Fundamental Physics

with

(Very Cold &) Ultra-Cold Neutrons (UCNs)

at the

Institut Laue Langevin (ILL) in Grenoble, France

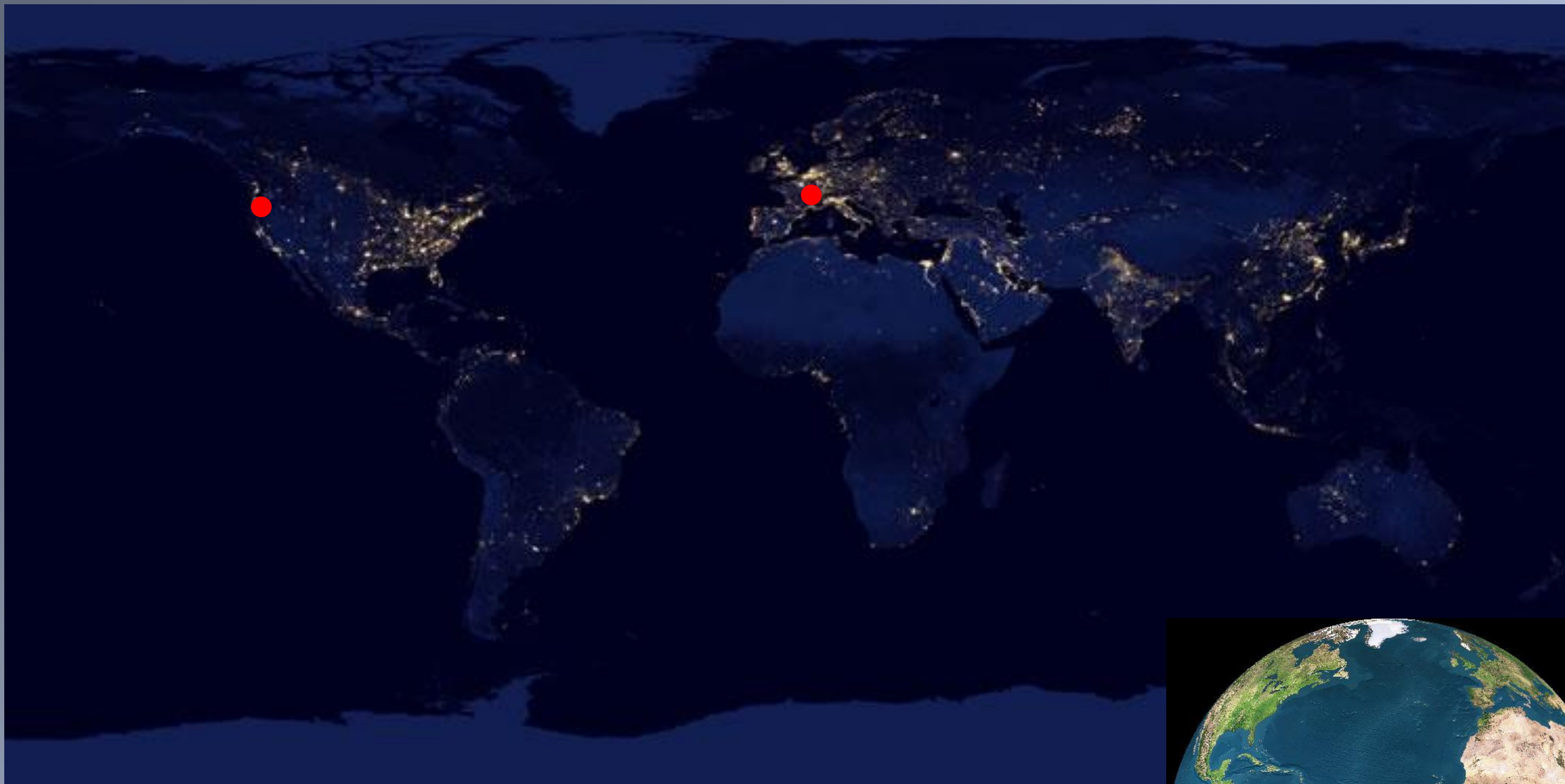
Peter Geltenbort

with the help of many colleagues and friends (as you can see on the numerous slides)

Very Hot (fission) Neutrons — **Ultracold Neutrons**

10^7 eV → **10^{-7} eV**

Setting the scene: Satellite photo of **Earth** at night (NASA)



door to door : ~ **8 500 km (5 300 miles)**

Last visit to UW, Atomic Physics Group, in Mai 1994

Setting the scene: Europe and France

ILL – CERN (~150 km): 1.5 hours by car

ILL – GANIL (~800 km): 7 hours by car

ILL – GSI (~750 km): 7 hours by car

Setting the scene: Grenoble (Capital of the French Alps)

(Host City of X Olympic Winter Games 1968)

Population: 180 000
380 000 (metro area)
Elevation: 214 m
Pic de Belledonne: 2 977 m

Amongst the flattest cities in France!

Seattle: 710 000
Seattle metro: 3 600 000

Elevation: 0 → 158 m

- The city benefits from the **highest concentration of strategic jobs in France after Paris**, with 14% of the employments, 35,186 jobs, 45% of which specialized in design and research.
- Grenoble is also the **largest research center in France after Paris** with 22,800 jobs (11,800 in public research, 7,500 in private research and 3,500 PhD students)

[Figures from Wikipedia, June 2015]

Outline

- ILL (Institut Laue Langevin) and its high flux reactor
- NPP (Nuclear and Particle Physics group)
- Ultra-Cold Neutrons (UCNs)
- Flagship experiments
  - Neutron Electric Dipole Moment (nEDM)
  - Neutron lifetime (nTau)
  - Gravitational Levels (GRS)

Everything started a bit more than 50 years ago

- Proposed in 1964 (Grenoble had knowledge + inclination)
- Laboratory agreed upon in 1967 by France and Germany
  - (Scientific) Founding fathers

    L. Néel (**NP 1970, antiferromagnetism**) and H. Maier-Leibnitz

Traité de l'Elysée: 22 January 1963

Interstate treaty: 19 January 1967

Louis Néel
1904 – 2000
Nobel Prize 1970
Antiferromagnetism

Heinz Maier-Leibnitz
1911 – 2000

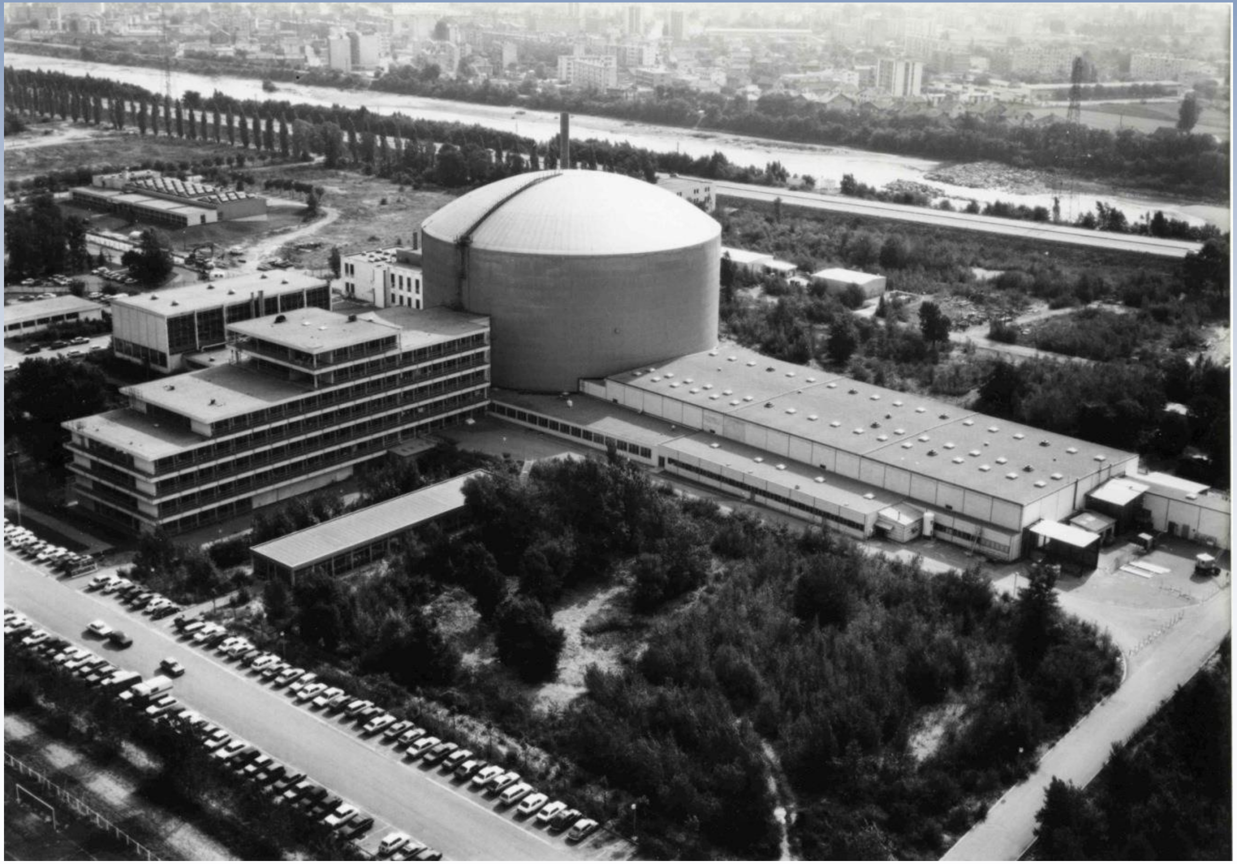
Ideas become concrete

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

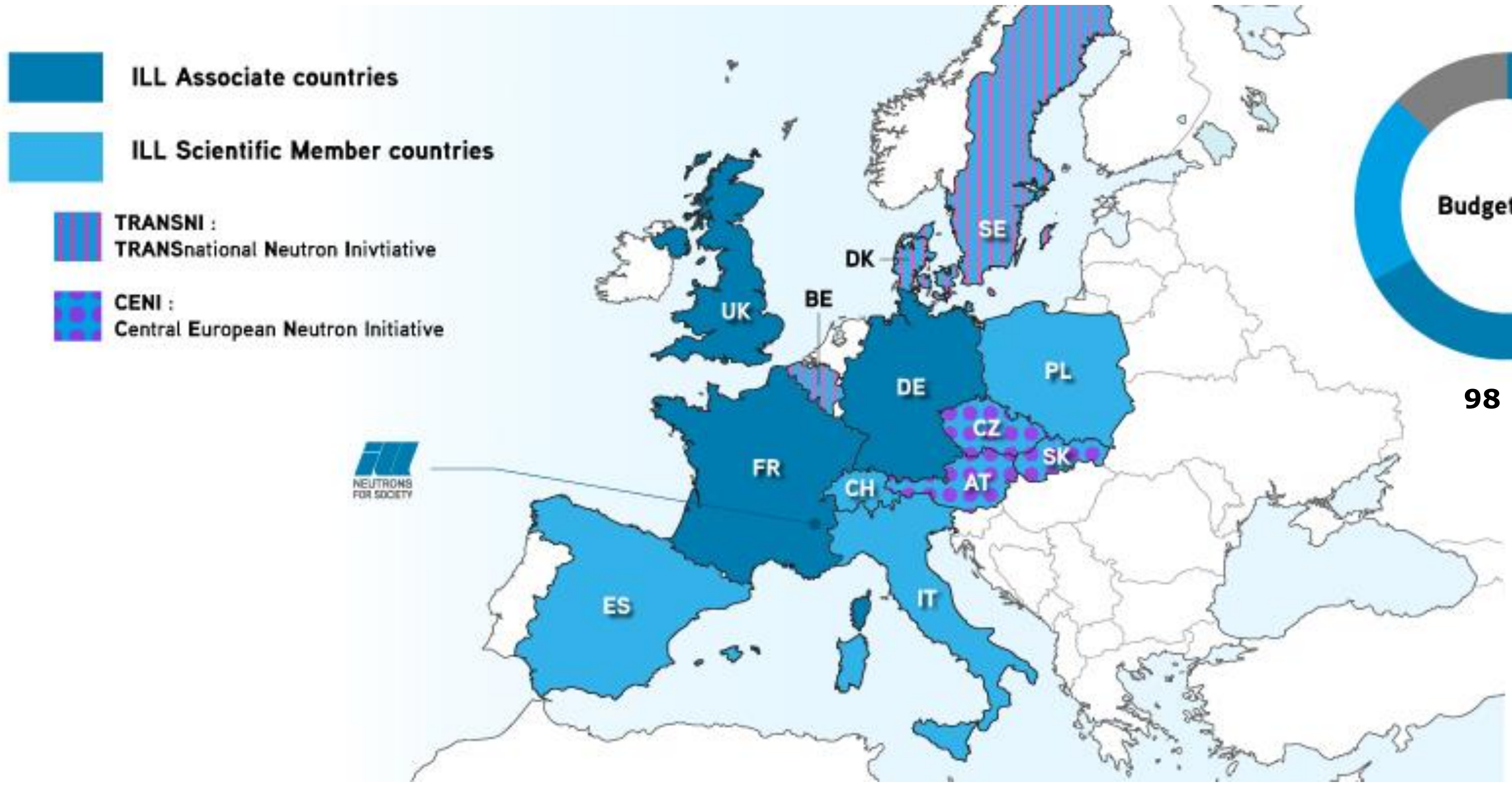
The Institut Laue-Langevin is an international research centre at the leading edge of neutron science and technology.

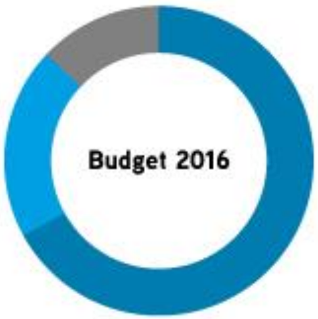
As the world's flagship centre for neutron science, the ILL provides scientists with a very high flux of neutrons feeding some 40 state-of-the-art instruments, which are constantly being developed and upgraded.

As a **service institute** the ILL makes its facilities and expertise available to visiting scientists. Every year, some 1400 researchers from over 40 countries visit the ILL. More than 800 experiments selected by a scientific review committee are performed annually. Research focuses primarily on fundamental science in a variety of fields: condensed matter physics, chemistry, biology, nuclear physics and materials science, etc.



THE ILL MEMBER COUNTRIES AND THEIR FINANCIAL PARTICIPATION





98 M€ (115 M$)

NEUTRONS FOR SOCIETY

Key figures about the ILL

1400 users from an active community of 12 000 scientists

850 experiments/year

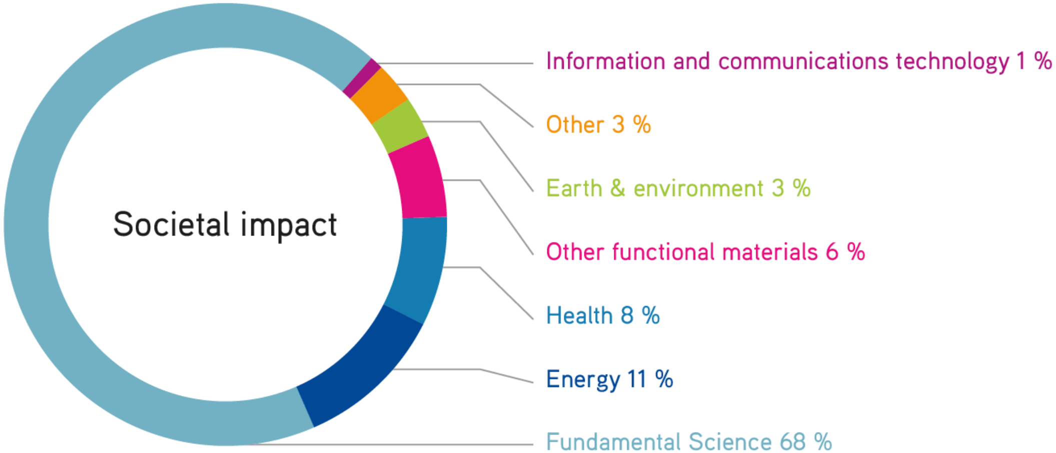
600 publications/year

>21000 pubs since 1973

38 countries

28 instruments + 10 CRG

4 cycles of 50 days/year



European Photon and Neutron (EPN) Science Campus

NEUTRONS FOR SCIENCE®

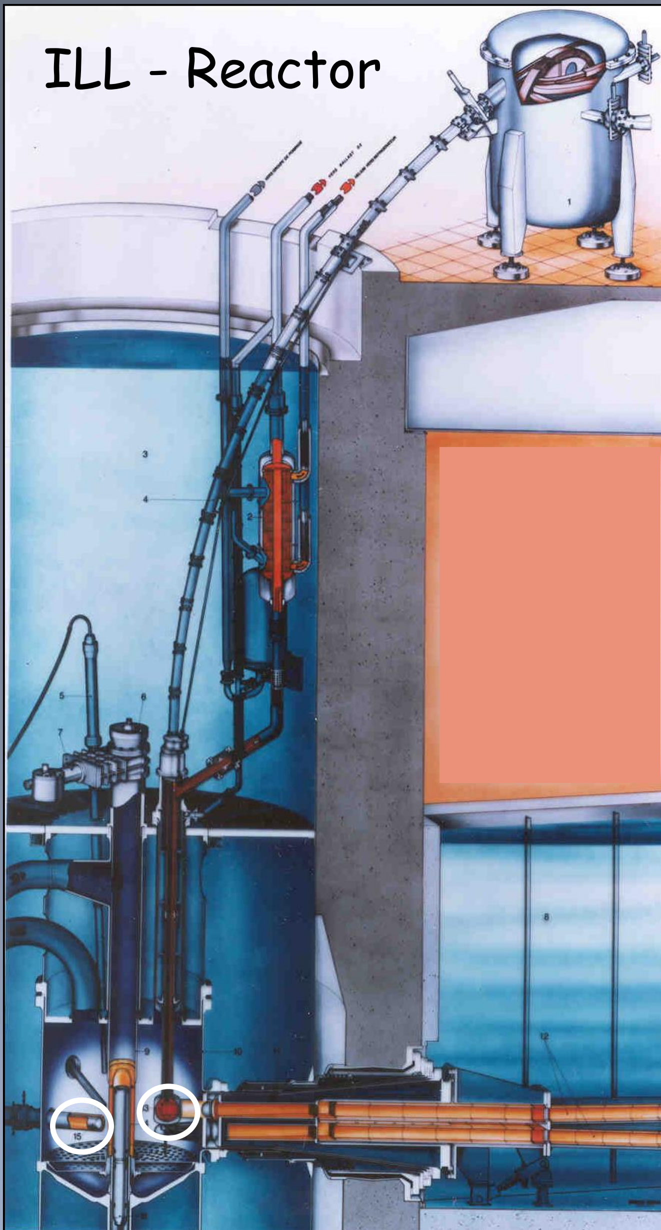
Institut Laue-Langevin (ILL) operates the most intense (reactor) neutron source in the world, feeding a suite of 40 high-performance instruments

European Synchrotron Radiation Facility (ESRF) is a world-leading synchrotron radiation source hosting 41 cutting-edge experimental stations

The Institut de Biologie Structurale (IBS) is a research centre in structural biology. The IBS possesses cutting edge facilities and is a partnership between CEA, CNRS and UJF

European Molecular Biology Laboratory (EMBL) Grenoble is an outstation of the EMBL organisation (HQ in Heidelberg), specialising in research in structural biology (in very close proximity to the ILL and the ESRF)

Neutron sources at the ILL



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

Moderator: D_2O at 300K $\rightarrow$ thermal neutrons

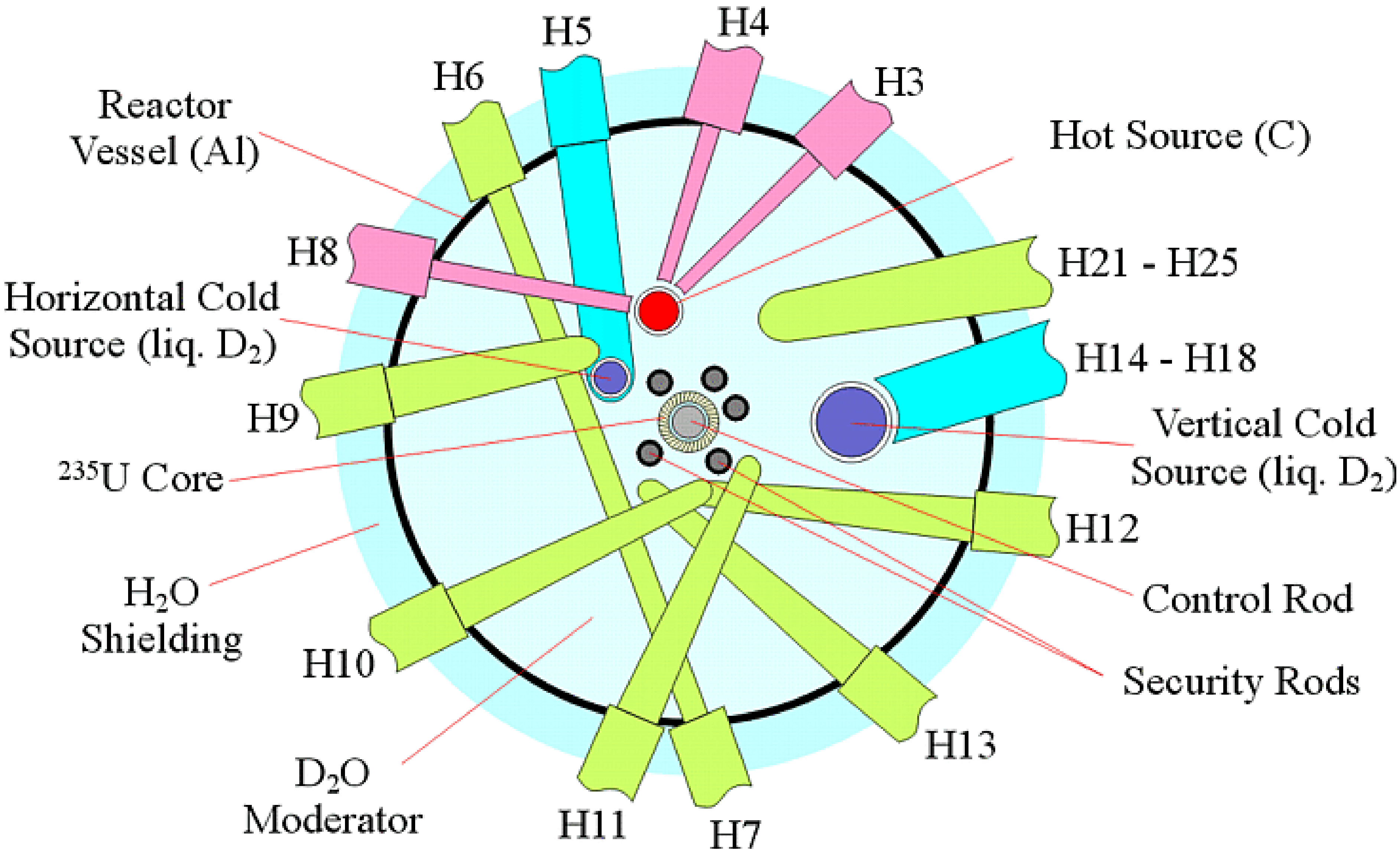
Hot source: 10 dm^3 of graphite at 2400 K

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

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

Thermal, cold and hot neutrons



NEUTRONS FOR SCIENCE

The Nuclear and Particle Physics group (NPP)

Nuclear physics

ILL-funded

PN1 (LOHENGRIN)
Recoil mass spectrometer for fission fragments

PN3 (GAMS)
Ultra-high resolution gamma ray spectrometer

FIPPS
Spectroscopy of exotic nuclei

Particle physics

PF1B
Facility for cold neutrons

PF2
Facility for ultracold and very cold neutrons

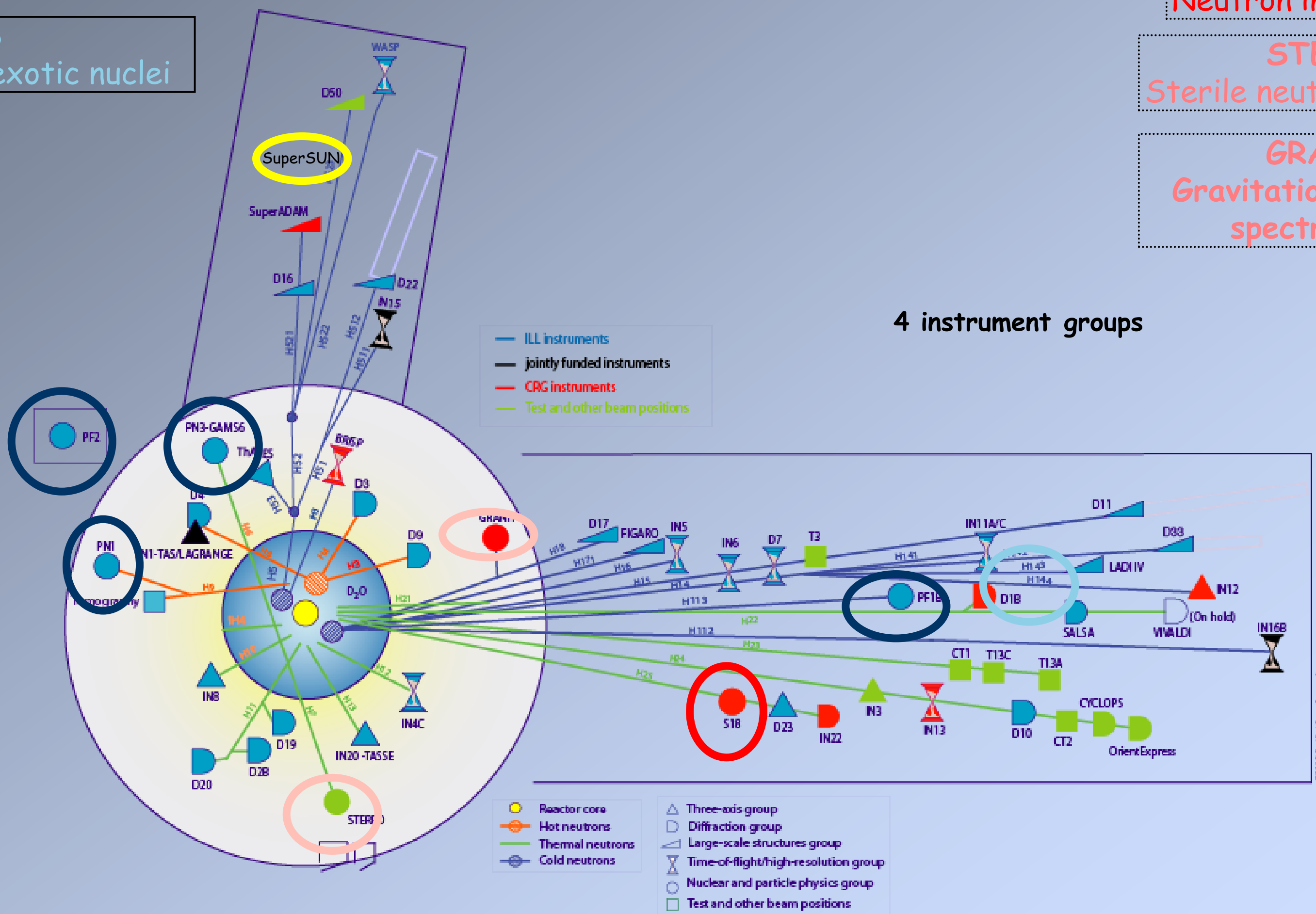
Collab. Research Group

~~(former PF1)~~
~~cryoEDM experiment~~
SuperSUN

S18 - perfect crystal
Neutron interferometer

STEREO
Sterile neutrino research

GRANIT
Gravitational neutron spectrometer



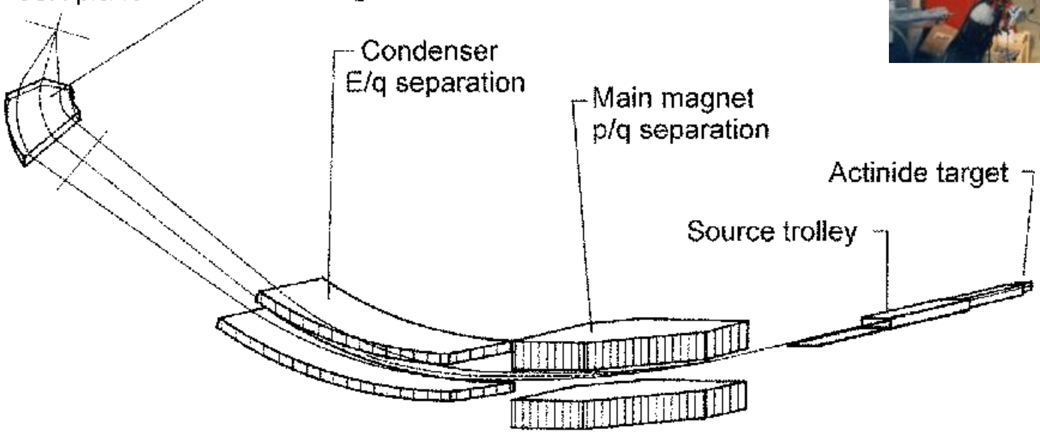
4 instrument groups

PN1: The fission fragment separator "Lohengrin"

U. Koester, Y.-H. Kim, N. Laurens

mass-separated fission fragments,

up to 10^5 per second, $T_{1/2} \geq \mu s$



$$m\,v^2 / r_{el} = q\,E \qquad m\,v^2 / r_{magn} = q\,v\,B$$

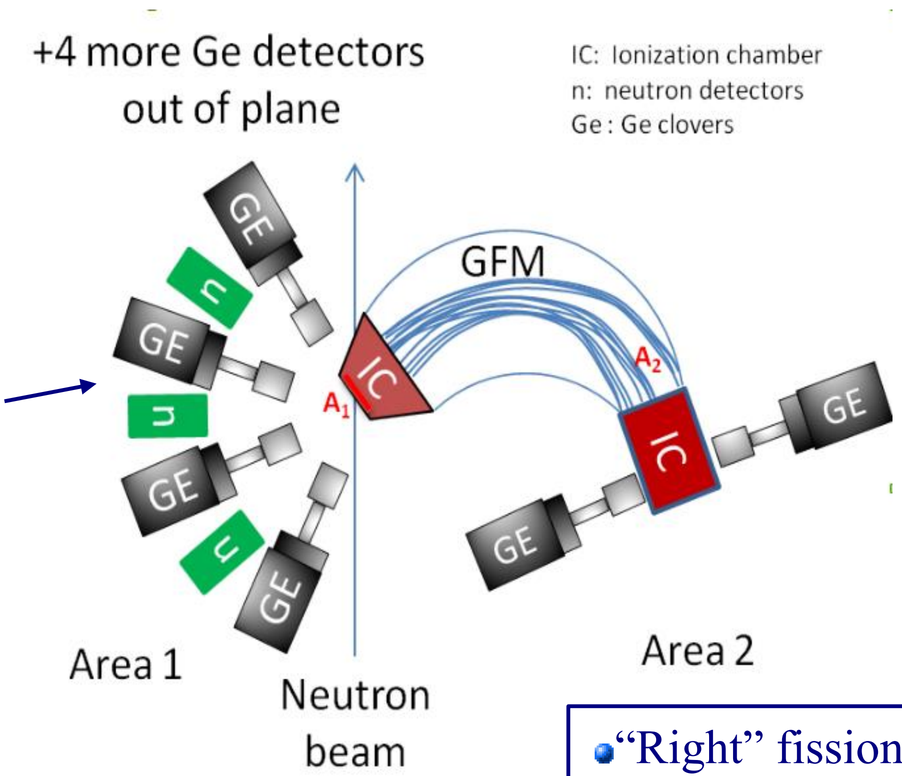
$$E_{kin} / q = E / 2\,r_{el} \qquad m\,v / q = B\,r_{magn}$$

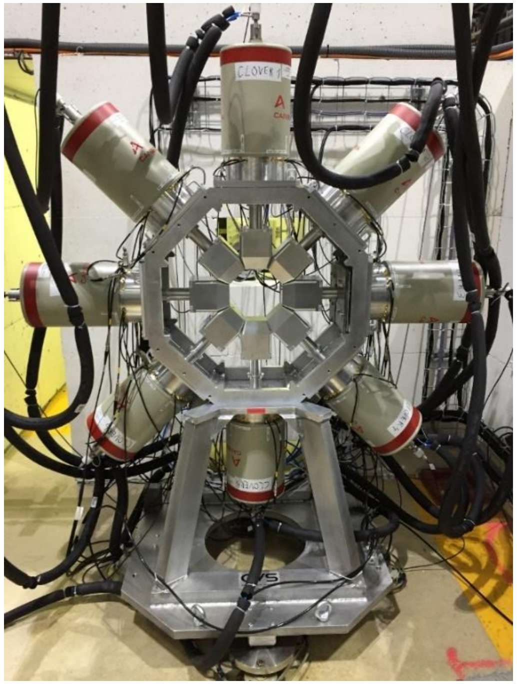
P. Armbruster et al., Nucl. Instr. Meth. 139 (1976) 213.

- n-flux 5.5×10^{14} cm^{-2}/s
- few mg fission target (various materials)
- several 10^{12} fissions/s

FIPPS: layout

F**I**ssion **P**roduct **P**rompt gamma-ray **S**pectrometer





- "Left" fission fragment: stopped in backing → Doppler free **γ detection** by Ge-array

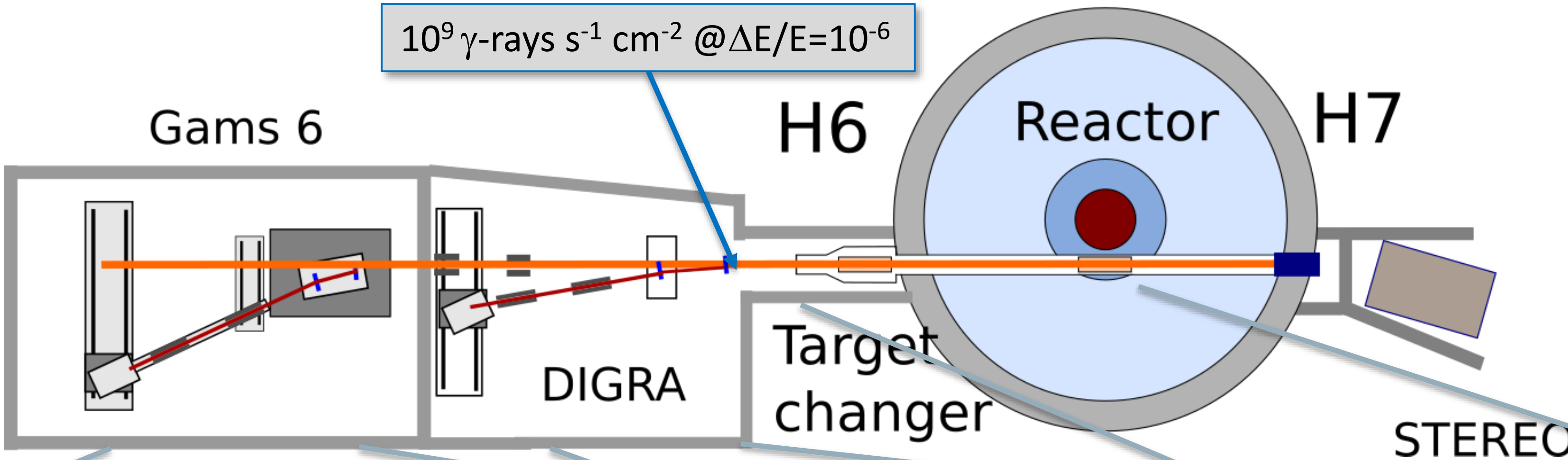
- "Right" fission fragment: → mass identification with a Gas-Filled magnet for **filtering**

Ancillary detectors:

\+ → neutron detectors for fission studies
→ LaBr3(Ce) for short lifetime (10 ps → 1 ns)
→ low energy Ge detectors
→ …

PN3: The high resolution gamma ray facility

General Layout and Parameters (PN3 since end 2014)



GAMS6: Ultra-High Resolution Spectrometer

- Two flat perfect crystals with $\Delta d/d < 10^{-8}$
- Angle interferometer: $\Delta\theta < 10^{-10}$ rad over 0.5 rad
- Solid angle: 10^{-11}

- GRID-Lifetime measurements
- Gamma Ray Metrology
- Gamma Ray refractive optics

DIGRA: multipurpose diffractometer / irradiation fac.

- Flat mosaic crystals
- Bent crystals
- Large/heavy objects can be scanned
- Solid angle: 10^{-7} – 10^{-6}

- Bent crystal spectroscopy
- Gamma Ray Laue Lens
- Gamma Ray Imaging tests

Inpile Irradiation Position:

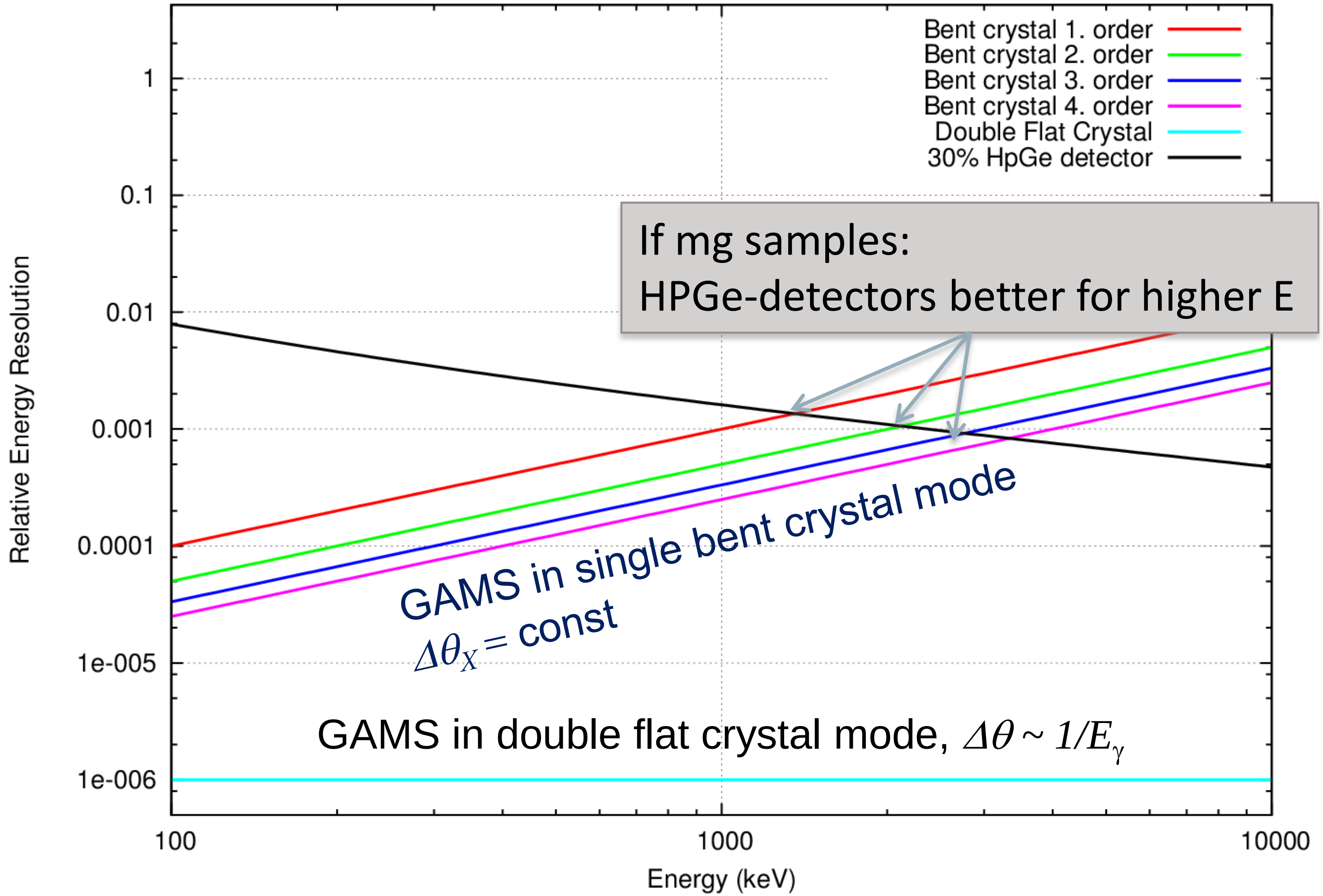
- Neutron flux: 5 x 10^{14} cm^2 s^{-1}
- 3 Samples 4 x 20 x 20 mm^3
- Orientation of samples in reactor is possible
- Sample change during reactor cycle
- Self heating: ~1 W/g

AND GAMMA RAY

T H E   E U R O P E A N   N E U T R O N   S O U R C E

NEUTRONS FOR SOCIETY

Overview on Energy resolution

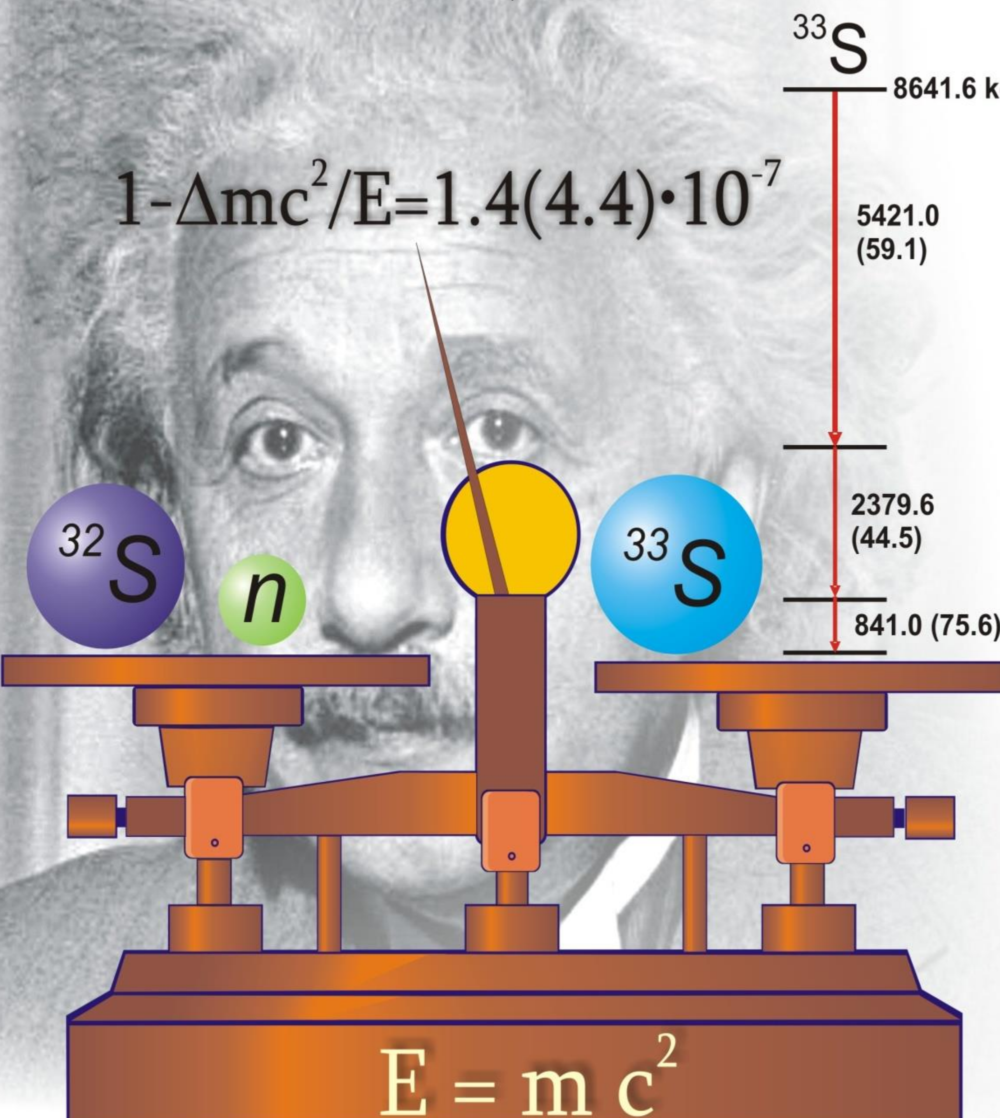


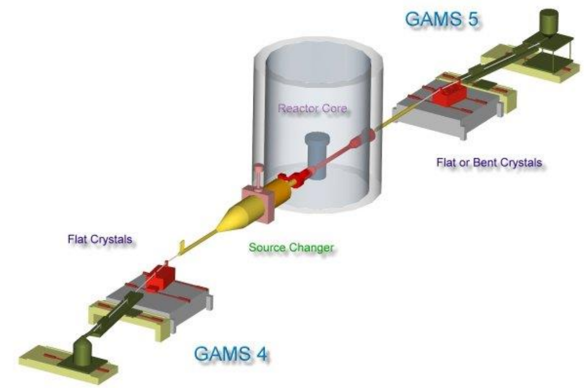
NEUTRONS FOR SOCIETY

Direct test of mass/energy relationship $E = mc^2$

2005 World Year of Physics – Einstein's "Miraculous year" 1905

ILL-MIT-NIST, Nature 430, 58 (2005)

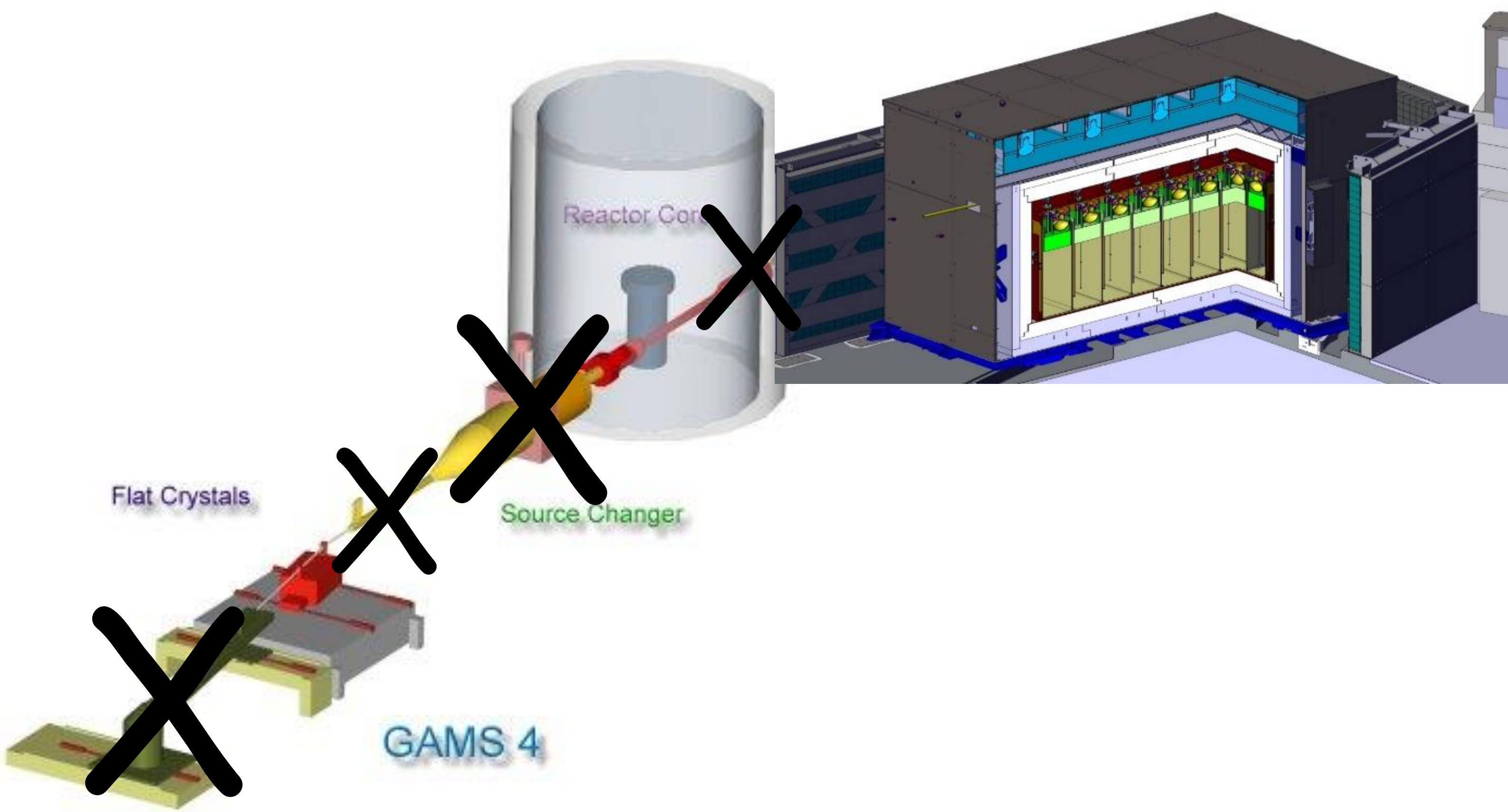




GAMS Interferometer ILL

Antineutrino detector STEREO

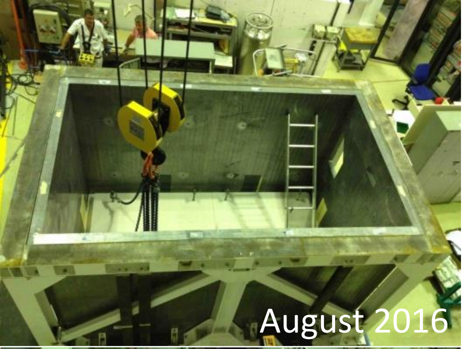
at the sealed end of beam tube H7

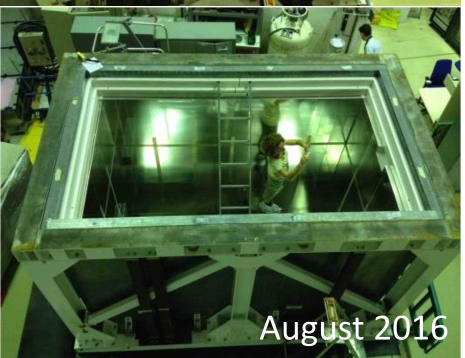


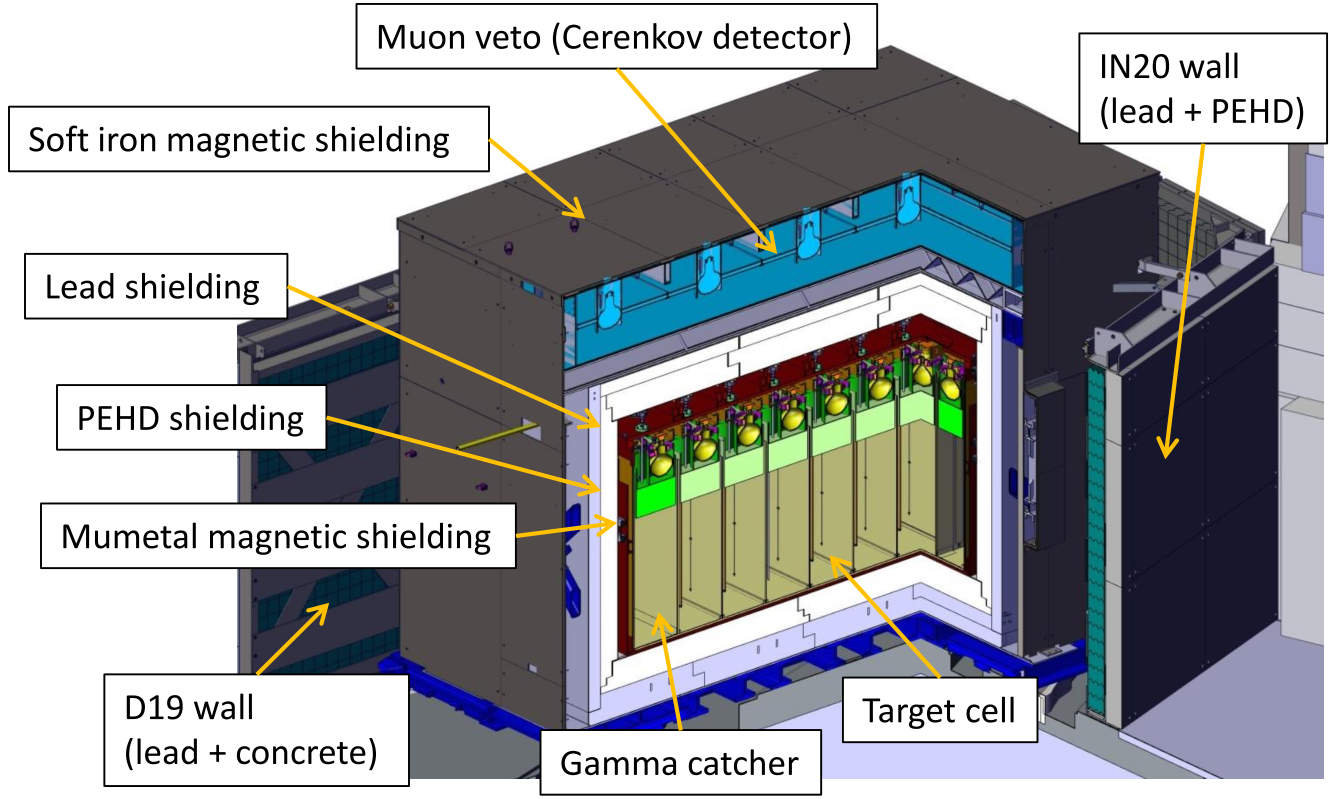
In April 2017 through beam tube H6/H7 removed and sealed

STEREO setup

detection of e-antineutrinos through **inverse beta-decay** in **gadolinium doped liquid scintillators**

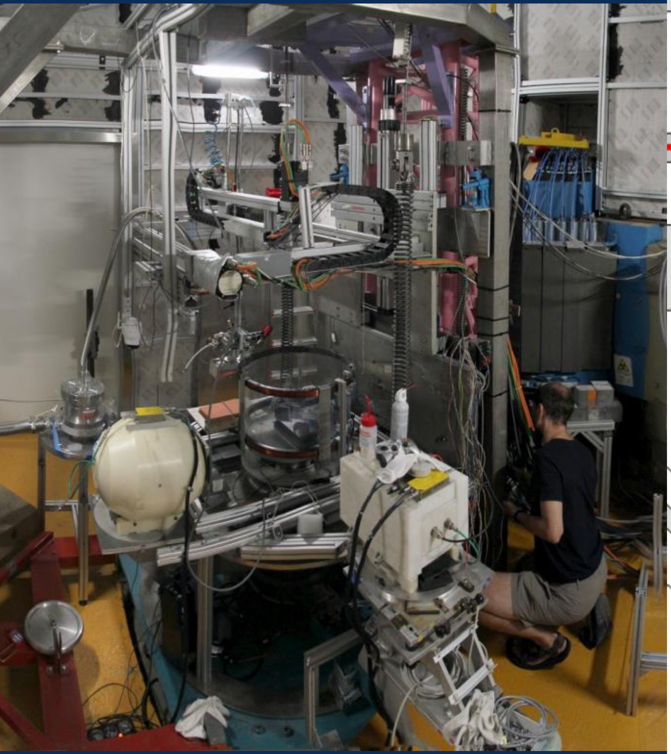


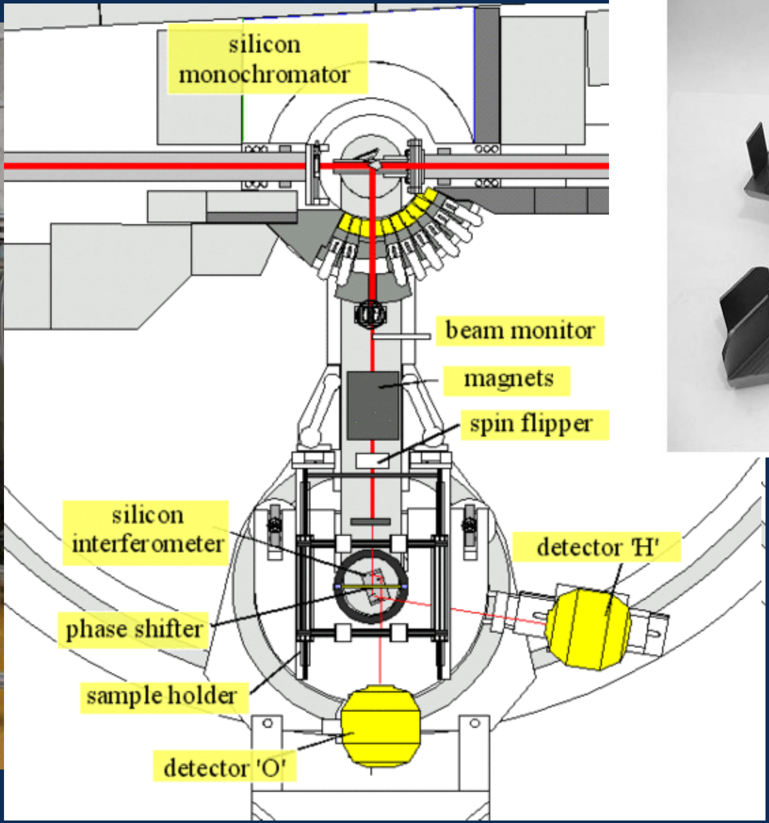




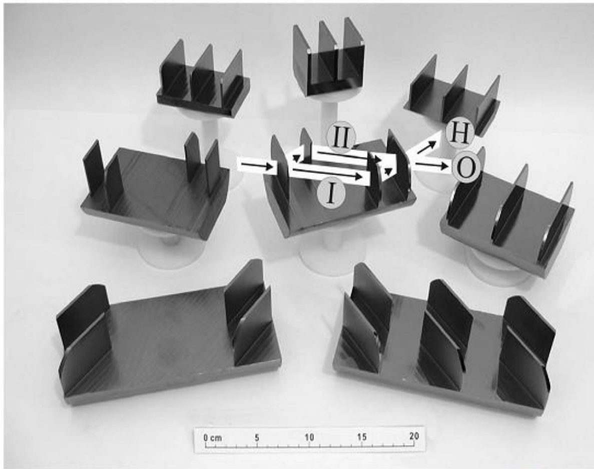
S18 - CRG instrument (Atominstitut, TU Vienna, Austria [H. Lemmel])

interferometer (perfect Si crystals) for basic neutron quantum optics, fundamental tests of quantum physics, neutron scattering lengths and USANS (ultra-small angle neutron scattering)





Neutron interferometer family



Lewis Caroll
Alice's Adventures in Wonderland
1865

Observation of a quantum Cheshire Cat in a matter wave interferometer experiment

Tobias Denkmayr[1], Hermann Geppert[1], Stephan Sponar[1], Hartmut Lemmel[1,2], Alexandre Matzkin[3], Jeff Tollaksen[4], and Yuji Hasegawa[1]*
[1] *Atominstitut, Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria*
[2] *Institut Laue-Langevin, 6, Rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
[3] *Laboratoire de Physique Théorique et Modélisation, CNRS Unité 8089, Université de Cergy-Pontoise, 95302 Cergy-Pontoise cedex, France0*
[4] *Institute for Quantum Studies and Schmid School of Science and Technology, Chapman University, One University Drive, Orange, CA 92866, USA*
(Dated: December 16, 2013)

From its very beginning quantum theory has been revealing extraordinary and counter-intuitive phenomena, such as wave-particle duality [1], Schrödinger cats [2] and quantum non-locality [3–6]. In the study of quantum measurement, a process involving pre- and postselection of quantum ensembles in combination with a weak interaction was found to yield unexpected outcomes [7]. This scheme, usually referred to as "weak measurements", can not only be used as an amplification technique [8–10] and for minimal disturbing measurements [11, 12], but also for the exploration of quantum paradoxes [13–17]. Recently the quantum Cheshire Cat has attracted attention [18–20]: a quantum system can behave as if a particle and its property (e.g. its polarization) are spatially separated. Up to now most

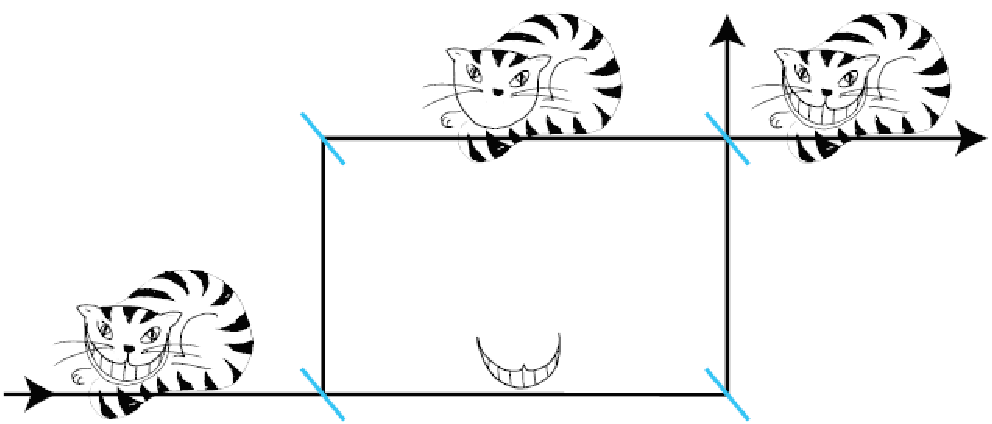


FIG. 1: Artistic depiction of the quantum Cheshire Cat: Inside the interferometer the Cat goes through the upper beam path, while its grin travels along the lower beam path.

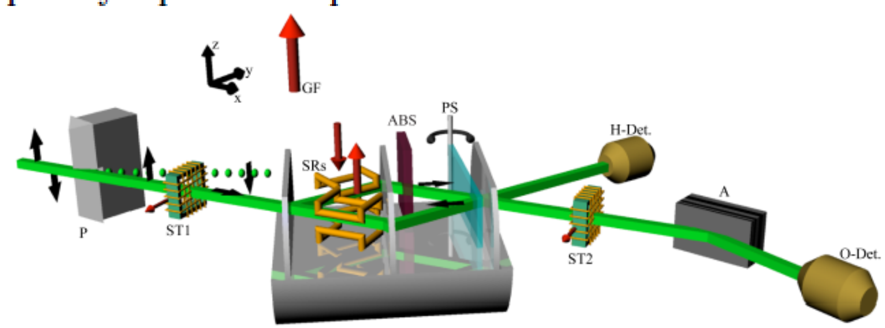
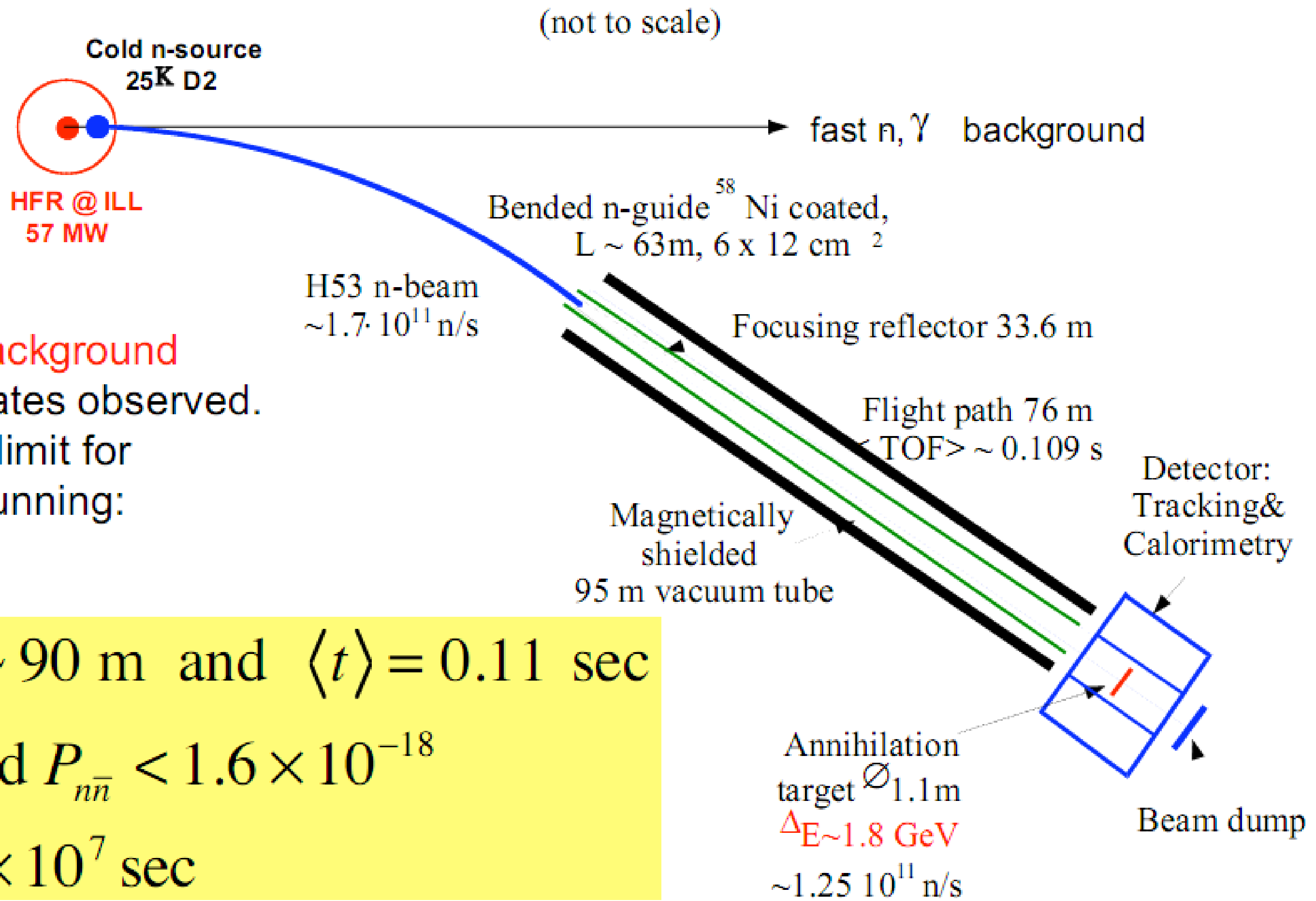


FIG. 2: Illustration of the experimental setup for the observation of a quantum Cheshire Cat in a neutron interferometer: The neutron beam is polarized by passing through magnetic birefringent prisms (P). To prevent depolarization, a magnetic guide field (GF) is applied around the whole setup. A spin turner (ST1) rotates the neutron spin by $\pi/2$. When entering the interferometer the neutron beam splits into two paths. Preselection of the system's wave function $|\psi_i\rangle$ is completed by two spin rotators (SRs) inside the neutron interferometer. These SRs are also used to perform the weak measurement of $\langle\hat{\sigma}_z\hat{\Pi}_I\rangle_w$ and $\langle\hat{\sigma}_z\hat{\Pi}_{II}\rangle_w$. The absorbers (ABS) are inserted in the beam paths when $\langle\hat{\Pi}_I\rangle_w$ and $\langle\hat{\Pi}_{II}\rangle_w$ are determined. The phase shifter (PS) makes it possible to tune the relative phase χ between the beams in path I and path II. The two outgoing beams of the interferometer are monitored by the H- and O-detector in reflected and forward directions, respectively. Only the neutrons reaching the O-detector are affected by postselection using a spin turner (ST2) and a spin analyzer (A).

N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)

"violates Baryon number by 2 units"



No GeV background
No candidates observed.
Measured limit for
a year of running:

$$\text{with } L \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$
$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$
$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Figure of merit for probability: NT^2 with N: # of free neutrons,
T: observation time per n while in "quasi-free" conditions

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**!

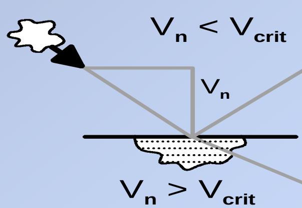
Long storage and observation times possible (up to several minutes)!

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 $\Delta E = m_n g \Delta h$	~ **100 neV** / Meter
Magnetic field $\Delta E = \mu_n B$	~ **60 neV** / Tesla

UCN discovery

OBSERVATION OF ULTRACOLD NEUTRONS

V. I. Lushchikov, Yu. N. Pokotilovskii, A. V. Strelkov, and F. L. Sha
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
ext

re
5
se
the
the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers cc

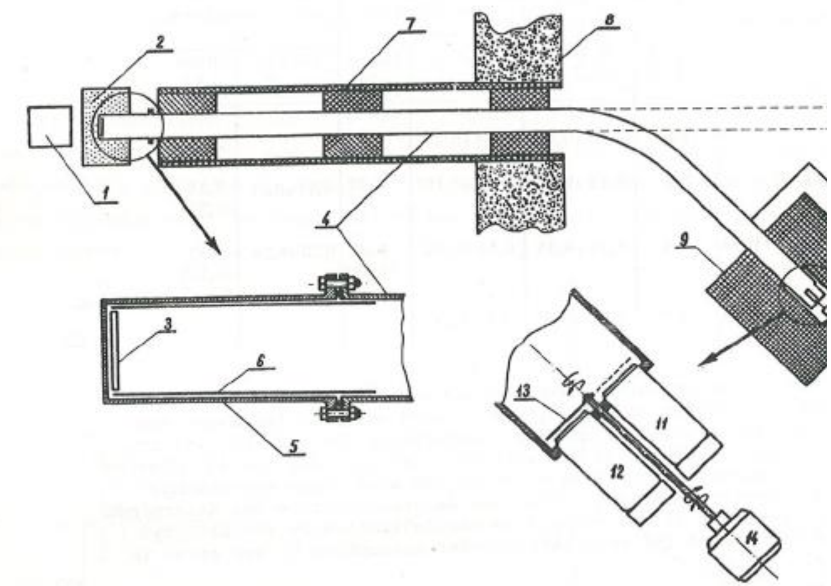


Fig. 1. Diagram of setup. 1- IBR reactor; 2, 3 - moderator (2 - paraffi
layer 1 mm thick); 4 - copper tube, 9.4 cm i.d., total length 10.5 m; 5 -
copper-foil cylinder; 7 - shield (paraffin with boron carbide); 8 - 2-m c
actor chamber; 9 - detector shield (paraffin); 10 - tube filling and evac
12 - detectors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

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

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

ron
re

ere the
target moved in the same direction as the neu-

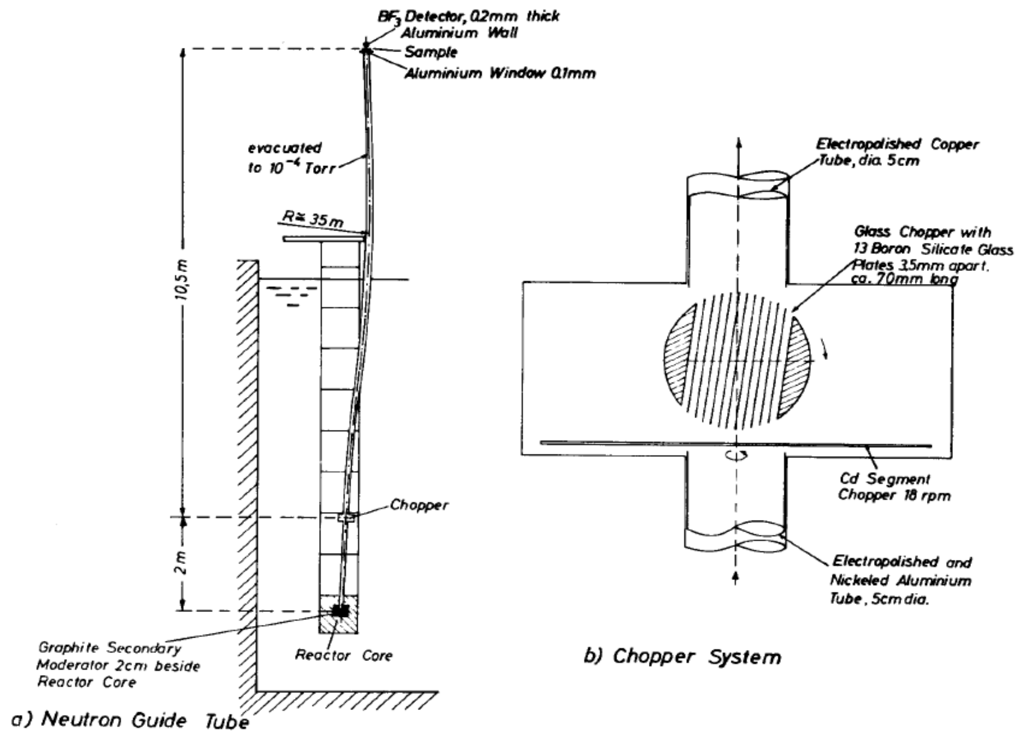
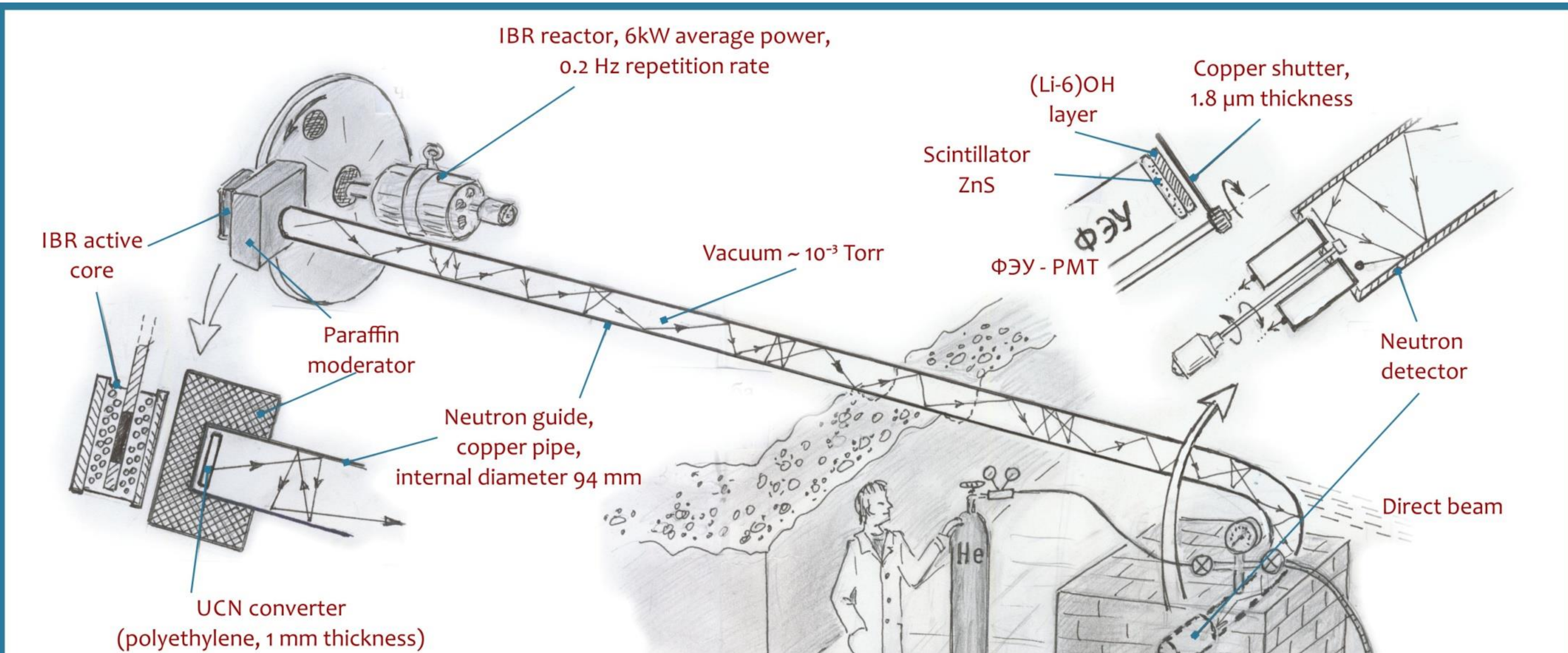


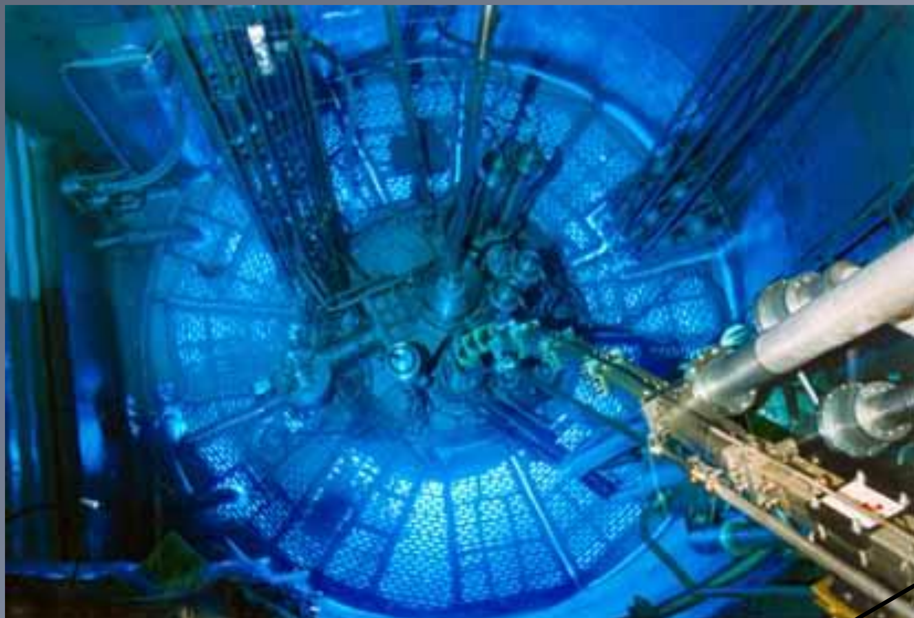
Fig. 1. Vertical beam tube for very slow neutrons.

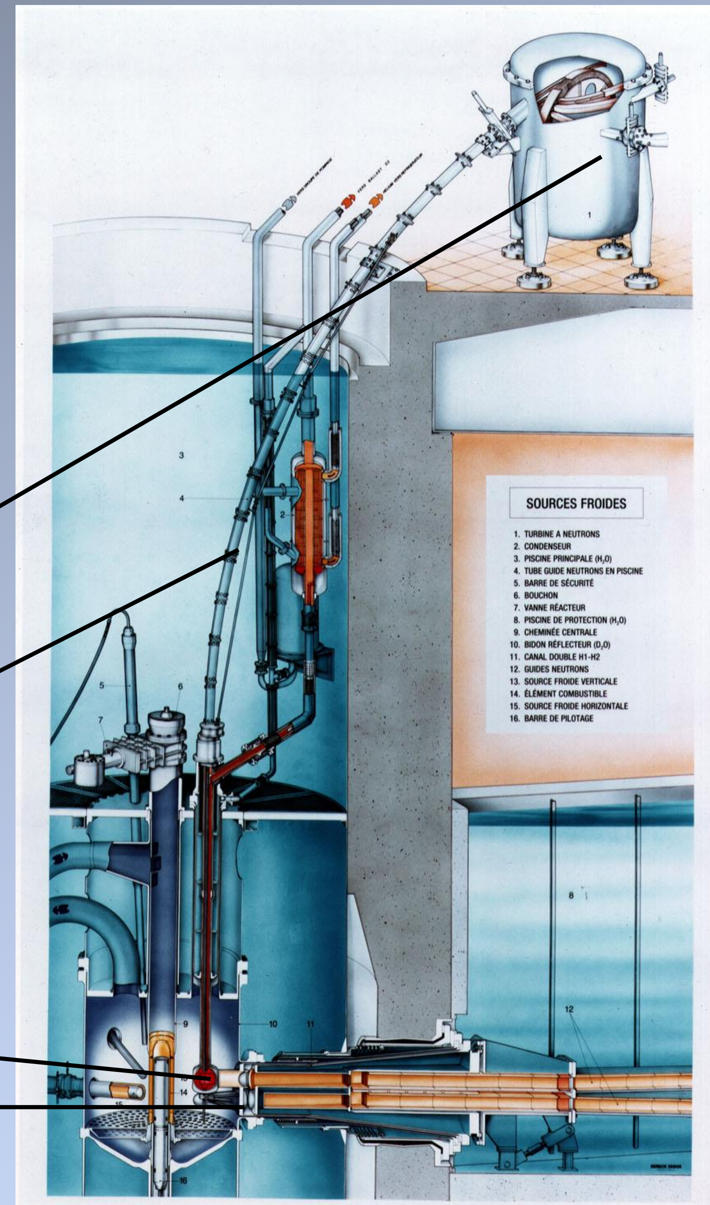
how UCN were "really" discovered in Dubna

drawing courtesy of A.V. Strelkov



The UCN/VCN facility PF2





Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

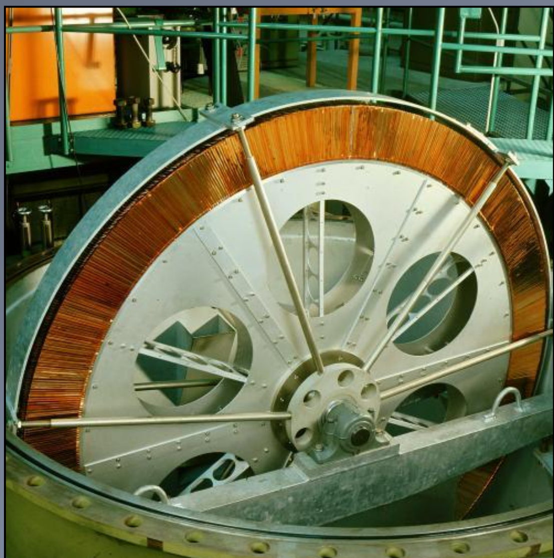
Reactor core

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

Generating Ultracold Neutrons (UCN)

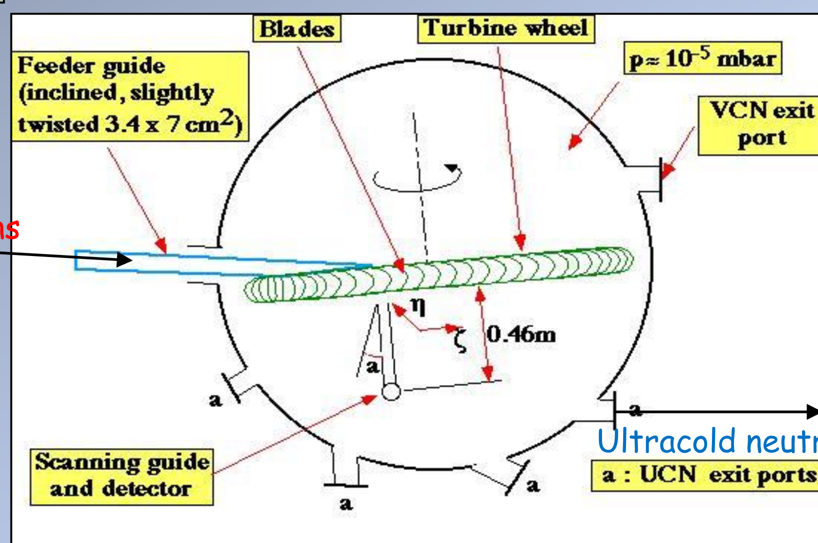
"Steyerl turbine"

Doppler shifting device



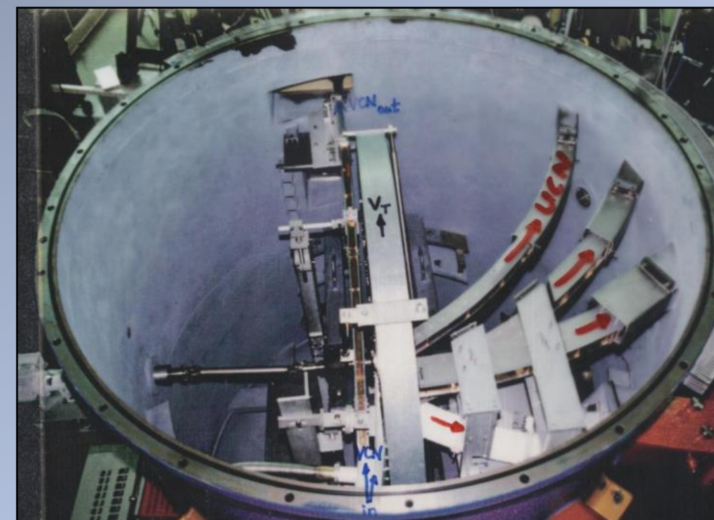
Steyerl turbine
at FRM-I (Munich)

Very cold neutrons



Ultracold neutrons

A. Steyerl et al.,
Physics Letters A 116 (1986) 347 - 352

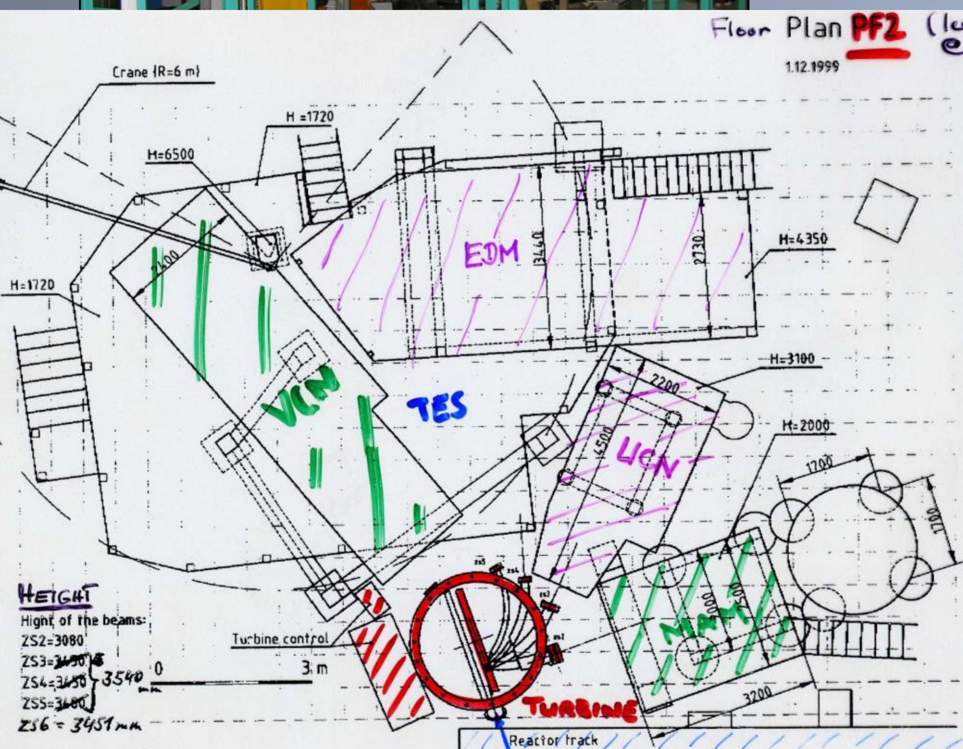


Steyerl turbine (2nd generation)
at PF2 / ILL
10 years later

The total UCN current density is 2.6×10^4 cm^{-2} s^{-1} up to $v_z = 6.2$ m/s and 3.3×10^4 cm^{-2} s^{-1} up to $v_z = 7$ m/s
The total UCN current amounts to more than a million UCNs/s.
Furthermore, we deduce from the TOF data special UCN densities of 87 cm^{-3} (for $v_z < 6.2$ m/s) and 110 cm^{-3} for $v_z < 7$ m/s

In a storage bottle experiment 36 UCNs per cm^{-3} (for $v_z < 6.2$ m/s) were detected!

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 ms^{-1}
ρ = ~50 cm^{-3} (at the experiment)
is :
v <= 7 ms^{-1}
ρ = ~20 cm^{-3} (at the experiment)

- *TES*

1 position for Very Cold Neutrons (VCN)

- *VCN beam*

v = 50 ms^{-1}
Φ = 10^8 cm^{-2} s^{-1}

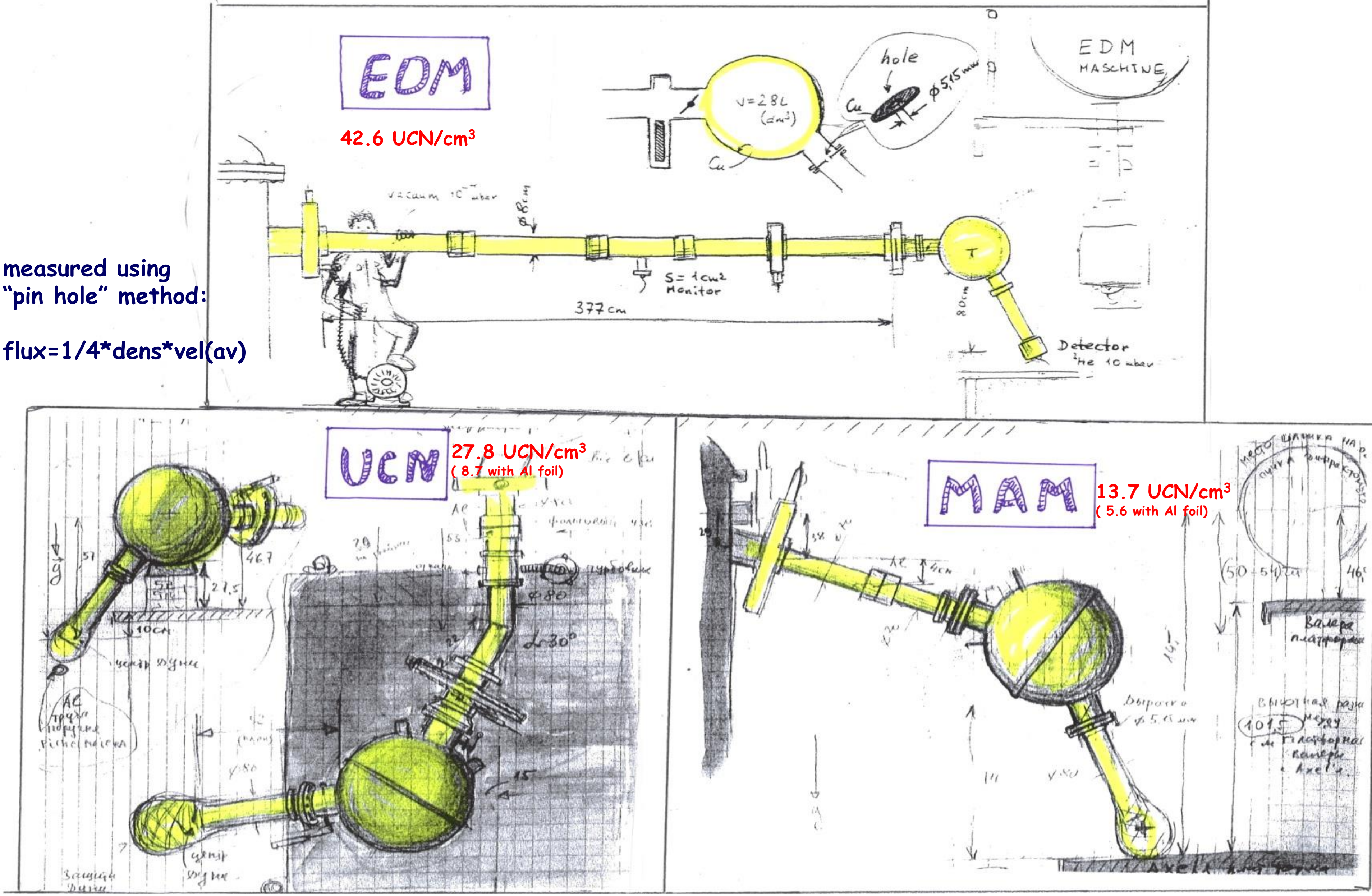
W. Drexel, Neutron News 1 (1990) 23

UCN densities (Cu sphere as UCN container)

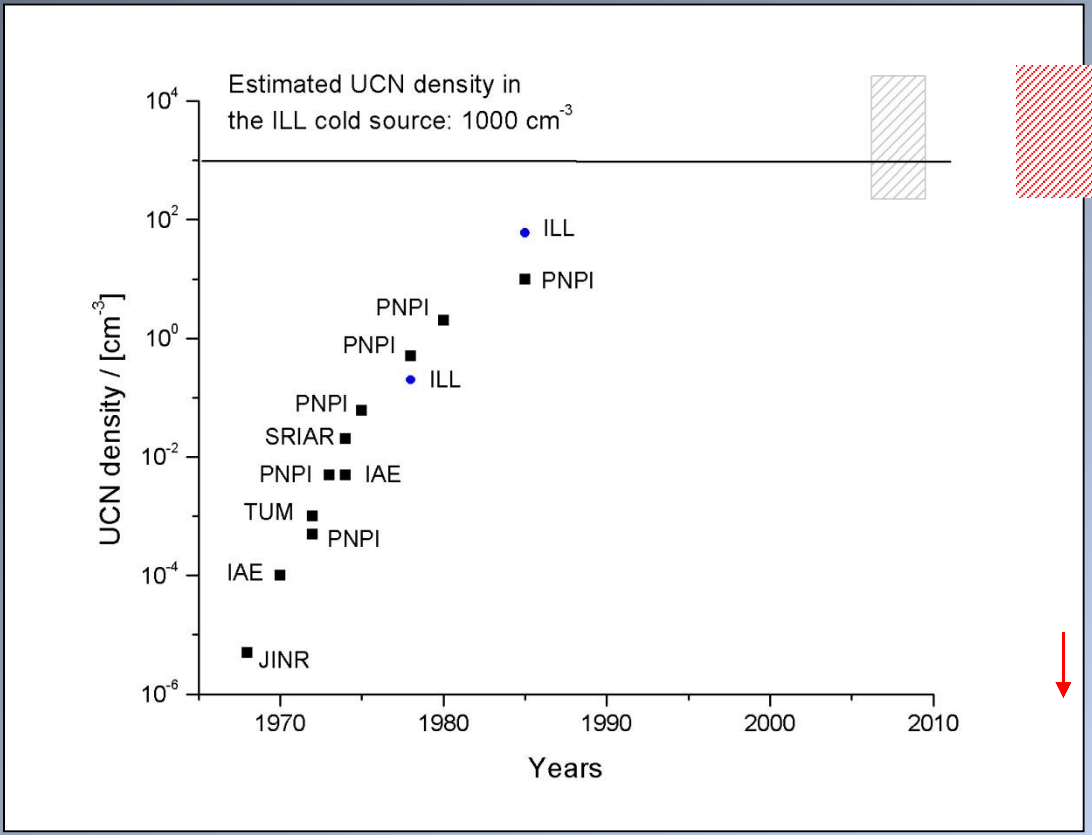
drawing (log book September 1999 on UCN flux measurements at different beam positions of PF2) **courtesy of A. Strelkov**

measured using "pin hole" method:

flux=1/4*dens*vel(av)



UCN facilities – Status and Future

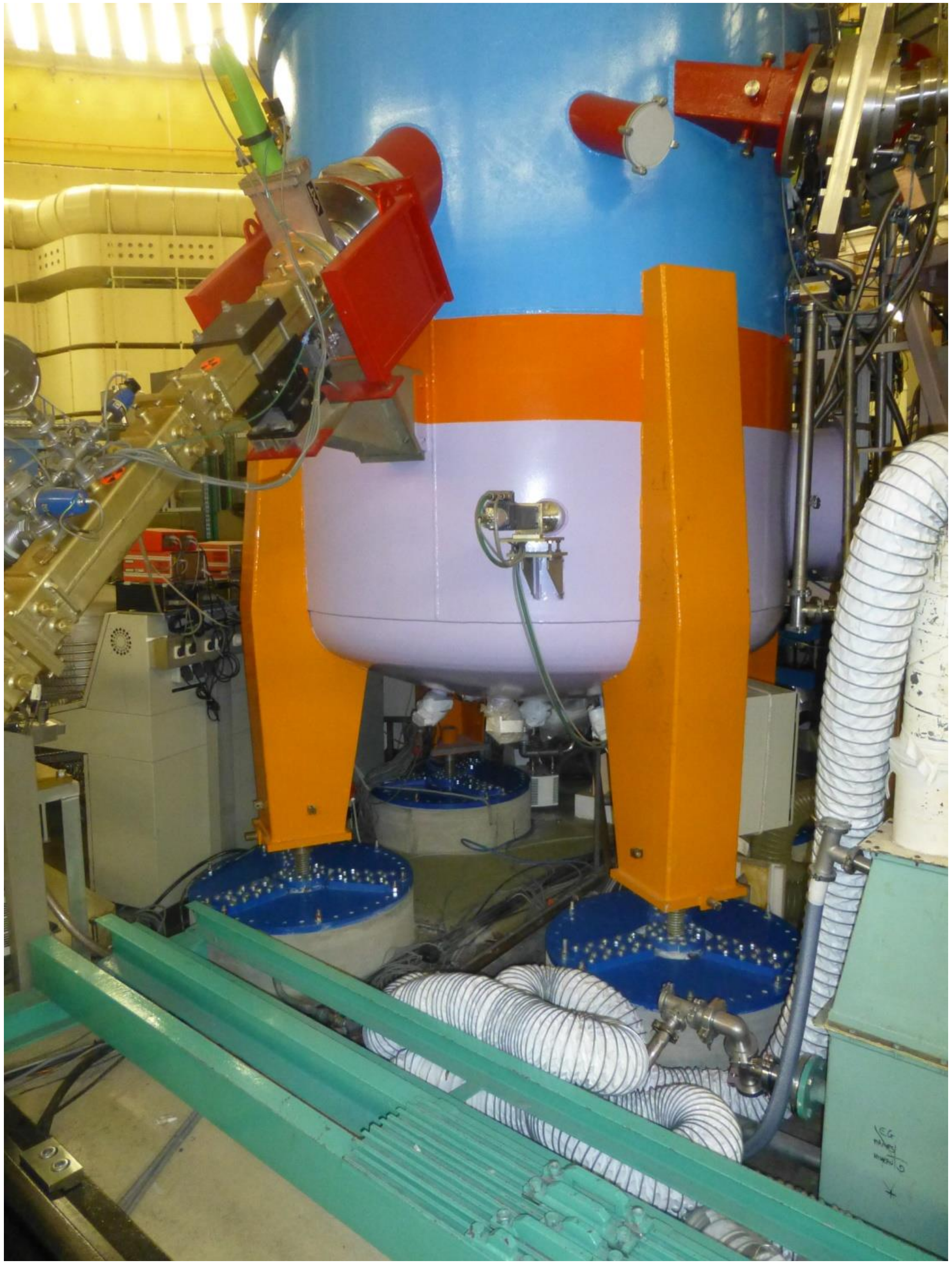


More and stronger UCN facilities in the future worldwide

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

Reactor tank and pool are very close ....

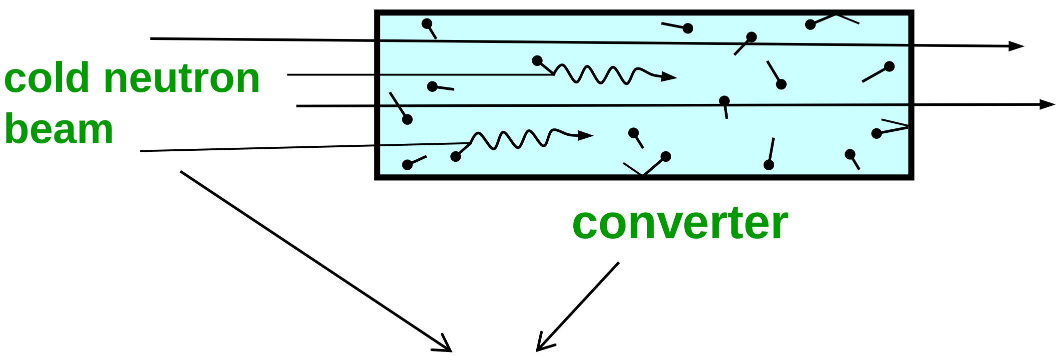
Fastening of the turbine to the floor

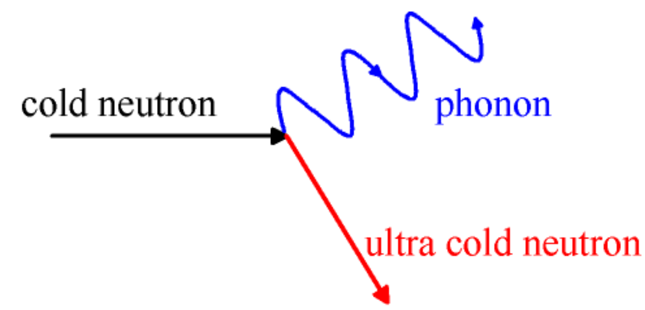


UCN production in He-II

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

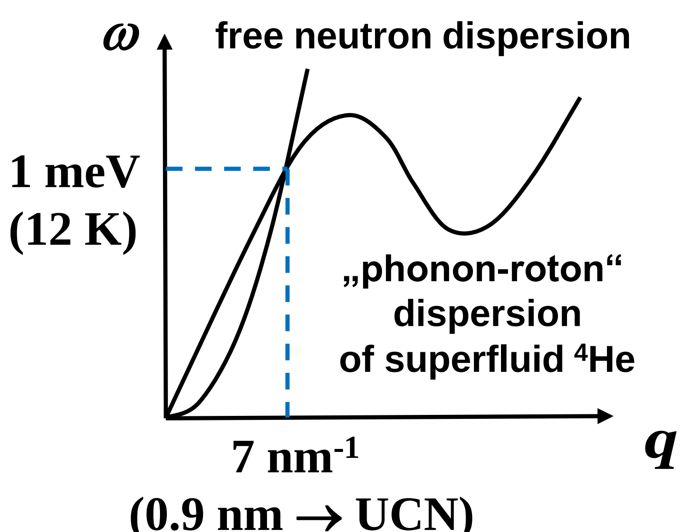
$\sigma_{capture}(^4He) = 0$





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

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



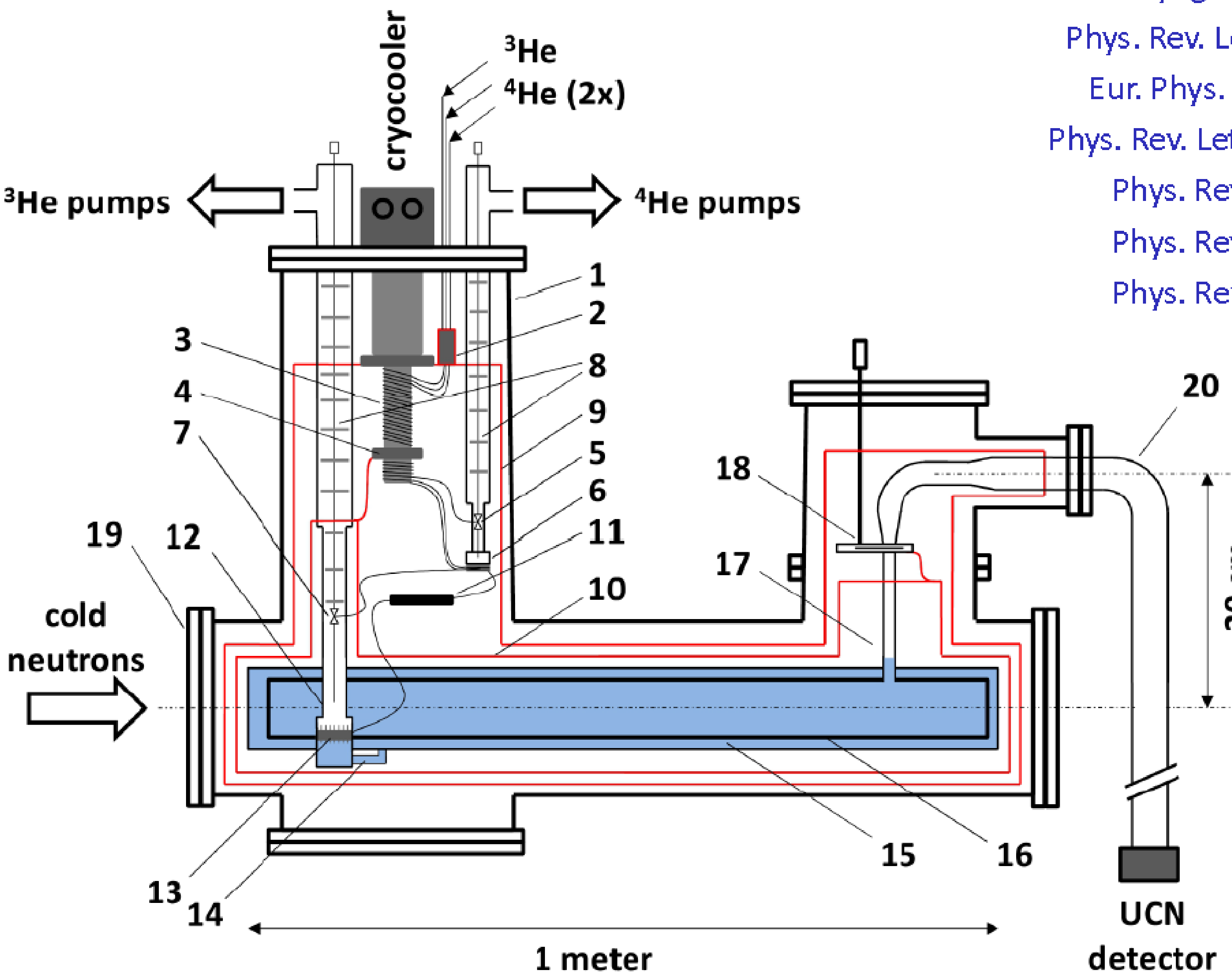
T [K]	τ_{max} [s]
1	100
0.8	310
0.7	510
0.5	820
0	880

→ **need T < 0.5 - 0.6 K and low-loss walls**

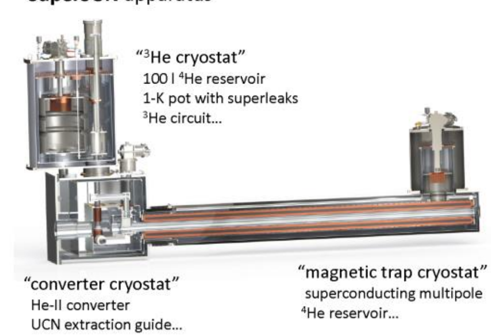
Source prototypes **SUN-1** & **SUN-2** (≥2004)

window- and gap-less vertical UCN extraction

Cryogenics **46** (2006) 799
Phys. Rev. Lett. **99** (2007) 104801
Eur. Phys. J. C **67** (2010) 589
Phys. Rev. Lett. **107** (2011) 134801
Phys. Rev. C **90** (2014) 015501
Phys. Rev. C **92** (2015) 024004
Phys. Rev. C **93** (2016) 025501

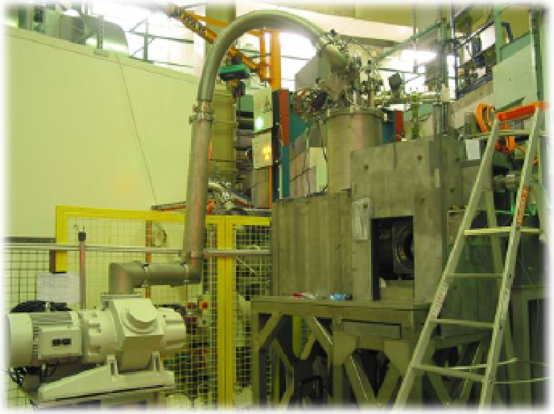


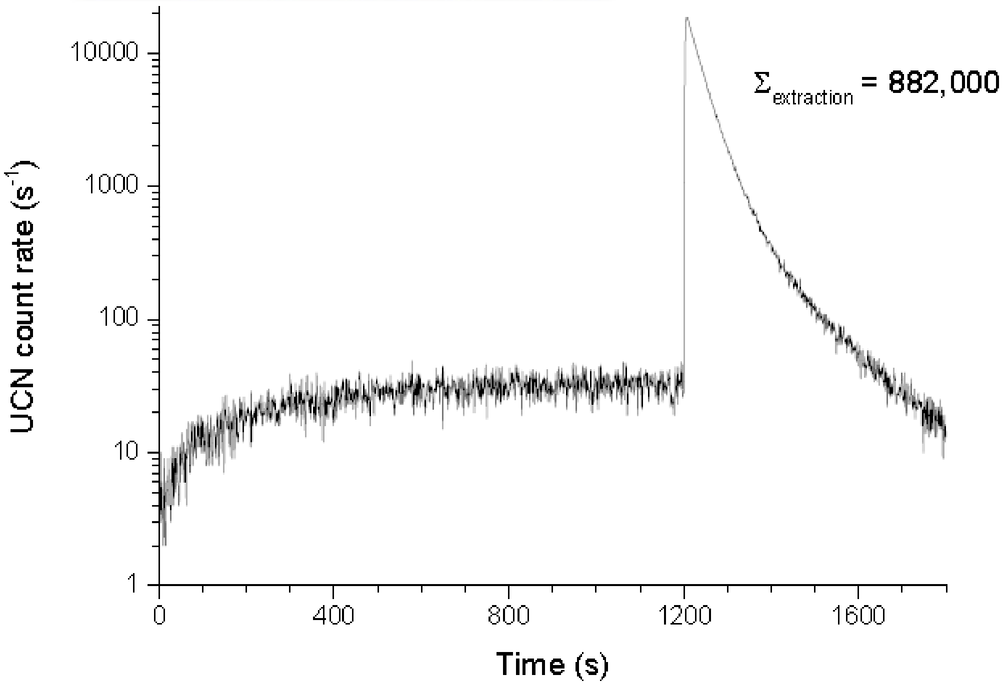
SuperSUN apparatus



SUN-2 performances (fomblin-coated converter vessel)

882000 accumulated UCN from 4 litres He-II (0.61 K) ~ **220/cm^3**

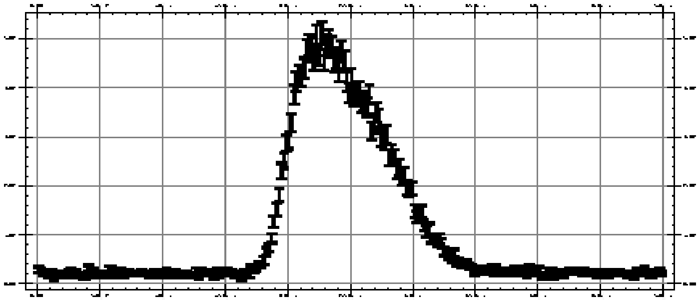




UCN ToF spectra:

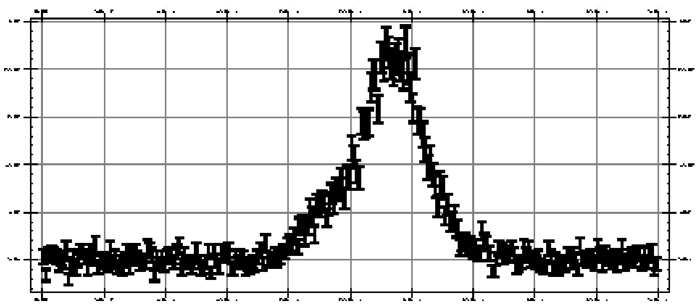
Open converter

v(max) = 5.1 m/s, $E_{||}$ = 144 neV



200 s accumulation

v(max) = 3.9 m/s, $E_{||}$ = 81 neV

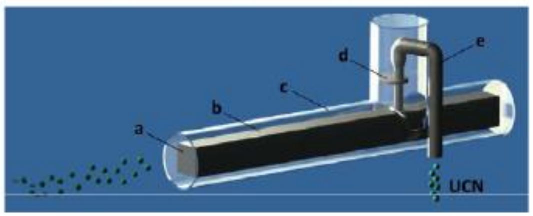


Long-term perspective

- long-term perspective:

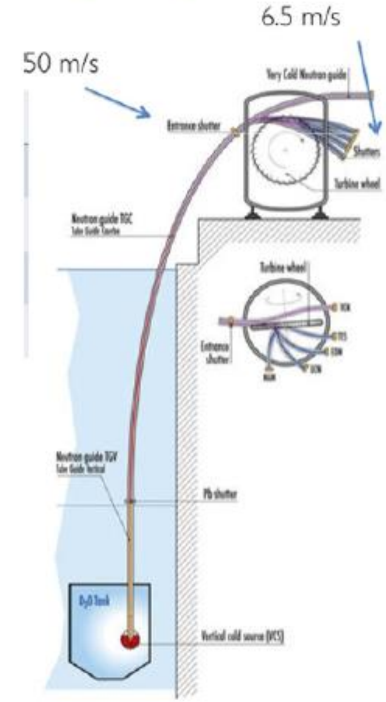
“UCN competence center at the ILL”

SuperSUN (SUN2)



highest UCN densities, very soft spectrum

- *dedicated (long-term) storage experiments*



PF2

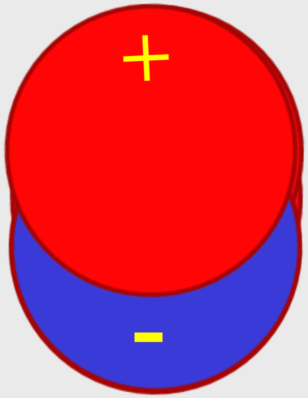
highest UCN flux

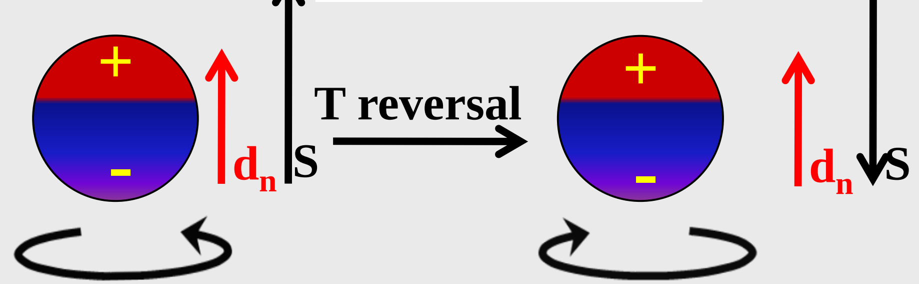
- *In-flight/ short-time experiments*

21

$$\mathcal{H} = -\mu \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} - d \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}$$

(non-relativistic interaction Hamiltonian)





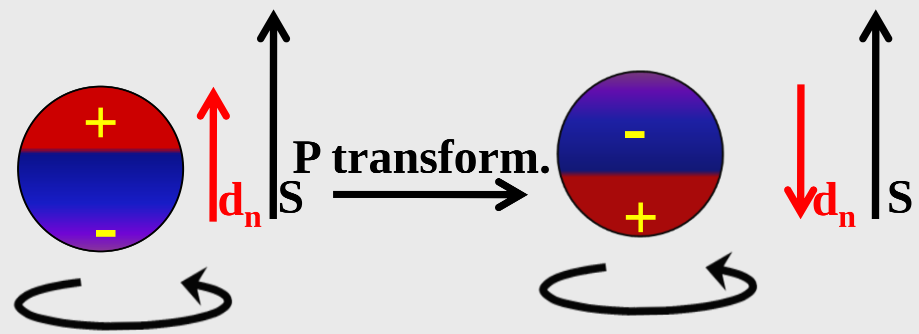
electric dipole moment d_n
spin S

Electric Dipole Moment:

neutron is electrically neutral

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

E.M. Purcell and N.F. Ramsey
Phys. Rev. 78, 807 (1950)



P & T violation

EDM d_n

CPT conservation ➔ CP violation

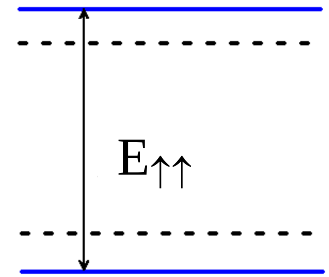
CP violation in Standard Model generates very small neutron EDM
Beyond the Standard Model contributions tend to be much bigger

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

Experiments:

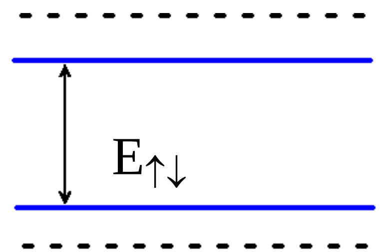
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

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

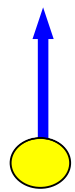
< 1 turn per month!

The difference is proportional to d_n and E:

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

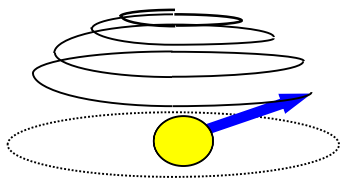
Ramsey method of Separated Oscillatory Fields

1.



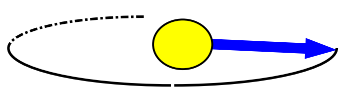
"Spin up" neutron...

2.



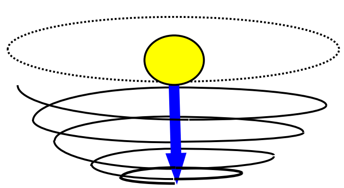
Apply π/2 spin flip pulse...

3.

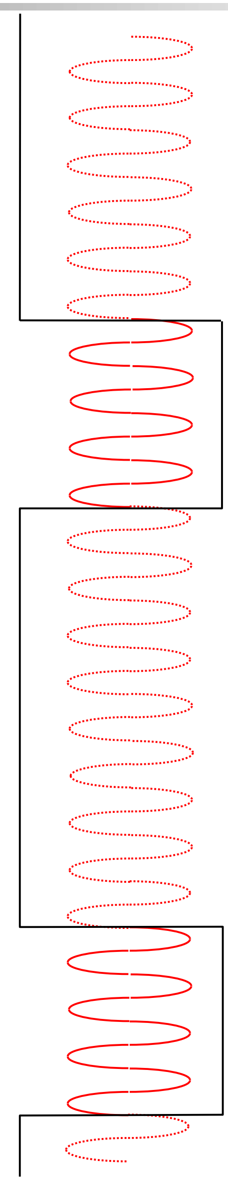


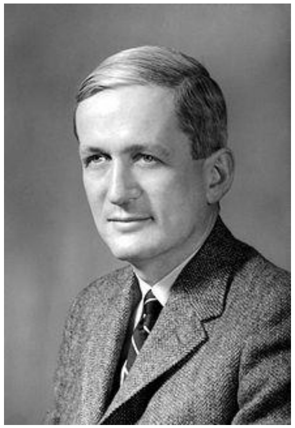
Free precession. ..

4.



Second π/2 spin flip pulse.





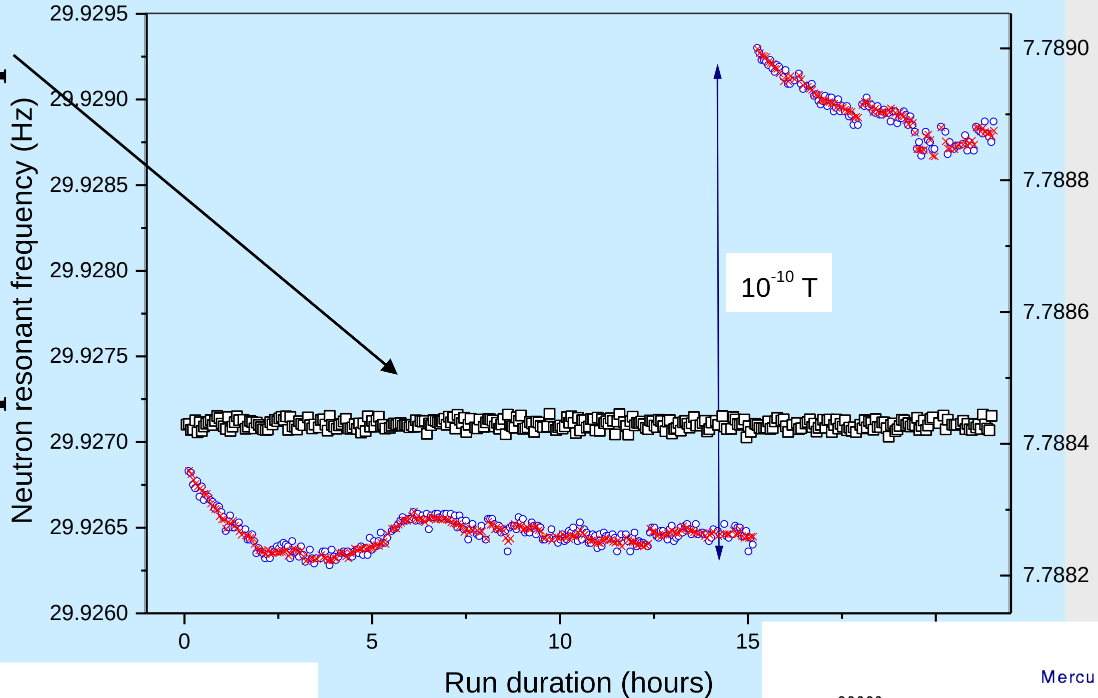
Norman F. Ramsey

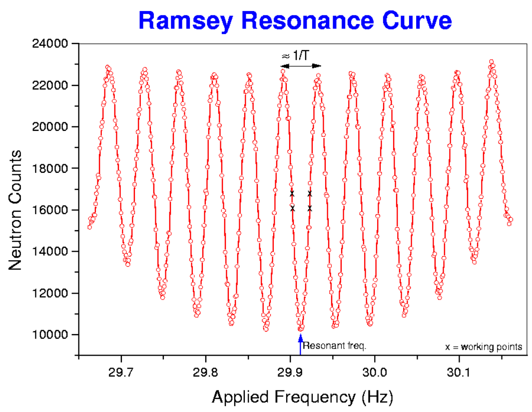
1915 – 2011

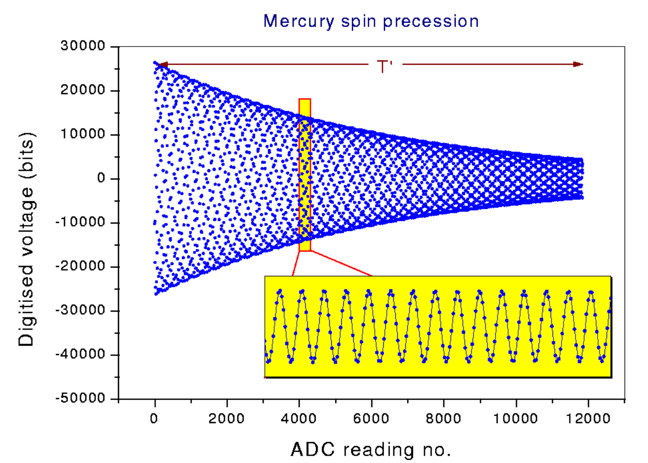
Nobel Prize in Physics 1989

"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks. ...

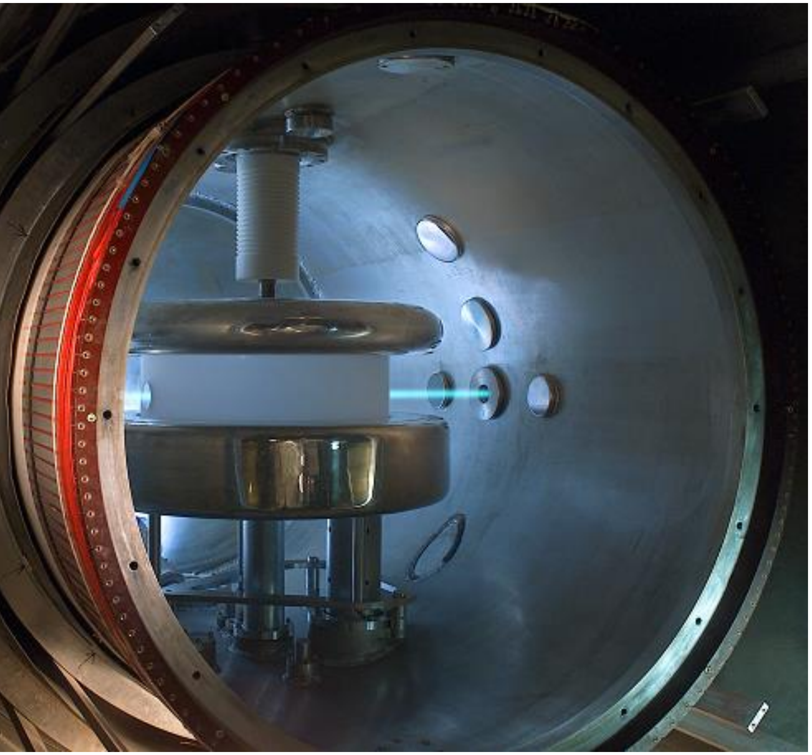
ratio R of precession frequencies

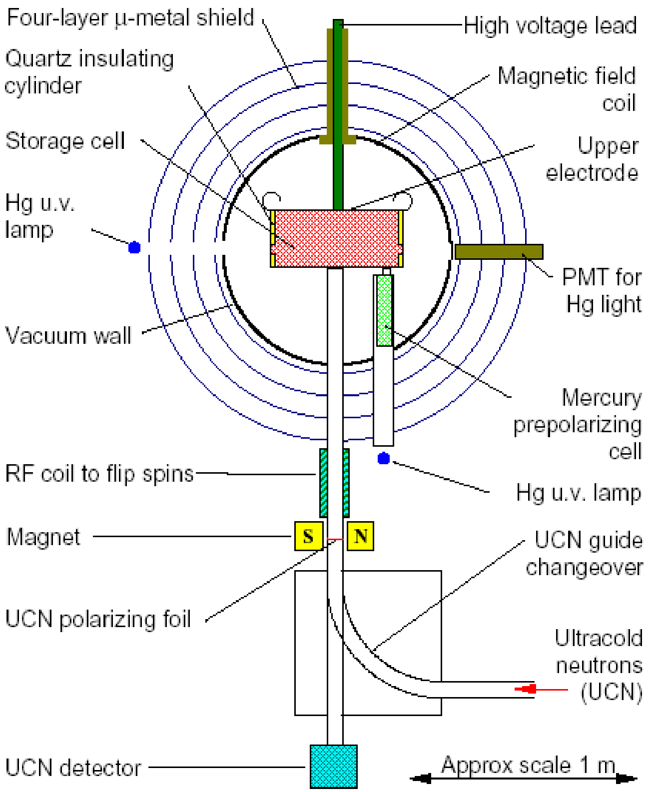






Room Temperature Results





University of Sussex

CCLRC

ILL NEUTRONS FOR SCIENCE

Room temperature neutron EDM result:

C.A. Baker et al., Phys. Rev. Lett. **97,** 131801 (2006)

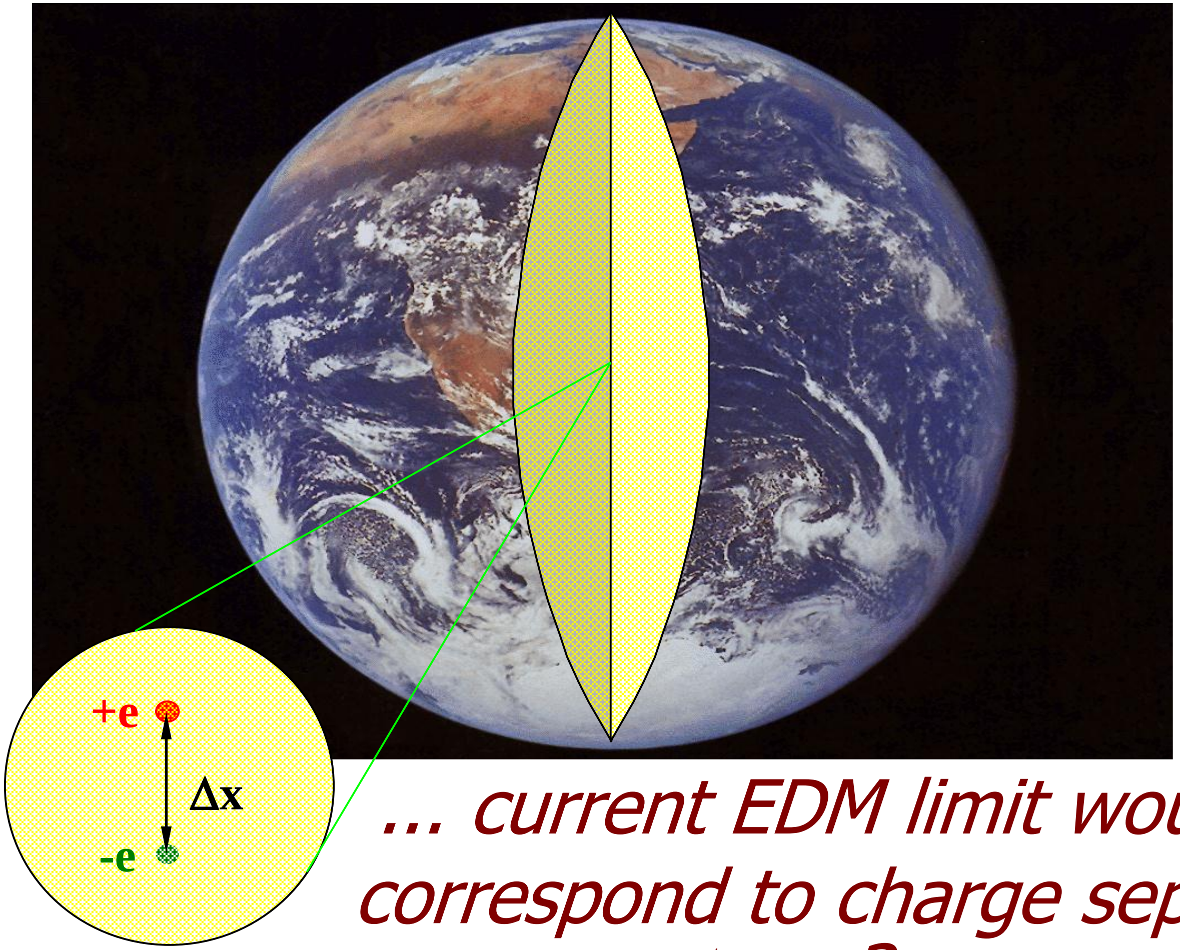
$$|d_n| < 2.9\times10^{-26}\ \text{e.cm (90\% C.L.)}$$

Reanalysis: J.M. Pendlebury et al., Phys. Rev. D **92,** 092003 (2015)

$$|d_n| < 3.0\times10^{-26}\ \text{e.cm (90\% C.L.)}$$

Reality check

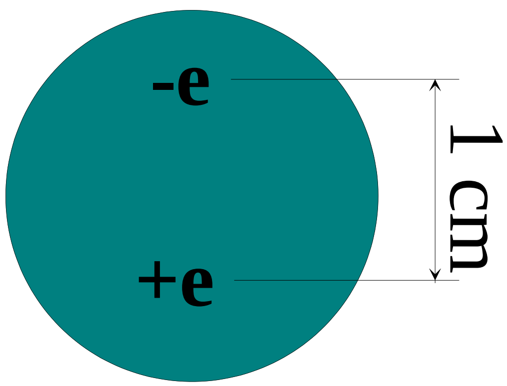
If neutron were the size of the Earth...



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

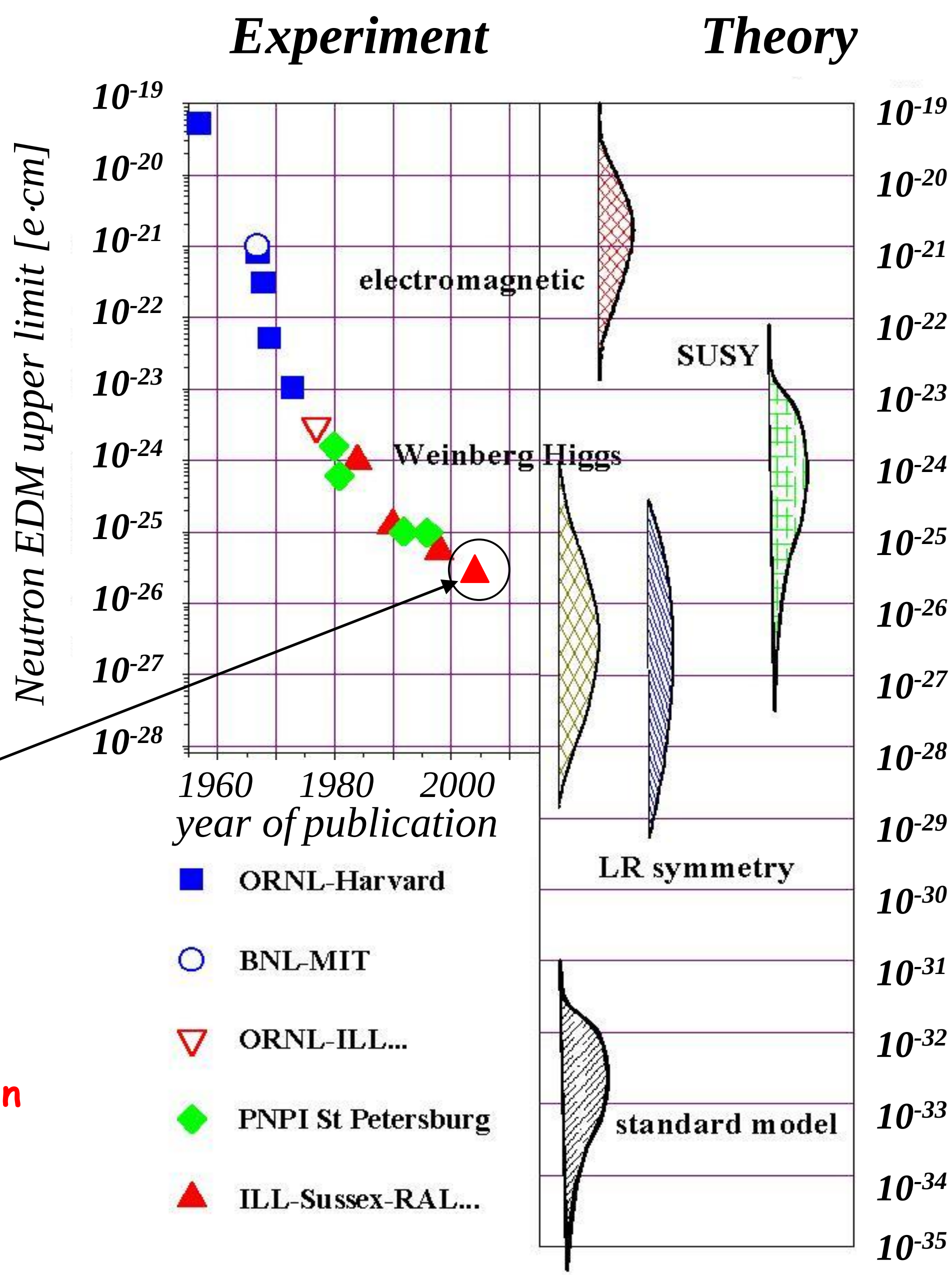
The neutron EDM: exp. vs theory

Progress at ~ order of magnitude per decade
Standard Model out of reach
Severe constraints on *e.g.* Super Symmetry



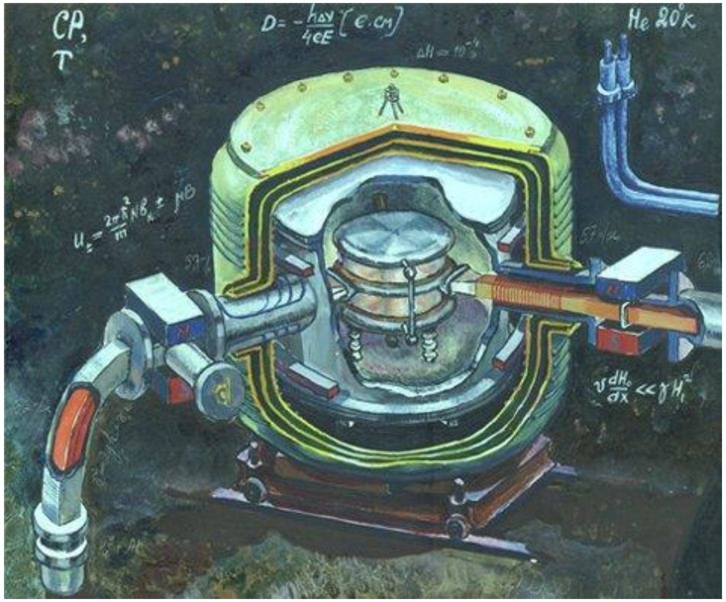
$d_n = 1\ e\cdot\text{cm}$

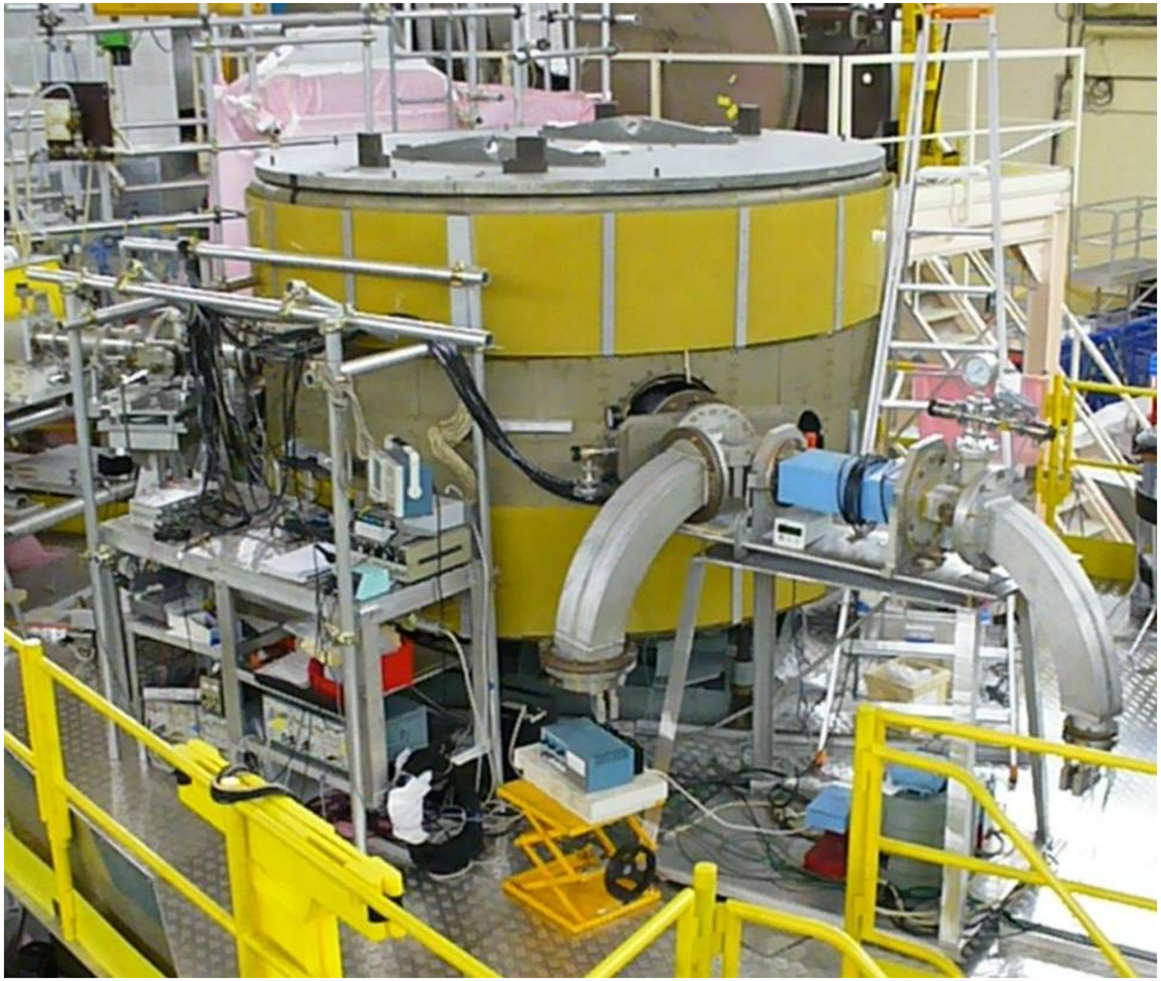
$|d_n| < 3 \times 10^{-26}\ e\cdot\text{cm}$



"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

PNPI double-chamber nEDM spectrometer at PF2/MAM





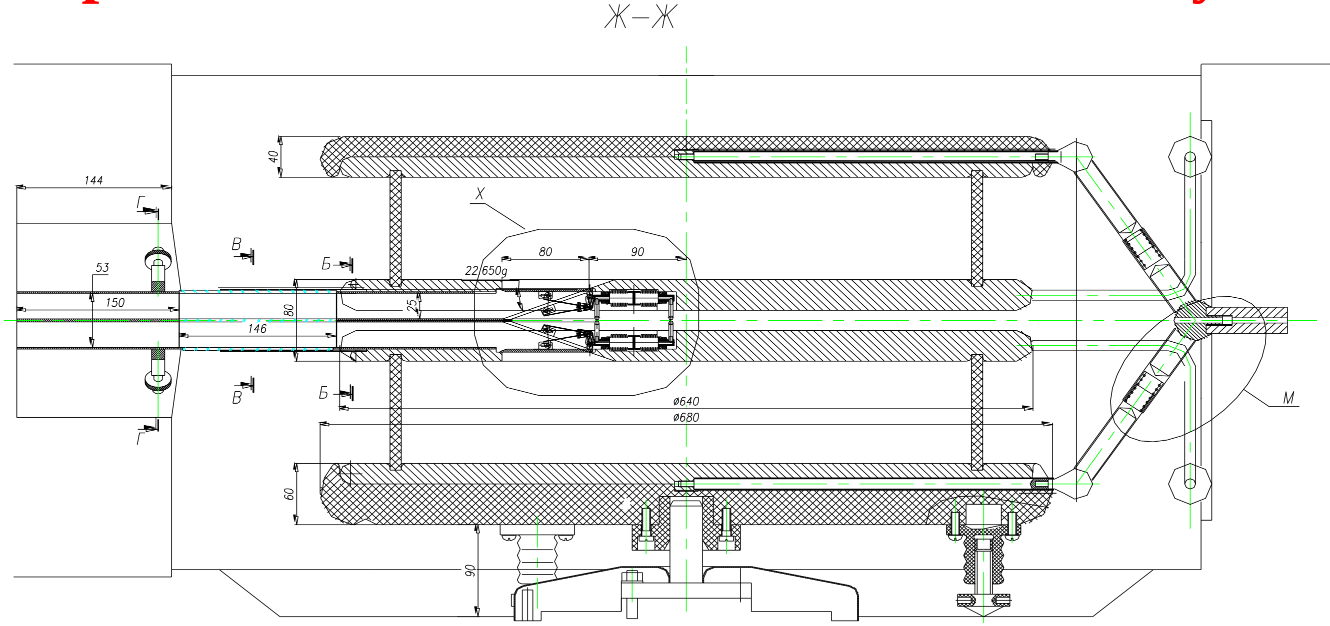
$$/nEDM/ \leq 5.5 \cdot 10^{-26} e \cdot cm$$

at 90% confidence level

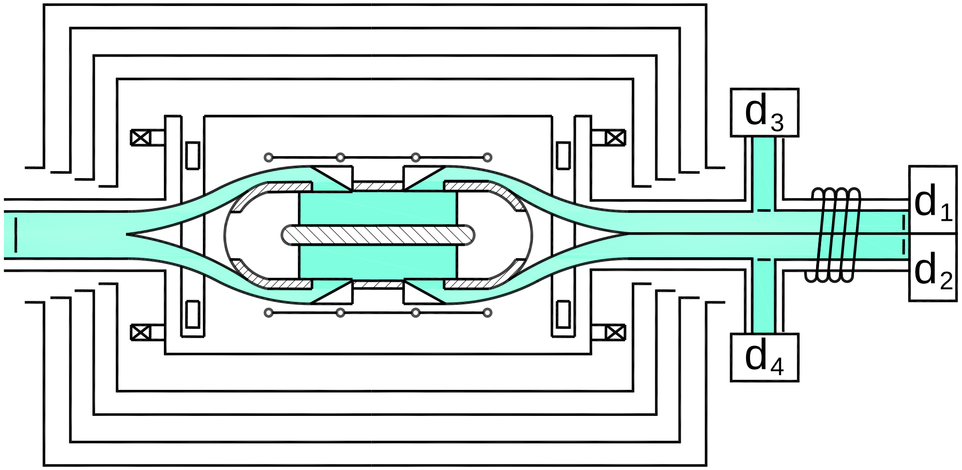
A.P. Serebrov et al., Pis'ma v ZhETF 99 (2014) 7

New scheme of UCN trap in EDM spectrometer

Expected factor UCN transmission intensity is about 2 - 3 times



New scheme



Old scheme

PanEDM @ ILL

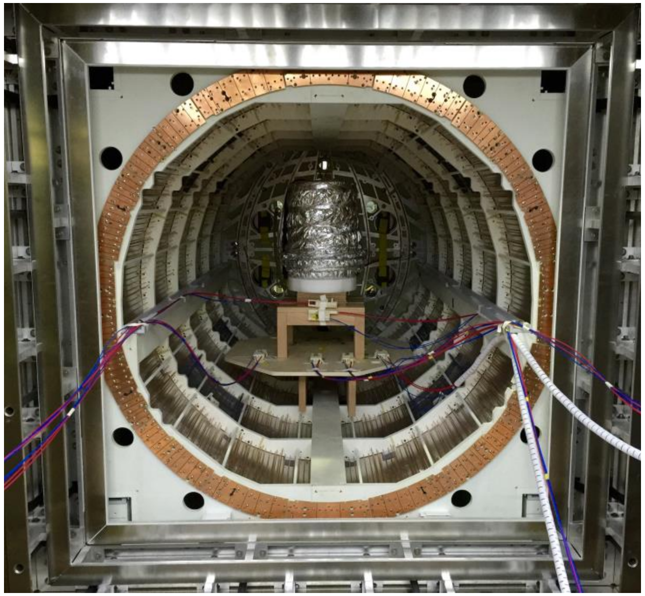
- Single-user facility
- Converter volume: 12 litres
- UCN production rate: 10^5 s^{-1} (E < 230 neV)
- UCN saturation number: 4×10^6 (2017, fomblin spectrum)
  2×10^7 (2019, polarised, E < 230 neV)

Purpose: pushing the limits in flagship experiments, notably:

Neutron EDM < 10^{-26} ecm

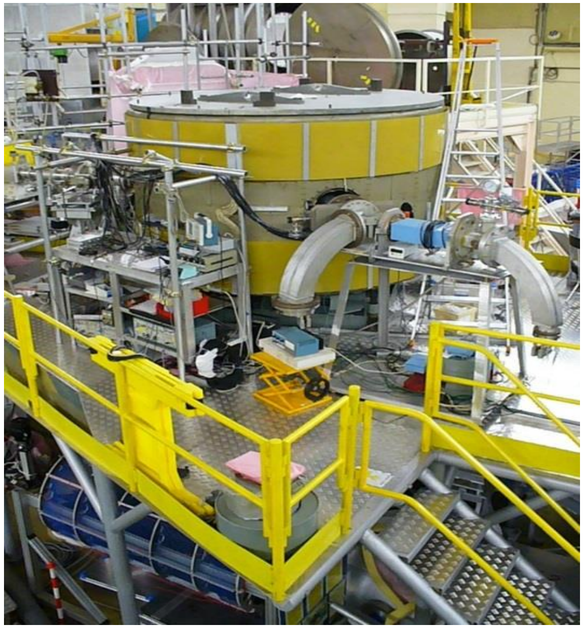
P. Fierlinger et al., TU Munich

A. Serebrov et al., PNPI Gatchina



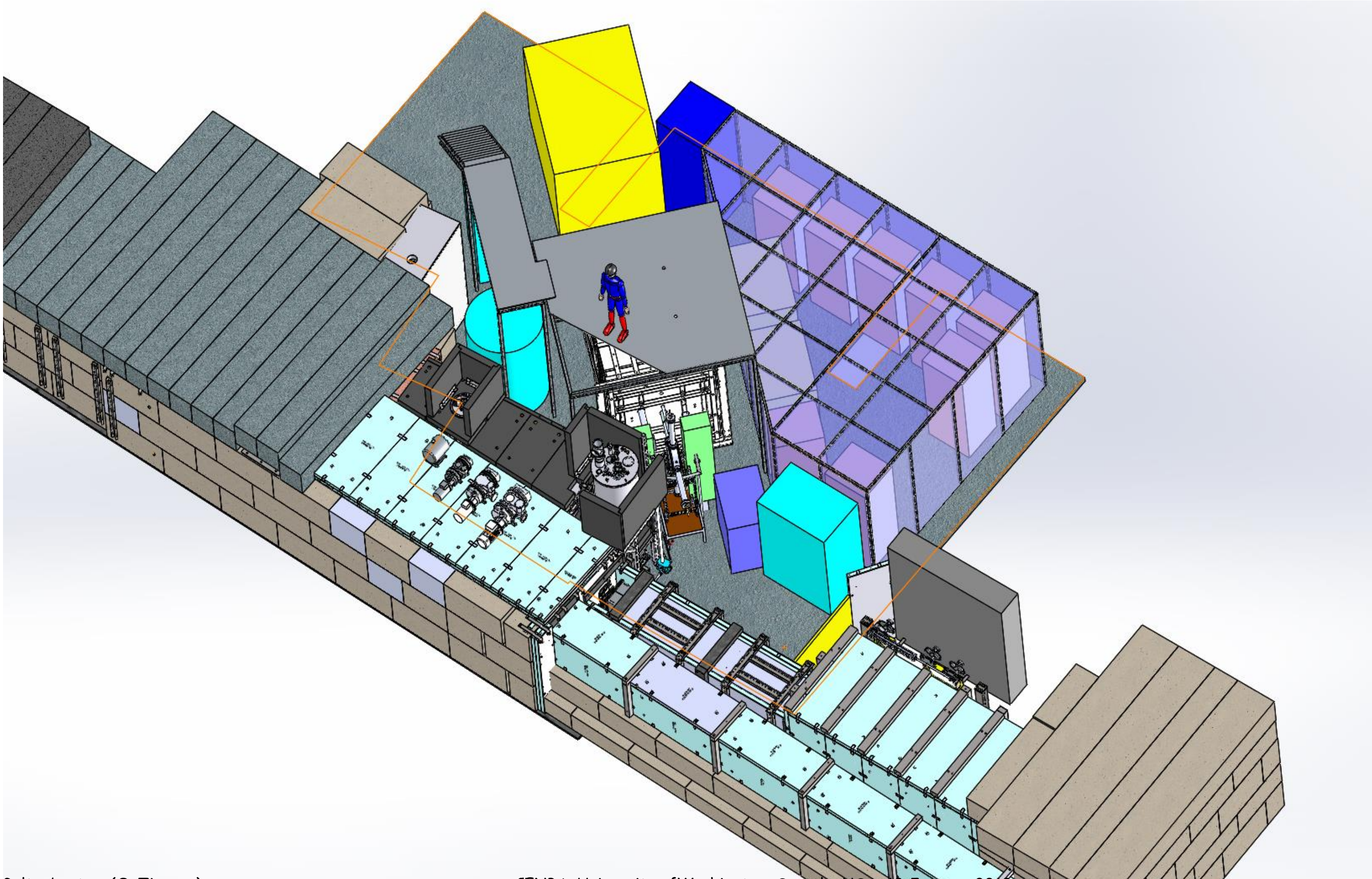
D. Beck, UI Urbana-Champaign

T. Chupp, UM Ann Arbor

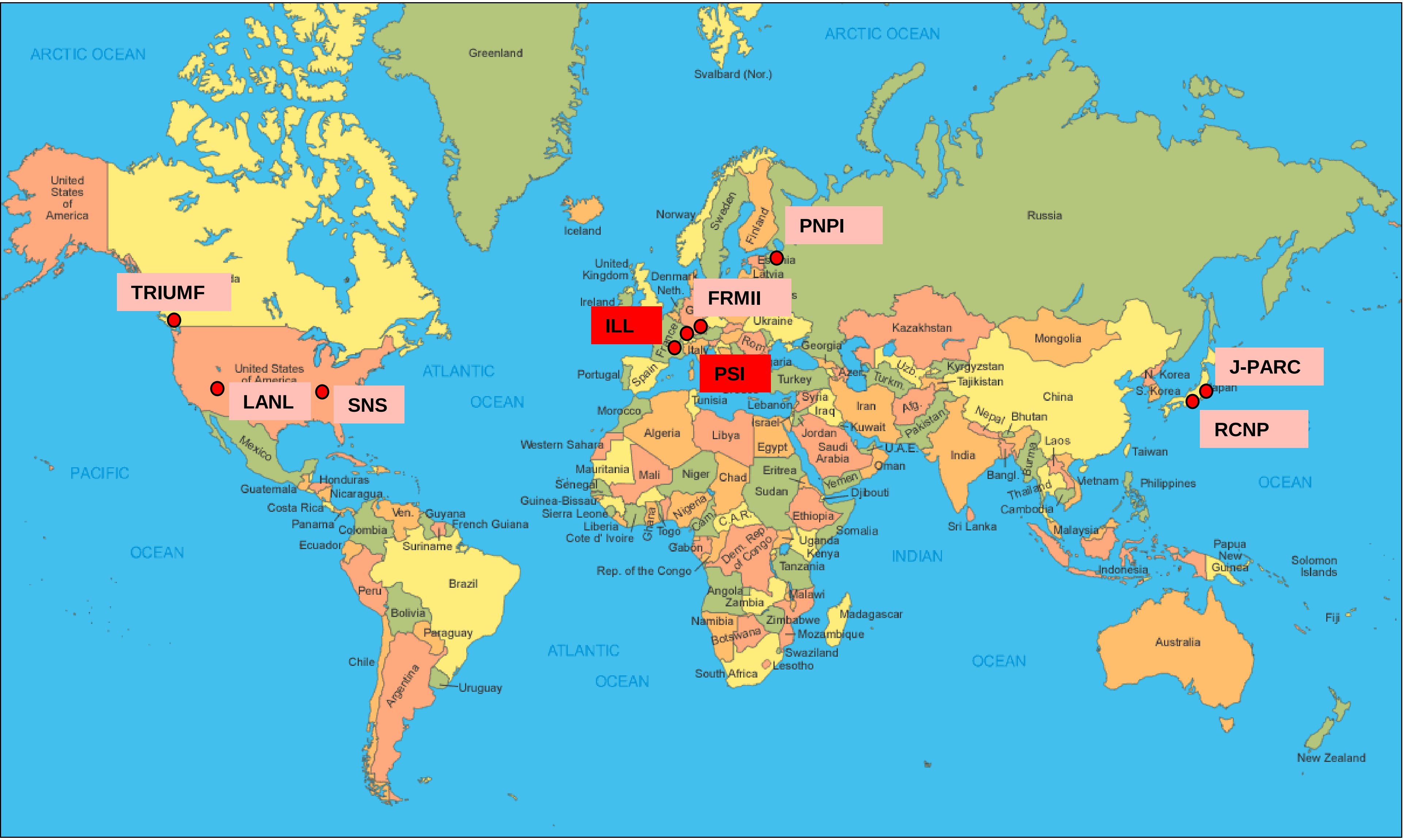


PanEDM @ SuperSUN on beam H523

	Stage I	Stage II
Sensitivity (1 σ) 100 days	**1.9×10^{-27} ecm**	**4.2×10^{-28} ecm**
Limit (90% C.L.) 100 days	**3.0×10^{-27} ecm**	**7.0×10^{-28} ecm**



Worldwide nEDM Searches



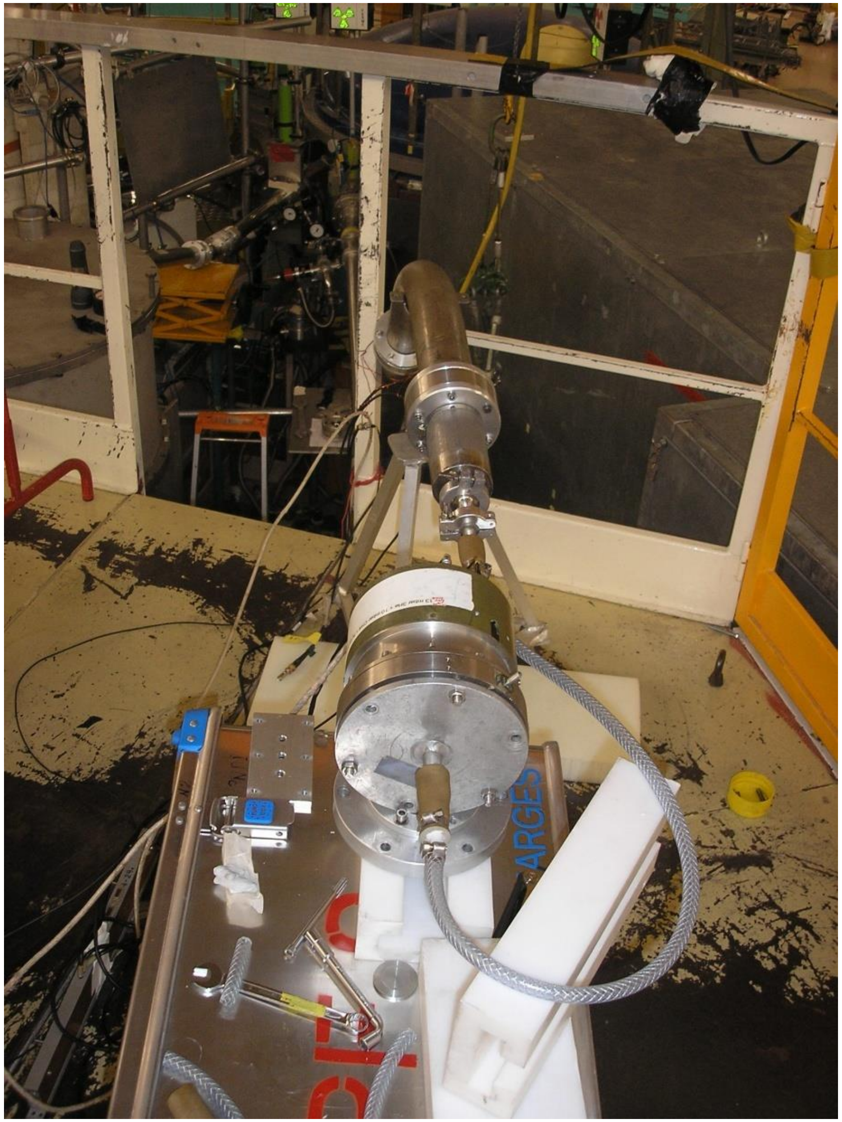

MACGYVER

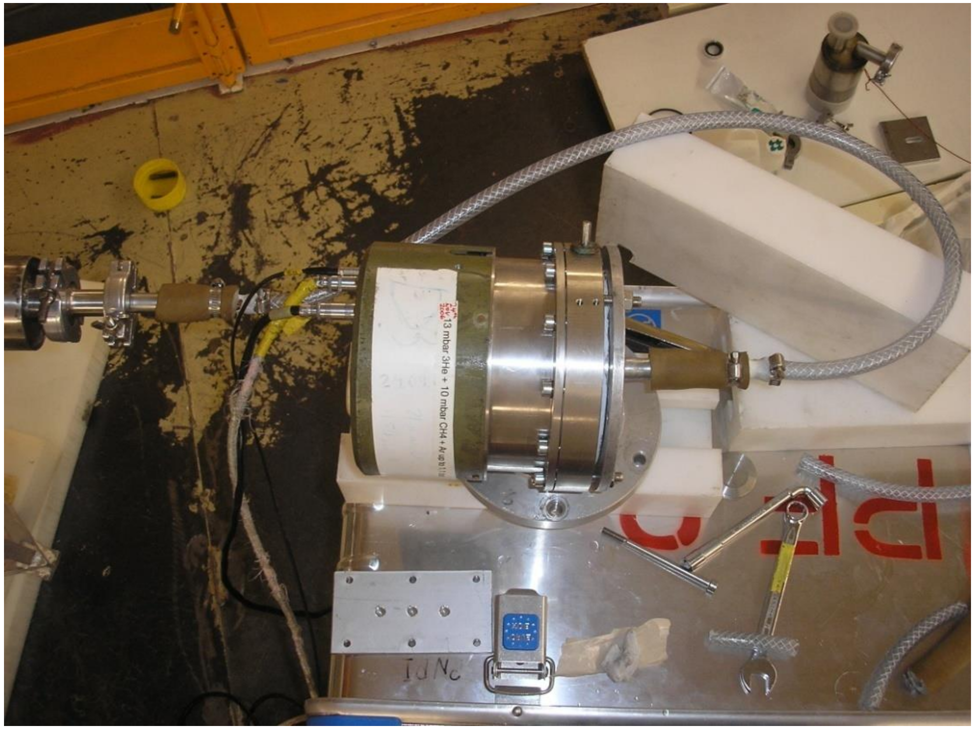

WHAT WOULD
MACGYVER DO?

UCN are always good for a surprise!

Transmission through flexible water hose

Yu. Panin et al., RRC KI Moscow

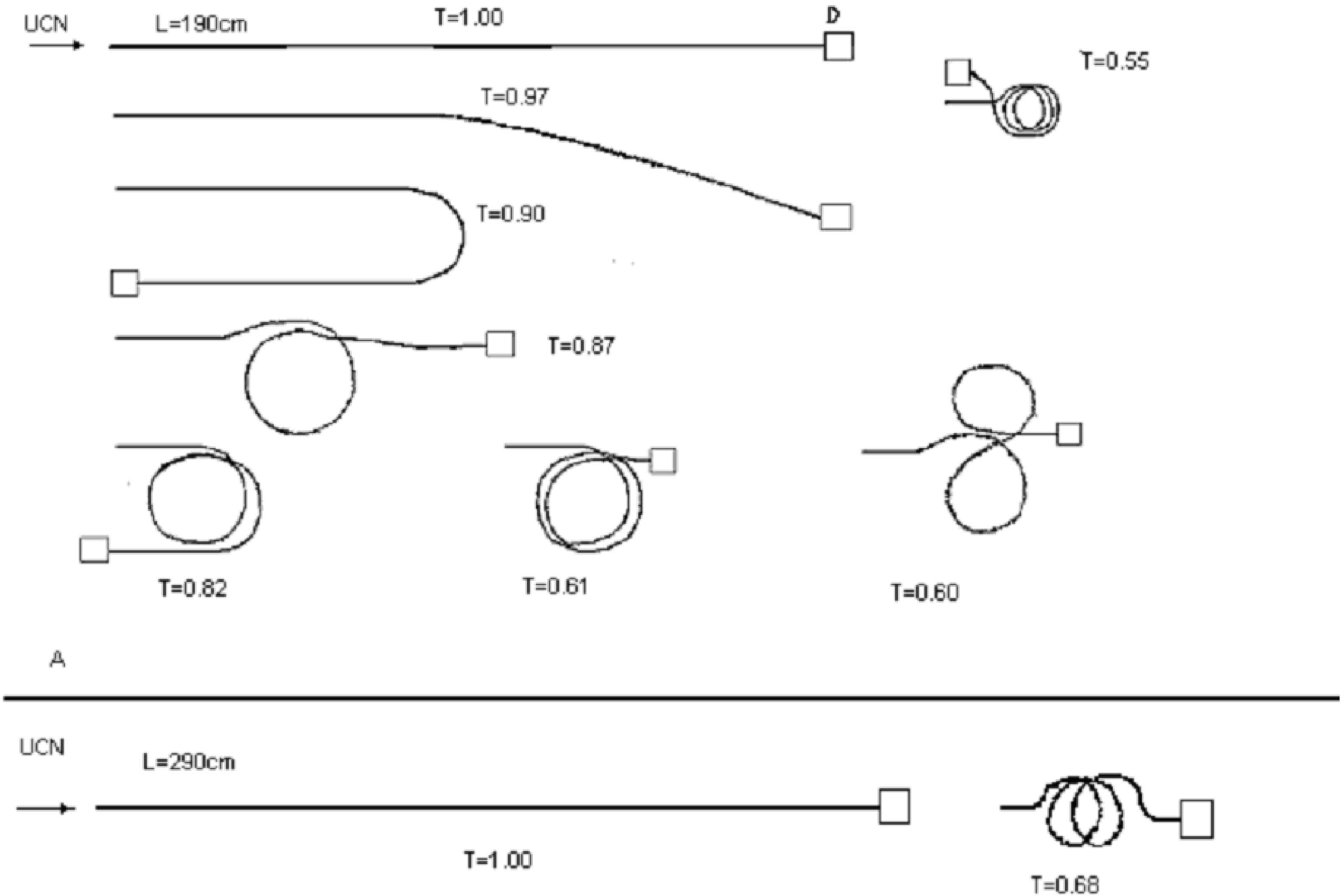




Surprising result
(80 cm hose with 8 mm inner diameter)

transmission around 85%

Relative Transmission Probability of "fancy guides"

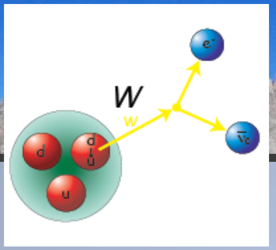


Top view:

- 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.

NEUTRONS FOR SCIENCE

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



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

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

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

Weak interaction theory

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

Neutrino physics

Neutrino induced reactions:

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

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

Neutrino detectors:

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

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

Cosmology

Solar pp-process:

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

Big bang:

Primordial elements' abundances

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

NEUTRONS FOR SCIENCE

Measurements of the neutron lifetime τ_n

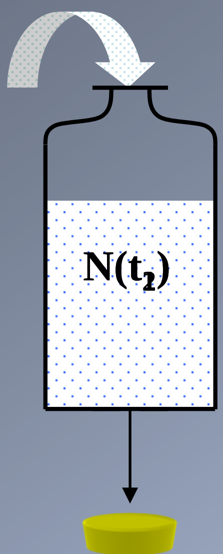
exponential decay law: $N = N_0 e^{-\lambda t}$

or, ultimately, measure the exponential decay directly

Storage experiments with UCN

"counting the surviving neutrons"

"UCN bottle"



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

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

→ 0 (experiment)

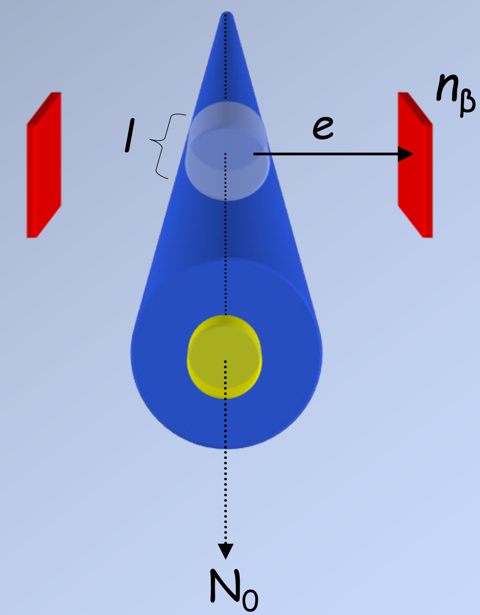
$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff}$$ → 0 (extrapolation)

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

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

Does the neutron lifetime depend on the measuring method?

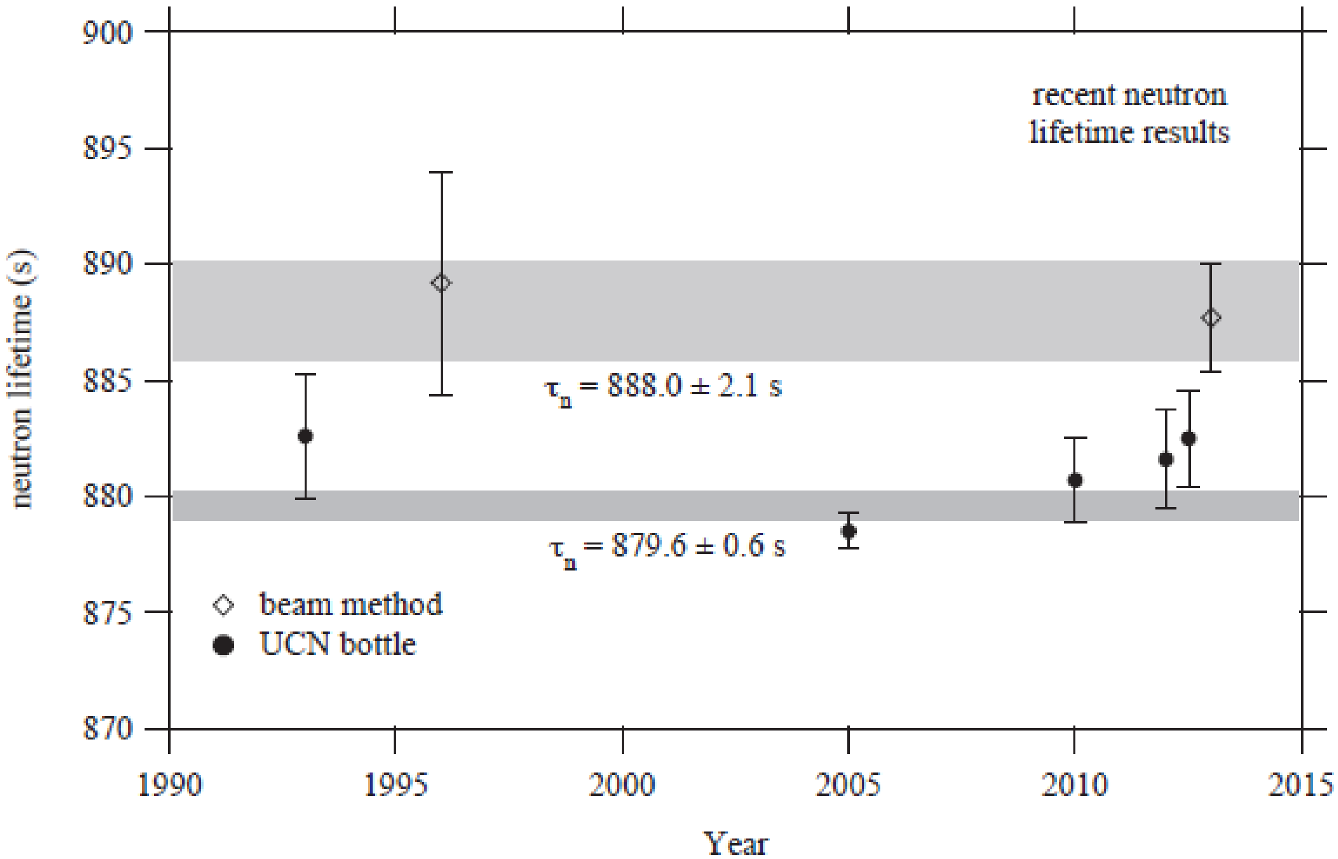
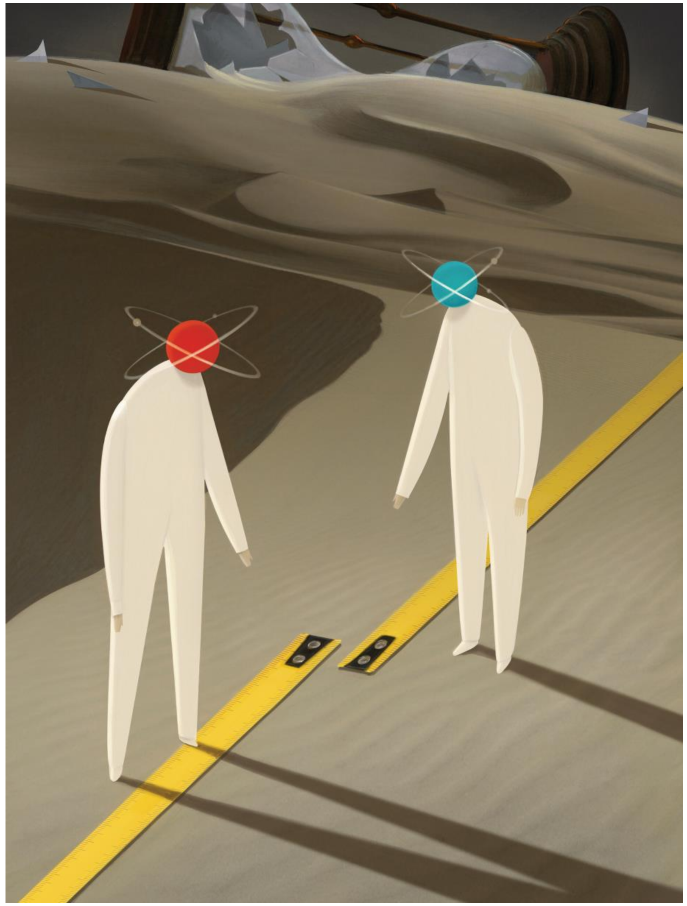


Figure 2: A summary of recent neutron lifetime measurements, showing the five UCN bottle [18, 16, 19, 20, 21] and two neutron beam [12, 15] results used in the 2014 PDG recommended value of $\tau_n = 880.3 \pm 1.1$ s. The shaded regions show the weighted average $\pm 1\sigma$ of each method, which disagree by 3.8σ.

F. Wietfeldt, arXiv:1411.3687v1 [nucl-ex]

For a broader public



PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort

IN BRIEF

The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.
Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

Illustration by Bill Mayer

April 2016, ScientificAmerican.com **37**

Translated and published in International Editions of Scientific American:

France, Germany, Italy, Spain

China, Japan,

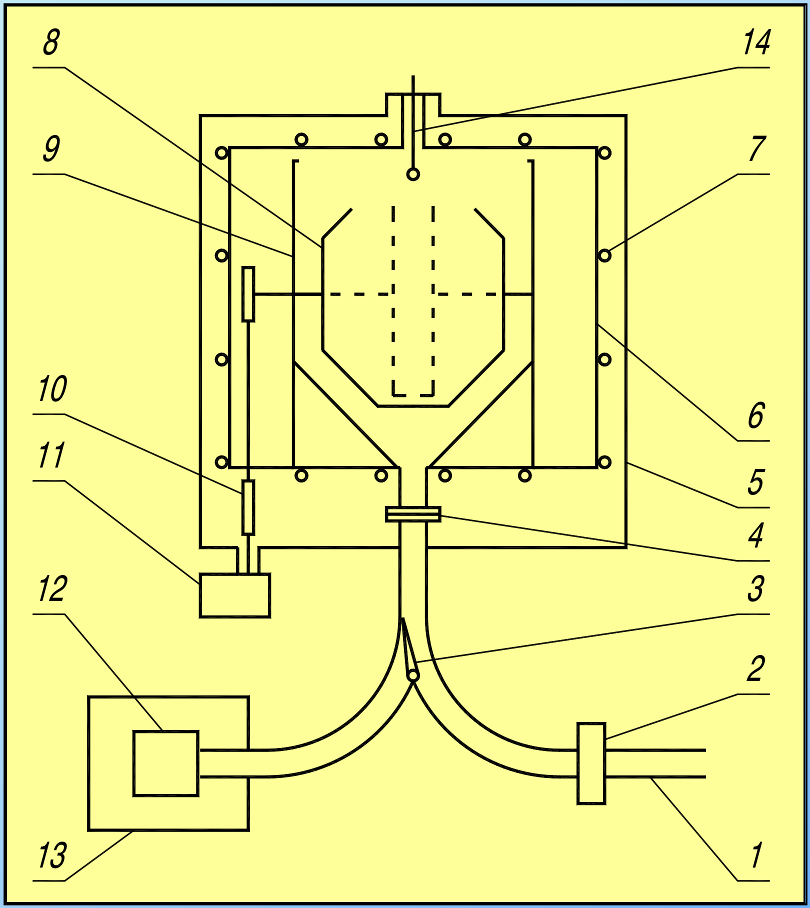
Russia, Poland, Israel, …

谜样的 9 秒：测不准的中子寿命

两个测量中子寿命的精密实验结果存在着差异。这种差异究竟反映了测量的误差，还是预示着一些更深层次的待解之谜？

撰文 杰弗里·L·格林（Geoffrey L. Greene） 彼得·格尔滕博特（Peter Geltenbort）
翻译 张寂潮 孙保华

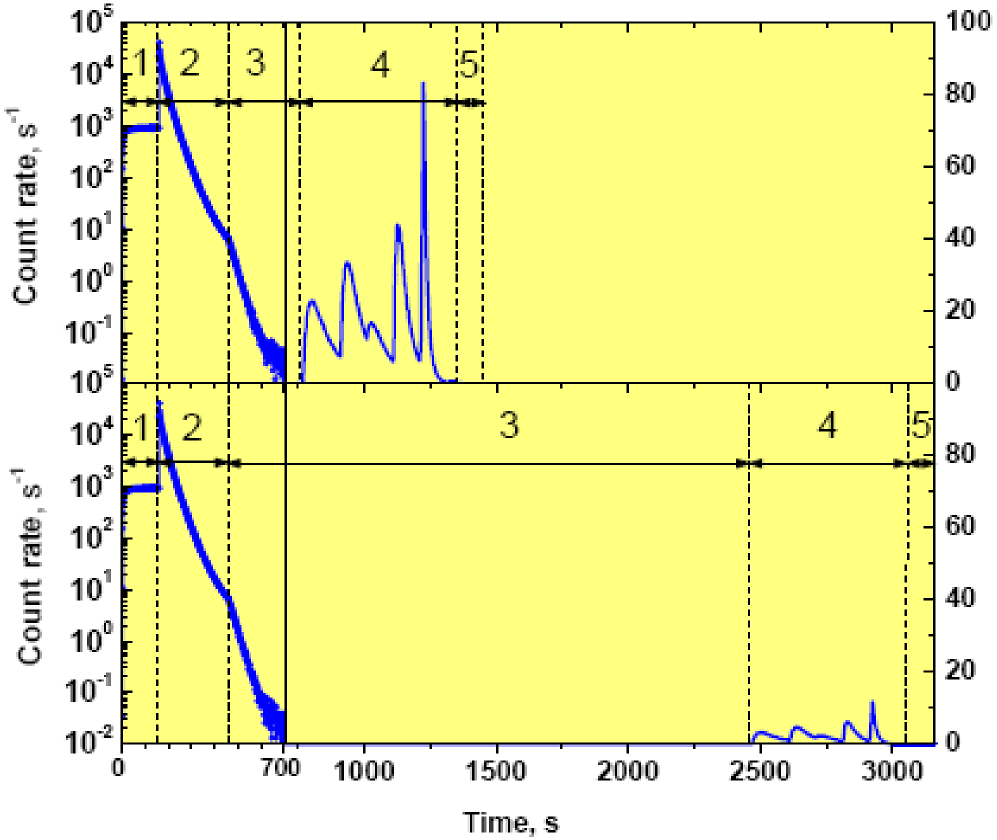
Scheme of “Gravitrap”, the gravitational UCN storage system



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

Typical measuring cycle



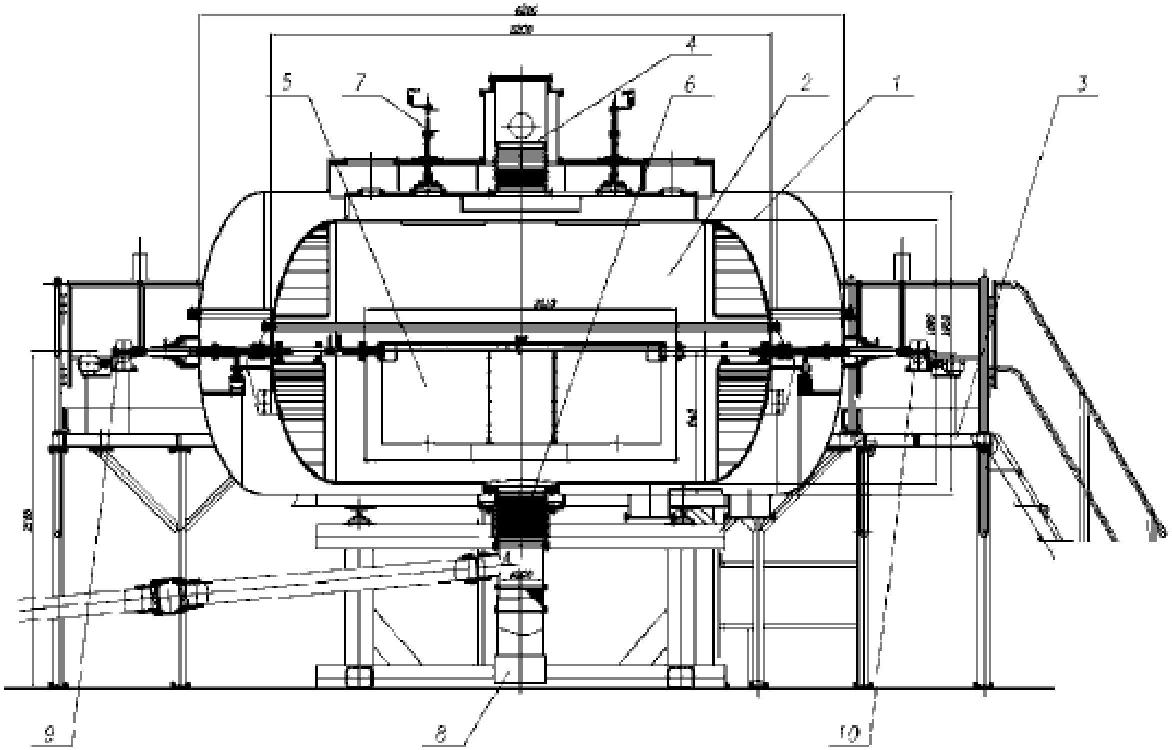
1. filling 160 s (time of trap rotation (35 s) to monitoring position is included);
2. monitoring 300 s;
3. holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included);
4. emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5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

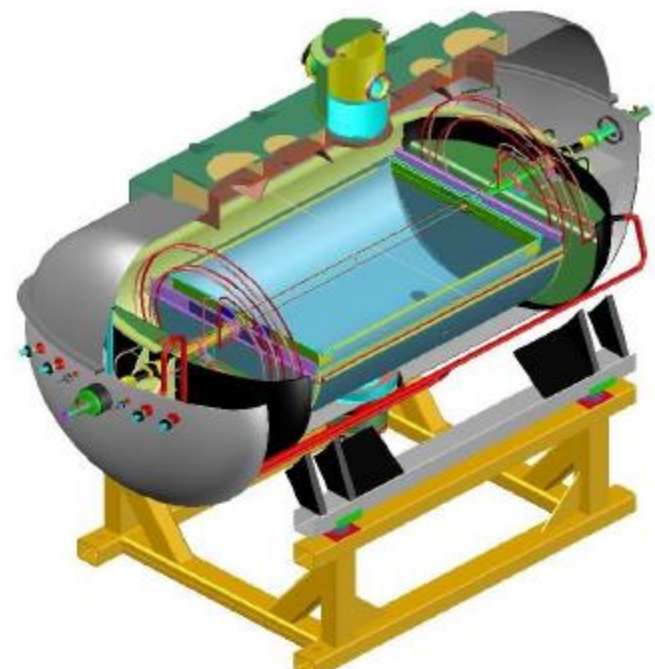
$$N(t_2) = N(t_1) \cdot \exp\left(-\frac{t - t_1}{\tau_{st}}\right)$$

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

A.P. Serebrov et al. , Phys Lett B 605, (2005) 72-78 : **(878.5 ± 0.8) s**

Scheme of Big Gravitational Trap





1 – external vacuum vessel; 2 – internal vacuum vessel; 3 – platform for service; 4 – gear for pumping out internal vessel; 5 – trap with insert in low position; 6 – neutron guide system; 7 – system of coating of trap and insert; 8 – detector; 9 – mechanism for turning trap; 10 – mechanism for turning insert

Table of systematic errors

Systematic effect	Value, s
Uncertainty of γ function calculating (MC)	0.1
Uncertainty of shape of function μ(E)	0.3
Uncertainty of trap dimensions (3 mm for diameter 1200 mm)	0.15
Uncertainty of trap angular position (2^o)	0.1
Uncertainty of difference for trap and insert coating	0.6
Total	0.7

Big Gravitational Trap with Fomblin grease coating

$$880.5 \pm 0.8_{st} \pm 0.7_{syst}$$

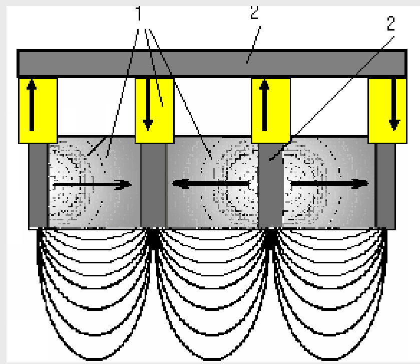
General principle and design

- 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.

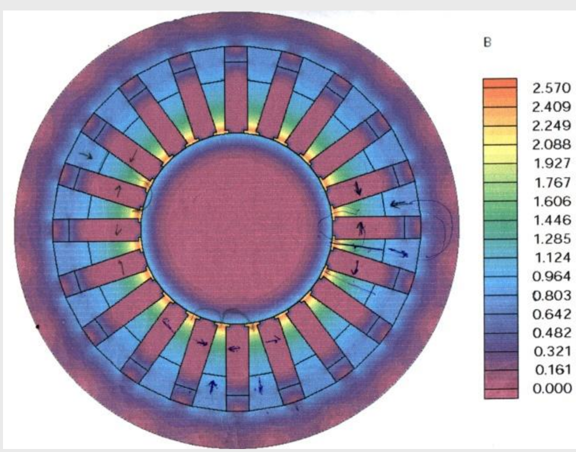
- **Step 1: 1D confinement**

  1 – permanent magnets

  2 – magnetic poles

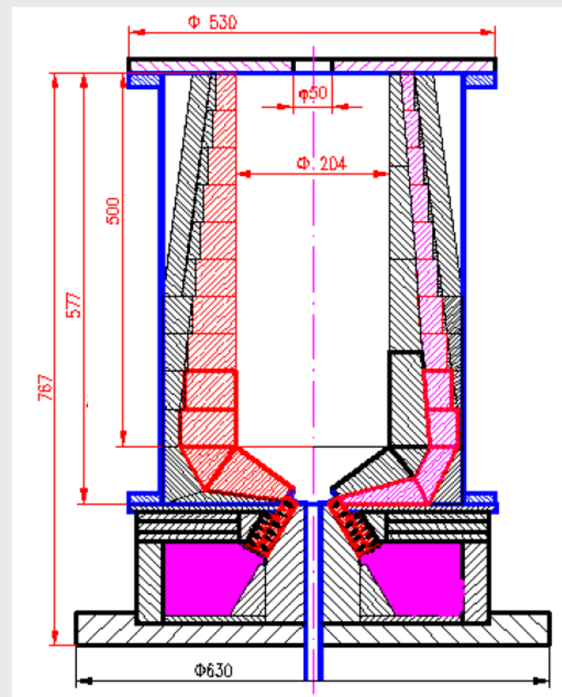


- **Step 2: 2D confinement**



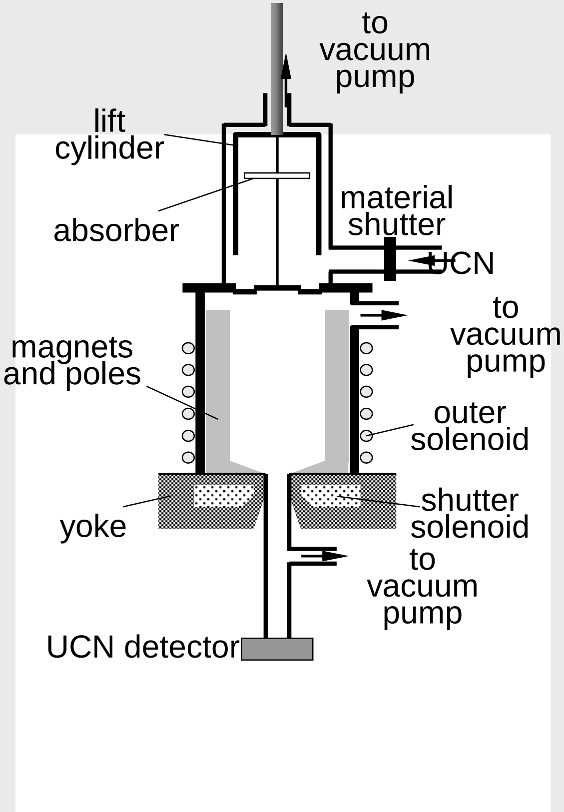
- **Step 3: 3D confinement**

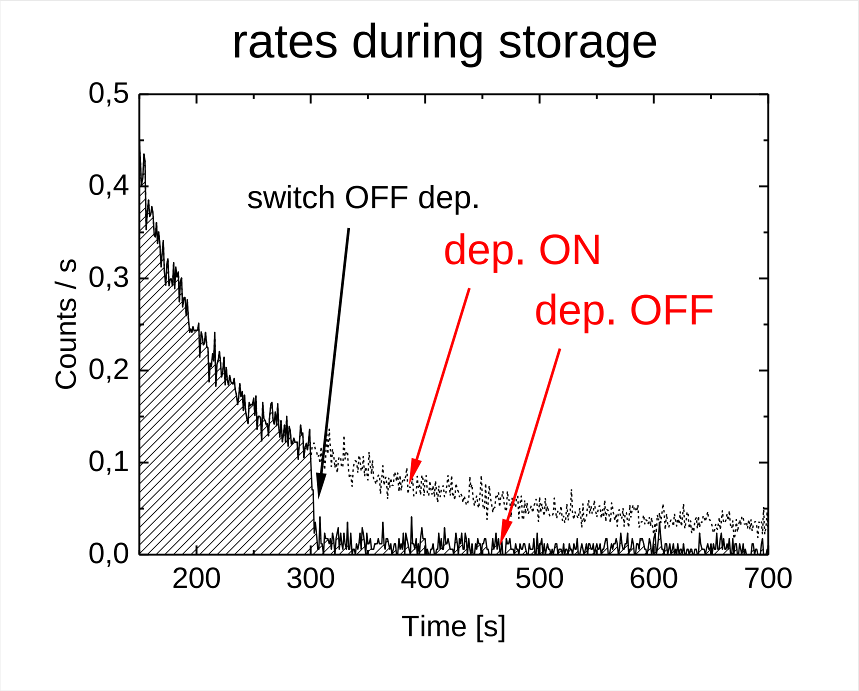
  - top (gravity)
  - bottom (magnetic shutter)



Trap leaks: tuning and monitoring

- Under optimized trapping conditions, leaks are very few → difficult to control.
- The outer solenoid produces an additional field to eliminate trap imperfections (zero field regions) and avoid leaks due to depolarization.
- Conversely, the outer solenoid can be tuned such as to increase zero field regions and hence leaks ("forced depolarization").

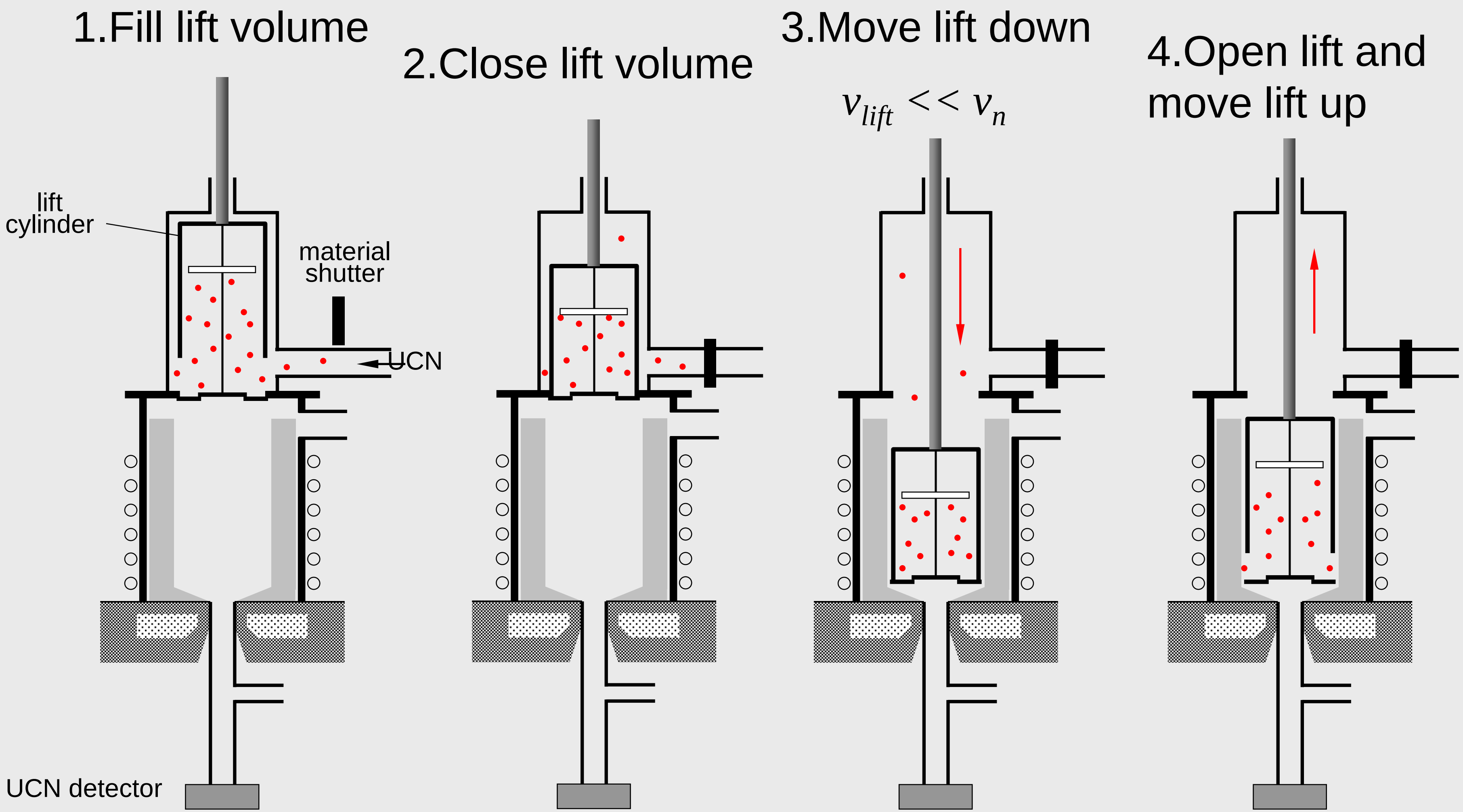




→ Intensity of leaks can be tuned

Trap filling sequence

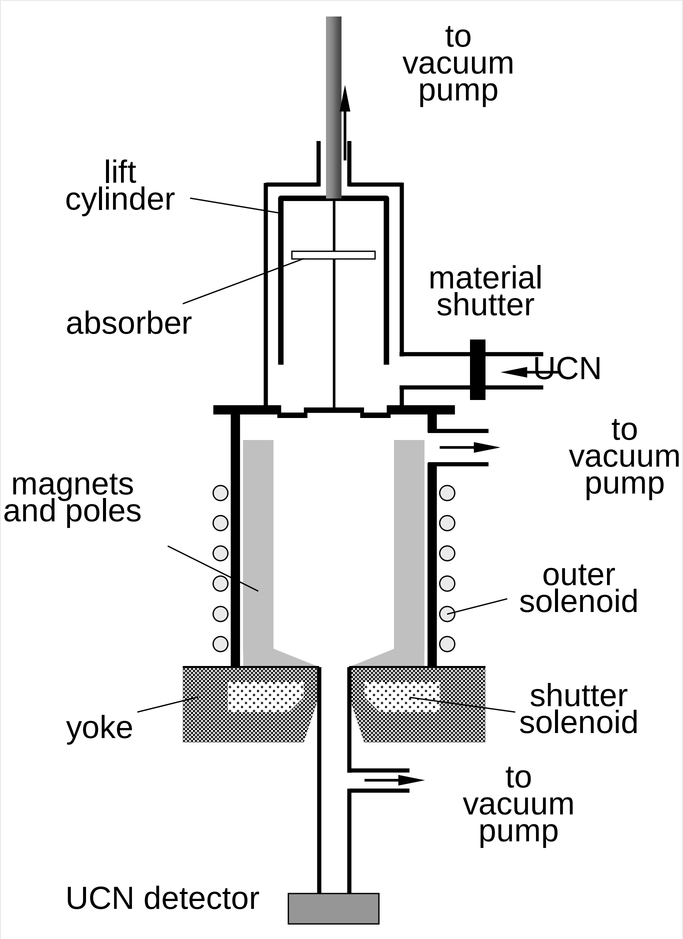
Trap filling is a critical issue for the magnetic storage of UCNs



(hence monitor filling sequence with UCN detector…)

Magnetic trap for neutron lifetime measurement

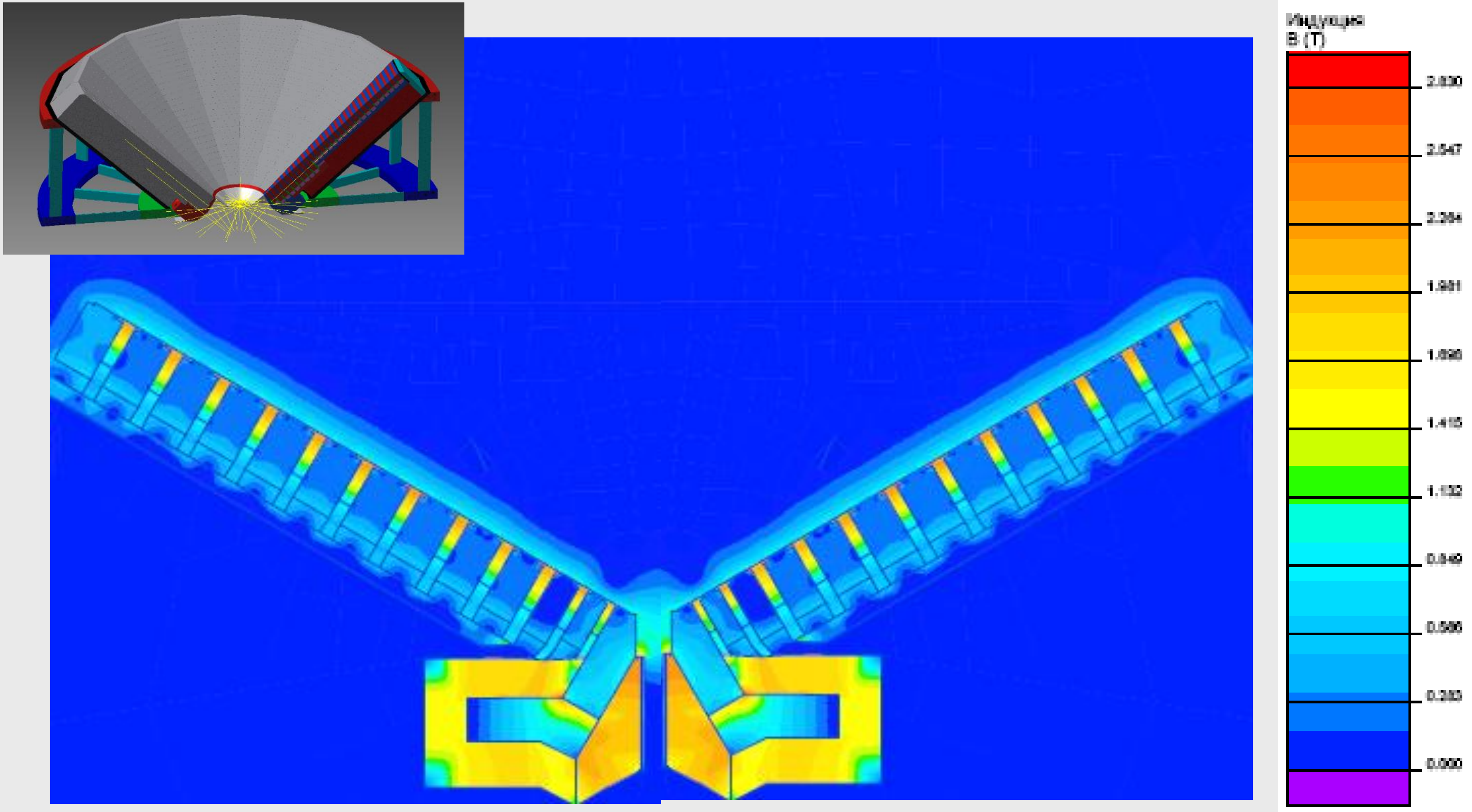
main elements: lift, trap, solenoid, shutter, detector



Lift: Fomblin coated Al cylinder + PE disk

(878.3 ± 1.9) s

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



Calculated magnetic field map of the new trap

Increasing of volume about 15 times

Increasing of storable UCNs due to boundary velocity increasing is about 8 times

Expected accuracy about 0.2 to 0.3 s

UCNτ: a measurement of the neutron lifetime using ultra-cold neutrons stored in an asymmetric magnetic trap at LANL*

We have developed a new method for measuring the neutron lifetime

- We have demonstrated an *in situ* active neutron detector that allows for many systematic tests and enables the measurement of corrections for cleaning effectiveness and phase space evolution
- We have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s
- All systematic uncertainties have been quantified by measurements
- During 2017/2018 running we hope to achieve a statistical uncertainty of ± 0.35 s (stat) ± 0.15 s (20 weeks of data)

*R. W. Pattie, et al, "Measurement of the neutron lifetime using an asymmetric magneto-gravatational trap and in situ detection", submitted to Science; **https://arxiv.org/abs/1707.01817**

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
(Dated: January 8, 2018)

There is a long-standing discrepancy between the neutron lifetime measured in beam and bottle experiments. We propose to explain this anomaly by a dark decay channel for the neutron, involving a dark sector particle in the final state. If this particle is stable, it can be the dark matter. Its mass is close to the neutron mass, suggesting a connection between dark and baryonic matter. In the most interesting scenario a monochromatic photon with energy in the range 0.782 MeV – 1.665 MeV and branching fraction 1% is expected in the final state. We construct representative particle physics models consistent with all experimental constraints.

arXiv: 1801.01124v1 [hep-ph] 3 Jan. 2018

(A) **Neutron $\rightarrow$ dark matter + photon**

UCNtau @ LANL is working on that

(B) **Neutron $\rightarrow$ dark matter +** e^+e^-

UCNA @ LANL is looking for those events in existing data

Worldwide nLifetime Searches

Neutrons in the gravity field

- Schrödinger equation with linearized gravity potential

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

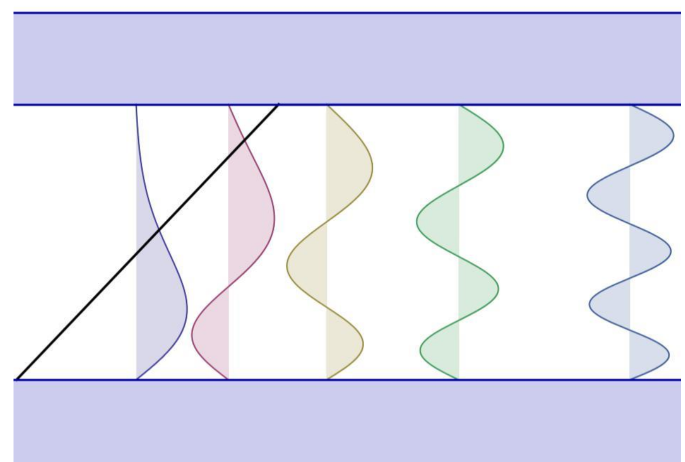
bc: $\varphi_n(0)=0, \quad \varphi_n(l)=0$

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

- bound, discrete states
- Non-equidistant energy levels

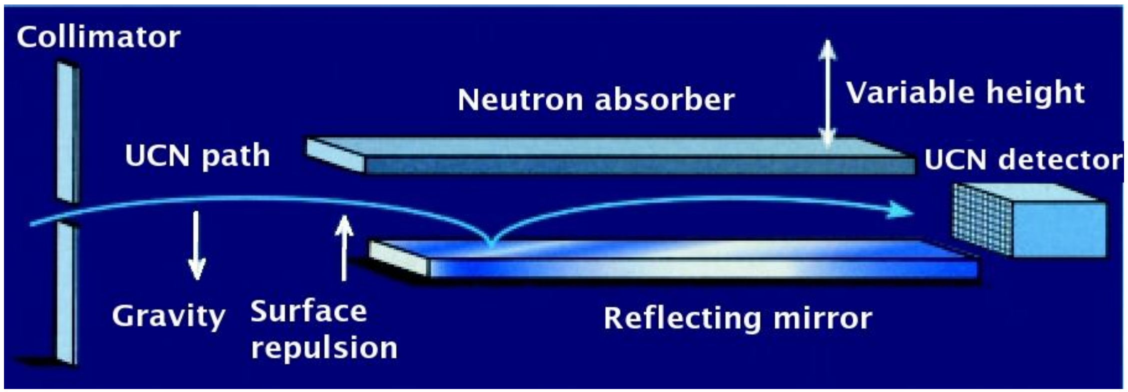
state	energy
1	1.41 peV
2	2.56 peV
3	3.98 peV

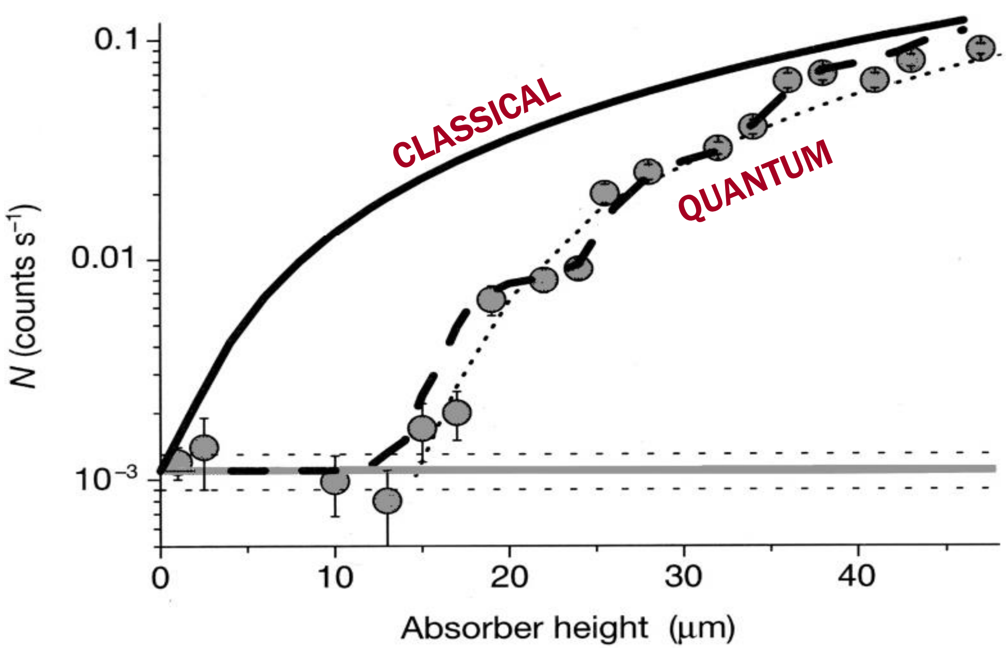
Slit width l=27 µm



Discovery of neutron quantum states in 1999

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





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

qBounce (H. Abele and his team, ATI Vienna)
Motivation

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

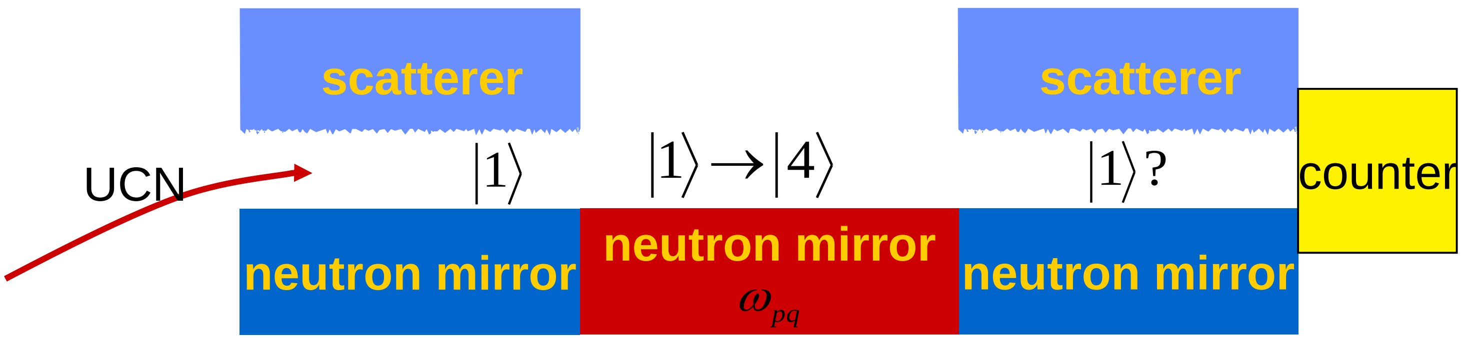
- Test of Newton’s gravity potential at small distances (microns)
- Detection of new forces
- Tests for chameleons, axions

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

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

Gravity Resonance Spectroscopy (GRS)

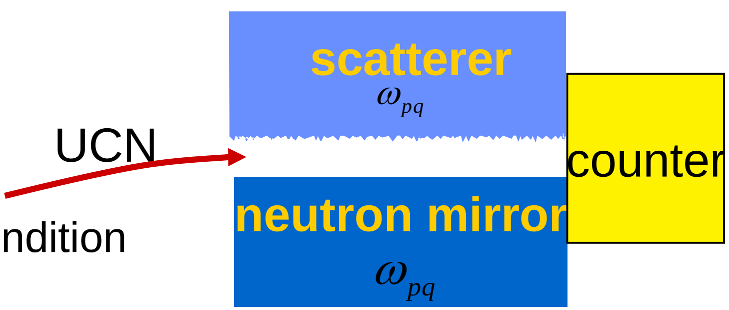
- **Rabi** setup (2012)

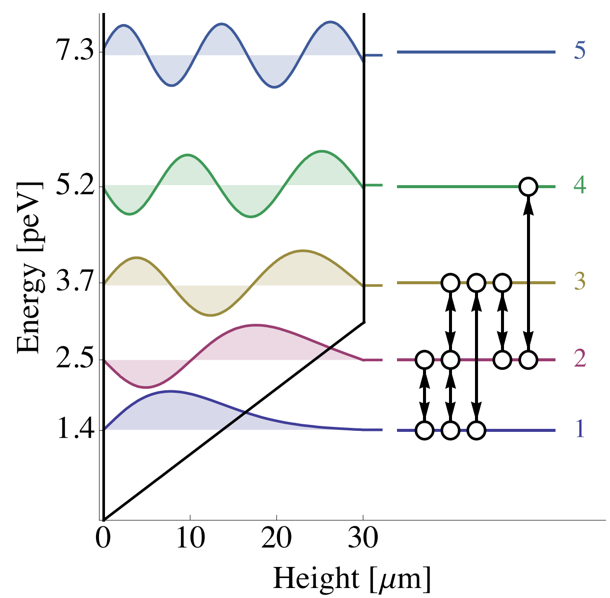


- First realisation (2009,2010)

Rabi-like experiment with **damping**

but scatterer introduces 2nd boundary condition





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

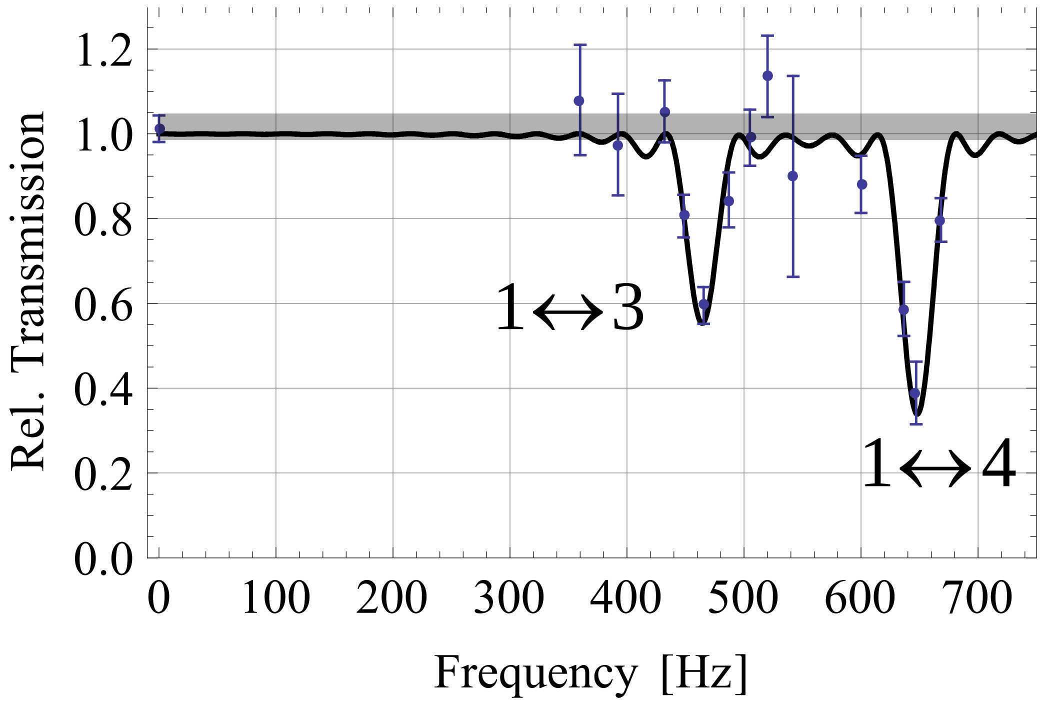
Results

Transitions 1-3 and 1-4 observed

1-3: (46 ± 5)% intensity drop

1-4: (61 ± 7)%

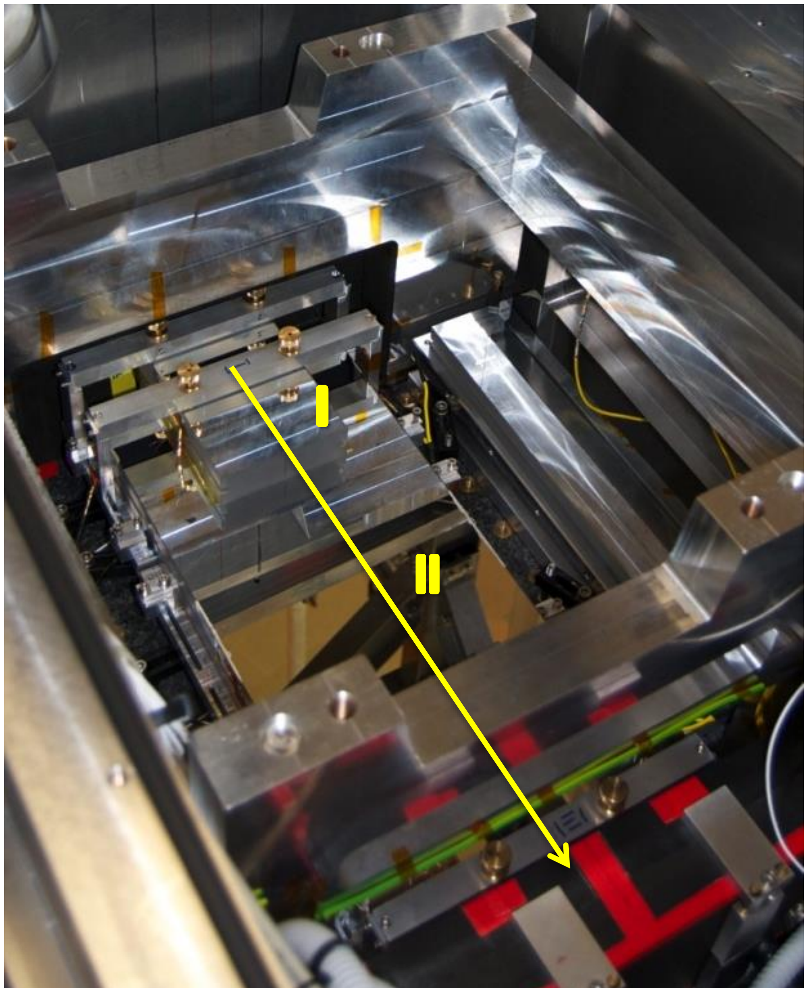
@ 2.1 mm/s

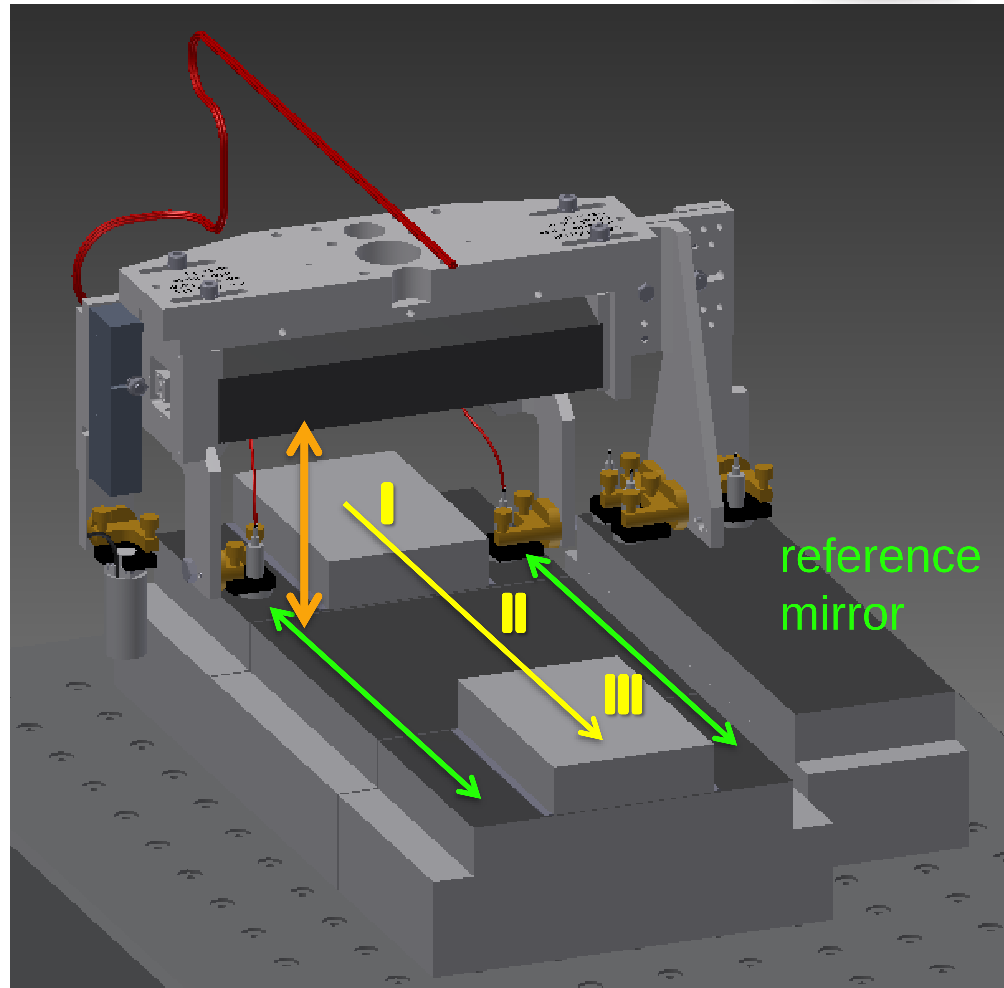


60 measurements

Preliminary, generic fit

Setup

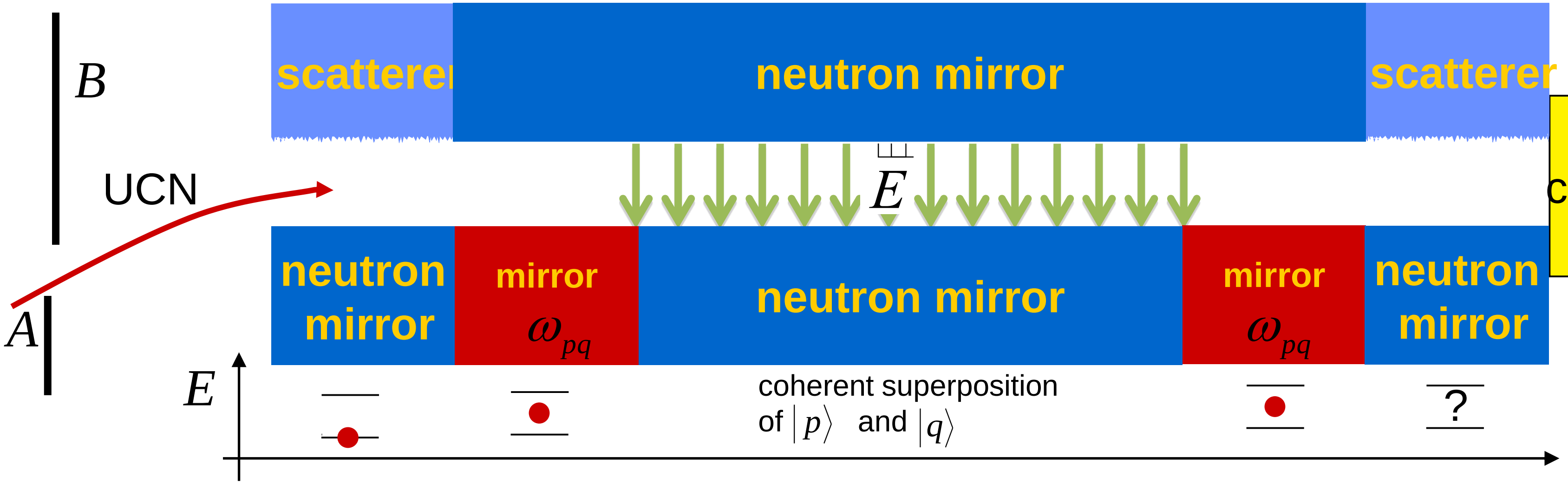




M. Horvath

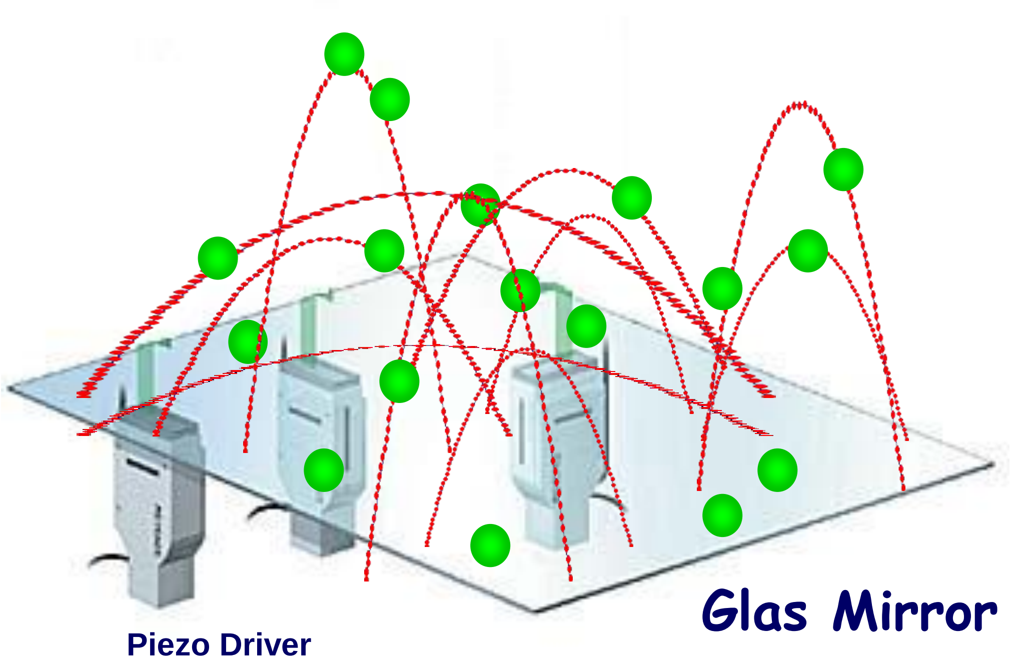
Outlook:
Probing neutrons neutrality

- Electric field modifies detectable phase



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

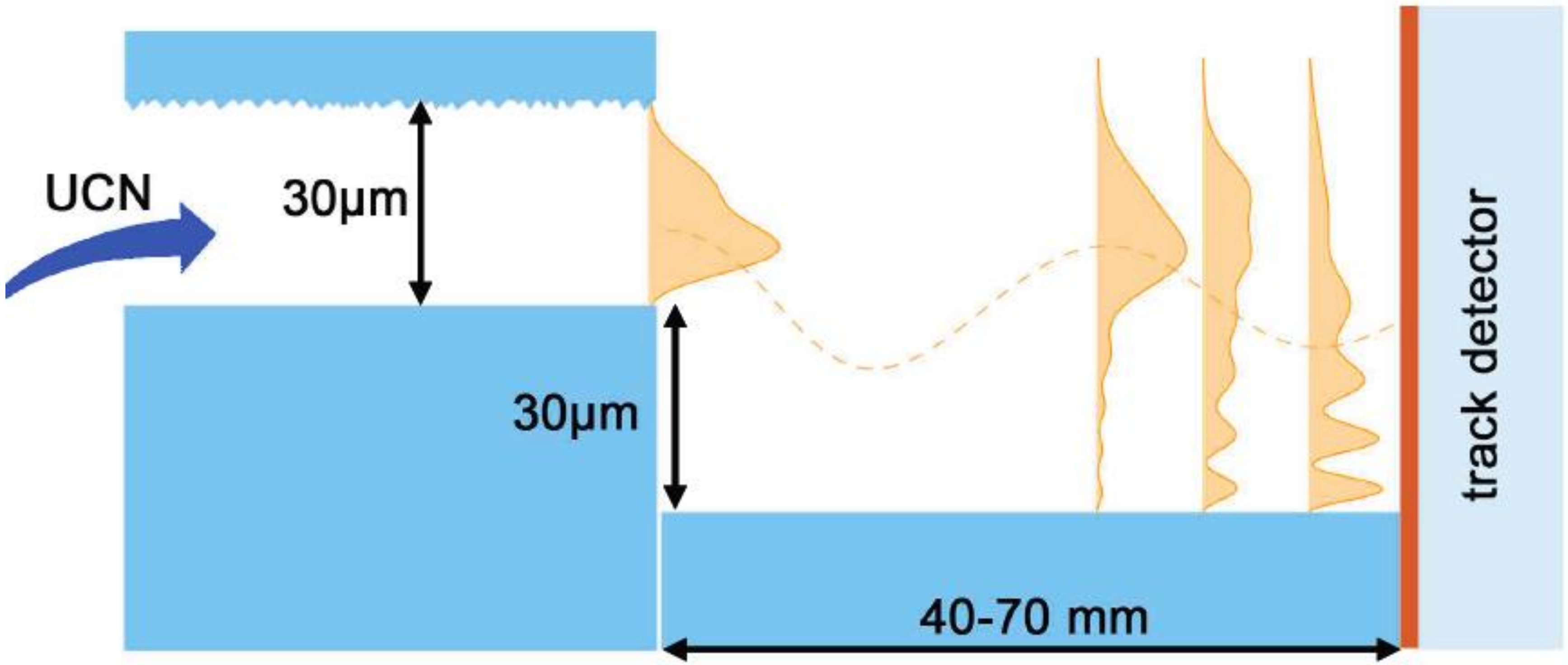
Realization of a Neutron Bouncing Ball Gravity Spectrometer



classical equation of motion for a falling body reflected on a mirror

quantum bouncing ultracold neutrons

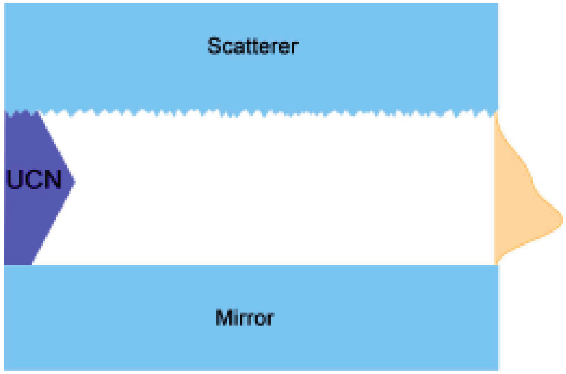
- State Selector
- Snapshots with spatial resolution detectors ~ 1.5 µm



L

Courtesy: M. Thalhammer

Preparation L = 0



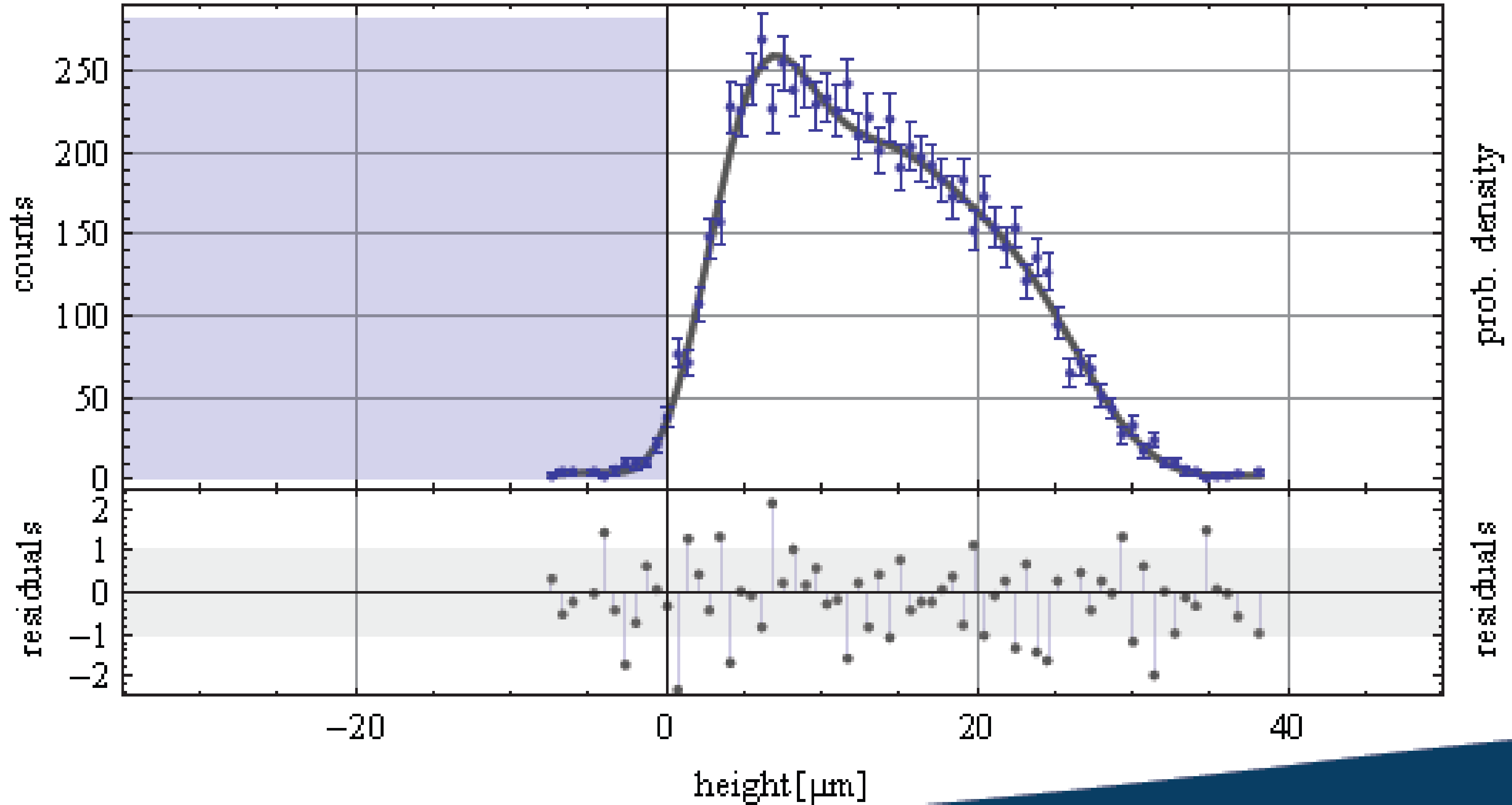
$$|\Psi_I(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

$|c_1|^2 = 45\%$

$|c_2|^2 = 36\%$

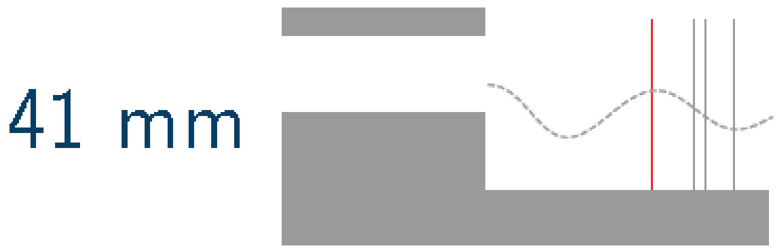
$|c_3|^2 = 18\%$

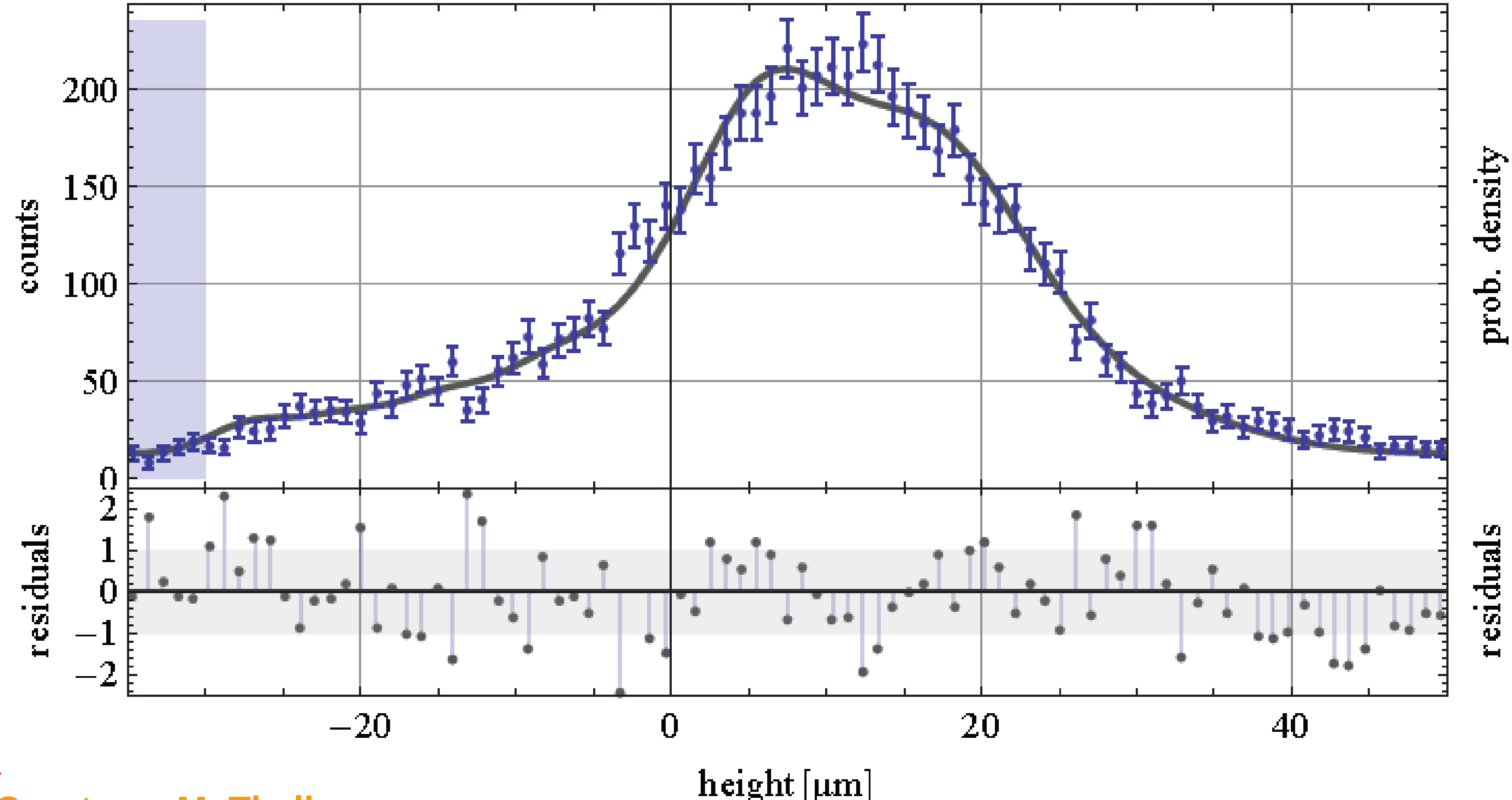
preliminary



Courtesy: M. Thalhammer

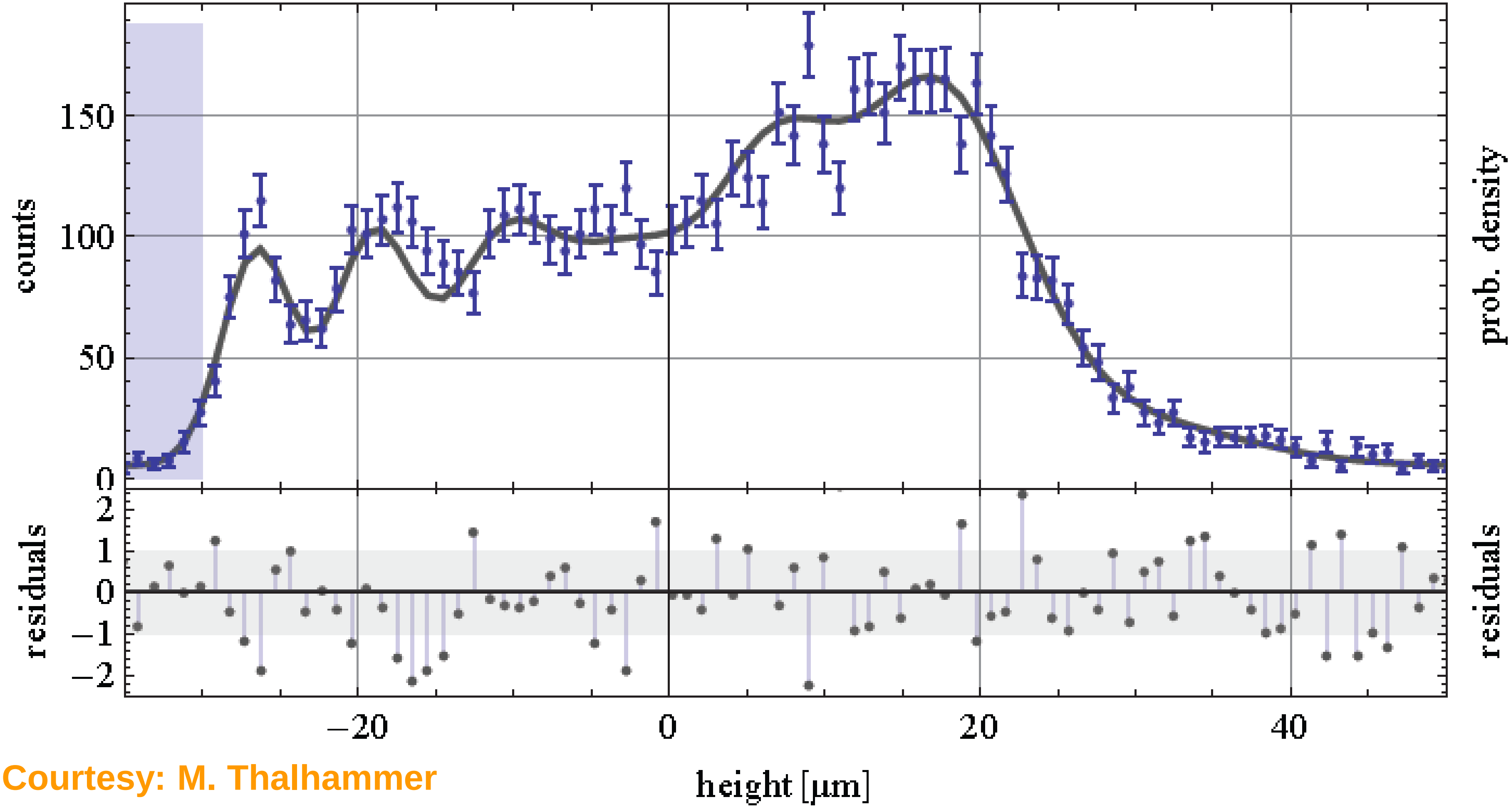
2nd bounce, 2nd turning point, L = 41 mm





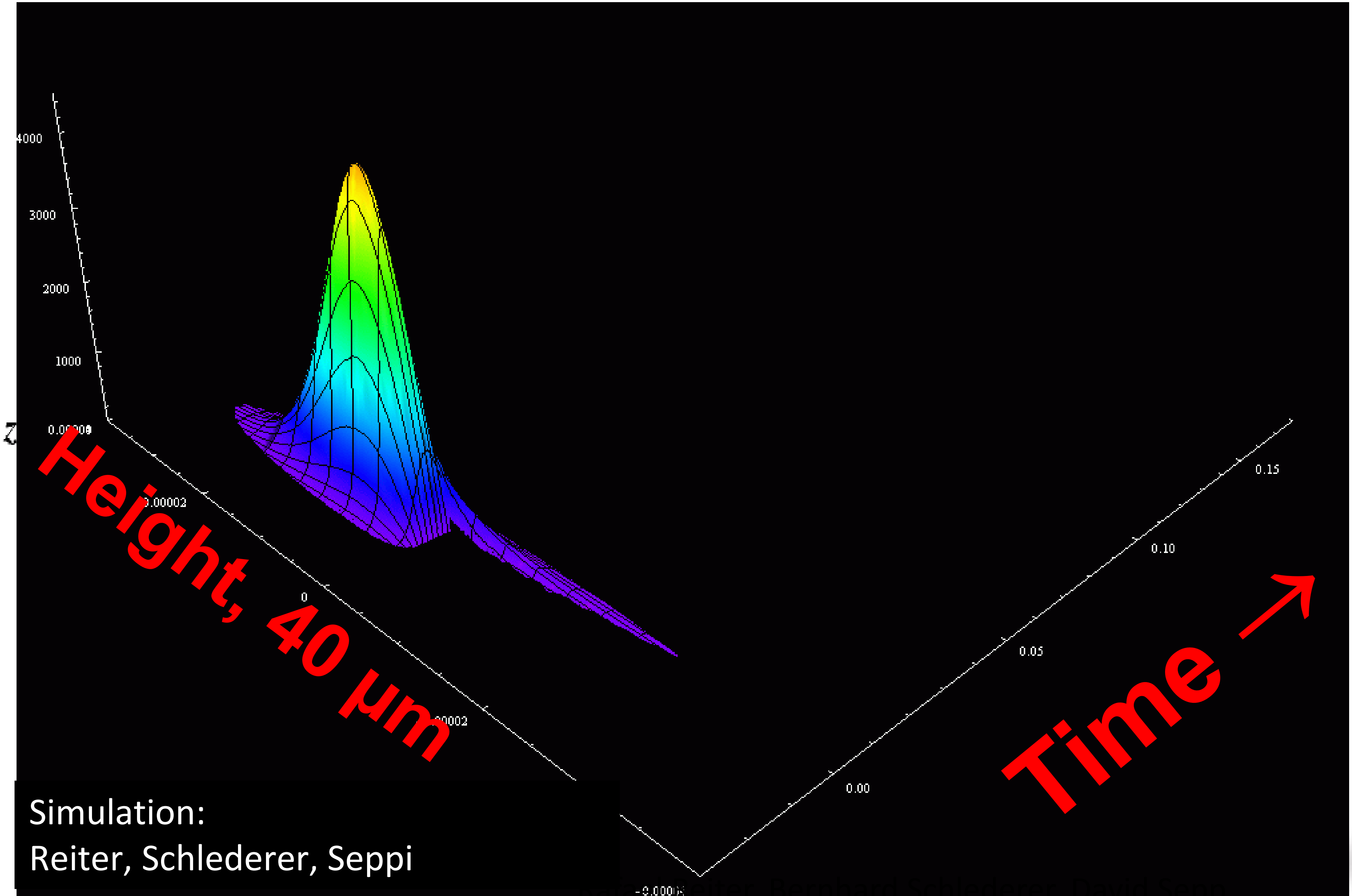
Courtesy: M. Thalhammer

Move downwards, L = 51 mm



Courtesy: M. Thalhammer

Show Case: *q*BOUNCE



To catch a chameleon

High-precision laboratory experiments with neutrons and atoms are converging to a verdict on 'chameleon fields' as a possible explanation of dark energy, explains **Tobias Jenke**.

The spatial distance between two points in the Universe increases with time, a discovery attributed to Lemaître. Independently of Friedmann, he derived the basic equations for a dynamic Universe, linking the solutions to Slipher's observation of redshift and Hubble's distance measurements of far-away galaxies. Seventy years later, observations of Type-Ia supernovae led by Perlmutter, Schmidt and Riess resulted in the surprising discovery that the expansion of the Universe is accelerating[1,2].

The driving force of the Universe's accelerating expansion is referred to as dark energy, a time-dependant generalization of the cosmological constant. Astronomical observations reveal that dark energy accounts for roughly 70% of the total energy density of our Universe. Its origin, however, is completely unknown.

One approach for explaining the source of dark energy involves a scalar field. The discovery of the Higgs boson confirmed the existence of fundamental scalar fields in nature, and many string-theory or supergravity models introduce scalar fields, which are massless on solar-system scales. However, as they generally couple to matter with gravitational strength, the resulting long-range force would violate precision tests of the equivalence principle (EP) of inertial and heavy mass — hence the search for a mechanism effectively screening contributions violating EP.

Khoury and Weltman suggested just such a screening mechanism in 2004[3]. They introduced a scalar field evolving cosmologically and coupling to matter, and called it the 'chameleon field', "since its physical properties, such as its mass, depend sensitively on the environment"[3]. The theory has two free parameters: a dimensionless coupling strength β, and an exponent n known as the Ratra–Peebles index. The scalar field acquires an effective mass that depends on the local matter density. In high-density regions (like on Earth), this mass is large and the range of the force mediated by the particle


LEON FILTER, HORN-BAD WEINBERG

is tiny — the EP-violating force is therefore exponentially suppressed. Consequently chameleon fields seem to be untestable using macroscopic bodies. On cosmological scales, however, the ambient mass density is very low, and the effective mass of the field is comparable to the present Hubble constant. This results in an interaction range of the mediated force of up to several thousands of parsecs. While the Universe expands, its mass density decreases, leading to amplification of the field, which drives the observed accelerated expansion of the Universe.

In 2011, Brax and Pignol discovered that chameleon theories could nevertheless be tested by means of tabletop experiments[4]. They suggested using quantum states of ultracold neutrons (UCNs) in the Earth's gravitational field. UCNs move very slowly, with velocities of a few metres per second. They are produced in sources like the PF2 neutron turbine at the Institut Laue-Langevin in Grenoble, France. On horizontal, flat surfaces, UCNs form bound quantum states in the linear gravity potential of the Earth. The typical spatial extent of the associated wavefunctions is a few tens of micrometres. Hence, the mass density of UCNs is too low for the screening mechanism of the chameleon field to be significant. The states have energy eigenvalues in the pico-eV range with unique energy differences. Therefore, any two states can be treated as an effective two-level system, enabling resonance spectroscopy techniques to be employed. These techniques were first used in 2009 and were immediately deployed to search for chameleon fields[5]: the existence of such fields would produce characteristic shifts in the transition frequencies measured. The experiment found no deviation from Newtonian gravity. As a conclusion, chameleon fields with a coupling strength β larger than 5.8×10^{8} were excluded, improving previous limits from atomic spectra by a factor of ten million.

Several communities have joined the search for chameleon fields. Today, the best experimental constraints come from an atom interferometry experiment[6] examining whether gravitational acceleration depends on local matter density. The testing of the total parameter space for chameleon fields is likely to be completed in the near future. As a result, chameleon fields may have to be ruled out as sources of dark energy. But, more excitingly, any positive result could explain the origin of one of the biggest mysteries in modern physics. □

TOBIAS JENKE is in the Nuclear and Particle Physics Group at the Institut Laue-Langevin, 71 Avenue des Martyrs, 38000 Grenoble, France.
e-mail: jenke@ill.fr

References

1. Riess, A. G. et al. Astron. J. 116, 1009–1038 (1998).
2. Perlmutter, S. et al. Astrophys. J. 517, 565–586 (1999).
3. Khoury, J. & Weltman, A. Phys. Rev. D 69, 044026 (2004).
4. Brax, P. & Pignol, G. Phys. Rev. Lett. 107, 111301 (2011).
5. Jenke, T. et al. Phys. Rev. Lett. 112, 151105 (2014).
6. Hamilton, P. et al. Science 349, 849–851 (2015).

m e Å s u R E_h F Ω °R μ_0 ε_0 α σ V R e

T. Jenke, Nature Physics 13, 920 (Sept. 2017)

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., Nucl. Instr. Meth. A 845 (2017) 552
Neutrons constrain dark energy and dark matter scenarios (2014)	
	T. Jenke et al., PRL **112** (2014) 151105
Does the neutron lifetime depend on the method used to measure it? (2015)	
	S. Arzumanov et al., Phys. Rev. B **745** (2015) 79
The neutron lifetime puzzle (2016)	
	G.L. Greene and P. Geltenbort, Scientific American 314 (2016) 36

I hope I could convince you that

ultracold neutrons

– due to the fact that they are storable –
continue to be
a fancy and **powerful tool in fundamental physics**

… and that

ILL's UCN facility PF2

and the other Nuclear and Particle Physics installations

are still very attractive places for fundamental research

Thank you, merci beaucoup, dankeschön for your attention!

Finally a kind of **advertising …**

http://indico.ill.fr/PPNS2018