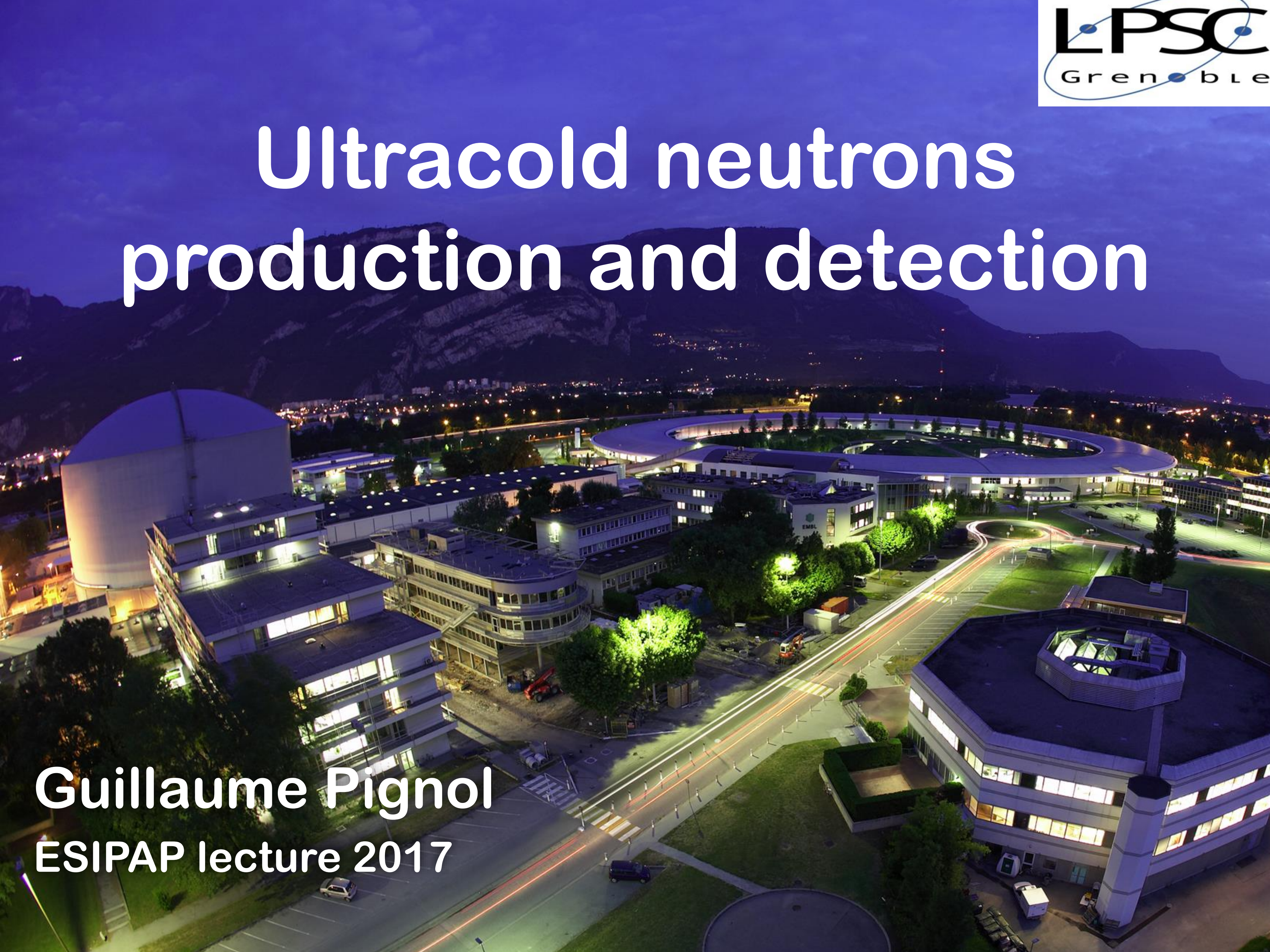
Ultracold neutrons production and detection



Guillaume Pignol

ESIPAP lecture 2017

The two frontiers of particle physics

1 Energy frontier

Probing new physics at high energy particle colliders
Example: production of the Higgs boson $m_H = 125\ \mathrm{GeV}$

2 Intensity frontier

Probing new physics by looking at very rare processes or testing the Standard Model with high precision.

Examples:

- $\mu \to e\,\gamma \qquad BR < 6 \times 10^{-13}$
- Proton lifetime $> 2 \times 10^{29}\ \mathrm{yr}$
- Neutron –antineutron oscillation time $> 10^{8}\ \mathrm{s}$
- Neutron electric dipole $< 3 \times 10^{-26}\ \mathrm{cm}$

Neutron particle physics is a subset of the intensity frontier program

Large neutron factories

Multi-disciplinary facilities

Biology
Chemistry
Material sciences
Magnetism
Nuclear physics
Particle physics

Outline

1 Neutron optics, ultracold neutrons

2 Fundamental physics with UCNs

- Neutron lifetime
- Electric dipole moment
- Gravity with neutrons

3 Neutron detection

4 UCN sources

Neutron spectrum

Fission ~ 2 MeV

Resonant capture ~ 10 eV

Thermal neutrons:
kT = 25 meV @ T =300 K

Fermi potentials ~ 100 neV

fast

epithermal

cold

ultracold

1 MeV

1 keV

1 eV

1 meV

1 μeV

1 neV

$\lambda < 0.1$ nm
"PARTICLE"

$\lambda > 0.1$ nm
"WAVE"

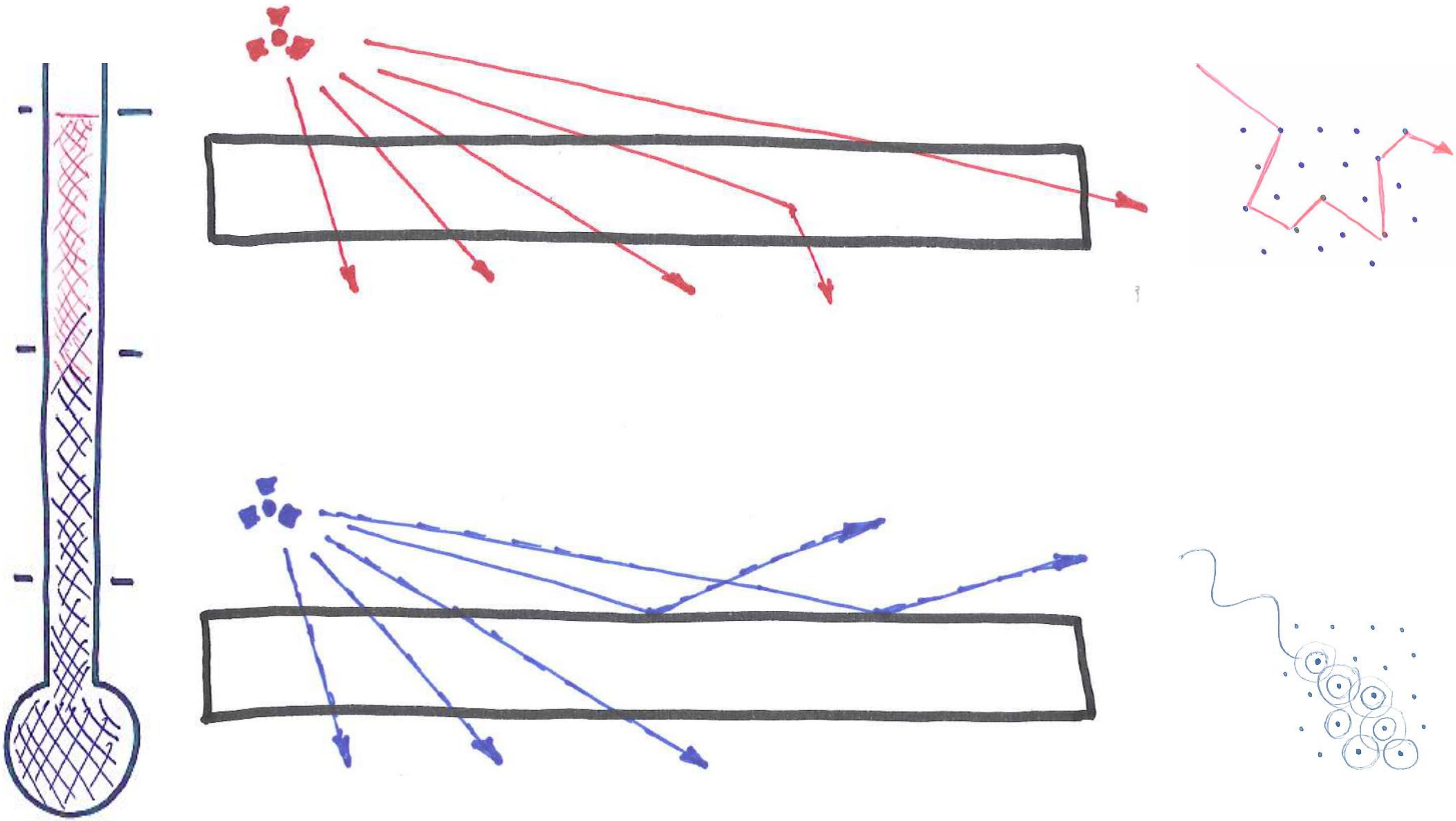
De Broglie wavelength

$$\lambda = \frac{2\pi\,\hbar}{\sqrt{2\,m\,E}}$$

Mirror effect (absent)

Mirror effect (present)

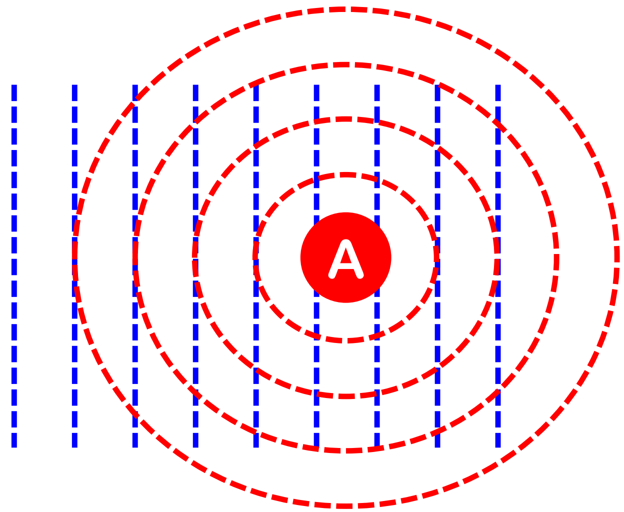
Particles and waves



Neutron interaction with a single nucleus

Potential scattering described by non-relativistic quantum scattering theory.
For nonrelativistic neutrons, nuclei look point-like ($kR_{\mathrm{nucl}} \ll 1$):

- Isotropic scattering
- Energy-independent



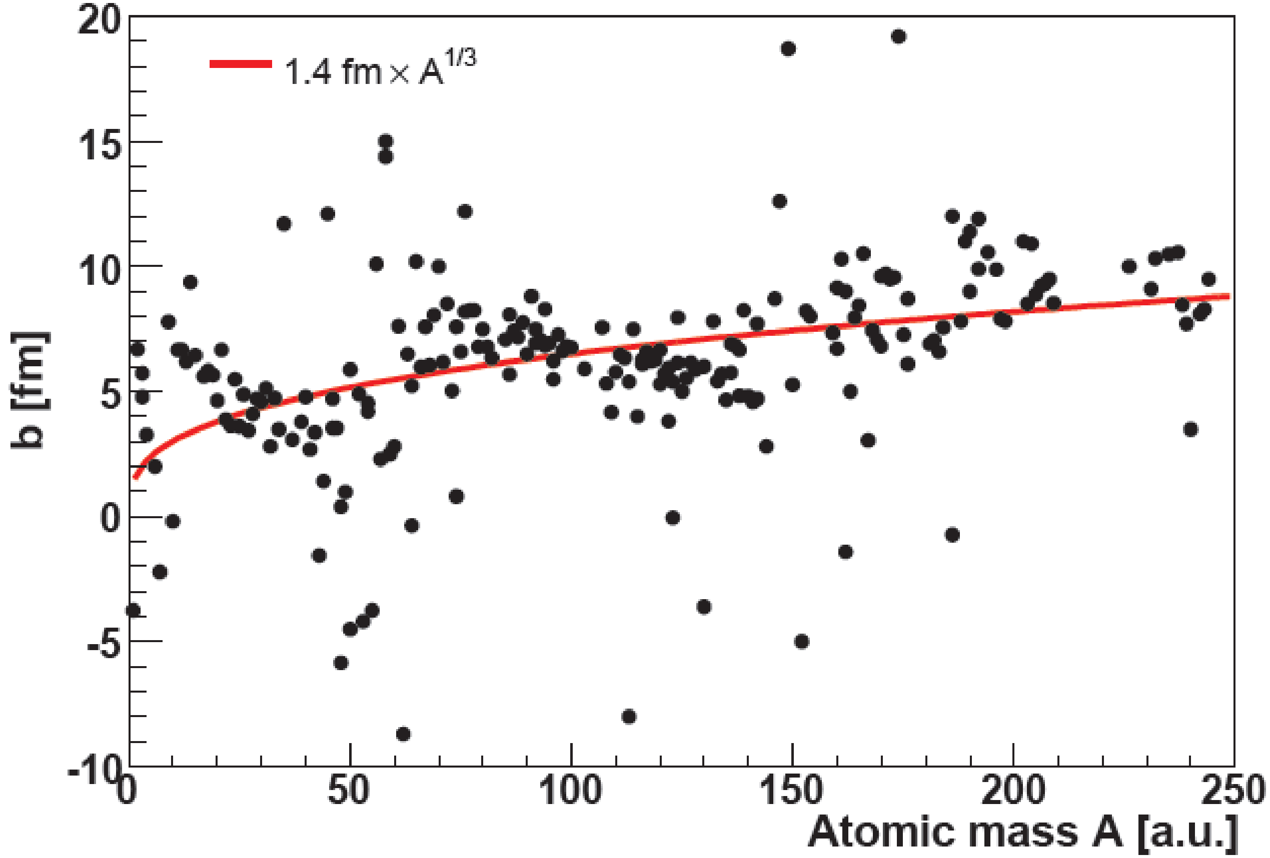
Neutron wave function corresponding to the scattering process

$$\psi(r) = e^{i\,k\,x} - b\,\frac{e^{i\,k\,r}}{r}$$

Scattering X-section

$$\sigma = 4\pi\, b^2$$

Measured neutron scattering lengths

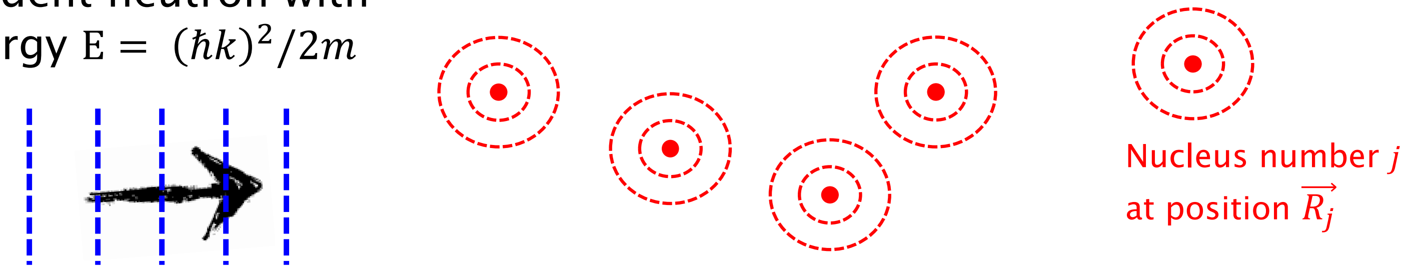


For a catalog, see http://www.ncnr.nist.gov/resources/n-lengths

Surprisingly, almost all nuclei have $b > 0$.

Neutron interaction with a collection of nuclei

Incident neutron with
energy $\mathrm{E} = (\hbar k)^2/2m$



Self consistency of the wave function

$$\psi(\vec{r}) = e^{i\,k\,x} - \sum_j \psi\left(\overrightarrow{R_j}\right) b \, \frac{e^{ik\left|\vec{r}-\overrightarrow{R_j}\right|}}{\left|\vec{r}-\overrightarrow{R_j}\right|}$$

Using the relation

$$(\Delta + k^2)\, \frac{e^{ik\left|\vec{r}-\overrightarrow{R_j}\right|}}{\left|\vec{r}-\overrightarrow{R_j}\right|} = -4\pi\, \delta\left(\vec{r} - \overrightarrow{R_j}\right)$$

We find the wave equation

$$(\Delta + k^2)\psi(\vec{r}) = 4\pi\, b \sum_j \delta\left(\vec{r} - \overrightarrow{R_j}\right) \psi(\vec{r})$$
$$\approx 4\pi\, b\, n\, \psi(\vec{r})$$

n is the nuclear density of the medium

Fermi potential

Defining the Fermi potential
of a medium

$$V_F = \frac{2\pi\hbar^2}{m} \; b\, n$$

The wave equation is a Schrodinger equation with the potential V

$$\left(-\frac{\hbar^2}{2m}\Delta + V_F\right)\psi(\vec{r}) = E\,\psi(\vec{r})$$

For cold neutrons, bulk matter is characterized by its Fermi potential.
We expect wave phenomena (refraction, reflection, tunnel transmission..).

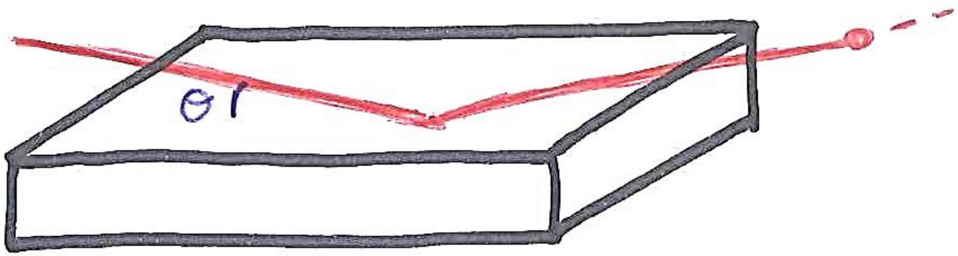
Examples

Material	b [fm]	n [cm^{-3}]	V_F
Aluminum	3.45	6.02 x 10^{22}	54 neV
Nickel (^{58}Ni)	14.4	9.13 x 10^{22}	340 neV
Natural Nickel		9.13 x 10^{22}	245 neV

For heterogeneous materials (atomically like water, or isotopically like natural nickel), one sums the Fermi potentials of each nuclear specie:

$$V_F = (2\pi\hbar^2)/m \sum_i b_i n_i$$

Total reflection of neutrons



Solid matter characterized by the Fermi potential V_F

Condition for total reflection of neutrons
Fermi, Zinn (1946)

$$E \sin^2 \theta < V_F$$

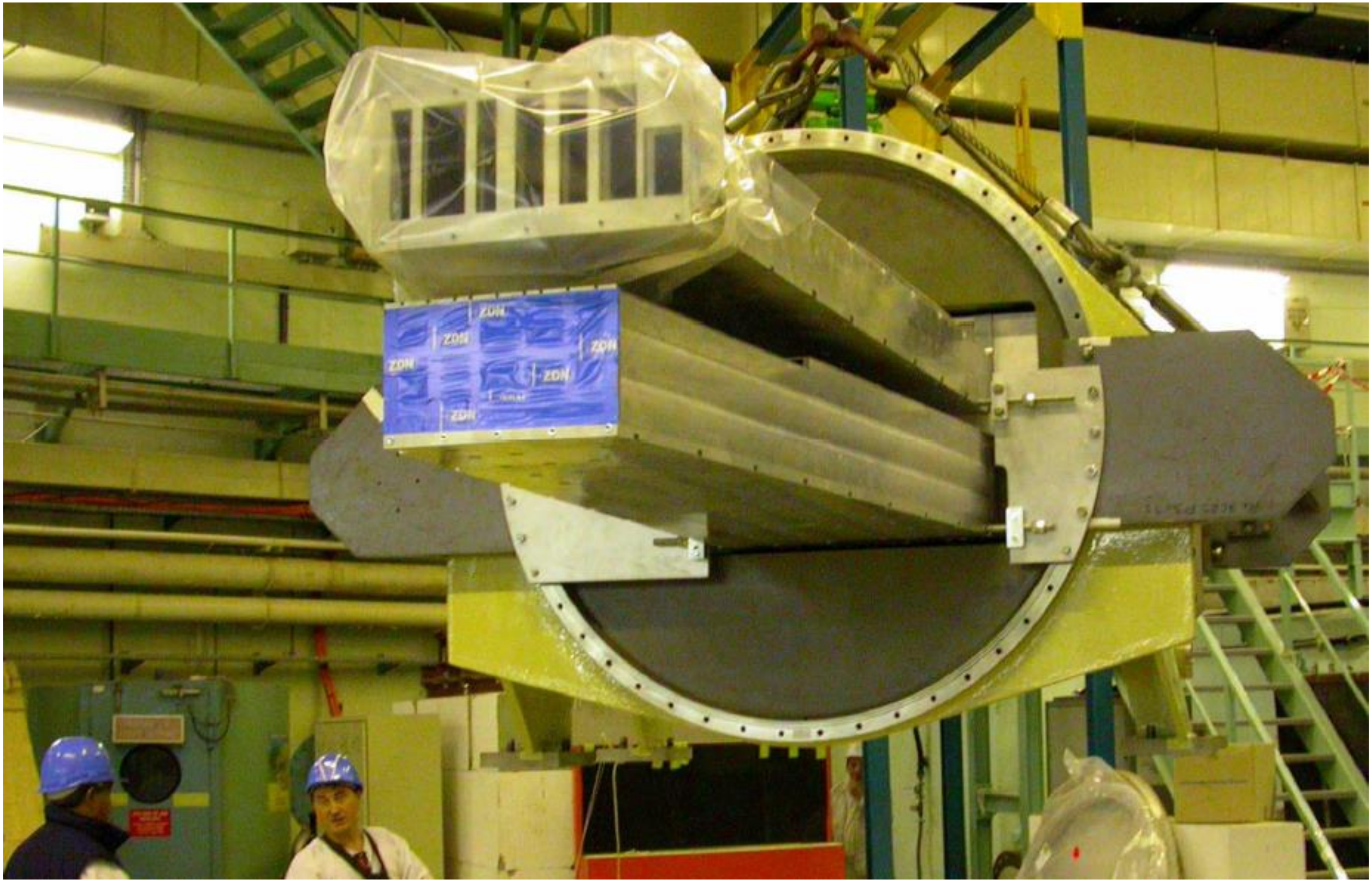
Example: thermal neutrons (E=25 meV) are guided through a Nickel guide (V=245 neV) provided

$$\theta < 0.2°$$

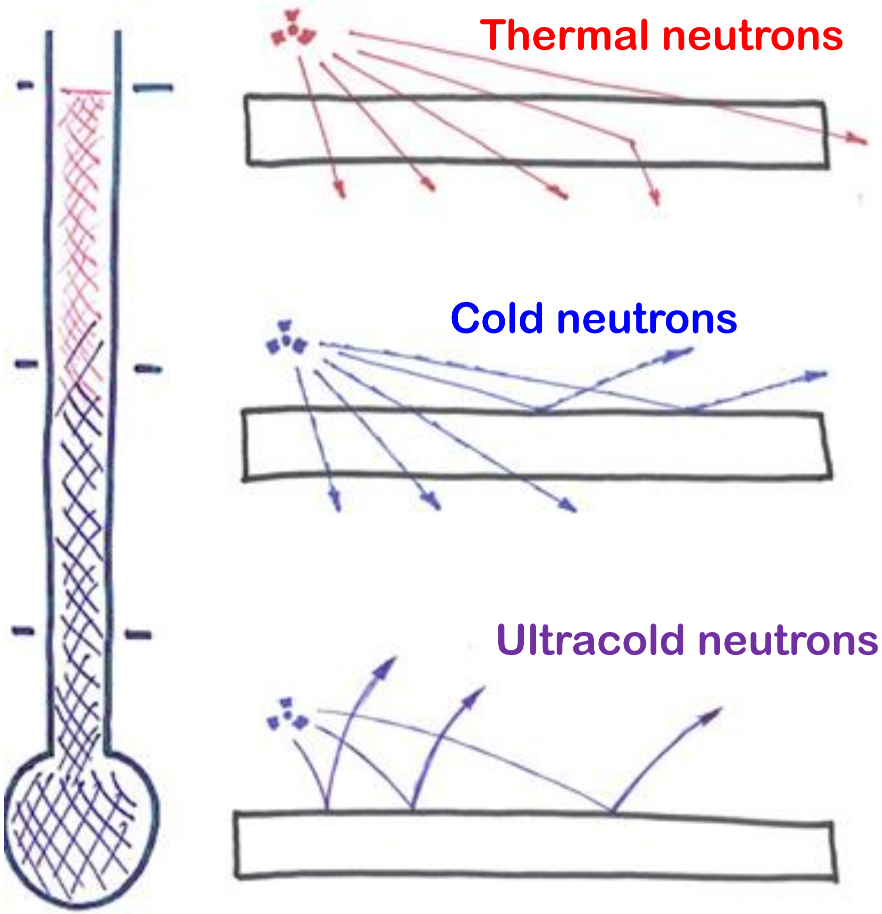
Application: transporting neutrons 100 m…

Institut Laue Langevin,
Grenoble High Flux Reactor

Neutron distribution channels at ILL



Ultracold neutrons (UCN)



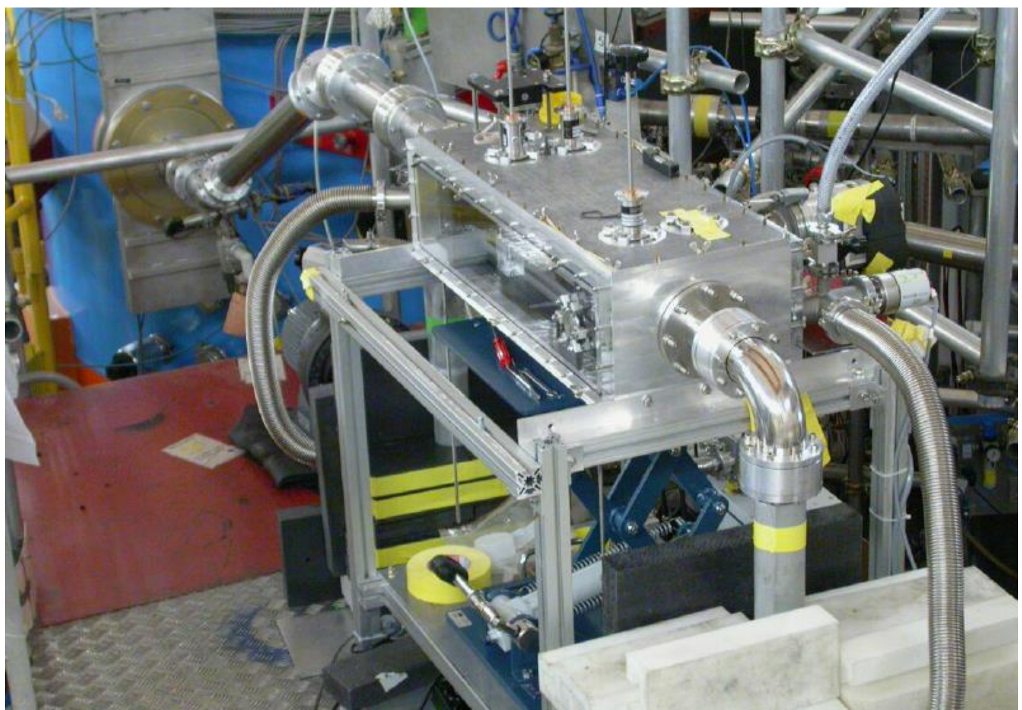
Neutrons with energy < 100 neV,
or velocity < 5 m/s

are reflected by material walls

UCN plumbing

UCNs are guided through evacuated stainless steel pipes (about 10 cm diameter) and bends.

Losses are generally percents/meter



UCNs and gravity

UCNs feel gravity

$$V(z) = mg\, z$$

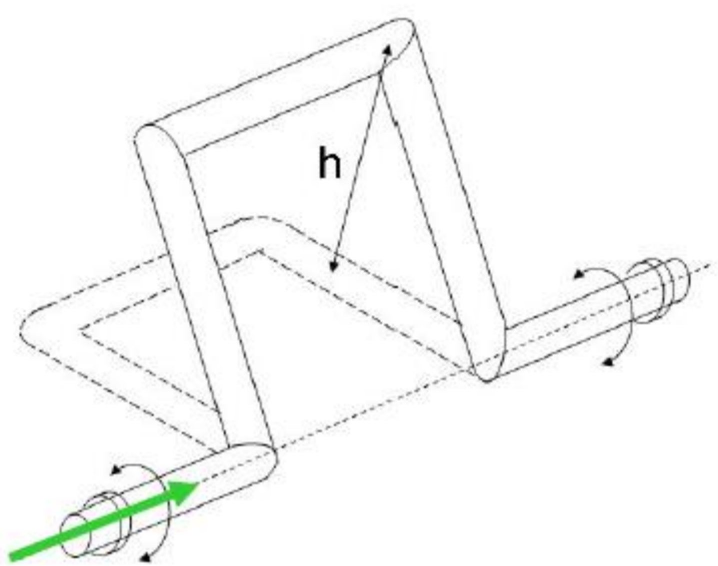
$$V(z = 1\ \mathrm{m}) = 102\ \mathrm{neV}$$

Very important for UCN techniques

- We accelerate UCNs to detect them (otherwise they would bounce off the detector window).
- Some UCN traps do not need a roof.
- Lifting an experiment by 50 cm can modify significantly the outcome!

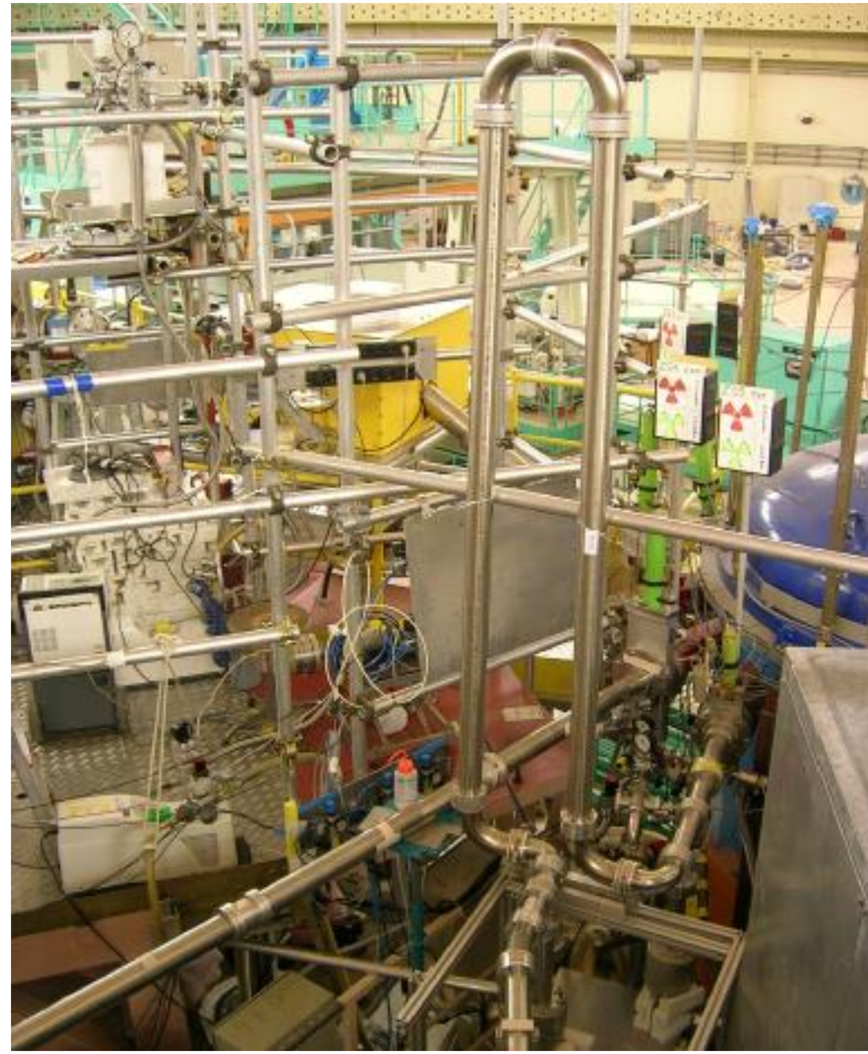
UCNs and gravity

The U device



If you want to remove UCNs with energy E<80 neV,

Just set h = 80 cm



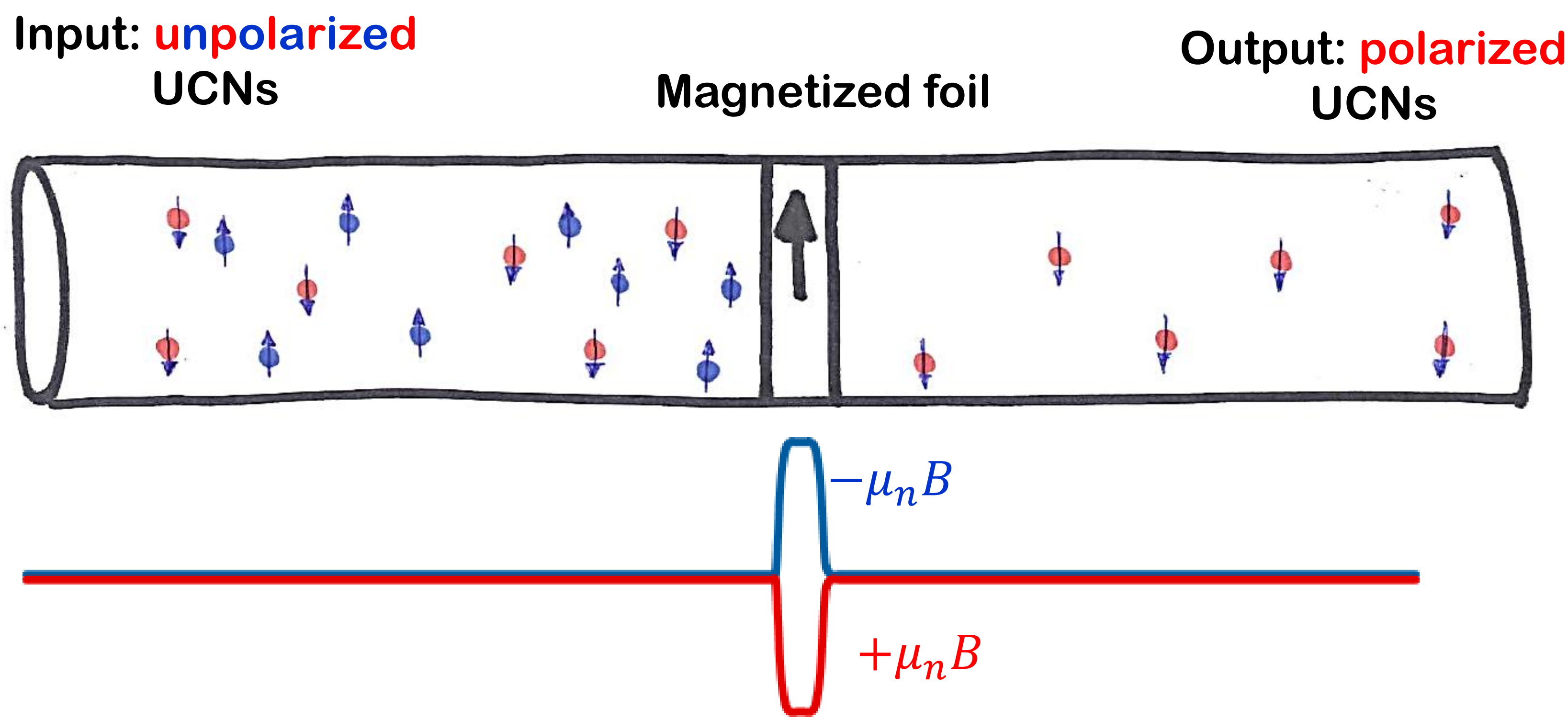
UCNs and magnetic fields

Neutron magnetic moment

$$\mu_n \times (1\ \mathrm{T}) = 60\ \mathrm{neV}$$

Magnetic fields act on the spin ½ neutron

$$V = -\vec{\mu}_n\,\vec{B}$$



Summary

UCNs can be manipulated using

- The nuclear force (Fermi potentials ~ 100 neV)
- The gravitational force (1 m = 100 neV)
- Magnetic fields (1T = 60 neV)

They are used to study the fundamental interactions and symmetries

- Weak interaction (beta decay period 10 min)
- Electromagnetic properties of the neutron (EDM)
- Gravitational effects

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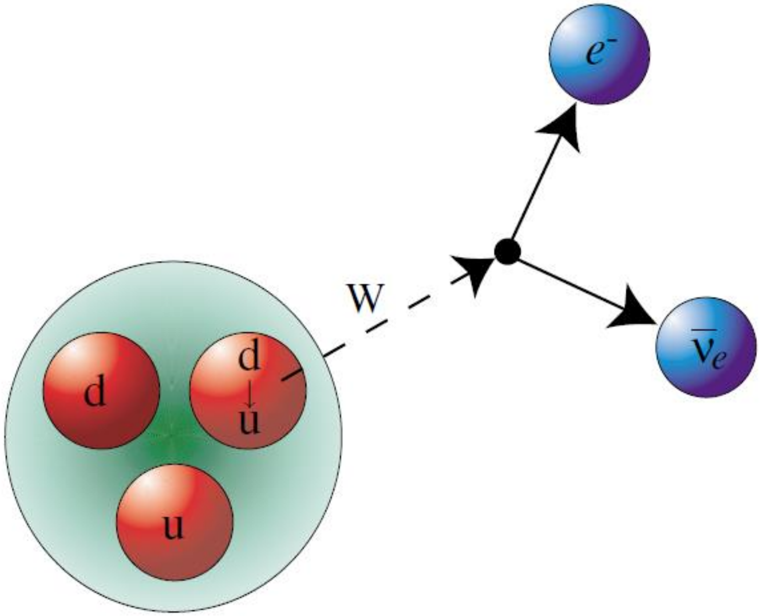
The neutron beta decay lifetime, why bother?



$$n \to p + e^- + \bar{\nu}_e + 782\ \mathrm{keV}$$

Free neutron lifetime

$$\tau_n = 880.0(9)\ \mathrm{s}$$
[PDG 2013]

- ***Particle physics:***

extracting CKM matrix element V_{ud}

- ***Astrophysics and Neutrinos***

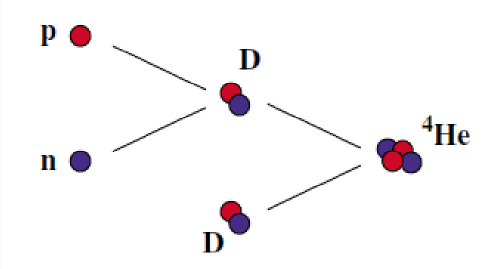
Calculating weak semi-leptonic processes like

$$p + p \to d + e^+ + \nu_e$$

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

- ***Cosmology***

Predicting the yields of the BigBang Nucleosynthesis



Two complementary experimental methods

Counting the dead neutrons: BEAM METHOD

A detector records the decay products in a well defined part of a neutron beam. A neutron beam is indeed radioactive due to beta decay.

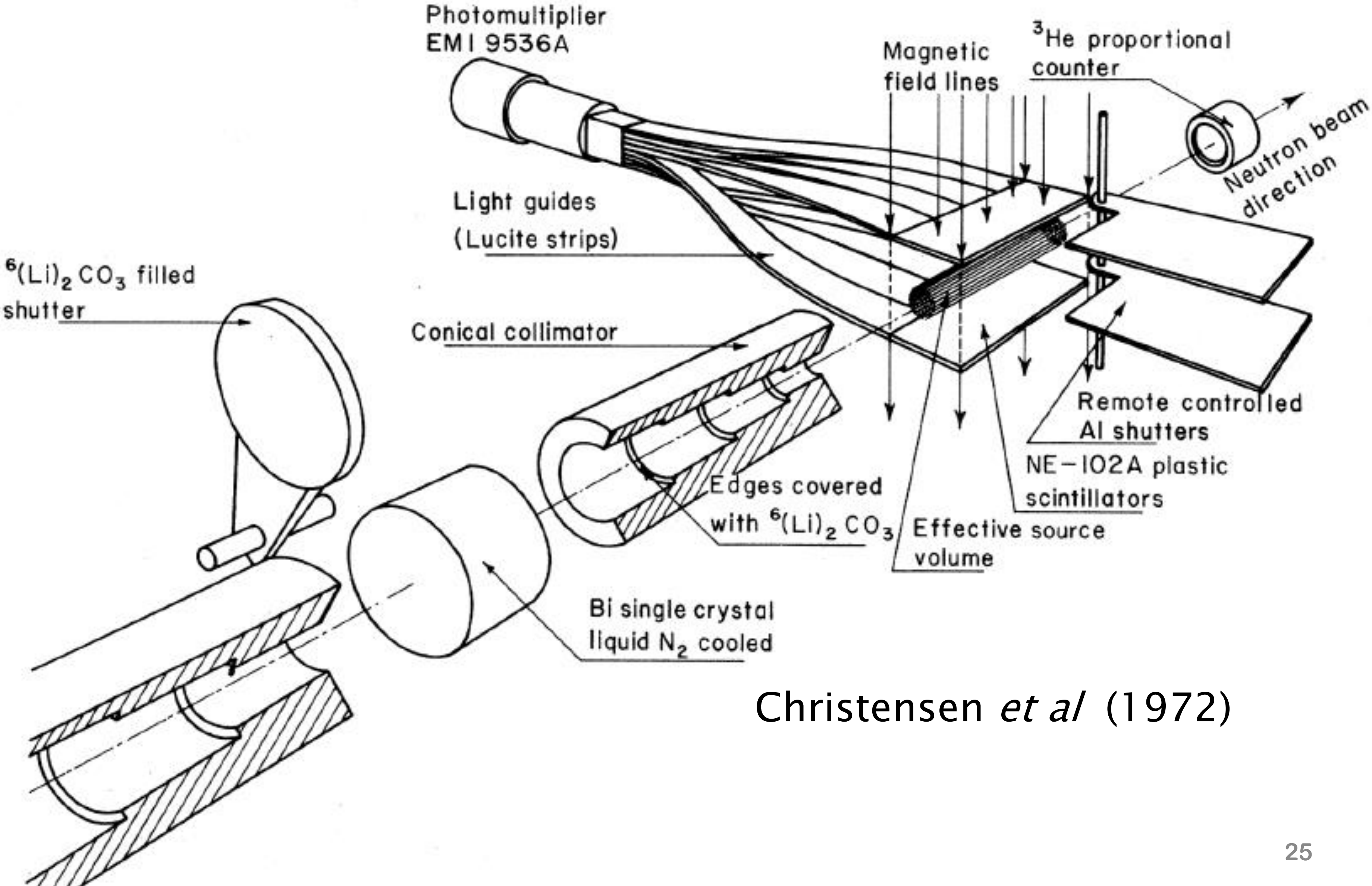
$$-\frac{dN}{dt} = \frac{N}{\tau_n}$$

Counting the surviving neutrons: BOTTLE METHOD

UCNs are stored in a bottle, the number of neutrons remaining in the bottle after a certain storage time t is measured.

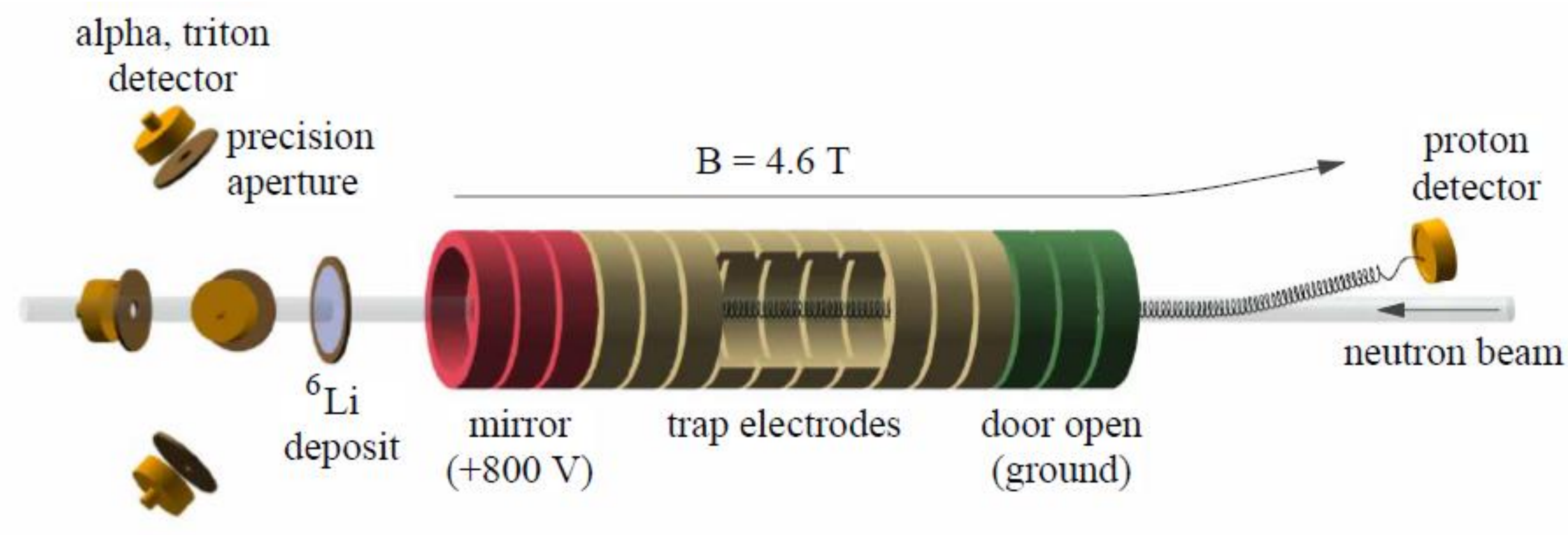
$$N(t) = N(0)e^{-t/\tau_n}$$

Early beam method: counting the beta electrons



Christensen *et al* (1972)

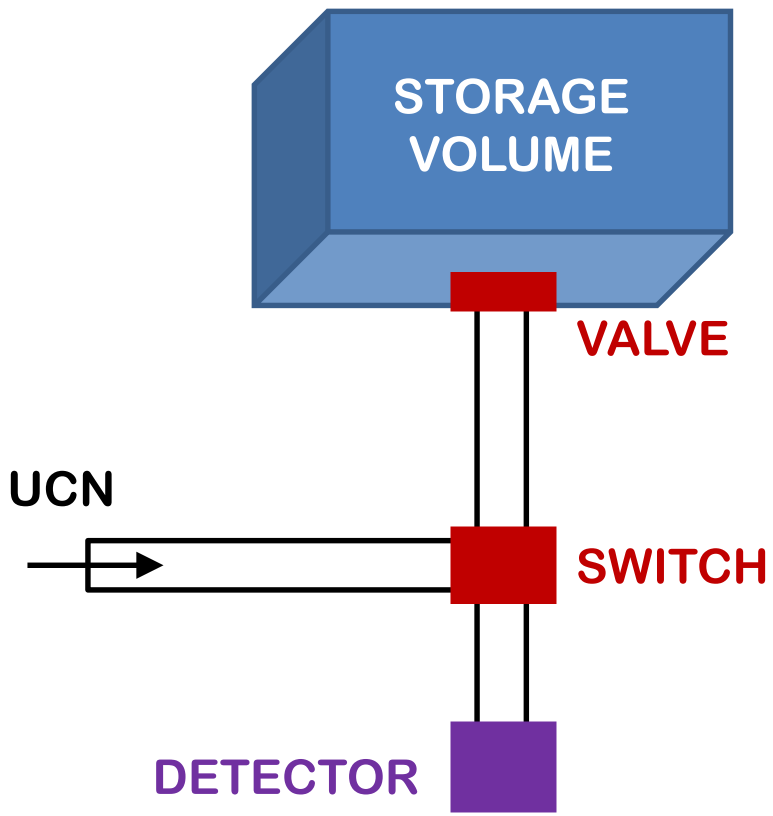
Modern beam method: counting the protons



Nico *et al* (2005)

Protons produced almost at rest
(endpoint energy = 800 eV)
are accumulated in a Penning trap.

Principle of a bottle UCN measurement



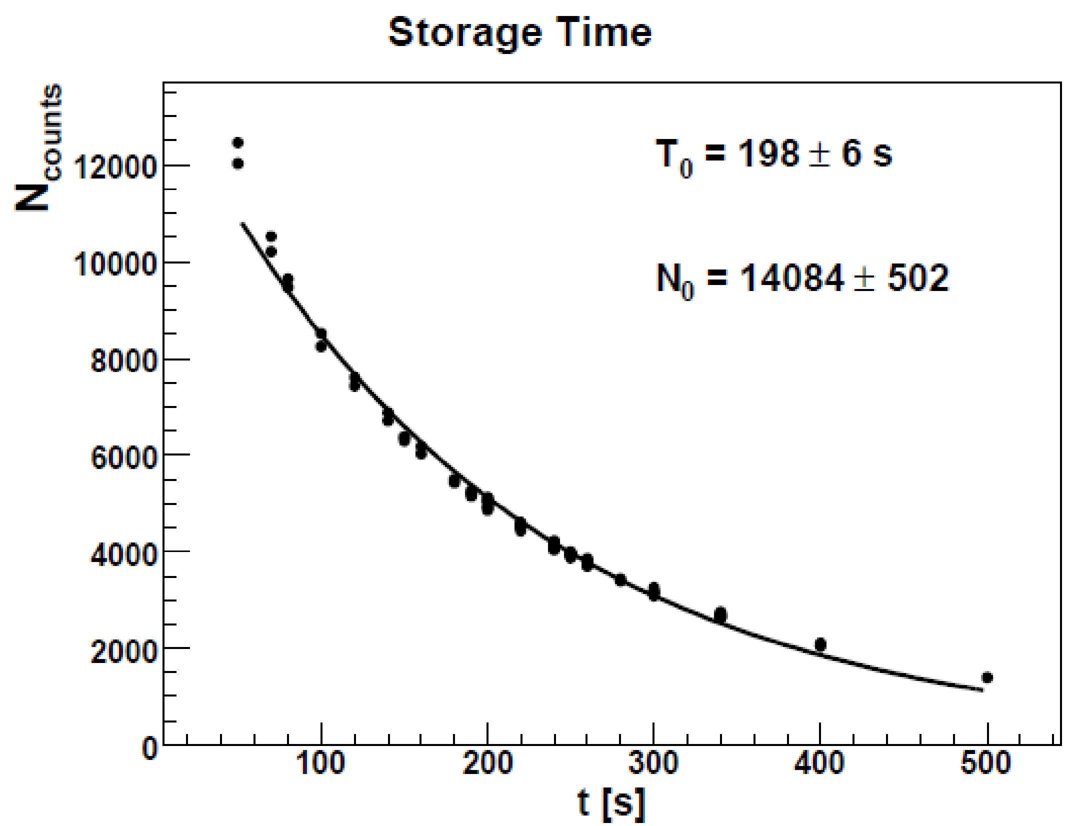
Typical sequence

1. Switch moved to FILL position, Valve OPEN for 20 s
2. Close Valve, Switch moved to EMPTY position
3. Wait period t
4. OPEN Valve, count neutrons

Repeat the sequence with different t

Principle of a bottle UCN measurement

Example: measured storage curve in the 20 L chamber of the EDM experiment



Problem: UCN losses at wall reflection are not negligible.

$$\frac{1}{\tau_{st}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}}$$

Estimating the wall losses

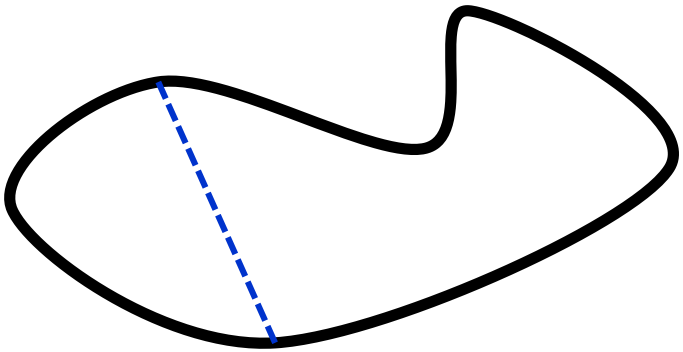
The probability for a UCN to be lost at a wall collision can be of the order of $\mu \approx 10^{-4}$

The mean free path between collisions is of the order of $\lambda \approx 30\ \mathrm{cm}$

The frequency of wall collisions for a velocity of 3 m/s is of the order of $f = \frac{v}{\lambda} \approx 10\ \mathrm{Hz}$

The partial lifetime due to wall losses is thus of the order of $\tau_{wall} = \frac{1}{f\mu} \approx 1000\ \mathrm{s}$

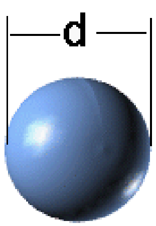
Good to know: the Clausius law



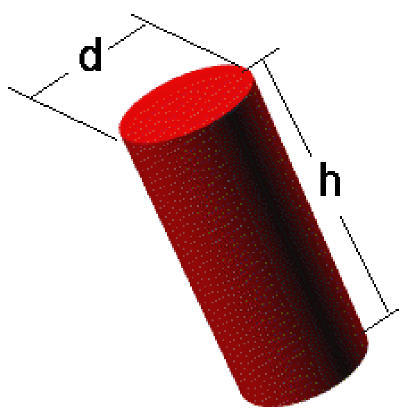
Consider a bottle with arbitrary shape, of volume V and surface S.

When mechanical equilibrium is achieved (isotropic velocity distribution) the mean free path between wall collisions is

$$\lambda = \frac{4\,V}{S}$$



$$\lambda = \frac{2d}{3}$$

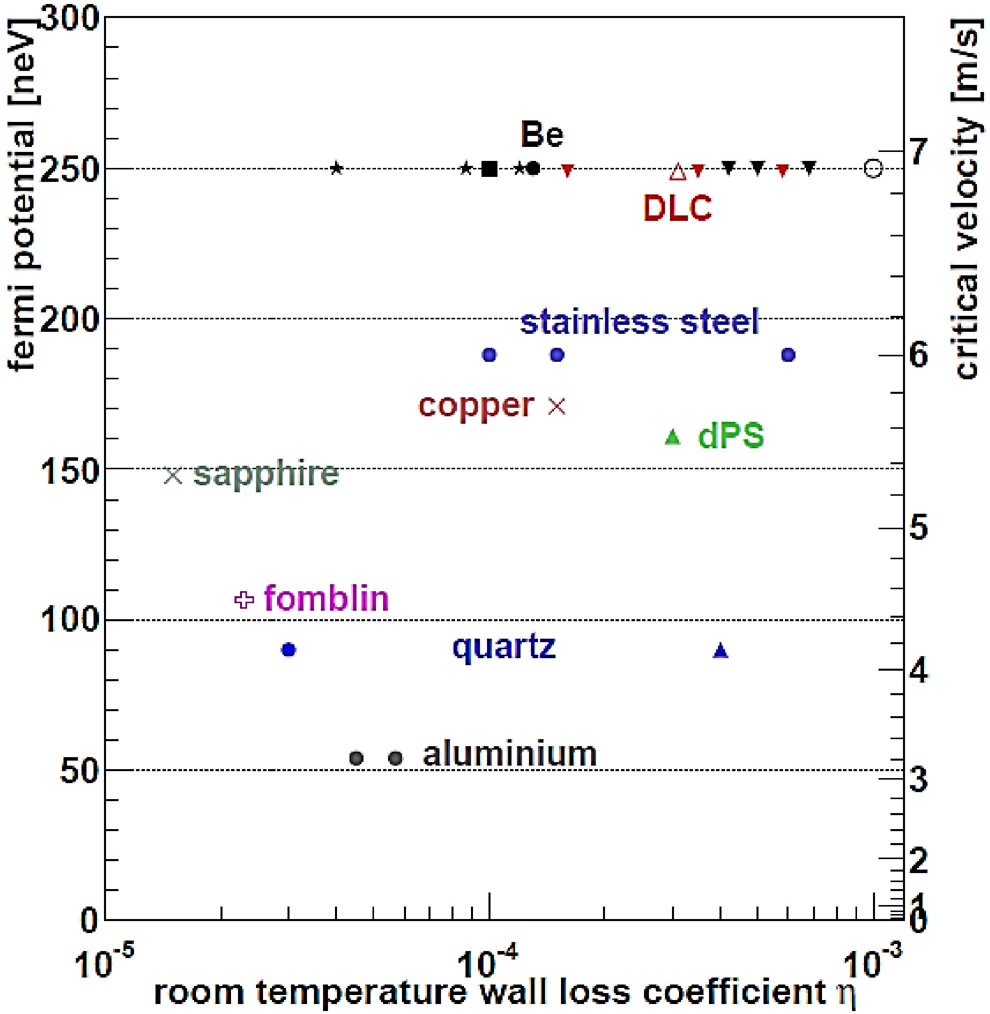


$$\lambda = \frac{dh}{d/2 + h}$$

$$\lambda = \frac{2abh}{ab + ah + bh}$$

Results valid without gravity!

More on wall losses (a complicated topic)

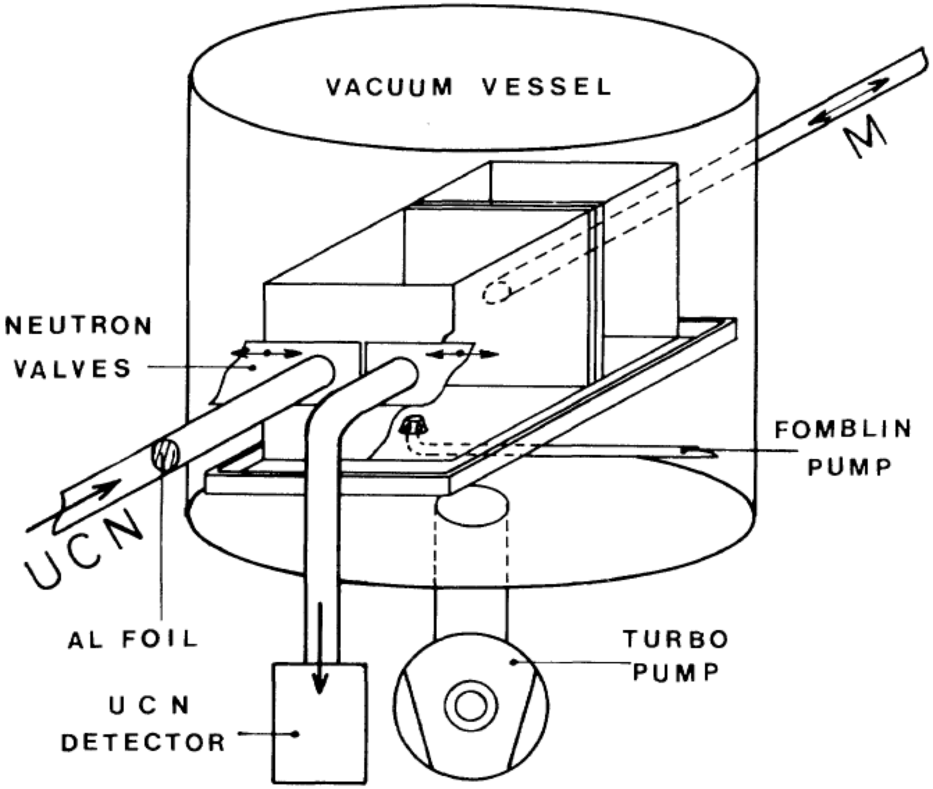


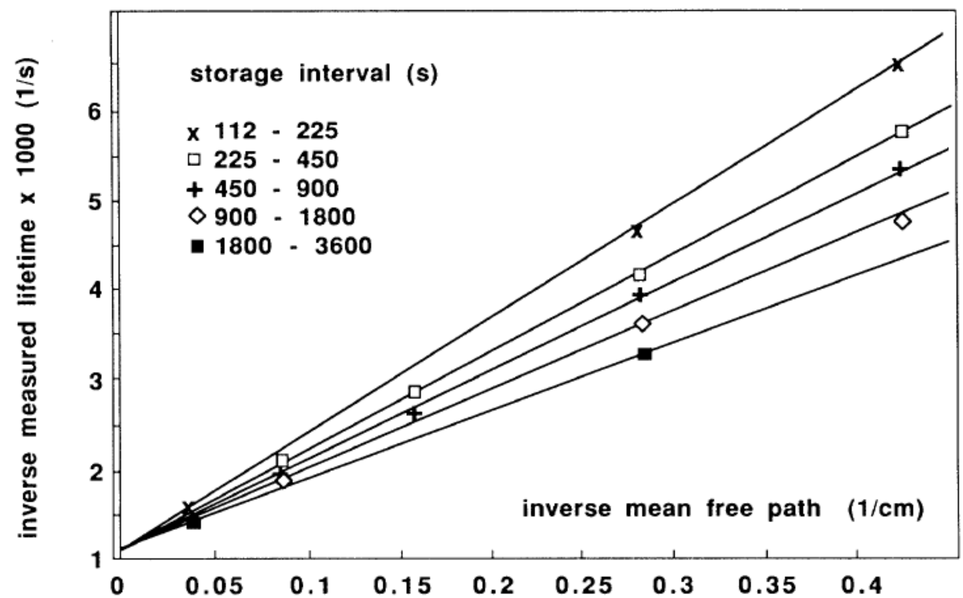
- The wall loss probability is energy-dependent

$$\mu(E) = 2\eta\left(\frac{V}{E}\operatorname{asin}\sqrt{\frac{E}{V}} - \sqrt{\frac{V}{E} - 1}\right)$$

- It depends on temperature (the colder the better)
- Losses can be calculated from absorption and inelastic scattering cross section data. But measured losses are generally higher, due to surface impurities (hydrogen, in particular)

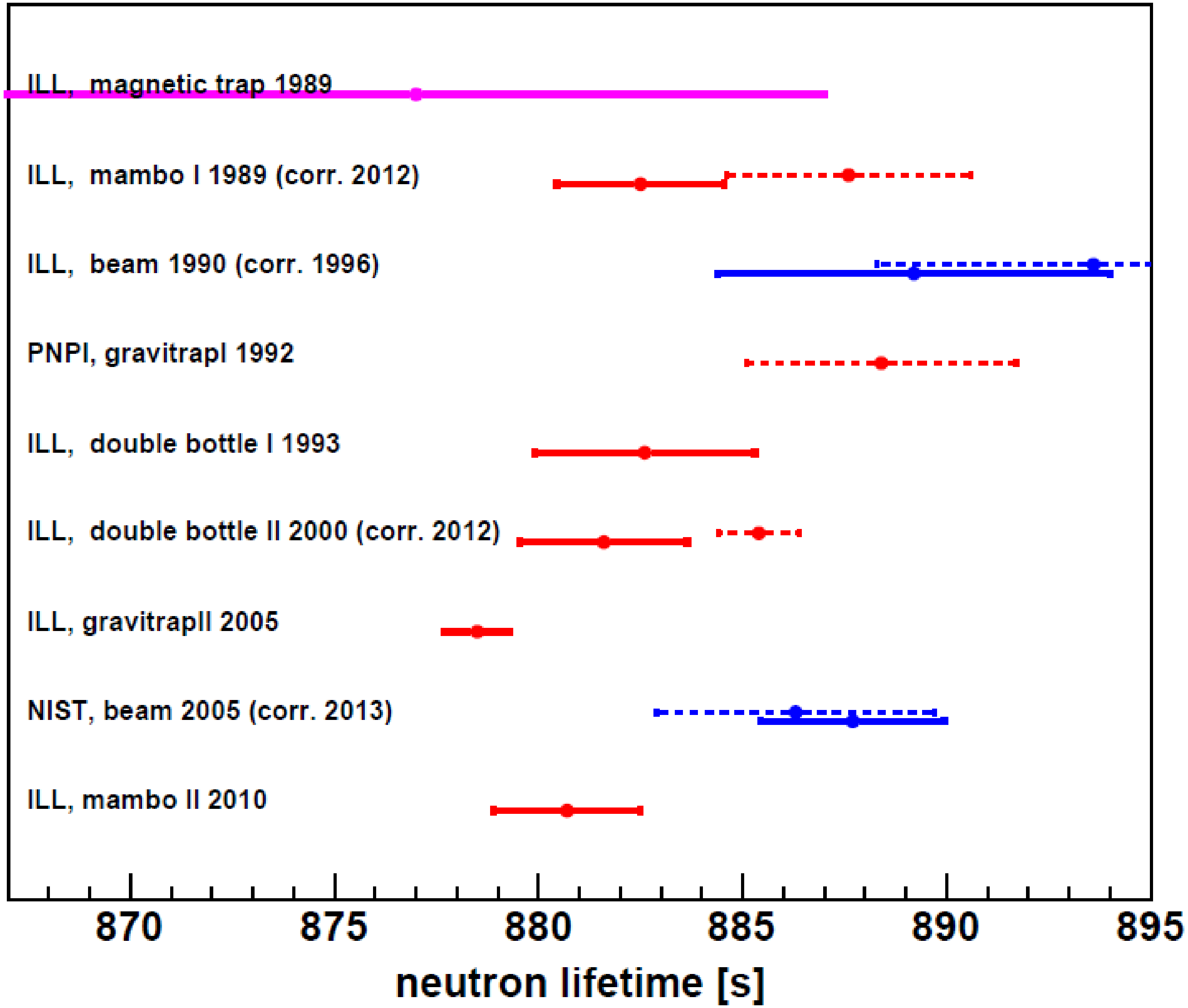
Example: MAMBO I (ILL, 1989)





The trap geometry is varied, one extrapolates the storage time to infinite mean free path

Current status on the neutron lifetime



The current situation

There is a 3.8 **σ** discrepancy

between the bottle method combination and the beam method combination.

To be continued…

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1 Neutron optics, ultracold neutrons

2 Fundamental physics with UCNs

- *Neutron lifetime*
- *Electric dipole moment*
- *Gravity with neutrons*

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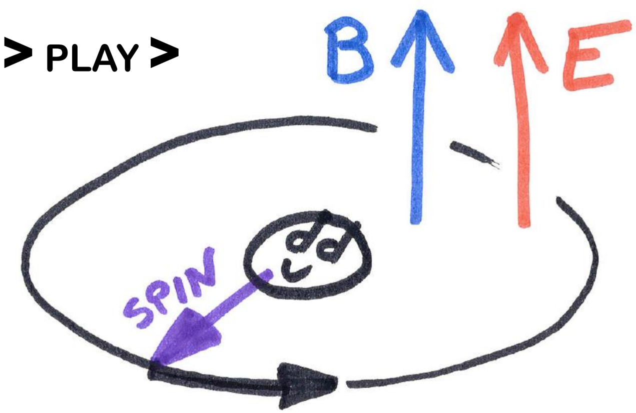
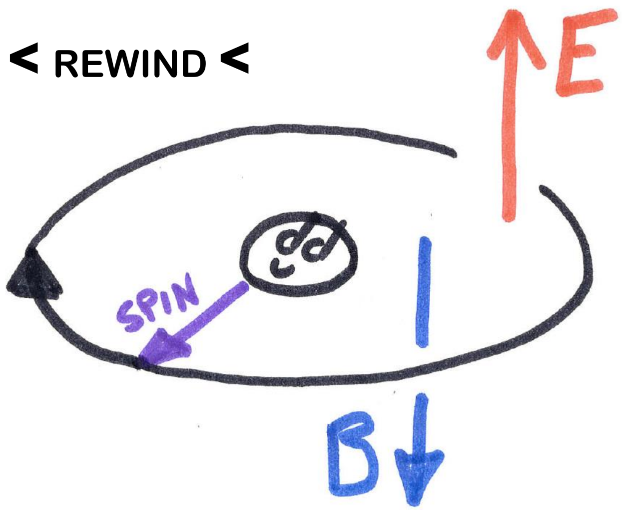
Neutron electric dipole moment (nEDM)





$$\hat{H} = -\mu_n B \hat{\sigma}_z - d_n E \hat{\sigma}_z$$

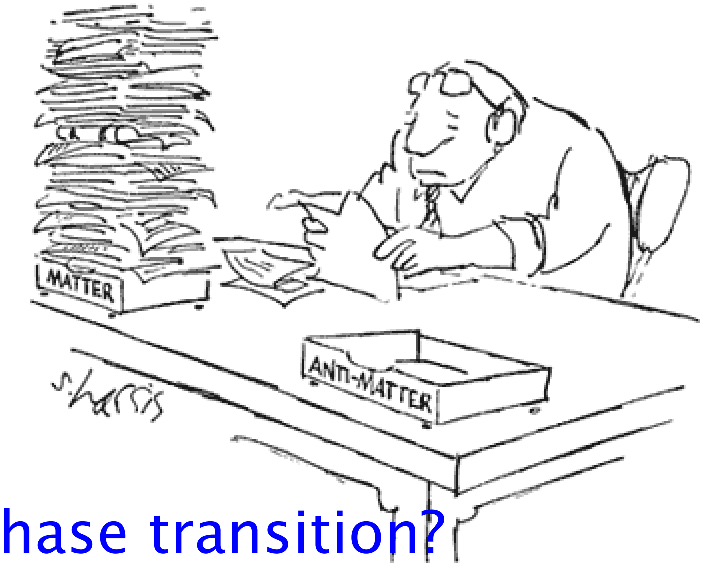
$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d_n E$$

A non-zero EDM violates T reversal
(thus violates CP symmetry)

Motivation:

- search for CP violation beyond the standard model
- Address the baryogenesis question

Explaining the baryogenesis



Sakharov conditions
To explain the matter-antimatter asymmetry in the Universe

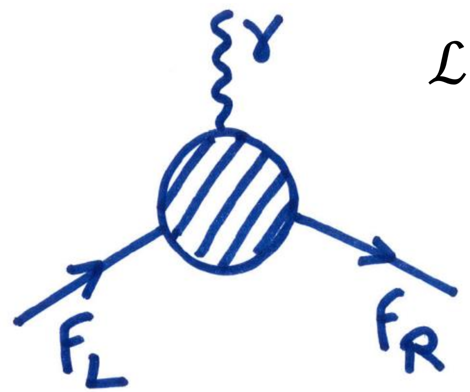
1 Departure from thermal equilibrium
It happens during a phase transition in the early universe... Electroweak phase transition?

2 *Violation of B conservation*
OK in the Standard Model

3 CP violation
The Standard Model (KM) CP violation does not generate enough asymmetry. One needs CP violation beyond the SM. This new physics would also generate a non zero neutron EDM.

CP symmetry and electric dipoles

EDMs: fermion–photon coupling – imaginary part of the diagram – generated by radiative corrections.



$$\mathcal{L} = -\frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\ F^{\mu\nu}$$

$$\rightarrow \hat{H} = d\ \hat{\boldsymbol{\sigma}}\boldsymbol{E}$$

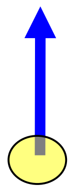
$$d_n < 300 \times 10^{-28}\ e\ \mathrm{cm}\ \ (\mathrm{Grenoble}, 2006)$$

$$d_p < 2000 \times 10^{-28}\ e\ \mathrm{cm}\ \ (\mathrm{Seattle}, 2016)$$

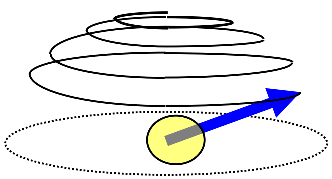
$$d_e < 0.9 \times 10^{-28}\ e\ \mathrm{cm}\ \ \ (\mathrm{Harvard}, 2014)$$

EDMs: indirect probe of new physics at distance 10^{-26} cm
LHC: direct probe of new physics at distance 10^{-17} cm

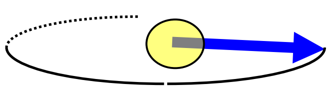
The Ramsey method



"Spin up" neutron...

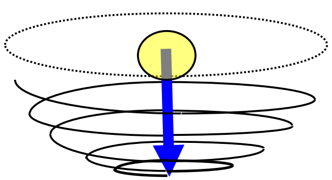


Apply $\pi/2$ spin-flip pulse...

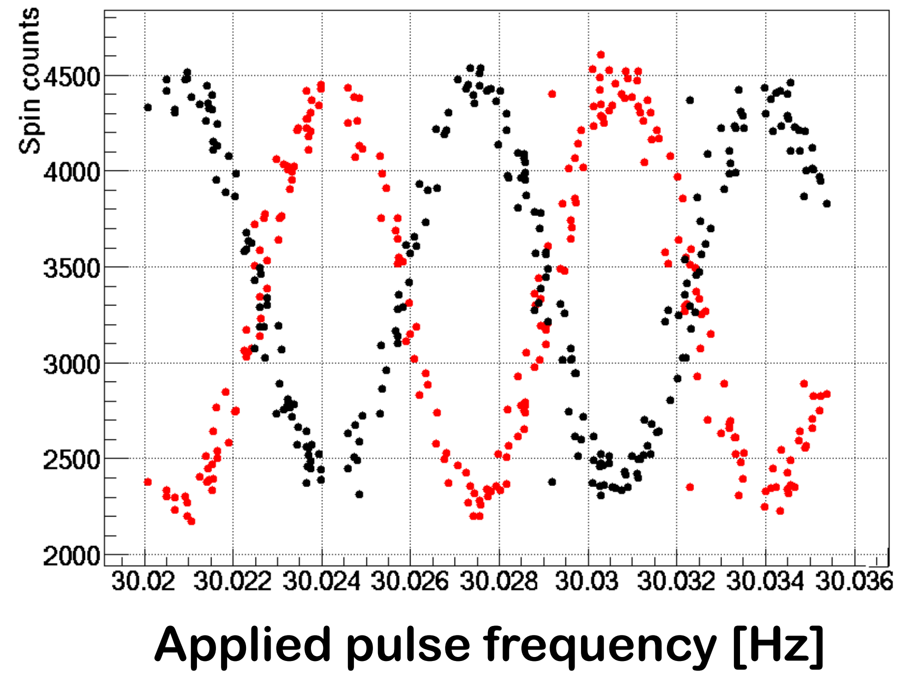


Free precession...

T = 180 s



Second $\pi/2$ spin-flip pulse



Statistical sensitivity

$$\sigma d_n = \frac{\hbar/2}{\alpha \ E \ T \sqrt{N}}$$

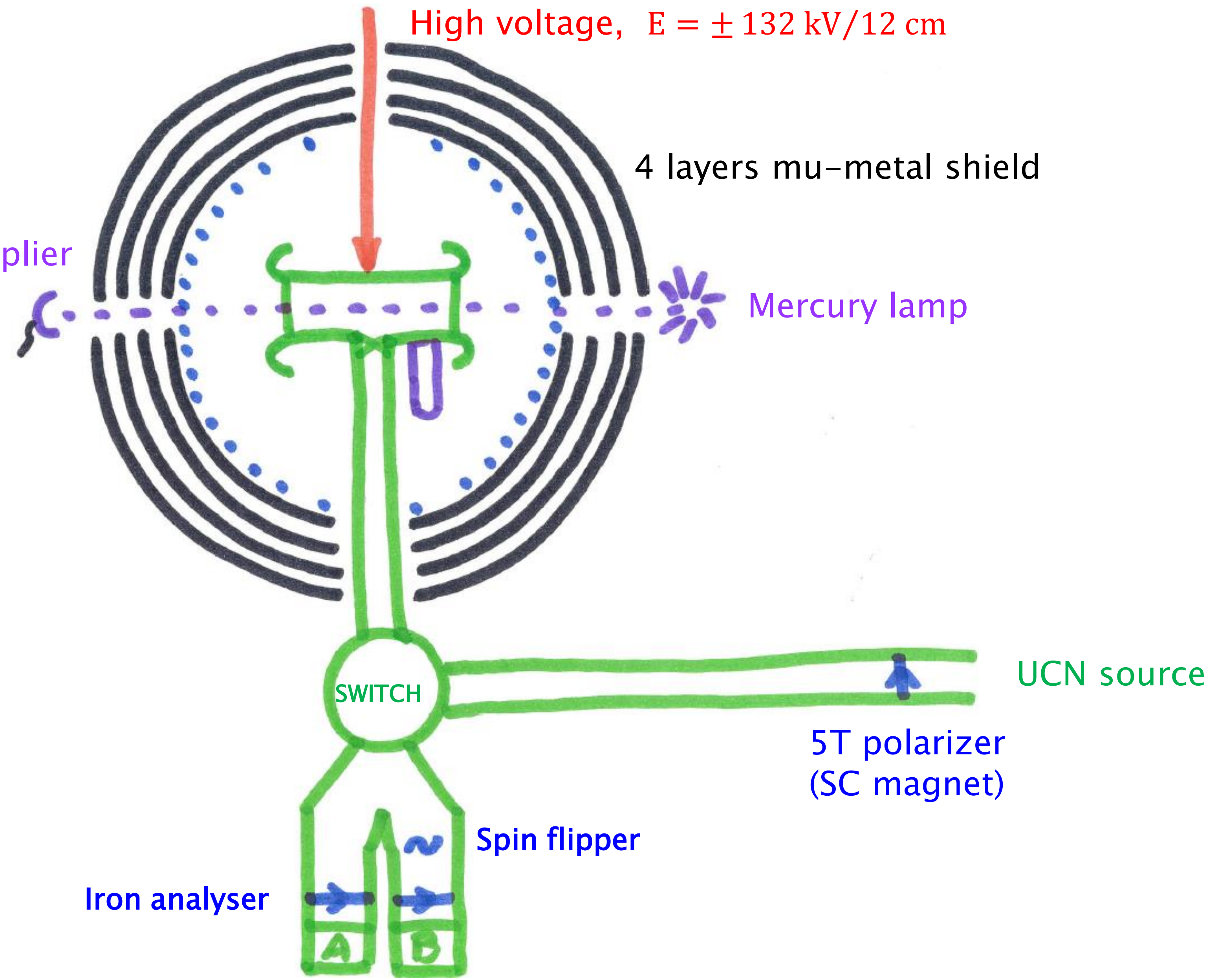
polarization

electric field

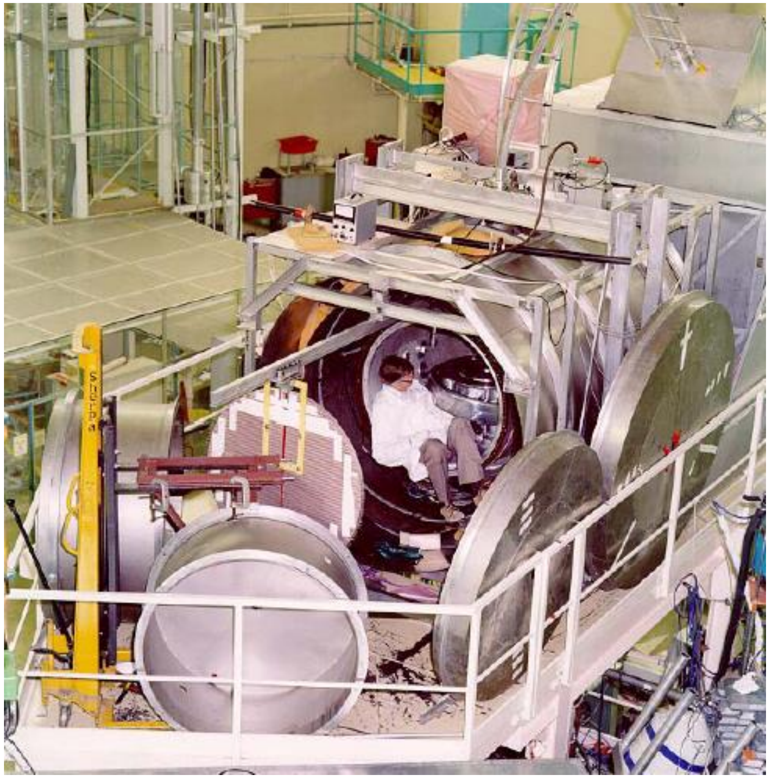
precession time

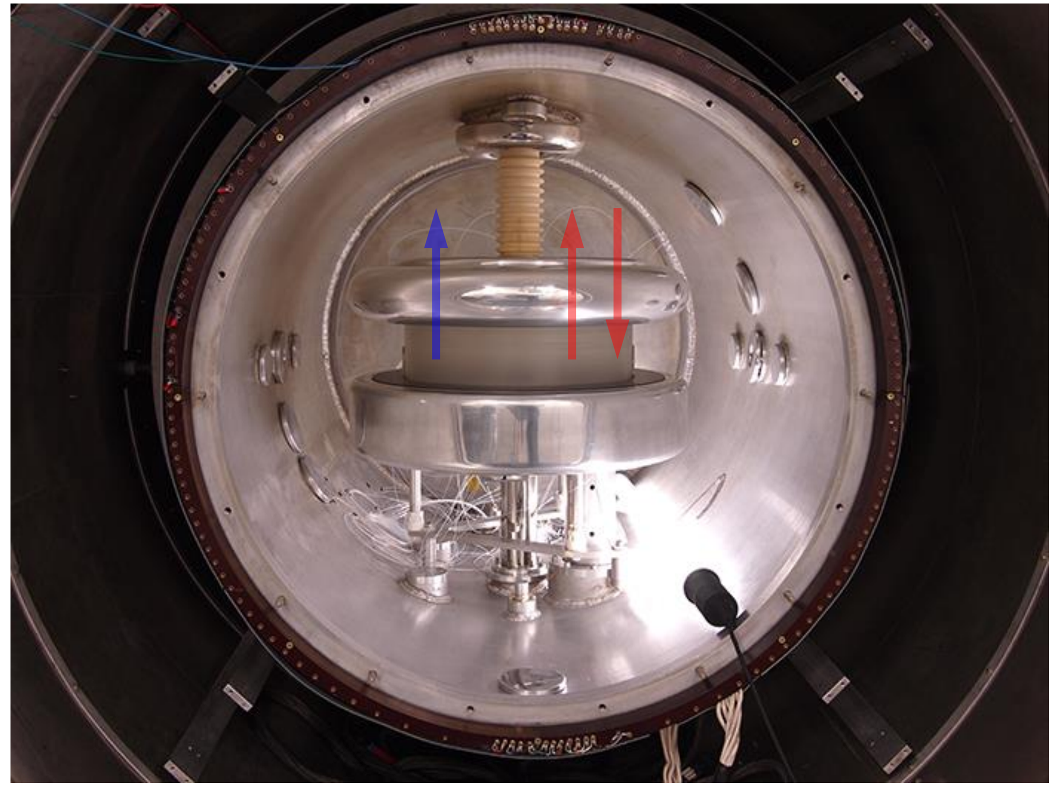
counts

The EDM apparatus



The EDM apparatus



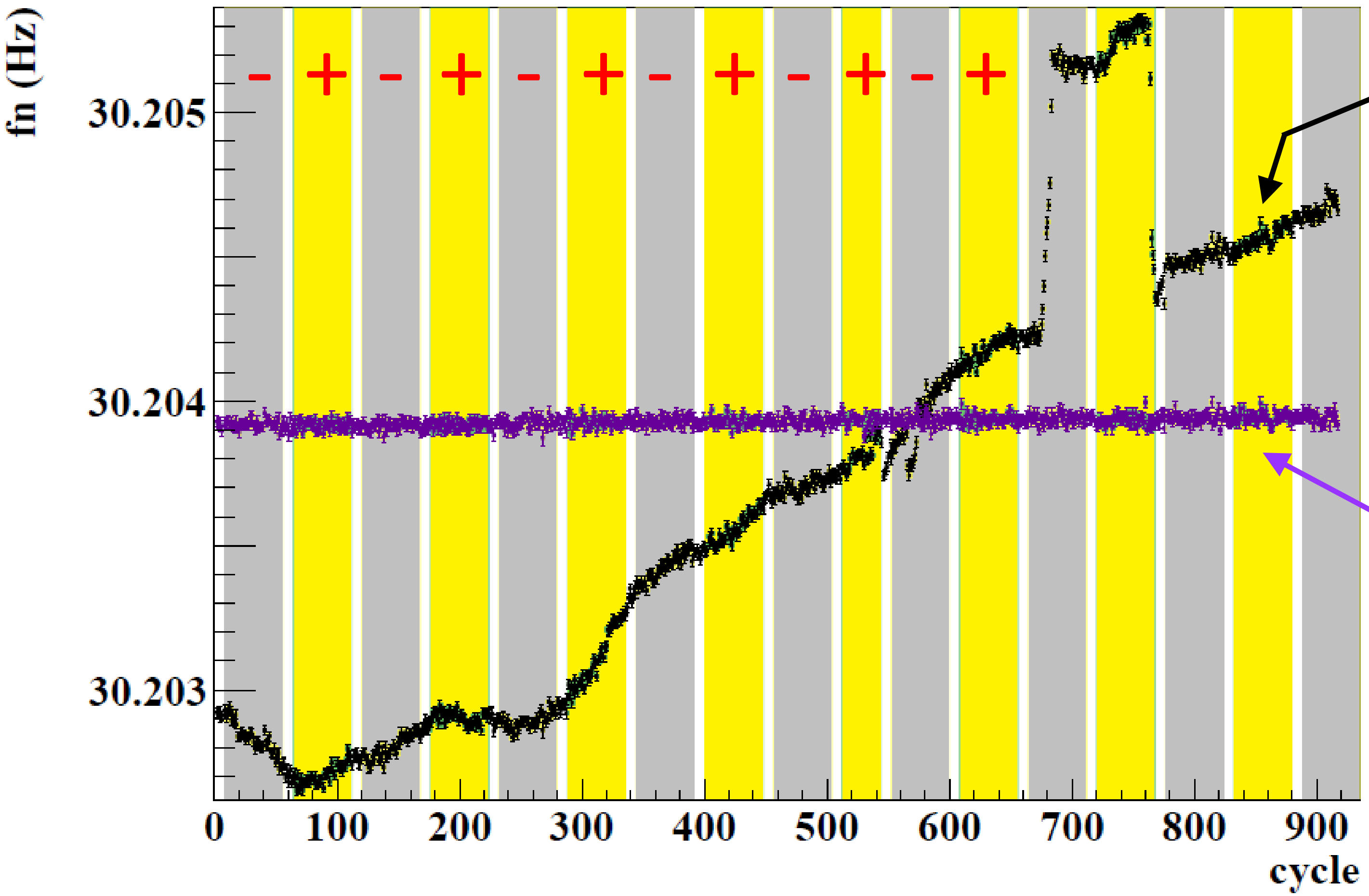


Apparatus installed at ILL PF2 (1986–2009), then moved to PSI

Best limit: $d_n < 3 \times 10^{-26}\, e$ cm obtained with $1998 - 2002$ data

[Baker *et al*, PRL (2006) ; Pendlebury *et al*, PRD (2015)]

Dealing with B-field fluctuations



Uncorrected neutron frequency

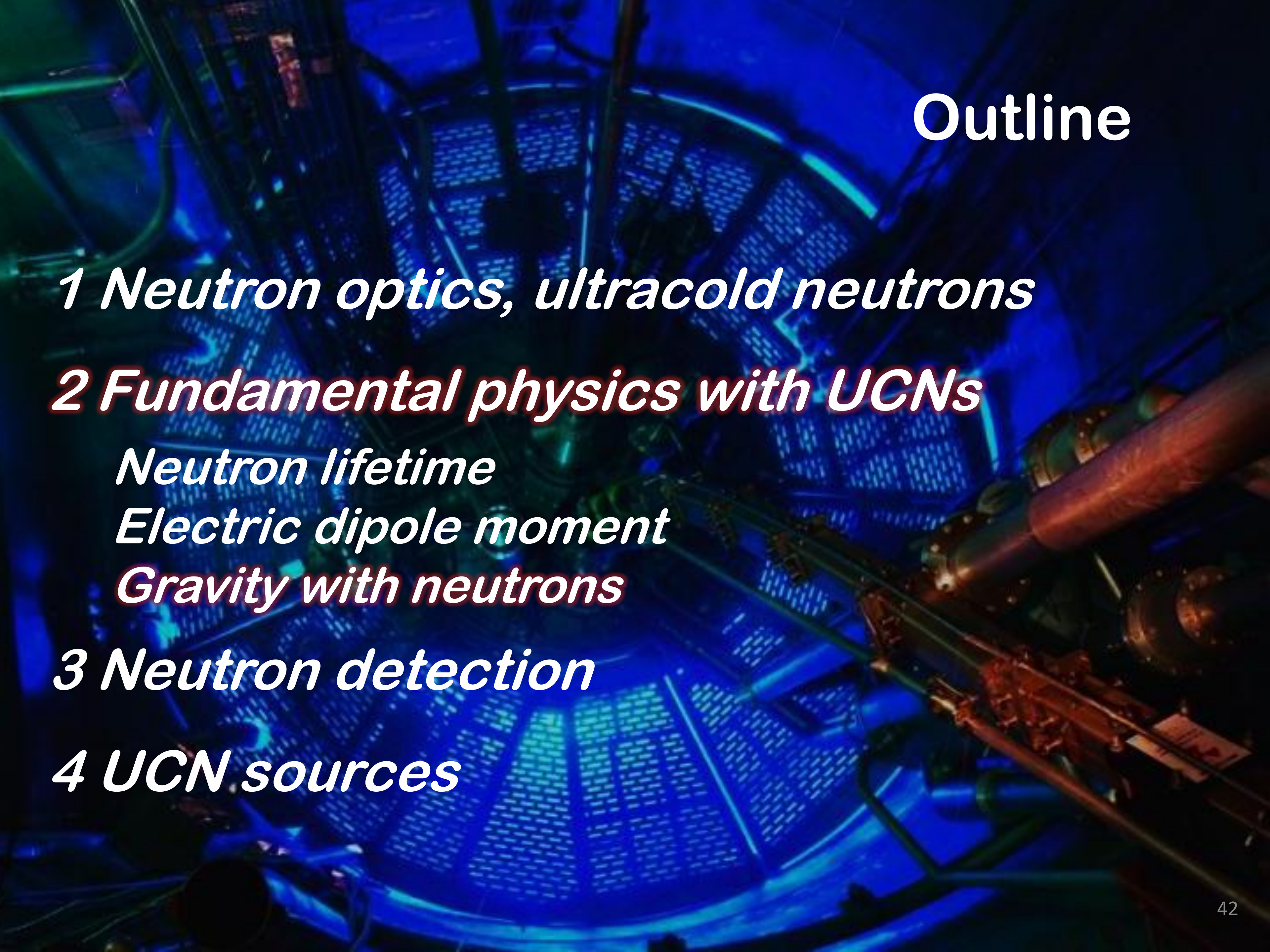
$$f_{\mathrm{n}} = \frac{\gamma_n}{2\pi} B$$

Mercury-corrected neutron frequency

$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$

$$f_{\mathrm{n}}^{\mathrm{corr}} \propto \frac{f_n}{f_{\mathrm{Hg}}}$$

The **mercury co-magnetometer** compensates for the magnetic field fluctuations…



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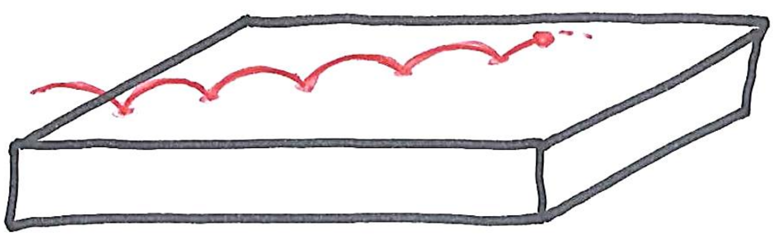
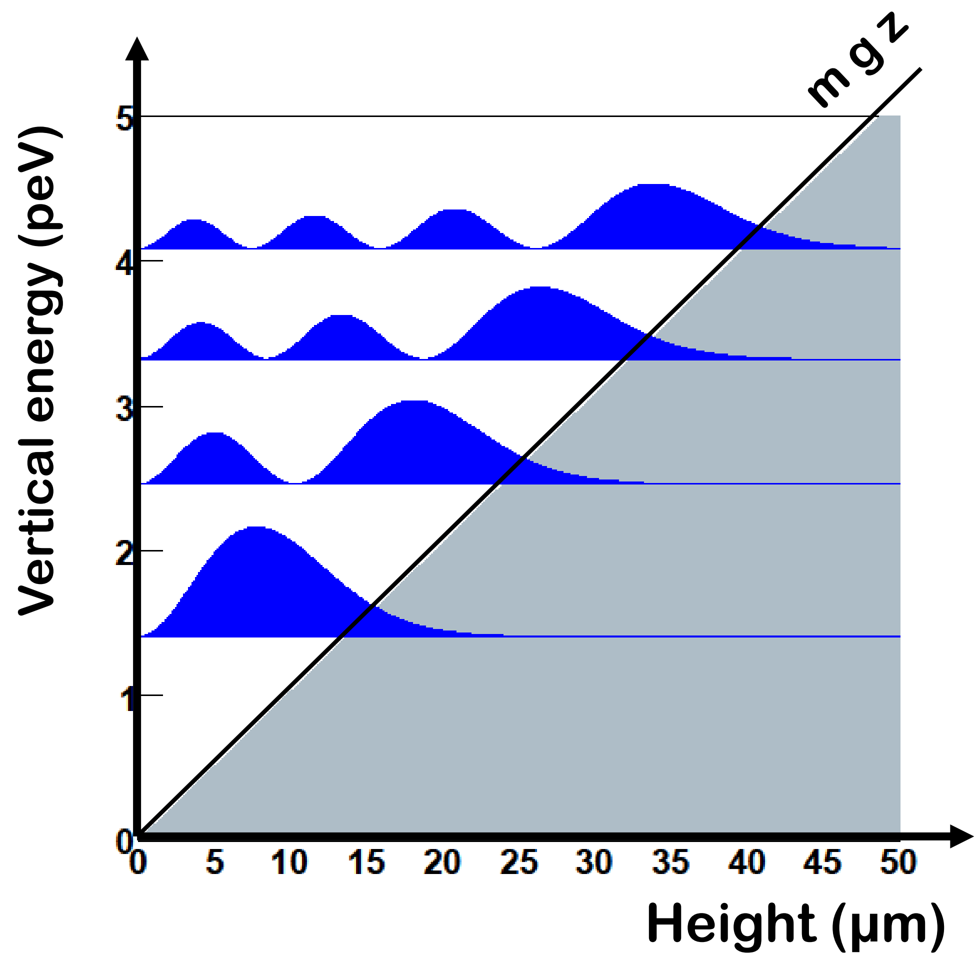
Bouncing neutrons: quantum states

Neutrons with energy < 100 neV can bounce above a glass mirror.

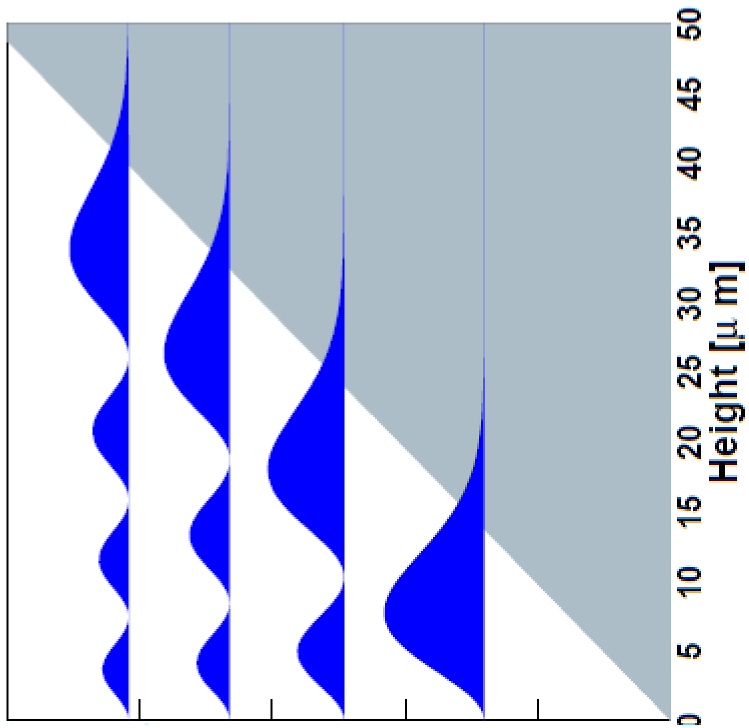


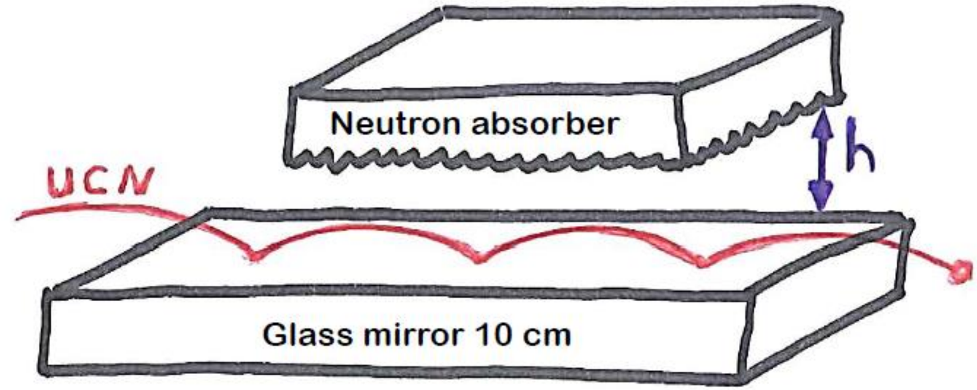
The vertical motion is a simple quantum well problem

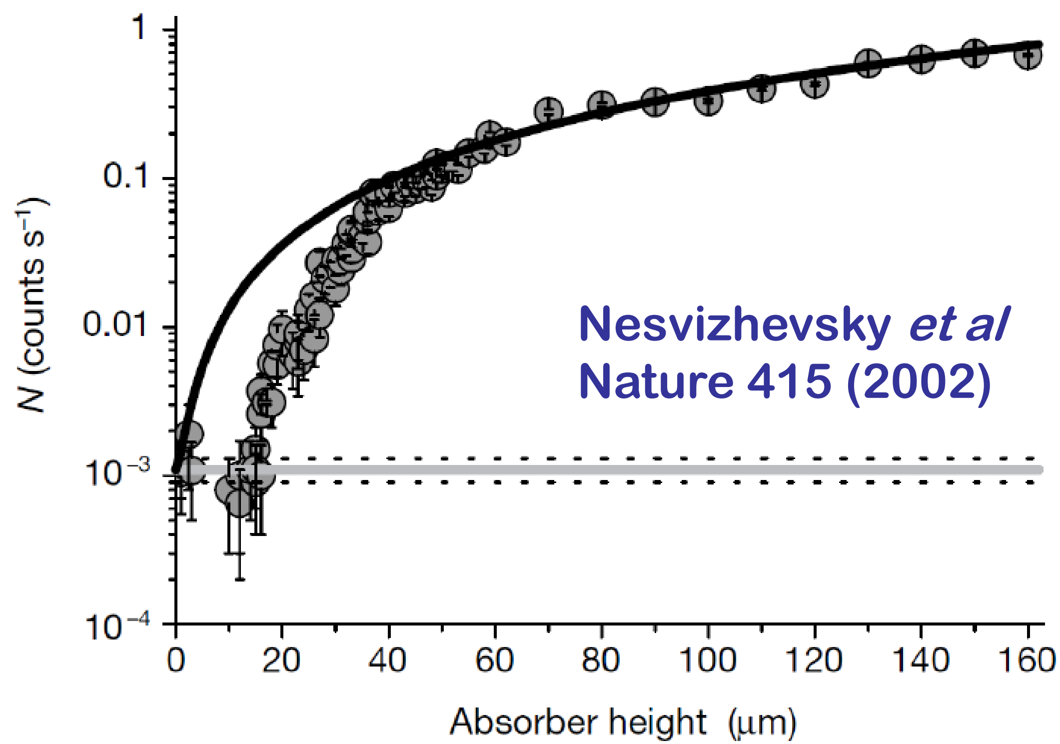
$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2}+mgz\,\psi=E\,\psi$$



Discovery of the quantum states at ILL Grenoble







Nesvizhevsky *et al*
Nature 415 (2002)

Outline

1 Neutron optics, ultracold neutrons

2 Fundamental physics with UCNs

- Neutron lifetime
- Electric dipole moment
- Gravity with neutrons

3 Neutron detection

4 UCN sources

Importance of neutron detection

Beyond the use in the very specialized UCN physics…

- Monitoring in nuclear reactors
- Radiation safety
- Detection of special nuclear materials (233U and 239Pu)
- Cosmic ray detection, monitoring the flux

- Neutrino detectors $\nu + p \rightarrow e^{+} + n$
- Most serious background in WIMP direct searches

  WIMP-induced nuclear recoil $\chi + N \rightarrow \chi + N$

  similar to fast neutron – induced recoil $\mathrm{n} + N \rightarrow n + N$

Remember: You can't directly "detect" neutrons…

Neutron inelastic reactions

- Neutron capture $n + {}^{A}\mathrm{X} \rightarrow {}^{A+1}\mathrm{X}^{*} + \gamma \quad \mathrm{a.k.a.}\ \ \mathrm{X}(n,\gamma)$
- Charged reactions $n + {}^{A}\mathrm{X} \rightarrow p + {}^{A}\mathrm{Y} \quad \mathrm{a.k.a.}\ \ \mathrm{X}(n,p)\mathrm{Y}$

  $n + {}^{A}\mathrm{X} \rightarrow \alpha + {}^{A-3}\mathrm{Y} \quad \mathrm{a.k.a.}\ \ \mathrm{X}(n,\alpha)\mathrm{Y}$

- Fission $n + {}^{235}\mathrm{U} \rightarrow PF_1 + PF_2 + \nu\, n \quad \mathrm{a.k.a.}\ \ \mathrm{U}(n,f)$

THE 1 /v LAW

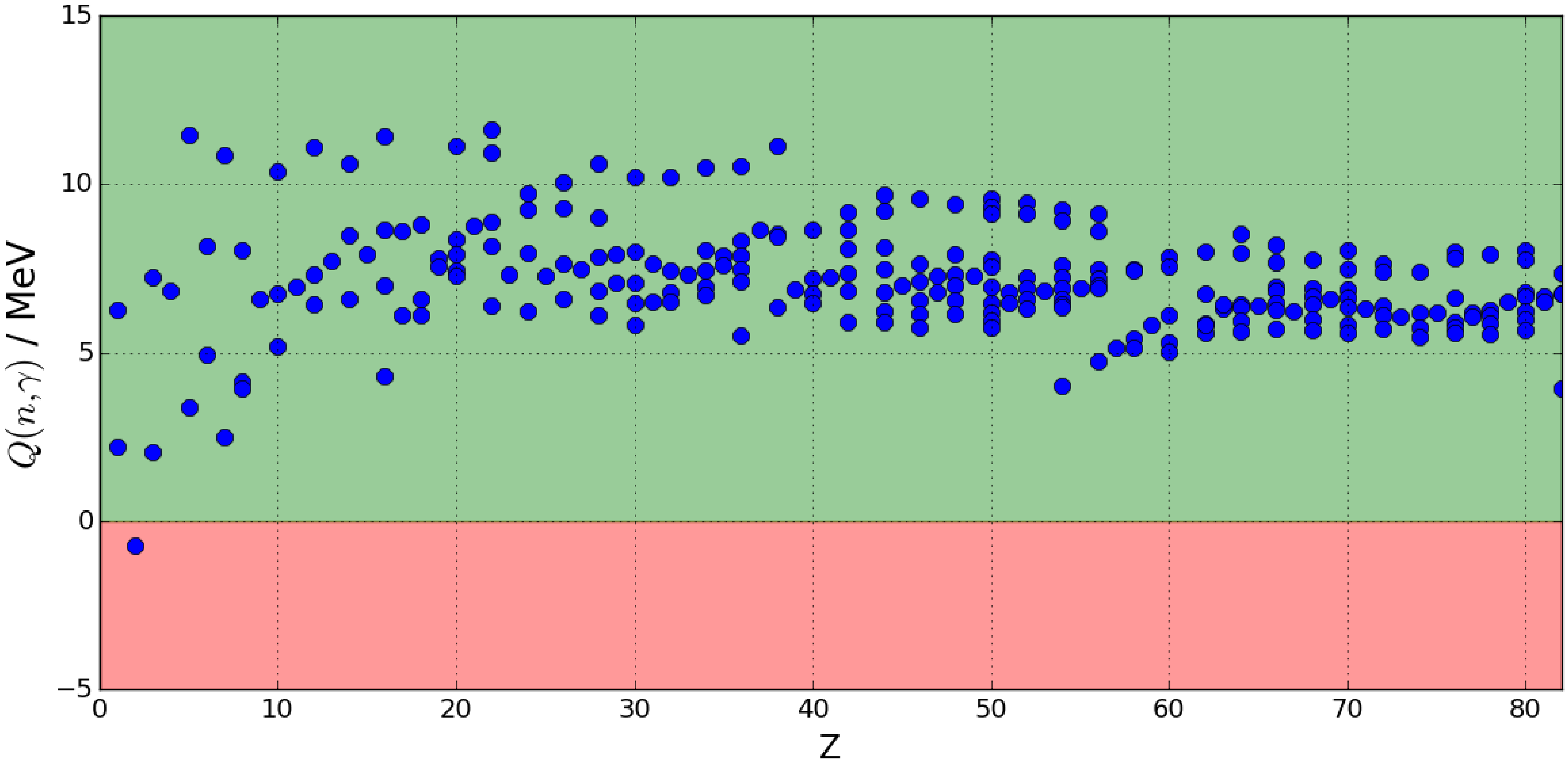
$$\sigma(v) = \sigma(v_0)\frac{v_0}{v}$$

One finds in tabulated neutron data the thermal cross sections

$$\sigma^{\mathrm{th}} = \sigma(2200\ \mathrm{m/s})$$

(n,γ) capture

$$n + {}^{A}_{Z}\mathrm{X} \rightarrow \gamma + {}^{A+1}_{Z}\mathrm{X}$$



Energy release

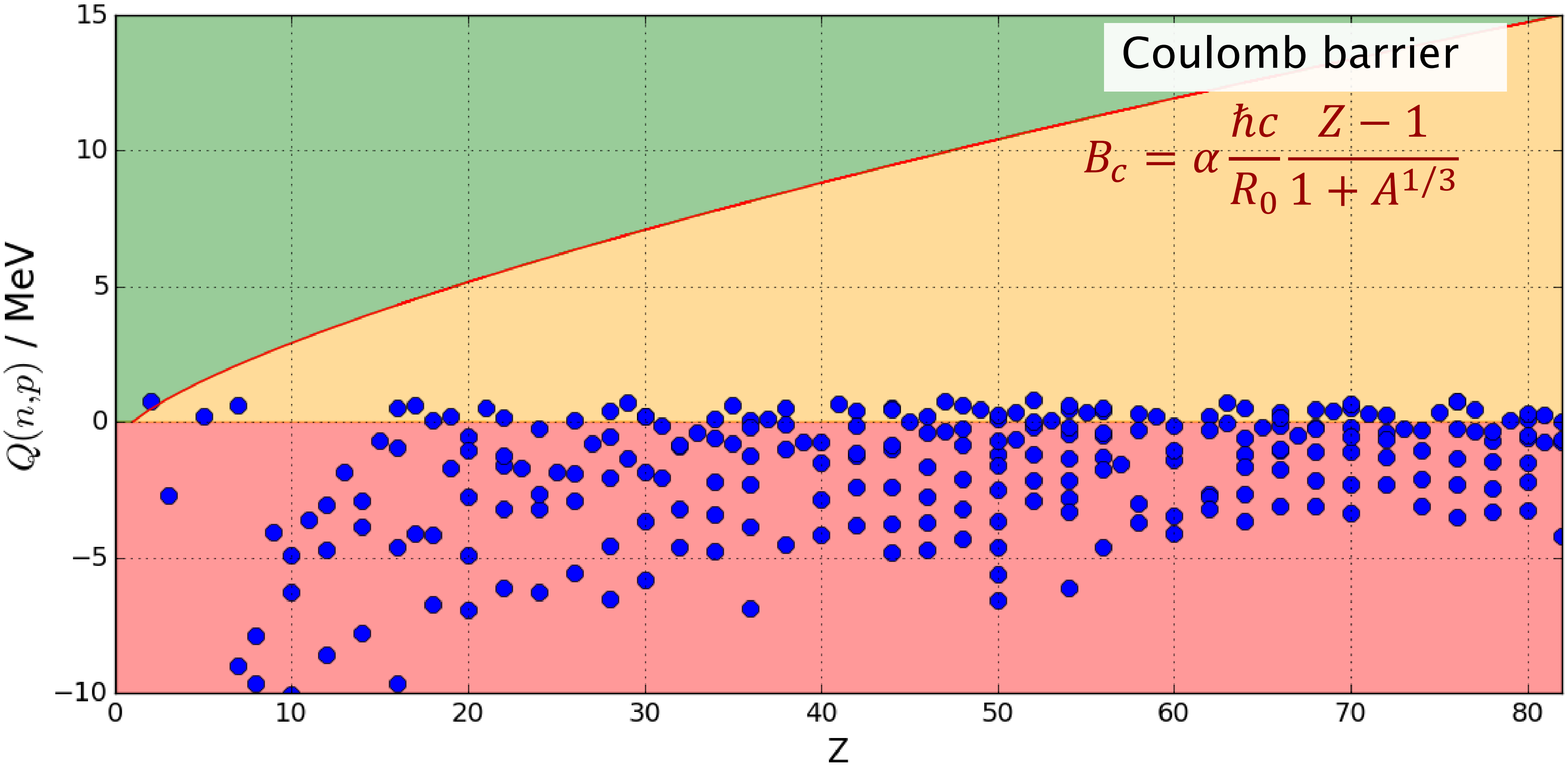
$$Q = (m_X + m_n - m_W)c^2$$

a.k.a. the neutron separation energy of the nucleus W.

All stable nuclei have Q>0 EXCEPT for $^4\mathbf{He}$. Thus, $^4\mathbf{He}$ is the only stable element with zero capture cross section for slow neutrons.

(n,p) reaction

$$n + {}^{A}_{Z}\mathrm{X} \rightarrow p + {}_{Z-1}^{\;\;\;A}\mathrm{Y}$$



Energy release

$$Q = \left(m_X + m_n - m_p - m_Y\right)c^2$$

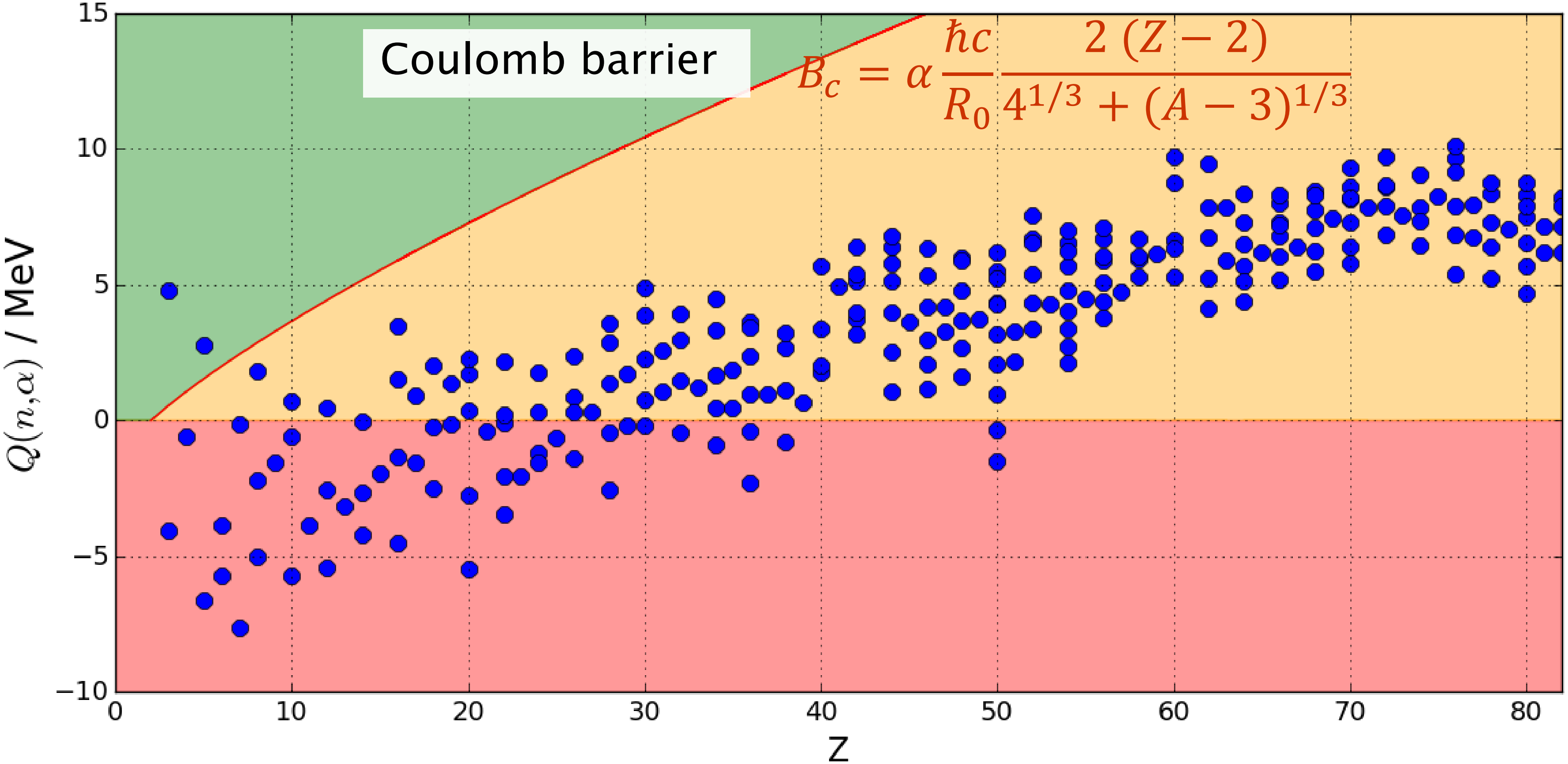
Slow neutrons undergo (n,p) reaction only if $Q > B_c$

Only one possibility

$$\boxed{n + {}^{3}\mathrm{He} \rightarrow p + t}$$

(n,α) reaction

$$n + {}^{A}_{Z}\mathrm{X} \rightarrow \alpha + {}^{A-3}_{Z-2}\mathrm{Y}$$



Energy release

$$Q = (m_X + m_n - m_\alpha - m_Z)c^2$$

Slow neutrons undergo (n,α) reaction only if $Q > B_c$

Only two possibilities

$$n + {}^{6}\mathrm{Li} \rightarrow \alpha + t$$
$$n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li}$$

Three neutron convertors

	$^{3}\mathbf{He}(\boldsymbol{n},\boldsymbol{p})$	$^{6}\mathbf{Li}(\boldsymbol{n},\boldsymbol{\alpha})$	$^{10}\mathbf{B}(\boldsymbol{n},\boldsymbol{\alpha})$
Abundance	0.014 %	7.6 %	19.9 %
σ^{th}	5330 barn	937 barn	3837 barn
Kinetic energy of products	$\boldsymbol{p}$: 0.57 MeV	$\boldsymbol{\alpha}$: 2.05 MeV	$\boldsymbol{\alpha}$: 1.47 MeV
	$\boldsymbol{t}$: 0.19 MeV	$\boldsymbol{t}$: 2.73 MeV	$\mathbf{Li}$: 0.84 MeV
			$\boldsymbol{\gamma}$: 0.48 MeV

Gaseous detectors:

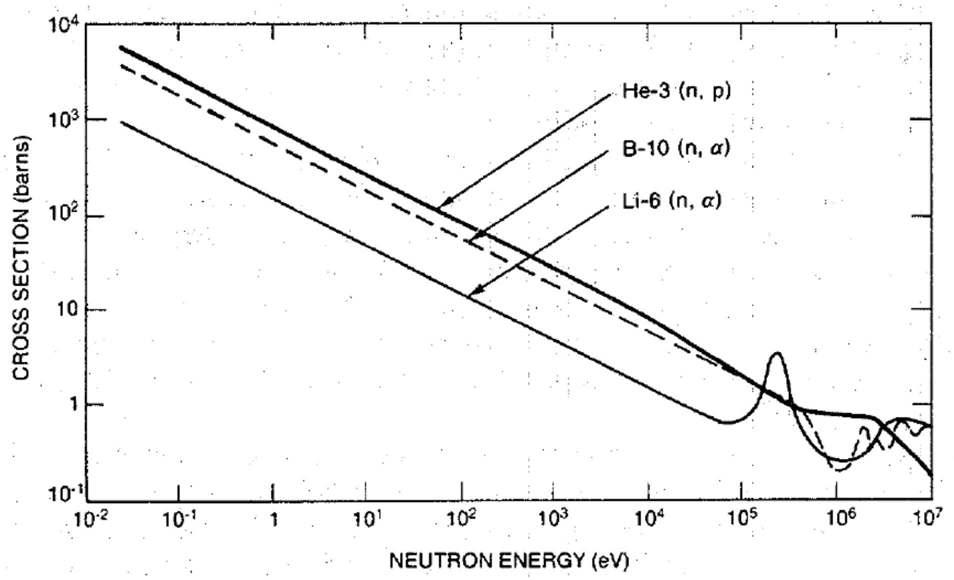
proportional counters filled with $^{3}\mathbf{He}$ or $\mathbf{BF_3}$

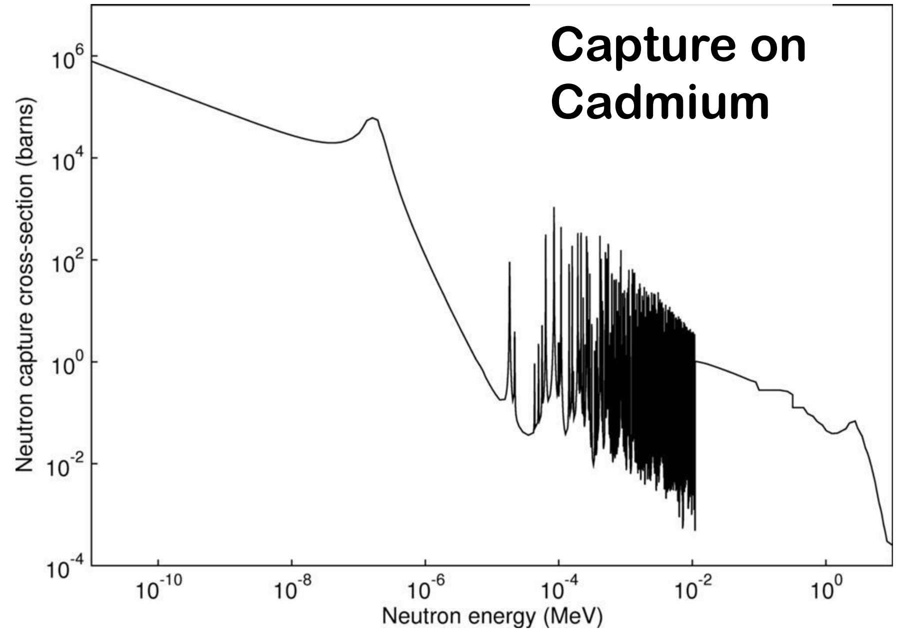
Solid detectors:

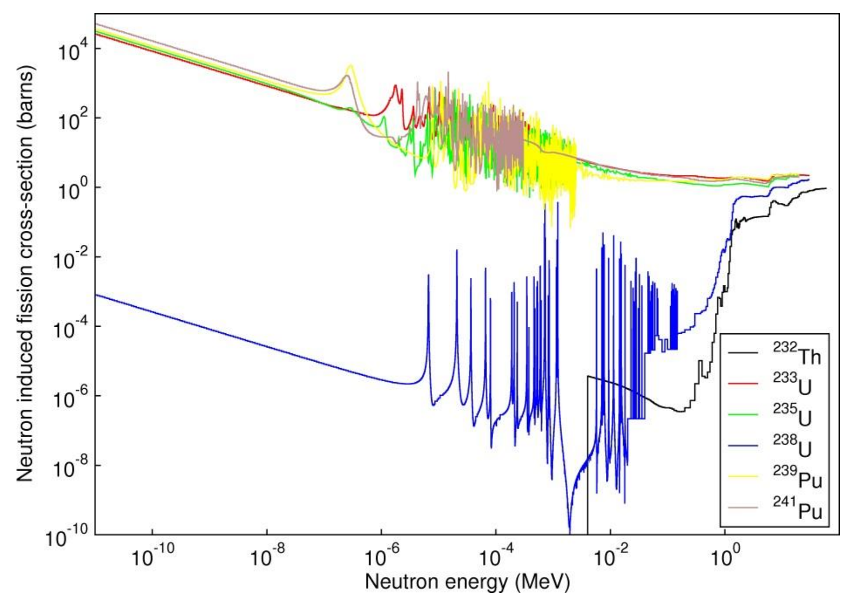
scintillators $\mathbf{LiF}$

silicon detectors with Boron solid conversion layer

Validity of the 1/v law







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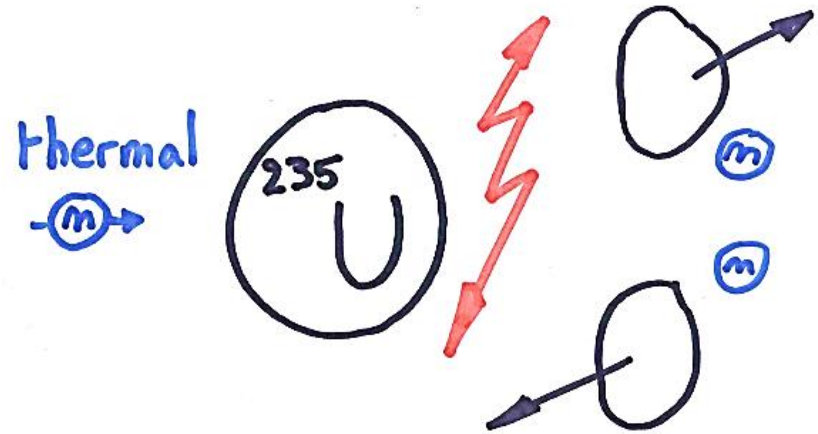
Big Neutron Sources

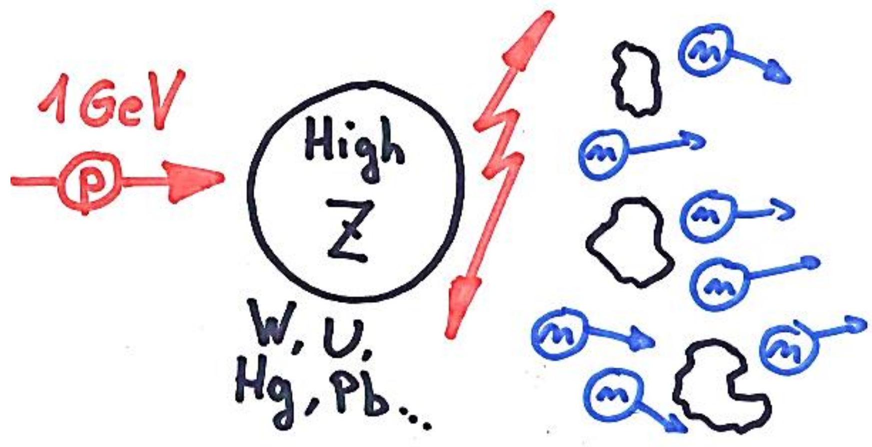
FISSION

- steady chain reaction
- ~ 2 neutron/fission
- Energy ~ 2 MeV



SPALLATION

- Accelerator driven
- Pulsed or steady
- ~ 20 neutrons/proton
- Energy ~ 20 MeV



Compare the neutron flux

PWR power reactor

Thermal neutron flux

~ 10^{14} n/cm^2/s

ILL high flux reactor

Thermal neutron flux

~ 1.5 x 10^{15} n/cm^2/s

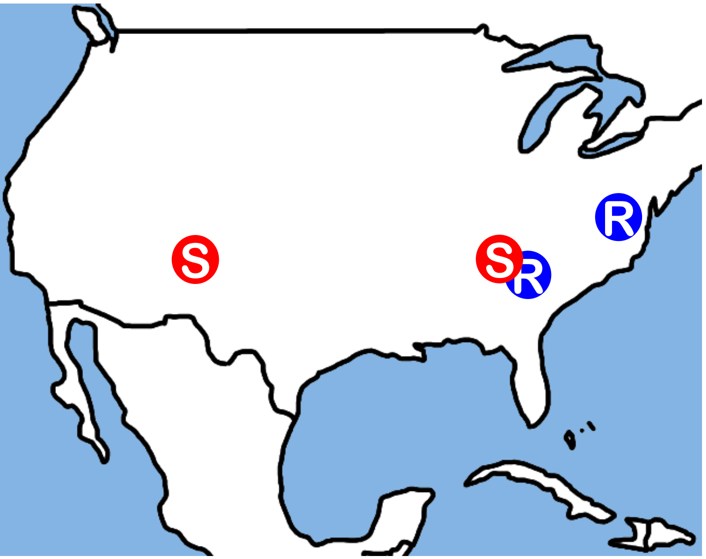
SNS pulsed source

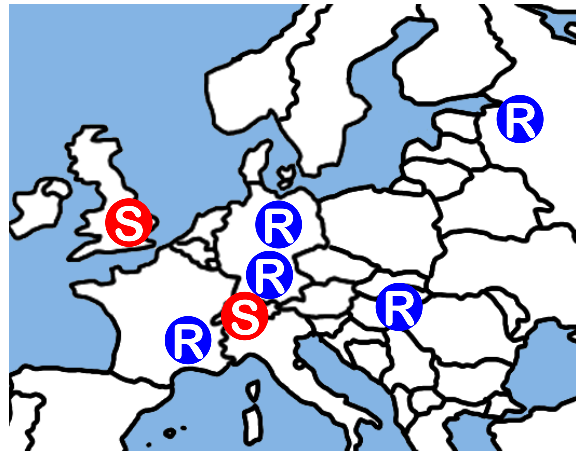
Thermal neutron flux

Peak ~ 3x10^{16} n/cm^2/s

Average ~ 4x10^{13} n/cm^2/s

About 20 Big Neutron Sources worldwide





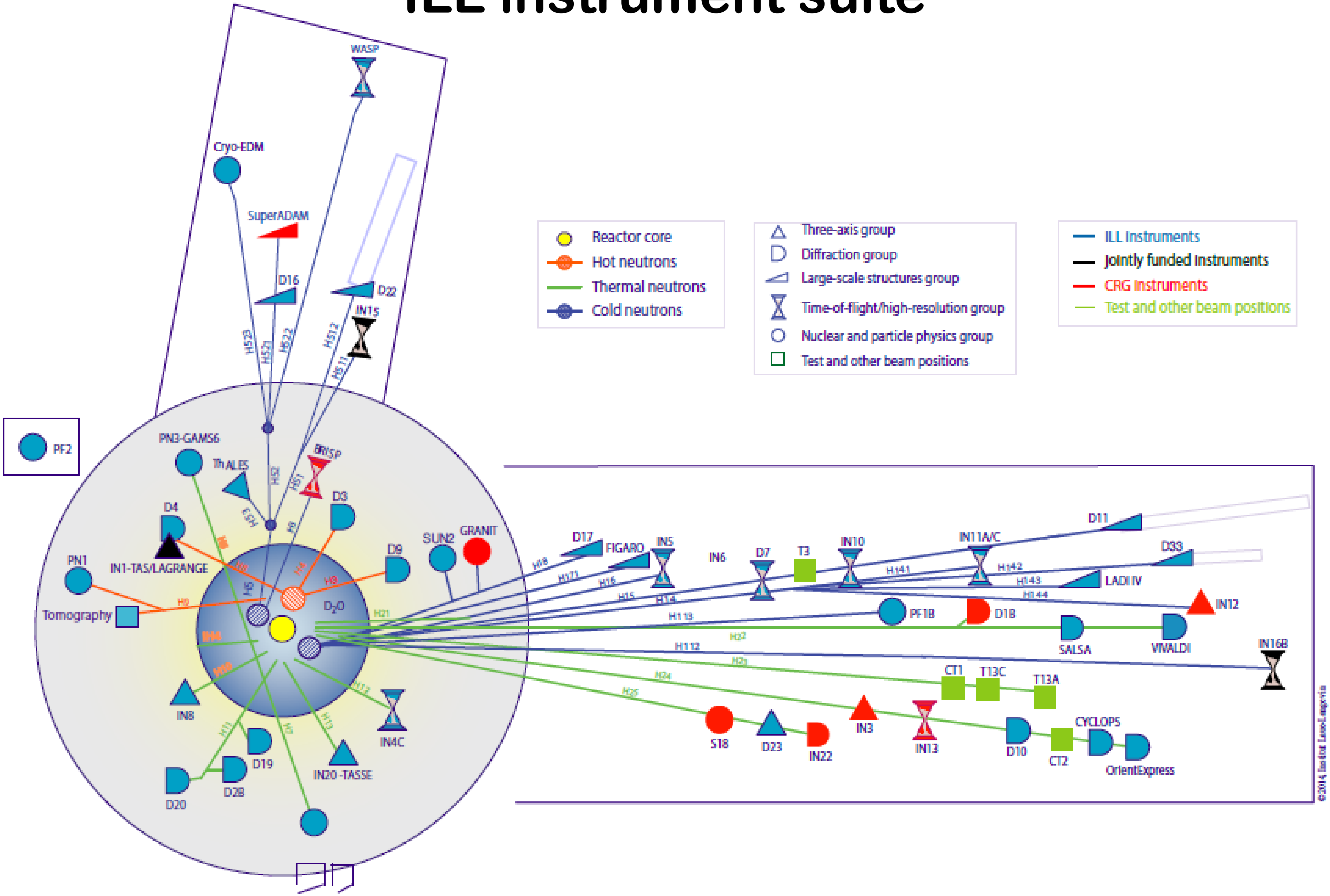
Reactor	City	Country	Th. Power	Instruments
ILL	Grenoble	France	58 MW	46
HFIR	Oak Ridge	USA	85 MW	12
CARR	Bejing	China	60 MW	12
FRM II	Munich	Germany	20 MW	19
HANARO	Daejon	Korea	30 MW	8
WWR-M	Gatchina	Russia	18 MW	19
NIST	Gaithersburg	USA	20 MW	28
JRR-3M	Tokai	Japan	20 MW	26
BRR	Budapest	Hungary	10 MW	11
OPAL	Sydney	Australia	20 MW	7
BER II	Berlin	Germany	10 MW	22

High flux reactors with cold neutron source available for users (there are 246 operational research reactors worldwide)

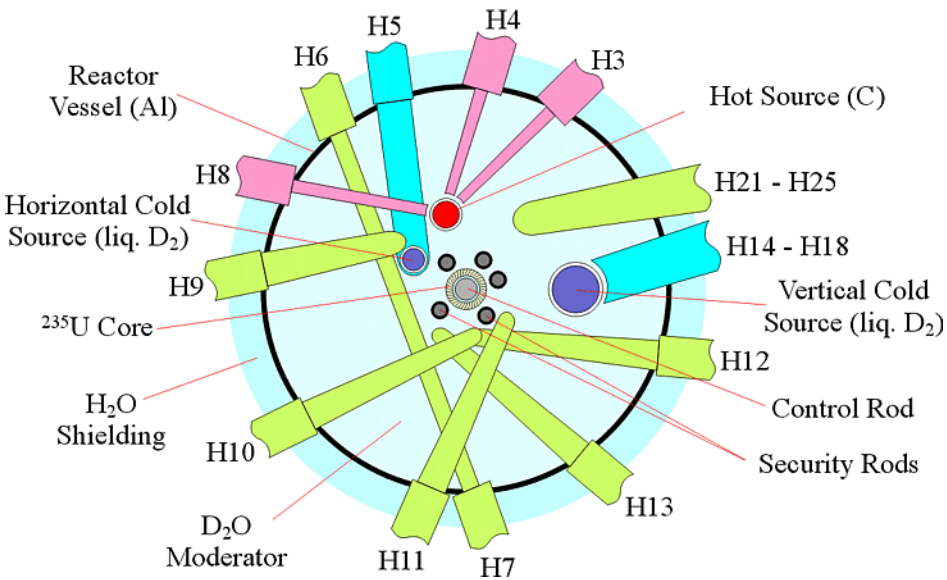
Spall. Source	City	Country	Beam Power	Instruments
SINQ @PSI	Villigen	Switzerland	1.5 MW	20
SNS @ORNL	Oak Ridge	USA	1.4 MW	25
JSNS @KEK	Tsukuba	Japan	0.3 MW	17
ISIS @RAL	Oxford	UK	0.2 MW	36
Lujan @LANSCE	Los Alamos	USA	0.1 MW	13

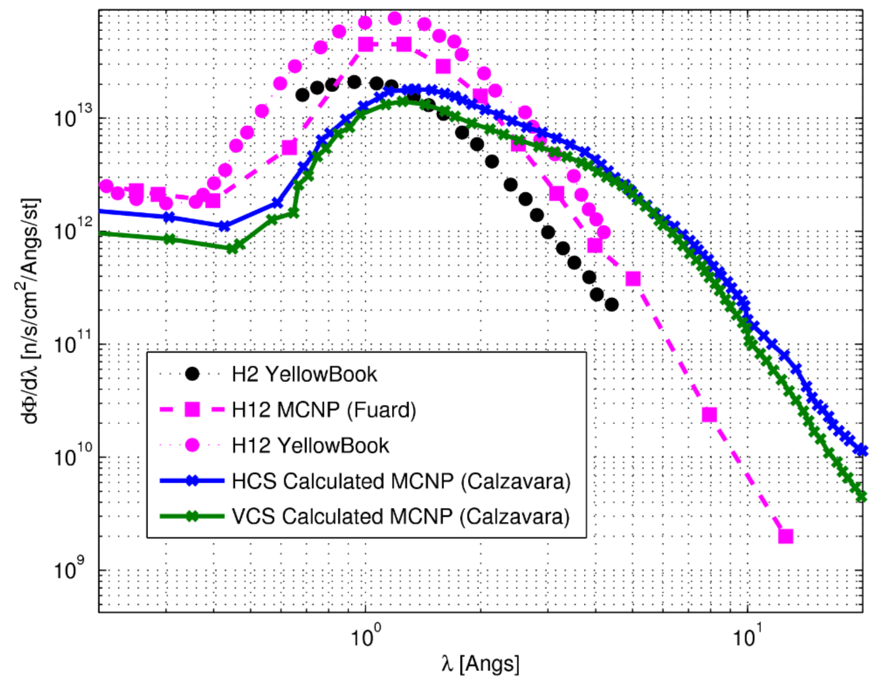
High intensity spallation sources available for users

ILL instrument suite



The ILL high flux reactor





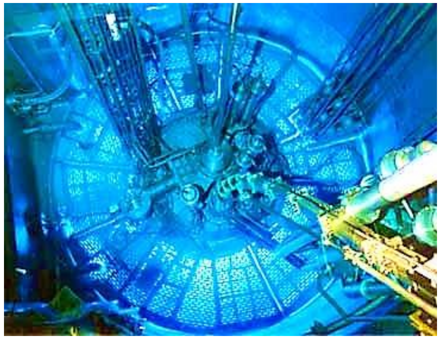
Thermal power: 58 MW

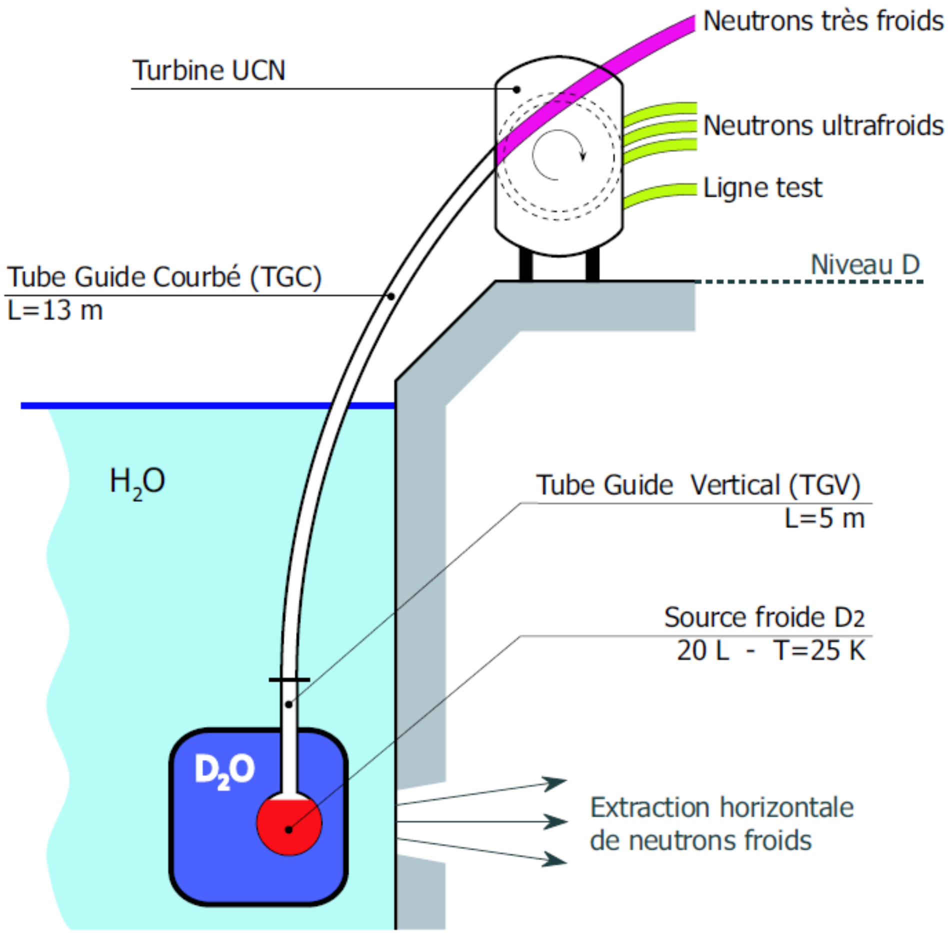
Heavy water moderator and reflector

Fuel: HEU (93.3% 235)

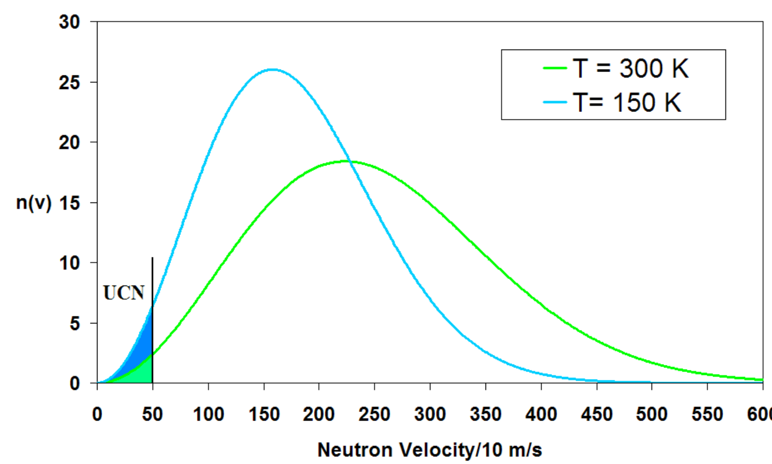
Cold source: 20 L of Liquid D2 at 20K

Source UCN PF2@ILL, since 1985

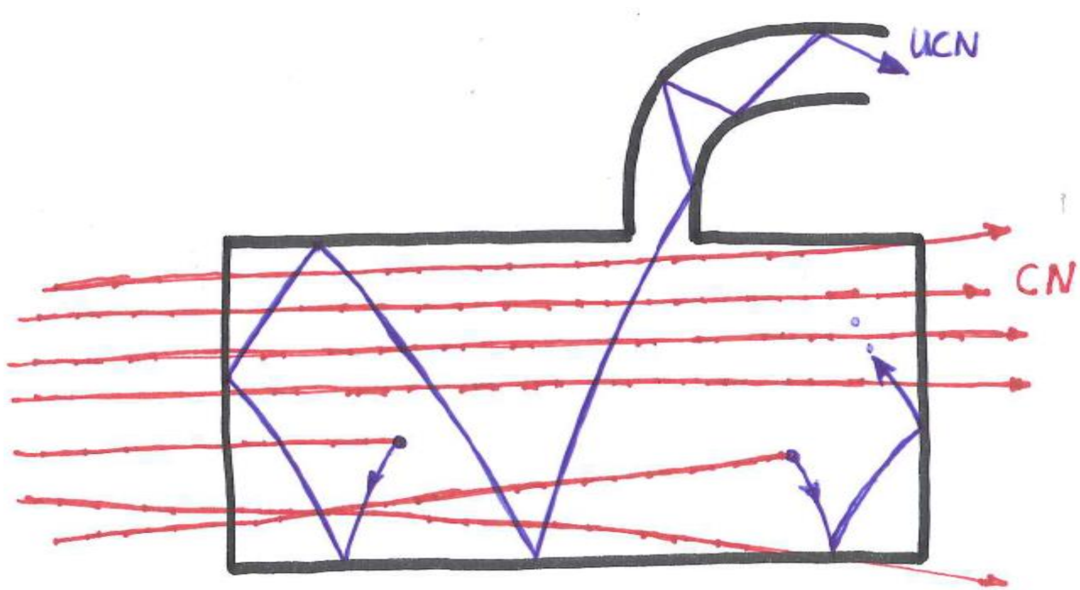


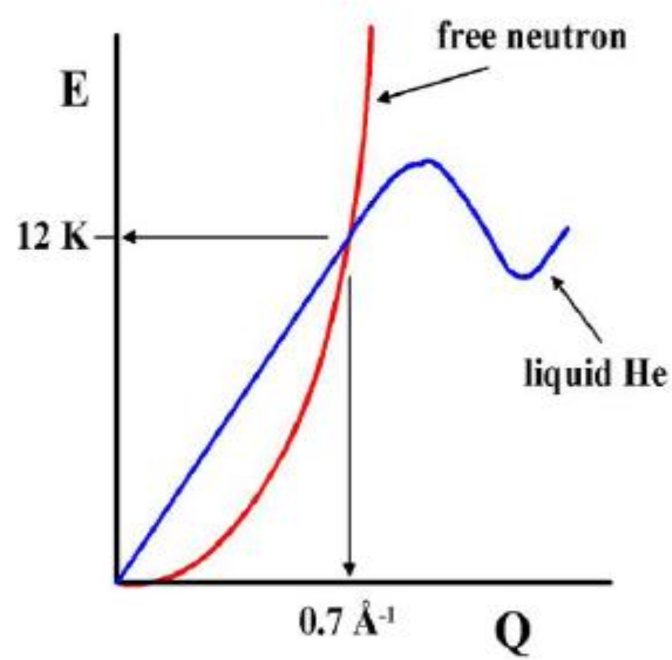


30 UCN / cm³



Superthermal production of UCNs in superfluid 4He



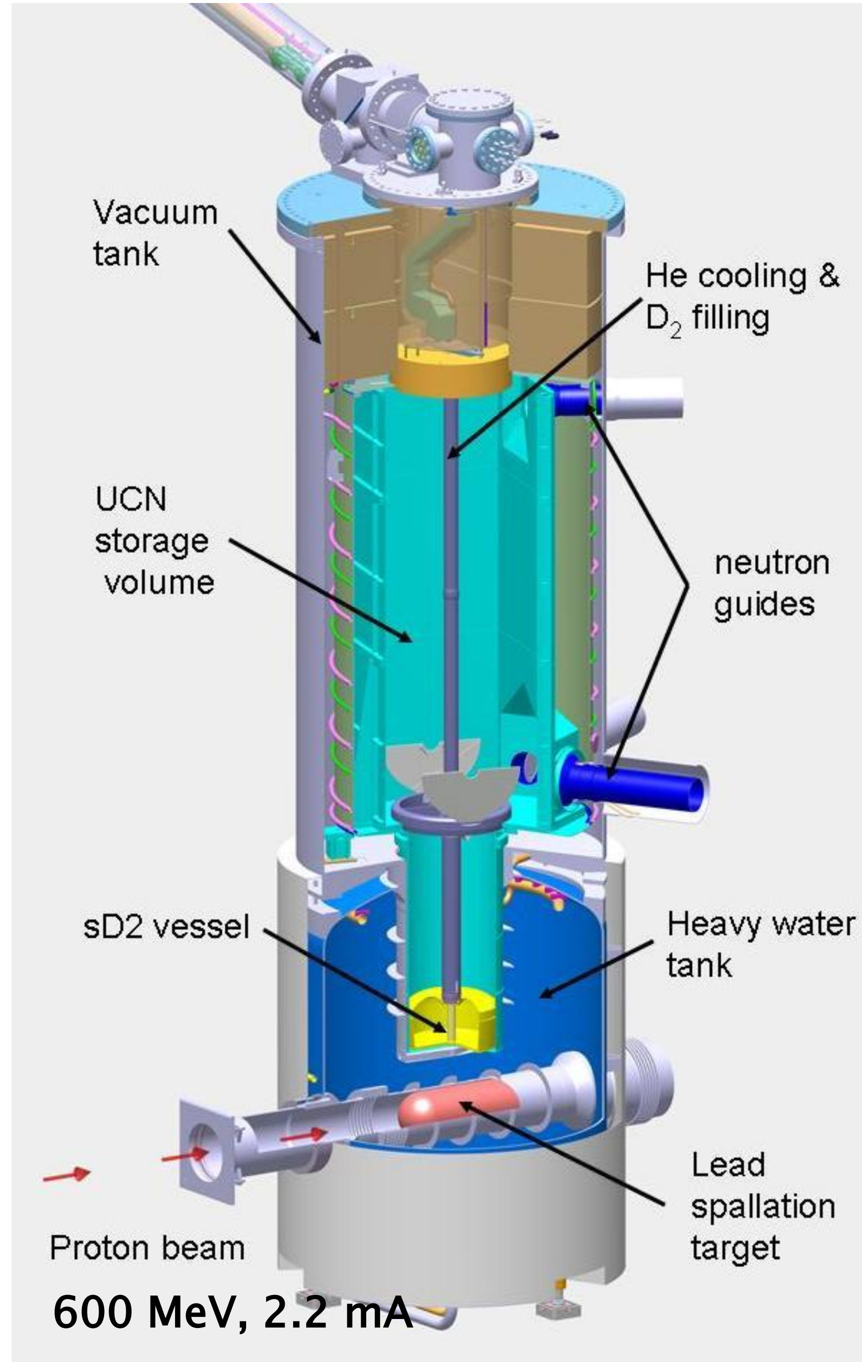


Input: intense beam of cold neutrons with a wavelength of 8.9 A

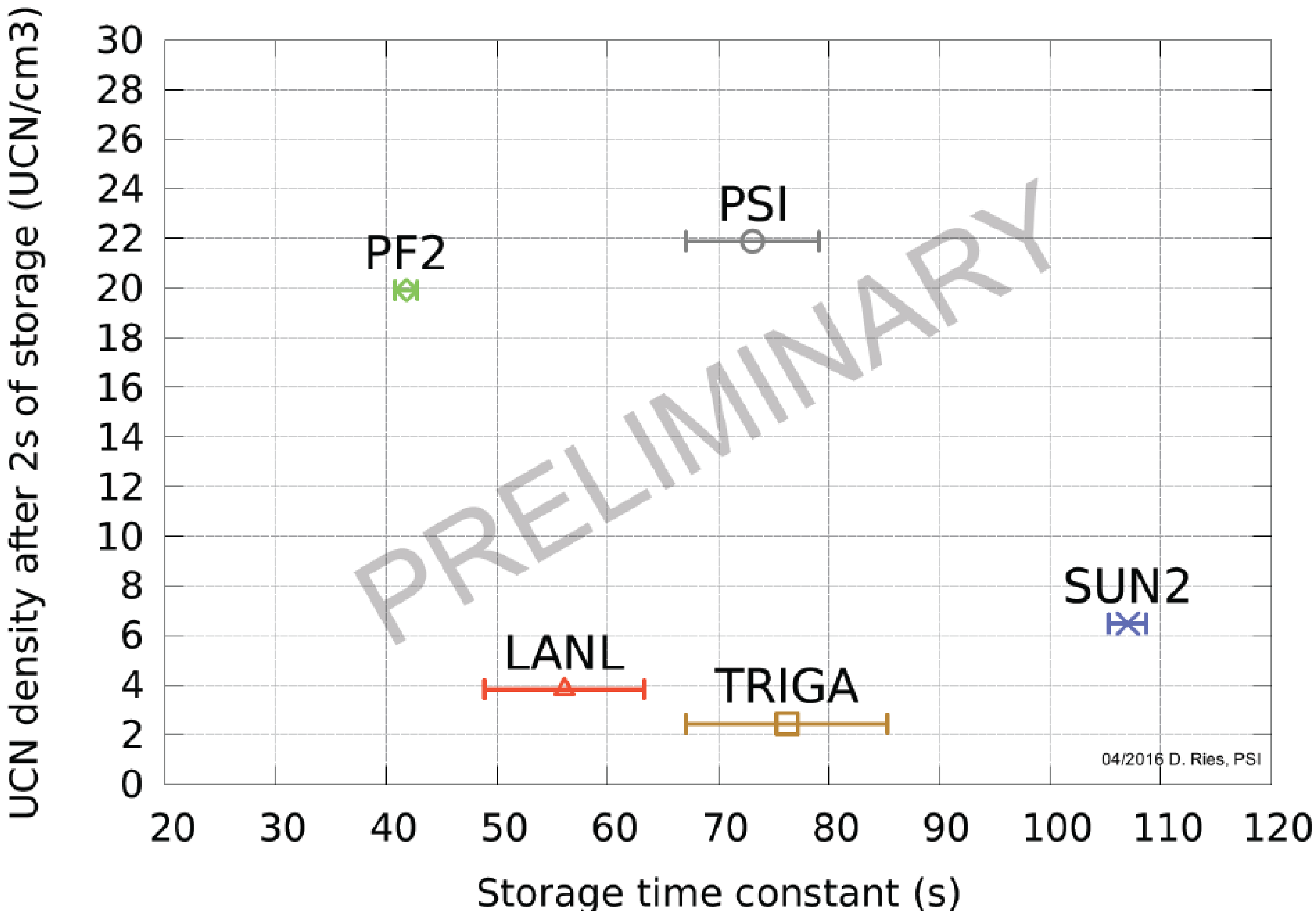
The superfluid Helium needs to be cooled down to 0.7 K

UCN source at the Paul Scherrer Institute

pulsed UCN source
One kick per 5 min
online since 2011



Finally a worldwide comparison of UCN sources



Diter Ries (PhD) stainless steel bottle