Latest News

from the

Institut Laue Langevin's (ILL's) Grenoble, France)

Ultra-Cold Neutrons (UCNs) Physics Program

PF2 team

Thomas Brenner

Peter Geltenbort

Tobias Jenke

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

Very Hot (fission) Neutrons → Ultracold Neutrons

10^{7} eV → 10^{-7} eV

http://www.ill.eu

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)

… all that followed by a movie (in case of interest)

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

Grenoble – Warsaw (~1 740 km): 17 hours by car
or 7.5 hours door to door by plane & bus

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

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

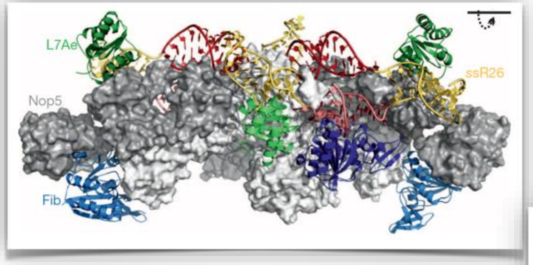
Amongst the flattest cities in France!

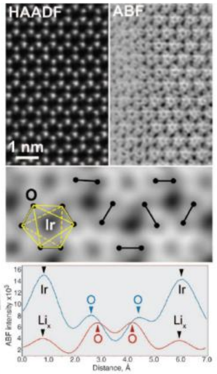
Warsaw **(Capital of Poland)**
Population: 1 700 000
Elevation: 113 m

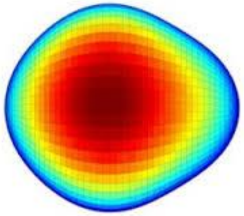
- The city benefits from the **highest concentration of strategic jobs in France after Paris**, with 14% of the employments, 35,186 jobs, 45% of which specialized in design and research.
- Grenoble is also the **largest research center in France after Paris** with 22,800 jobs (11,800 in public research,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

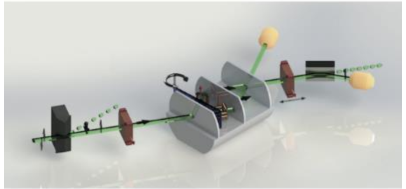
We live in a materials world

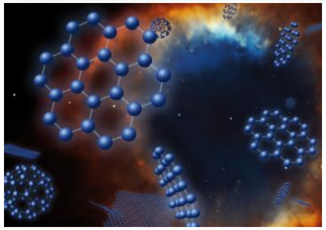
Understanding materials underlies all of modern technology.

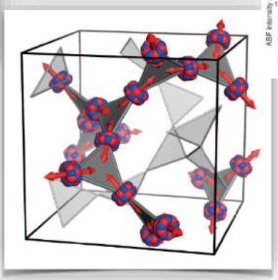


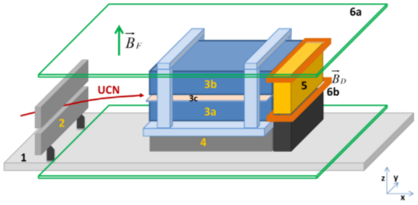


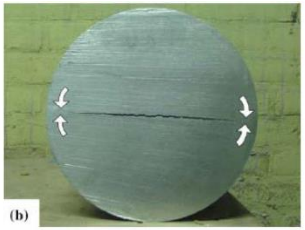


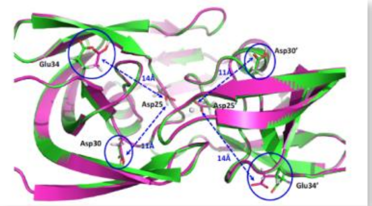


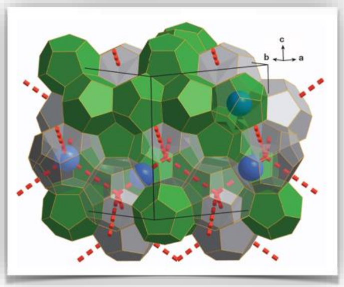


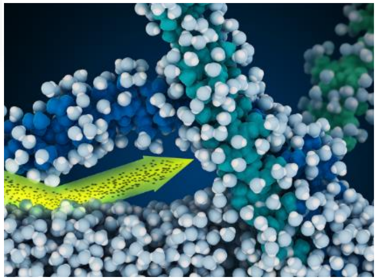


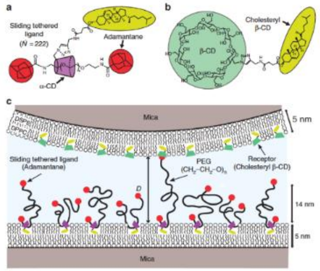


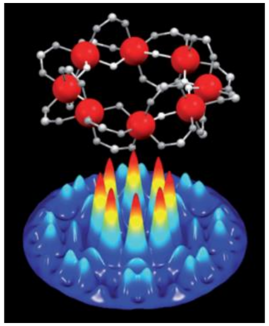












THE EUROPEAN NEUTRON SOURCE

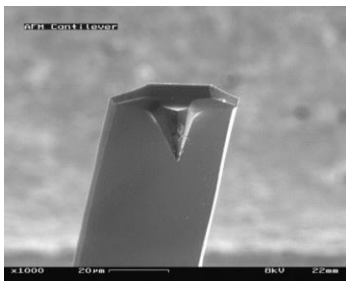
NEUTRONS FOR SOCIETY

A large number of potent tools

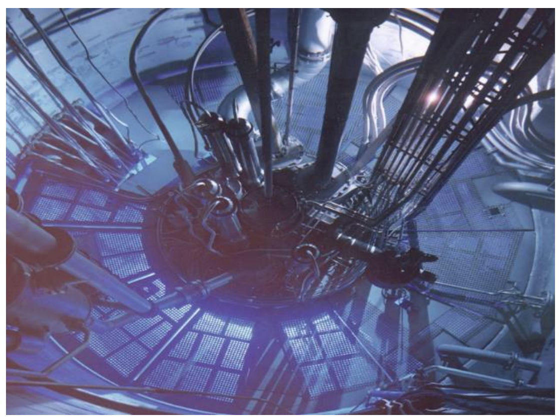
Europe has the world's leading infrastructure
for characterizing materials.

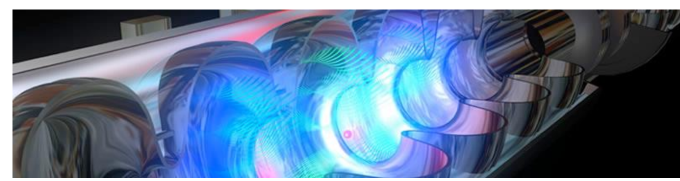
NMR

Microscopy



Neutron scattering





X-rays

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

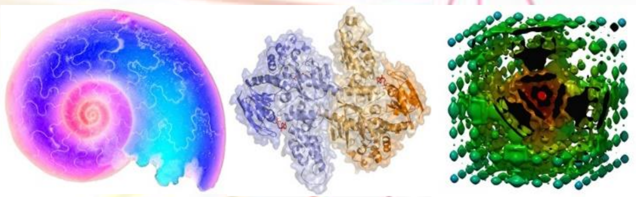
Neutrons, a powerful probe (1)

The properties of matter and materials are largely determined by their structure and dynamics at the **atomic scale** - *distance between atoms ~ 1 Å = 1/100 000 000 cm*

The wavelength of the neutron is comparable to atomic sizes and the dimensions of atomic structures, which explains why neutrons **can "see" atoms**.

Therefore neutrons are an ideal tool to understand the world around us, telling scientists:

Where is **which** atom?
How does it **bind**?
How does it **move**?
What surrounds it?

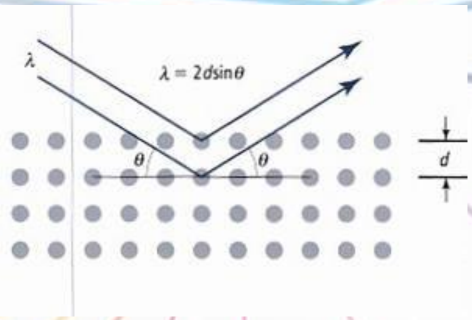


Neutrons, a powerful probe (2)

They are electrically neutral: they can **penetrate deep** into matter.

Neutrons possess a spin, and therefore is sensitive to the **magnetic properties** of atoms.

They can **distinguish** between different **elements** and their various **isotopes** (in particular H_2O versus D_2O)



It is a **non-destructive** technique

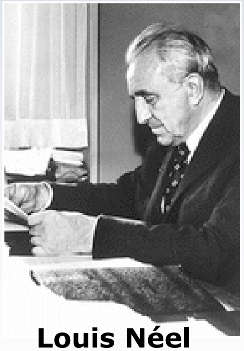
Everything started a bit more than 50 years ago

- 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

ILL's 50th Anniversary
19 January 2017

16 (out of 33) **ILL directors** celebrating the 50th anniversary party

I experienced **25 directors** during my time (December 1983 until today) at the ILL

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.

Neutron production

Fission Reactions

$n^1 + U^{235}$ 2 fission fragments

$+ 2.5\ n^1 + 200$ MeV

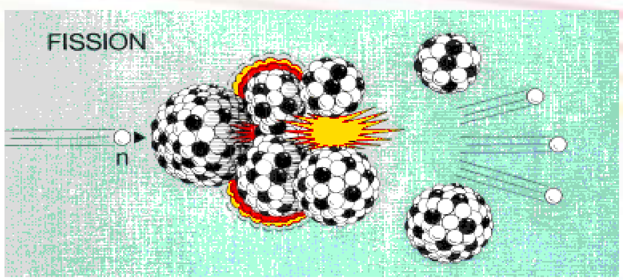
thermal

1 neutron to maintain chain reaction

1 neutron escapes & is available for use

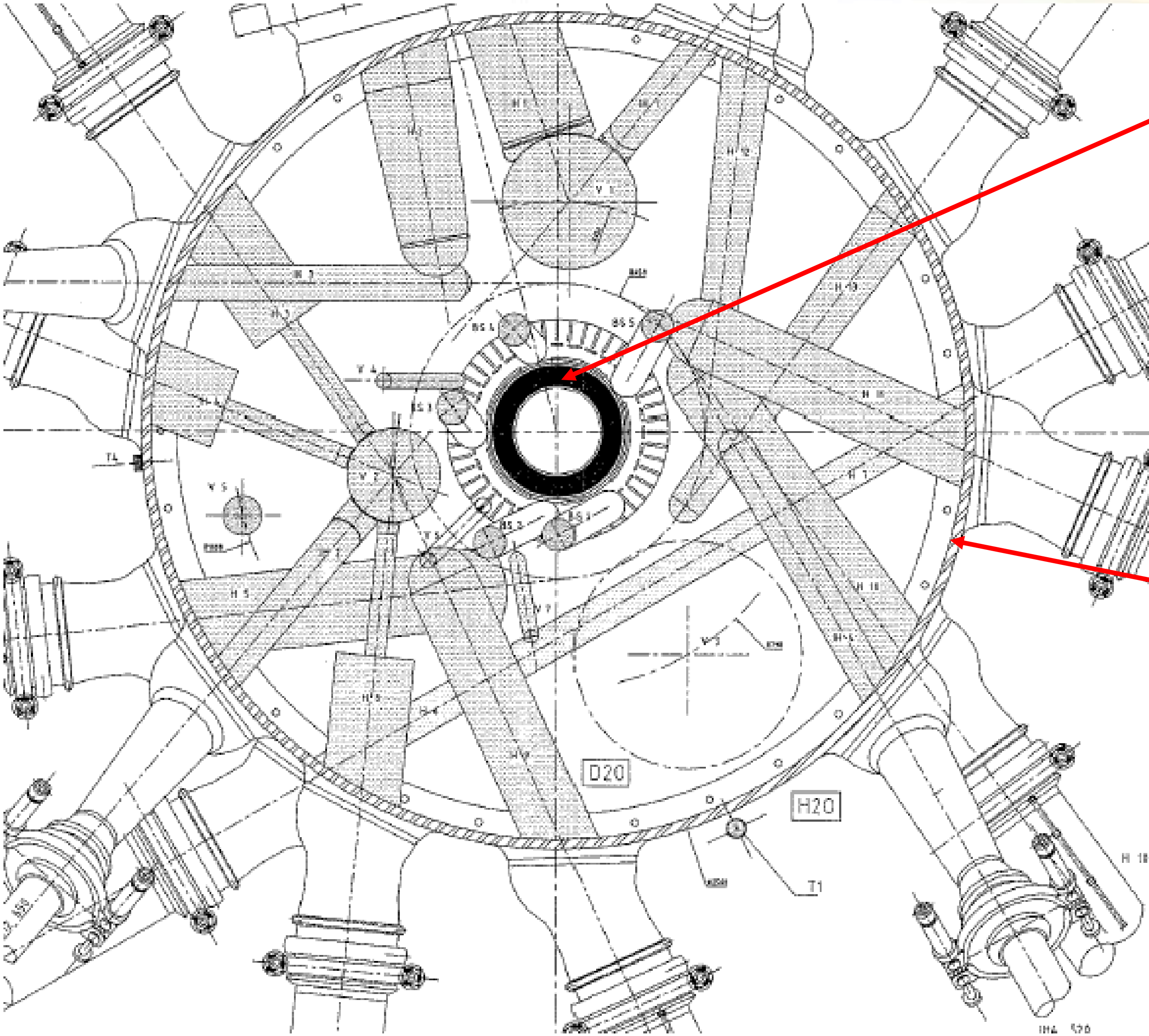
0.5 neutrons absorbed

No. of fissions/sec $= \dfrac{50 \times 10^6 \text{ watts}}{200 \text{ MeV/fission}}$



2 to 3 neutrons

Mise en musique sur le RHF or the core of the High Flux Reactor



Cœur (reactor core):

- ^{235}UAl 93%
- 8,5 kg d’ ^{235}U
- 280 plaques (plates)
- 57,8 MW
- 45 jours (days)

Bloc Pile (tank): D_2O

- R = 125 cm
- V = 12 m^3

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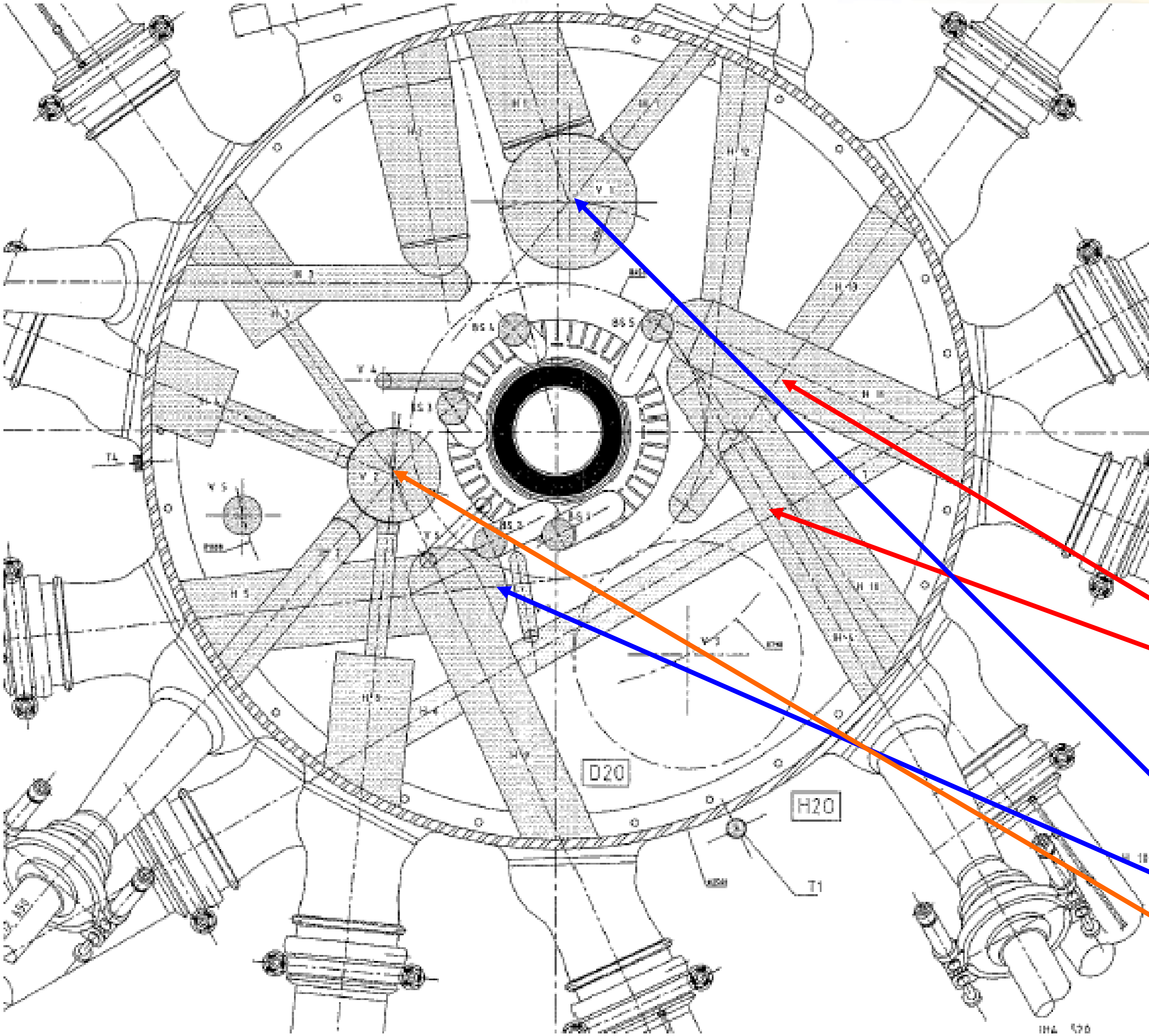
Mise en musique sur le RHF or the core of the High Flux Reactor

Fuel element

THE

Mise en musique sur le RHF or the core of the High Flux Reactor



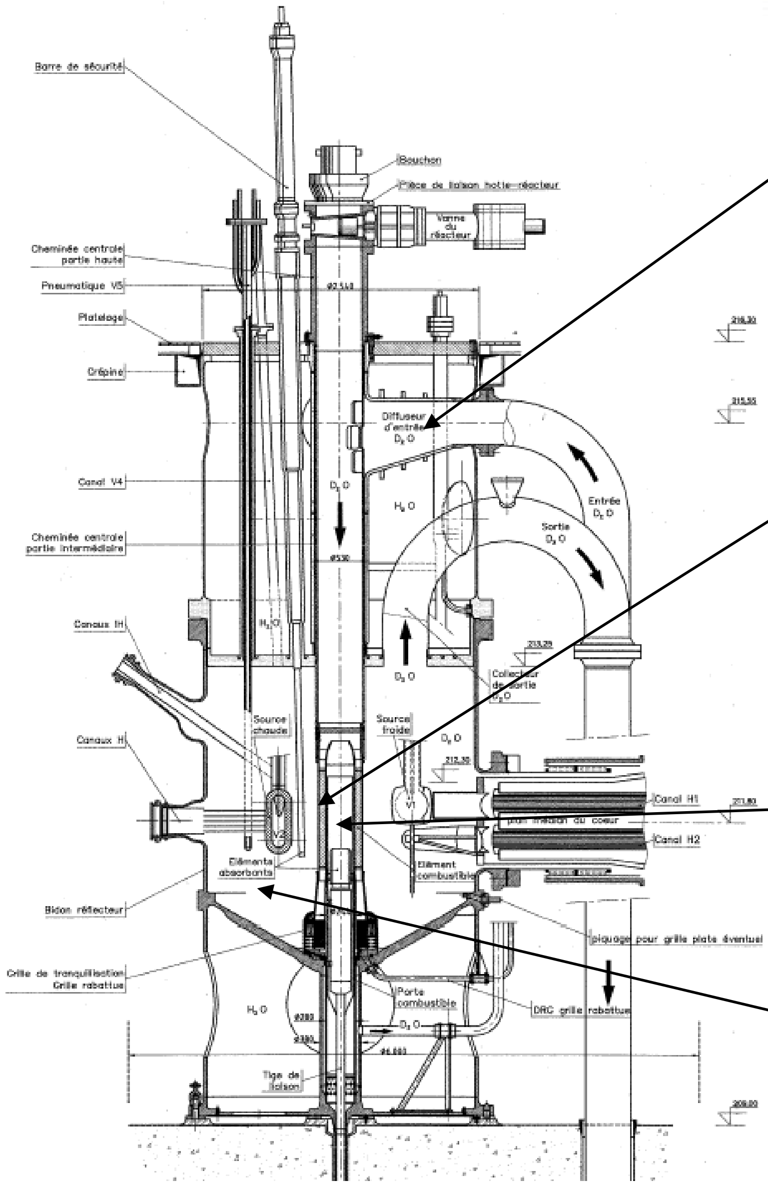
Canaux (channels):

- 13 Horizontaux
- 4 inclinés (inclined)

Sources (moderators):

- SFV (vertical cold source)
- SFH (horizontal cold s.)
- SC (hot source)

Le Bloc Pile dans son ensemble (reactor tank)



Entrée D_2O :

- $Q_{entrée} = 2350\ m^3.h^{-1}$
- $P_{entrée} = 14$ bar
- $T_{entrée} = 25$ à 30 °C
- $V_{cheminée} = 5\ m.s^{-1}$

Entre les plaques :

- $Q_{PP} = 2270\ m^3.h^{-1}$
- DT = 18 °C
- DP = 10 bar
- $V = 17\ m.s^{-1}$

Dans le trou central :

- Refroidissement barre pilotage
- $Q_{CRAB} = 80\ m^3.h^{-1}$

Dans la cuve :

- grille de tranquillisation
- $V < 0,8\ m.s^{-1}$

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Chantiers marquants (remarkable building and construction sites)

- Changement du bloc pile 91-94 (change of the reactor tank)
  - Première mondiale réussie =>

    en 2017 le RHF est un réacteur « jeune »

- RMC : mise à niveau sismique (earthquake) : 2002-2006
  - Séisme Majoré de Sécurité : M = 5,7

- STR : REX-Fukushima : 2011-2017

  le RHF est le premier réacteur avec un Noyau Dur

The Nuclear and Particle Physics group (NPP)

NEUTRONS FOR SCIENCE

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

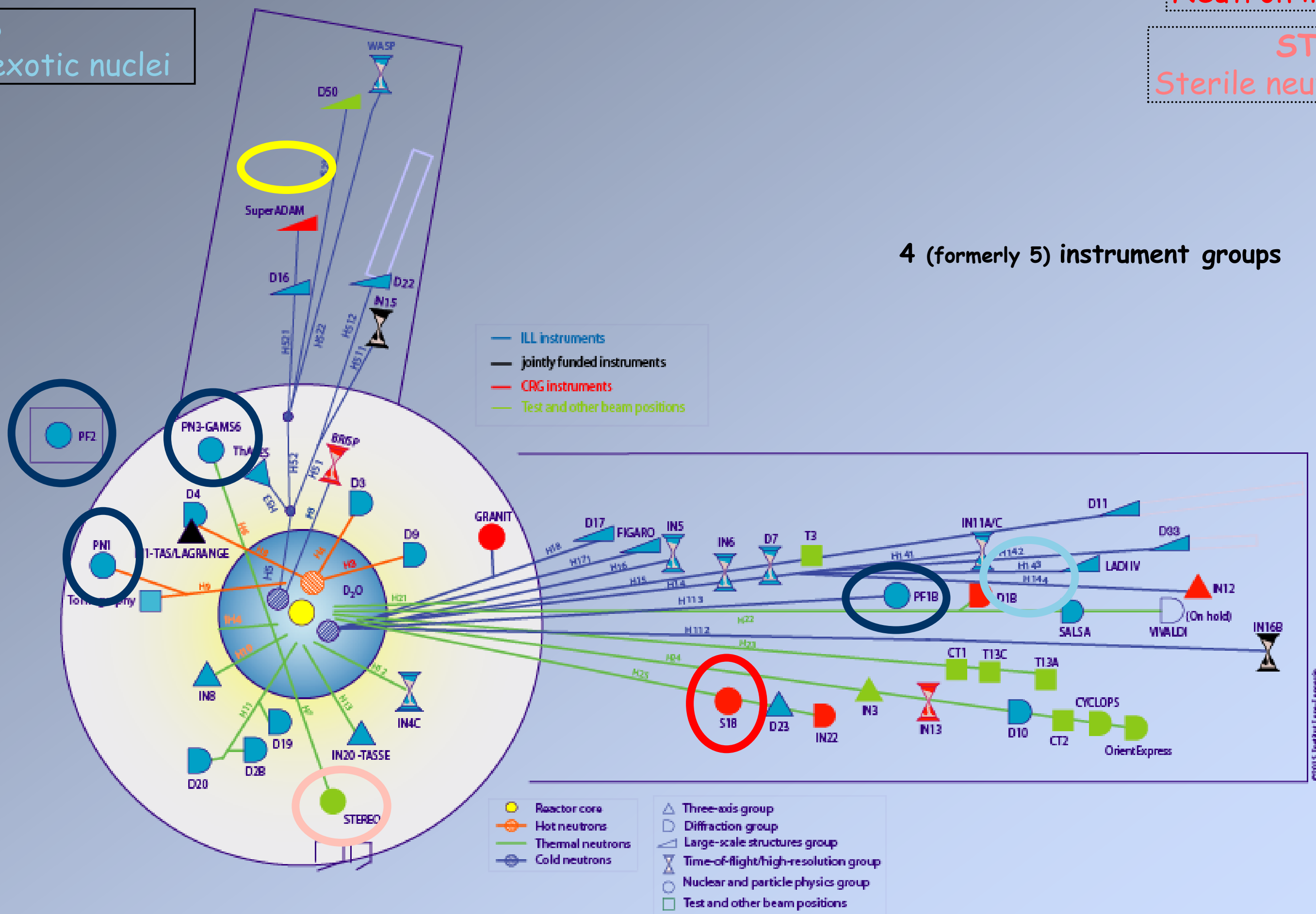
Collaborating Research Groups

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

S18 - perfect crystal
Neutron interferometer

STEREO
Sterile neutrino research

4 (formerly 5) **instrument groups**



Science at ILL

850 experiments/year

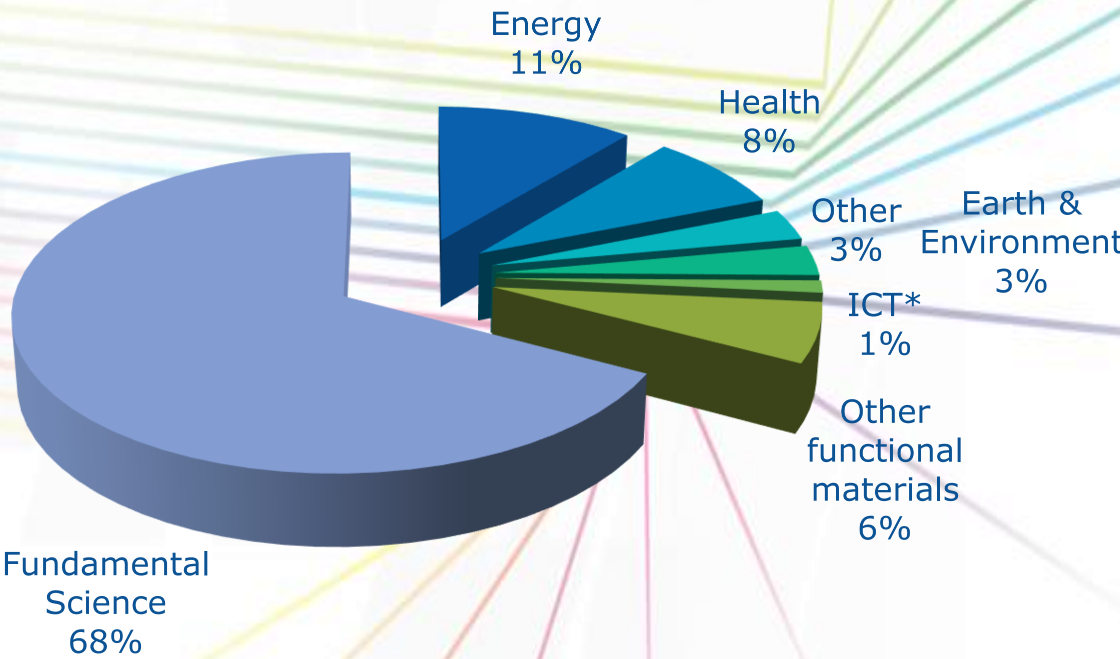
1400 users

38 countries

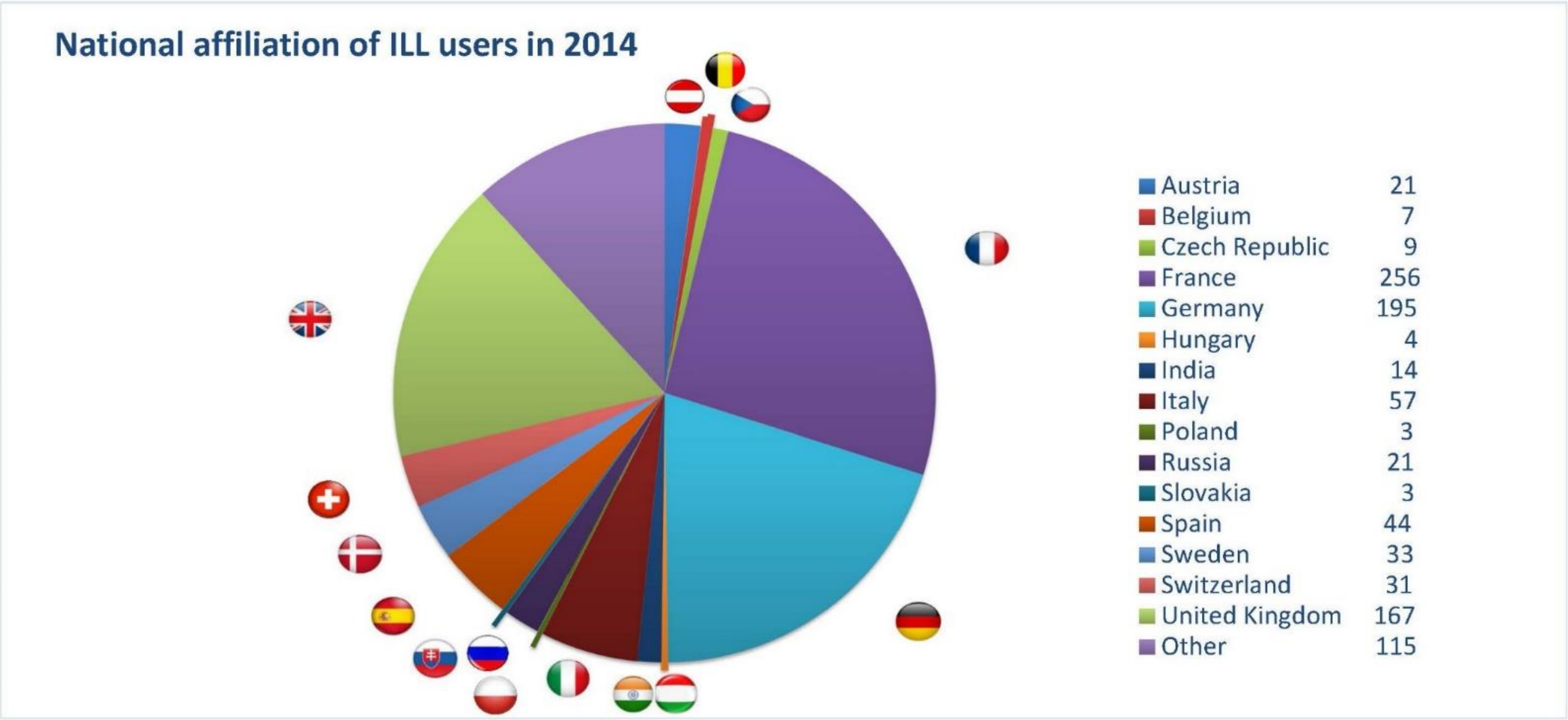
28 instruments + 10 CRG

650 publications/year

Societal impact



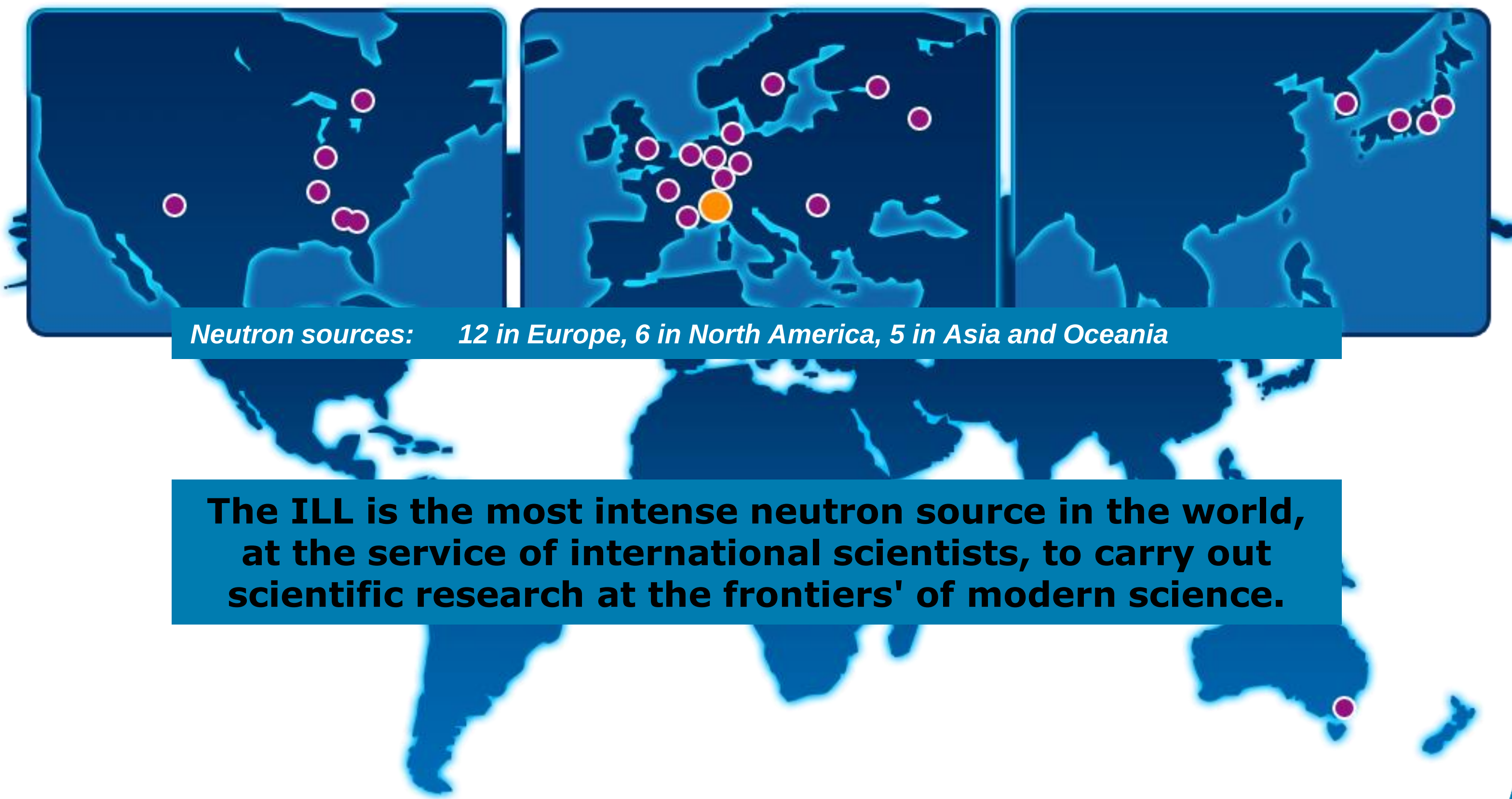
ILL users


National affiliation of ILL users in 2014
Austria 21
Belgium 7
Czech Republic 9
France 256
Germany 195
Hungary 4
India 14
Italy 57
Poland 3
Russia 21
Slovakia 3
Spain 44
Sweden 33
Switzerland 31
United Kingdom 167
Other 115

Institut Laue-Langevin – founded in 1967, user operation since 1972

World leader in neutron science and technology

After more than **40 years** in operation, we are still **number ONE**



Neutron sources: *12 in Europe, 6 in North America, 5 in Asia and Oceania*

The ILL is the most intense neutron source in the world, at the service of international scientists, to carry out scientific research at the frontiers' of modern science.

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

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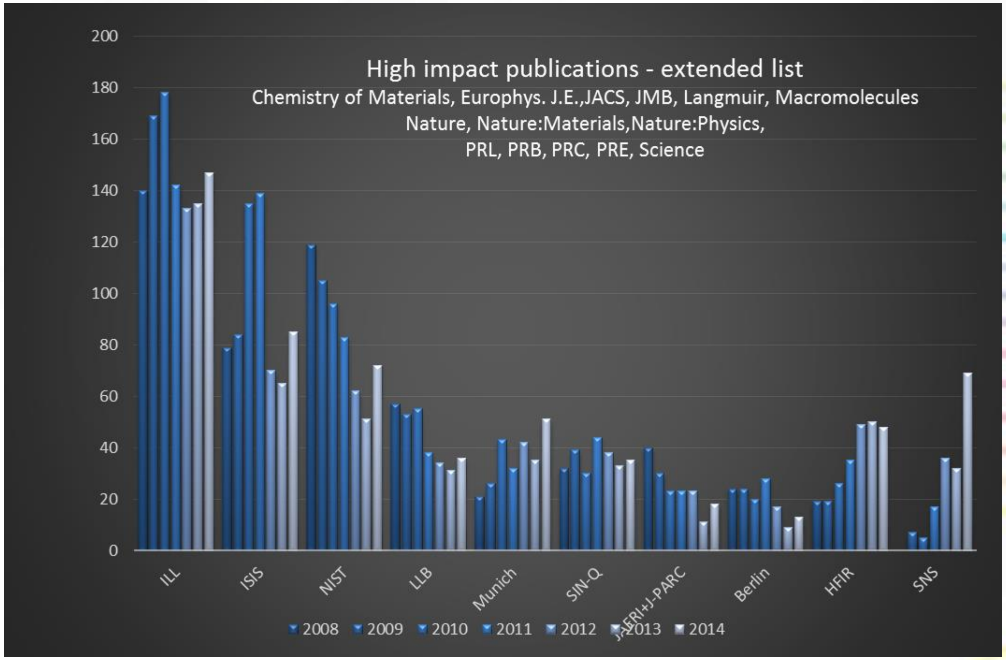
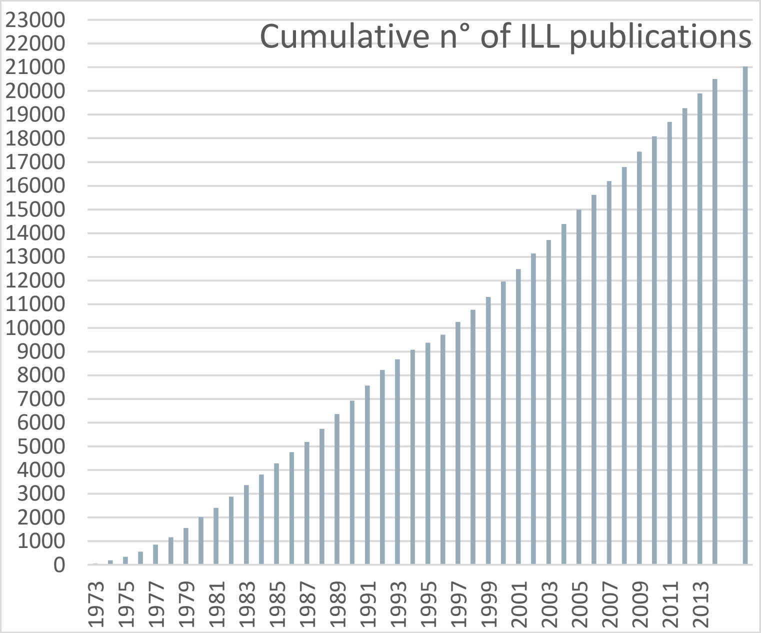
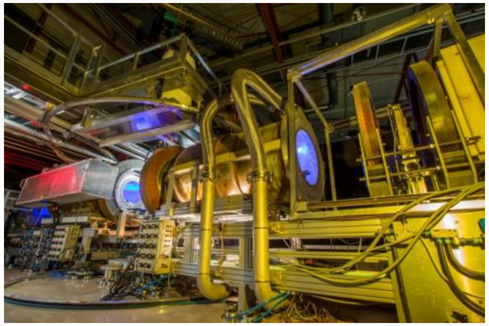
Record figures for publications in high-impact scientific journals





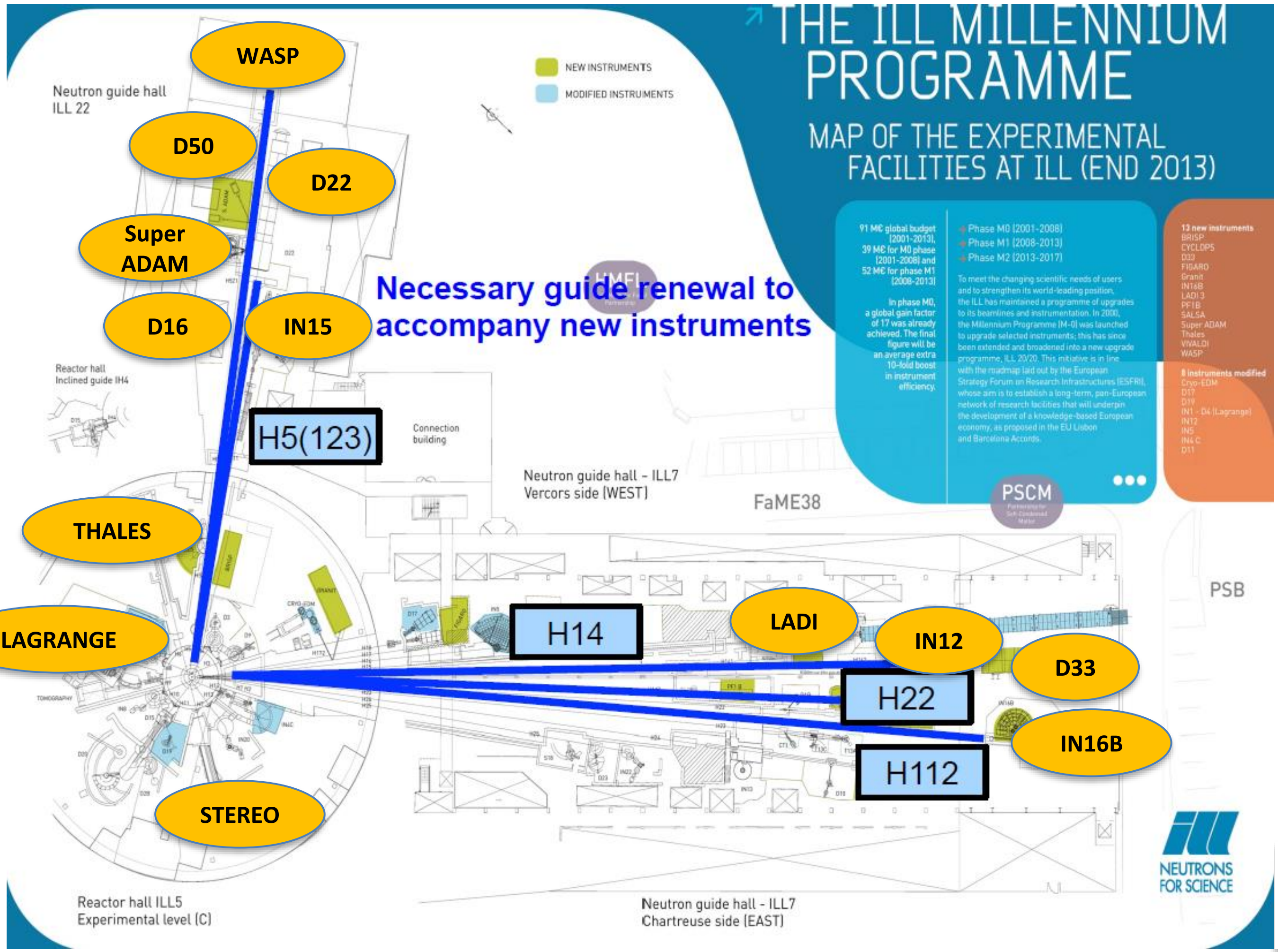
The ILL modernisation programmes



The Millenium Programme, 2001-2016

During this period we have:

- built or upgraded **28 instruments;**
- replaced or renewed a great part of our neutron guides, making them 'twice as bright';
- improved our technical devices, from cryostats to magnets, new polarised optics and a new electronic instrument control system...



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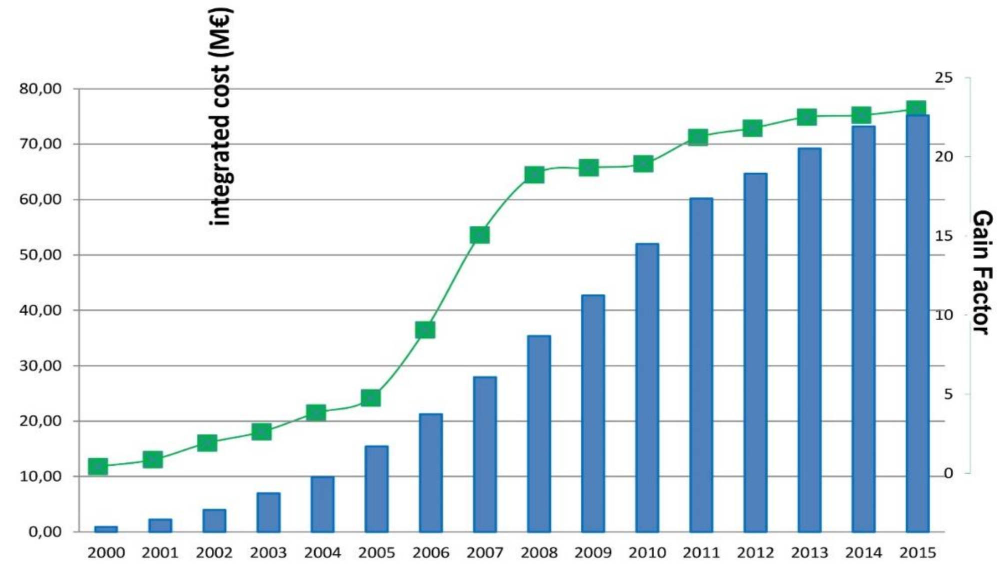
… as a result, the average neutron detection rate on the instruments has been improved by almost 25 times!



The Endurance programme

Today we are setting our sights on the horizon of 2030.

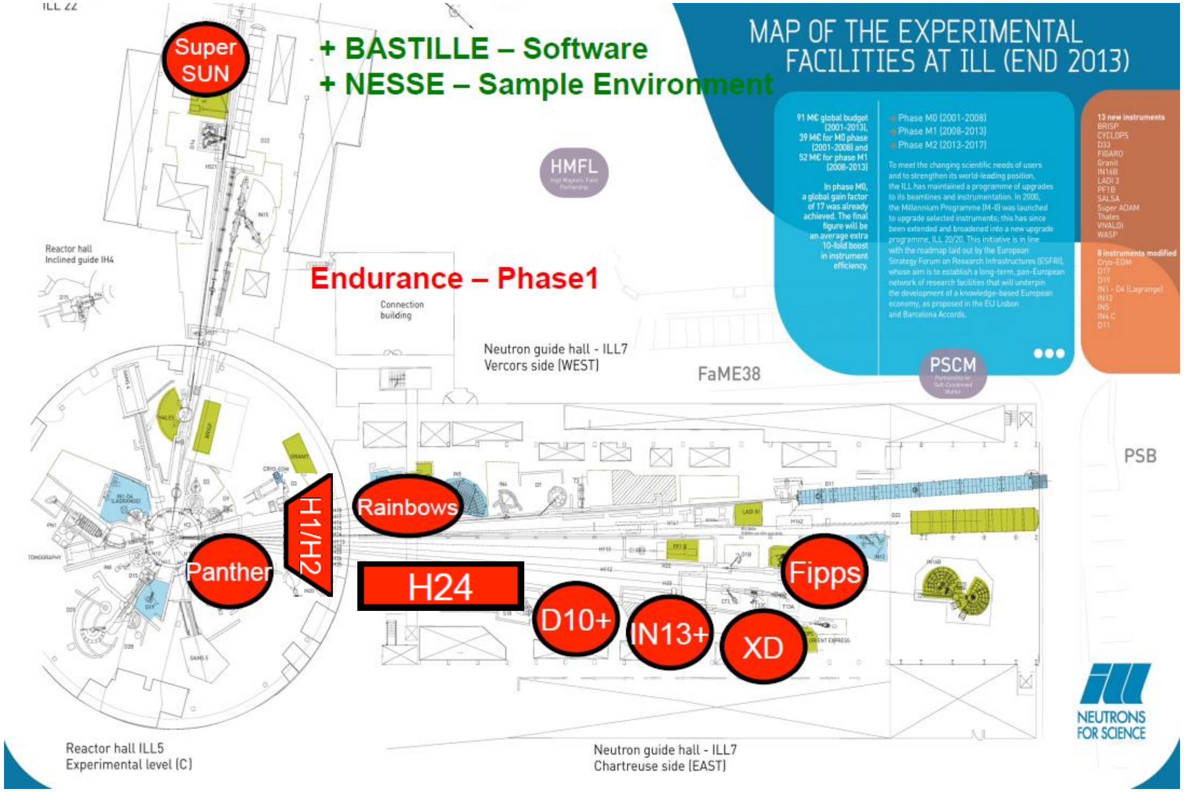
Our goals:

- preserve our position of leadership by drawing on our strengths
- offer new possibilities in the fields of magnetism, materials science, soft matter, biology and particle physics

Future developments for the instrument suite and scientific infrastructure (phase 1):

- 9 instrument projects (amongst them 2 in our NPP group)
- Creation or refurbishment of neutron guides
- 2 infrastructure projects: sample environment and data analysis software

Endurance phase 1



THE EUROPEAN NEUTRON SOURCE

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European Photon and Neutron (EPN) Science Campus

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

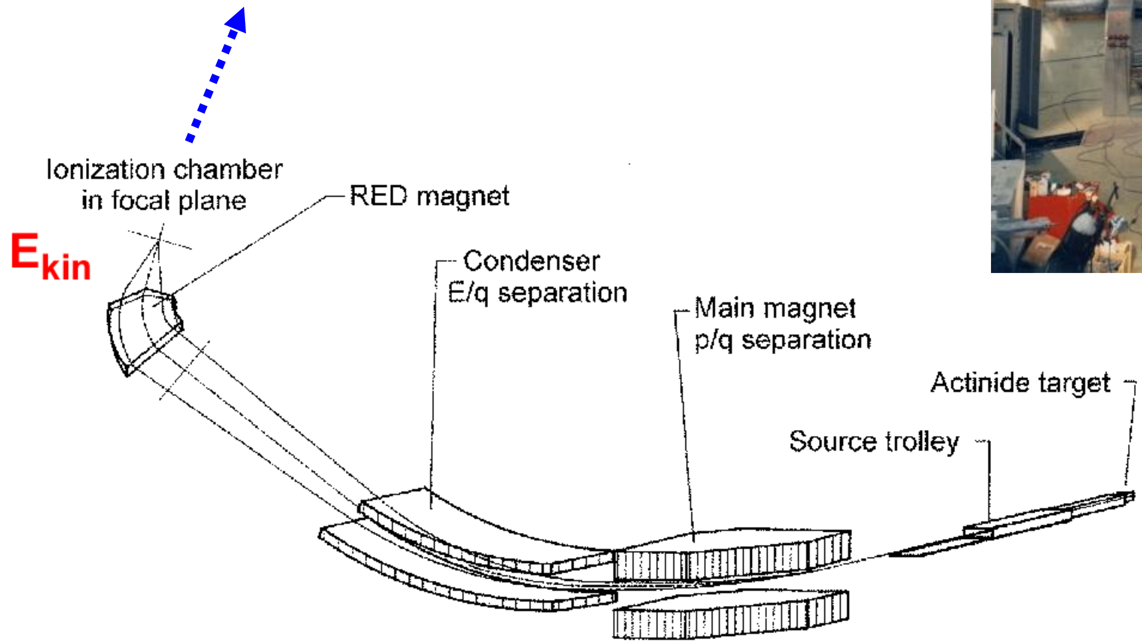
European Molecular Biology Laboratory (EMBL) Grenoble is an outstation of the EMBL organisation (HQ in Heidelberg), specialising in research in structural biology (in very close proximity to the ILL and the ESRF)

PN1: The fission fragment separator "Lohengrin"

(H. Faust), U. Koester, A. Blanc, N. Laurens

mass-separated fission fragments,

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



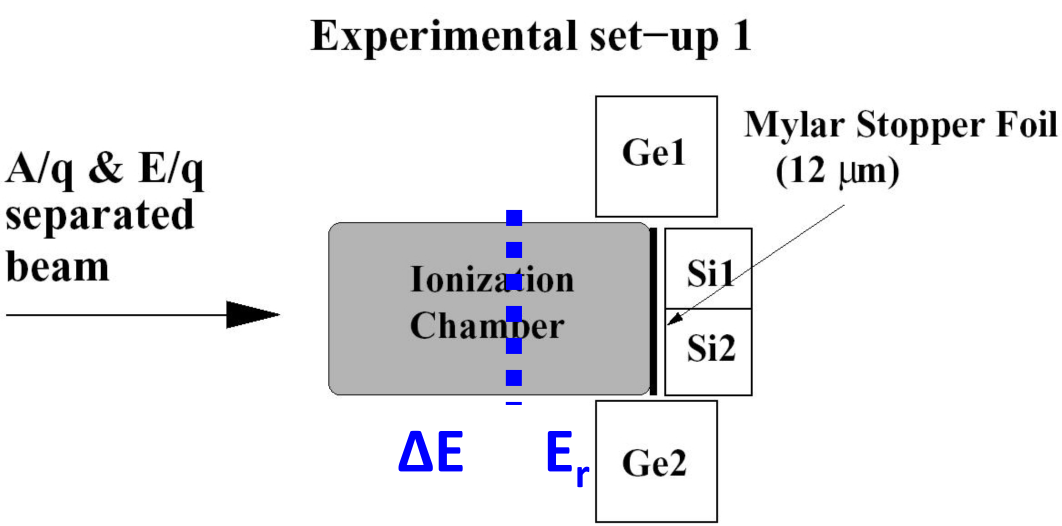
$$m\,v^2 / r_{el} = q\,E \qquad m\,v^2 / r_{magn} = q\,v\,B$$

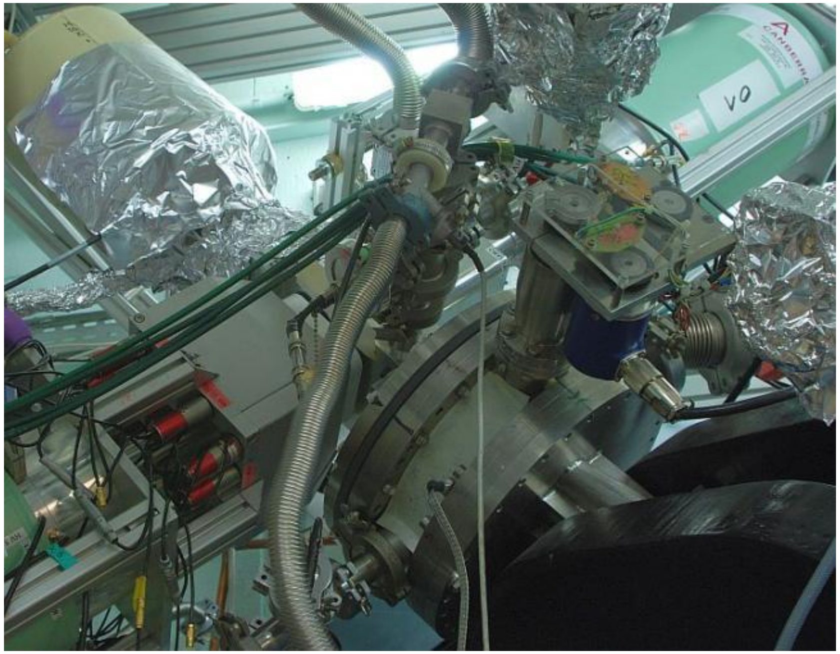
$$E_{kin} / q = E / 2\,r_{el} \qquad m\,v / q = B\,r_{magn}$$

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

Detection setup for fission product spectroscopy





Gamma ray detection

Conversion-electron detection

Z *identification* via energy loss (Bethe Bloch)

$$\frac{dE}{dx} \sim \frac{Z^2}{E}$$

Over 70 microsecond isomers studied so far at LOHENGRIN: $T_{1/2} \geq 0.5\ \mu s$

FIPPS

FIssion Product Prompt γ–ray Spectrometer

and its first experimental campaign

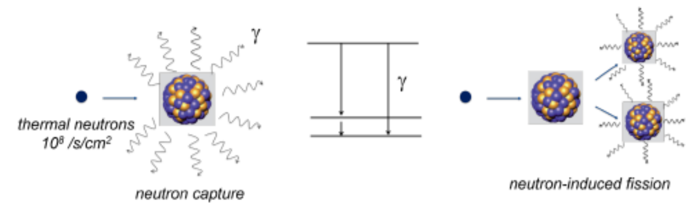
γ–ray spectroscopy after slow neutron-induced reactions

(n,γ)

→ close to stability

→ structure at low spin (below n-separation energy)

→ cross-sections (applications)

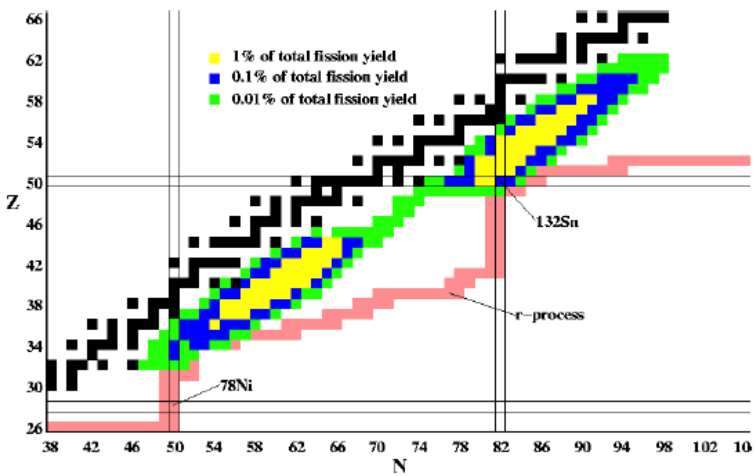


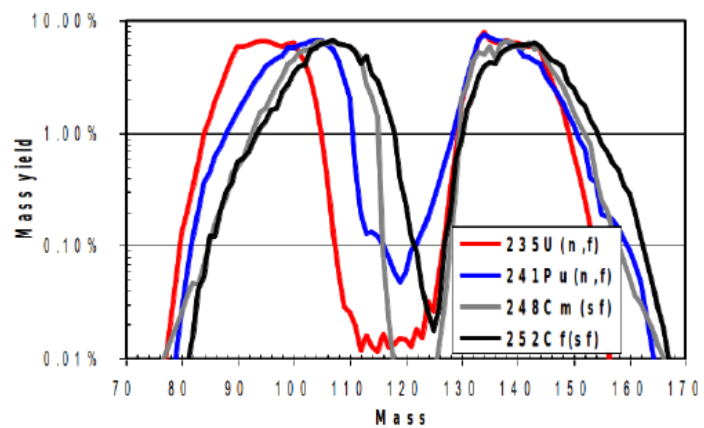
(n,fission)

→ away from stability

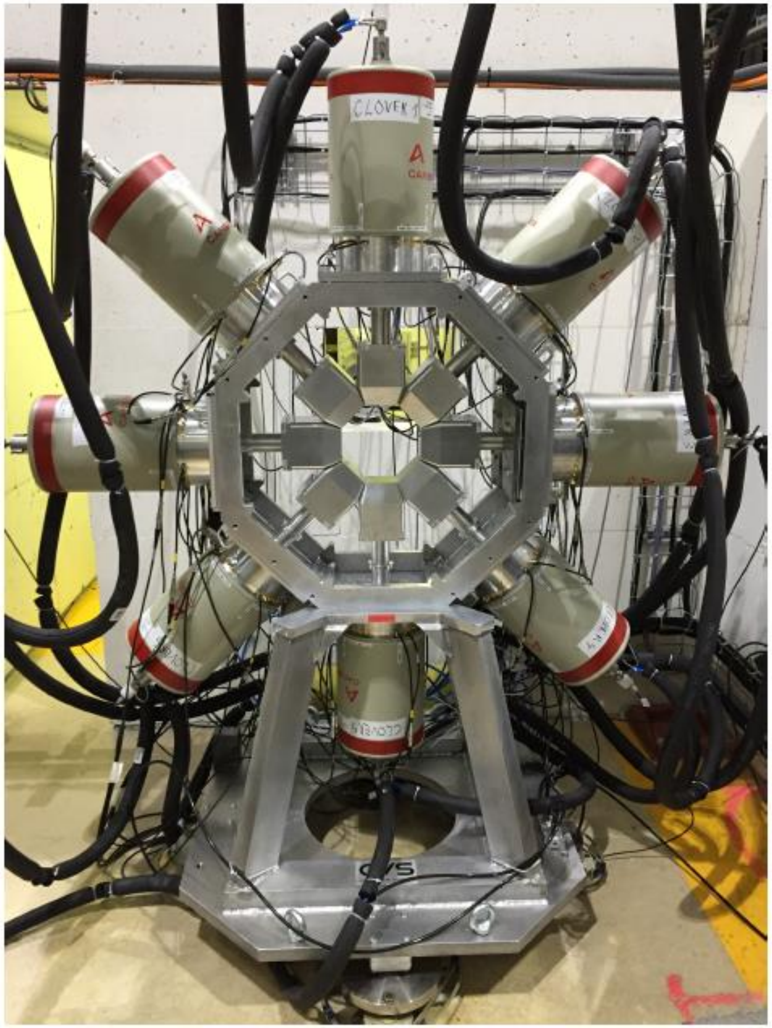
→ fission yields and dynamics

→ structure of n-rich nuclei





The new ILL instrument FIPPS (phase I)

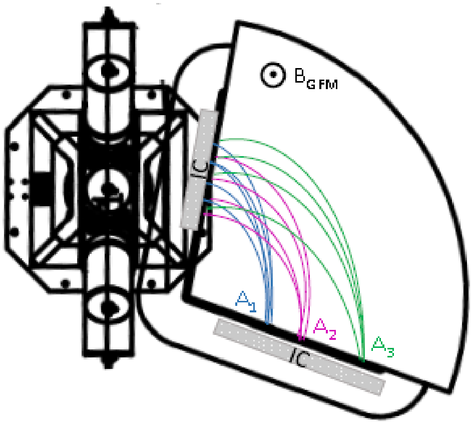


- ✓ intense thermal neutron pencil beam
- ✓ stable, radioactive and actinide targets
- ✓ γ–ray detection:
  - → high-resolution HPGe clovers
  - → symmetry around target position
  - → digital electronics, list-mode data
- ✓ ancillary detectors

Study the structure of n-rich nuclei and fission mechanism

HPGe clovers + Gas-Filled-Magnet (GFM) for fission fragment selection

FIPPS phase II project submitted for *Endurance II*



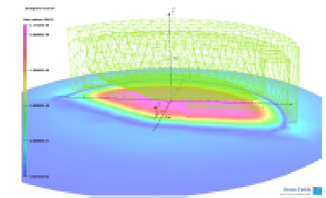
$\Delta A/A = 2.2\,\%$

acceptance:

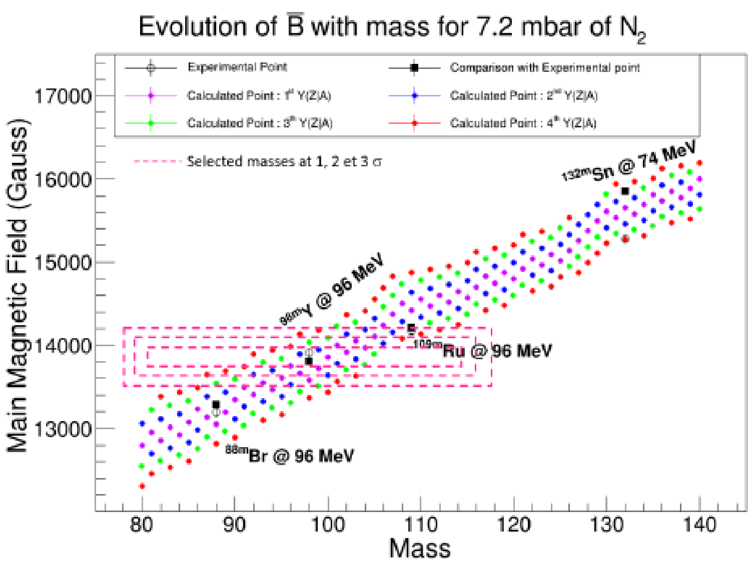
$0.4\,\%$ extracted beam;

full reconstruction of ion tracks using a low-pressure TPC

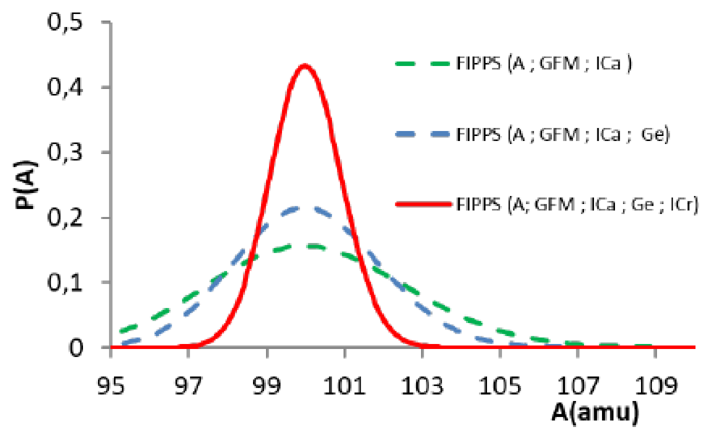
$\rightarrow 3.5\,\%$



superconducting magnet designed by E. Froidefond (LPSC Grenoble)

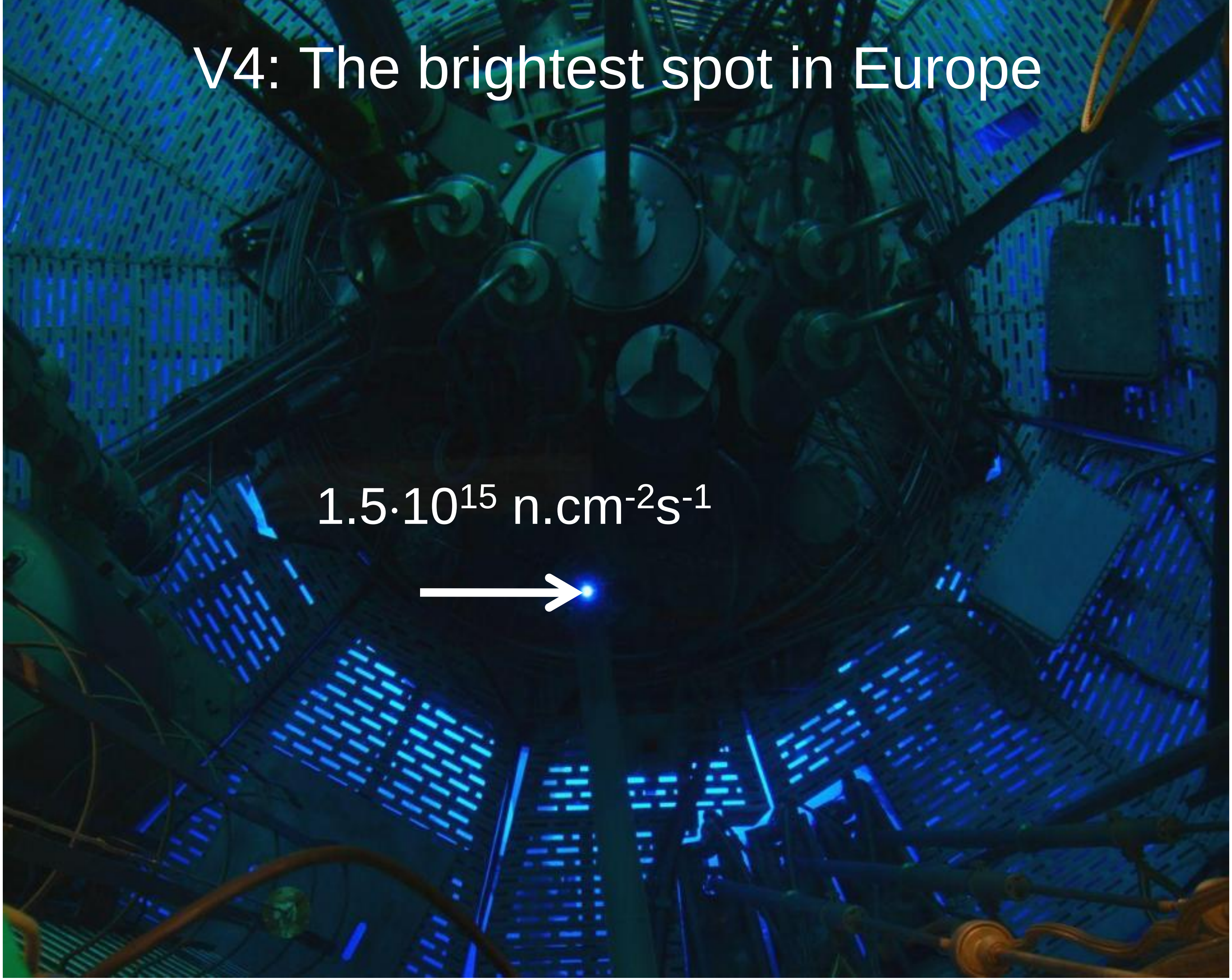


A. Chebbouibi PhD Thesis



G. Kessedjian et al.

V4: The brightest spot in Europe



Targeted radionuclide therapies in the clinic

Thyroid: ^{131}I^{-}

Brain: ^{90}Y-mab ,^{131}I-mab (I/II), ^{211}At-mab (I), ^{213}Bi-pept.(I)

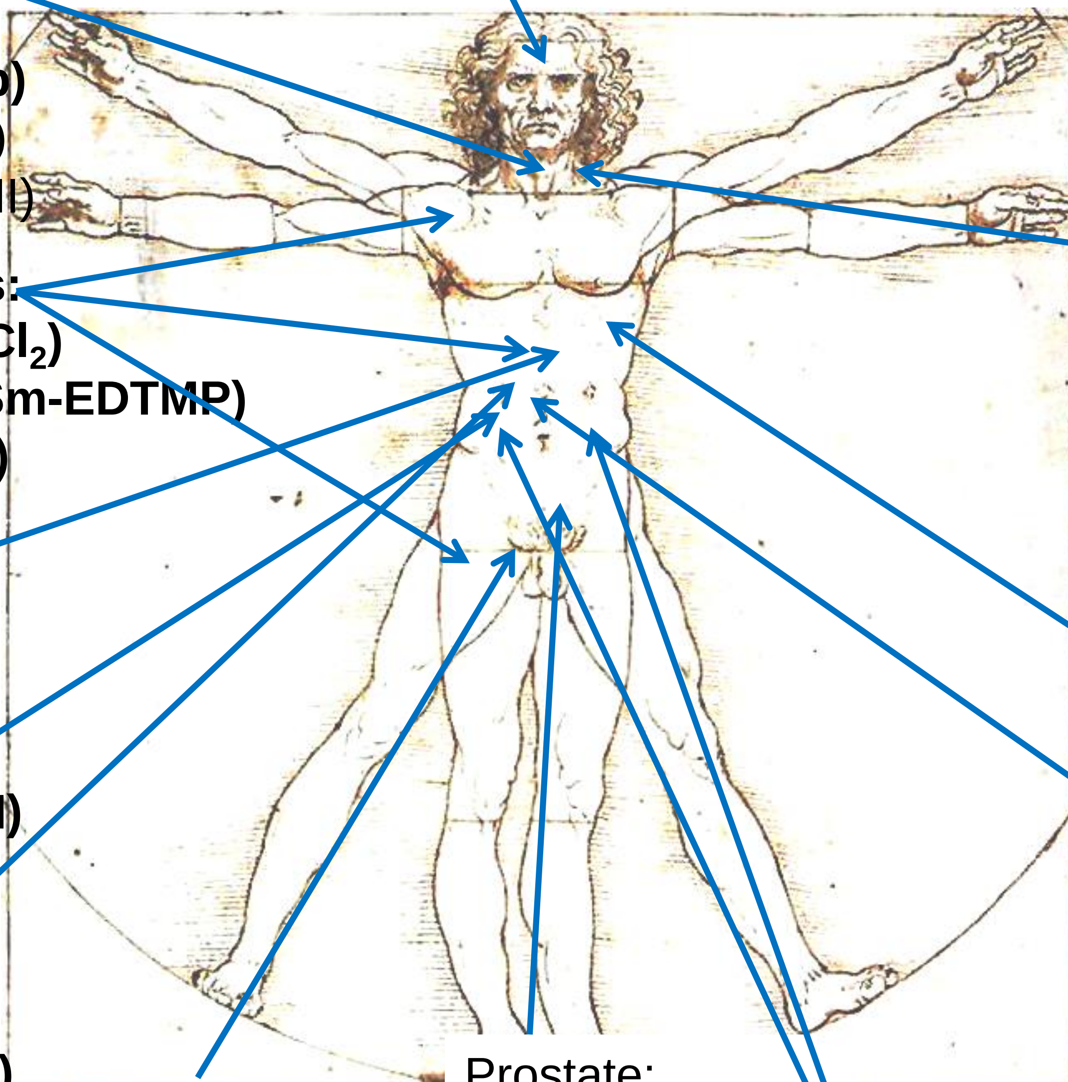
Lymphoma:
Zevalin® (^{90}Y-mab)
Bexxar® (^{131}I-mab)
^{131}I/**^{177}Lu**-mabs (I/II)

Bone metastases:
Metastron® (^{90}SrCl$_2$)
Quadramet® (^{153}Sm-EDTMP)
Xofigo® (^{223}RaCl$_2$)

Neuroblastoma:
^{131}I-MIBG

Neuroendocrine (GEP-NET):
^{177}Lu-peptides (III)

Liver (HCC):
Theraspheres® &
SIRspheres® (^{90}Y)
^{188}Re-Lipiodol (II)
^{166}Ho-microspheres



Leukemia, myeloma:
^{131}Y-mab (III),
^{213}Bi/^{225}Ac-mab (II)

Medullary Thyroid:
^{131}I-mab (II)
^{90}Y/**^{177}Lu**-pept.

Breast:
^{90}Y-mab, ^{131}I^{-} (II),
^{212}Pb-mab (I)

Lung (SCLC):
^{177}Lu-mab (II)

Pancreas:
^{90}Y-mab (III)

Ovary:
^{212}Pb-mab (I)
^{90}Y/**^{177}Lu**-mab

Colon & rectum:
^{131}I-mab (II)

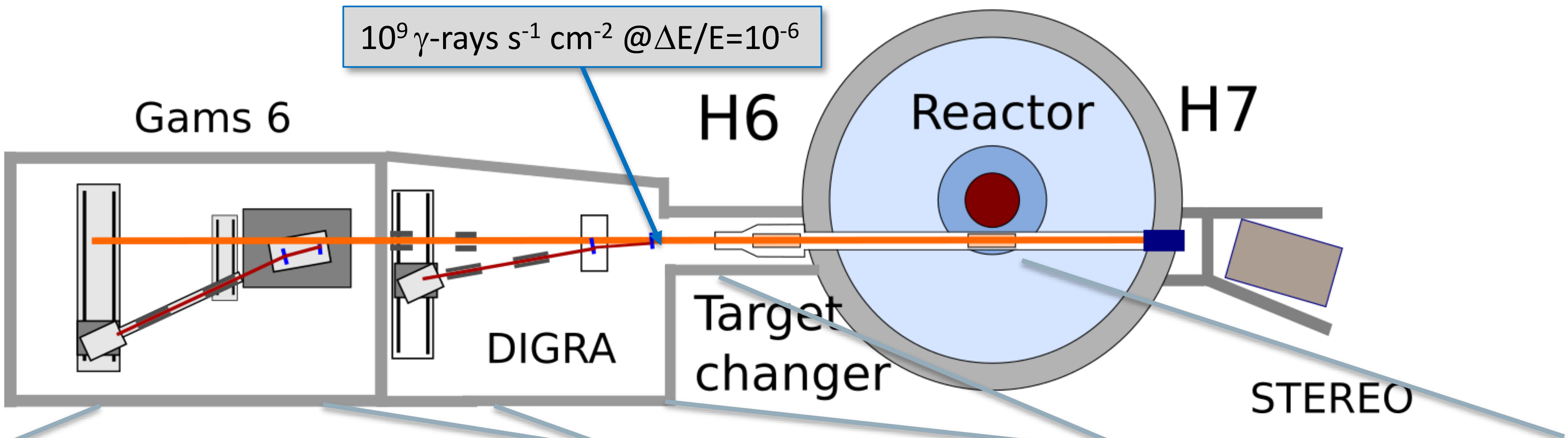
Prostate:
^{177}Lu-mab (II)
^{177}Lu-PSMA (I)

Kidneys (RCC):
^{90}Y/**^{177}Lu**-mab (II)

Melanoma:
^{213}Bi-mab(I)

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: $10^{-7} – 10^{-6}$

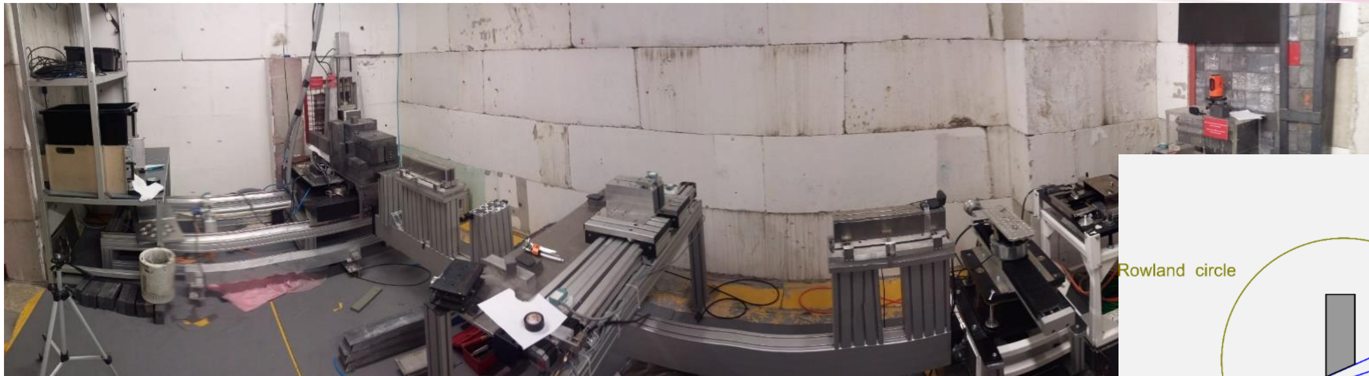
- Bent crystal spectroscopy
- Gamma Ray Laue Lens
- Gamma Ray Imaging tests

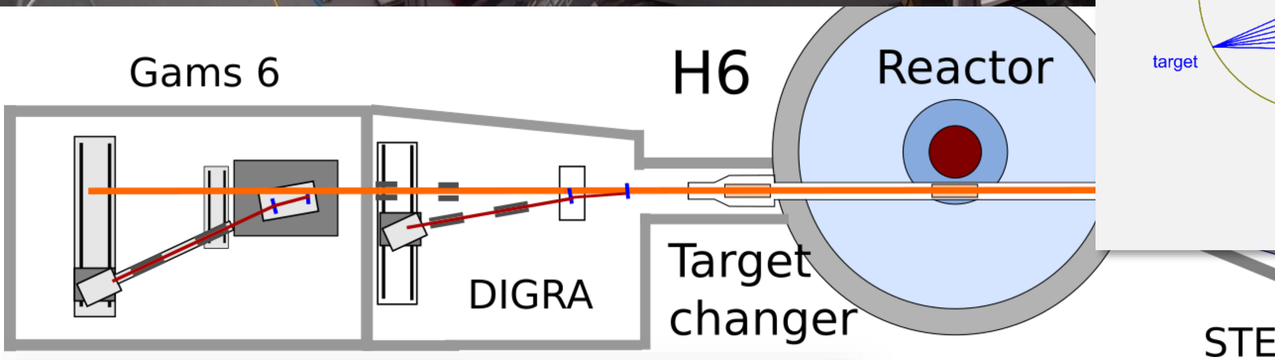
Inpile Irradiation Position:

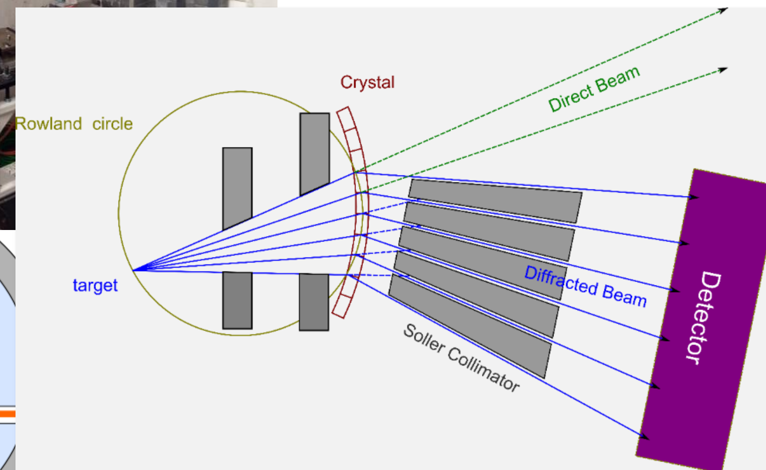
- Neutron flux: 5 x 10^{14} cm^2 s^{-1}
- 3 Samples 4 x 20 x 20 mm^3
- Orientation of samples in reactor is possible
- Sample change during reactor cycle
- Self heating: ~1 W/g

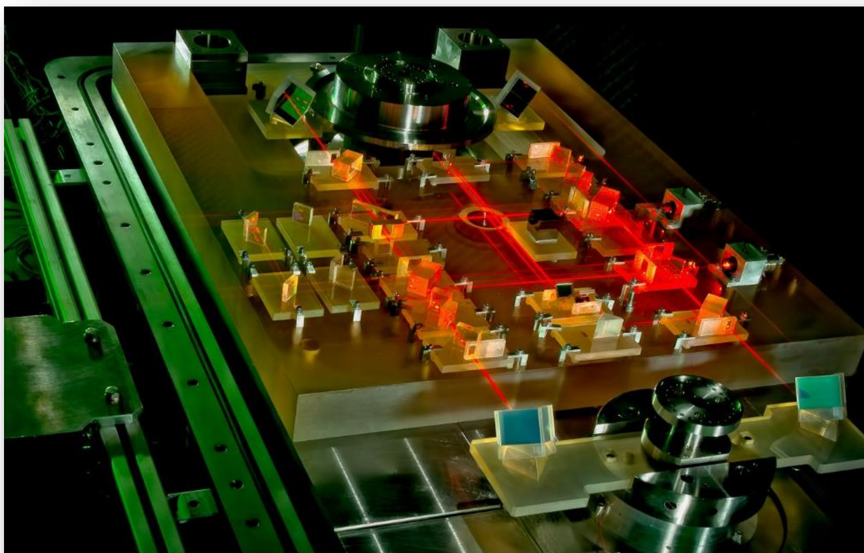
AND GAMMA RAY

GAMS & DIGRA

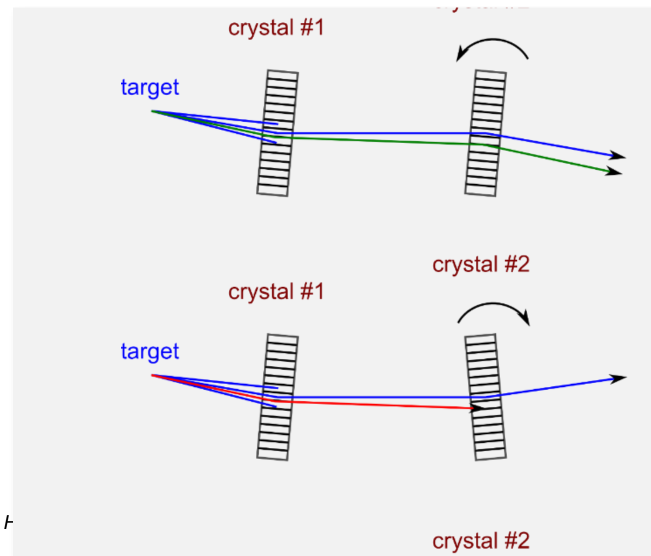




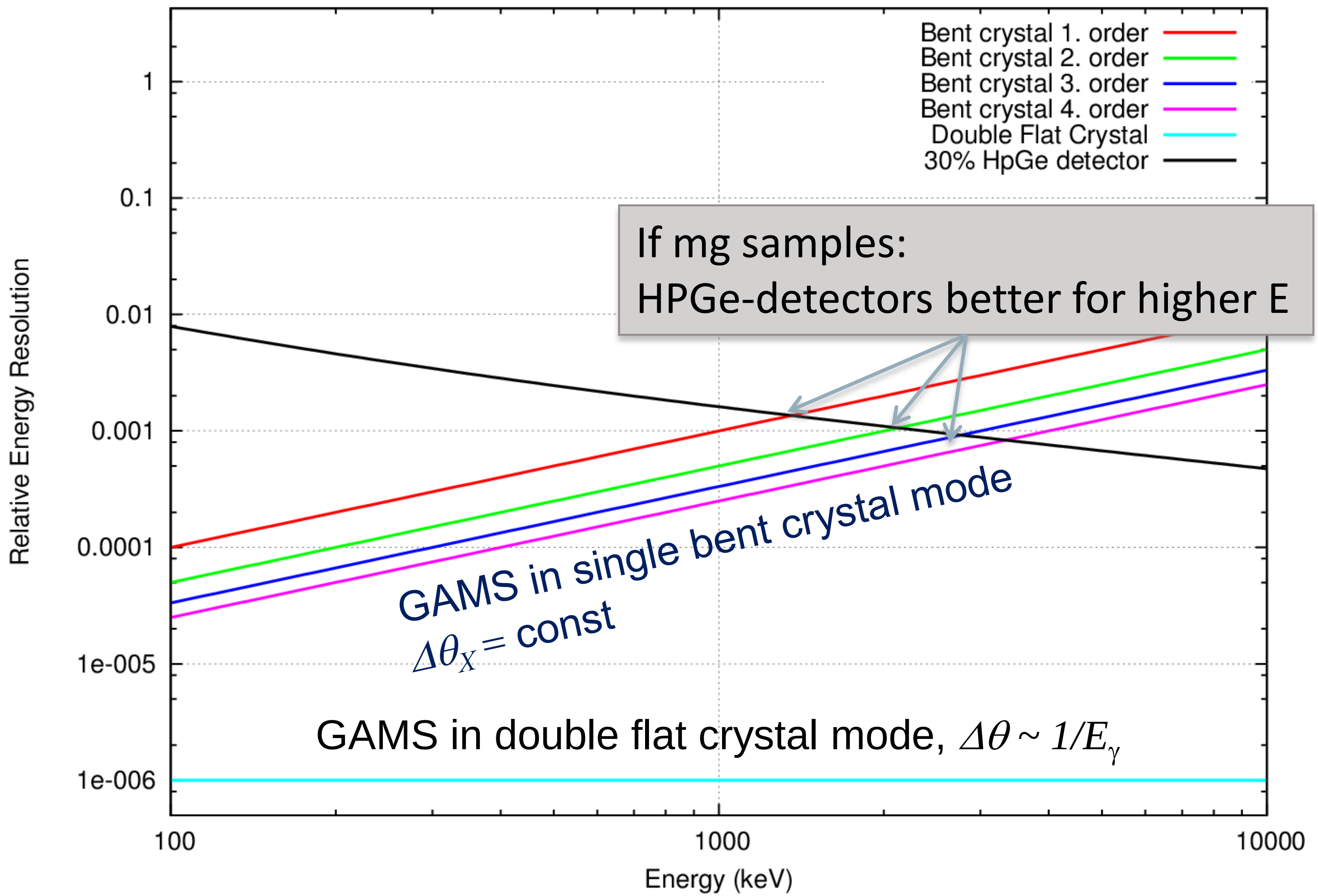




STEREO



Overview on Energy resolution

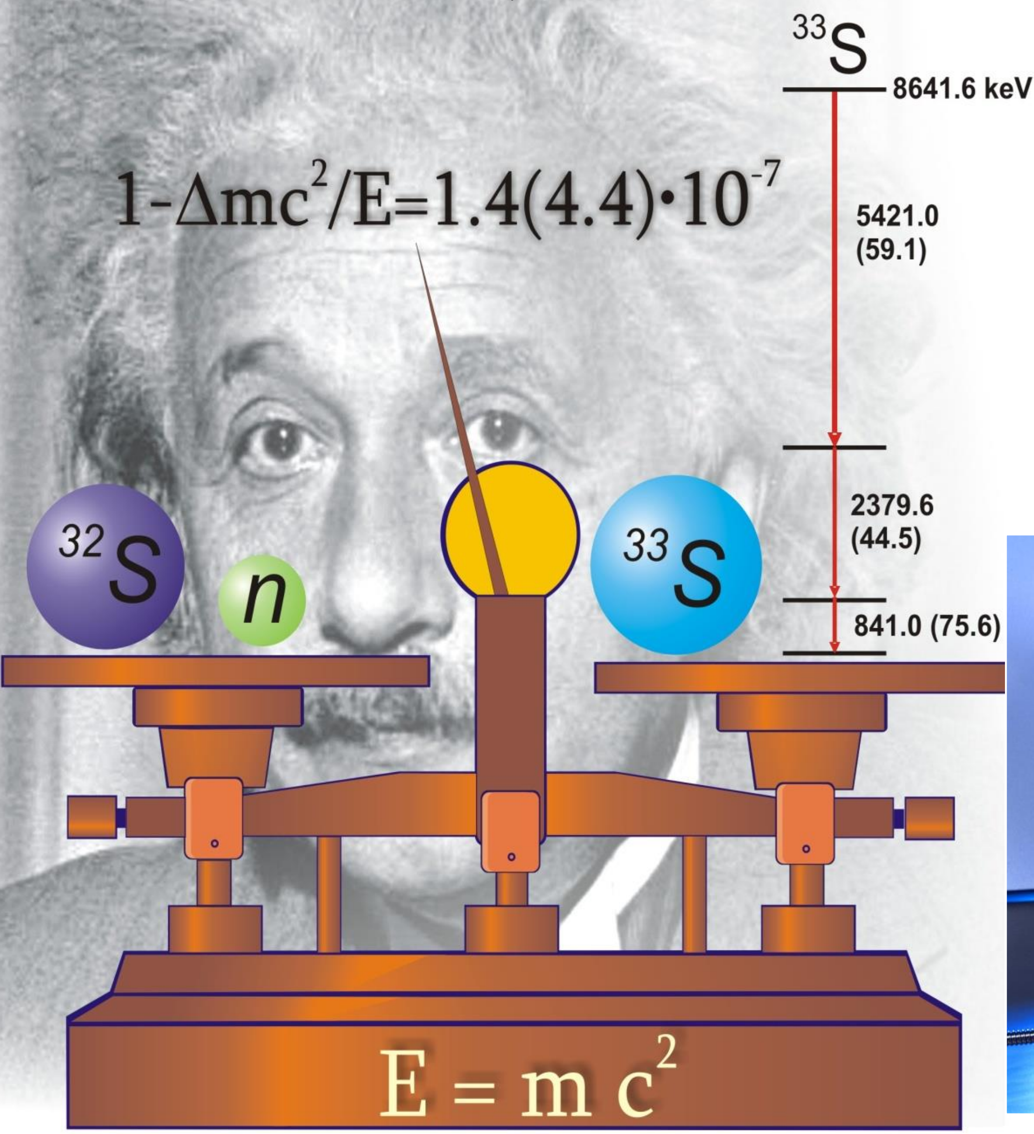


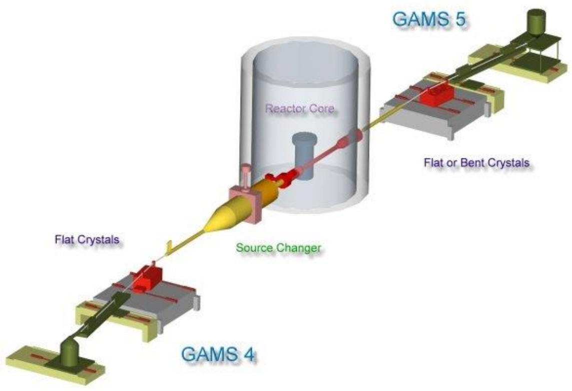
NEUTRONS FOR SOCIETY

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

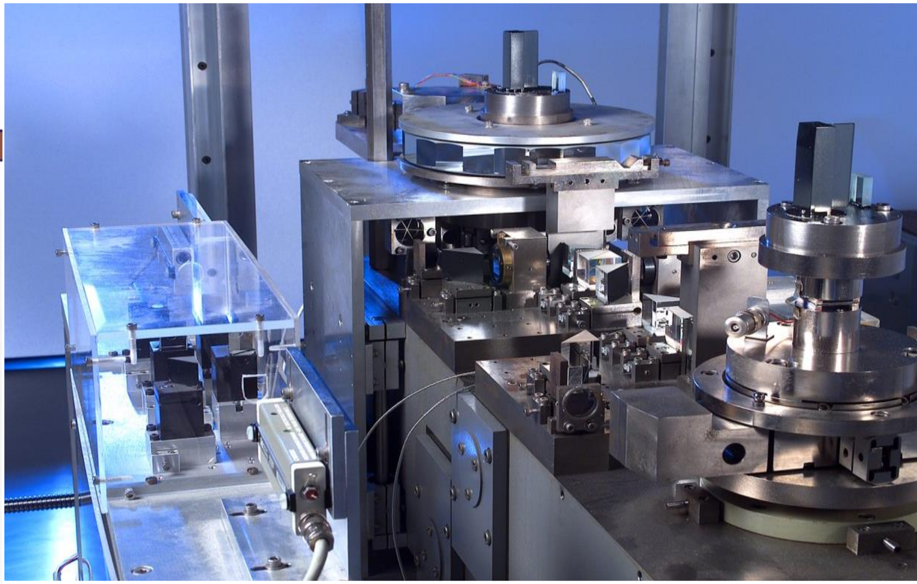
2005 World Year of Physics – Einstein's "Miraculous year" 1905

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



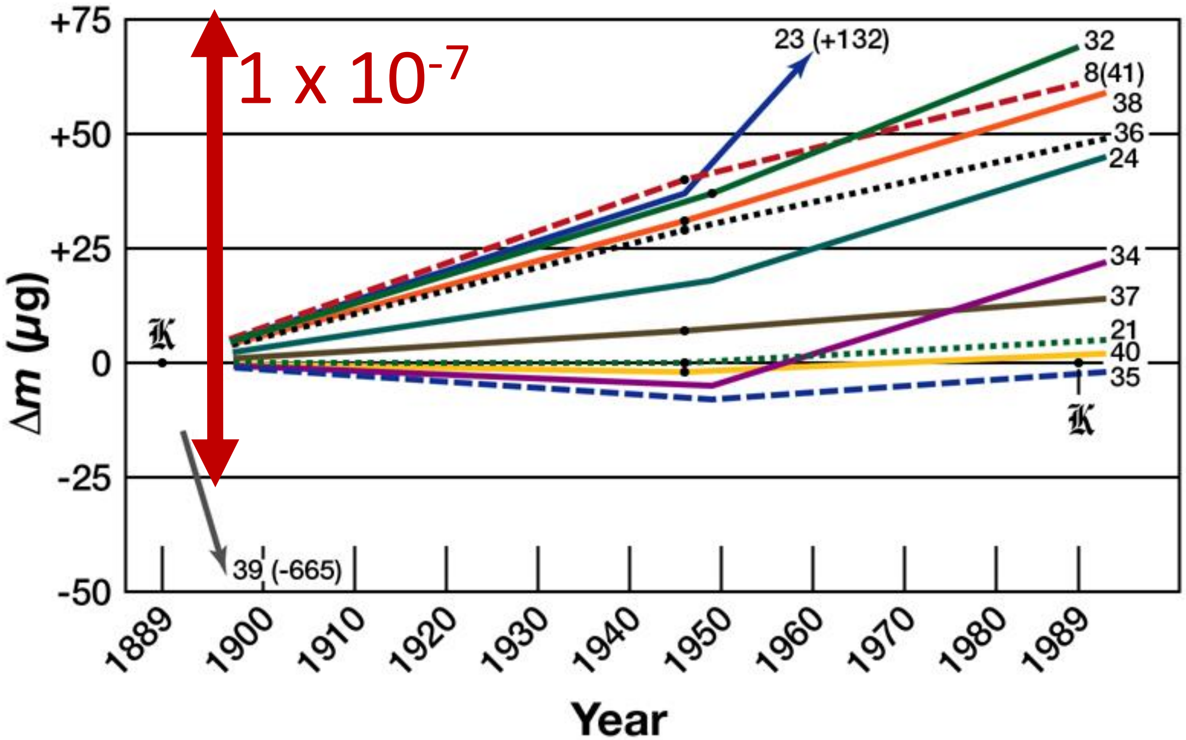


GAMS Interferometer ILL



Current concept of mass definition

Cross comparison of copies of kg prototype stored at BIPM in Paris, France



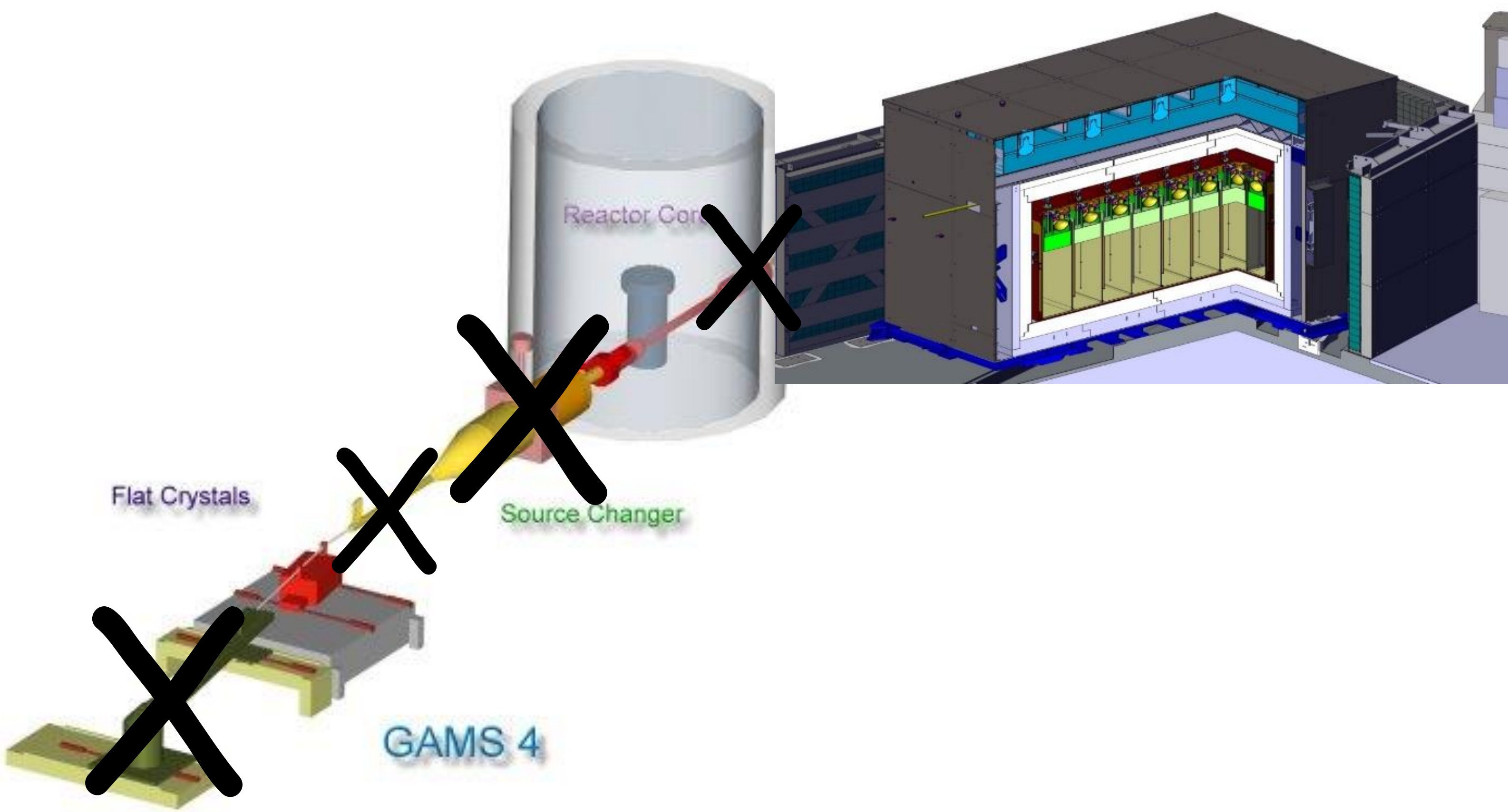
<u>More modern concept:</u> Linking Masses to Frequency via *h*

requires: $E=mc^2$

Antineutrino detector STEREO

at the sealed end of beam tube H7

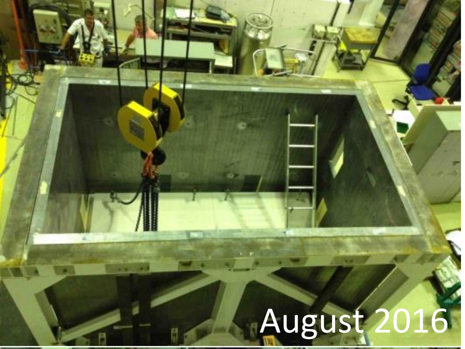
STEREO

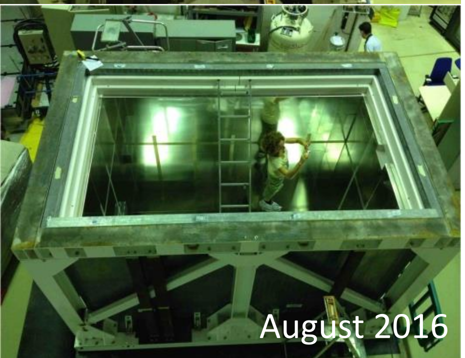


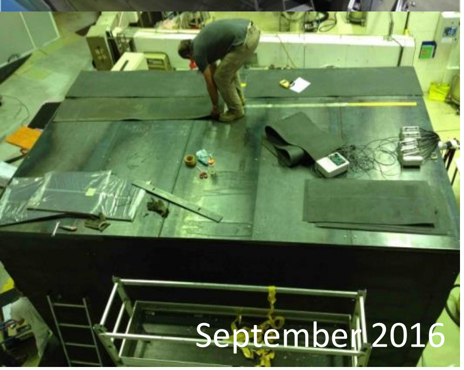
In April 2017 through beam tube H6/H7 removed and sealed

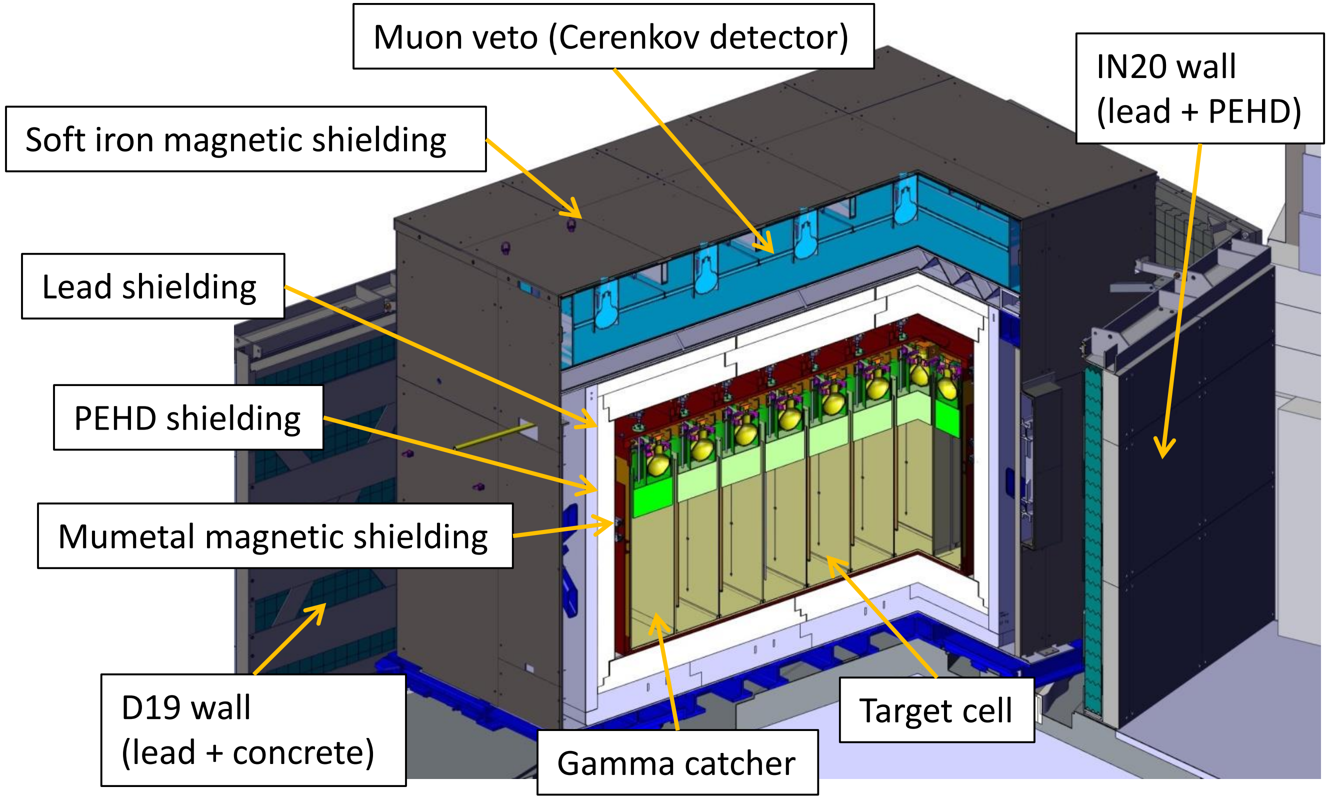
STEREO setup

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



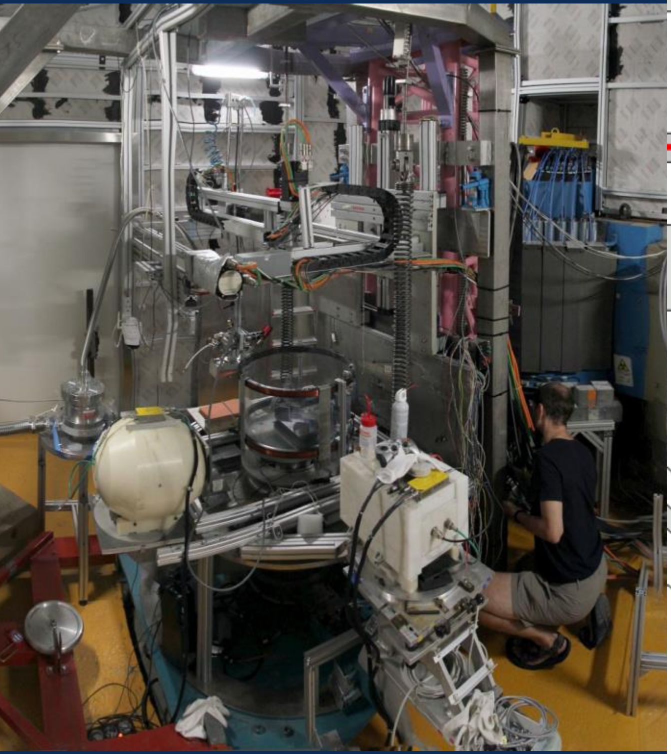


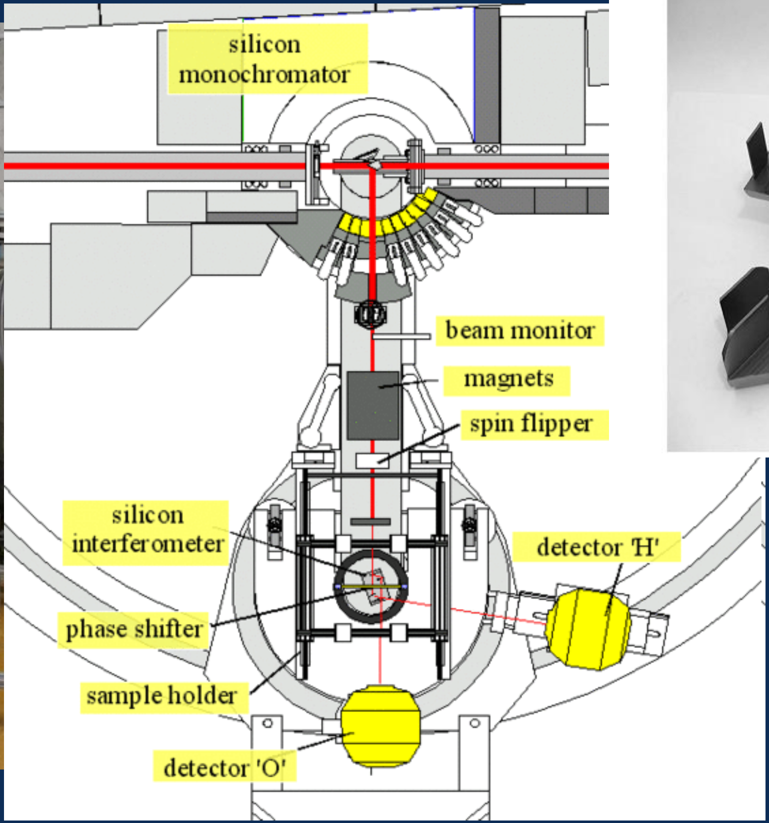


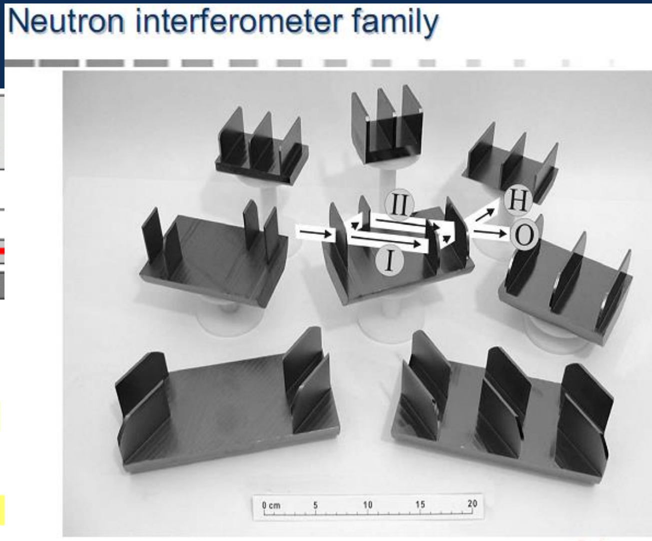


S18 - CRG instrument (Atominstitut, TU Vienna, Austria [T. Jenke])

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







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

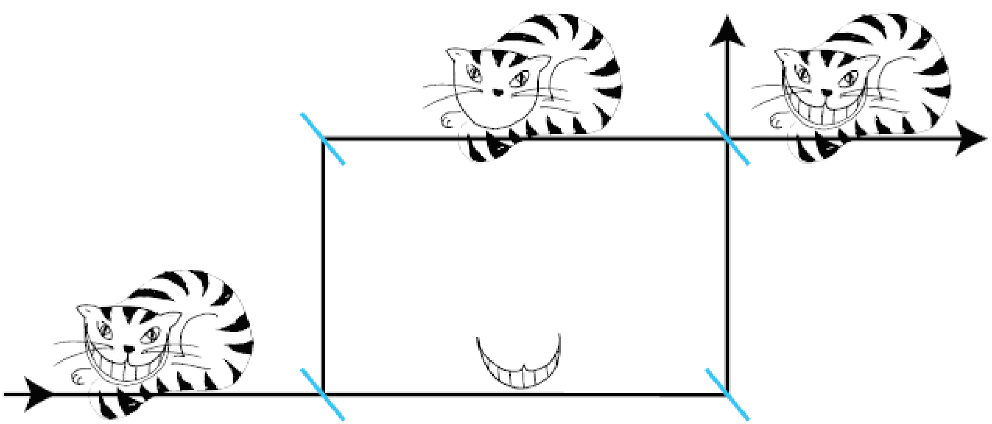


FIG. 1: Artistic depiction of the quantum Cheshire Cat: Inside the interferometer the Cat goes through the upper beam path, while its grin travels along the lower beam path.

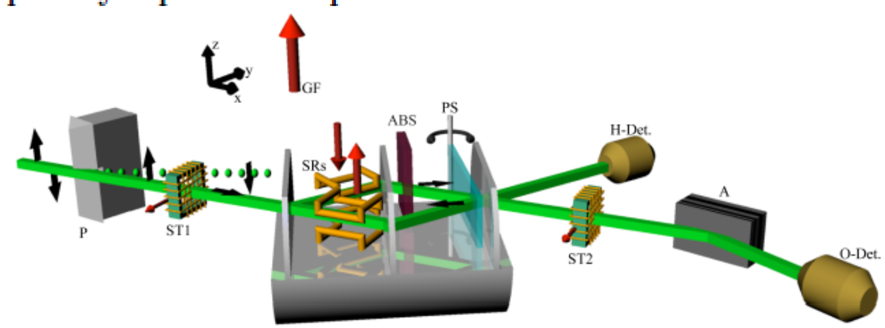


FIG. 2: Illustration of the experimental setup for the observation of a quantum Cheshire Cat in a neutron interferometer: The neutron beam is polarized by passing through magnetic birefringent prisms (P). To prevent depolarization, a magnetic guide field (GF) is applied around the whole setup. A spin 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).

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**!

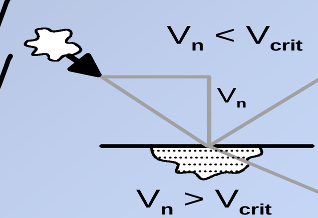
Long storage and observation times possible (up to several minutes)!

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

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 $E \cdot \sin^2\Theta \lesssim V$ or $\sin\Theta \lesssim \sin\Theta_c = (V/E)^{\frac{1}{2}}$
1946/47	Fermi & collaborators	demonstrate **TOTAL REFLECTION** (basis for n guides) led to speculations: if $E \lesssim V$ then **STORABLE**
1959	Zel'dovich	put it into **print**, estimates absorption times and **densities** (~50cm^{-3}!)
1961	Vladimirski	suggests **vertical extraction**
1963	Doroshkevich	suggests **berillyium** and estimates the loss rates (as a function of temperatrure) due to wall vibrations $\lesssim 10^{-7}s^{-1}$
1966	Steyerl	proposes a **neutron turbine** for $10^{-8} \lesssim E \lesssim 10^{-9}$ 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** at FRM in Garching
1980	Kosvintsev et al.	earliest **material bottle n lifetime experiments** at SM-2 reactor in Dimitrovgrad
1983	Bates	**Fomblin** oil as fluid wall coating
1985	Steyerl et al.	2nd generation **turbine** at ILL's vertical cold source: **PF2**
1989	Mampe et al.	first n lifetime experiment using material bottle at the ILL setting **new standard of precision**

UCN discovery

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
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the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers co

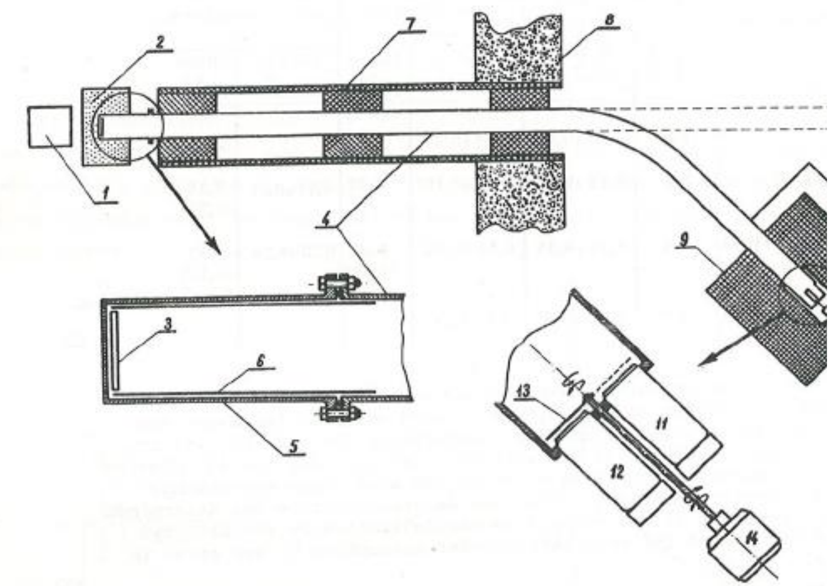

Fig. 1. Diagram of setup. 1- IBR reactor; 2, 3 - moderator (2 - paraffi
layer 1 mm thick); 4 - copper tube, 9.4 cm i.d., total length 10.5 m; 5 -
copper-foil cylinder; 7 - shield (paraffin with boron carbide); 8 - 2-m c
actor chamber; 9 - detector shield (paraffin); 10 - tube filling and evac
12 - detectors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

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

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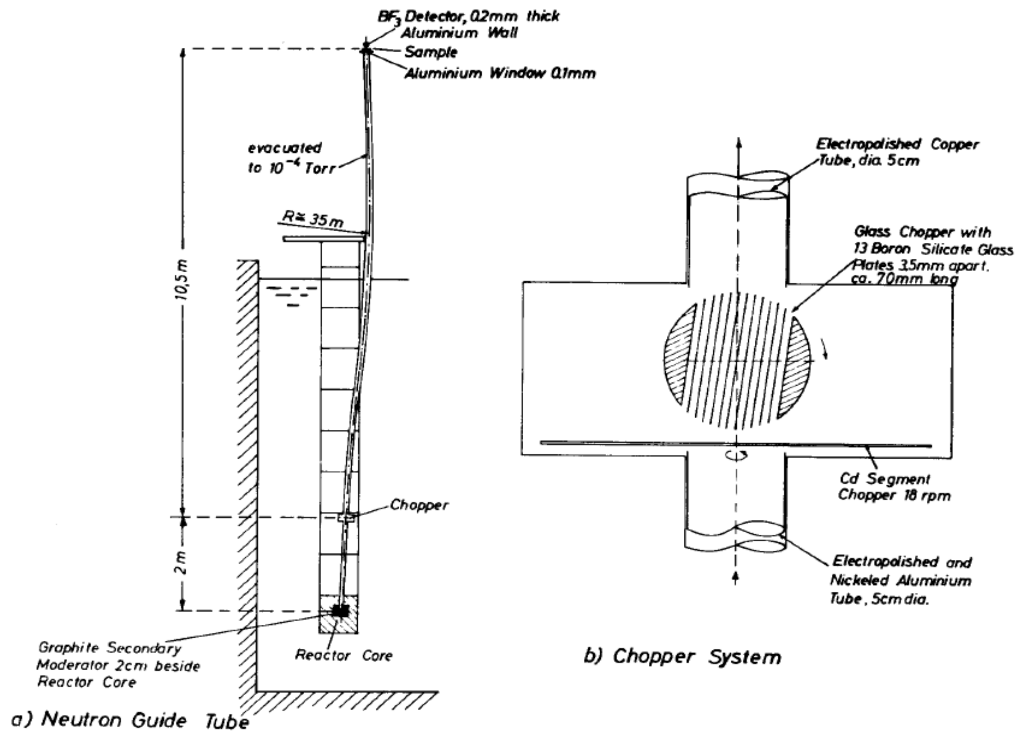
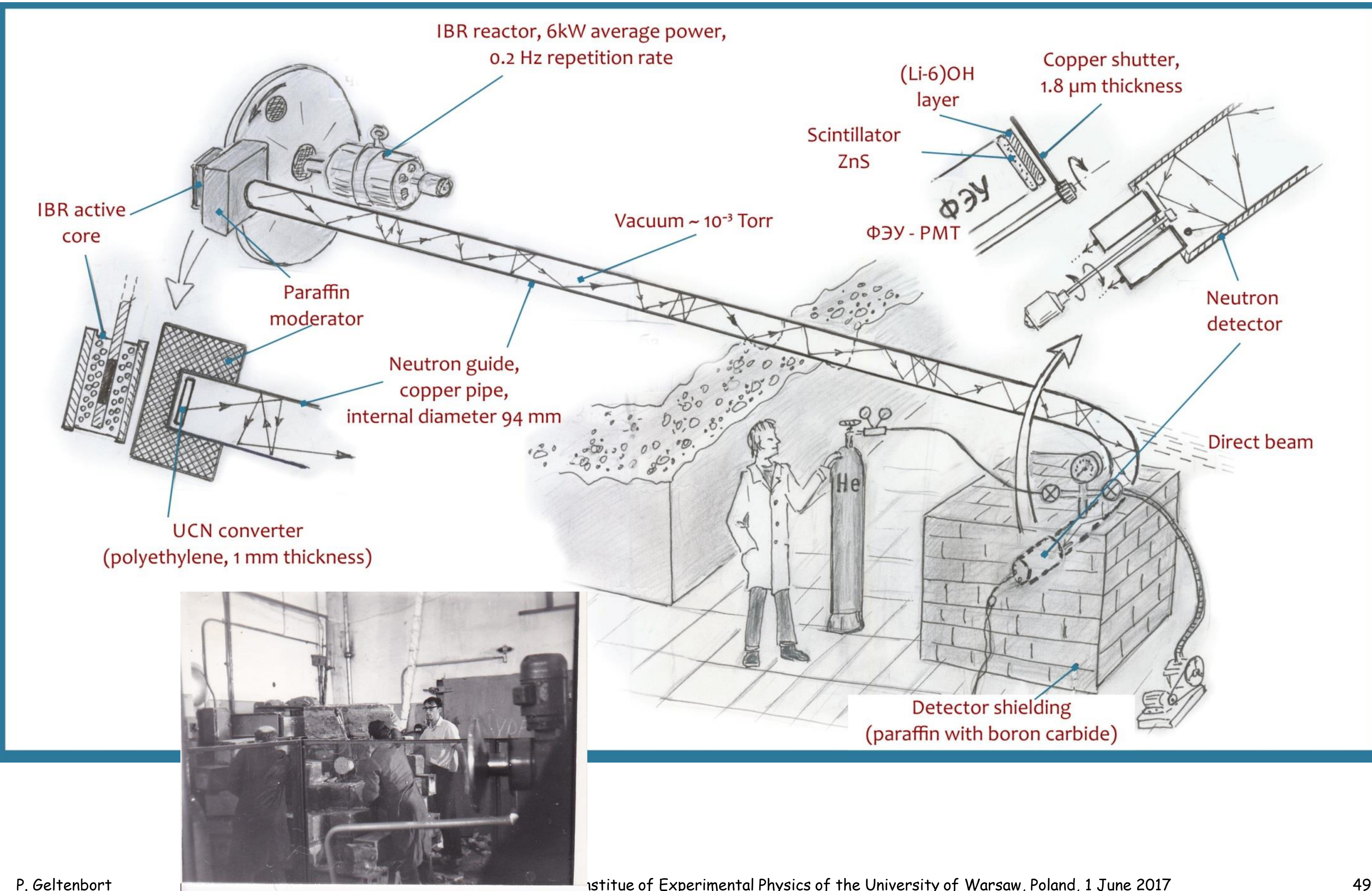


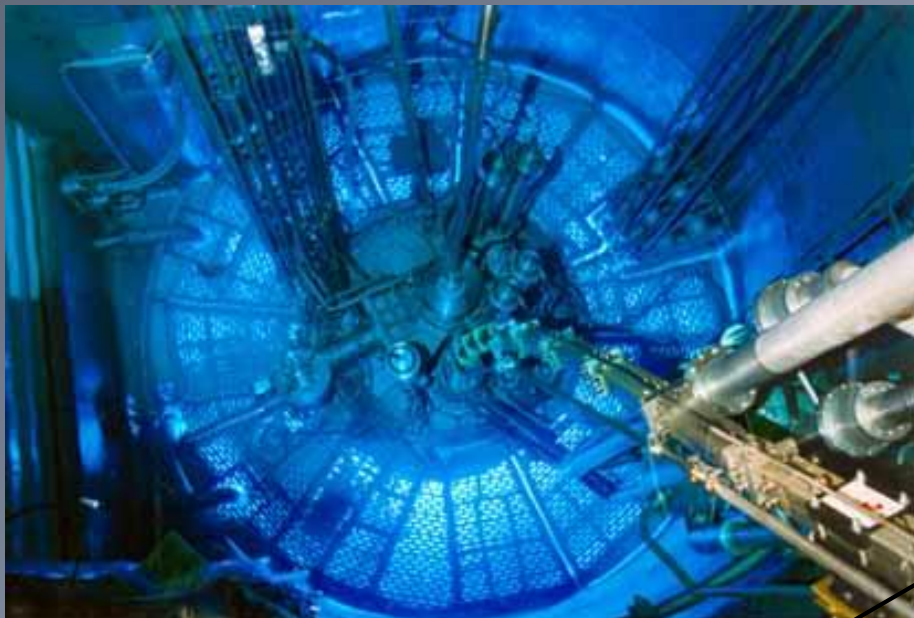
Fig. 1. Vertical beam tube for very slow neutrons.

how UCN were "really" discovered in Dubna

drawing courtesy of A.V. Strelkov
who will celebrate his 80th anniversary this year!



The UCN/VCN facility PF2

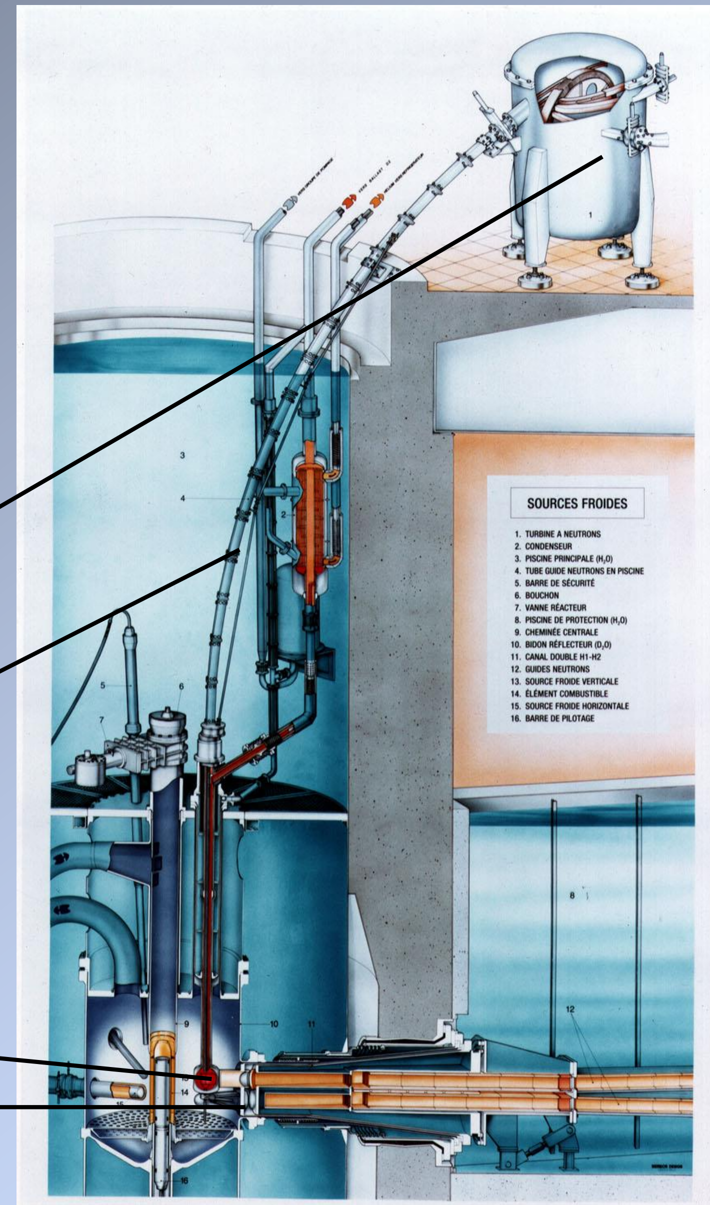


Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

Reactor core

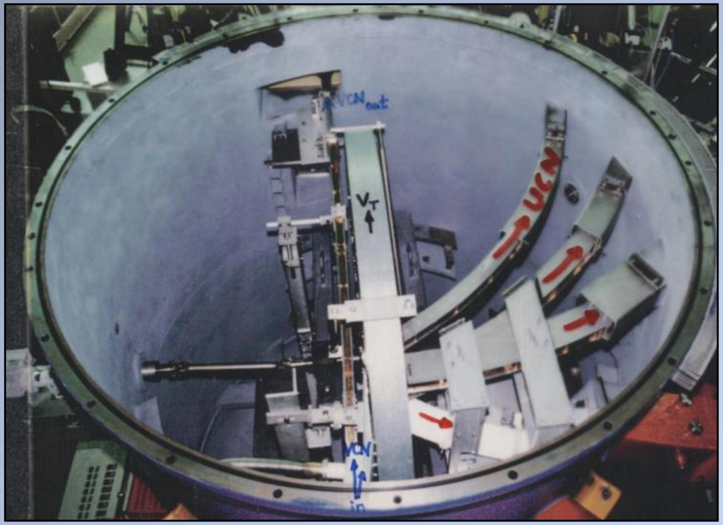


A. Steyerl et al., Phys. Lett. A116 (1986) 347

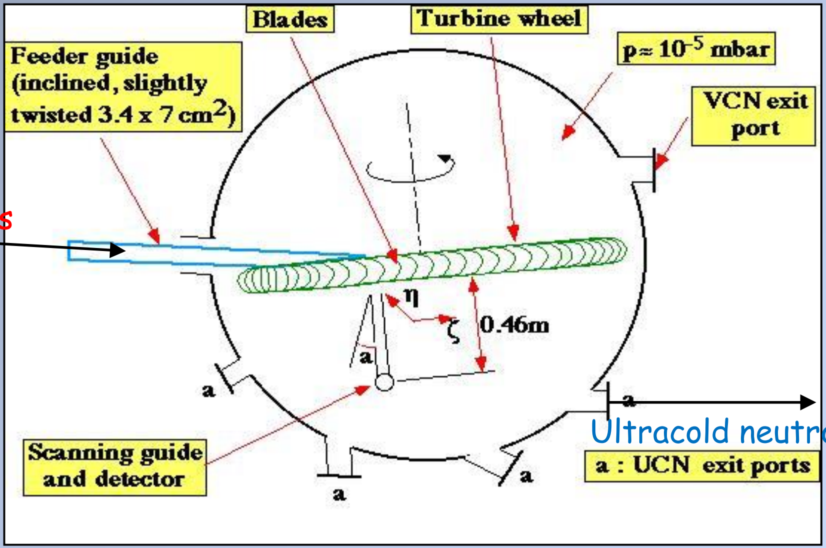
Generating Ultracold Neutrons (UCN)

"Steyerl turbine"
Doppler shifting device

Steyerl turbine
at FRM-I (Munich)



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

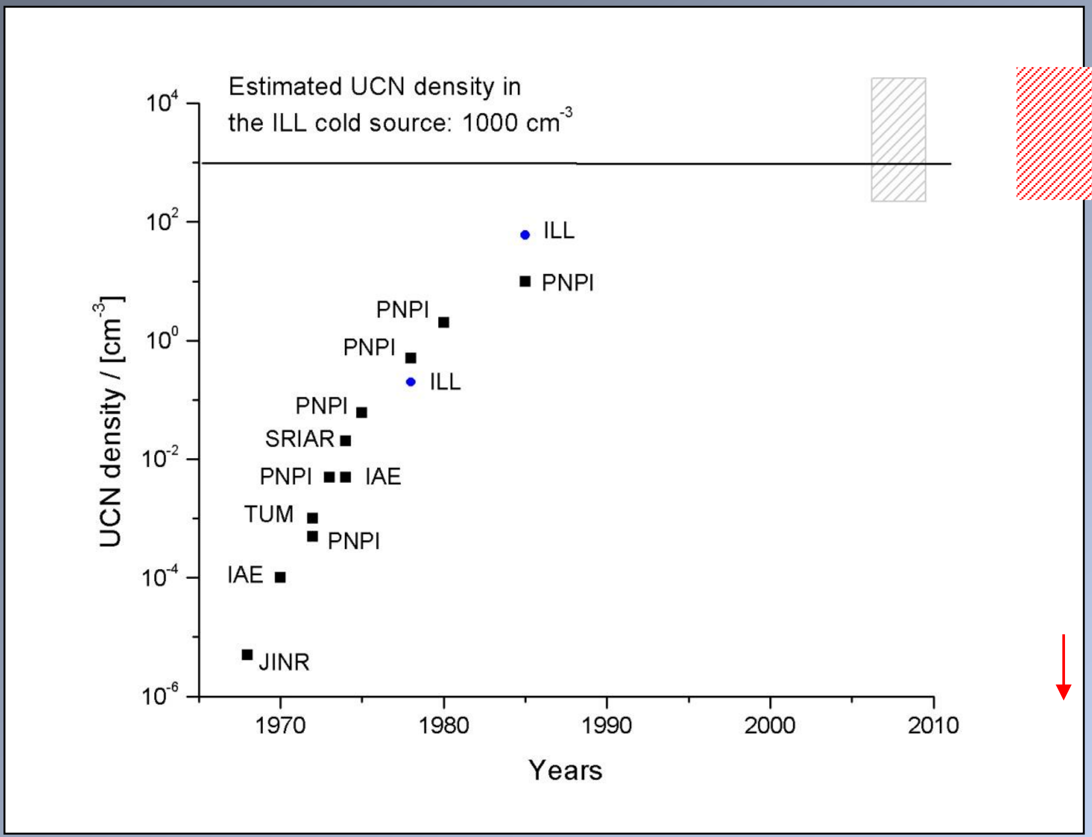


A. Steyerl et al.,
Physics Letters A 116 (1986) 347 - 352

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!

UCN facilities - Status and Future



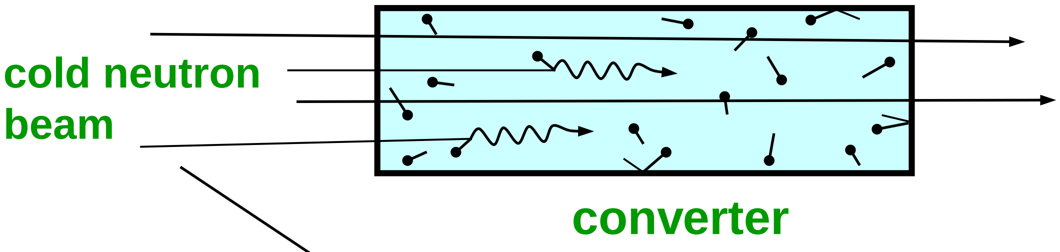
More and stronger UCN facilities in the future worldwide

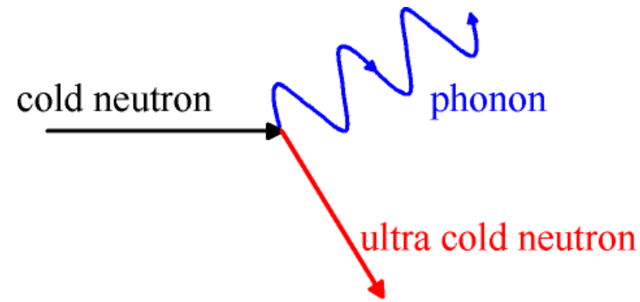
- **PSI** (CH)
- **Mainz** / **Munich (D)**
- **ILL** (F)
- **LANL** / **NIST** / **SNS** / **NCSU (USA)**
- **RCNP** (J) then TRIUMF (Canada) JPARC (J)
- **PNPI (RUS)**

UCN production in He-II

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

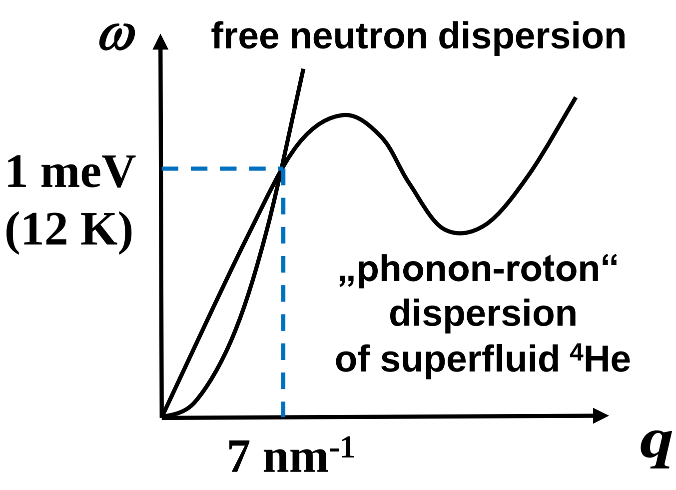
$\sigma_{capture}$ (^{4}He) = 0





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

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



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

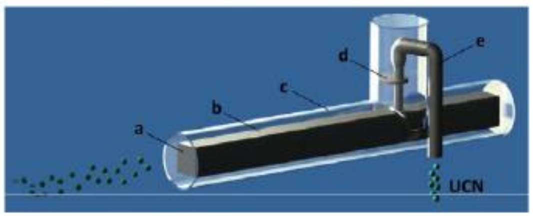
→ **need T < 0.5 - 0.6 K and low-loss walls**

Long-term perspective

- long-term perspective:

"UCN competence center at the ILL"

SuperSUN (SUN2)



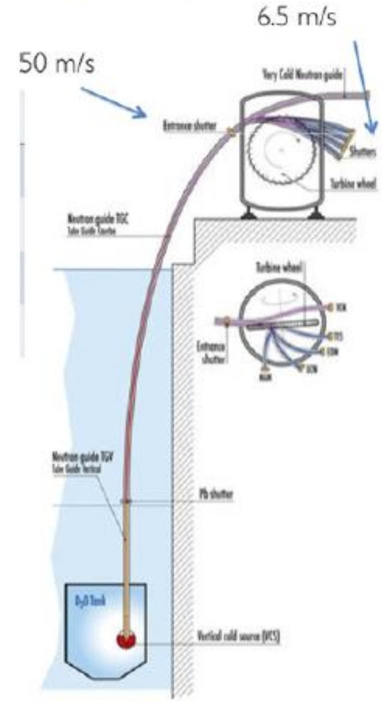
highest UCN densities, very soft spectrum

- *dedicated (long-term) storage experiments*

PF2

highest UCN flux

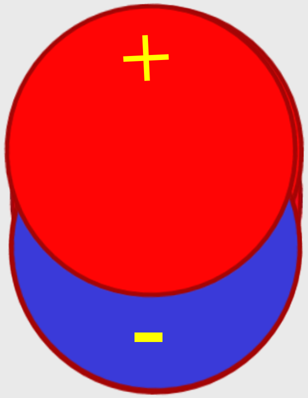
- *In-flight/ short-time experiments*

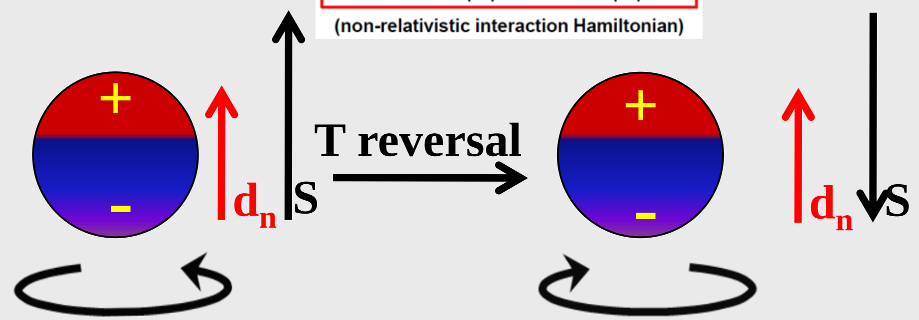


21

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

(non-relativistic interaction Hamiltonian)





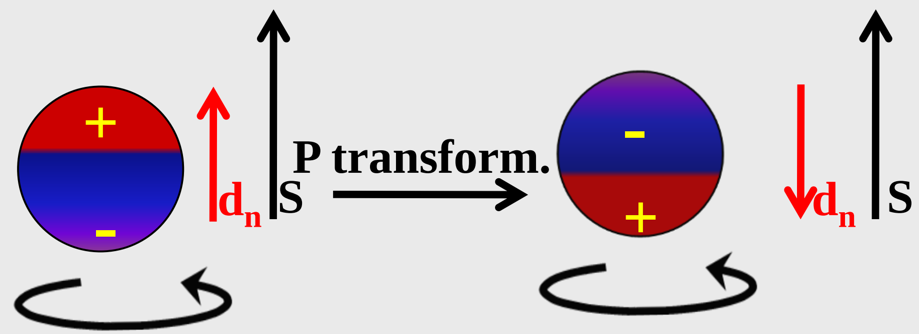
electric dipole moment d_n

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

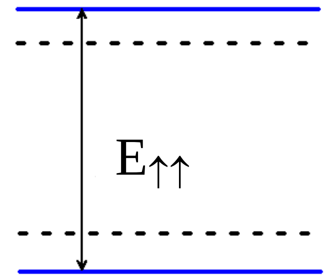
CPT conservation ➔ CP violation

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

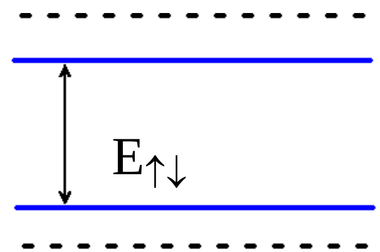
Experiments:
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

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



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

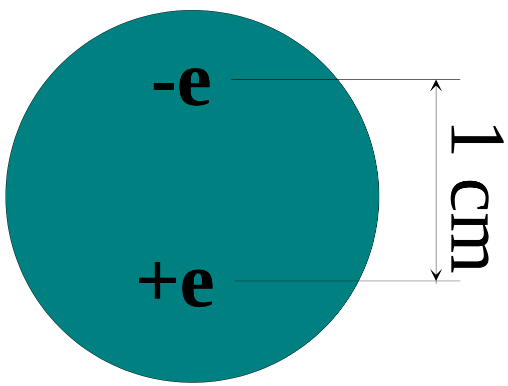
Need to measure change in Larmor precession frequency to a very high degree : < 1μHz
< 1 turn per month!

The difference is proportional to d_n and E:

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

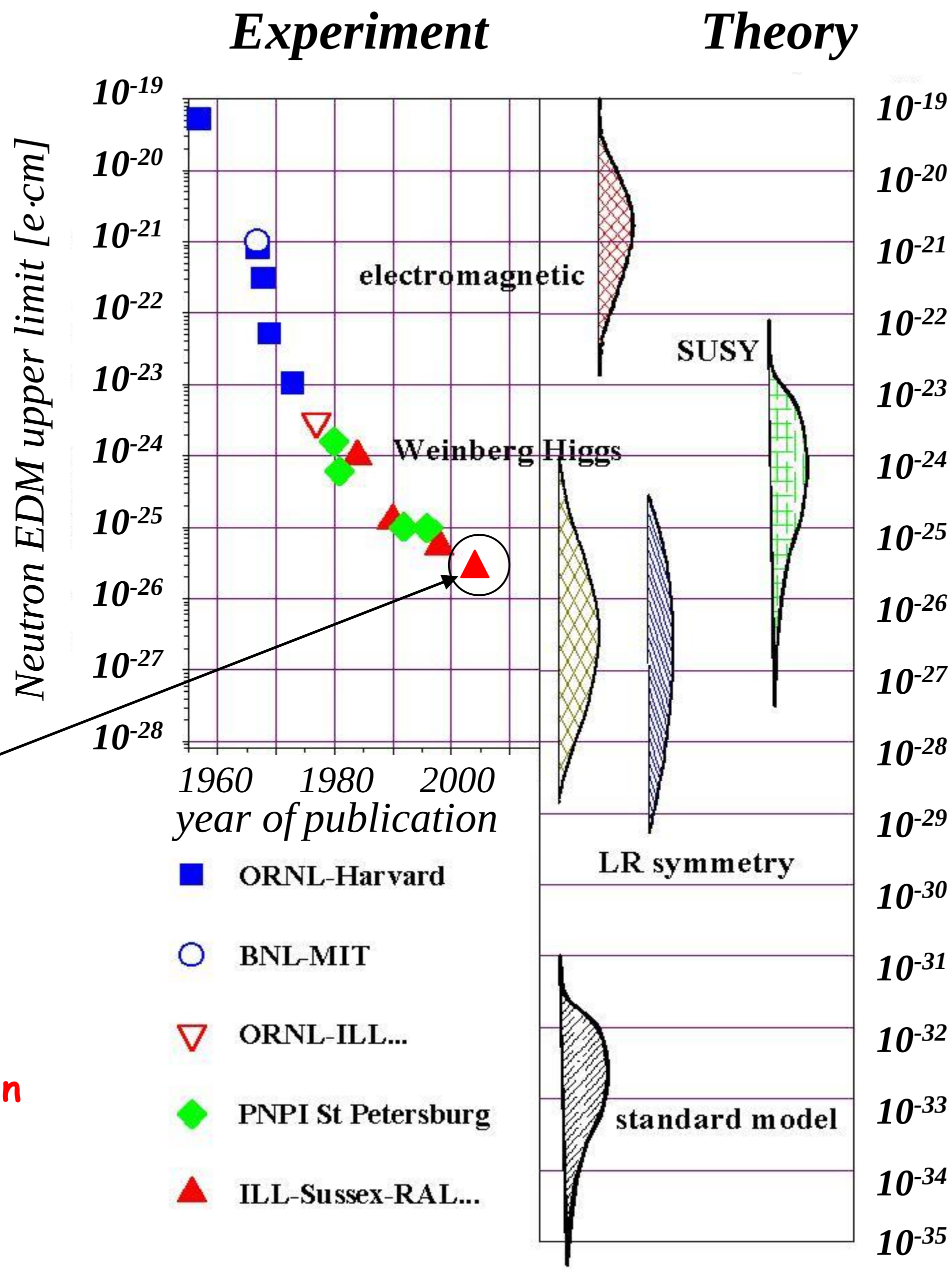
The neutron EDM: exp. vs theory

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



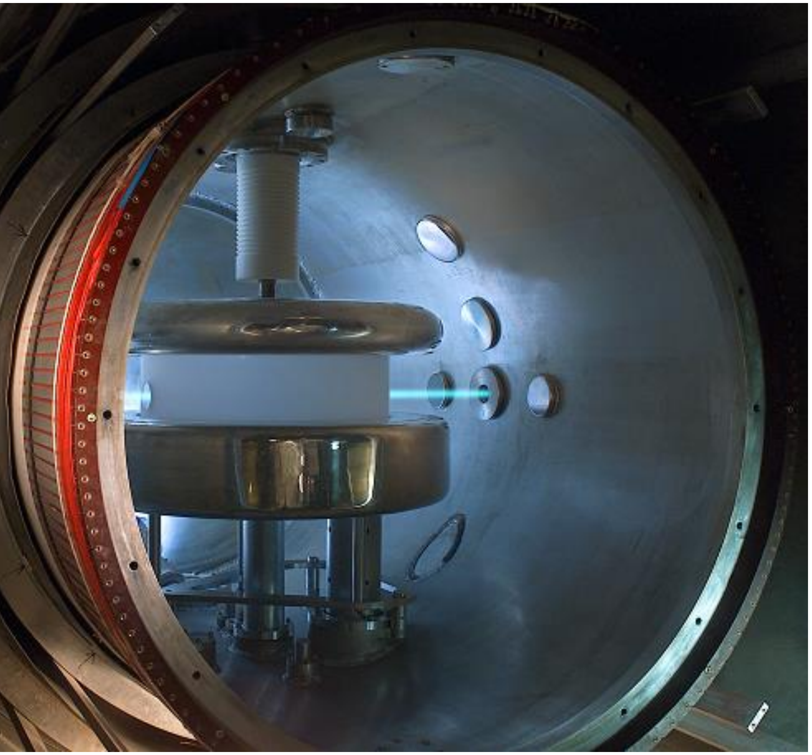
$d_n = 1\ e{\cdot}\mathrm{cm}$

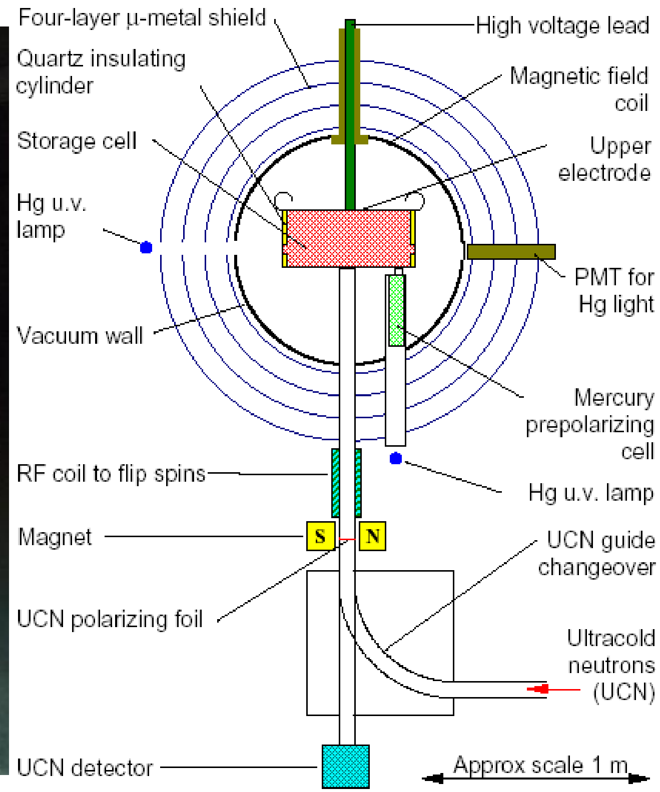
$|d_n| < 3 \times 10^{-26}\ e{\cdot}\mathrm{cm}$



"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

Room Temperature Results





University of Sussex

CCLRC

NEUTRONS FOR SCIENCE

Room temperature neutron EDM result:

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

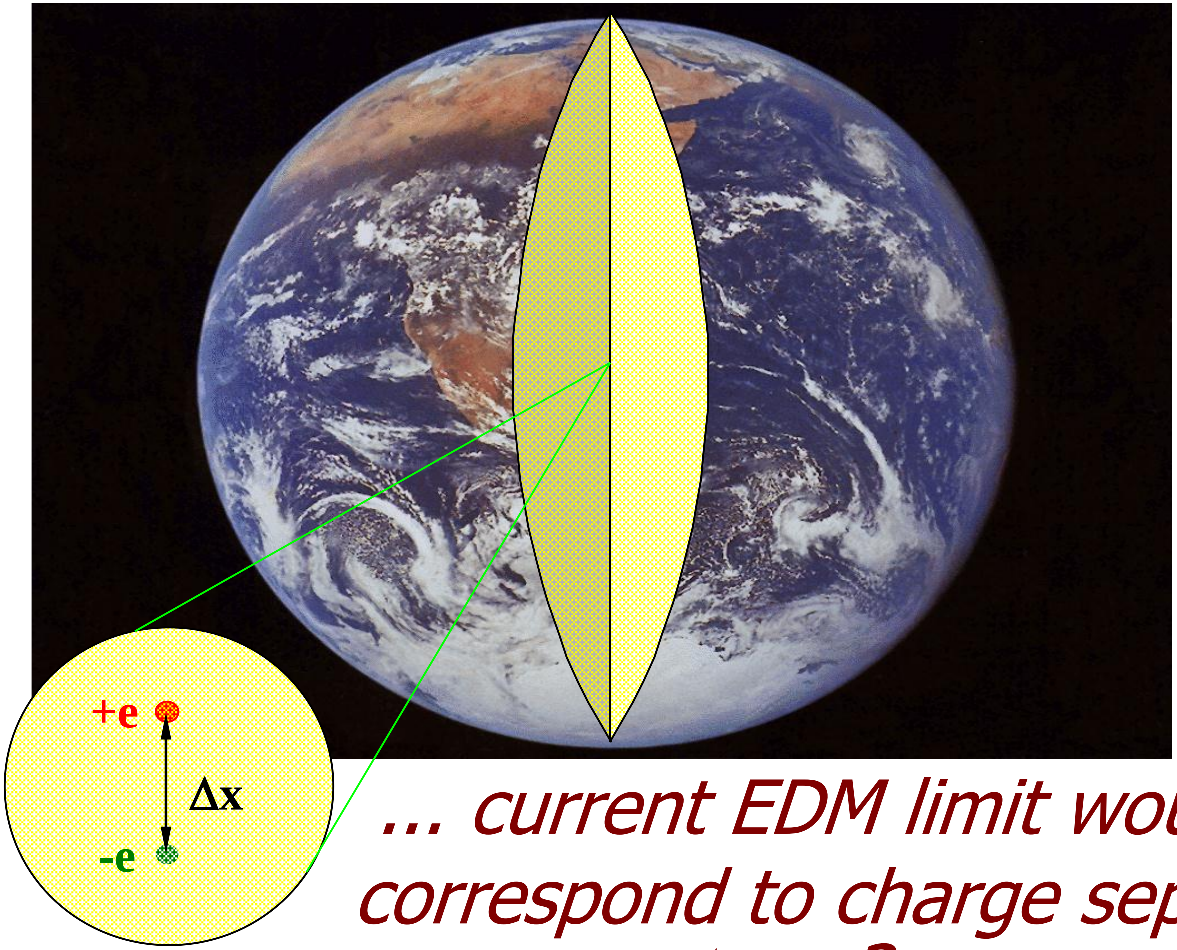
$$|d_n| < 2.9\times10^{-26}\ \mathrm{e.cm}\ (90\%\ \mathrm{C.L.})$$

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

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

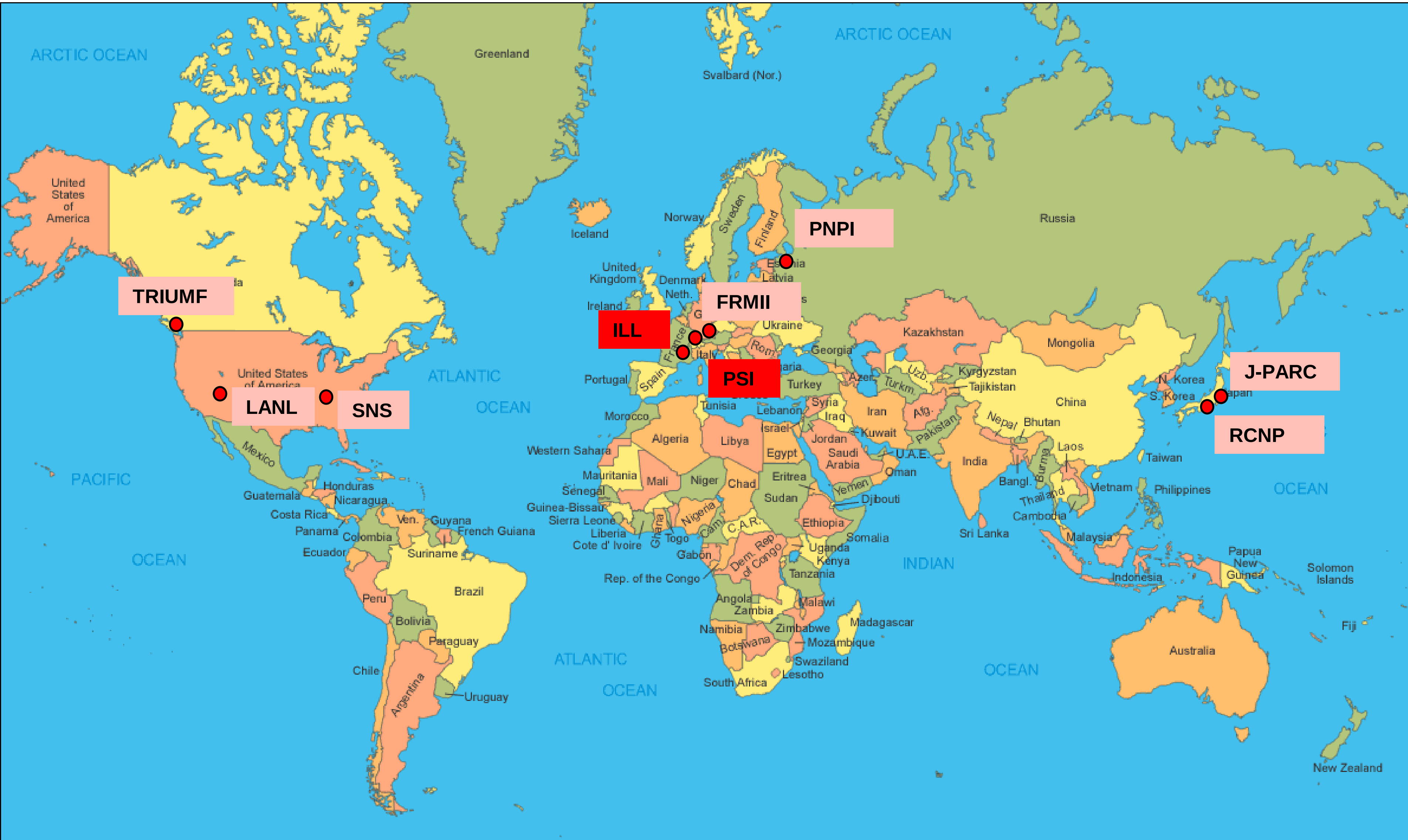
Reality check

If neutron were the size of the Earth...



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

Worldwide nEDM Searches



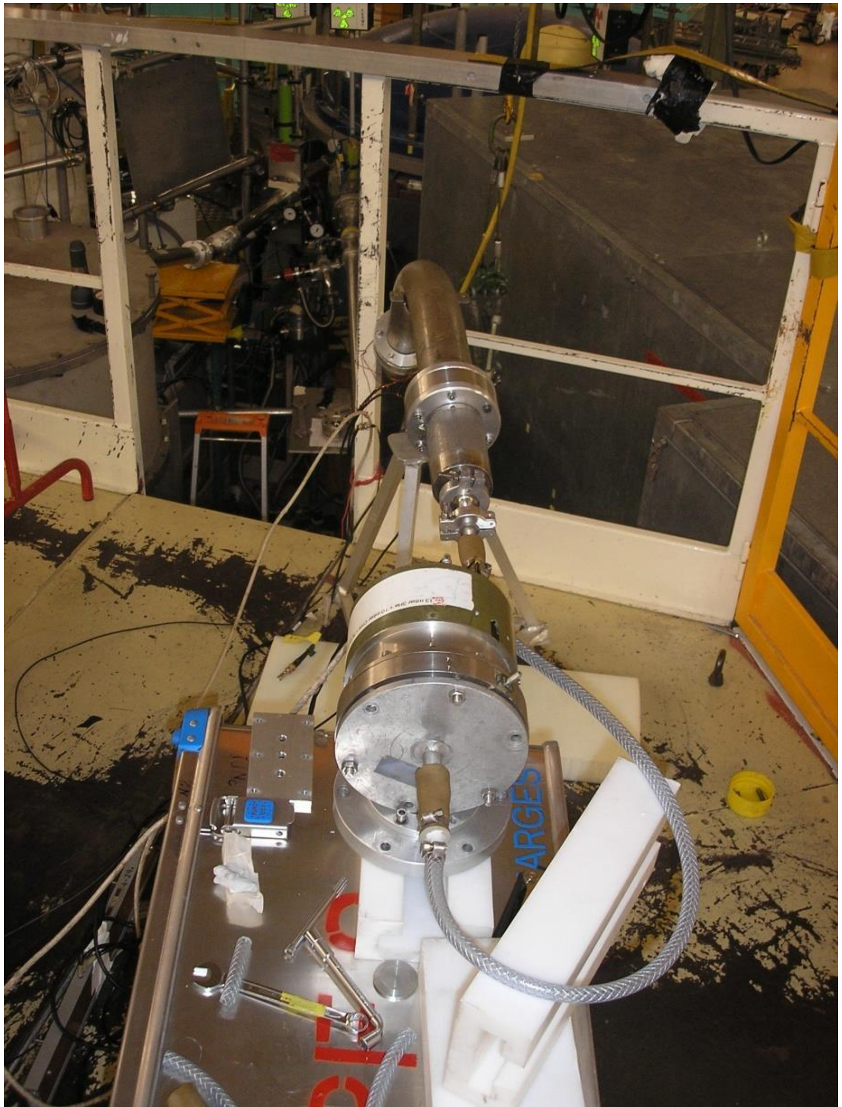

MACGYVER

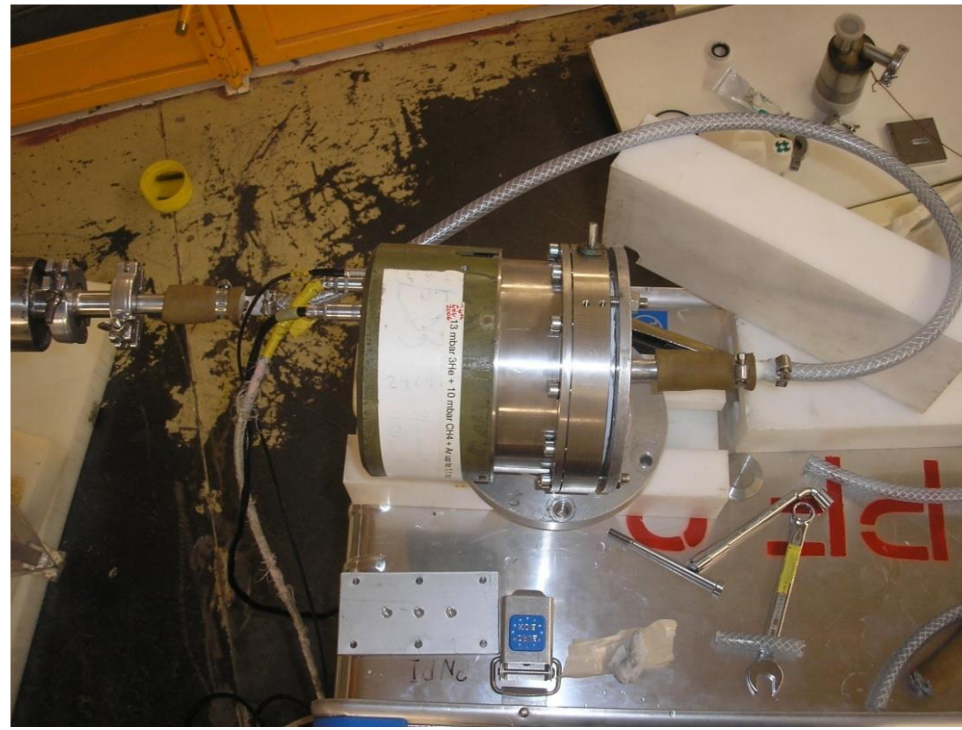

WHAT WOULD
MACGYVER DO?

UCN are always good for a surprise!

Transmission through flexible water hose

Yu. Panin et al., RRC KI Moscow

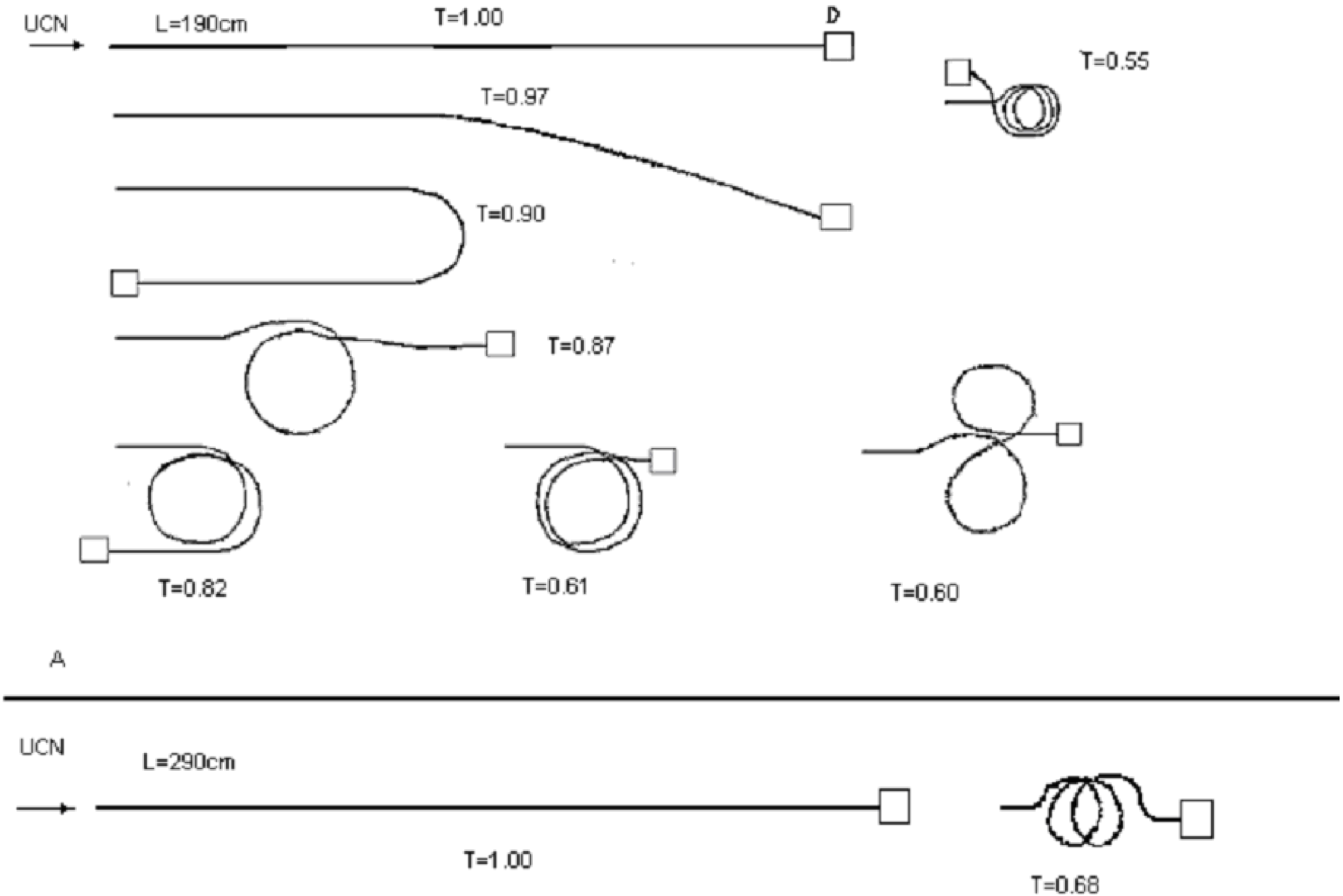




Surprising result
(80 cm hose with 8 mm inner diameter)

transmission around 85%

Relative Transmission Probability of "fancy guides"

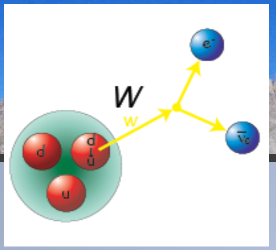


Top view:

- 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: $n \to p + e^- + \overline{\nu}_e$ (+782 keV)



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

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

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

Together with measurements of *asymmetry coefficients* in neutron decay

Extraction of $g_{V,}$ g_A and V_{ud}

Weak interaction theory

Neutrino physics

Cosmology

Neutrino induced reactions:

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

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

Neutrino detectors:

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

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

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

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

Solar pp-process:

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

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

Measurements of the neutron lifetime τ_n

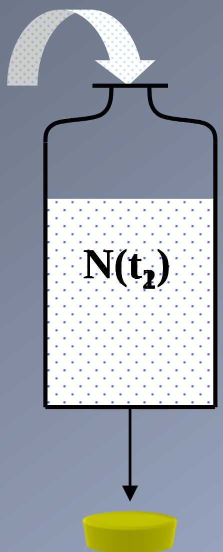
exponential decay law: $N = N_0 e^{-\lambda t}$

or, ultimately, measure the exponential decay directly

Storage experiments with UCN

"counting the surviving neutrons"

"UCN bottle"



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

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \underbrace{\frac{1}{\tau_{wall}}}_{} + \underbrace{\frac{1}{\tau_{leak}} + \frac{1}{\tau_{vacuum}} + \ldots}_{\to 0 \text{ (experiment)}}$$

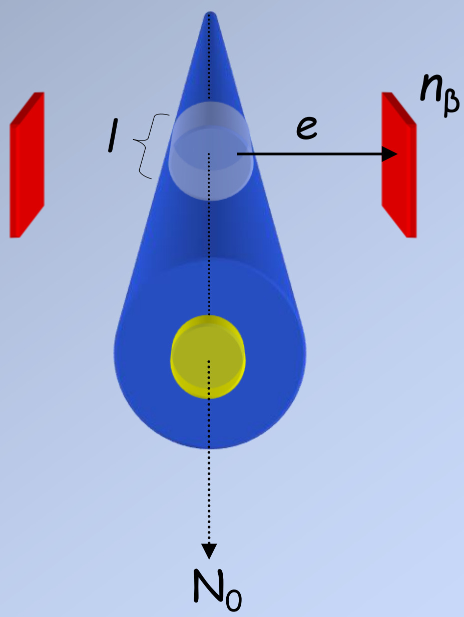
$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff} \to 0 \text{ (extrapolation)}$$

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

Two relative measurements

Beam experiments with cold neutrons

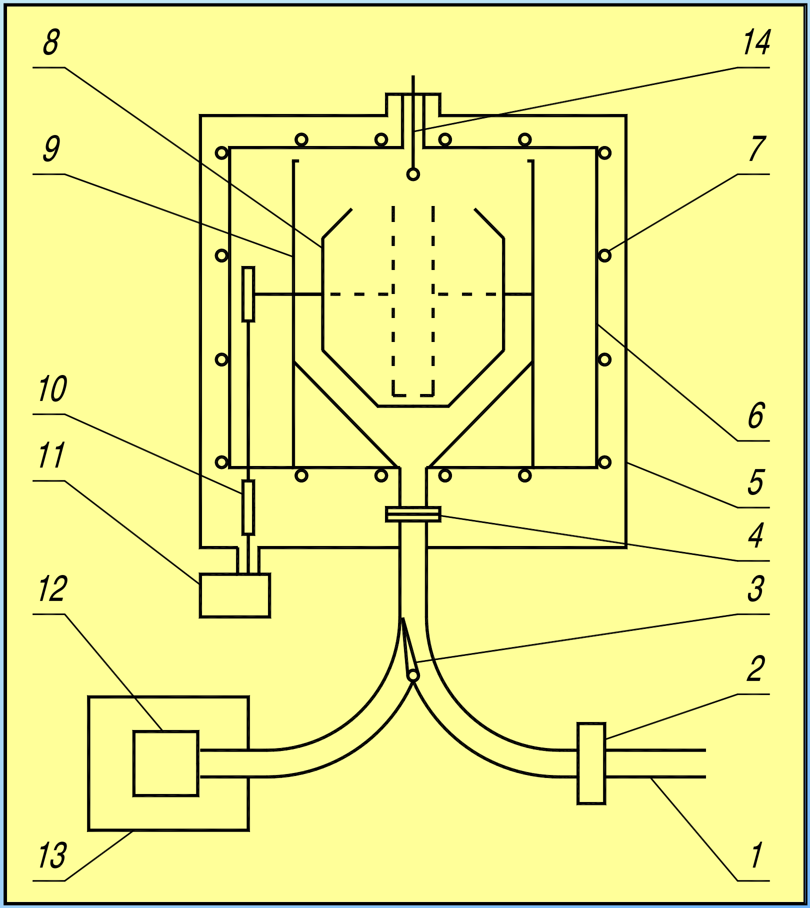
"counting the dead neutrons"



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

Two absolute measurements

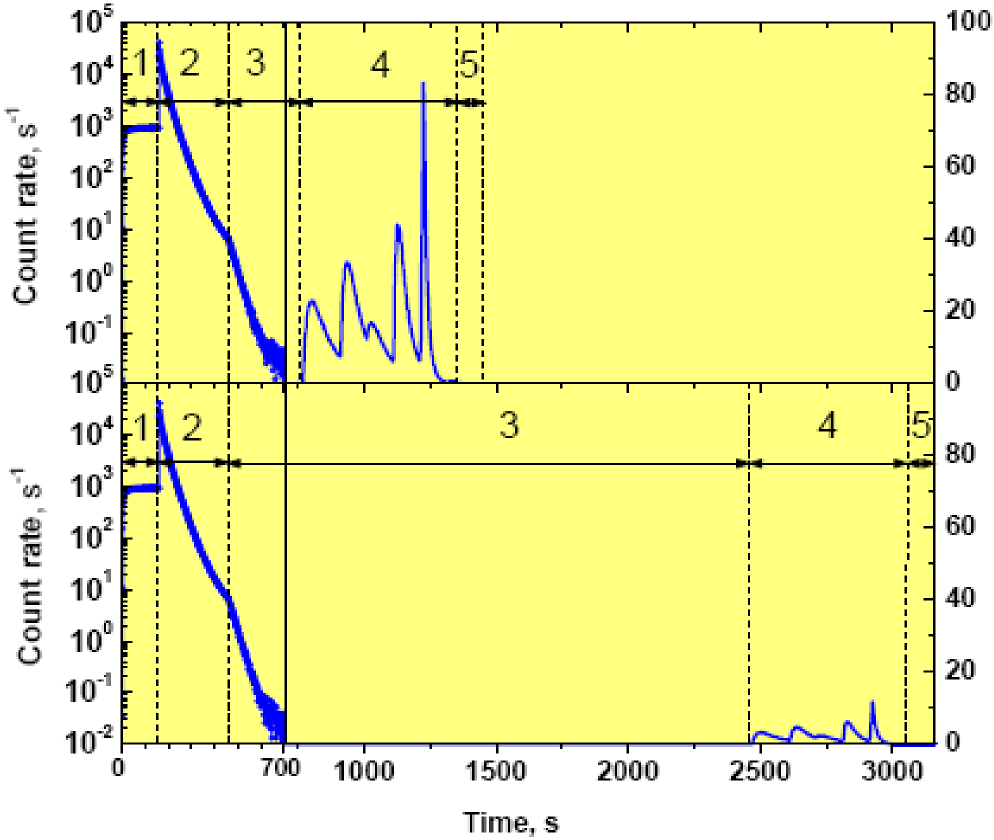
Scheme of "Gravitrap", the gravitational UCN storage system



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

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.

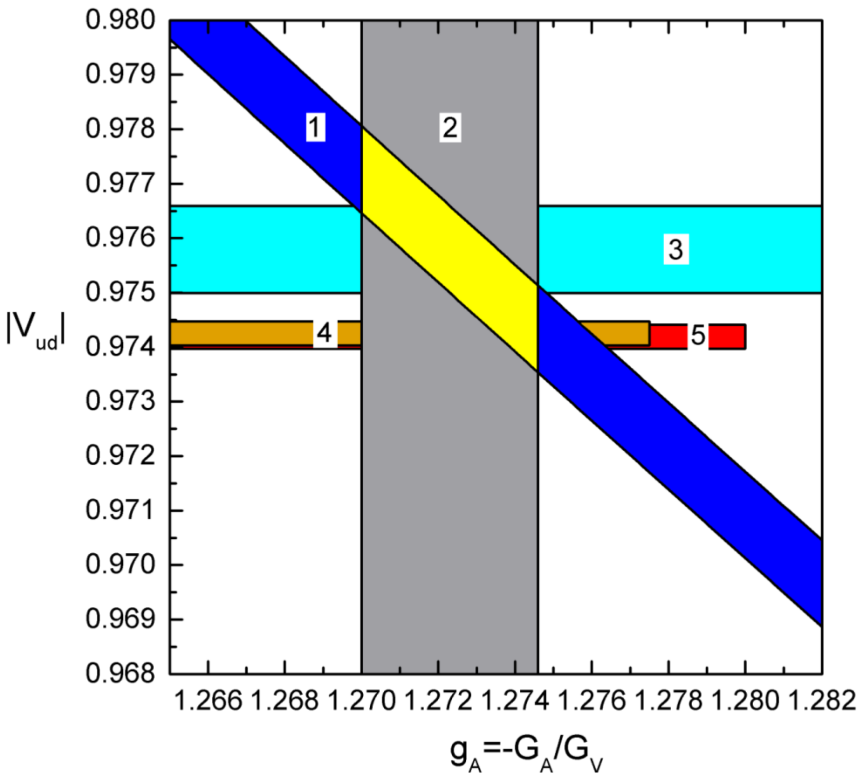
$$N(t_2) = N(t_1) \cdot \exp\left(-\frac{t - t_1}{\tau_{st}}\right)$$

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

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

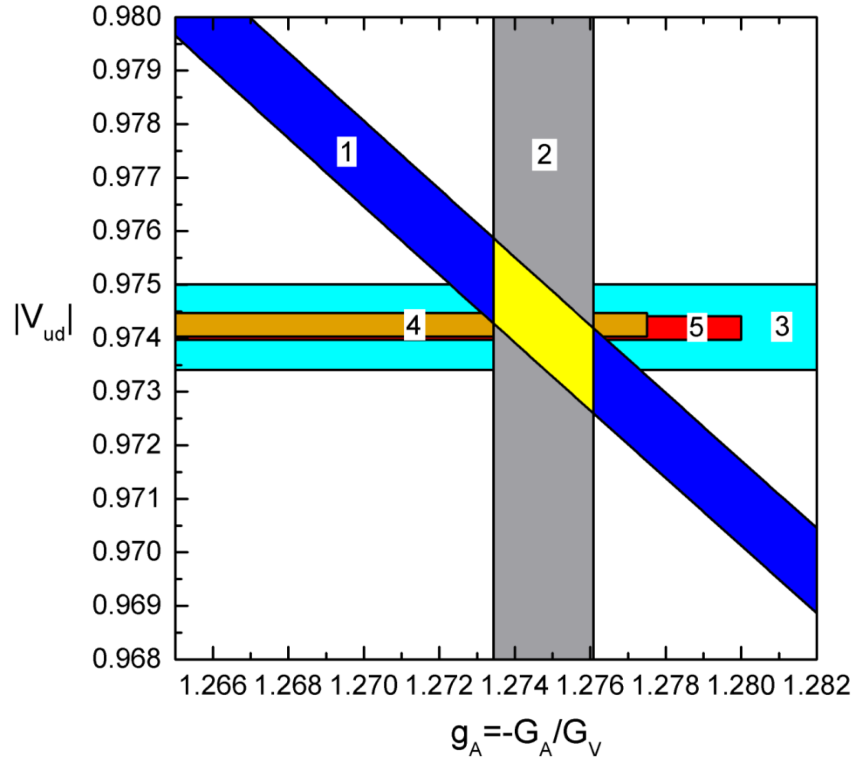
Test for Standard Model

PDG data



Dependence of the CKM matrix element $|V_{ud}|$ on the values of the neutron lifetime and the axial coupling constant g_A. (1) neutron lifetime, PDG 2015; (2) neutron β-asymmetry, PDG 2015; (3) neutron β-decay, PDG 2015; (4) unitarity; (5) $0^+ \rightarrow 0^+$ nuclear transitions.

The best accuracy data



Dependence of the CKM matrix element $|V_{ud}|$ on the values of the neutron lifetime and the axial coupling constant g_A. (1) neutron lifetime, PDG 2015; (2) neutron β-asymmetry, PERKEO II; (3) neutron β-decay, PDG 2015 + PERKEO II; (4) unitarity; (5) $0^+ \rightarrow 0^+$ nuclear transitions.

Does the neutron lifetime depend on the measuring method?

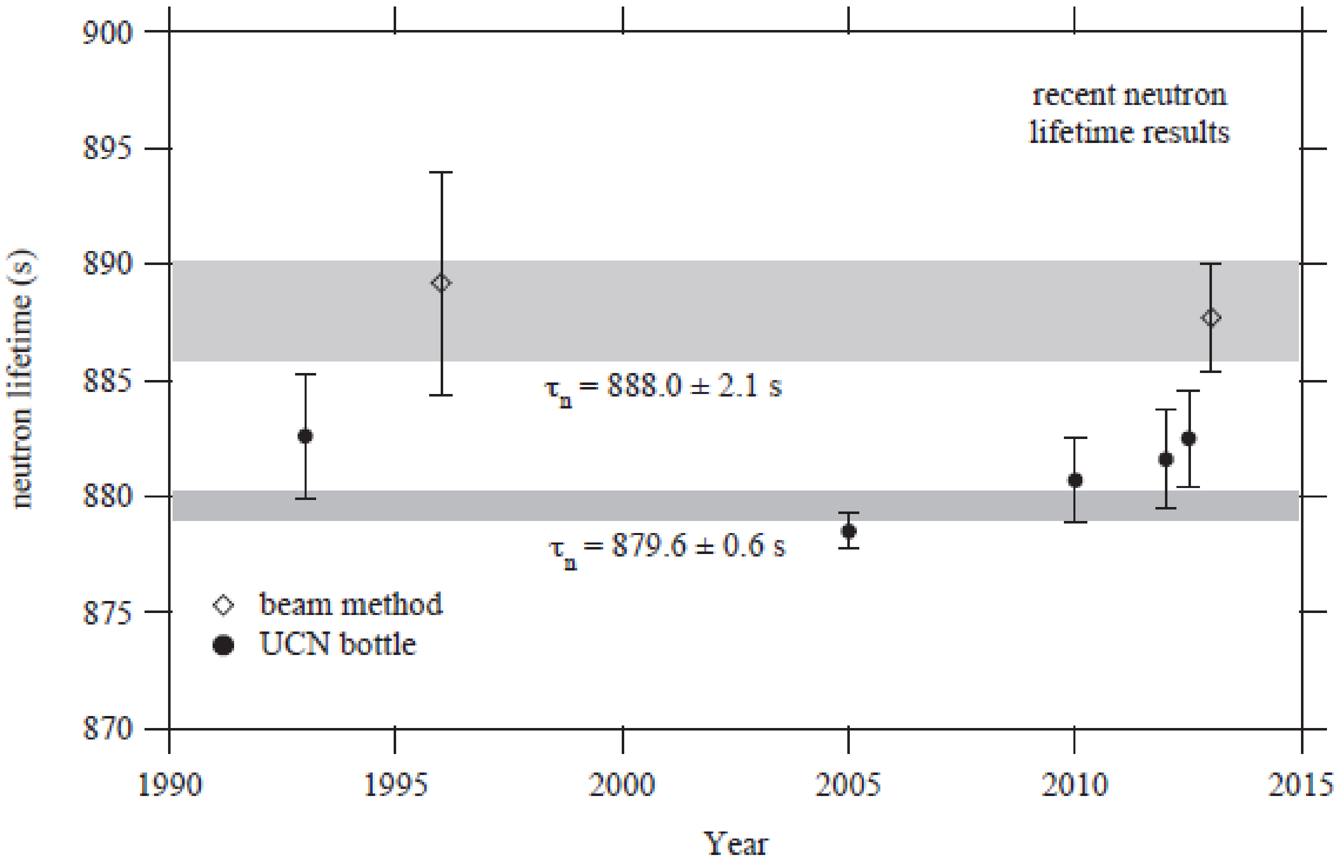
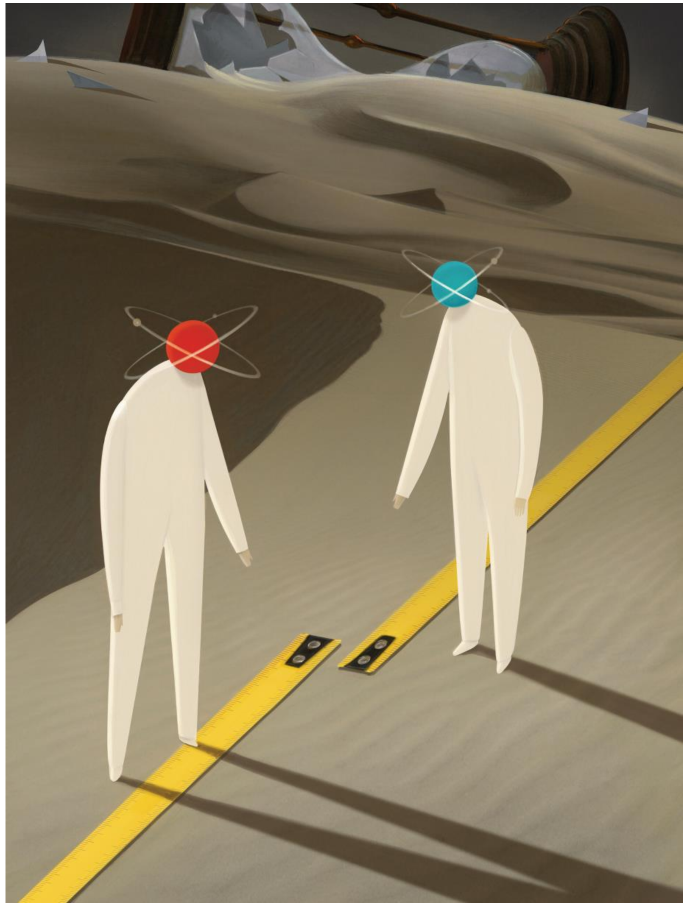
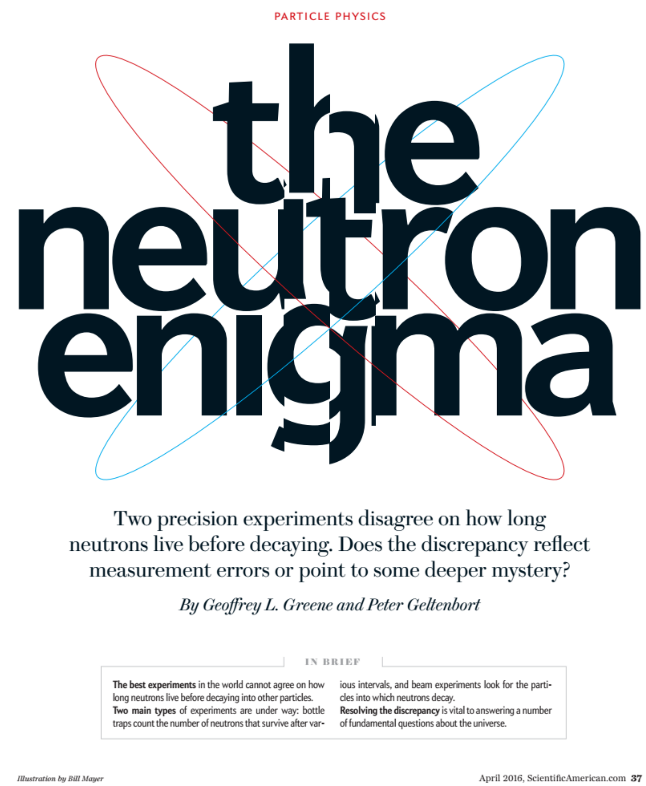


Figure 2: A summary of recent neutron lifetime measurements, showing the five UCN bottle [18, 16, 19, 20, 21] and two neutron beam [12, 15] results used in the 2014 PDG recommended value of $\tau_n = 880.3 \pm 1.1$ s. The shaded regions show the weighted average $\pm 1\sigma$ of each method, which disagree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

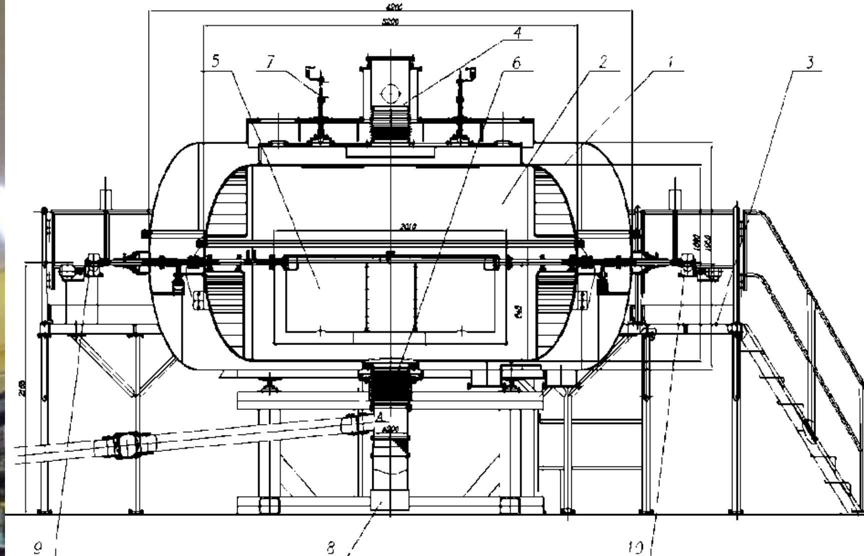
Russia, Poland, Israel, …

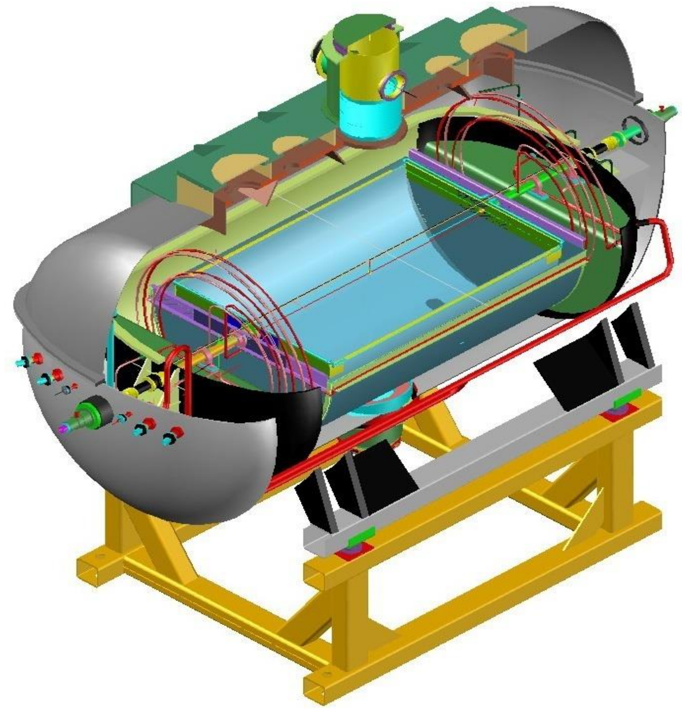
谜样的9秒：测不准的中子寿命

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

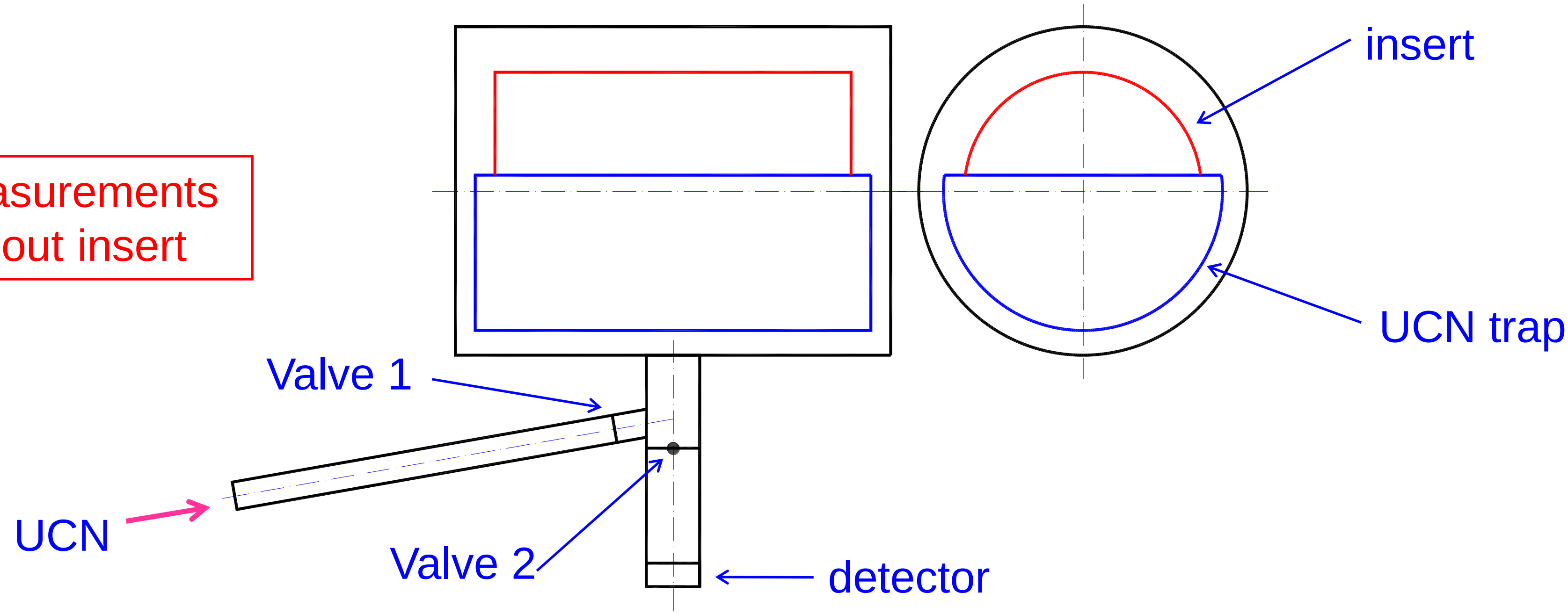
New setup - ***Big Gravitational Trap***



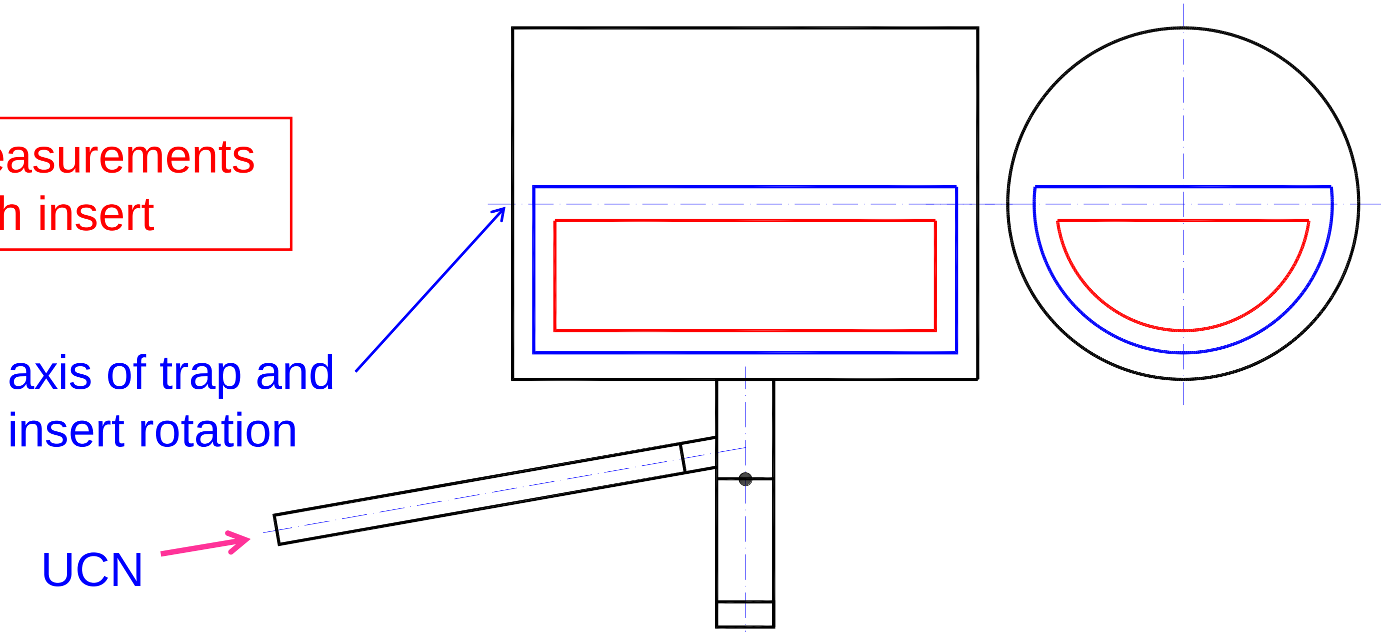


Scheme of Big Gravitational Trap

measurements without insert



measurements with insert



Method of neutron lifetime determination

$$\tau_1^{-1} = \tau_n^{-1} + \eta\gamma_1$$

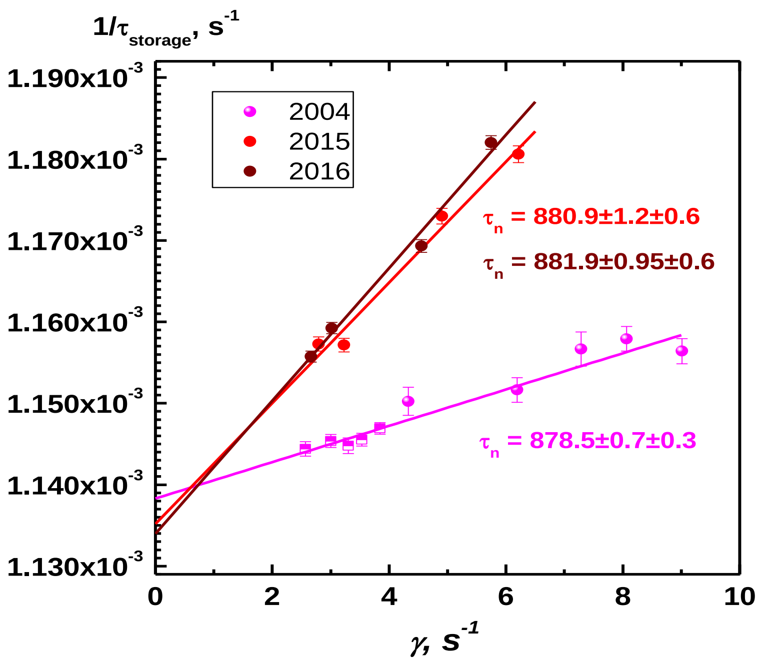
$$\tau_2^{-1} = \tau_n^{-1} + \eta\gamma_2$$

$$\tau_n^{-1} = (\tau_1^{-1} + \tau_2^{-1})/2 - \eta(\gamma_1 + \gamma_2)/2$$

$$\eta = (\tau_1^{-1} - \tau_2^{-1})/(\gamma_1 - \gamma_2)$$

We can measure two different storage times (τ_1, τ_2) correspondent to two different collisions frequencies (γ_1 , γ_2)

The lifetime of a free neutron (τ_n) is determined by the extrapolation to an infinite trap size with zero collision frequency.



The probability of UCN losses for one collision (η) can also be experimentally determined. However, the collision frequencies (γ_1 , γ_2) of UCNs with the surfaces have to be calculated by Monte Carlo simulations.

The Big Gravitational Trap

with Fomblin grease coating at liquid nitrogen temperature

Results of neutron lifetime measurements :

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

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

Worldwide nLifetime Searches

Neutrons in the gravity field

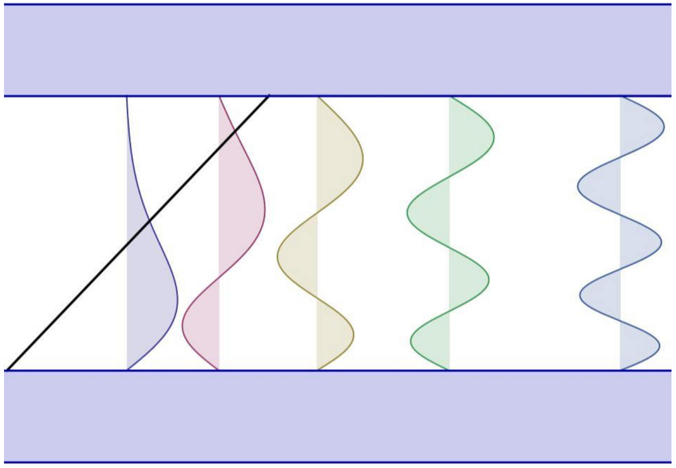
- Schrödinger eq. with linearized gravity potential

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

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

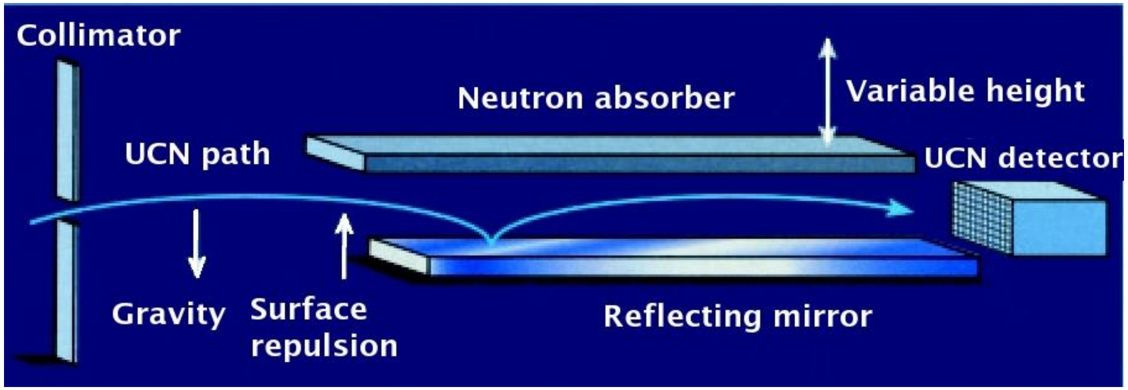


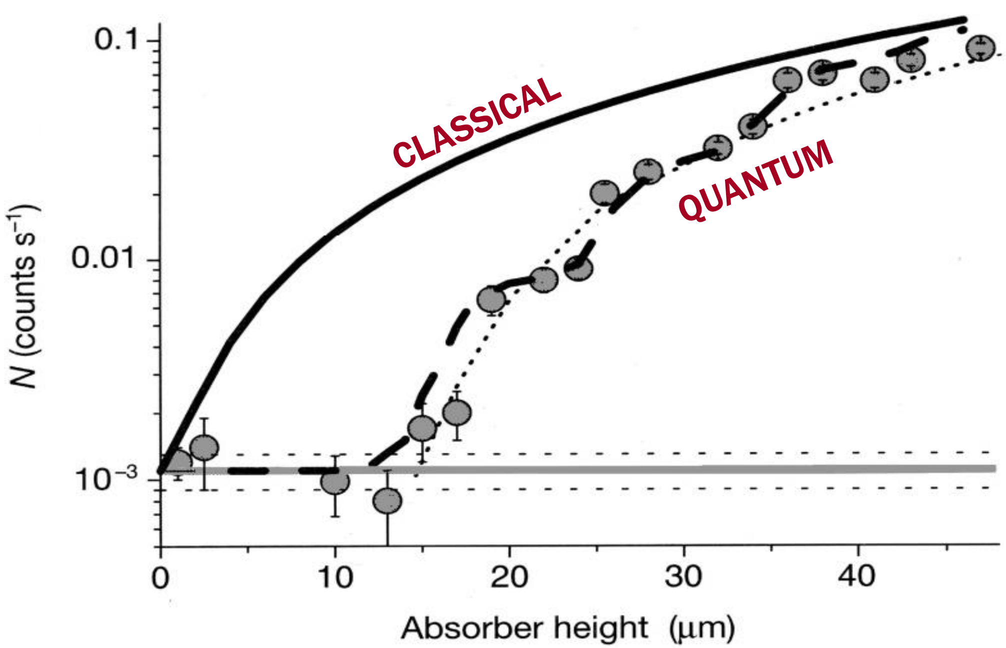
state	energy
1	1.41 peV
2	2.56 peV
3	3.98 peV

Slit width l=27 µm

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

quantum bouncing ultracold neutron precision experiment

Gravity at short distances (µm)

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

UCN

Quantum Mechanics

- quantum interference
  phases
- highly sensitive methods:
  resonance spectroscopy

$$E = h\nu$$

Experimental Gravity & Cosmology:

- Large extra dimensions
- Cosmological Constant
- spin-dependent new interactions (ALP)
- dark energy models (chameleon fields)

Gravity & Quantum Physics

- WEP test in quantum regime
- COW discrepancy
- Quantum transport phenomena

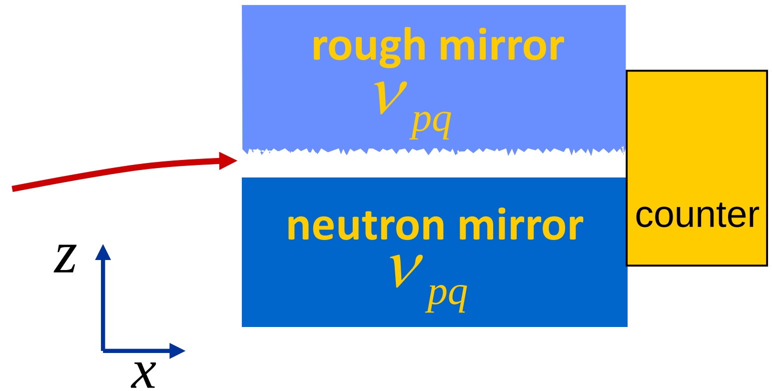
(Neutron physics) technologies

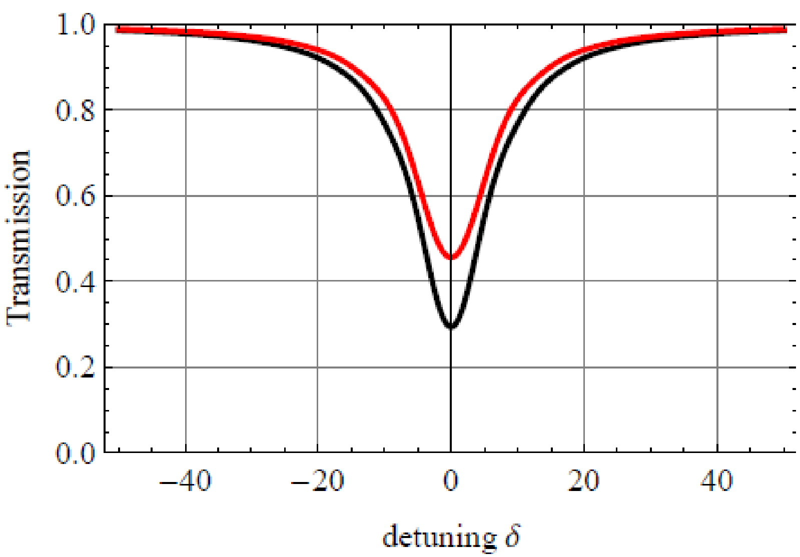
- UCN detector physics
- Neutron optics & materials
- Vibration analysis
- Micro- and nanopositioning

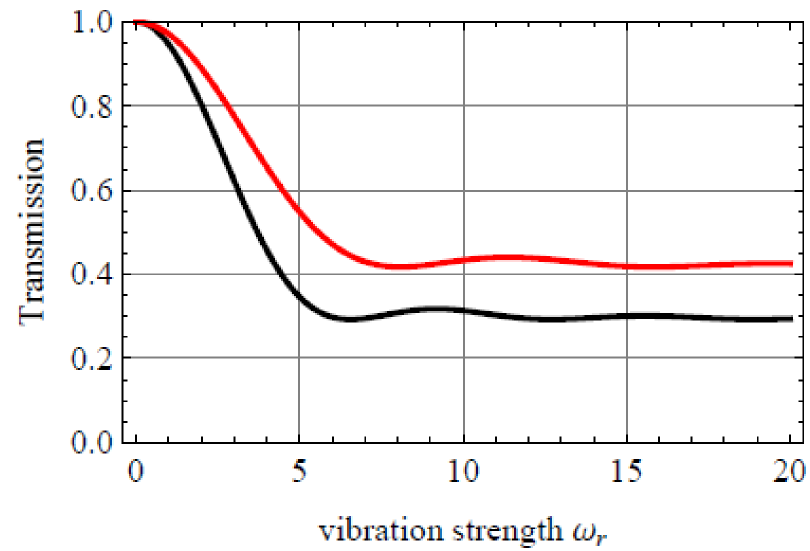
7

Concept of a Simplified Rabi Setup

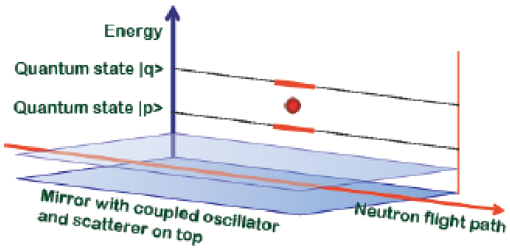
- minimal number of parameters:
  - slit width l
  - state-dep. lifetimes τ_n
  - (complex) coefficients c_n
  - time of flight t $(f[t])$
  - oscillation:
    - frequency ν
    - amplitude A
    - phase ν_0
- measure:
  - transmission $N \cdot |\psi|^2$







Gravity Resonance Spectroscopy



nature physics
LETTERS
PUBLISHED ONLINE: 17 APRIL 2011 | DOI: 10.1038/NPHYS1970

Realization of a gravity-resonance-spectroscopy technique

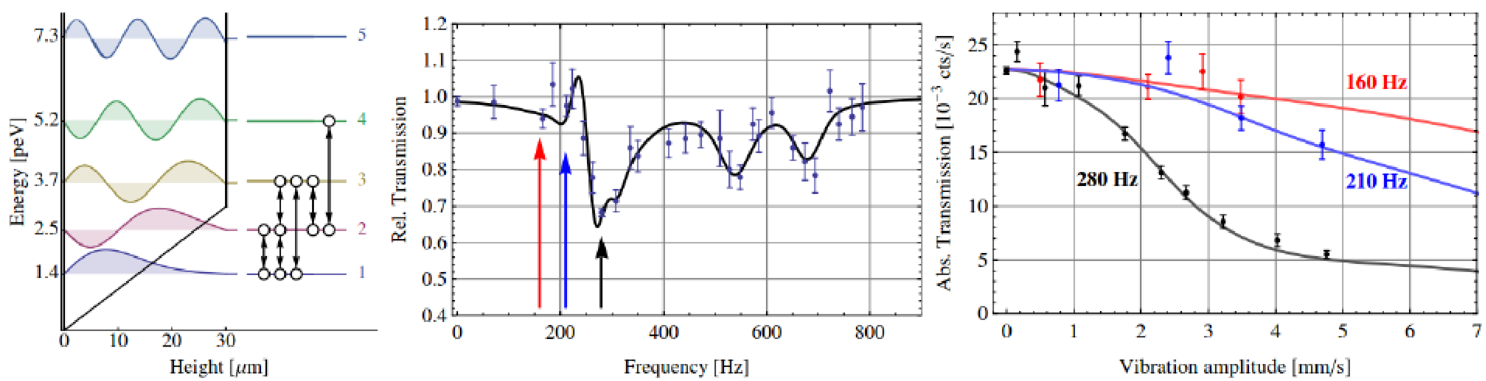
Tobias Jenke[1], Peter Geltenbort[2], Hartmut Lemmel[1,2] and Hartmut Abele[1,3,4]*

Selected for a Viewpoint in *Physics*
PRL 112, 151105 (2014) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2014

Gravity Resonance Spectroscopy Constrains Dark Energy and Dark Matter Scenarios

T. Jenke,[1,*] G. Cronenberg,[1] J. Burgdörfer,[2] L. A. Chizhova,[2] P. Geltenbort,[3] A. N. Ivanov,[1] T. Lauer,[4] T. Lins,[1,†] S. Rotter,[2] H. Saul,[1,‡] U. Schmidt,[5] and H. Abele[1,§]
[1]*Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Wien, Austria*
[2]*Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria*
[3]*Institut Laue-Langevin, BP 156, 6 Rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
[4]*FRM II, Technische Universität München, Lichtenbergstraße 1, 85748 Garching, Germany*
[5]*Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*
(Received 26 November 2013; published 16 April 2014)

- first-time realization in 2009
- precision measurements in 2010 & 2011
- output:
  - experimental limits on Non-Newtonian gravity
  - study of rough surfaces
    (quantum transport phenomena)



Tobias Jenke, Atominstitut TU Wien

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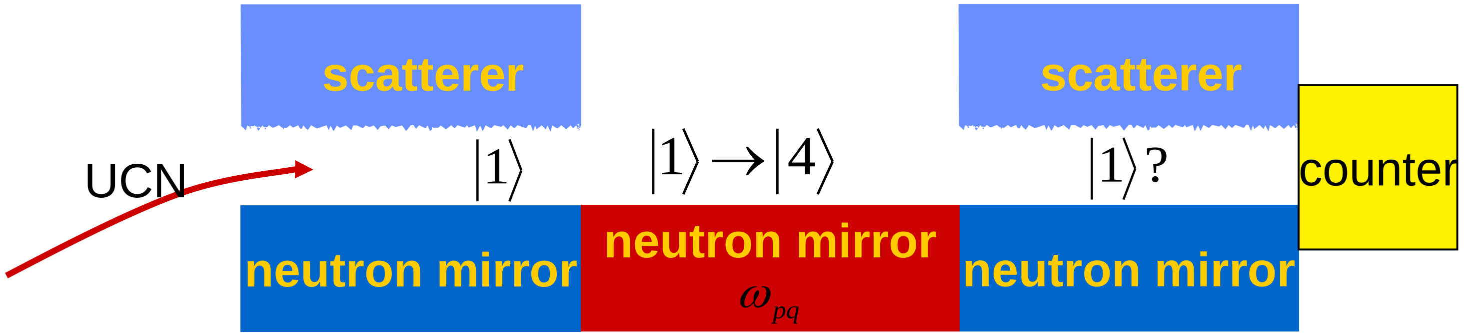
Gravity Resonance Spectroscopy (GRS)

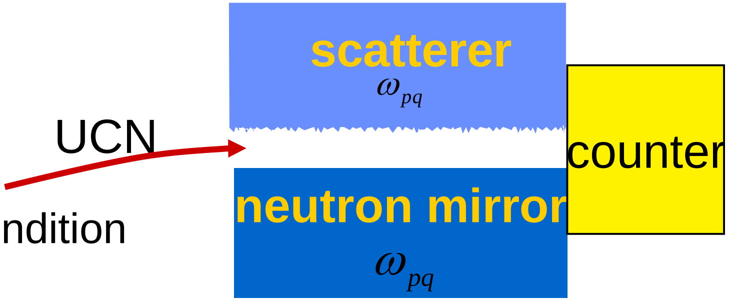
- **Rabi** setup (2012)

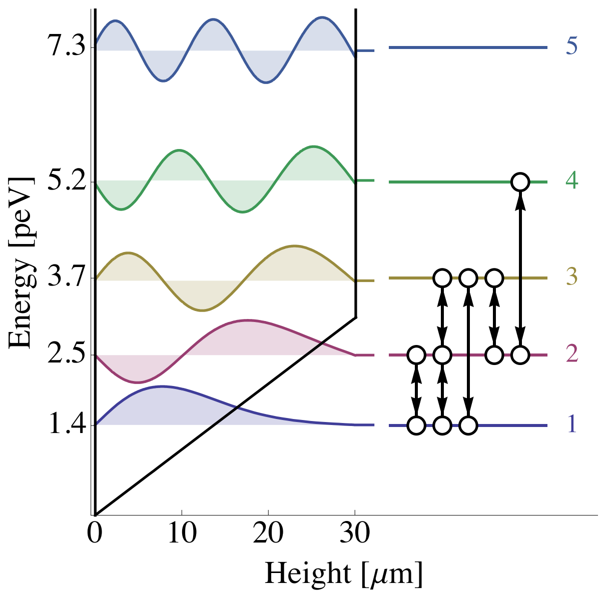


- First realisation (2009,2010)

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)

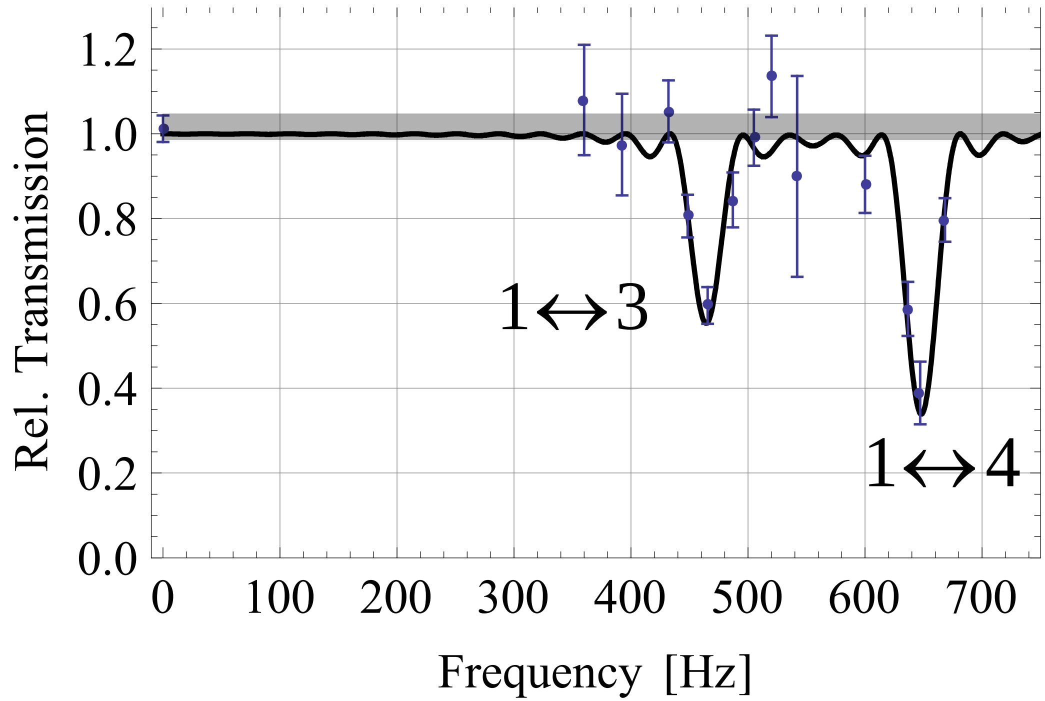
Results

Transitions 1-3 and 1-4 observed

1-3: (46 ± 5)% intensity drop

1-4: (61 ± 7)%

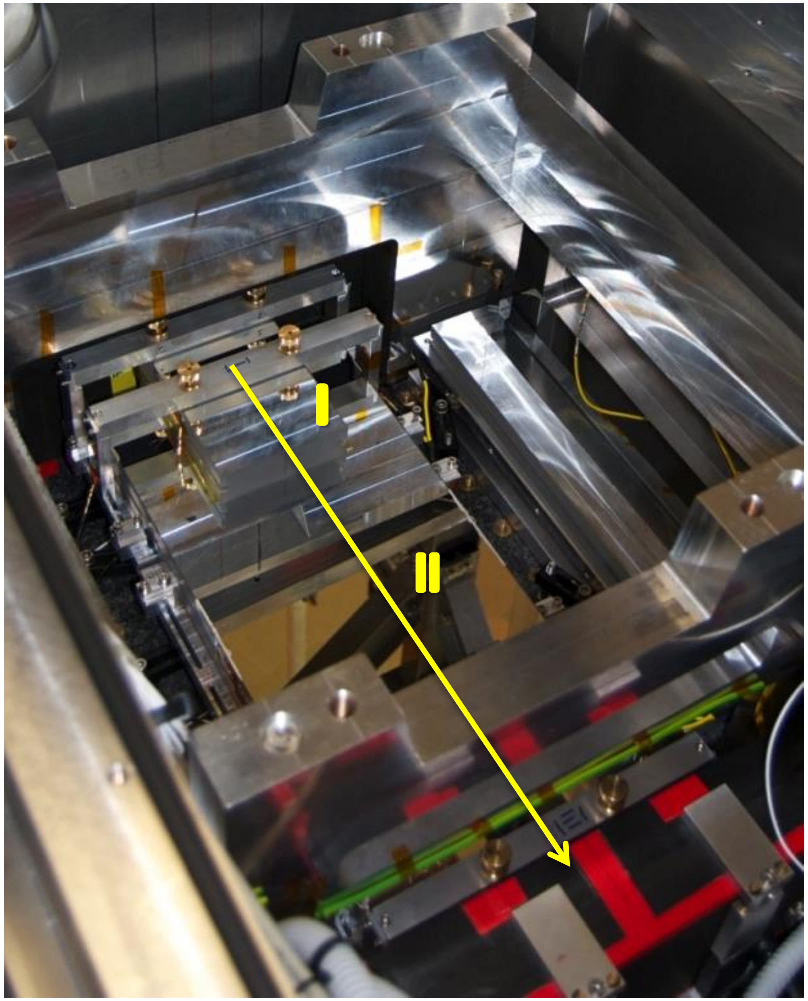
@ 2.1 mm/s

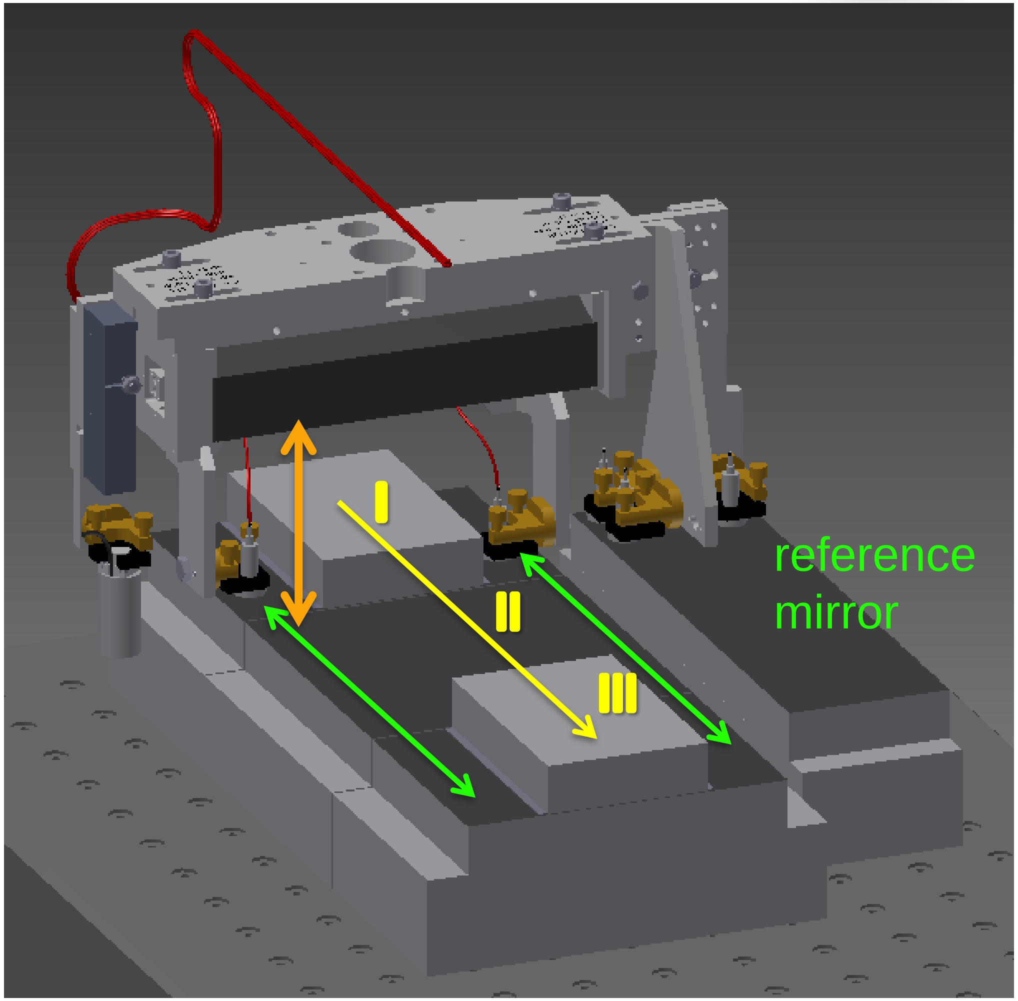


60 measurements

Preliminary, generic fit

Setup

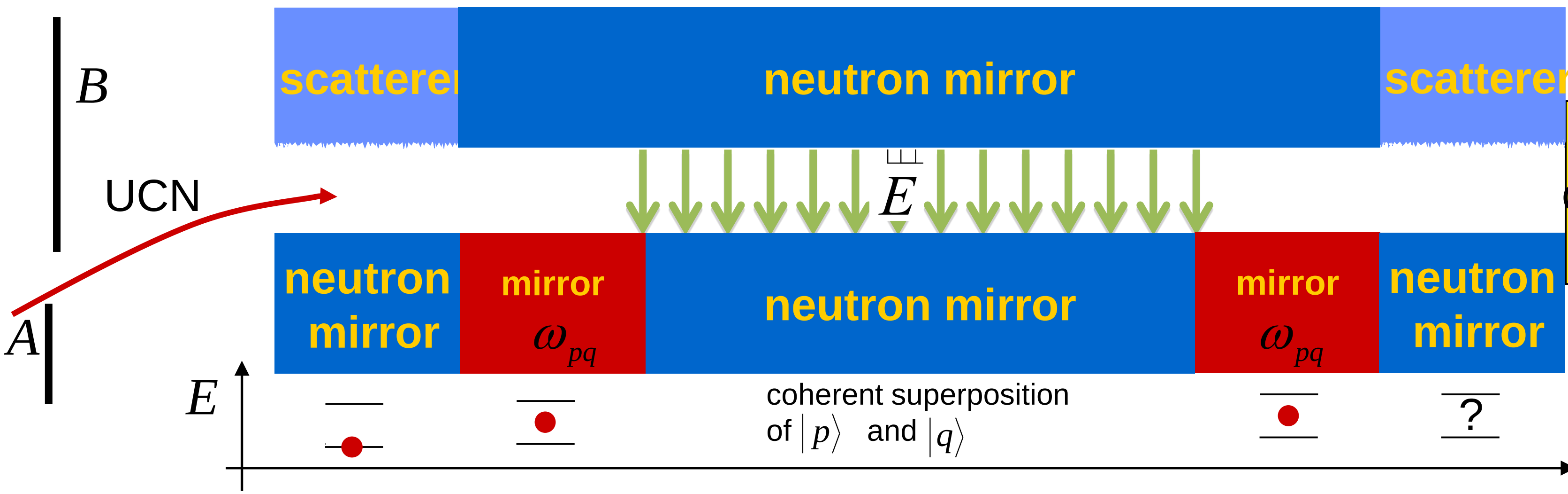




M. Horvath

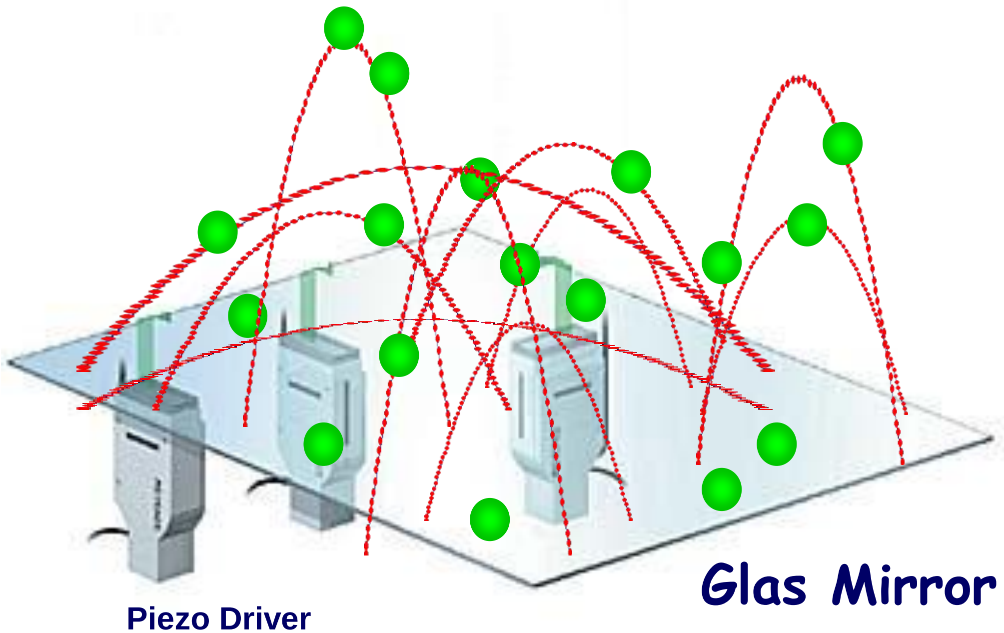
Outlook:
Probing neutrons neutrality

- Electric field modifies detectable phase



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

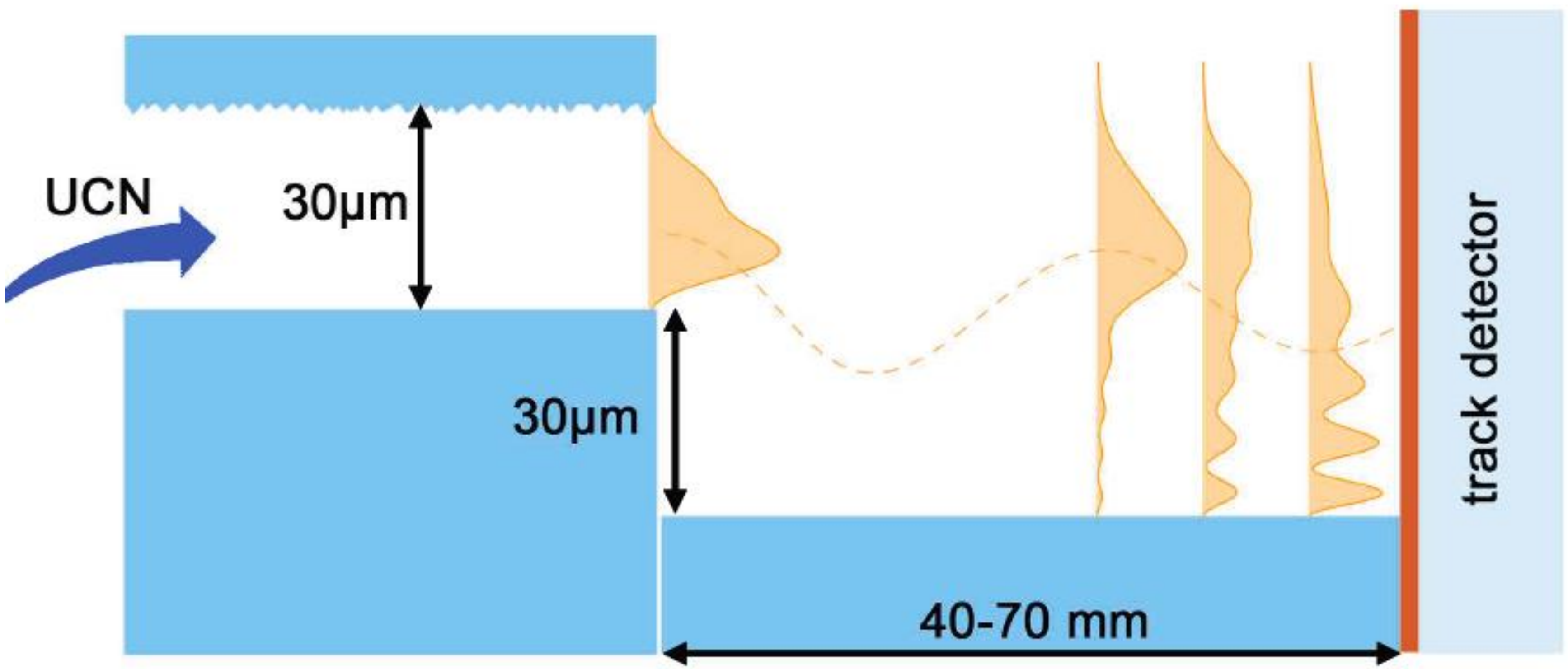
Realization of a Neutron Bouncing Ball Gravity Spectrometer



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

quantum bouncing ultracold neutrons

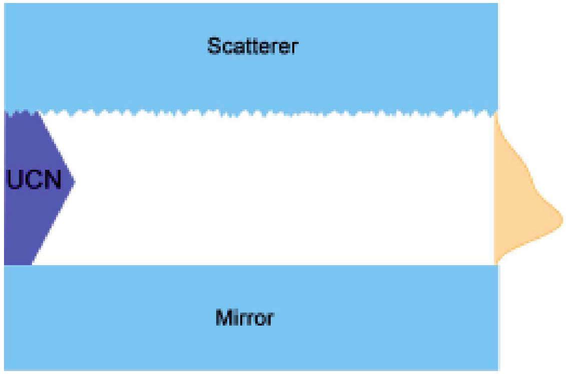
- State Selector
- Snapshots with spatial resolution detectors ~ 1.5 µm



L

Courtesy: M. Thalhammer

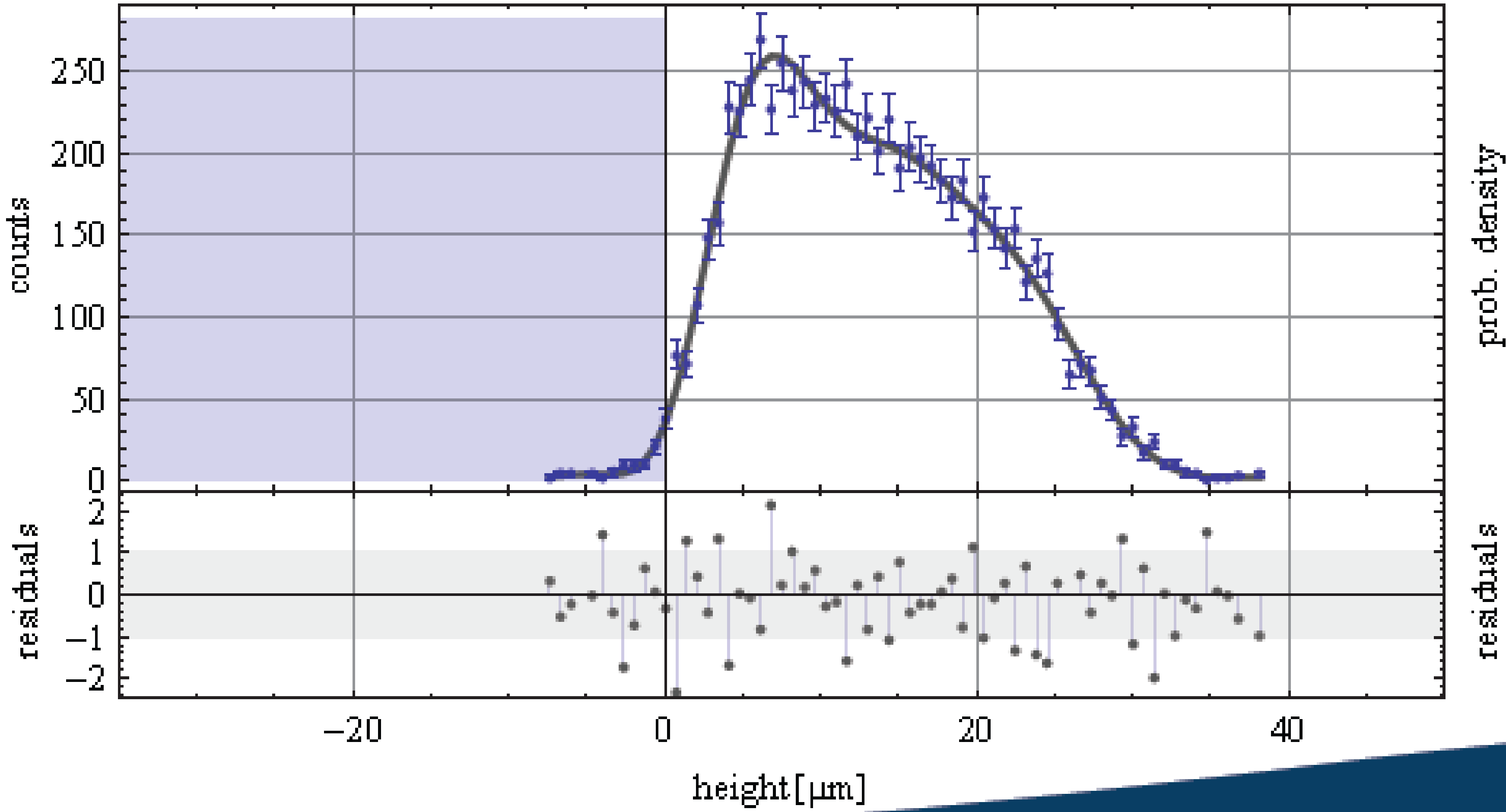
Preparation L = 0



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

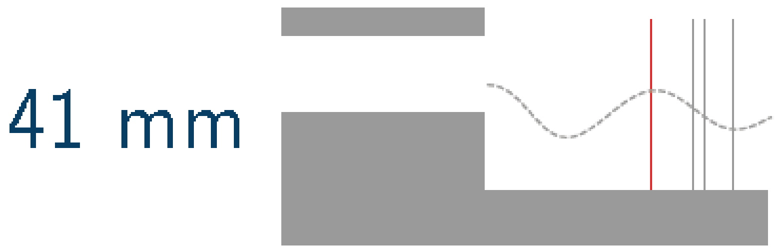
$$|c_1|^2 = 45\%$$
$$|c_2|^2 = 36\%$$
$$|c_3|^2 = 18\%$$

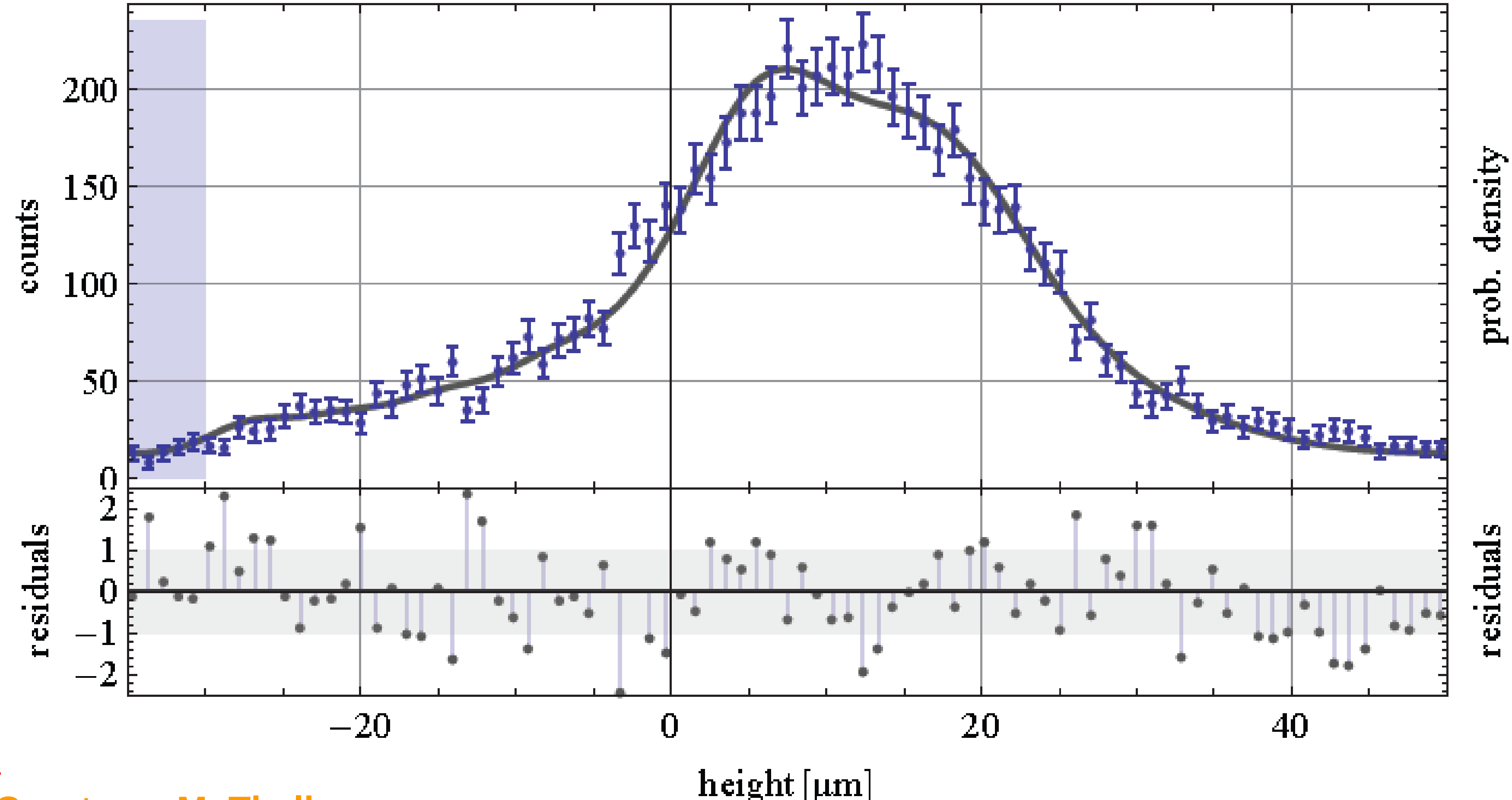
preliminary



Courtesy: M. Thalhammer

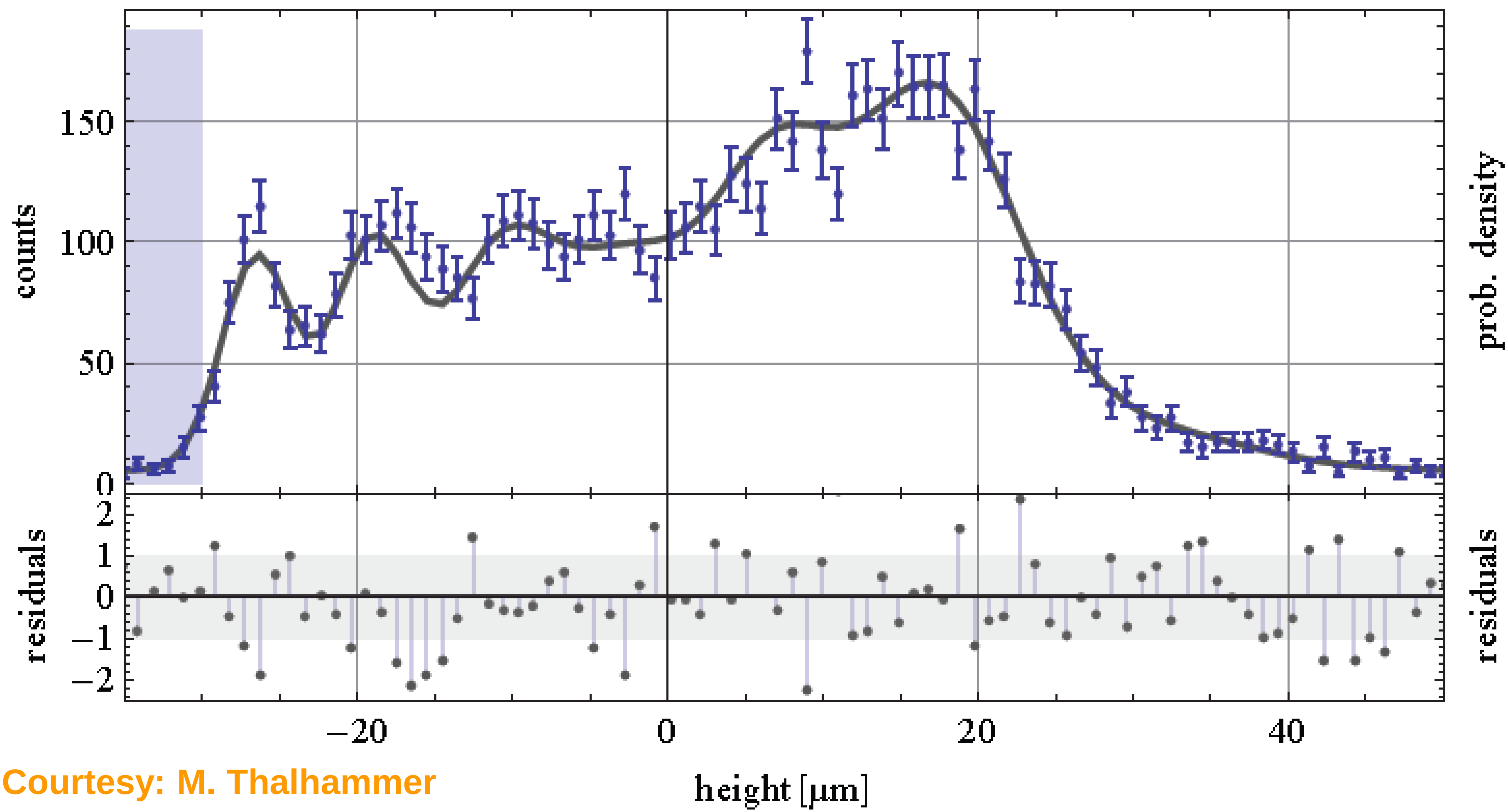
2nd bounce, 2nd turning point, L = 41 mm





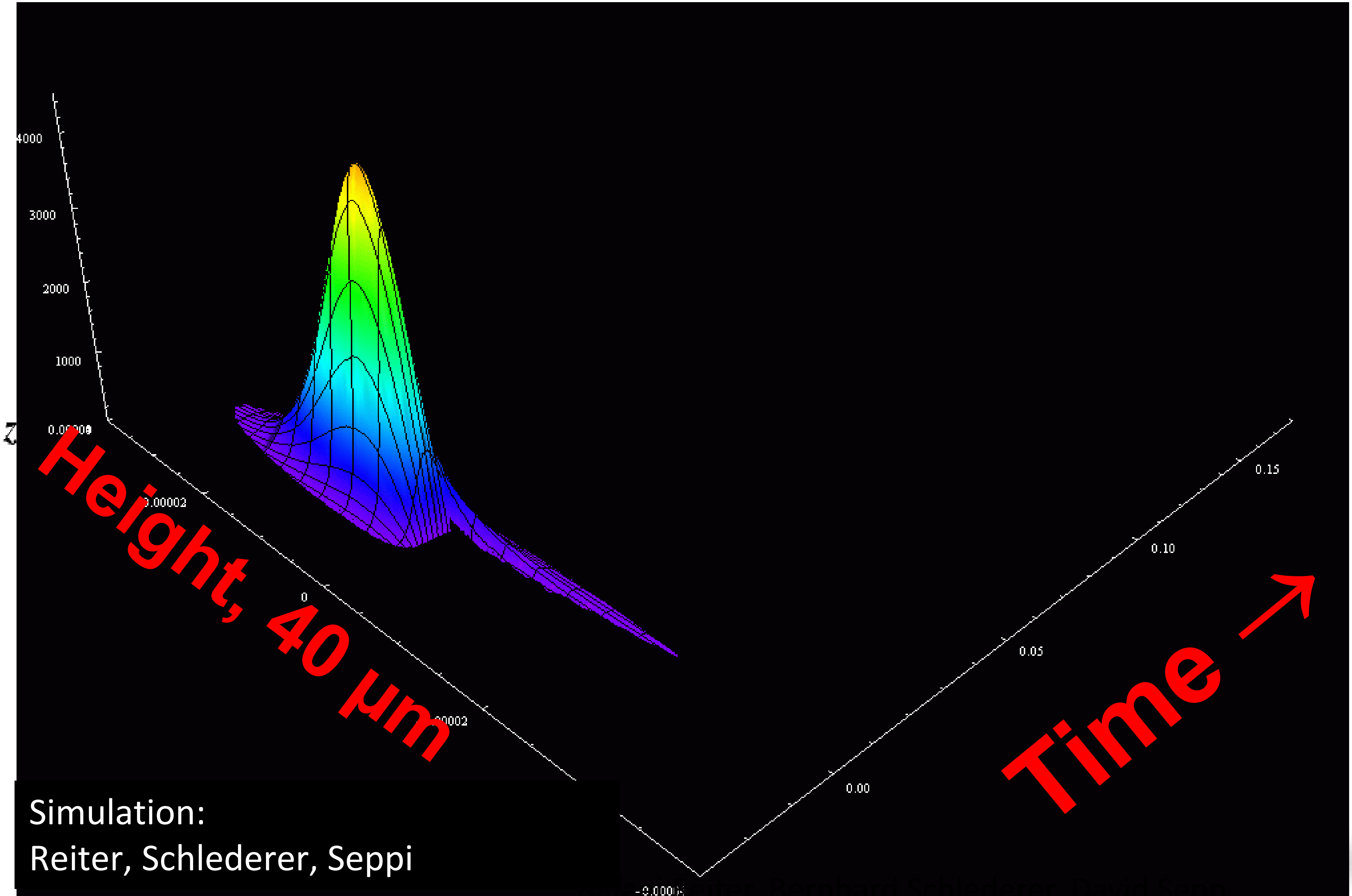
Courtesy: M. Thalhammer

Move downwards, L = 51 mm



Courtesy: M. Thalhammer

Show Case: qBOUNCE



Recent PF2 highlights in ILL's Annual Report

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 (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

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!