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 : ~ **8 300 km** (22 hours from door to door)

This is my **first ever** visit to China! Thanks for the invitation to give a plenary talk.

Setting the scene: Europe and France

- ● Grenoble, France
  2 650 km
- ● Dubna, Russia

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!

Xi'an: 8 700 000 (2015)
Metro: 12 900 000

Elevation: 405 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

Interstate treaty: 19 January 1967

Traité de l'Elysée: 22 January 1963

Louis Néel
1904 – 2000
Nobel Prize 1970
Antiferromagnetism

Heinz Maier-Leibnitz
1911 – 2000

Ideas become concrete

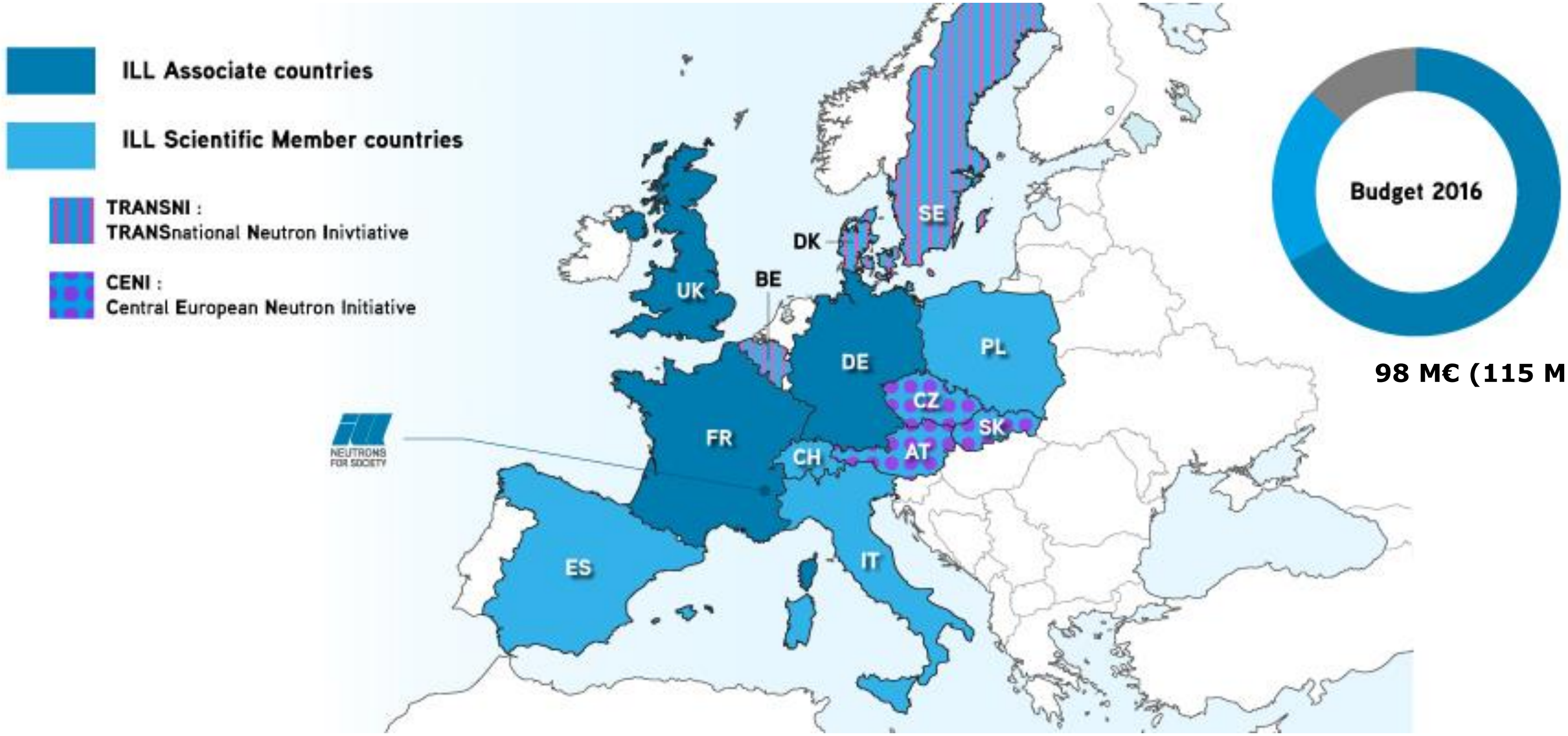
- Reactor first critical in 1971
- Operational for researchers (user service) in 1972 – 58 MW
- UK joined in 1973

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$)

KEY FIGURES ABOUT THE ILL

1400 users from an active community of 12 000 scientists

850 experiments/year

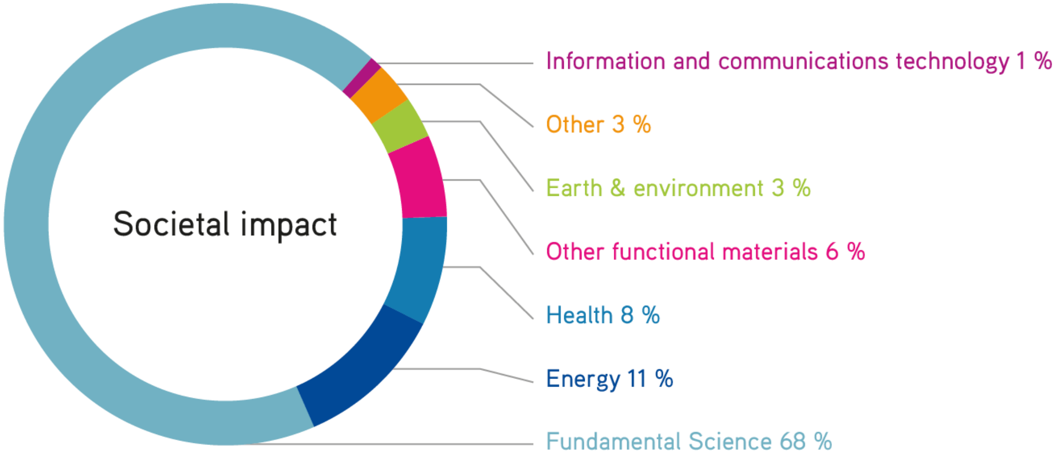
600 publications/year

>21000 pubs since 1973

38 countries

28 instruments + 10 CRG

4 cycles of 50 days/year



European Photon and Neutron (EPN) Science Campus

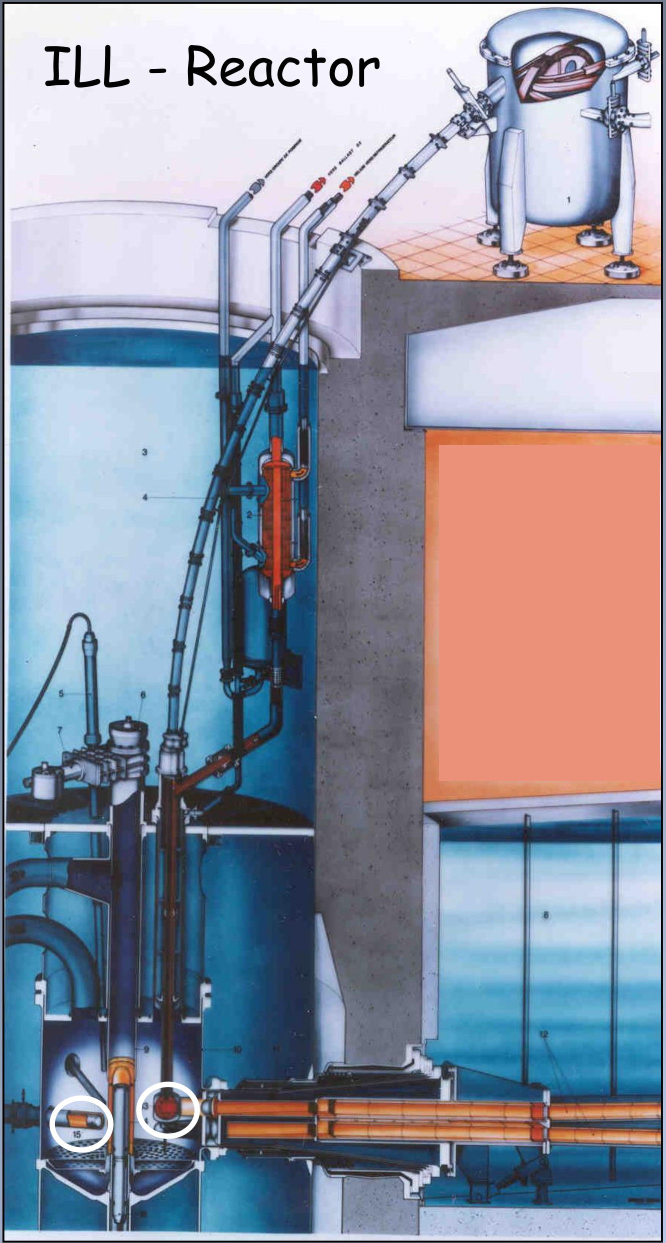
Institut Laue-Langevin (ILL) operates the most intense (reactor) neutron source in the world, feeding a suite of 40 high-performance instruments

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



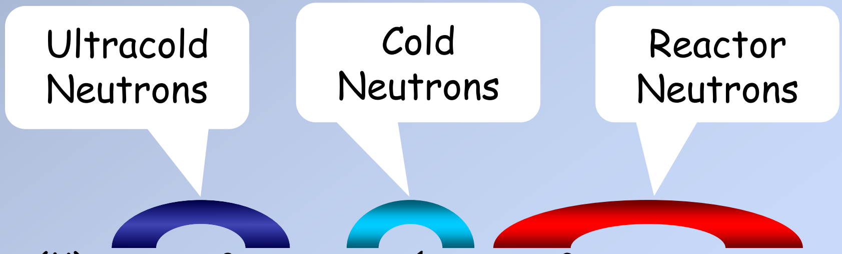
Fuel (chain reaction): $^{235}U(n_{th},f)$ → fission neutrons

Moderator: D_2O at 300K → thermal neutrons

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

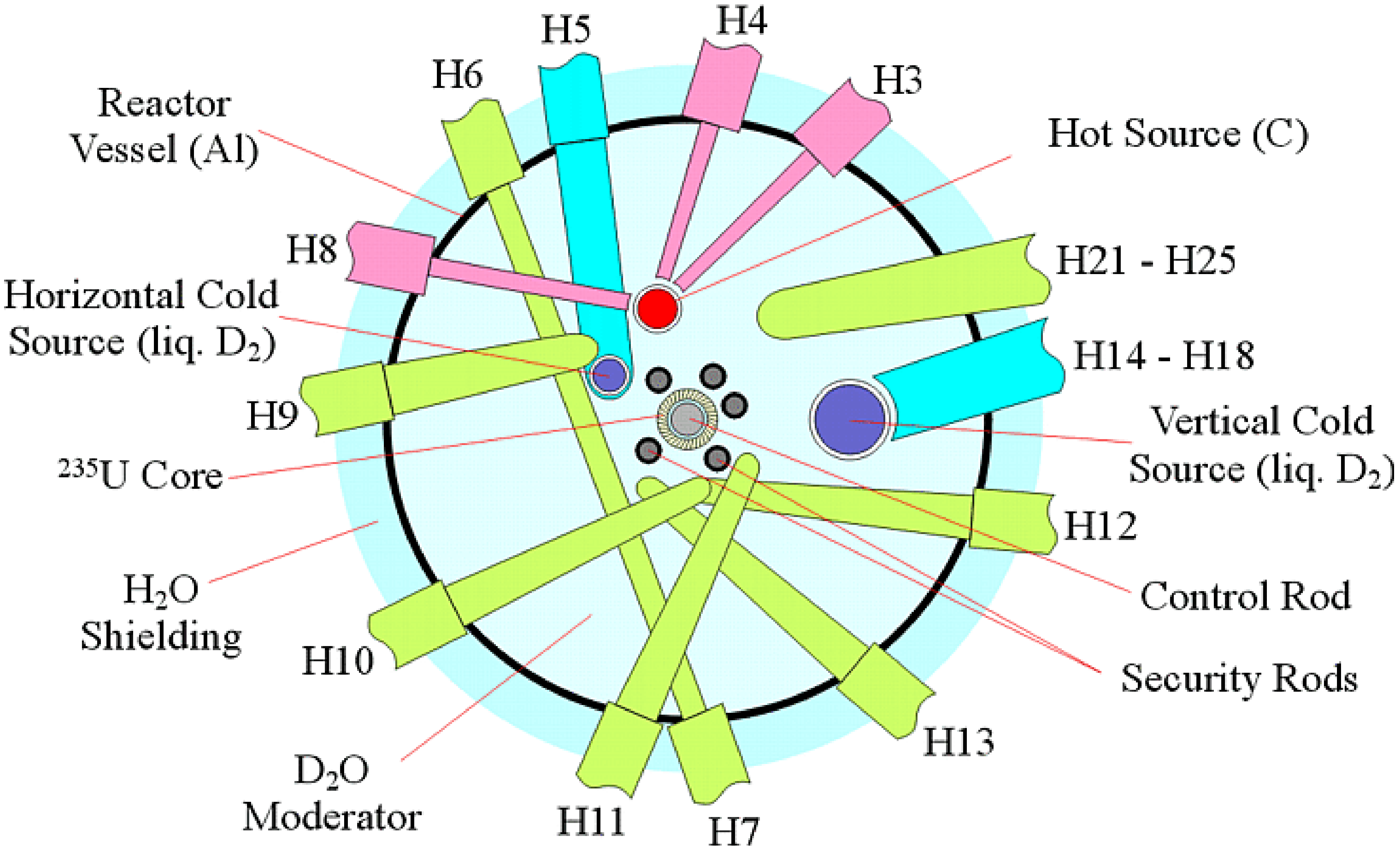
Cold source (horizontal): 6 dm^3 of liquid D_2 at 25 K

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



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



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

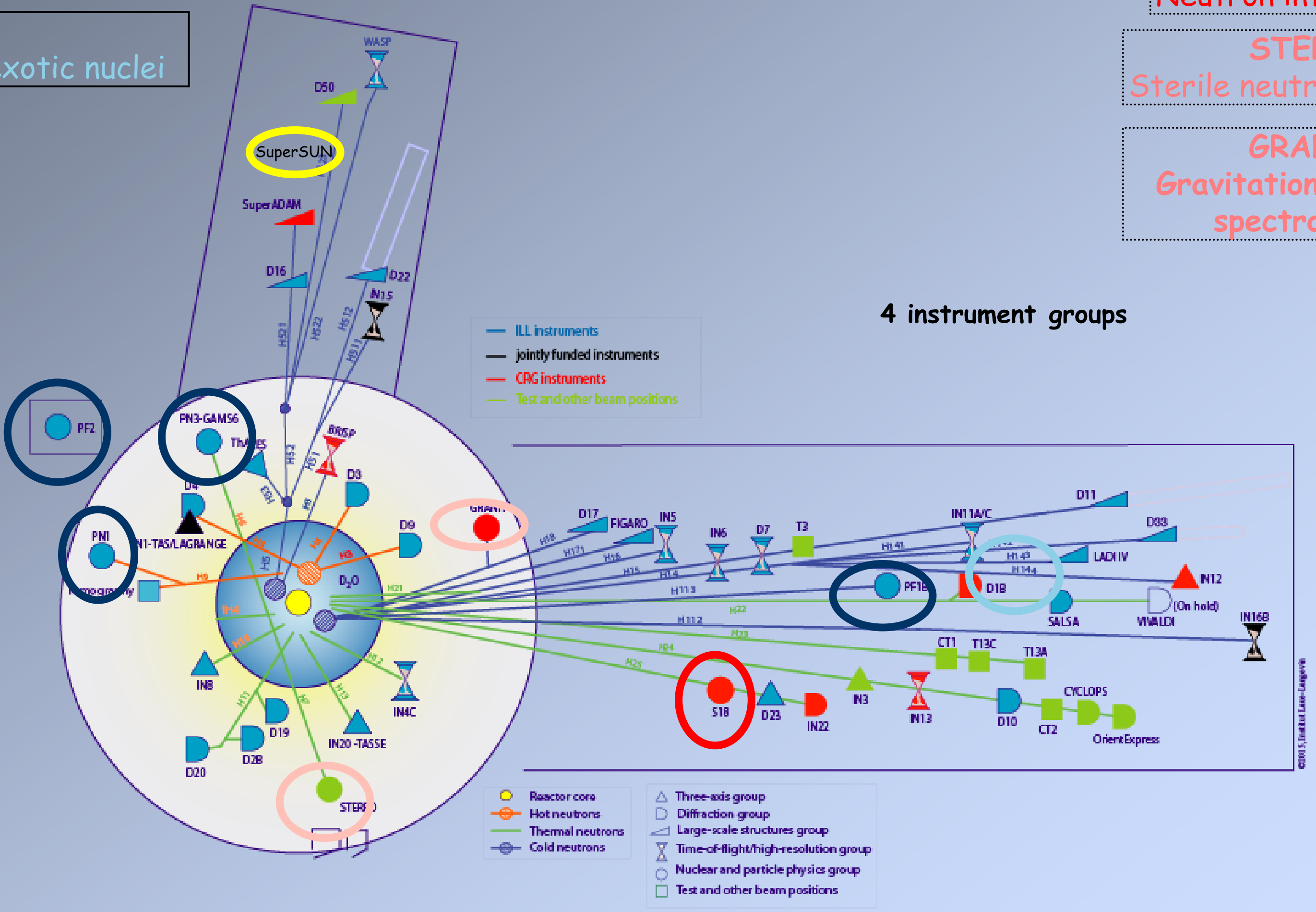
Collab. Research Group

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

S18 - perfect crystal
Neutron interferometer

STEREO
Sterile neutrino research

GRANIT
Gravitational neutron spectrometer



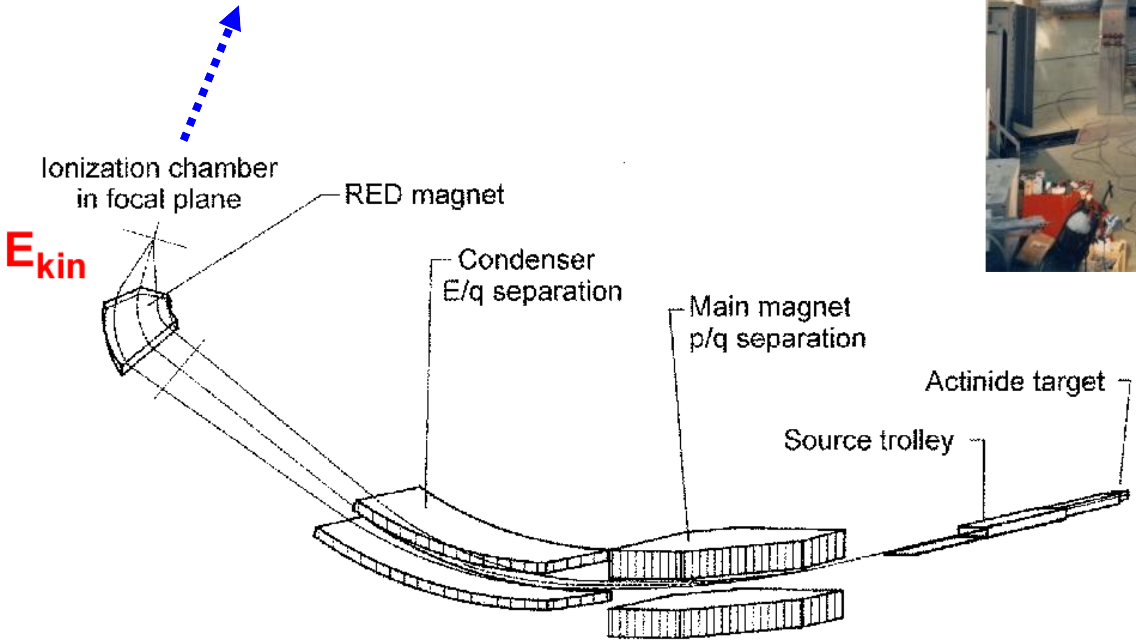
4 instrument groups

PN1: The fission fragment separator "Lohengrin"

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

mass-separated fission fragments,

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



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

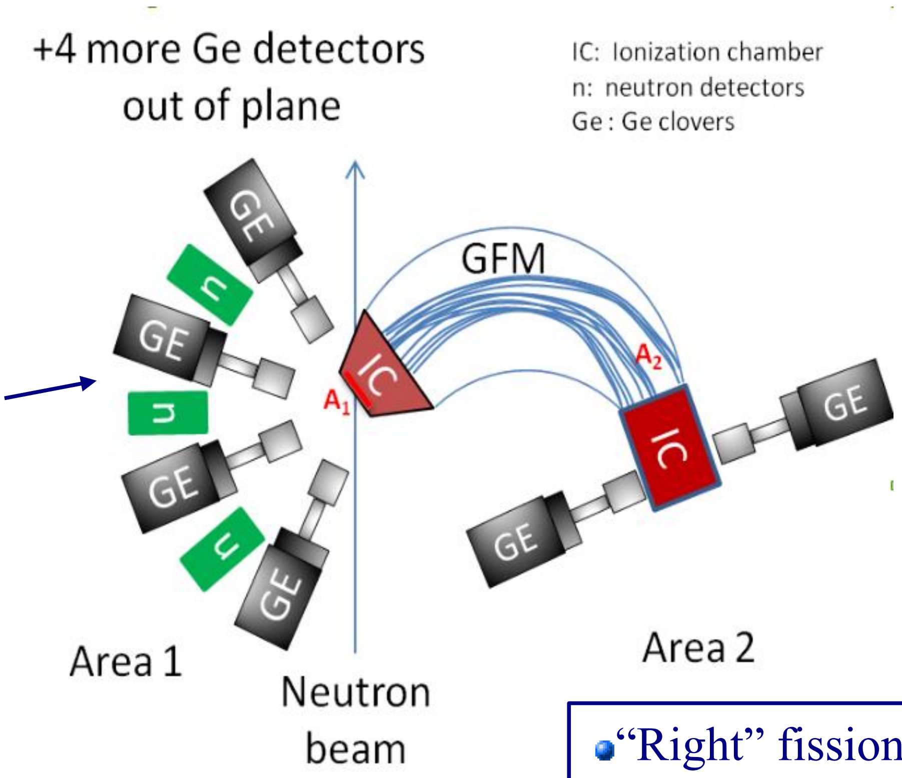
$$E_{kin} / q = E / 2 r_{el} \qquad m v / q = B r_{magn}$$

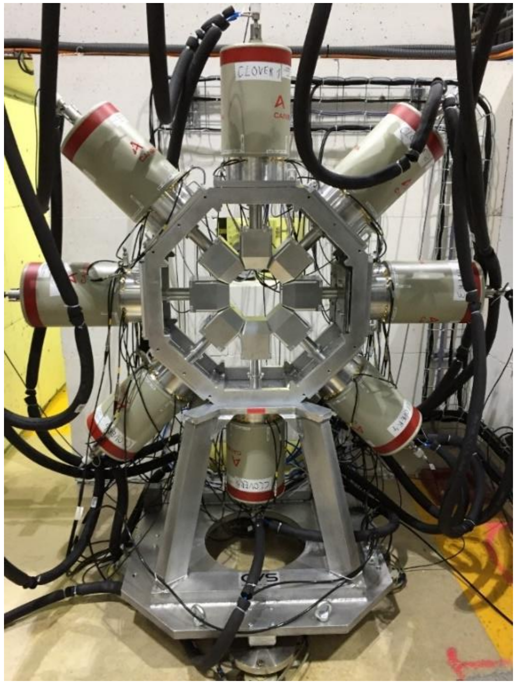
P. Armbruster et al., Nucl. Instr. Meth. 139 (1976) 213.

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

FIPPS: layout

FIssion **P**roduct **P**rompt gamma-ray **S**pectrometer





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

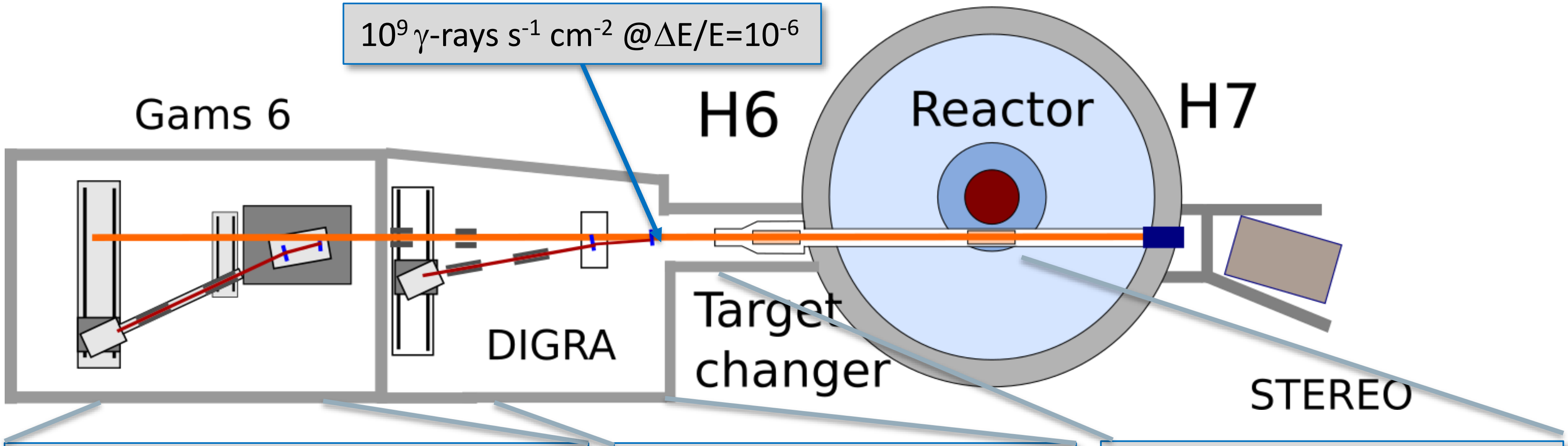
- "Right" fission fragment: → mass identification with a Gas-Filled magnet for **filtering**

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:

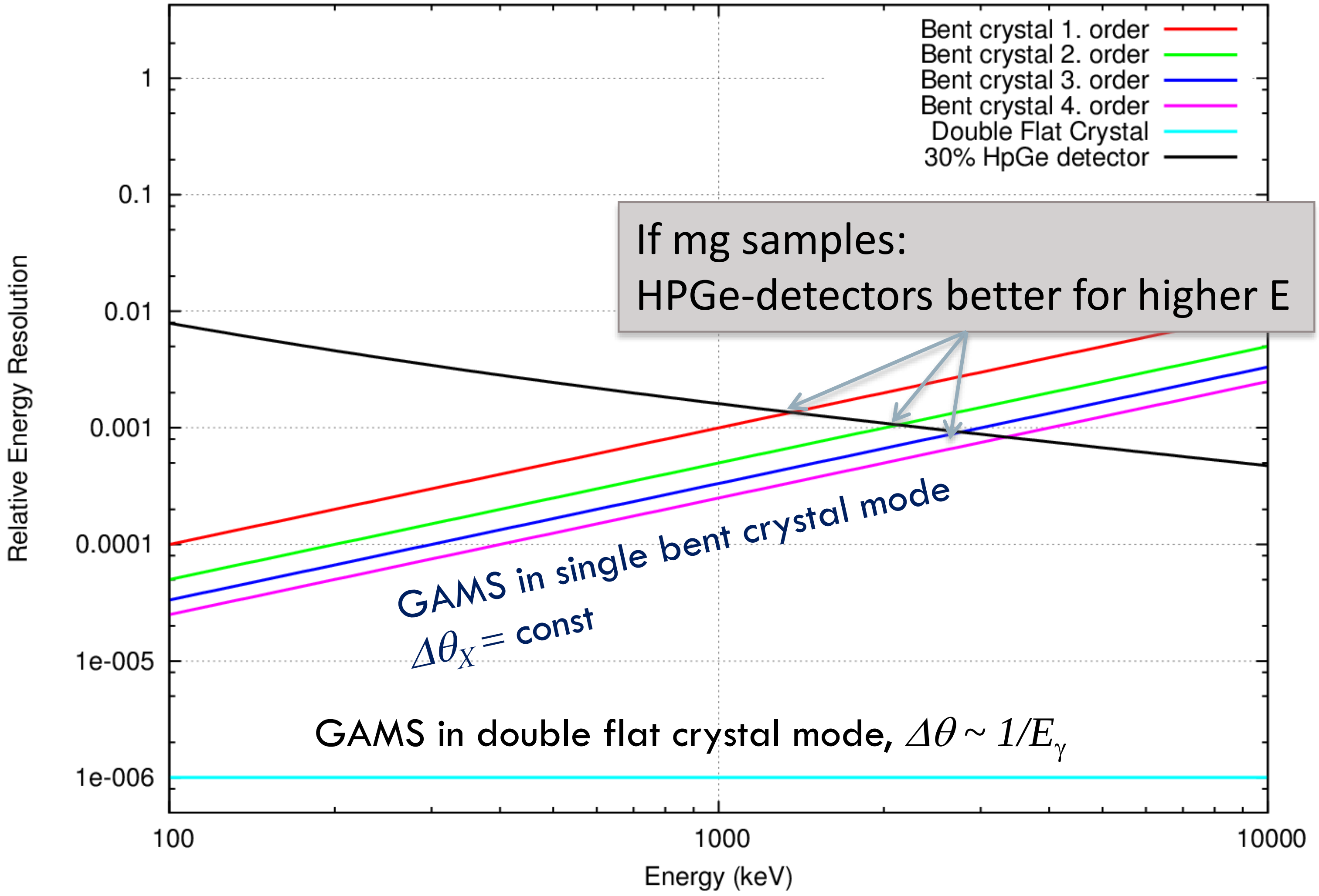
- Neutron flux: 5×10^{14} cm^2 s^{-1}
- 3 Samples $4 \times 20 \times 20$ mm^3
- Orientation of samples in reactor is possible
- Sample change during reactor cycle
- Self heating: ~1 W/g

AND GAMMA RAY

THE EUROPEAN NEUTRON SOURCE

NEUTRONS FOR SOCIETY

Overview on Energy resolution



If mg samples:
HPGe-detectors better for higher E

GAMS in single bent crystal mode

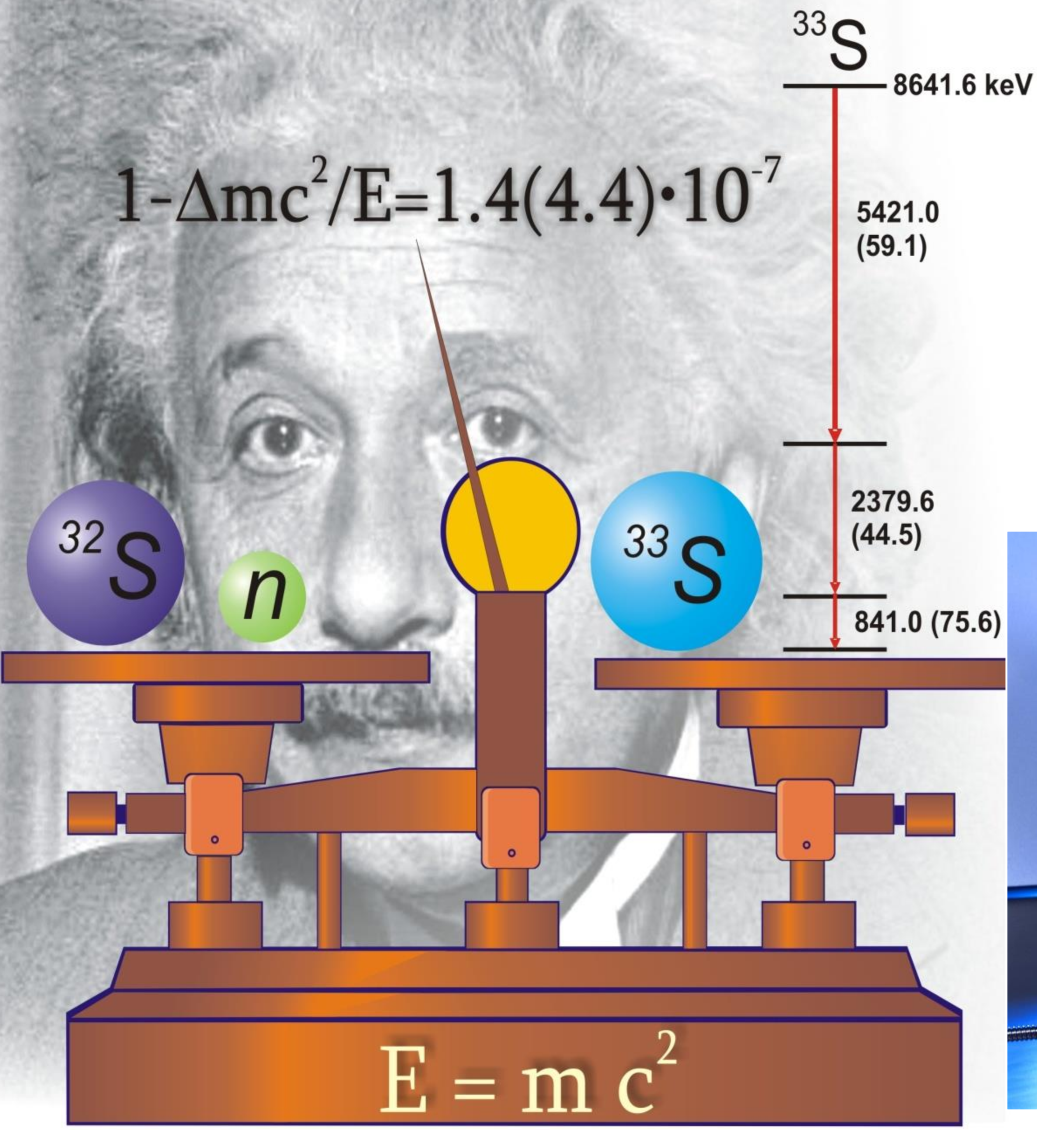
$\Delta\theta_X = \text{const}$

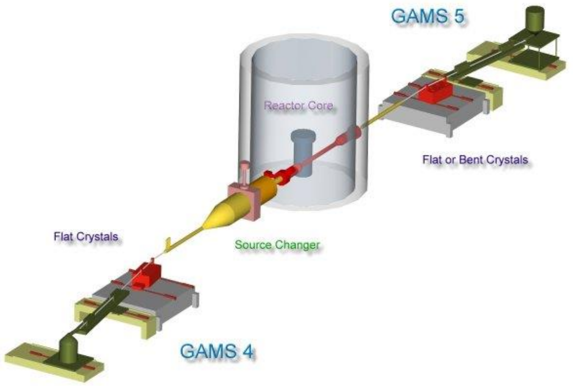
GAMS in double flat crystal mode, $\Delta\theta \sim 1/E_\gamma$

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

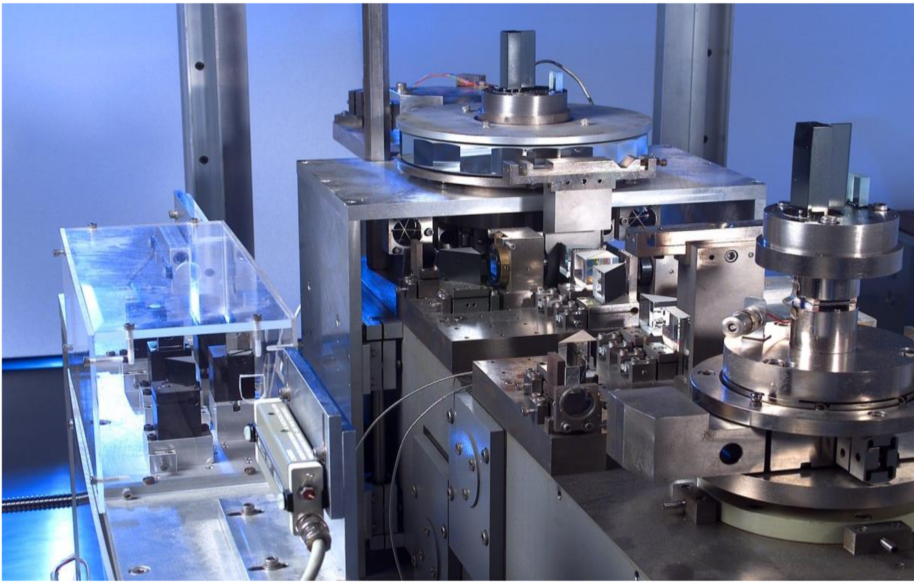
2005 World Year of Physics – Einstein's "Miraculous year" 1905

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



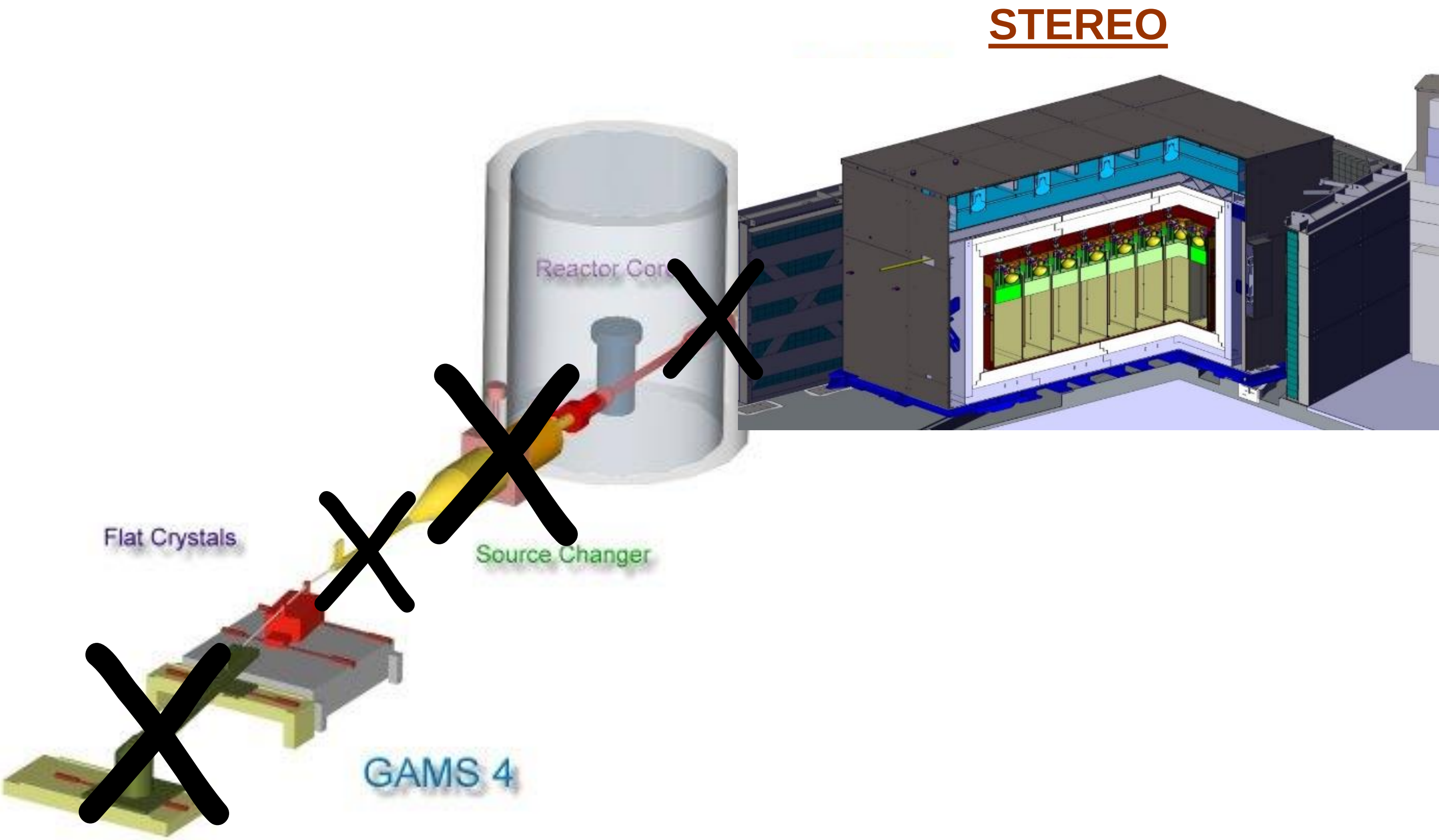


GAMS Interferometer ILL



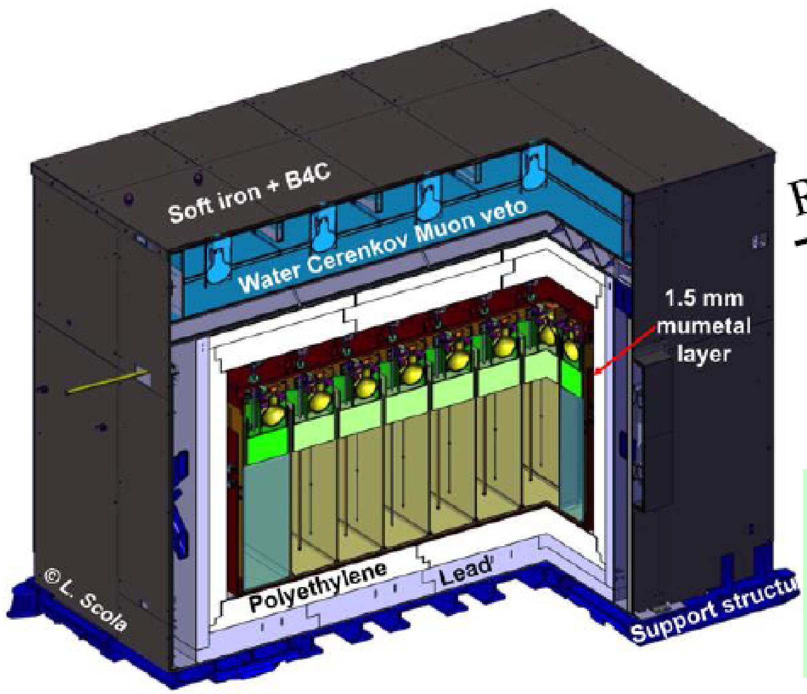
Antineutrino detector STEREO

at the sealed end of beam tube H7



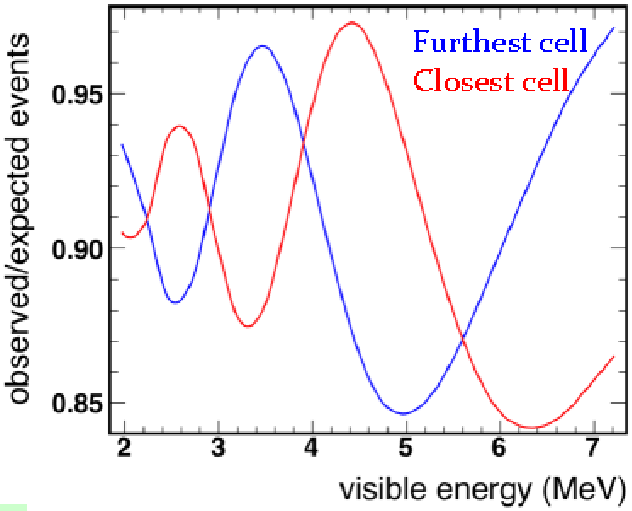
In April 2017 through beam tube H6/H7 removed and sealed

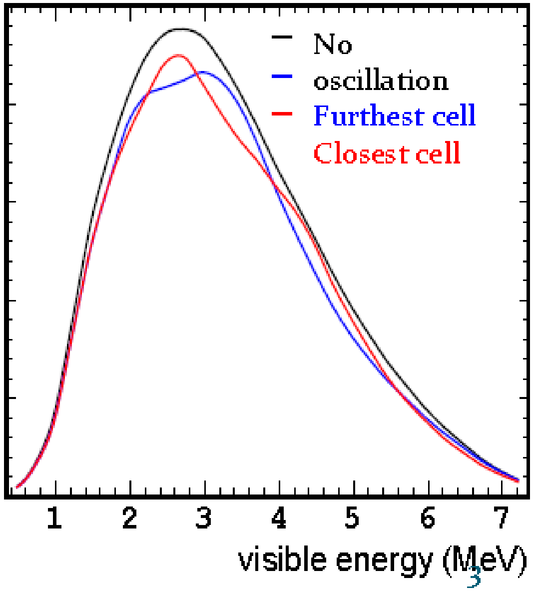
STEREO Detector



20 cm thick acrylic buffers for homogeneous detector response. PMT coupling via oil bath.

$\sin^2(2\theta)=0.14$, $\Delta m^2=2.4$ eV^2





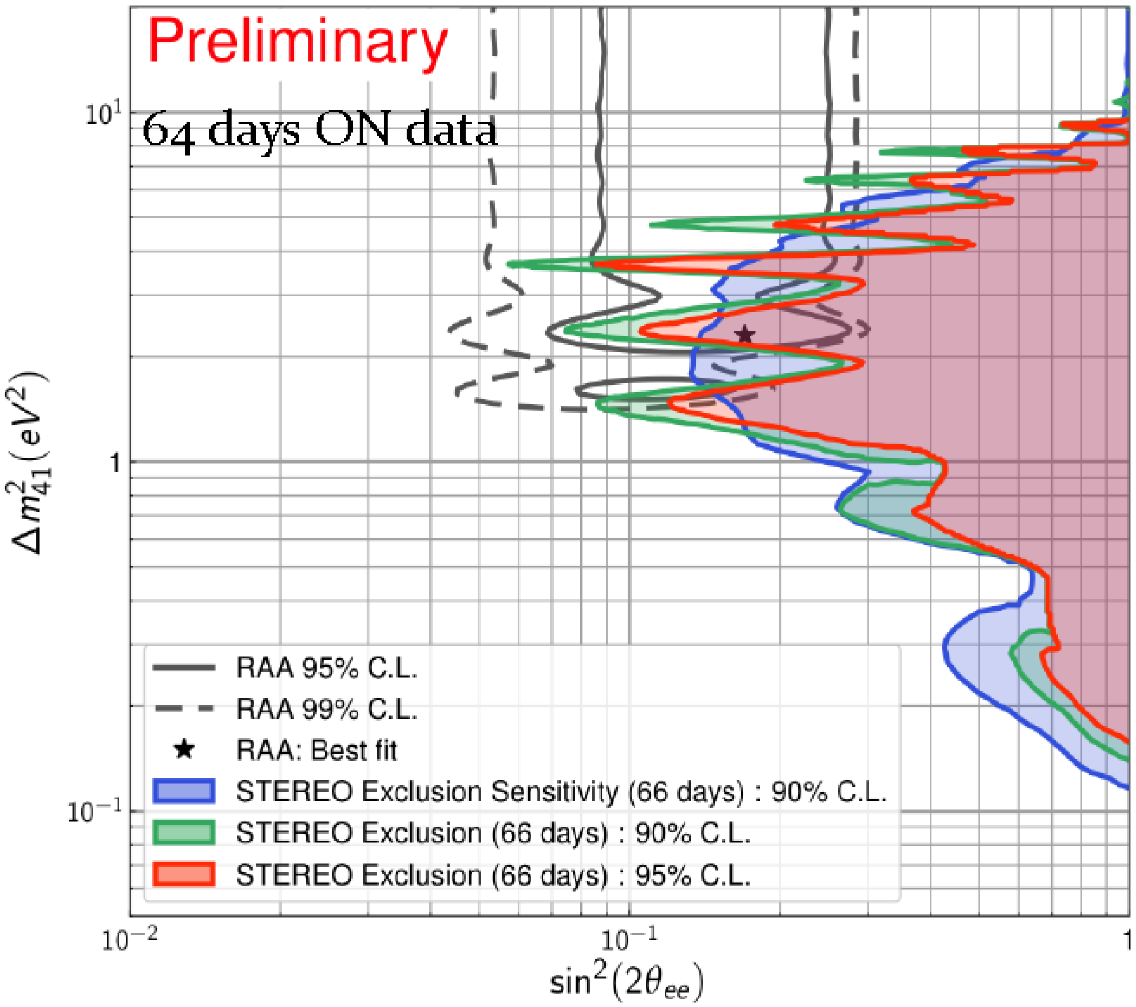
Liquid Scintillator

Target: 6 identical cells
- Gd-loaded (0.2% in mass)
- V_{tot}= 2.2 x 0.9 x 0.9 m^3

Gamma catcher (unloaded):
- Vetos ext. background
- Captures escaping γ's

STEREO exclusion contours

- Raster scan approach.
- $\Delta\chi^2$ law simulated in each Δm^2 bin.
- Reject oscillation amplitudes larger that statistical fluctuations for a given C.L.



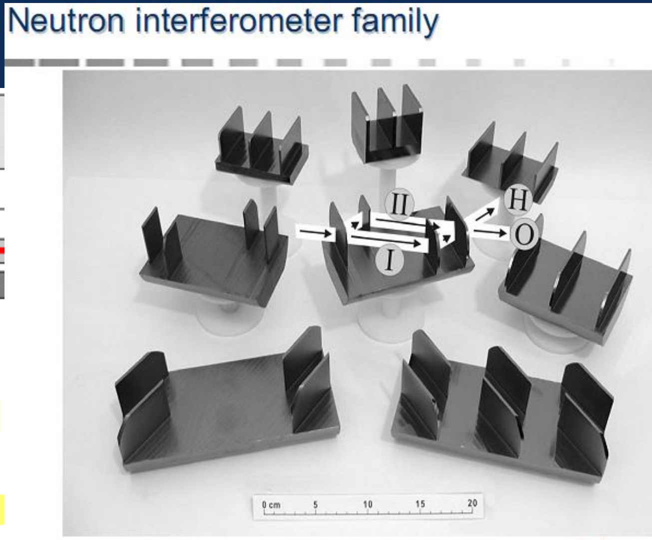
→ Reject at 98.8% C.L. the RAA oscillation best fit value
→ Contour sensitivity will be extended with more statistic

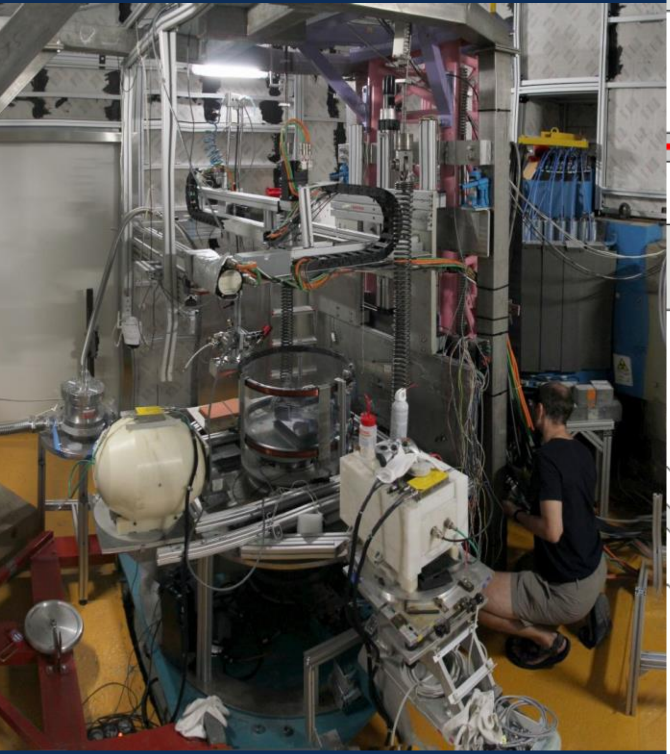
Nuclear and particle physics at ILL

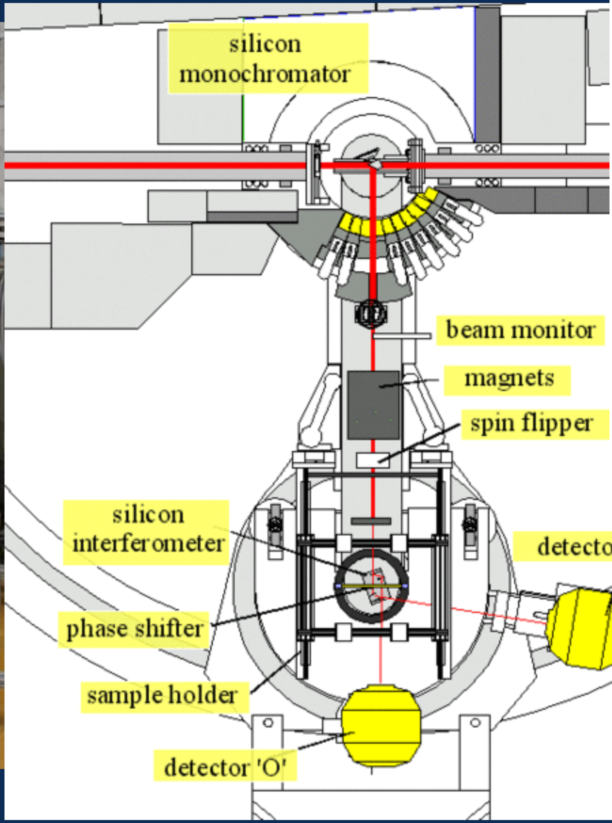
S18 - CRG instrument (Atominstitut, TU Vienna, Austria [H. Lemmel])

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

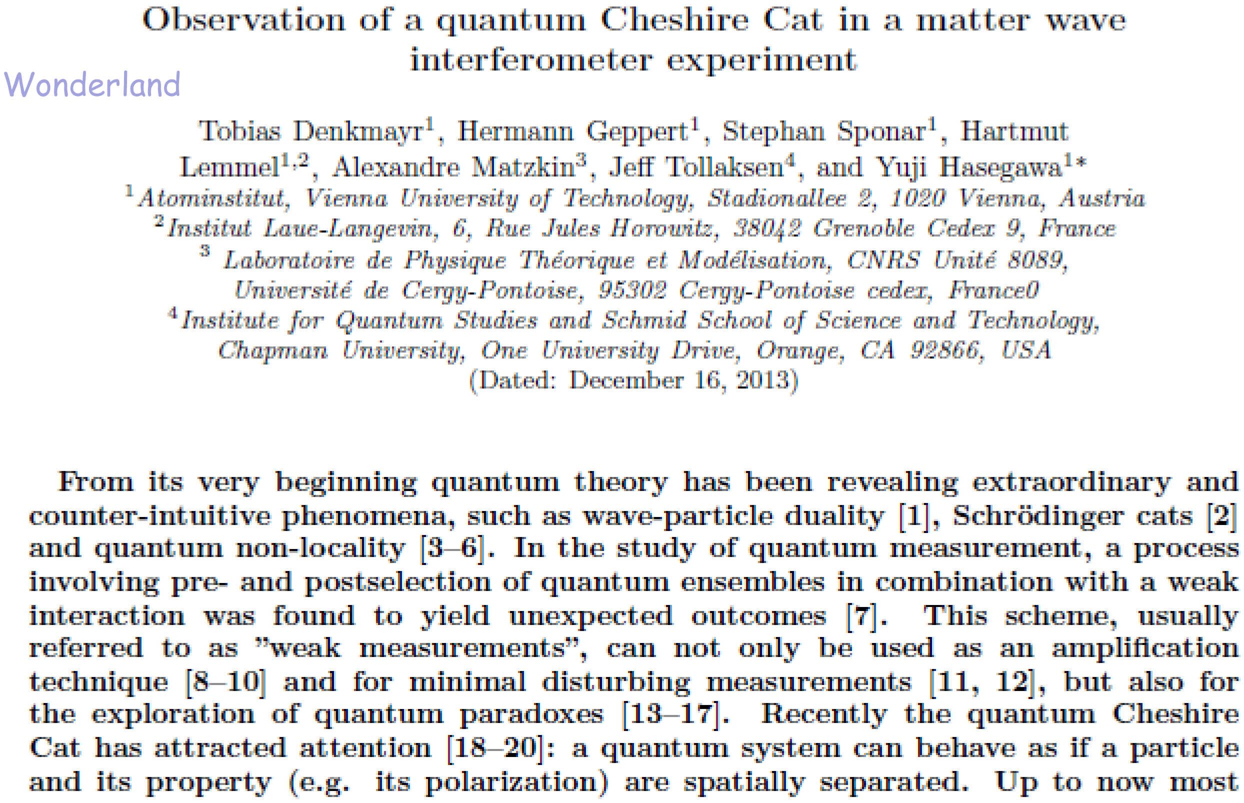
Neutron interferometer family







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]*
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[2] *Institut Laue-Langevin, 6, Rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
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(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

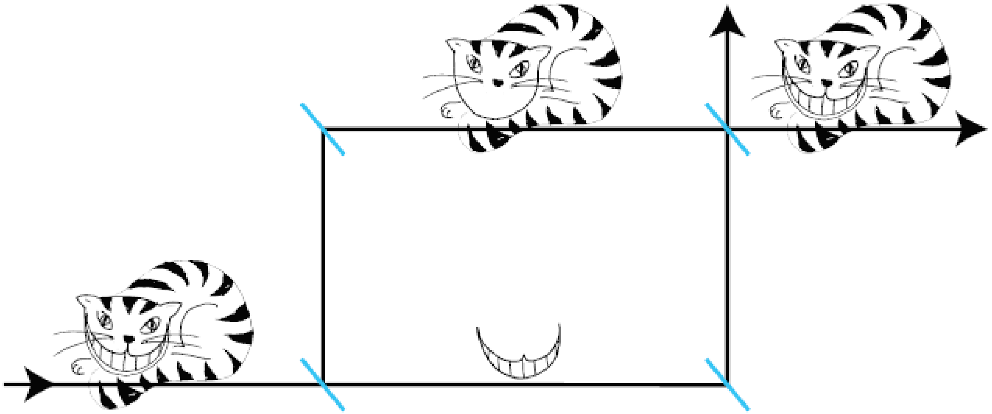


FIG. 1: Artistic depiction of the quantum Cheshire Cat: Inside the interferometer the Cat goes through the upper beam path, while its grin travels along the lower beam path.

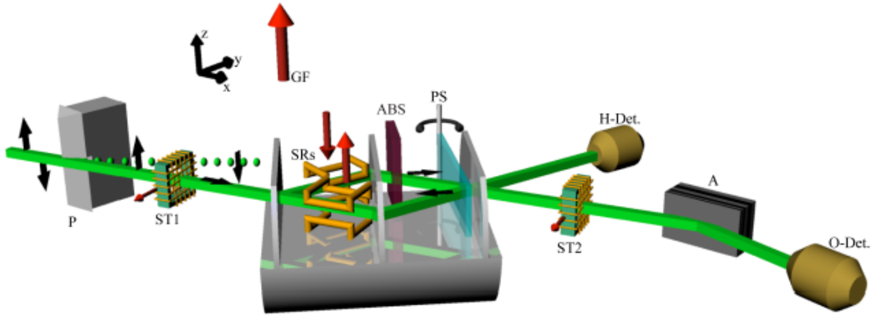


FIG. 2: Illustration of the experimental setup for the observation of a quantum Cheshire Cat in a neutron interferometer: The neutron beam is polarized by passing through magnetic birefringent prisms (P). To prevent depolarization, a magnetic guide field (GF) is applied around the whole setup. A spin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

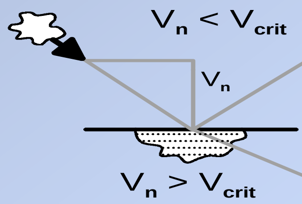
Long storage and observation times possible (up to several minutes)!

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.

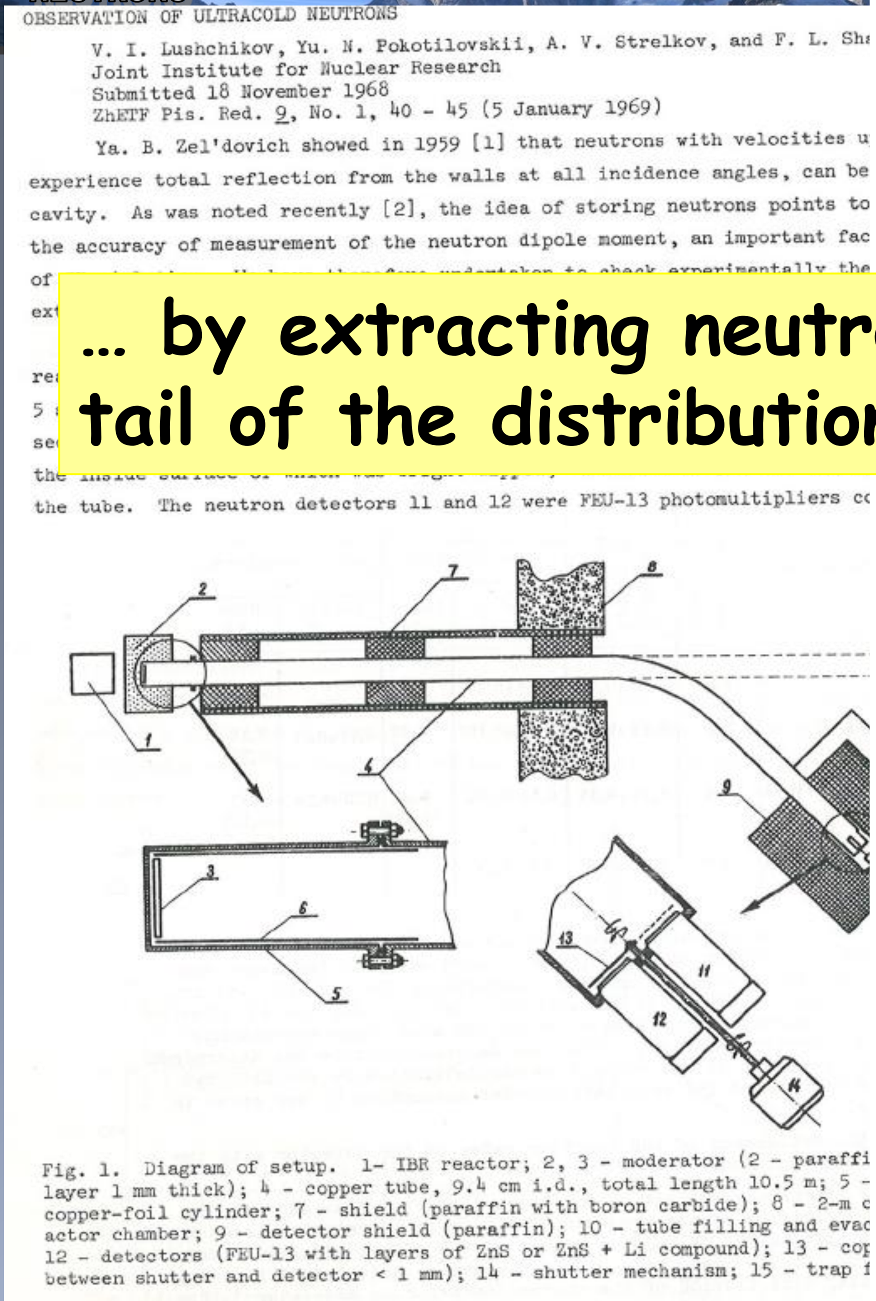
- beryllium 252 neV
- stainless steel 200 neV



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

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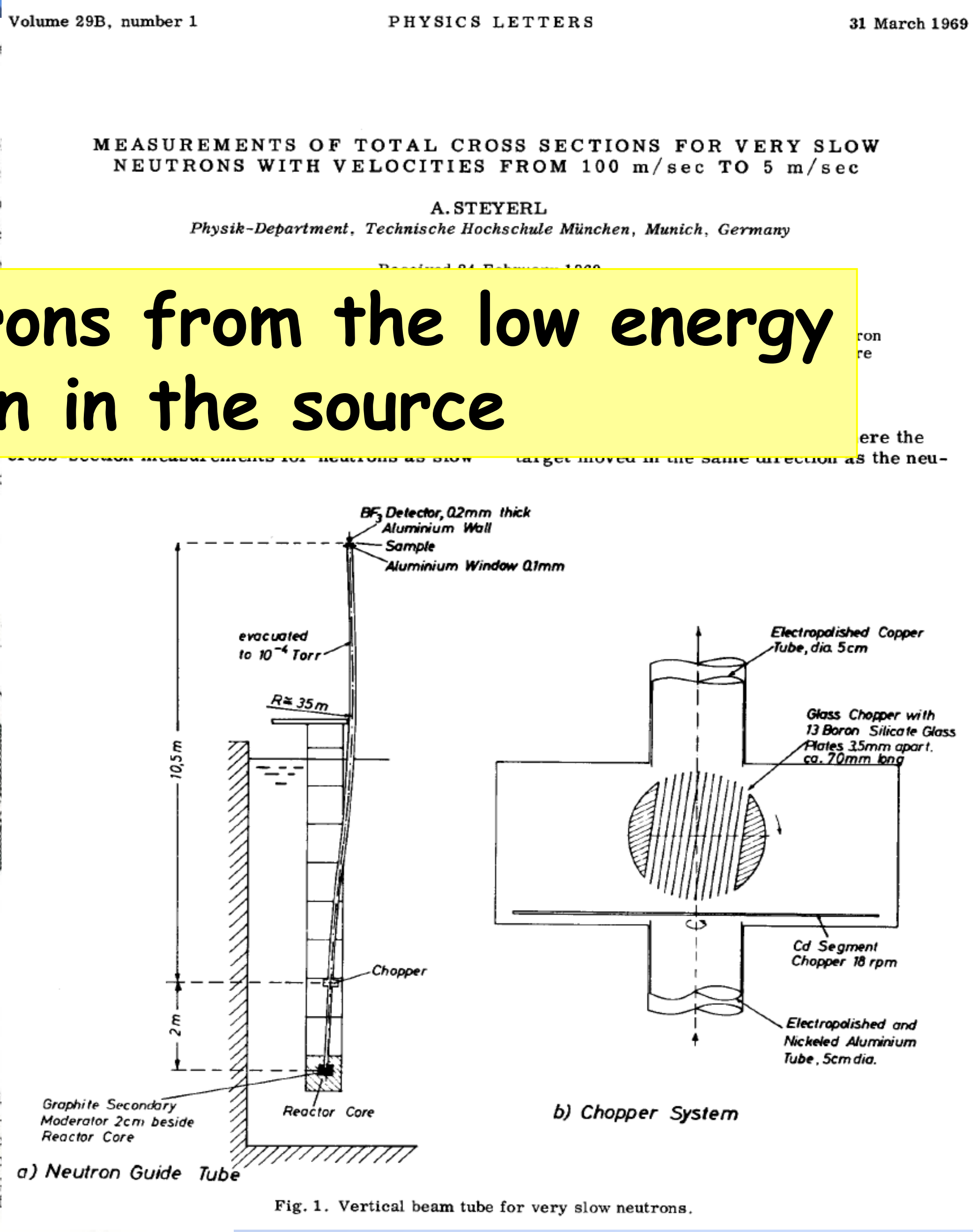
the
the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers co

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

ron
re

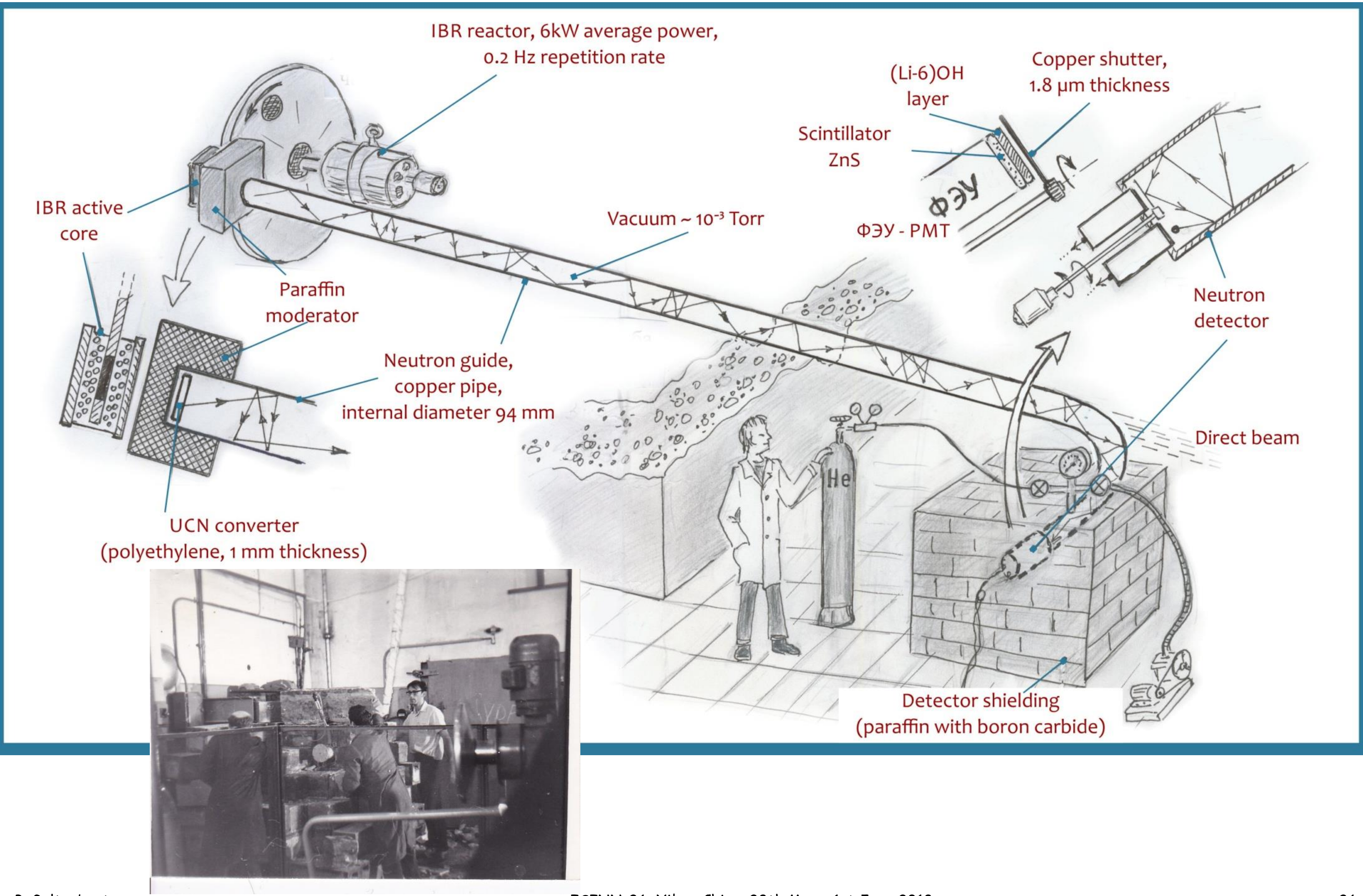
ere the
target moved in the same direction as the neu-

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

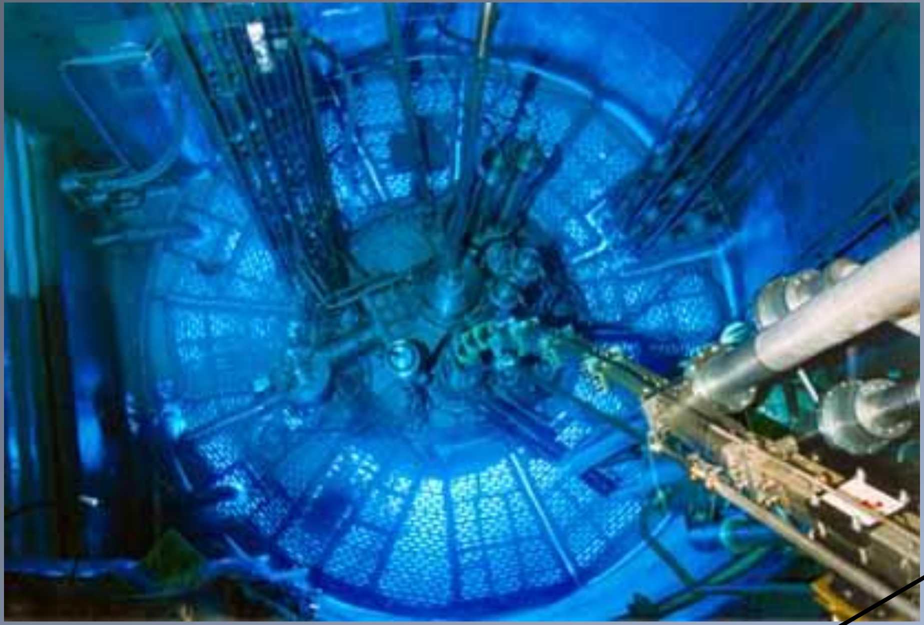
… by extracting neutrons from the low energy tail of the distribution in the source

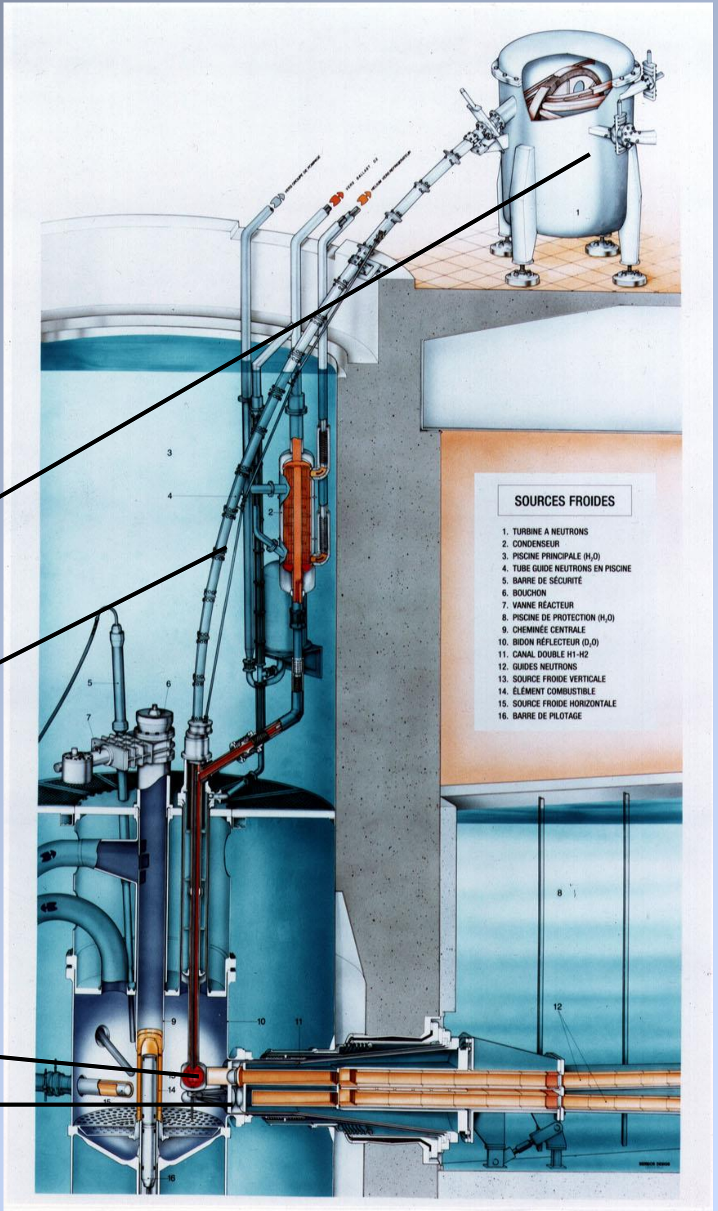
how UCN were “really” discovered in Dubna

drawing courtesy of A.V. Strelkov



The UCN/VCN facility PF2





Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

Reactor core

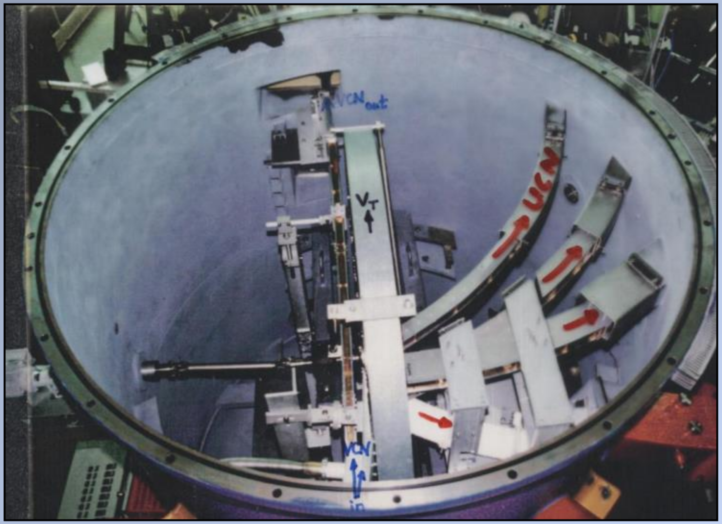
A. Steyerl et al., Phys. Lett. A116 (1986) 347

Generating Ultracold Neutrons (UCN)

"Steyerl turbine"

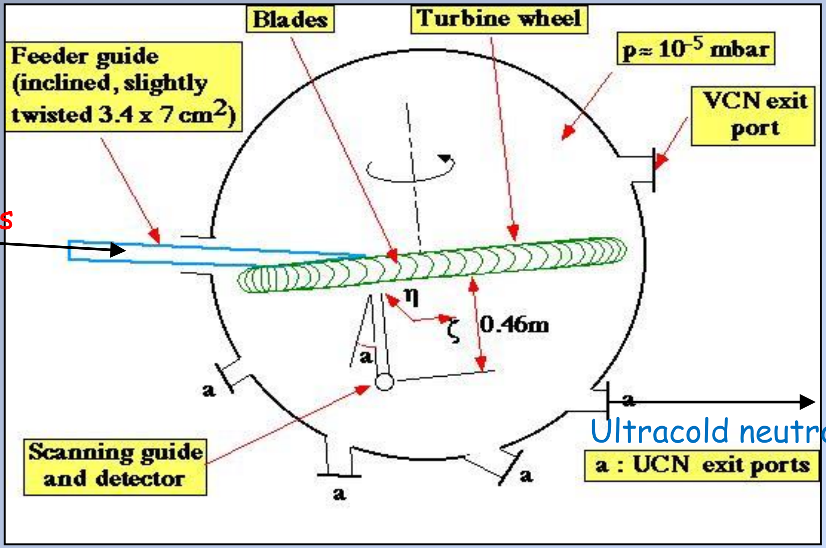
Doppler shifting device

Steyerl turbine
at FRM-I (Munich)



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

Very cold neutrons



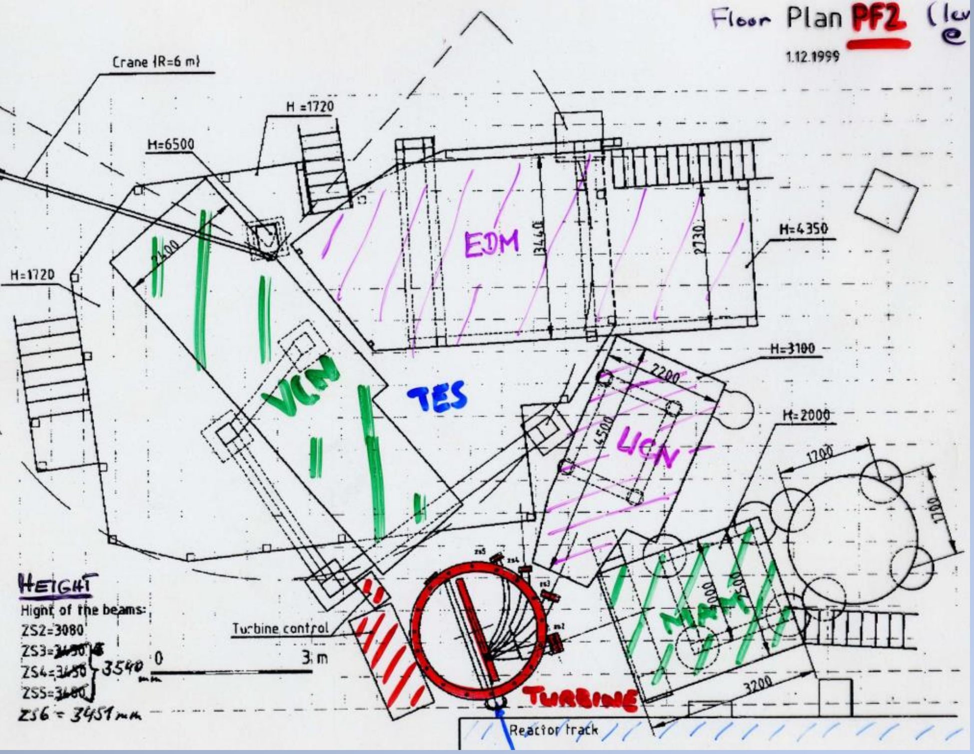
Ultracold neutrons

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!

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 :
$v = 5\ ms^{-1}$
$\rho = \sim 50\ cm^{-3}$ (at the experiment)
is :
$v <= 7\ ms^{-1}$
$\rho = \sim 20\ cm^{-3}$ (at the experiment)

- *TES*

1 position for Very Cold Neutrons (VCN)

- *VCN beam*

$v = 50\ ms^{-1}$
$\Phi = 10^8\ cm^{-2}\ s^{-1}$

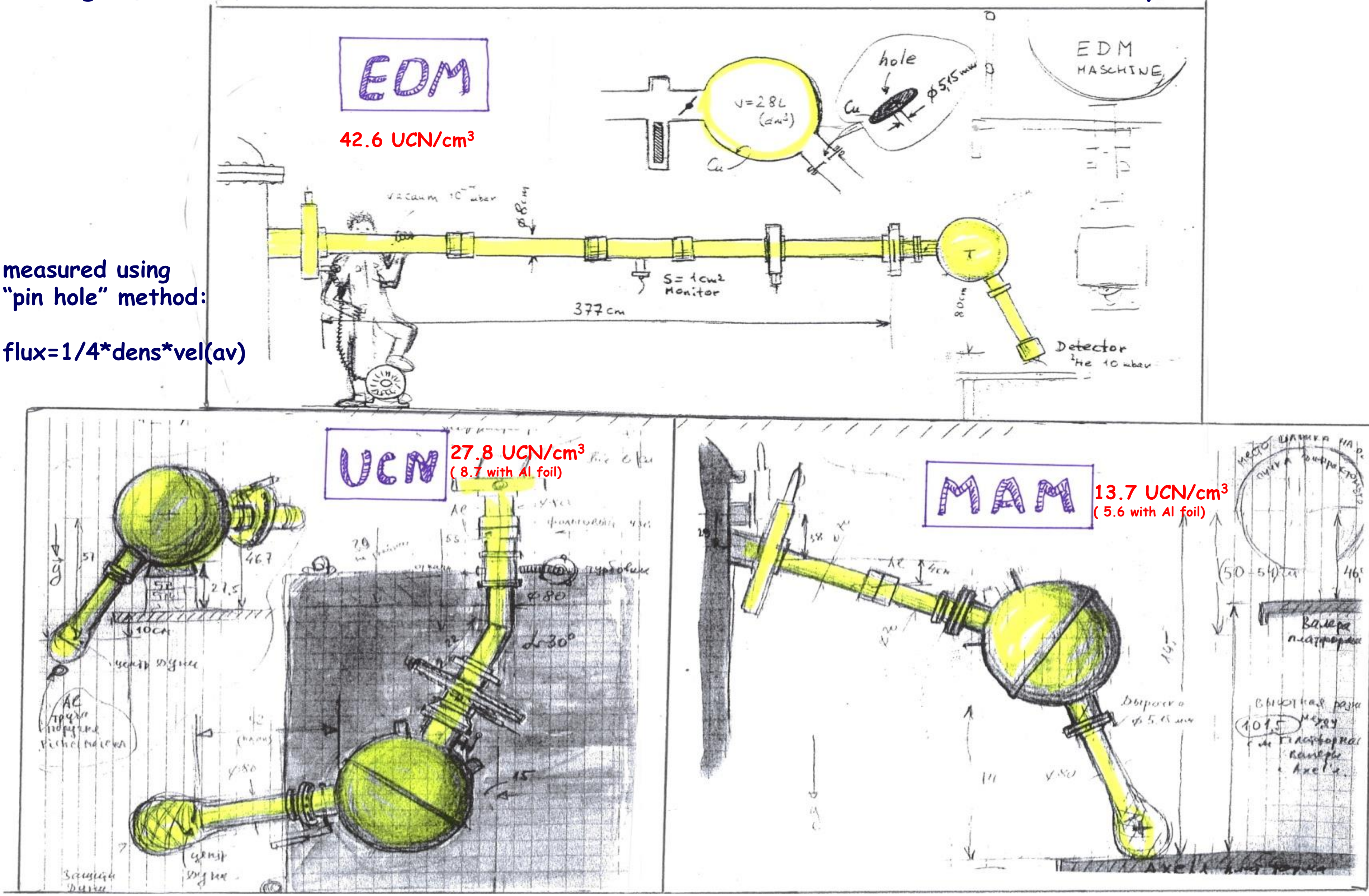
W. Drexel, Neutron News 1 (1990) 23

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)

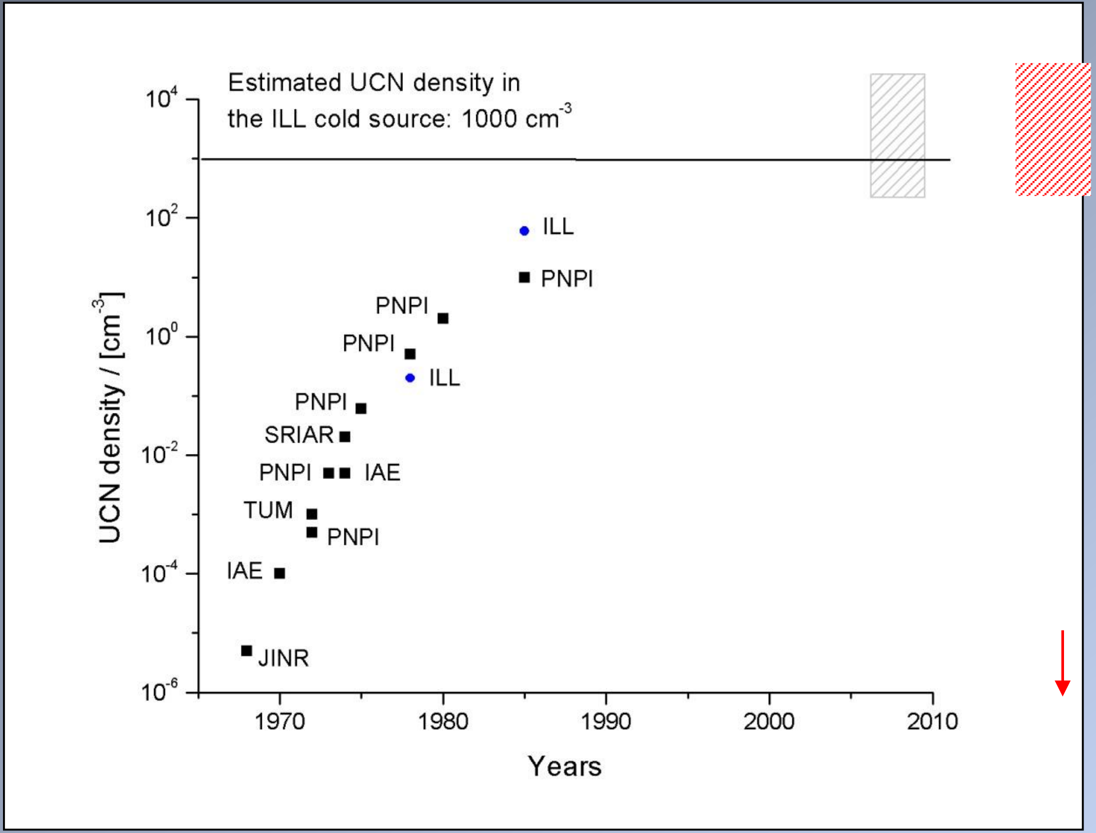


42.6 UCN/cm^3

27.8 UCN/cm^3
(8.7 with Al foil)

13.7 UCN/cm^3
(5.6 with Al foil)

UCN facilities – Status and Future



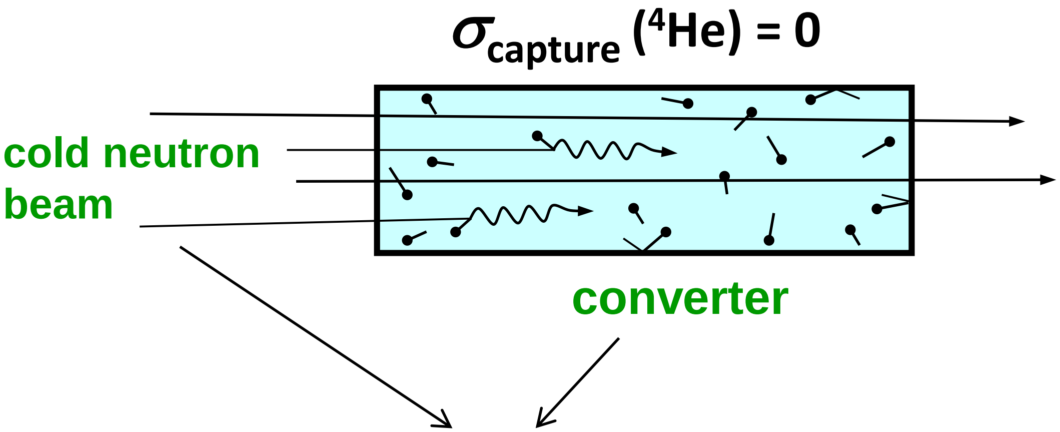
More and stronger UCN facilities in the future worldwide

- 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 ....

UCN production in He-II

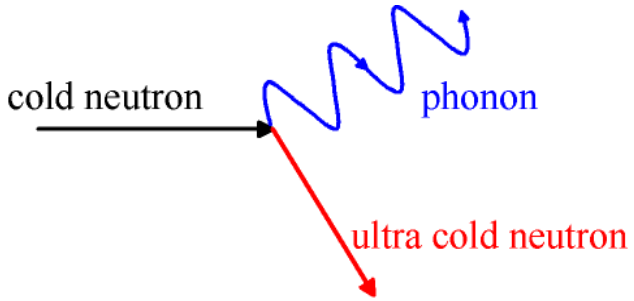
R. Golub, J.M. Pendlebury, PL **53A** (1975) 133



σ_{capture} (^{4}He) = 0

cold neutron beam

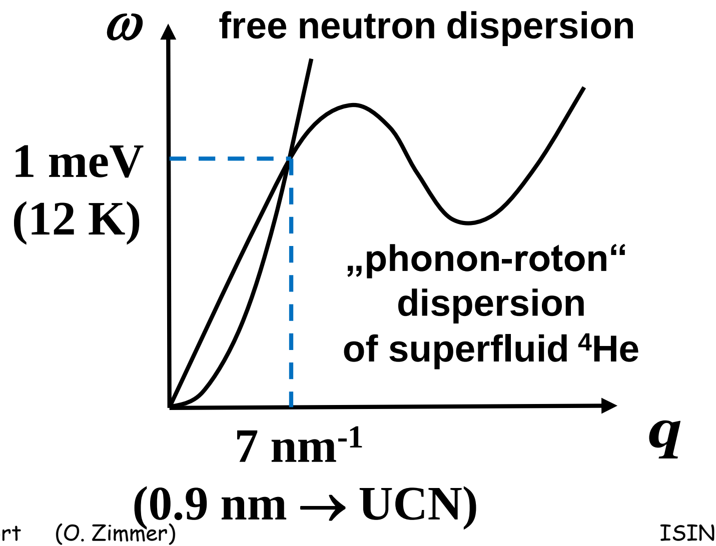
converter



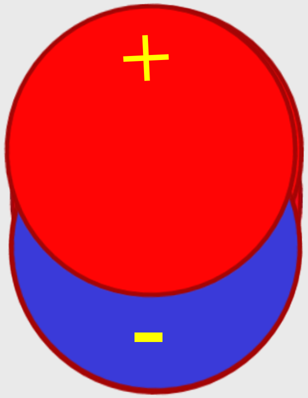
$$\rho_{\text{UCN}} = P\tau$$

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

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



Electric Dipole Moment:

neutron is electrically neutral

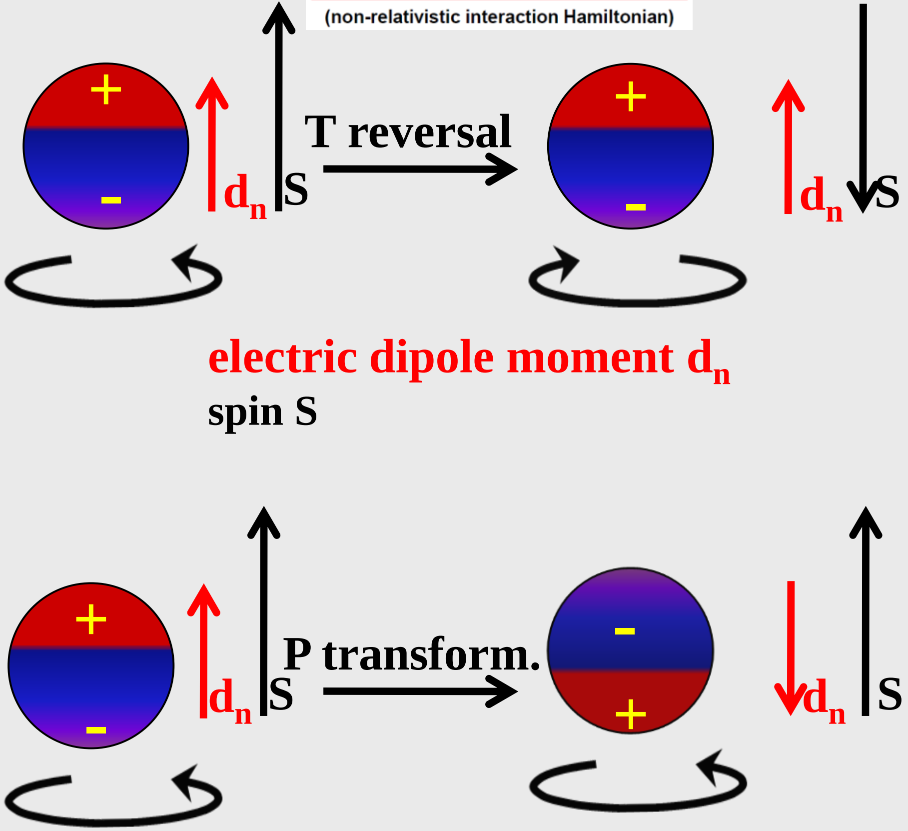
If average positions of positive and negative charges do not coincide:

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

EDM d_n

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

(non-relativistic interaction Hamiltonian)



electric dipole moment d_n
spin S

P & T violation

CPT conservation ➔ CP violation

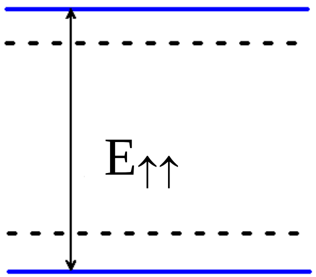
CP violation in Standard Model generates very small neutron EDM
Beyond the Standard Model contributions tend to be much bigger

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

Experiments:

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

Compare the precession frequency for parallel fields:

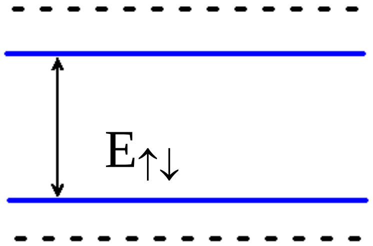


$$\nu_{\uparrow\uparrow} = E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$

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

< 1 turn per month!

to the precession frequency for anti-parallel fields

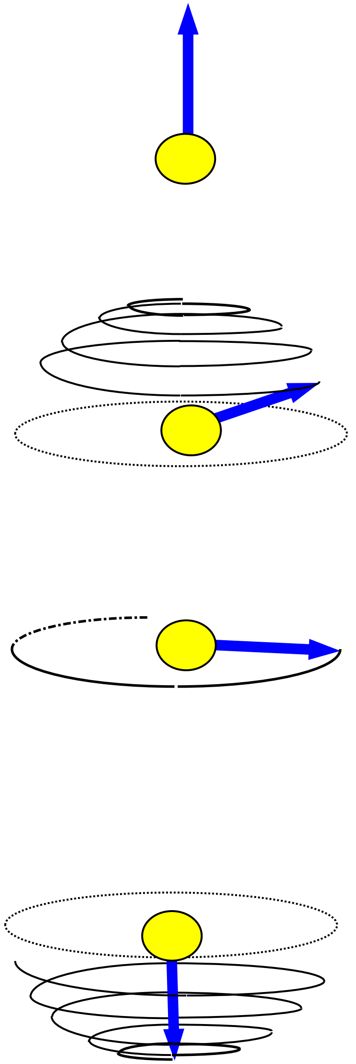


$$\nu_{\uparrow\downarrow} = E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

The difference is proportional to d_n and E:

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

Ramsey method of Separated Oscillatory Fields

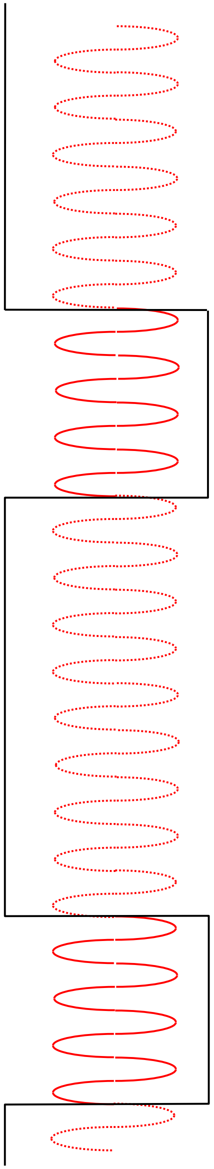


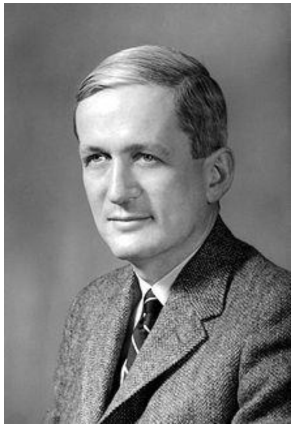
1. *“Spin up” neutron...*

2. *Apply π/2 spin flip pulse...*

3. *Free precession...*

4. *Second π/2 spin flip pulse.*





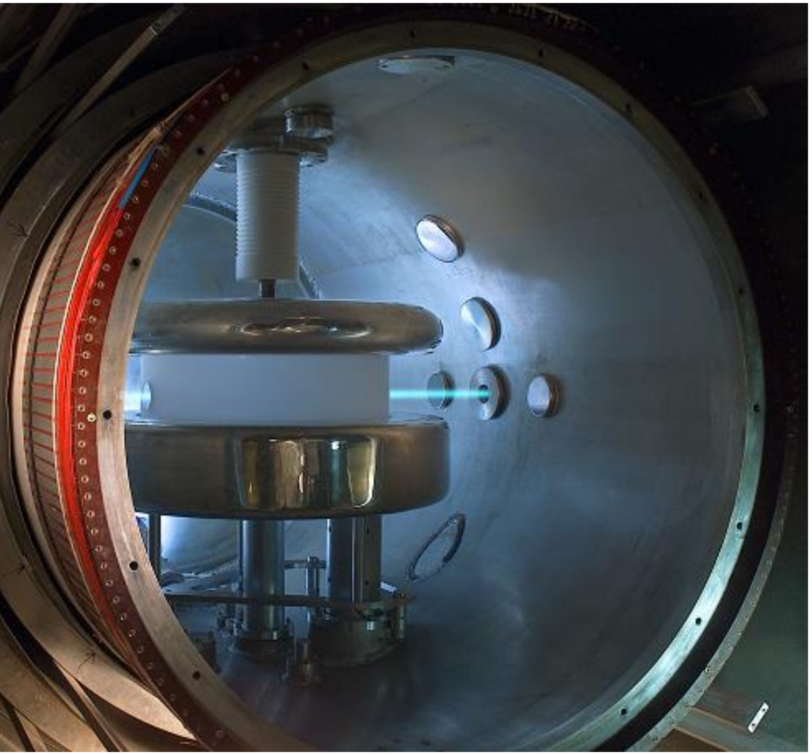
Norman F. Ramsey

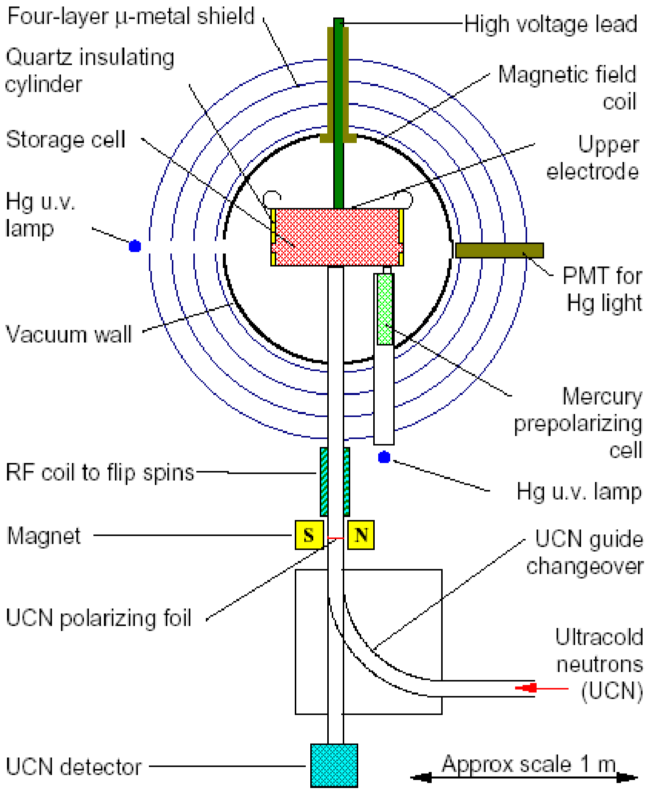
1915 – 2011

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. ...

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)

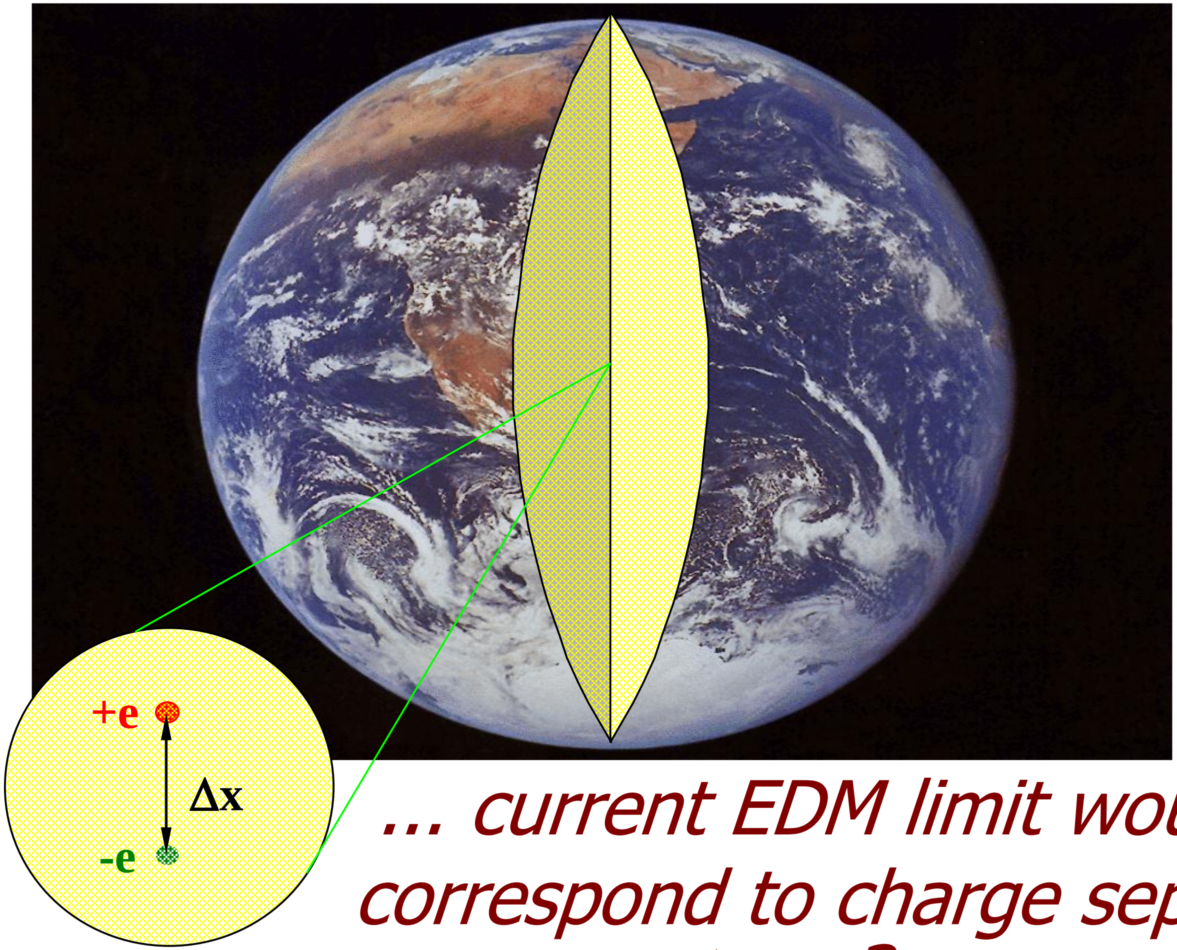
$|d_n| < 2.9\times10^{-26}$ e.cm (90% C.L.)

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

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

Reality check

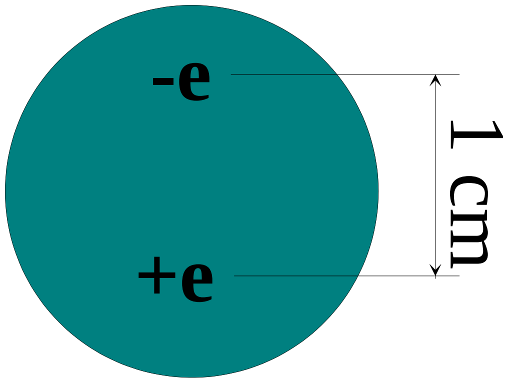
If neutron were the size of the Earth...



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

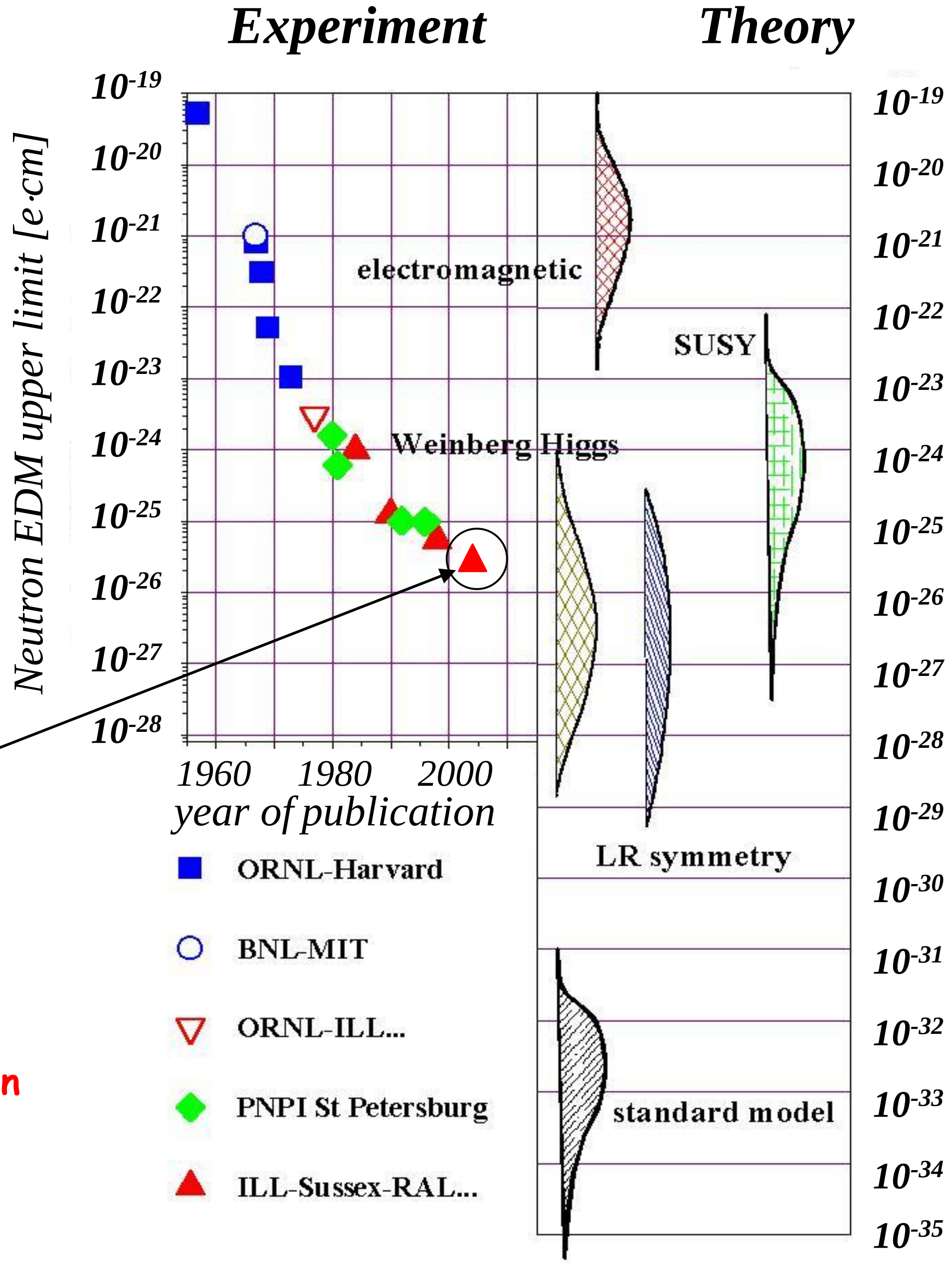
The neutron EDM: exp. vs theory

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



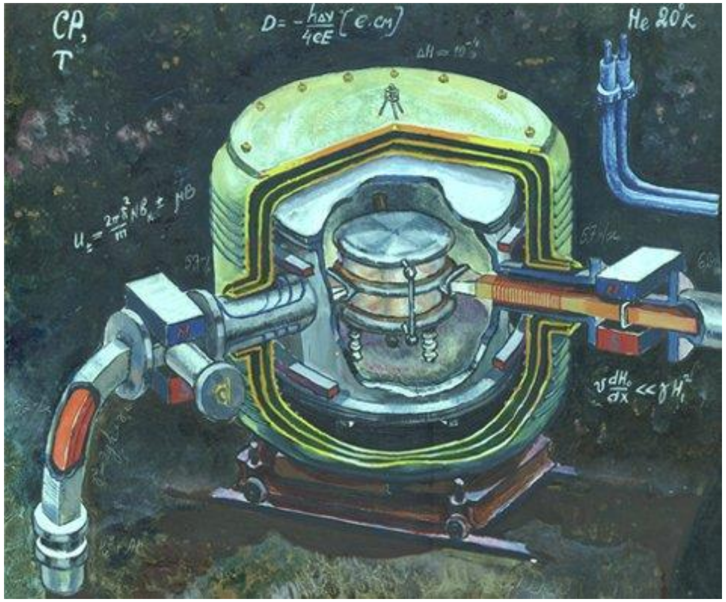
$d_n = 1\ e\cdot\text{cm}$

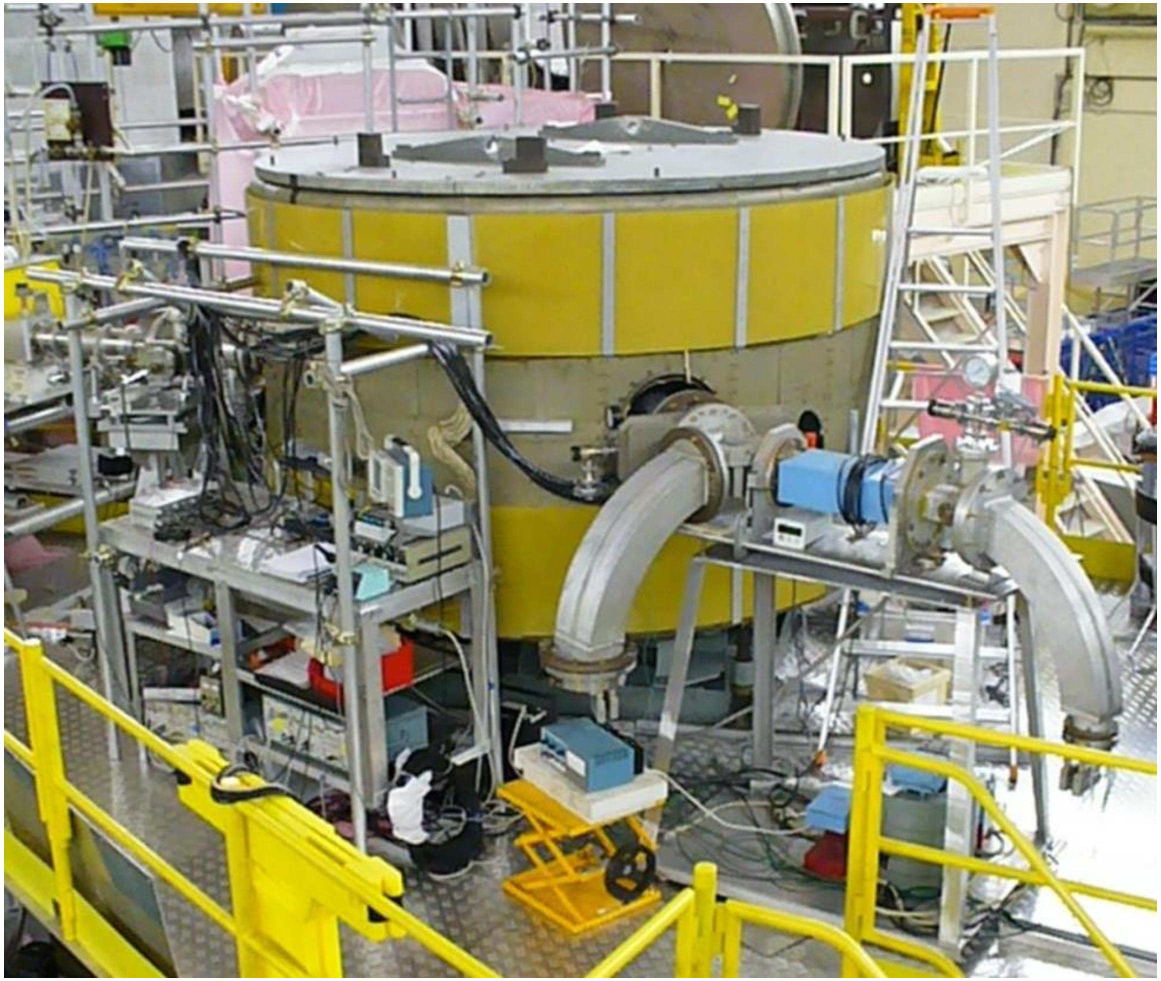
$|d_n| < 3 \times 10^{-26}\ e\cdot\text{cm}$



"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



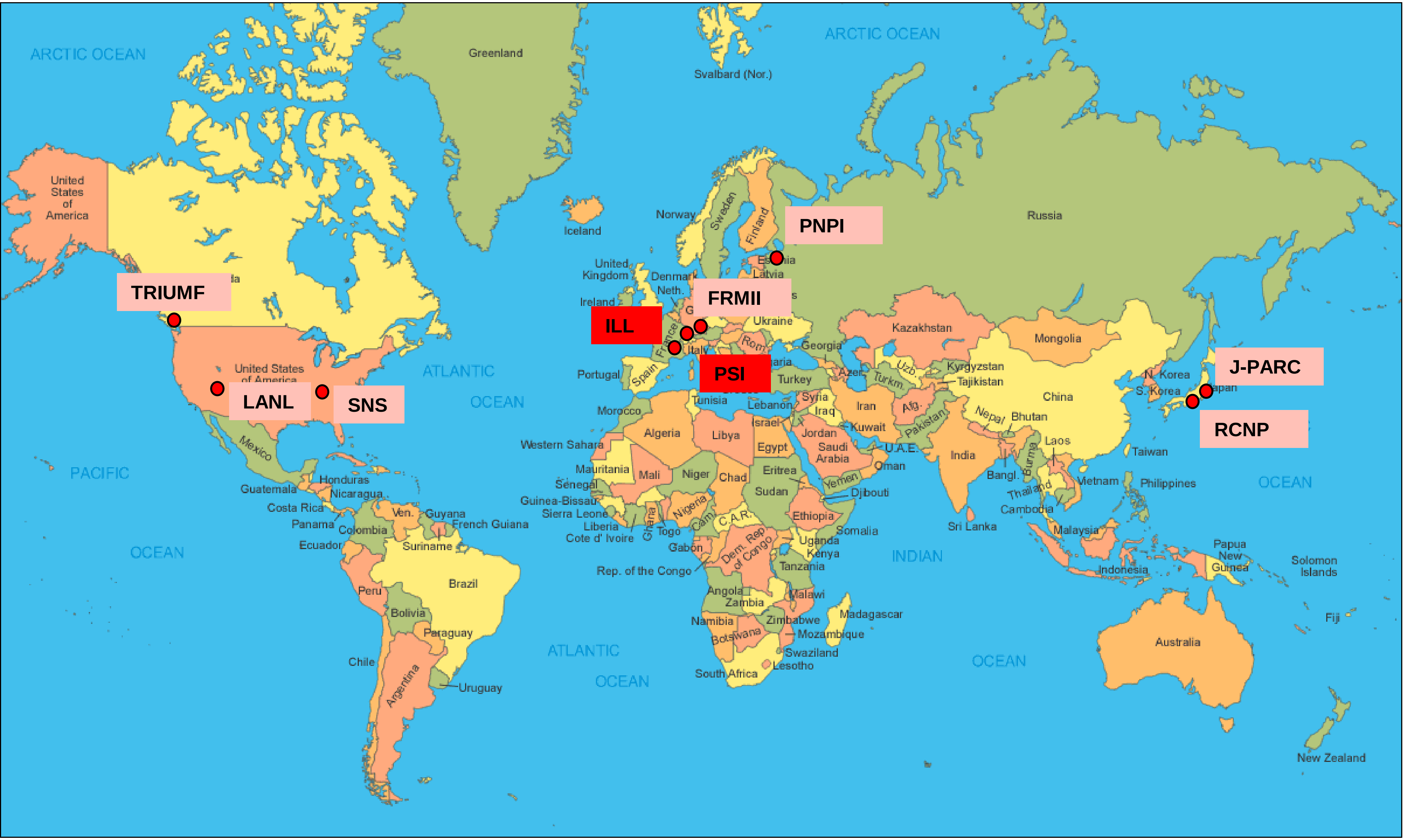


$$/nEDM/ \leq 5.5 \cdot 10^{-26}\, e \cdot cm$$

at 90% confidence level

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

Worldwide nEDM Searches

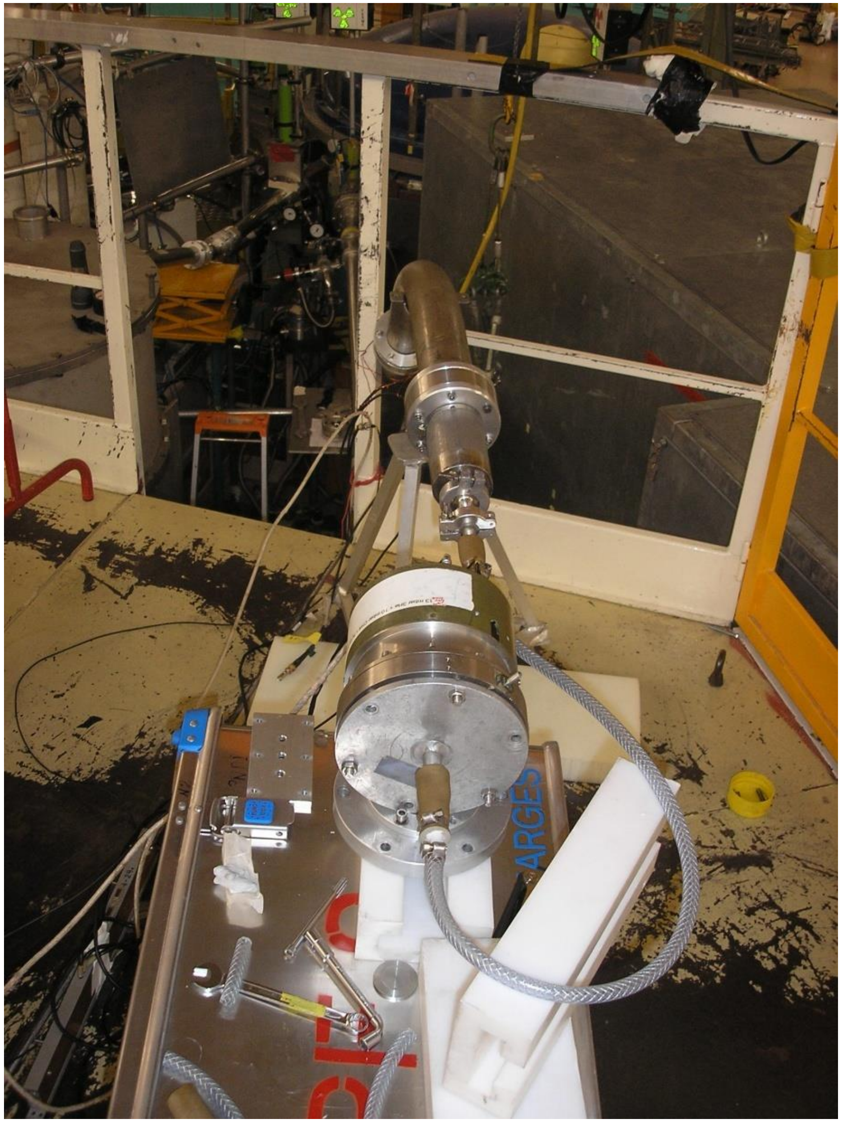


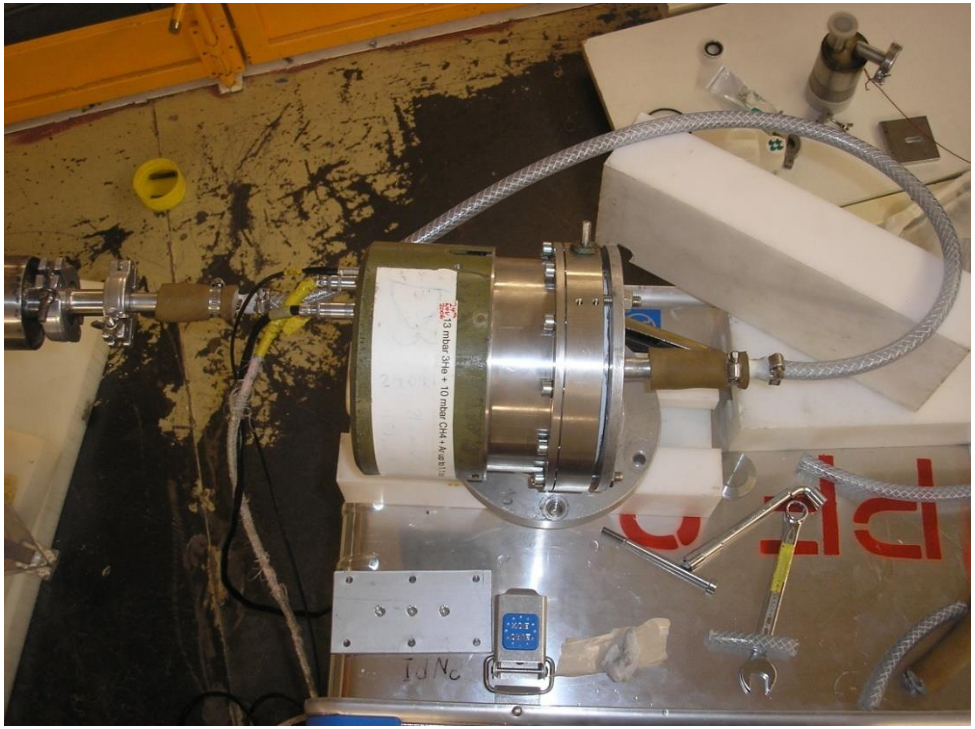

WHAT WOULD MACGYVER DO?

UCN are always good for a surprise!

Transmission through flexible water hose

Yu. Panin et al., RRC KI Moscow

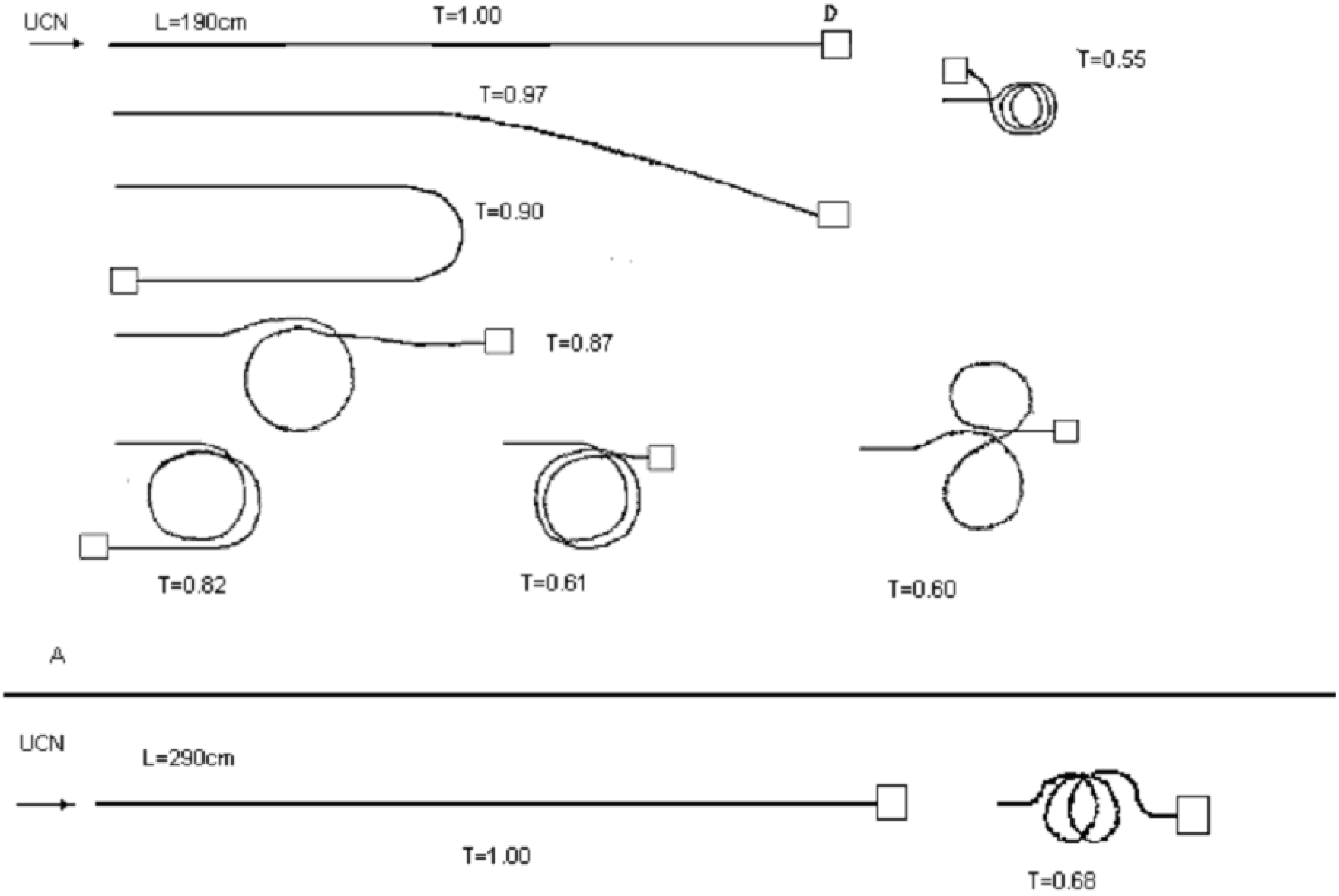




Surprising result
(80 cm hose with 8 mm inner diameter)

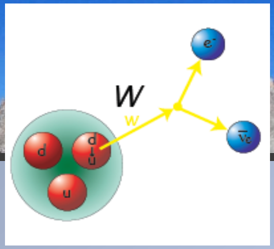
transmission around 85%

Relative Transmission Probability of “fancy guides”



<u>Top view:</u>

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



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

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

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

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

Together with measurements of *asymmetry coefficients* in neutron decay ⇐ ***Weak interaction theory***

↓

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:

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

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

Neutrino detectors:

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

↓

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

Cosmology

⇓

Solar pp-process:

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

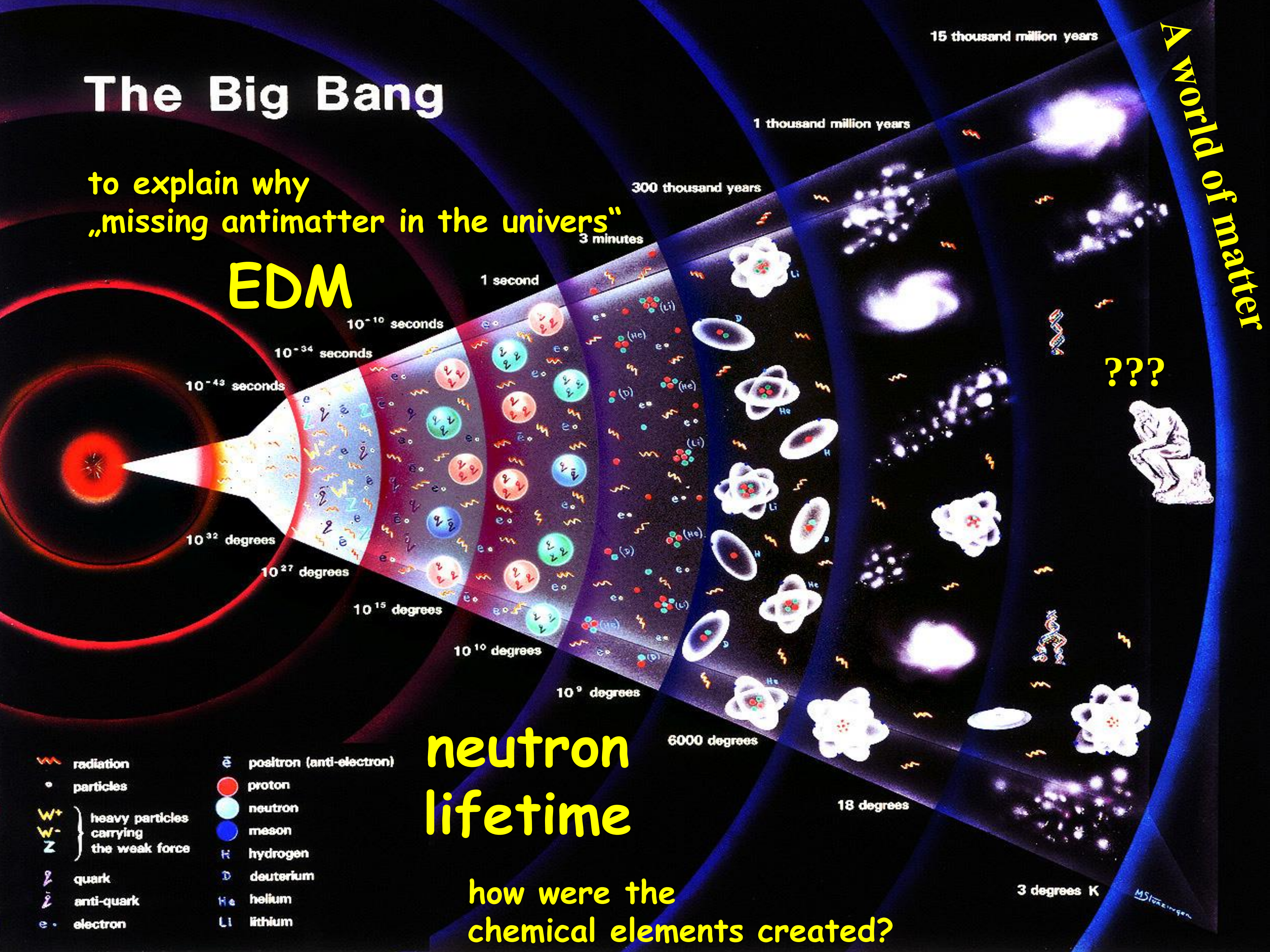
Big bang:

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



to explain why
„missing antimatter in the univers“

EDM

A world of matter

???

neutron
lifetime

how were the
chemical elements created?

Measurements of the neutron lifetime τ_n

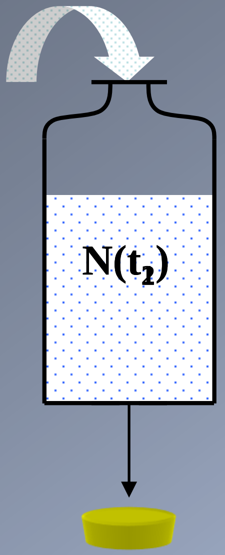
exponential decay law: $N = N_0 e^{-\lambda t}$

or, ultimately, <u>measure the exponential decay directly</u>

<u>Storage experiments with UCN</u>

"counting the surviving neutrons"

"UCN bottle"



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

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

→ 0 (experiment)

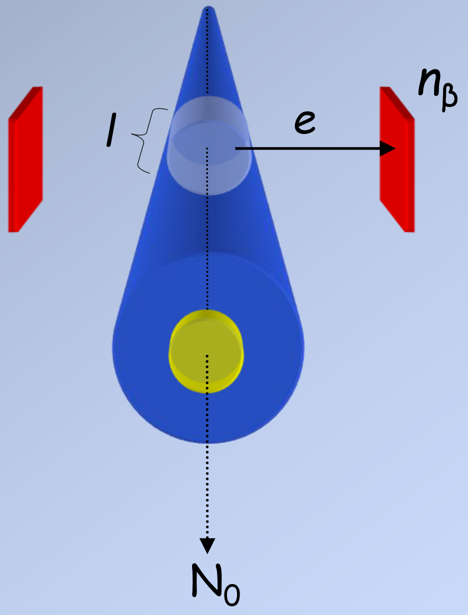
$$\frac{1}{\tau_{\text{wall}}} = \mu \cdot v_{\text{eff}}$$ → 0 (extrapolation)

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

Two relative measurements

<u>Beam experiments with cold neutrons</u>

"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?

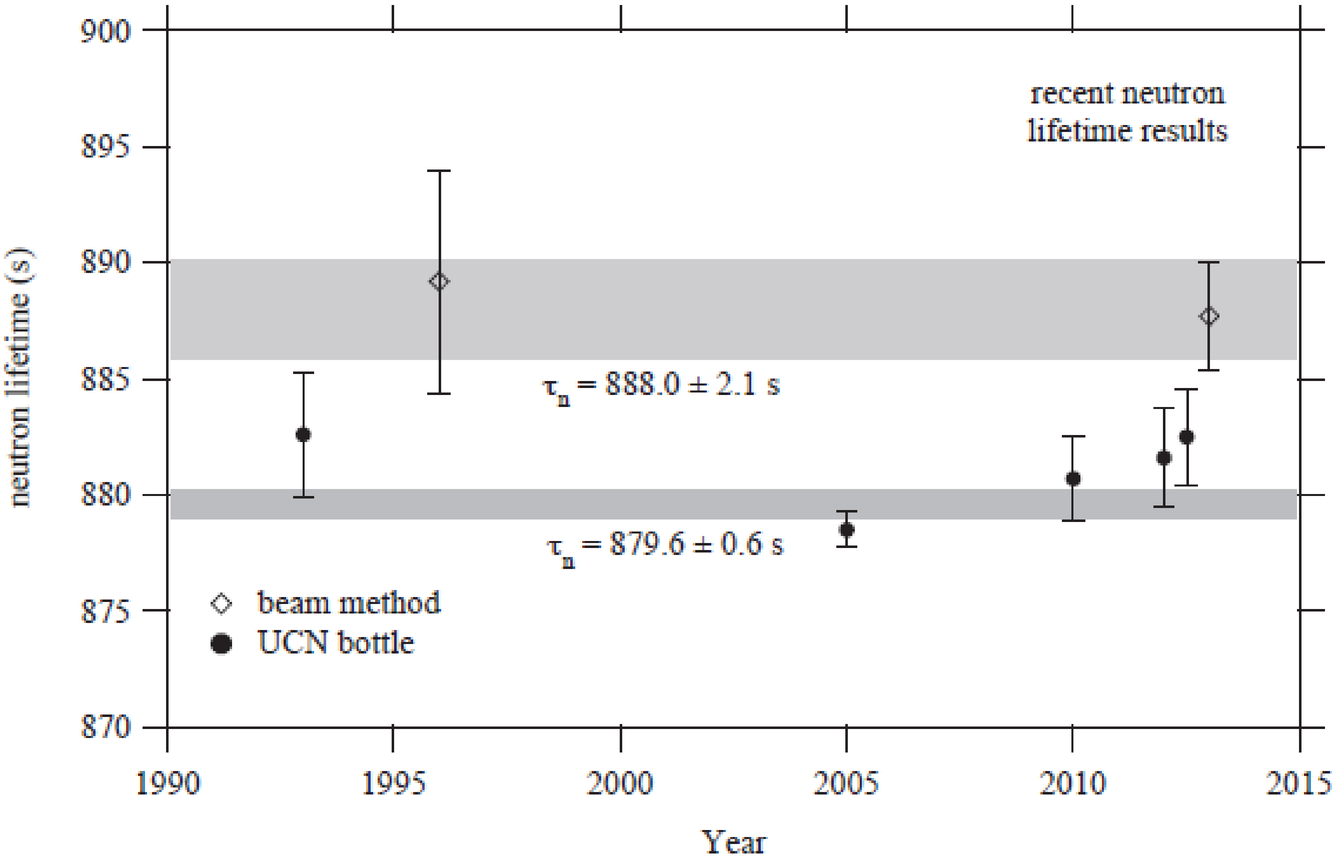
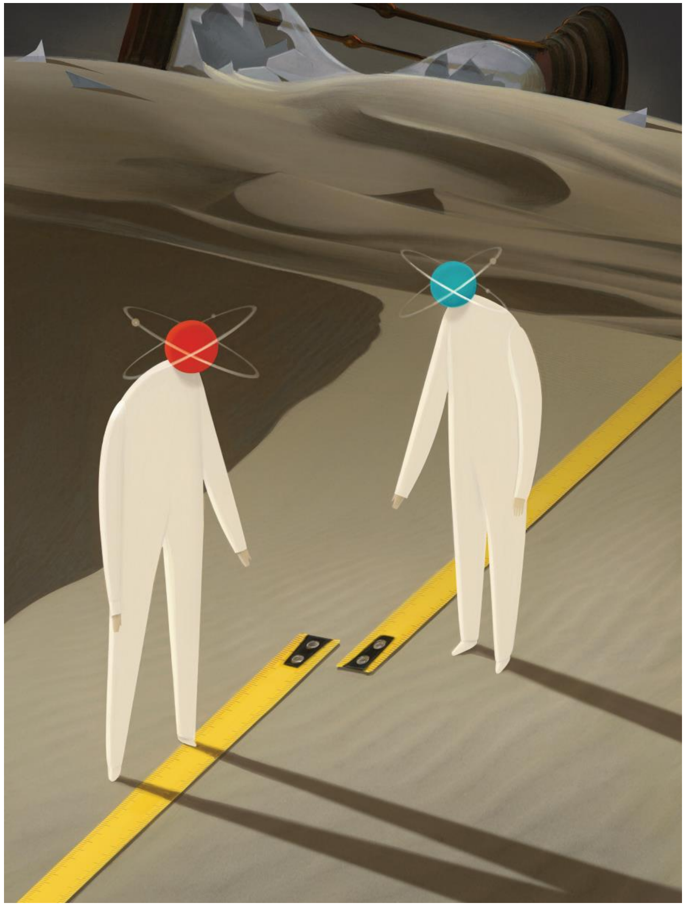
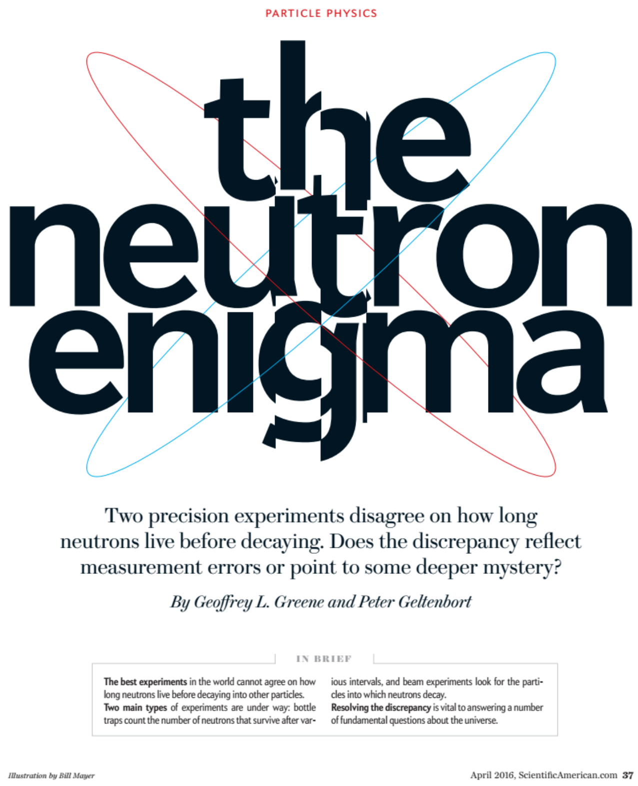


Figure 2: A summary of recent neutron lifetime measurements, showing the five UCN bottle [18, 16, 19, 20, 21] and two neutron beam [12, 15] results used in the 2014 PDG recommended value of $\tau_n = 880.3 \pm 1.1$ s. The shaded regions show the weighted average $\pm 1\sigma$ of each method, which disagree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

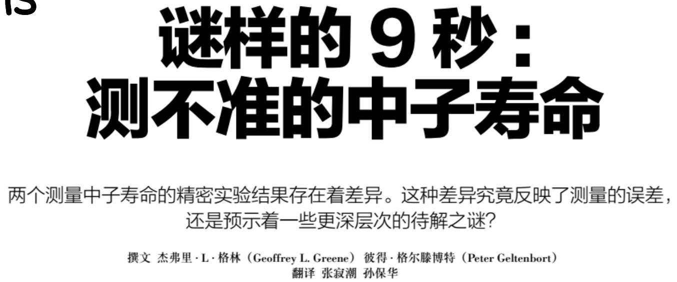
April 2016, ScientificAmerican.com **37**

Translated and published in International Editions of Scientific American:

France, Germany, Italy, Spain

China, Japan,

Russia, Poland, Israel, …

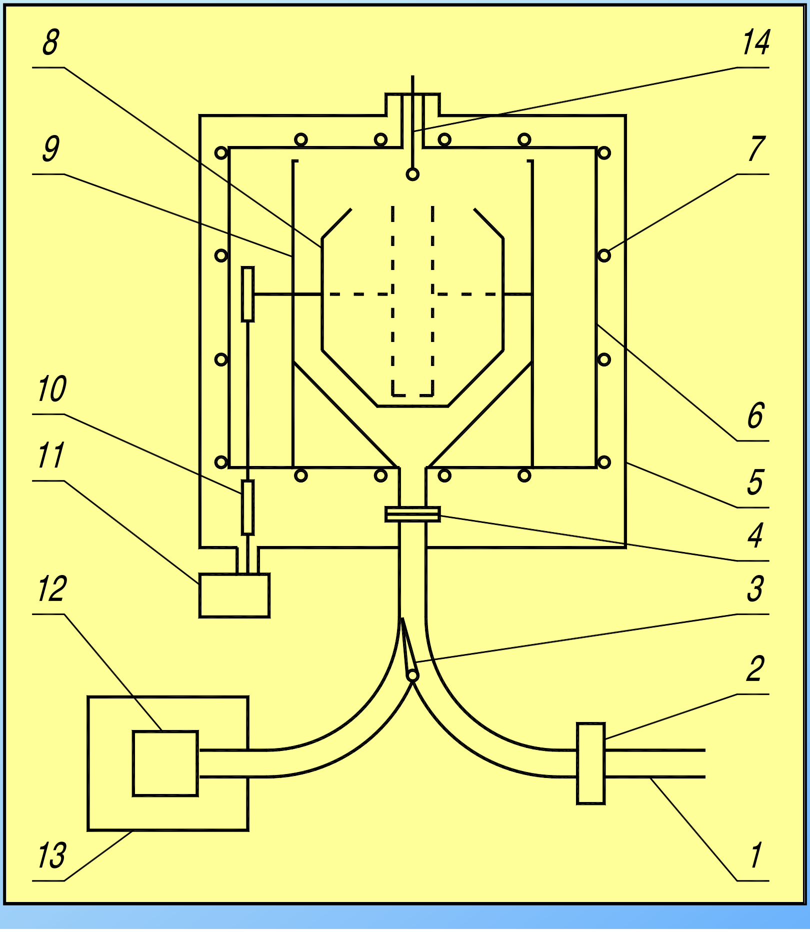


谜样的 9 秒：
测不准的中子寿命

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

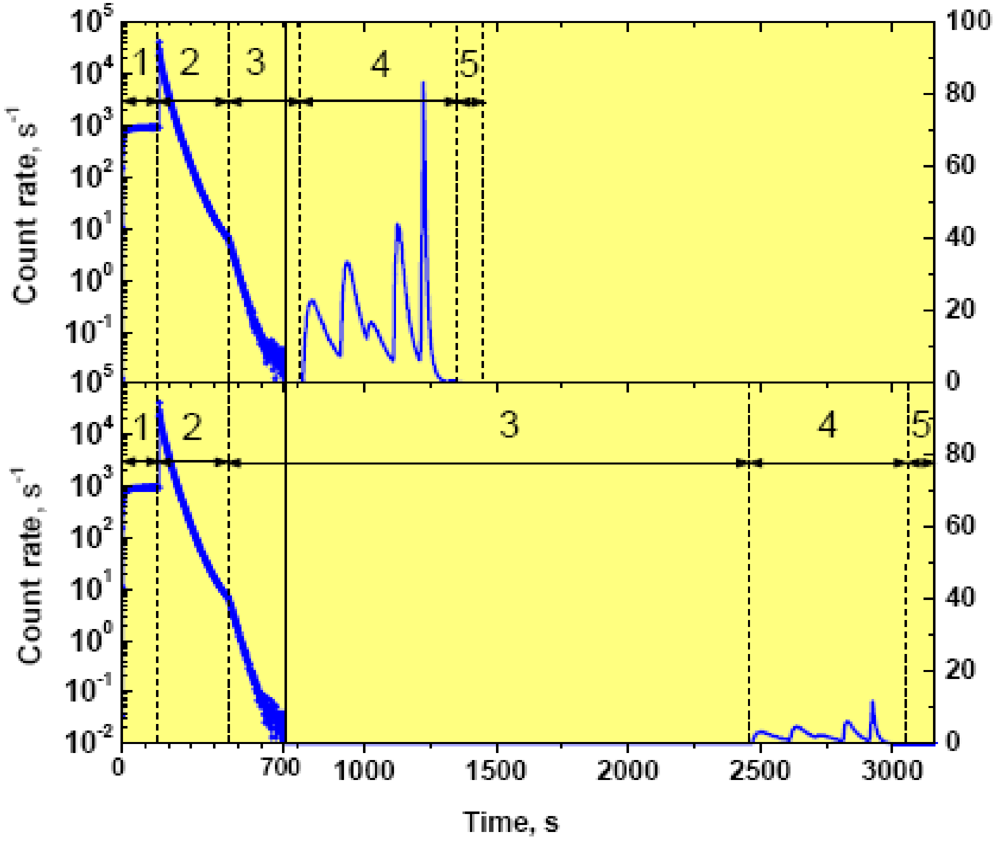
Scheme of “Gravitrap”, the gravitational UCN storage system



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

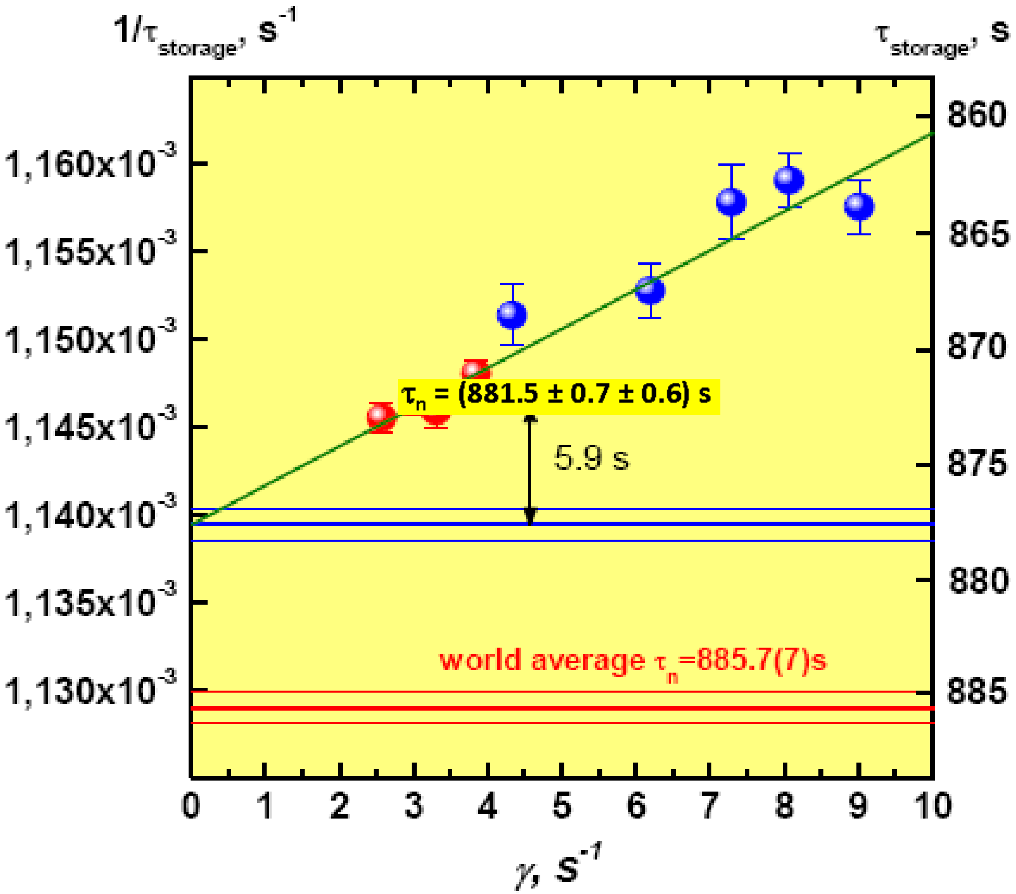


1. filling 160 s (time of trap rotation (35 s) to monitoring position is included);
2. monitoring 300 s;
3. holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included);
4. emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5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

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

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

Extrapolation to n-lifetime



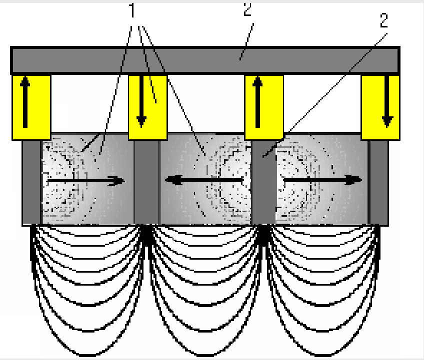
A.P. Serebrov et al. , Phys Lett B 605, (2005) 72-78 : **(878.5 ± 0.8) s**

General principle and design

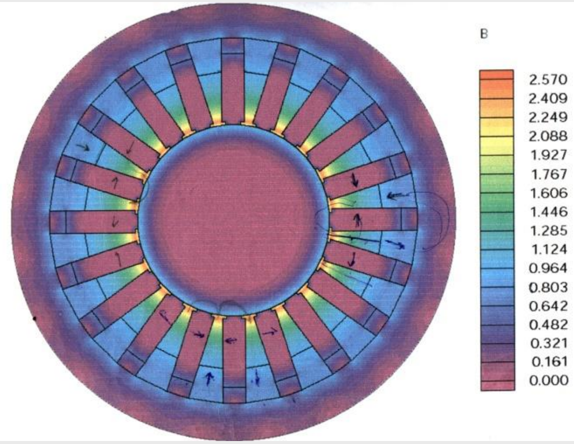
- For μ_n = -60.3 neV/T, a 2T field generates a 120 neV barrier.
- Force due to field gradient, $F = -\mu\,(dB/dz)$, repels only one spin state.
- Use permanent magnets.

- **Step 1: 1D confinement**

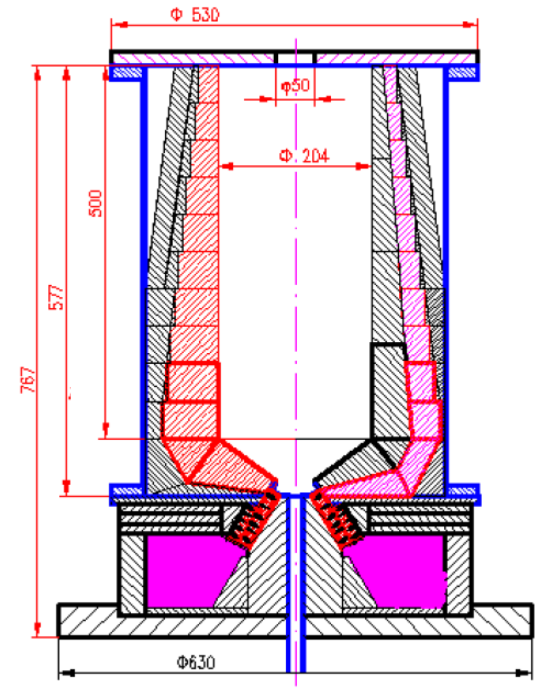
1 – permanent magnets
2 – magnetic poles



- **Step 2: 2D confinement**

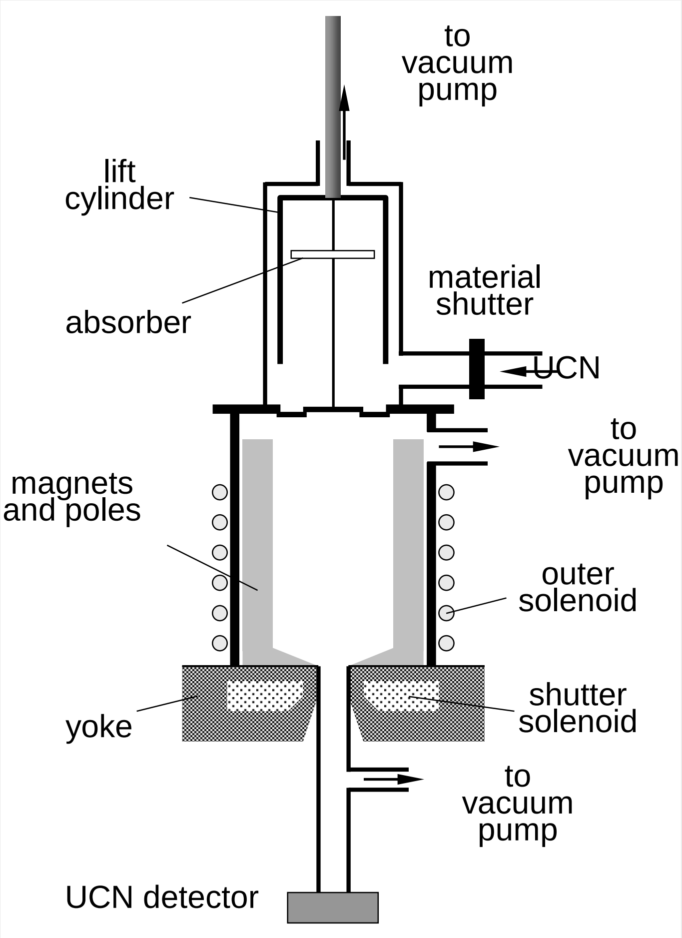


- **Step 3: 3D confinement**
  - top (gravity)
  - bottom (magnetic shutter)



Magnetic trap for neutron lifetime measurement

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



Lift: Fomblin coated Al cylinder + PE disk

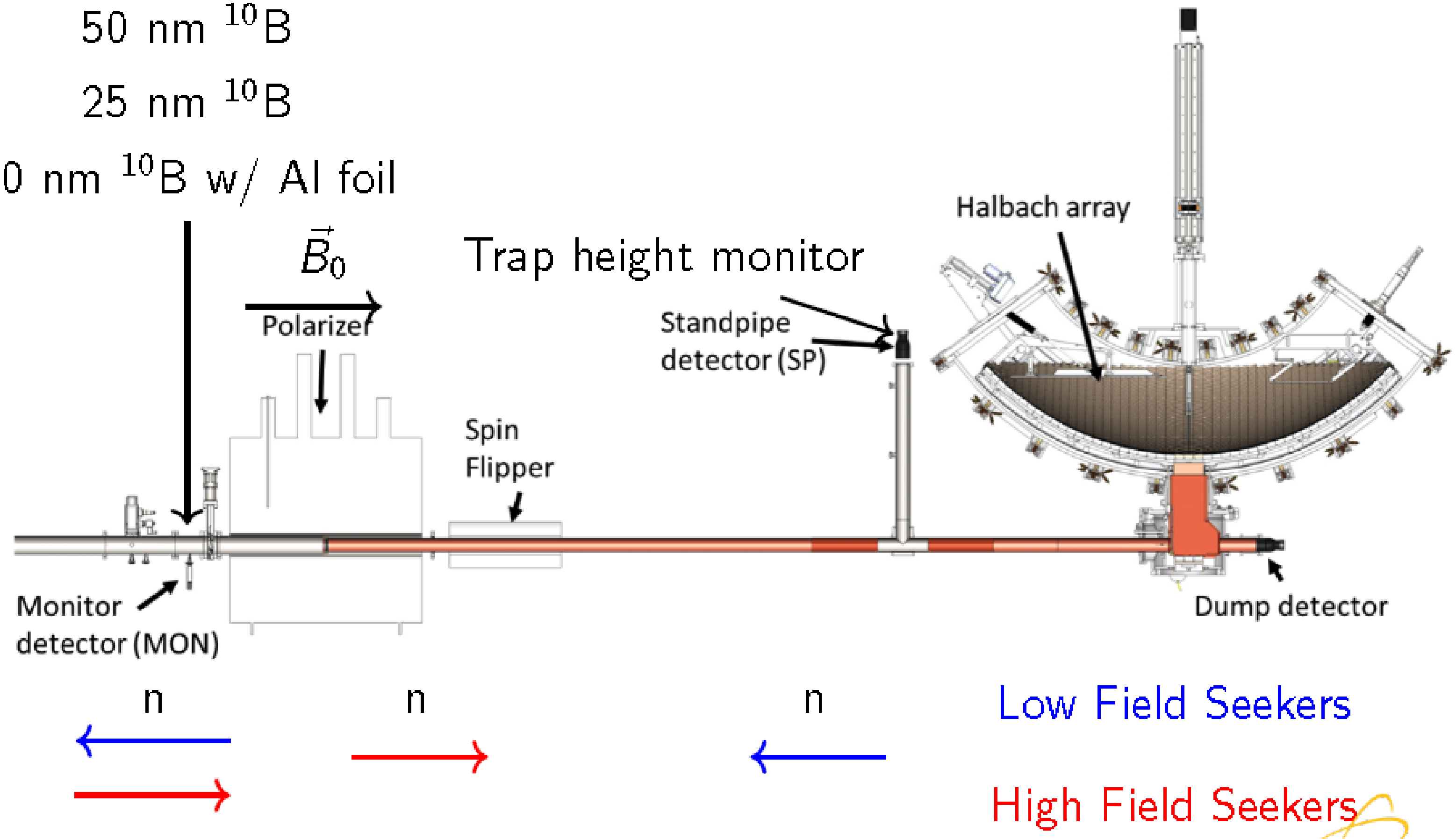
(878.3 ± 1.9) s

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

Side view of the experiment

UCN Monitors:

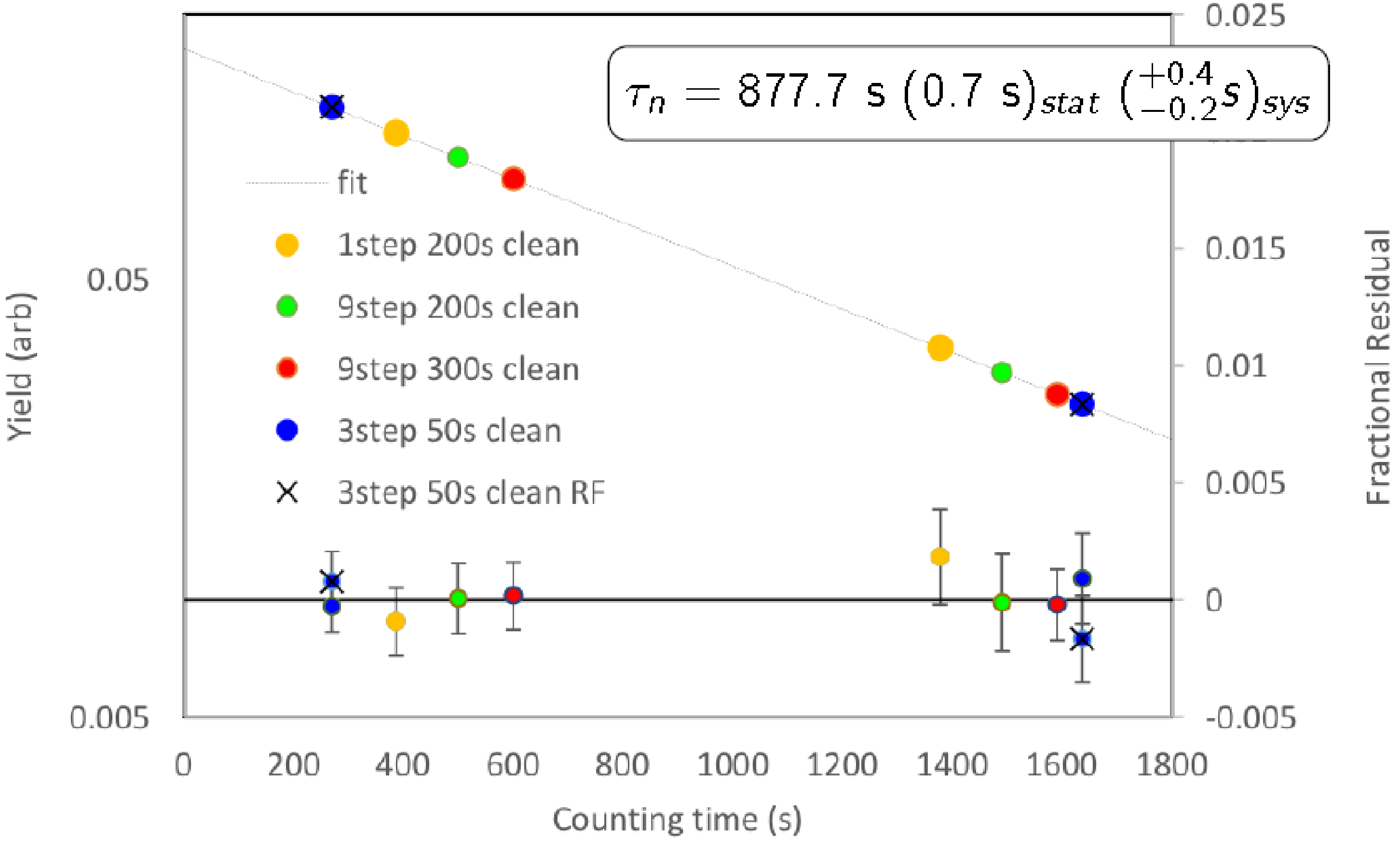
- 50 nm ^{10}B
- 25 nm ^{10}B
- 50 nm ^{10}B w/ Al foil



Low Field Seekers

High Field Seekers

2016-2017 Lifetime Results



$$\tau_n = 877.7\ \text{s}\ (0.7\ \text{s})_{stat}\ (^{+0.4}_{-0.2}\text{s})_{sys}$$

4

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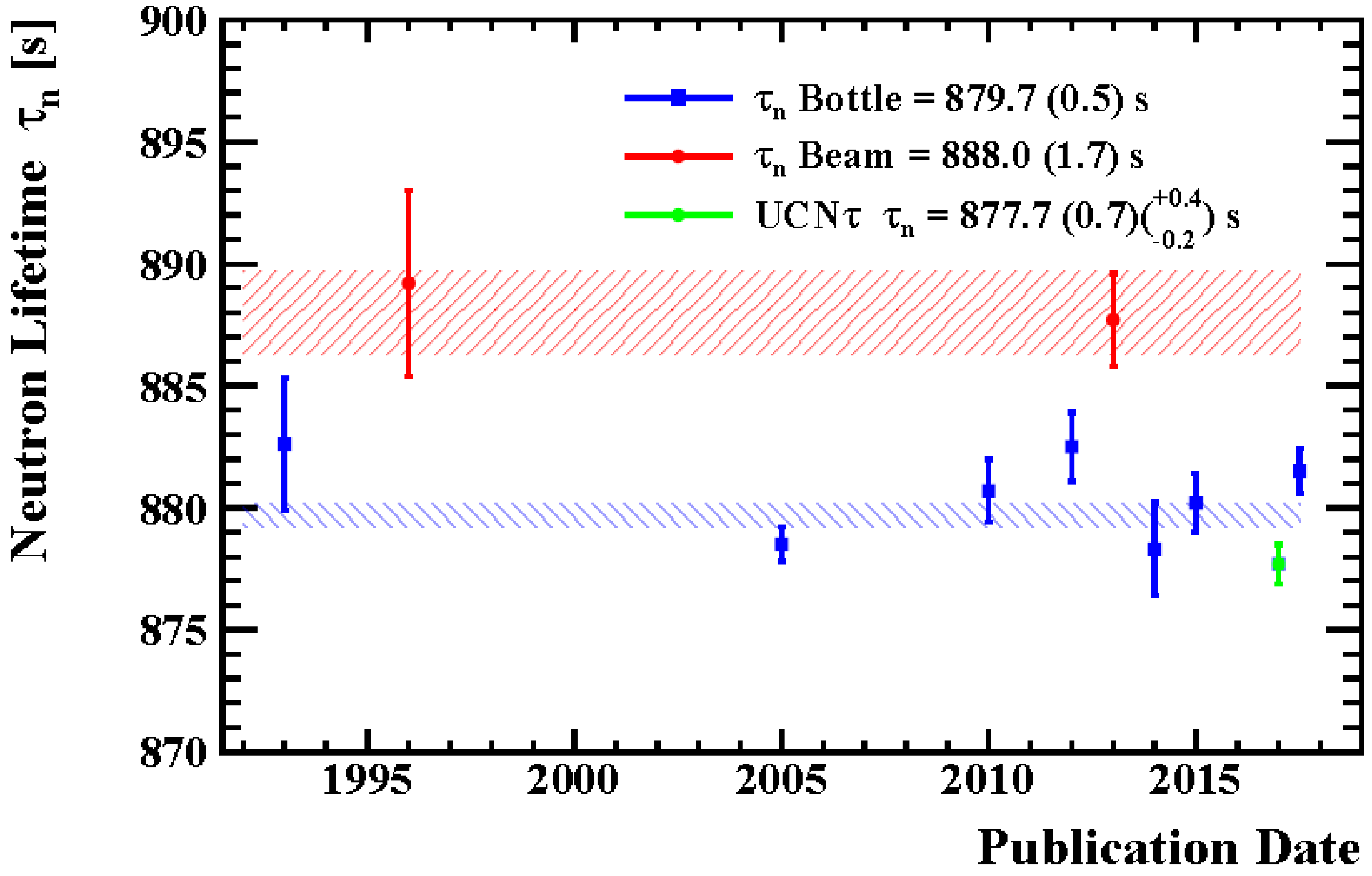
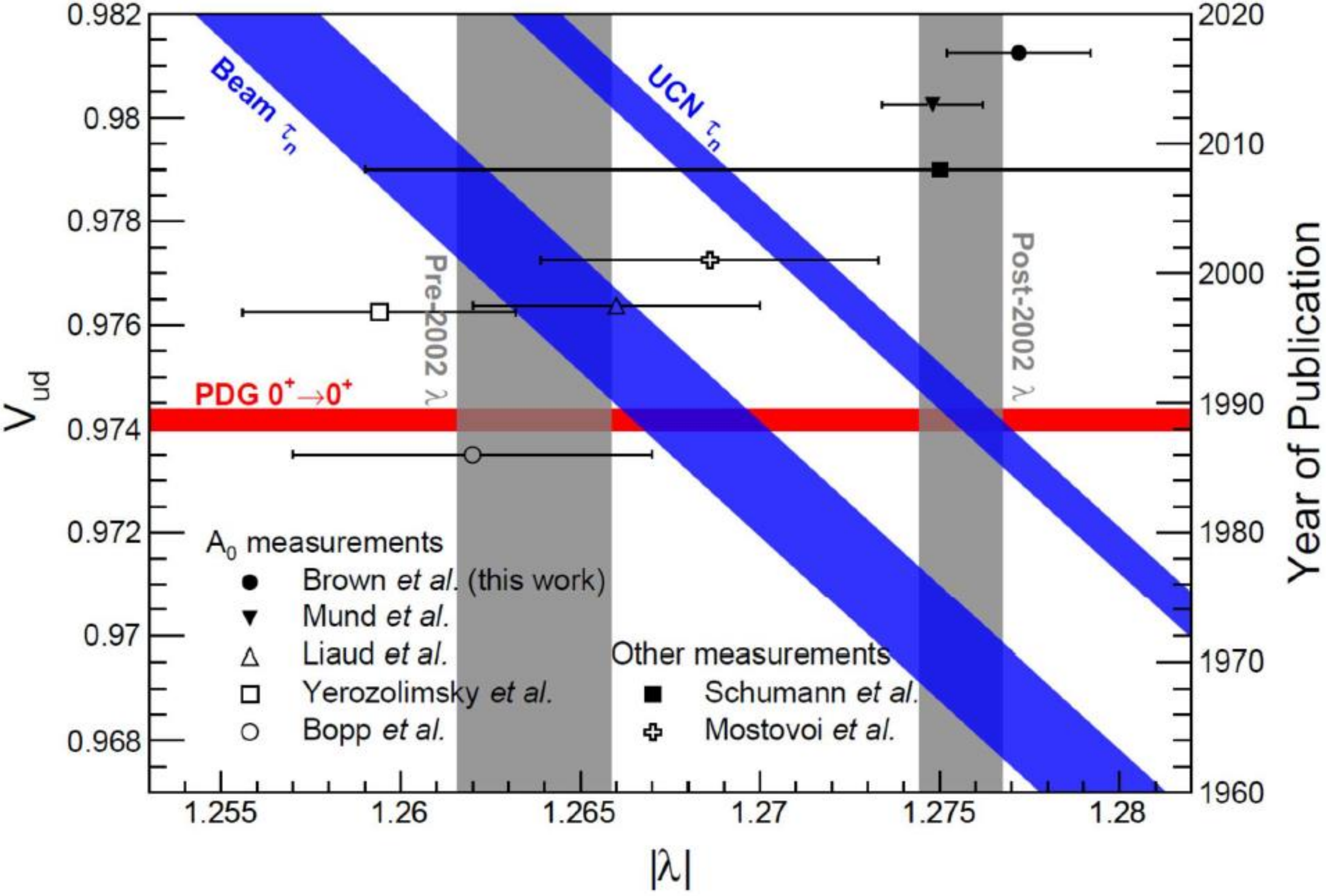
[4] R. W. Pattie Jr *et al*, Science **360**, 6389 p.627-632 (2018) (arXiv:1707.01817)

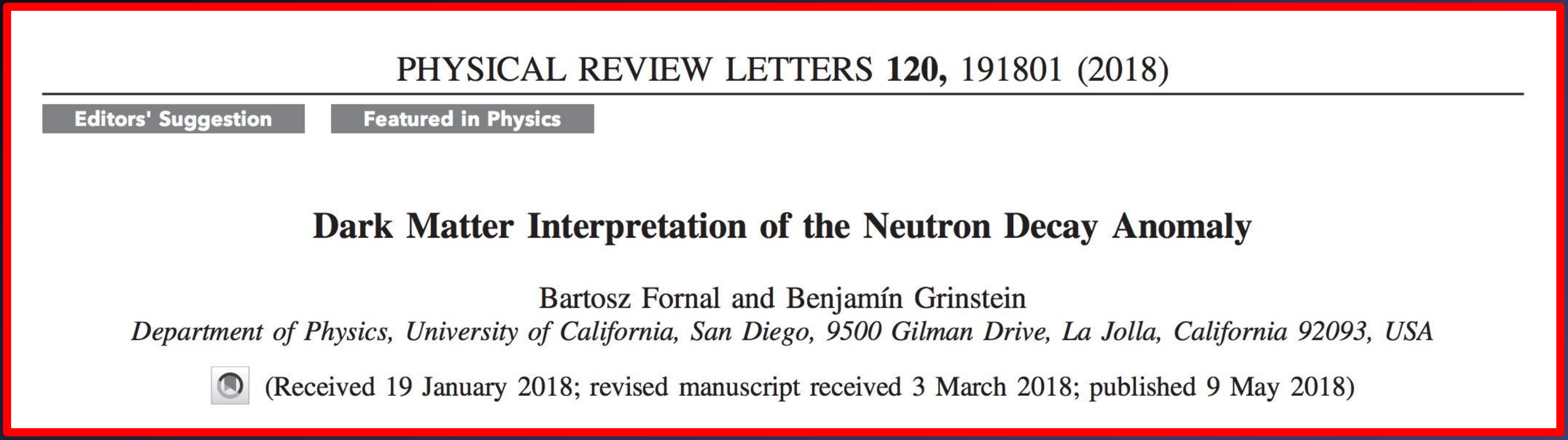
How does this compare?



Experimental Landscape: τ_{n}, V_{ud}



Neutron dark decay



PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion **Featured in Physics**

Dark Matter Interpretation of the Neutron Decay Anomaly

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(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

$$\boxed{\mathrm{Br}(n \to p + \text{anything}) \approx 99\%}$$

Remaining 1% :

- → $\boxed{n \to \text{SM particles (other than } p)}$ ✗
- → $\boxed{n \to \text{dark particle(s)} + \text{SM particle(s)}}$ ✓
- → $\boxed{n \to \text{dark particles}}$ ✓

Possible decay channels

$$937.900 \text{ MeV} < M_f < 939.565 \text{ MeV}$$

Neutron → dark particle + photon

Neutron → dark particle + e^+e^-

Neutron → two dark particles

Neutron → …

Wishful thoughts

- ***“Missing Neutrons May Lead a Secret Life as Dark Matter”,***
  C. Moskowitz, Scientific American (January 29, 2018)

- ***It would be truly amazing if the good old neutron turned out to be the particle enabling us to probe the dark matter sector of the universe***

Worldwide nLifetime Searches

Neutrons in the gravity field

- Schrödinger equation with linearized gravity potential

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

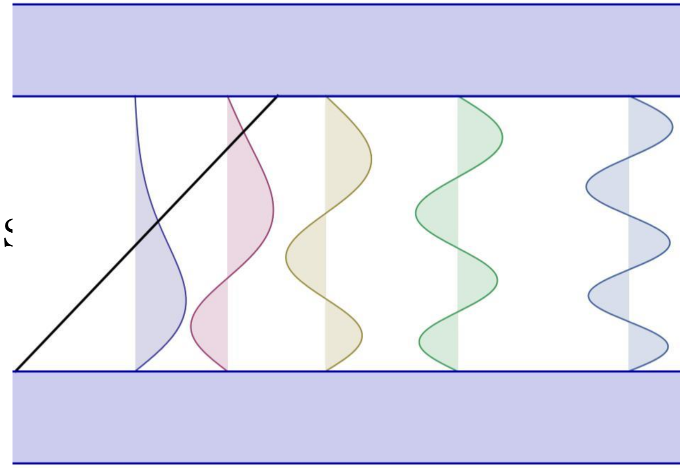
bc: $\varphi_n(0)=0, \quad \varphi_n(l)=0$

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

- bound, discrete states
- Non-equidistant energy levels

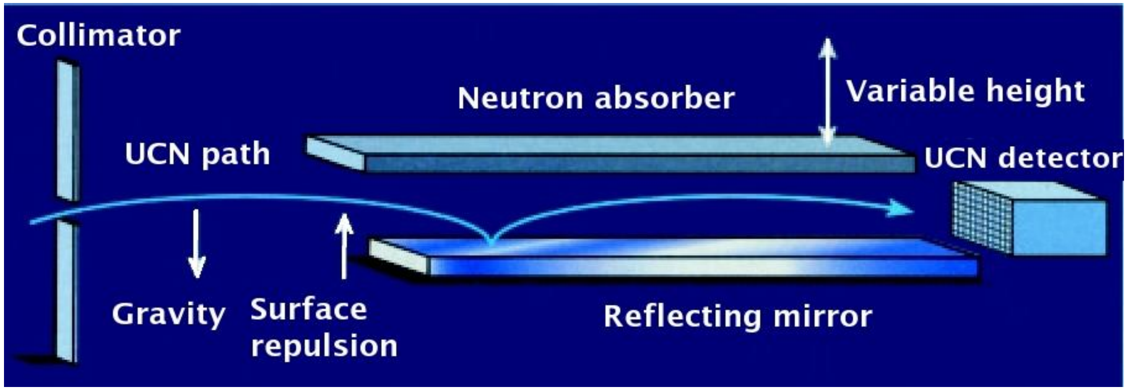
state	energy
1	1.41 peV
2	2.56 peV
3	3.98 peV

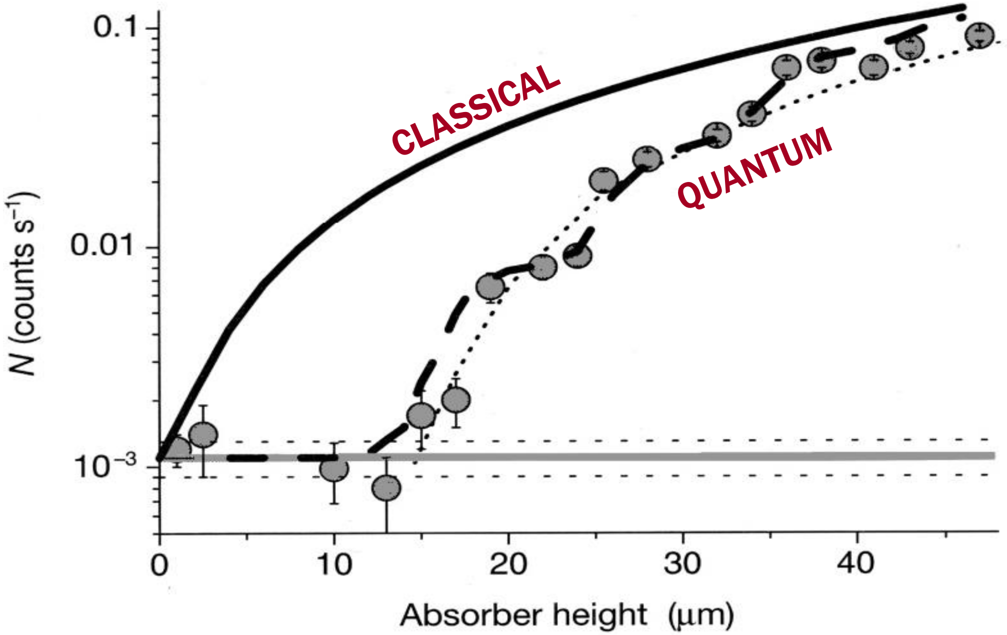
Slit width l=27 μm



Discovery of neutron quantum states in 1999

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





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

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

Motivation

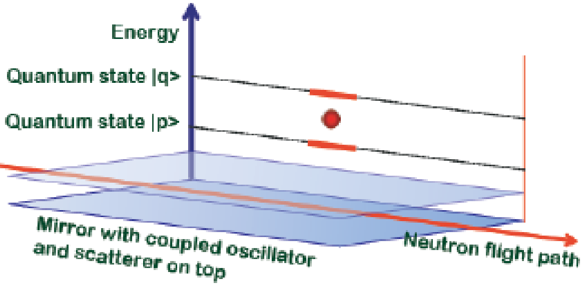
- qBounce: quantized gravity bound states of ultra-cold neutrons

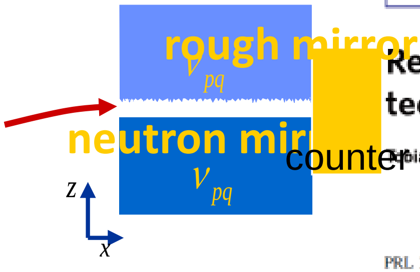
- Test of Newton’ s gravity potential at small distances (microns)
- Detection of new forces
- Tests for chameleons, axions

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

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

Gravity Resonance Spectroscopy



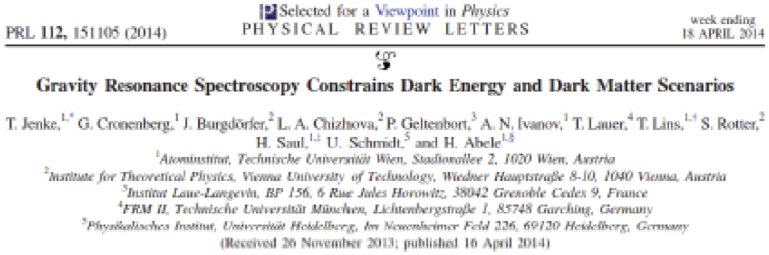


nature physics LETTERS

PUBLISHED ONLINE: 17 APRIL 2011 | DOI: 10.1038/NPHYS1970

Realization of a gravity-resonance-spectroscopy technique

bias 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,§]
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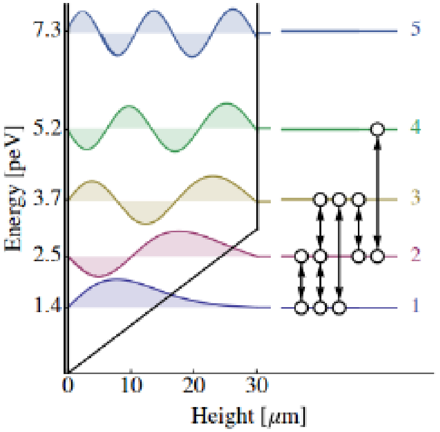
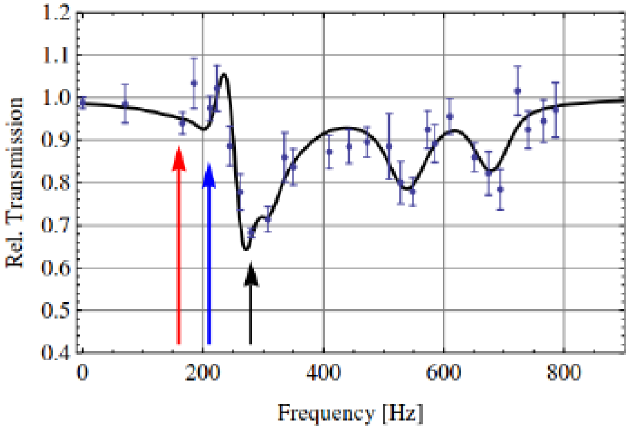
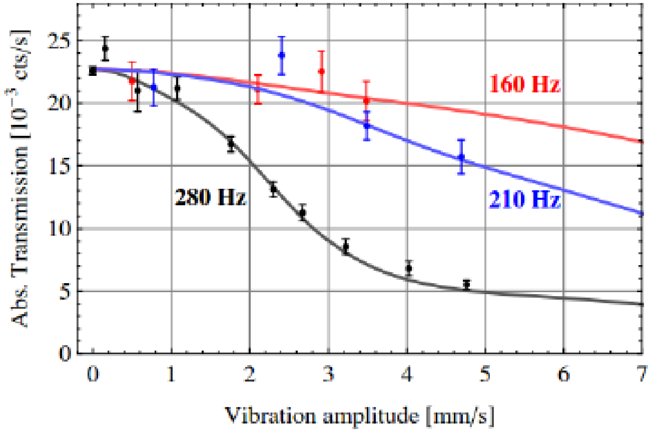
[3]*Institut Laue-Langevin, BP 156, 6 Rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
[4]*FRM II, Technische Universität München, Lichtenbergstraße 1, 85748 Garching, Germany*
[5]*Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*

(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)

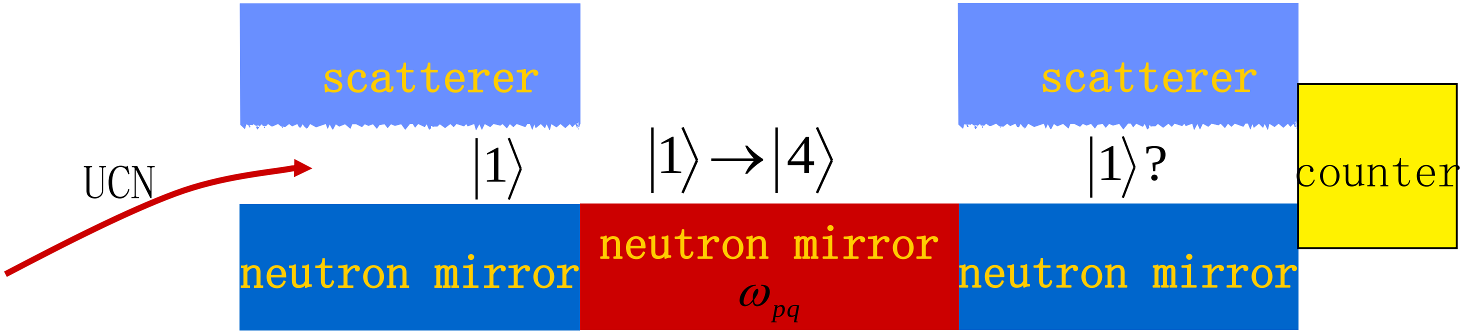






Gravity Resonance Spectroscopy (GRS)

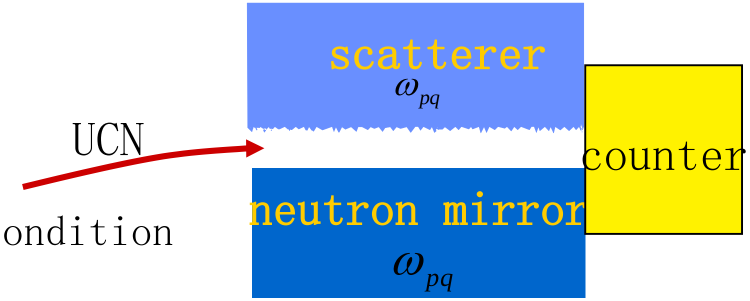
- **Rabi** setup (2012)

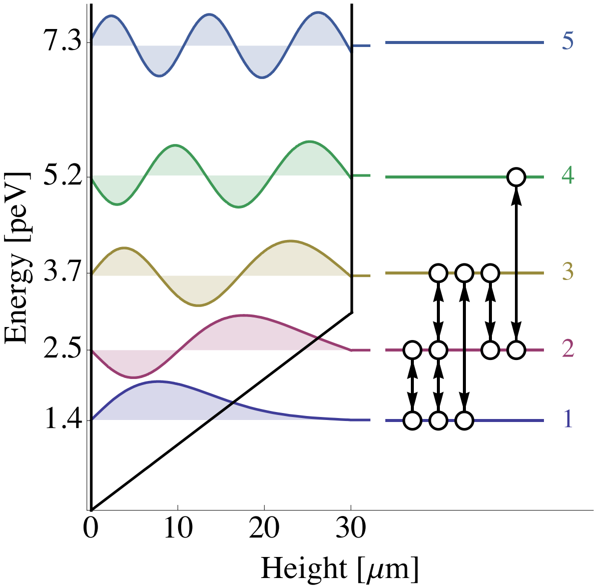


- First realisation (2009, 2010)

Rabi-like experiment with **damping**

but scatterer introduces 2^{nd} boundary condition





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

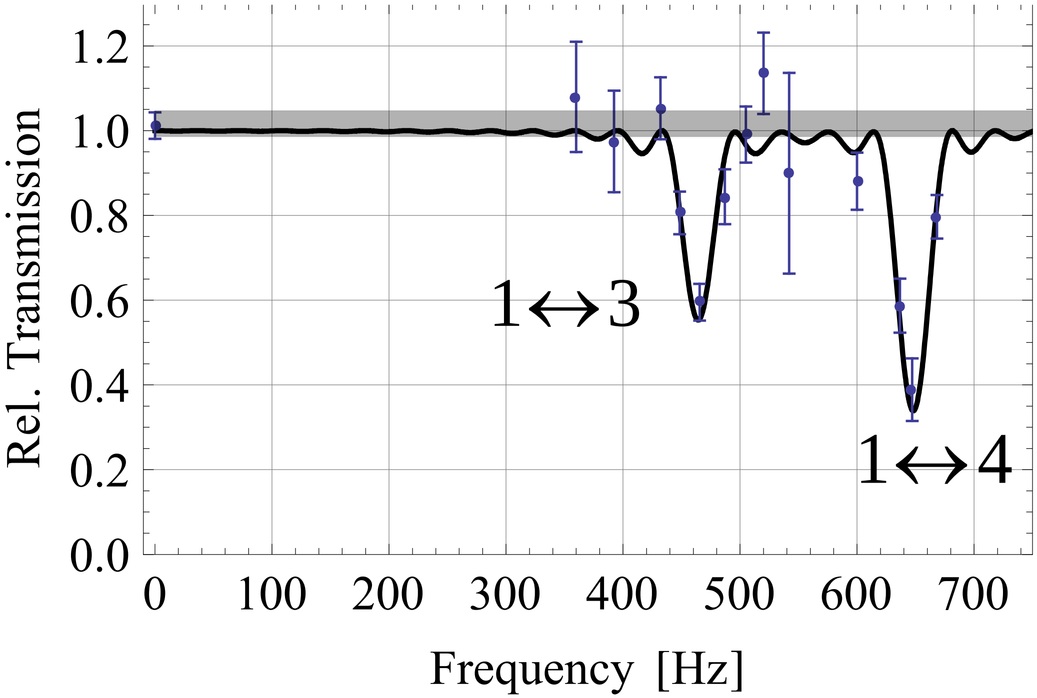
Results

Transitions 1-3 and 1-4 observed

1-3: (46 ± 5)% intensity drop

1-4: (61 ± 7)%

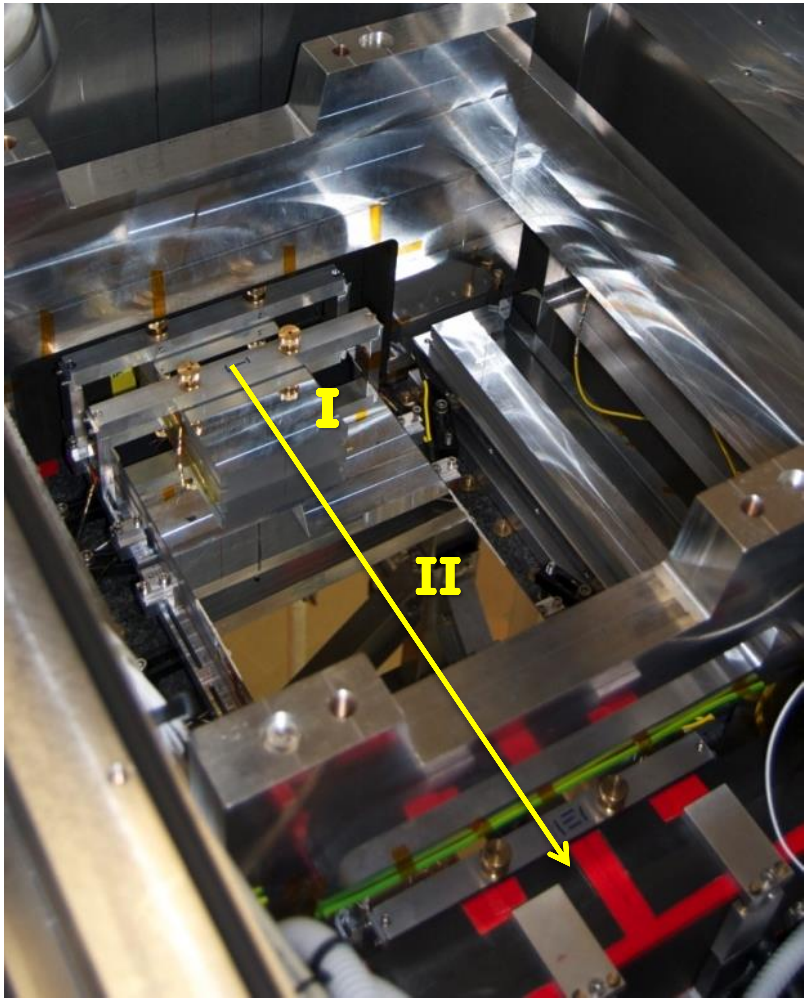
@ 2.1 mm/s

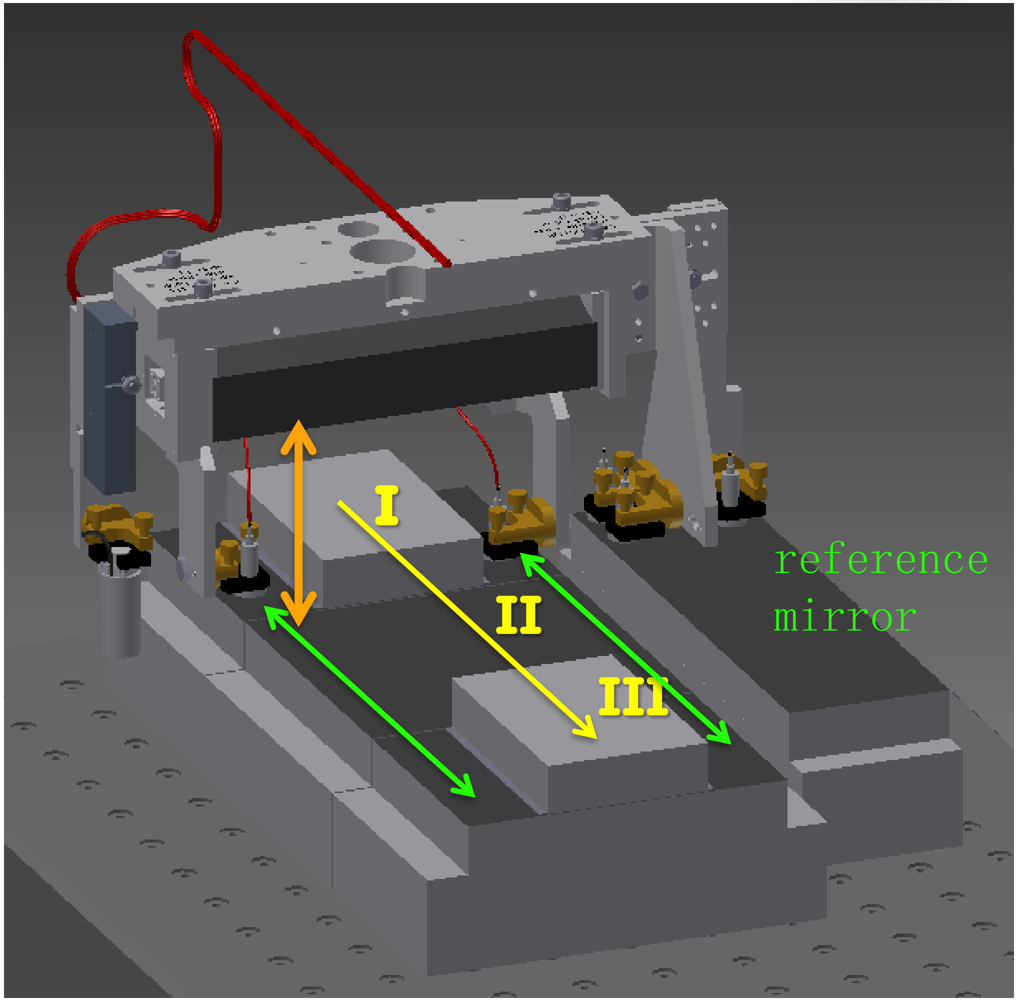


60 measurements

Preliminary, generic fit

Setup

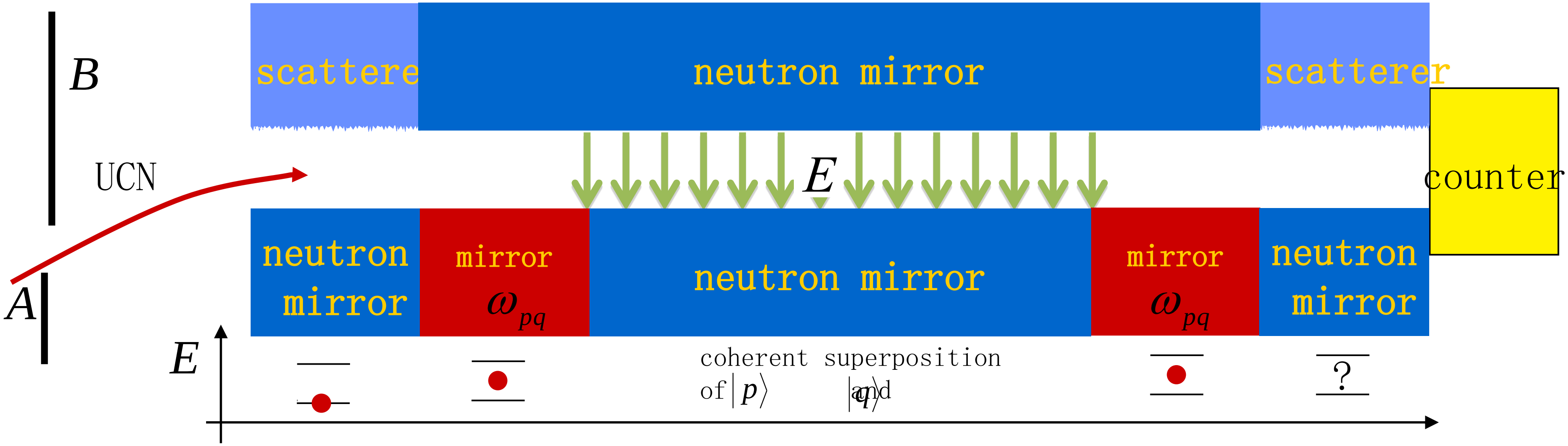




M. Horvath

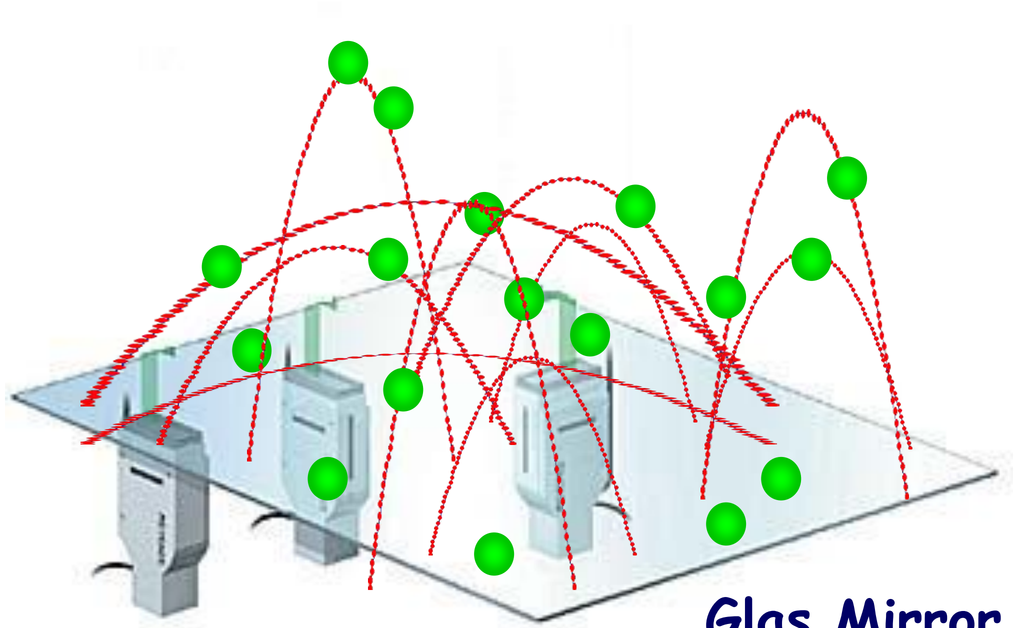
Outlook:
Probing neutrons neutrality

- Electric field modifies detectable phase



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

Realization of a Neutron Bouncing Ball Gravity Spectrometer



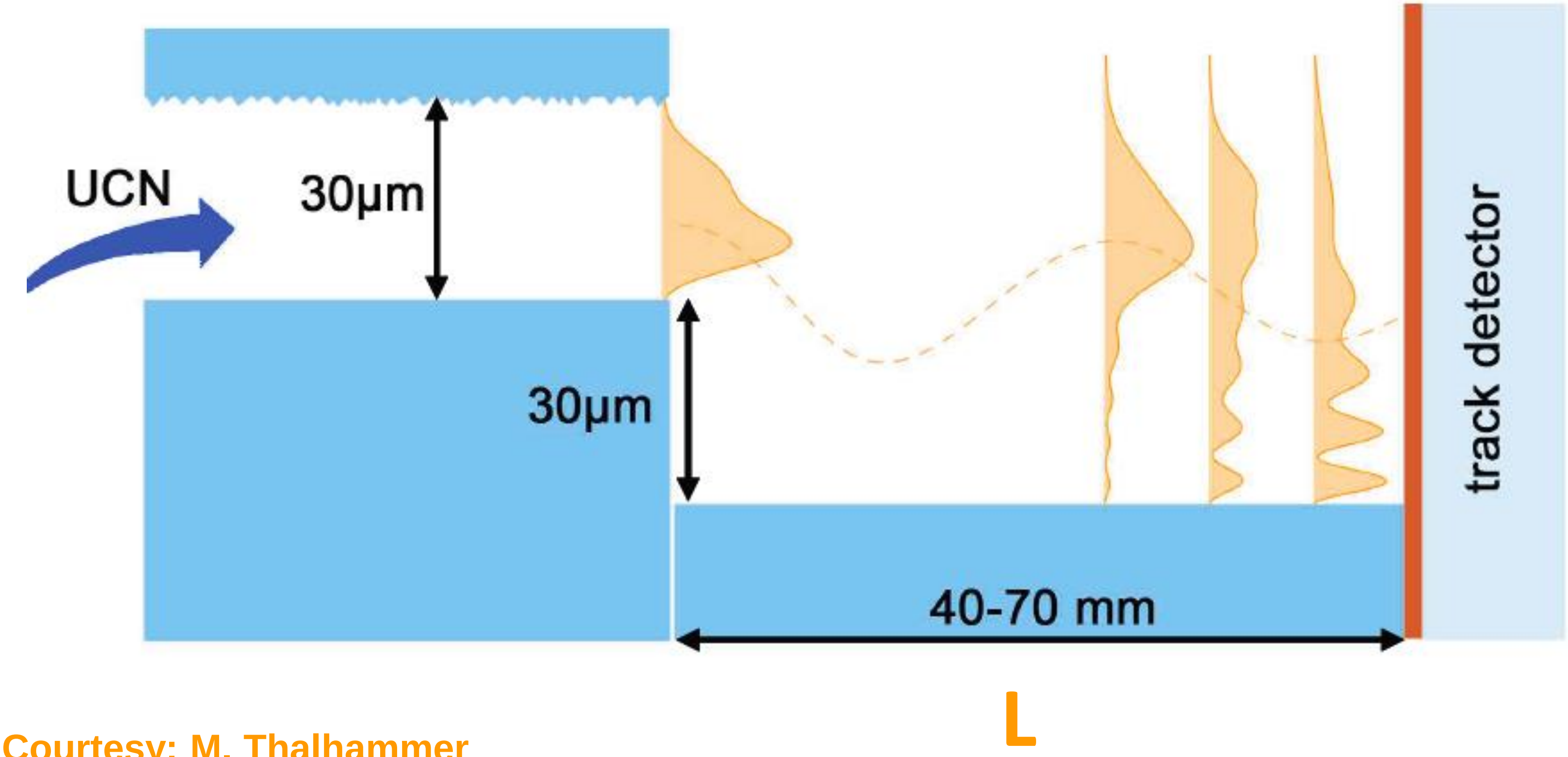
Glas Mirror

Piezo Driver

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

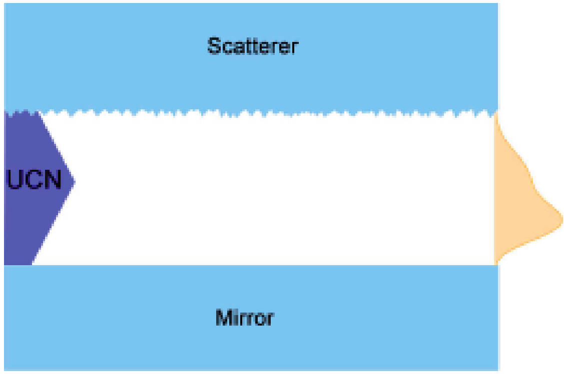
quantum bouncing ultracold neutrons

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



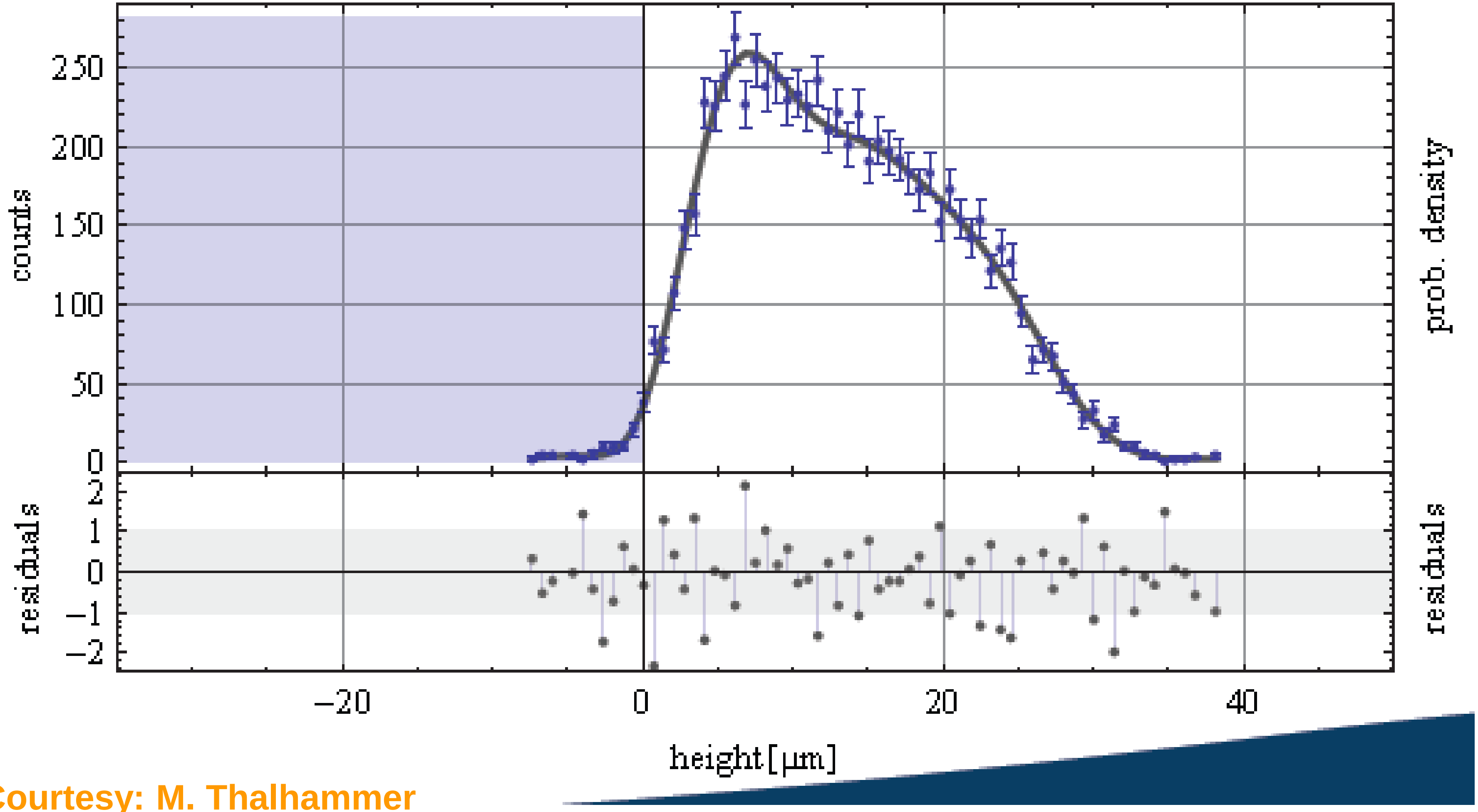
Courtesy: M. Thalhammer

Preparation L = 0



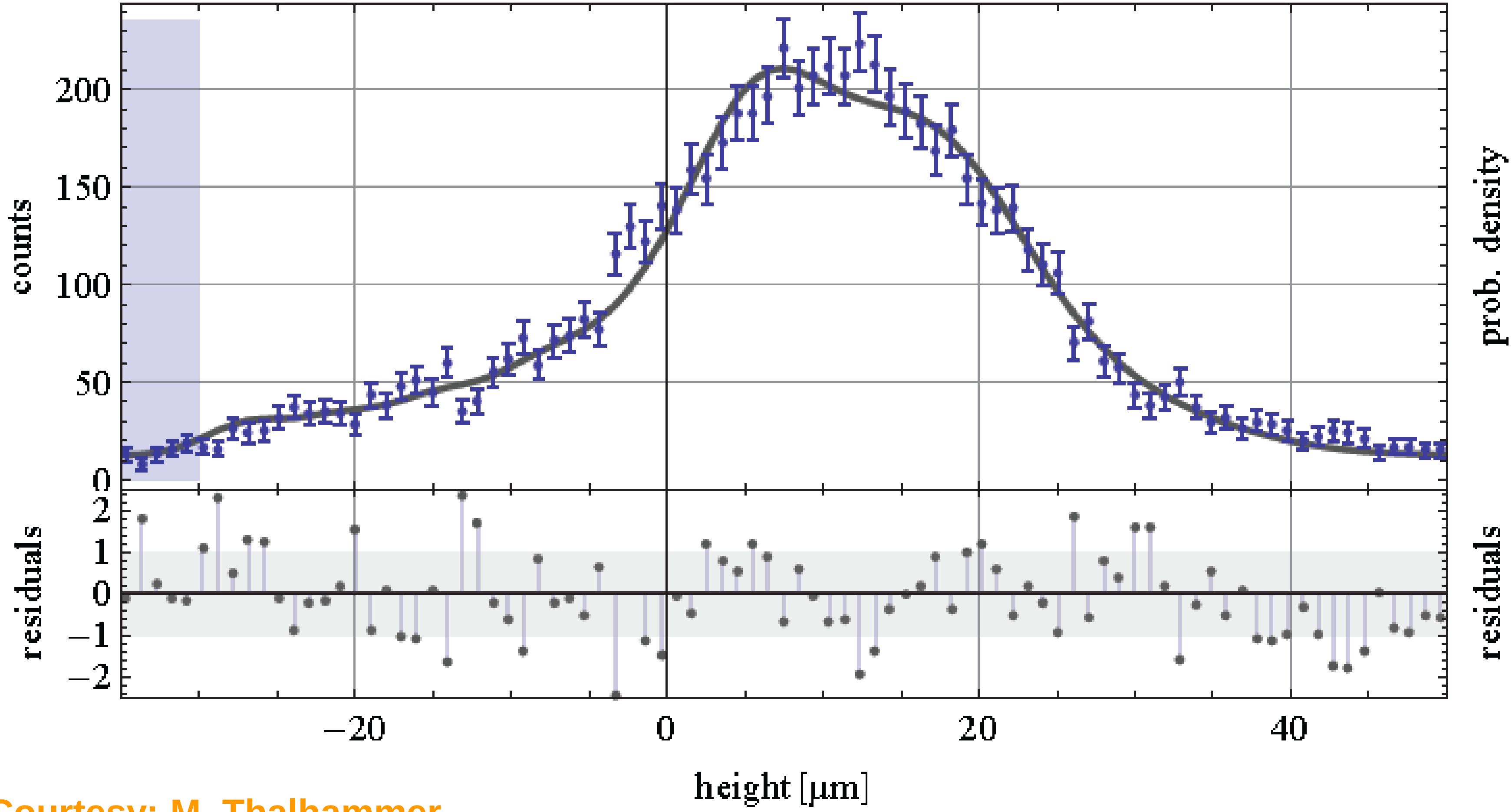
$$|\Psi_I(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

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



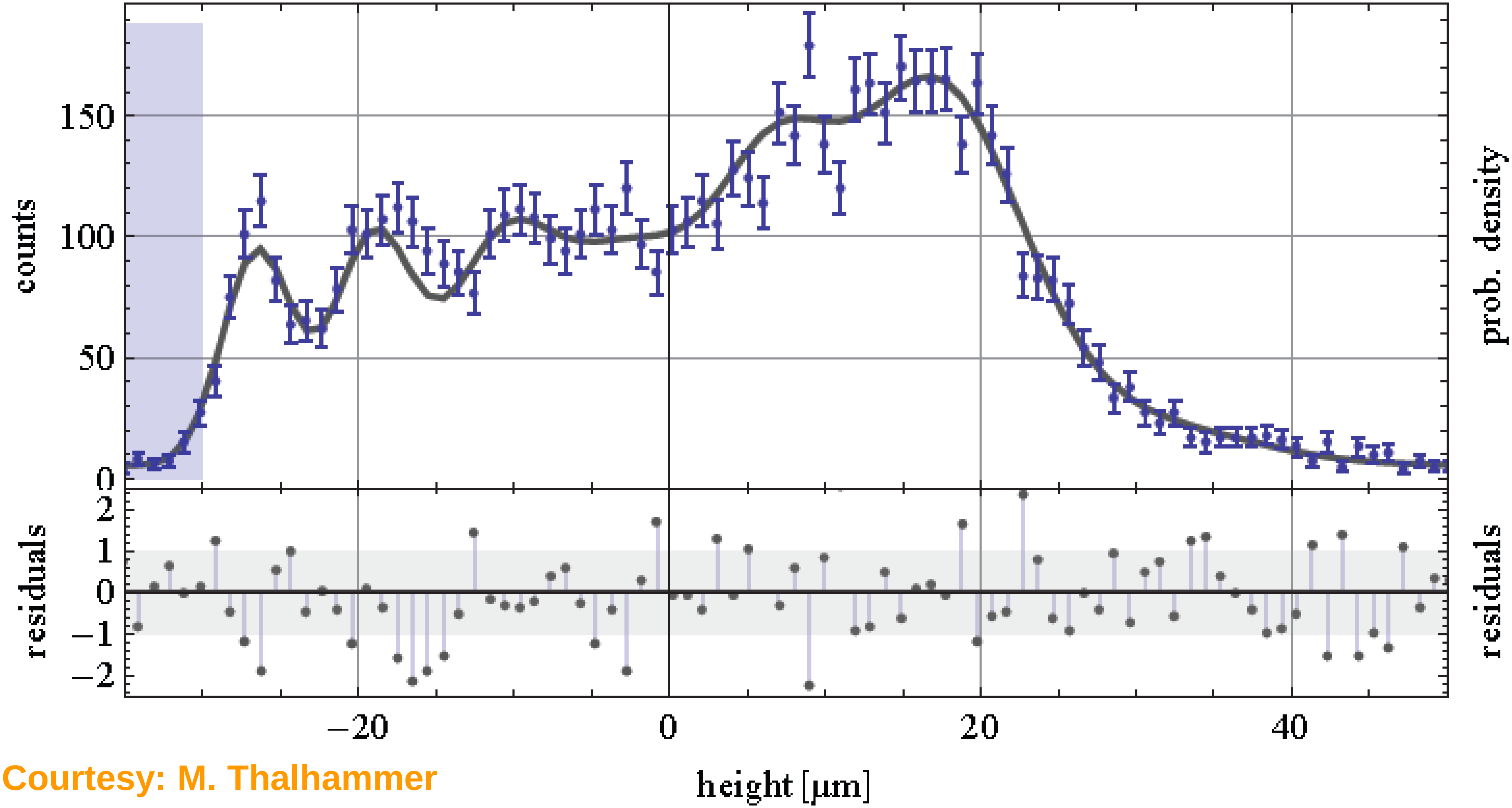
Courtesy: M. Thalhammer

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



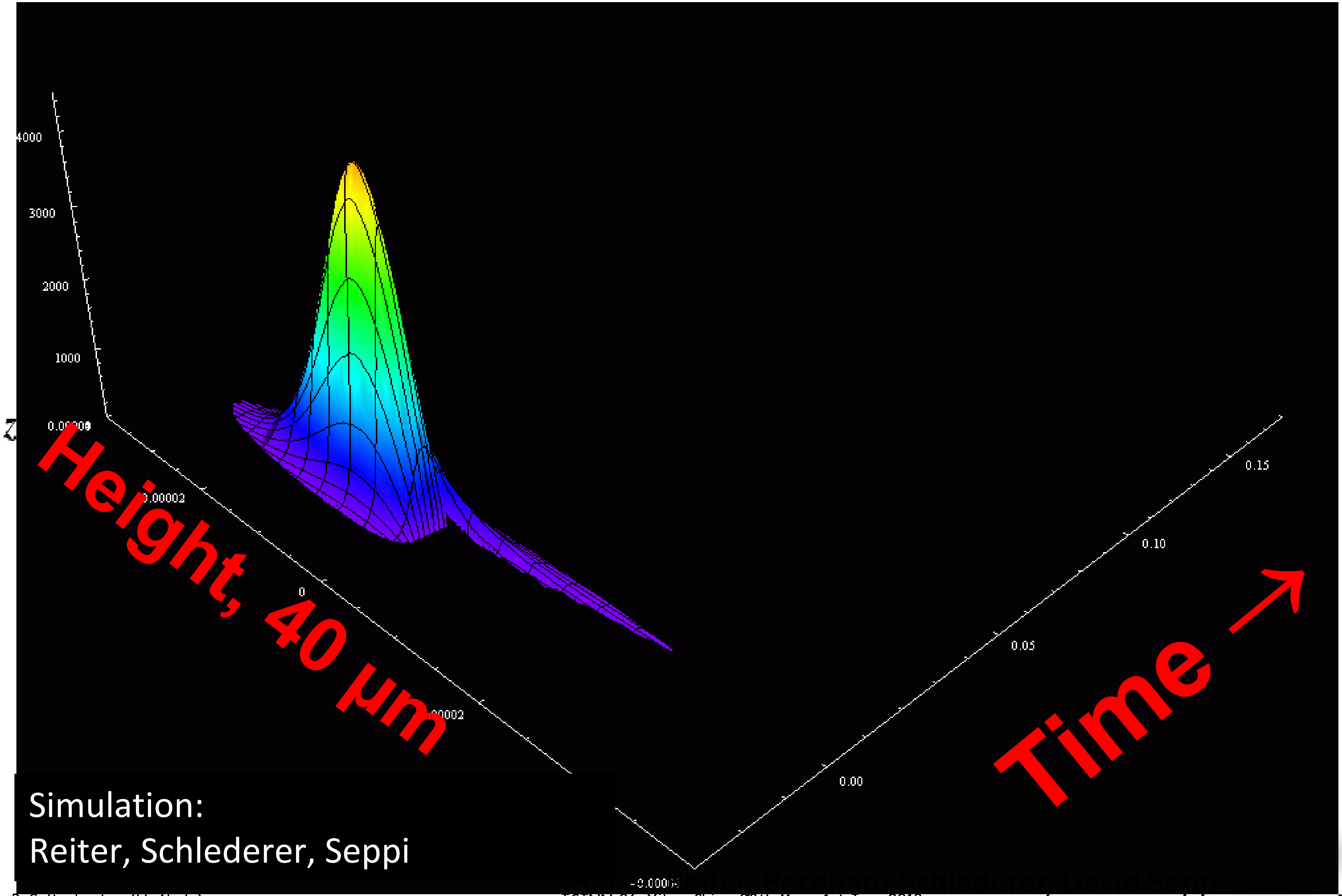
Courtesy: M. Thalhammer

Move downwards, L = 51 mm



Courtesy: M. Thalhammer

Show Case: *q*BOUNCE



Simulation:
Reiter, Schlederer, Seppi

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

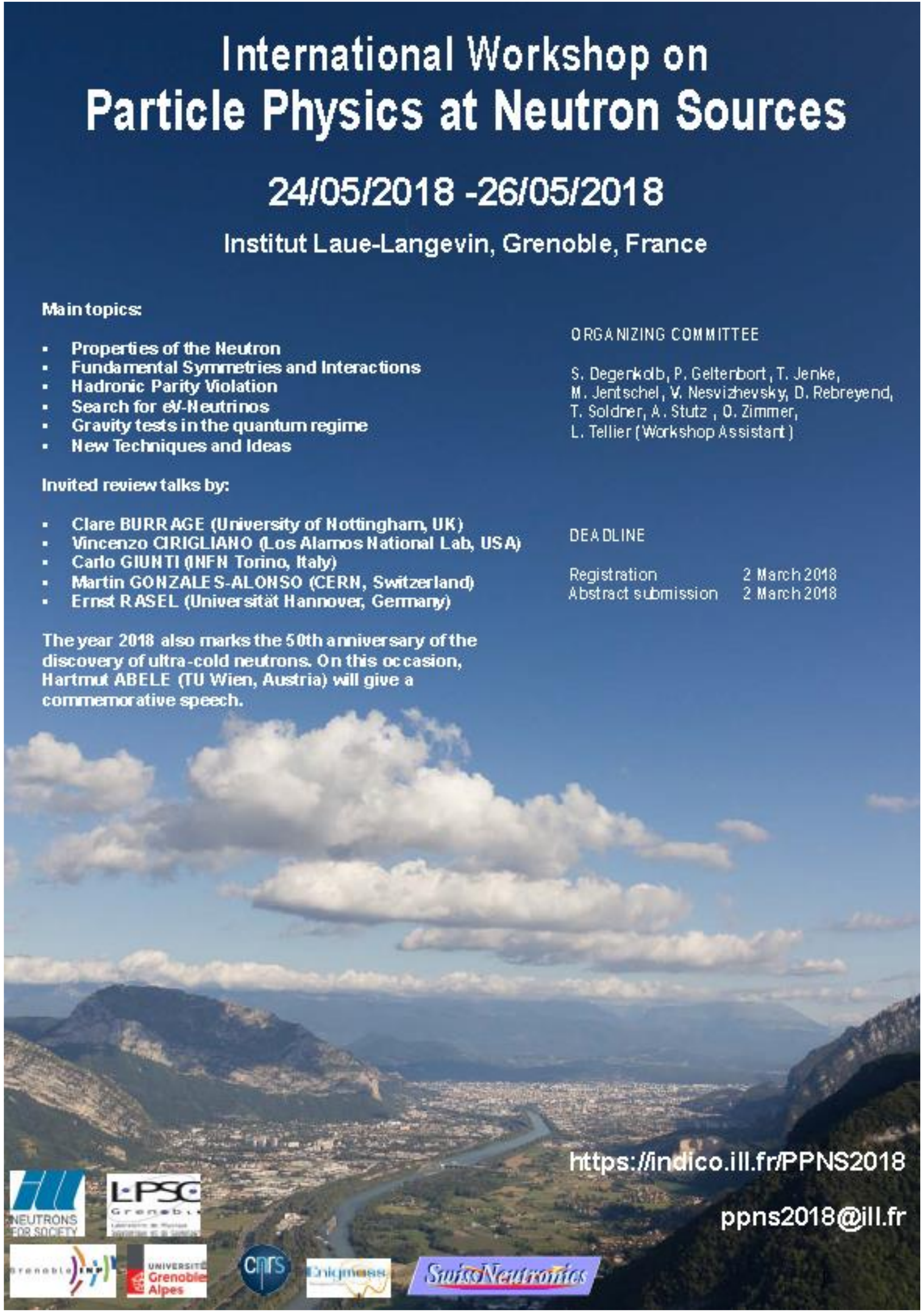
are still very attractive places for fundamental research

Thank you, merci beaucoup, dankeschön for your attention!

~140 participants

6 invited talk
35 contributed talks
~60 posters

can be found on
http://indico.ill.fr/PPNS2018



International Workshop on Particle Physics at Neutron Sources

24/05/2018 -26/05/2018

Institut Laue-Langevin, Grenoble, France

Main topics:

- Properties of the Neutron
- Fundamental Symmetries and Interactions
- Hadronic Parity Violation
- Search for eV-Neutrinos
- Gravity tests in the quantum regime
- New Techniques and Ideas

Invited review talks by:

- Clare BURRAGE (University of Nottingham, UK)
- Vincenzo CIRIGLIANO (Los Alamos National Lab, USA)
- Carlo GIUNTI (INFN Torino, Italy)
- Martin GONZALES-ALONSO (CERN, Switzerland)
- Ernst RASEL (Universität Hannover, Germany)

The year 2018 also marks the 50th anniversary of the discovery of ultra-cold neutrons. On this occasion, Hartmut ABELE (TU Wien, Austria) will give a commemorative speech.

ORGANIZING COMMITTEE

S. Degenkolb, P. Geltenbort, T. Jenke,
M. Jentschel, V. Nesvizhevsky, D. Rebreyend,
T. Soldner, A. Stutz , O. Zimmer,
L. Tellier (Workshop Assistant)

DEADLINE

Registration	2 March 2018
Abstract submission	2 March 2018

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