.8<br>$878.5 \pm 0.7_{stat} \pm 0.3_{sys}$ | Storage of ultra-cold neutrons | Serebrov et al. 2005<br>PLB 605(2005)72 |
| 886.8 ± 3.42 | Neutron beam experiment | M.S. Dewey et al. 2003 |
| 885.4 ± 0.95<br>$885.4 \pm 0.9_{stat} \pm 0.4_{sys}$ | Storage of ultra-cold neutrons | S. Arzumanov et al. 2000<br>PLB 483(2000)15 |
| 889.2 ± 4.8 | Neutron beam experiment | J. Byrne et al. 1995 |
| 882.6 ± 2.7 | Storage of ultra-cold neutrons | W. Mampe et al. 1993 |
| 888.4 ± 3.1 ± 1.1 | Storage of ultra-cold neutrons | V. Nesvizhevski et al. 1992 |
| 878 ± 27 ± 14 | Neutron beam experiment | R. Kosakowski 1989 |
| 887.6 ± 3.0 | Storage of ultra-cold neutrons | W. Mampe et al. 1989 |
| 877 ± 10 | Storage of ultra-cold neutrons | W. Paul et al. 1989 |
| 876 ± 10 ± 19 | Neutron beam experiment | J. Last et al. 1988 |
| 891 ± 9 | Neutron beam experiment | P. Spivac et al. 1988 |
| 872 ± 8 | Storage of ultra-cold neutrons | A. Serebrov et al. 1987 |
| 870 ± 17 | Neutron beam experiment | M. Arnold et al. 1987 |
| 903 ± 13 | Storage of ultra-cold neutrons | Y.Y. Kosvintsev et al. 1986 |
| 875 ± 95 | Storage of ultra-cold neutrons | Y.Y. Kosvintsev et al. 1980 |
| 937 ± 18 | Neutron beam experiment | J. Byrne et al. 1980 |
| 881 ± 8 | Neutron beam experiment | L. Bondarenko et al. 1978 |
| 918 ± 14 | Neutron beam experiment | C.J. Christensen et al. 1972 |
| 885.7 ± 0.8 | world average 2004 | PDG 2004 |



# Discovery of neutron quantum states in 1999

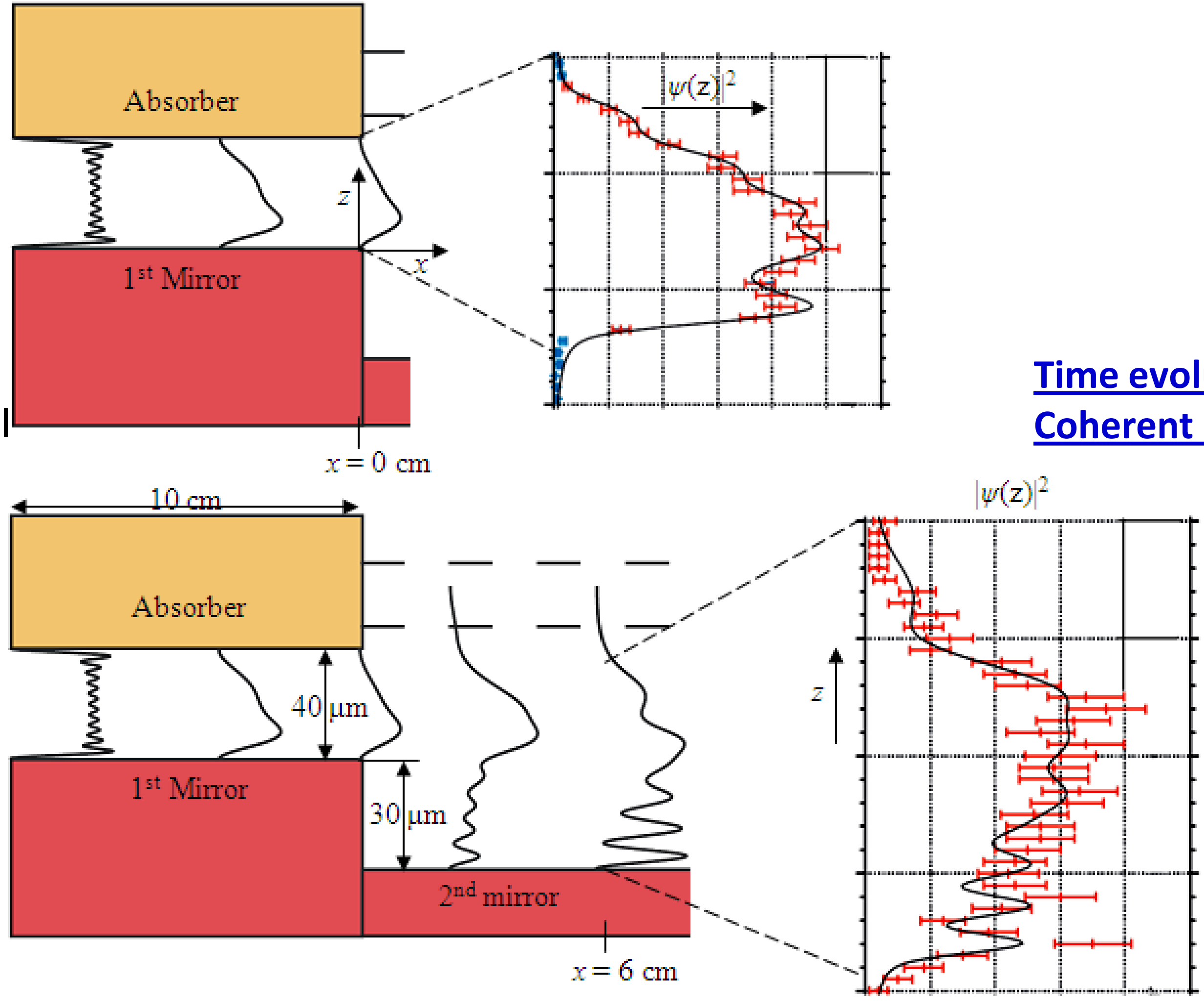
Nesvizhevsky *et al*, Nature **415** (2002)





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

# The Quantum Bouncer, Results

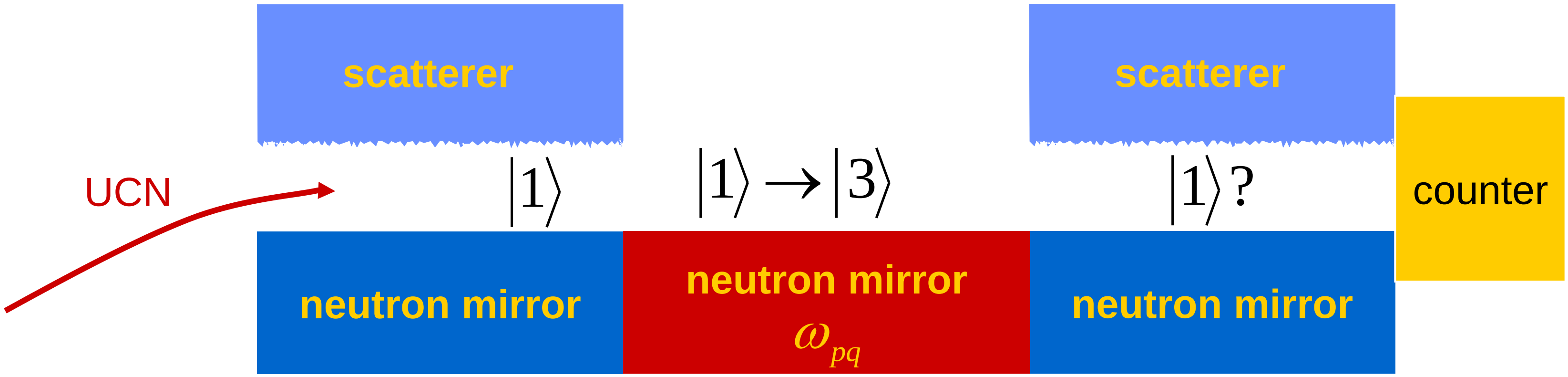


**Time evolution of Coherent Superposition**

**Abele, H., Jenke, T., Stadler, D., & Geltenbort, P. N*ucl. Phys.* A827, 593c (2009), see also Dubbers 2010**

# On the way towards a Resonance Spectroscopy Technique

- First Idea: „Standard“ Rabi Experiment



scatterer

scatterer

UCN

$|1\rangle$

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

$|1\rangle ?$

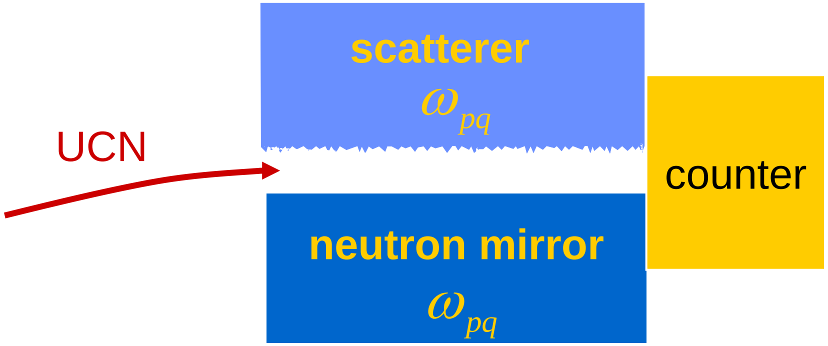
counter

neutron mirror

neutron mirror $\omega_{pq}$

neutron mirror

- Better Idea: Simplified Setup, „Rabi Flopping with Damping“



scatterer $\omega_{pq}$

UCN

counter

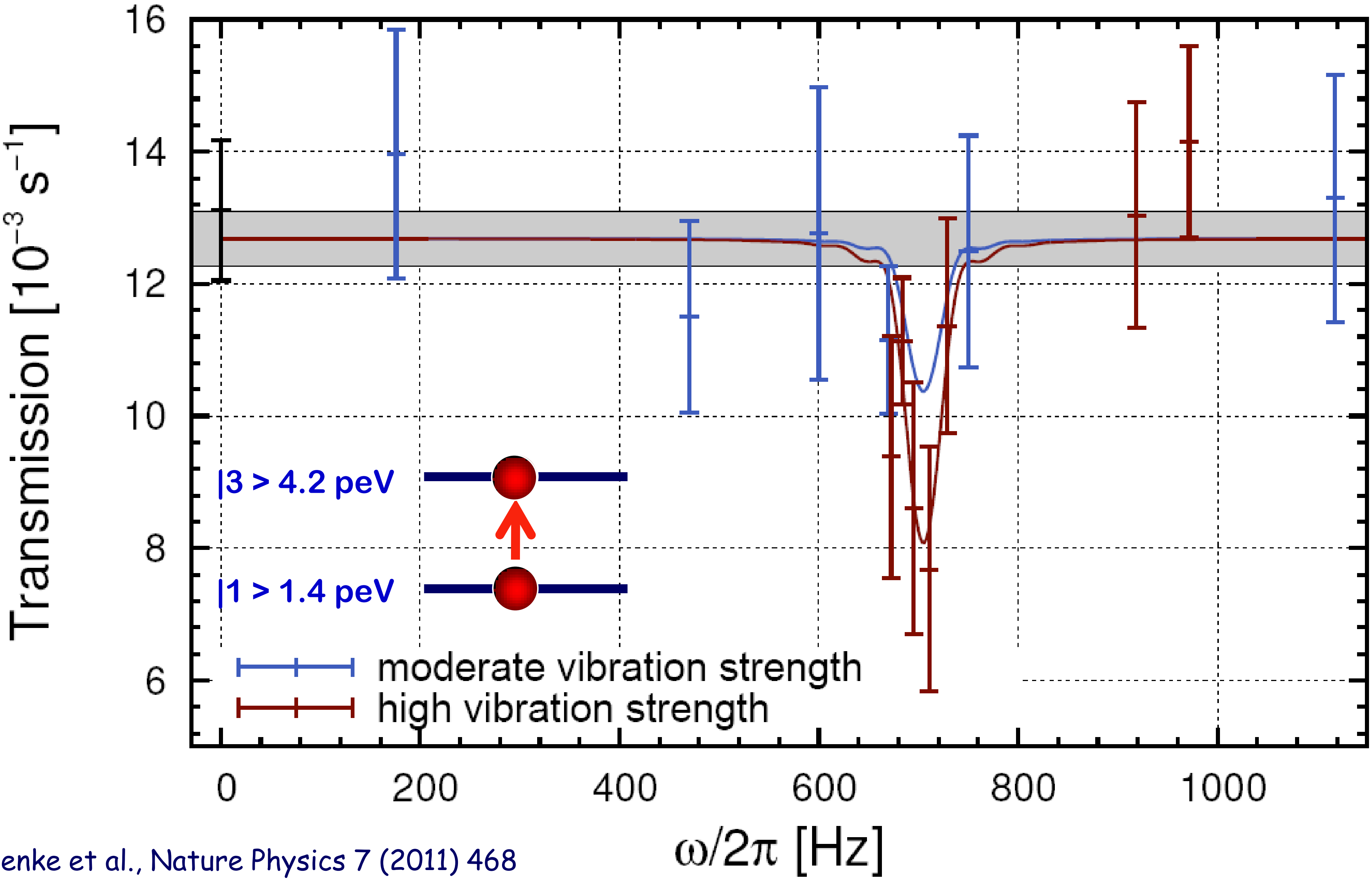
neutron mirror $\omega_{pq}$

- proof of technique possible
- simple (well-known) setup
- avoids „steps“
- better transmission (short)
- perfectly PF2-compatible

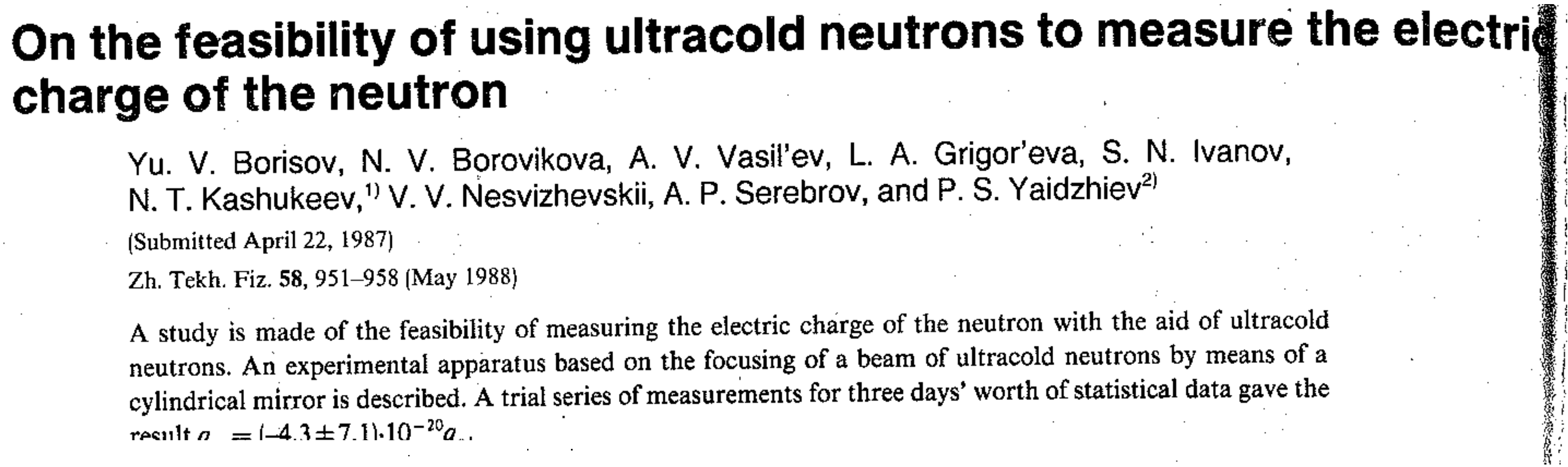
- in principle (probably) limited by knowledge of gap height l (can be removed by measuring > 1 resonance )

**T. Jenke, PhD Thesis, 2011**

# Gravity Resonance Spectroscopy and Excitation



T. Jenke et al., Nature Physics 7 (2011) 468



# On the feasibility of using ultracold neutrons to measure the electri charge of the neutron

Yu. V. Borisov, N. V. Borovikova, A. V. Vasil'ev, L. A. Grigor'eva, S. N. Ivanov, N. T. Kashukeev,(1) V. V. Nesvizhevskii, A. P. Serebrov, and P. S. Yaidzhiev(2)

(Submitted April 22, 1987)
Zh. Tekh. Fiz. 58, 951–958 (May 1988)

A study is made of the feasibility of measuring the electric charge of the neutron with the aid of ultracold neutrons. An experimental apparatus based on the focusing of a beam of ultracold neutrons by means of a cylindrical mirror is described. A trial series of measurements for three days' worth of statistical data gave the result $q = (-4.3\pm7.1)\cdot10^{-20}q$.

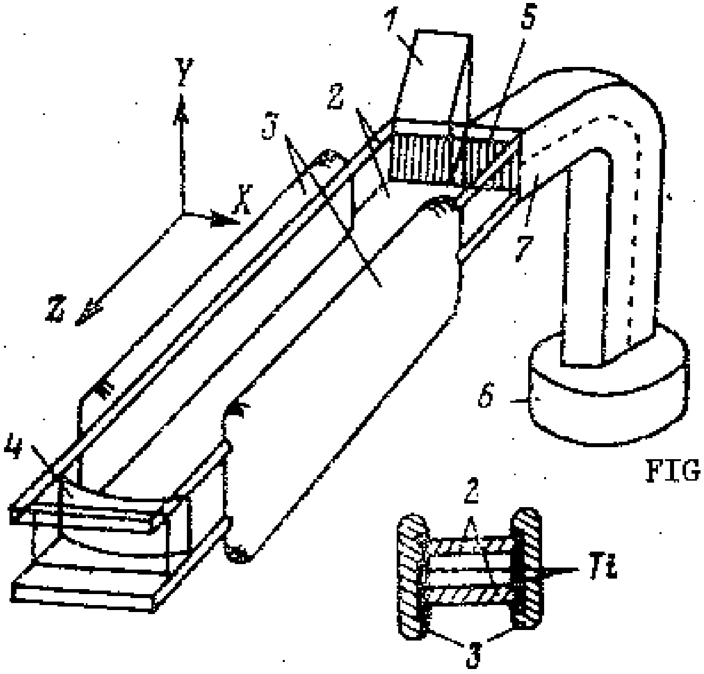


FIG. 1.

I hope I could convince you
that not only ILL and Grenoble are worth a visit
but also that ultracold neutrons are
– due to the fact that they are storable –
a fancy and powerful tool in fundamental physics

For more information: www.ill.eu
or just call me **+33 (0)47620 7242** or geltenbort@ill.fr

Recent review "The neutron and its role in cosmology and particle physics"
by D. Dubbers & M. Schmidt, **arXiv:1105.3694**, Rev. Mod. Phys. (in print)

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