Ultracold neutrons

UNIVERSITÉ Grenoble Alpes

Guillaume.Pignol@lpsc.in2p3.fr

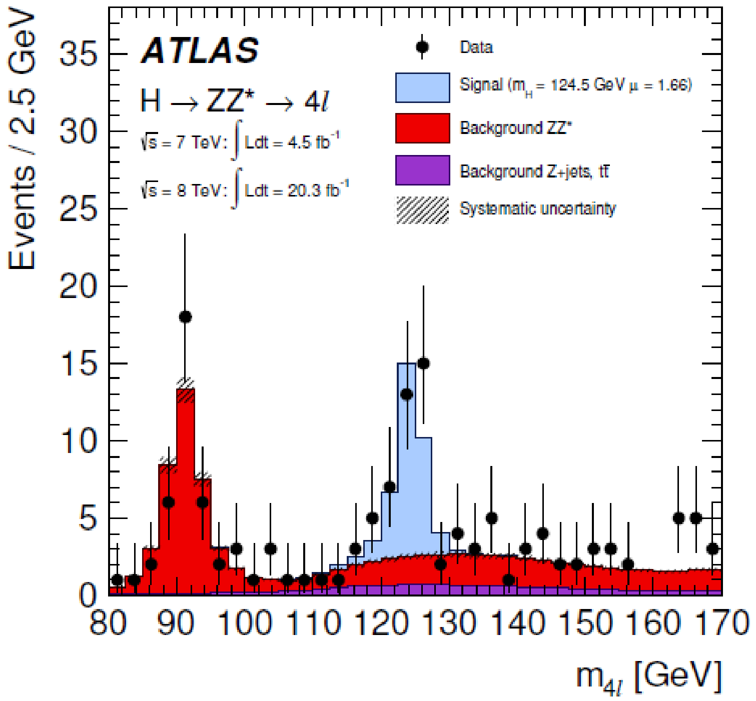
ESIPAP, febuary 2018

1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. Fundamental physics with UCNs
   - Neutron lifetime
   - Electric dipole moment
   - Gravity with neutrons

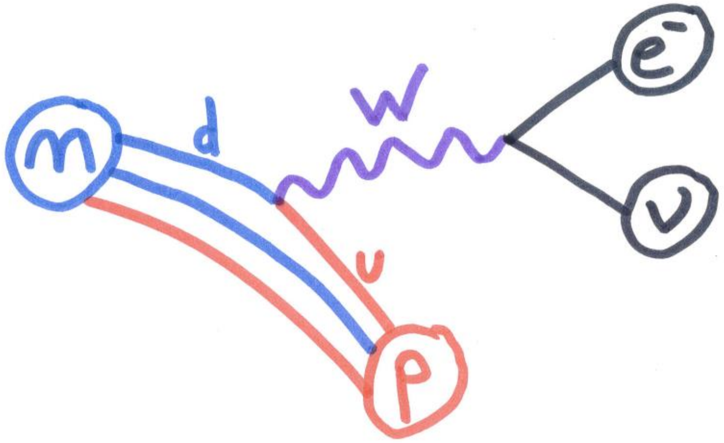
Two frontiers of particle physics

Energy frontier (LHC): producing heavy unstable particles at colliders, e.g.

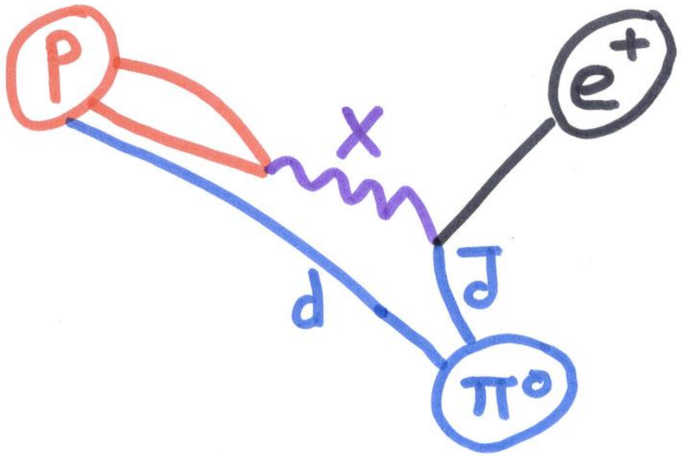
- W boson, $m_W = 80$ GeV
- Higgs boson, $m_H = 125$ GeV
- Dark matter particle?



Precision frontier: detecting the effect of virtual particles.
The neutron beta decay, lifetime of 15 minutes, proceeds via the exchange of the virtual W.
Fundamental structure of the Standard Model inferred from properties of the decay (e.g. parity violation).



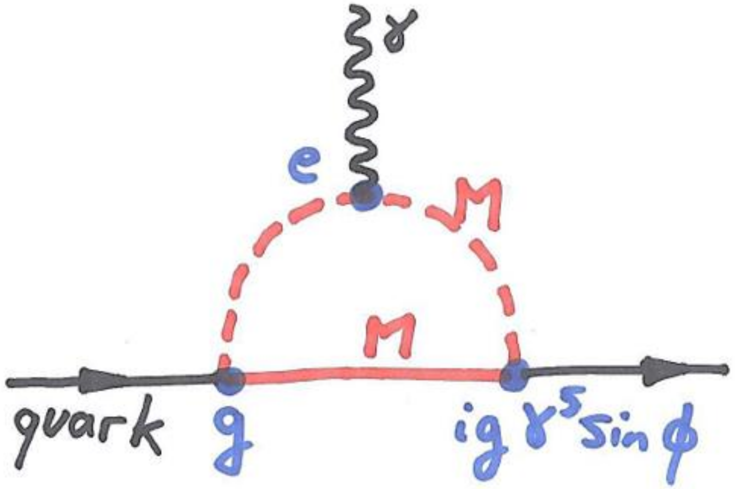
New physics at the precision/intensity frontier



New particles could induce super-rare decays.
Example: a new boson with $m_X = 10^{15}$ GeV could induce the proton decay with a lifetime of

$$\tau_p \approx \frac{M_X^4}{\alpha^2 m_p^5} \approx 10^{33} \text{ years}$$

It would violate the conservation of baryon and lepton number.



New particles could induce exotic couplings.
An **electric dipole moment** (EDM) is an interaction of the spin of a particle with the electric field.
This coupling **violates time reversal symmetry**, and is connected with the matter-antimatter asymmetry of the Universe.

The search for the EDM of the neutron is highly sensitive to interesting new physics.

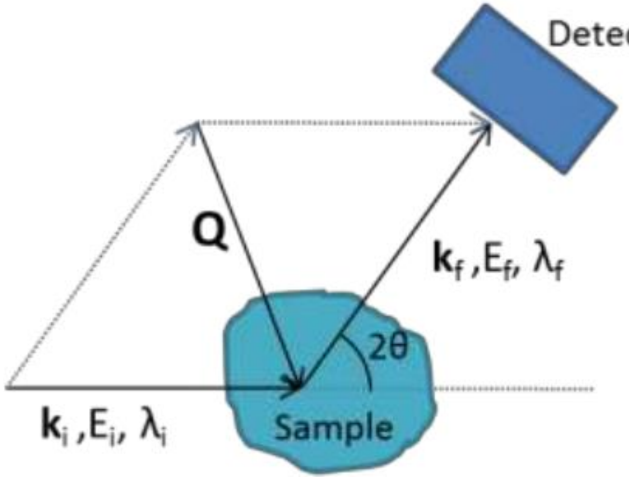
Experiments at the precision/intensity frontier

- **Proton decay, neutrino-less double beta decay**
  low background, underground detectors.
- **Rare decays of K mesons** where CP violation was discovered
  intense production of K with proton beam on fixed target
- **Rare decays of B mesons** LHCb, Babar, Belle
  particle colliders as B factories
- **Experiments with muons** e.g. search for $\mu \rightarrow e\,\gamma$ decay
  proton beam on target $\rightarrow$ pions $\rightarrow$ muons
- **Precision experiments with antiprotons** to test CPT symmetry
  production and deceleration of antiprotons
- **Precision experiments with neutrons:** β decay, gravity, test of CP symmetry
  intense neutron sources, slowing down of neutrons to produce
  ULTRACOLD neutrons

Large neutron factories

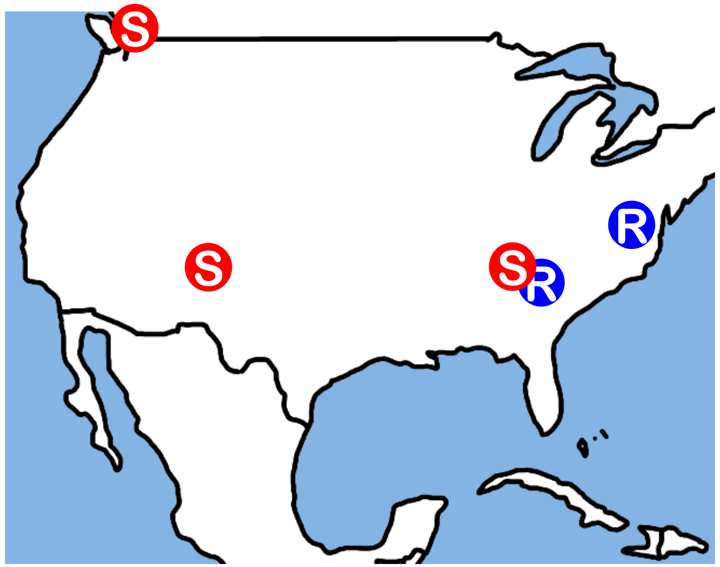
multi-disciplinary facilities

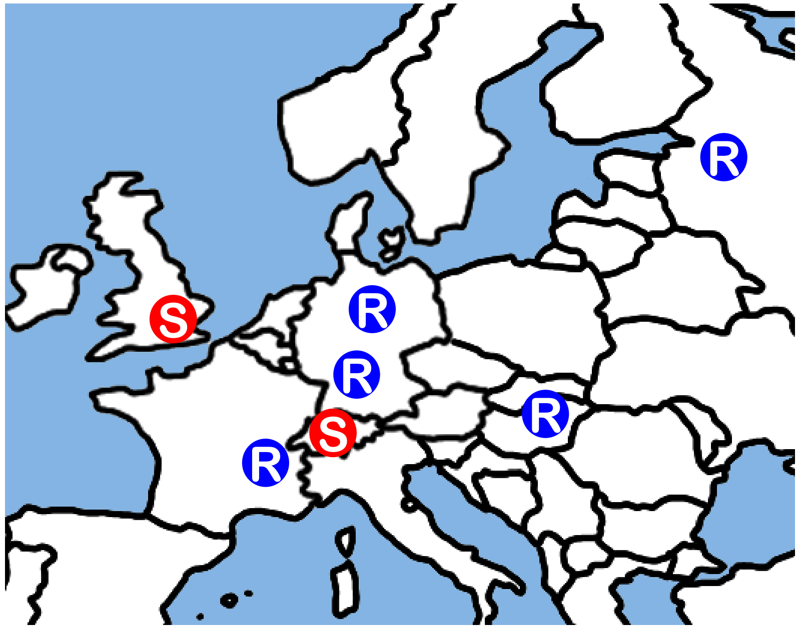
Biology
Chemistry
Material sciences
Magnetism
Nuclear physics
Particle physics



A typical neutron scattering experiment

About 20 Big neutron sources in the world





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

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

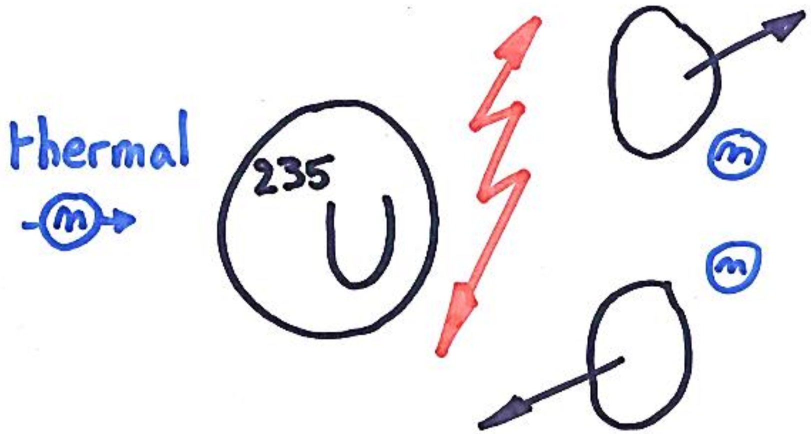
Spall. Source	City	Country	Beam Power
SINQ @PSI	Villigen	Switzerland	1.5 MW
SNS @ORNL	Oak Ridge	USA	1.4 MW
JSNS @KEK	Tsukuba	Japan	0.3 MW
ISIS @RAL	Oxford	UK	0.2 MW
Lujan @LANSCE	Los Alamos	USA	0.1 MW

High intensity spallation sources

Fission or Spallation sources

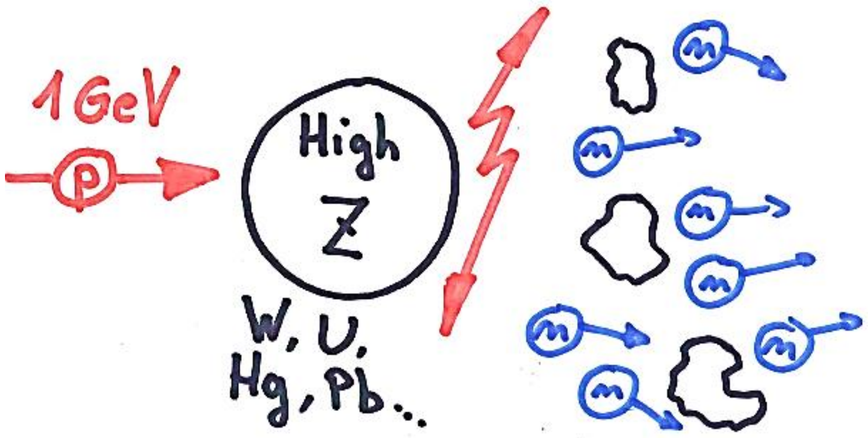
FISSION

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



SPALLATION

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



Compare the flux

PWR power reactor 3 GW

Thermal neutron flux

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

ILL high flux reactor 58 MW

Thermal neutron flux

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

SNS pulsed source (60 Hz)

Thermal neutron flux

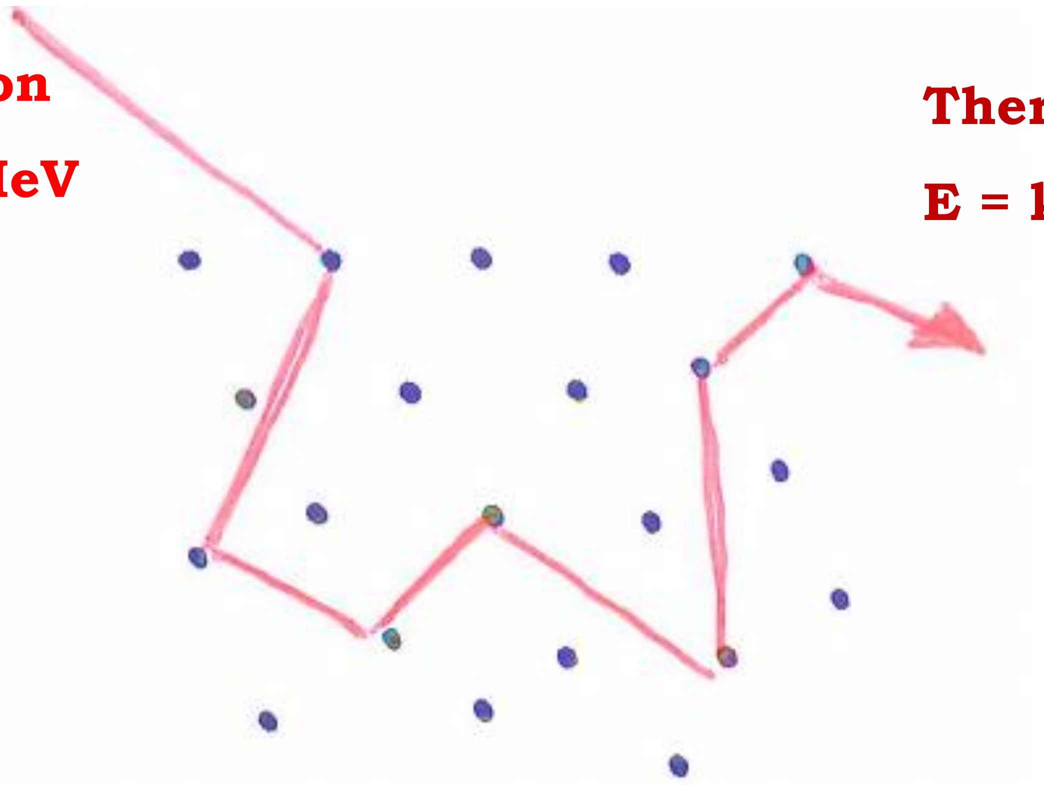
Peak ~ 3×10^{16} n/cm^2/s

Average ~ 4×10^{13} n/cm^2/s

Thermalization of fast neutrons

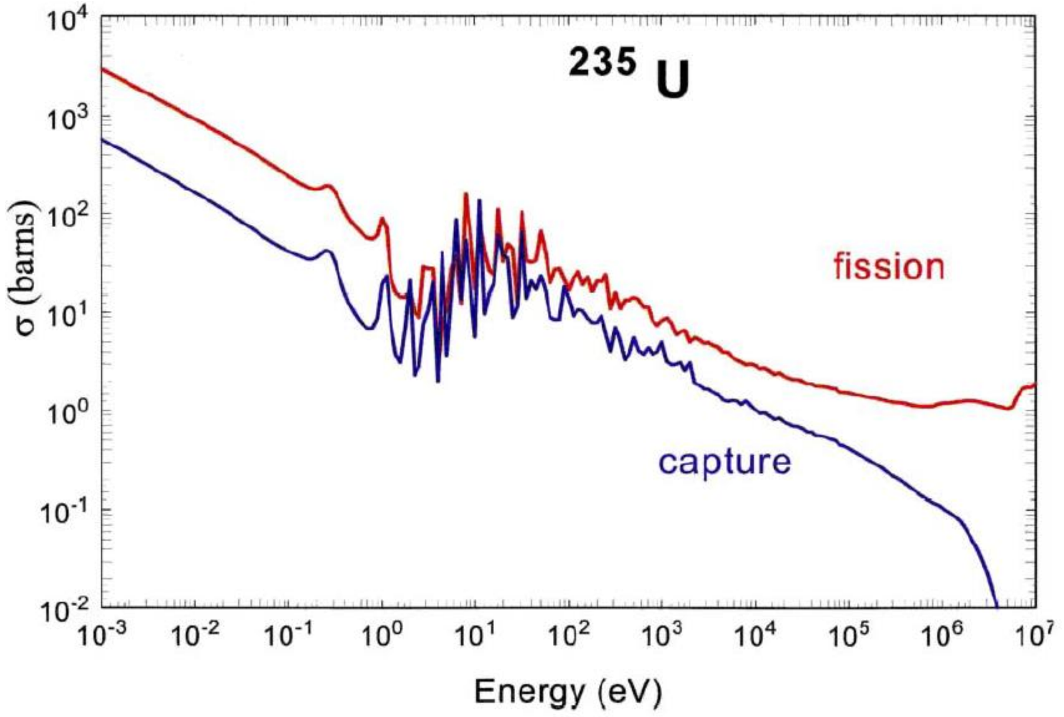
Fast neutron

E = a few MeV



Thermal neutron

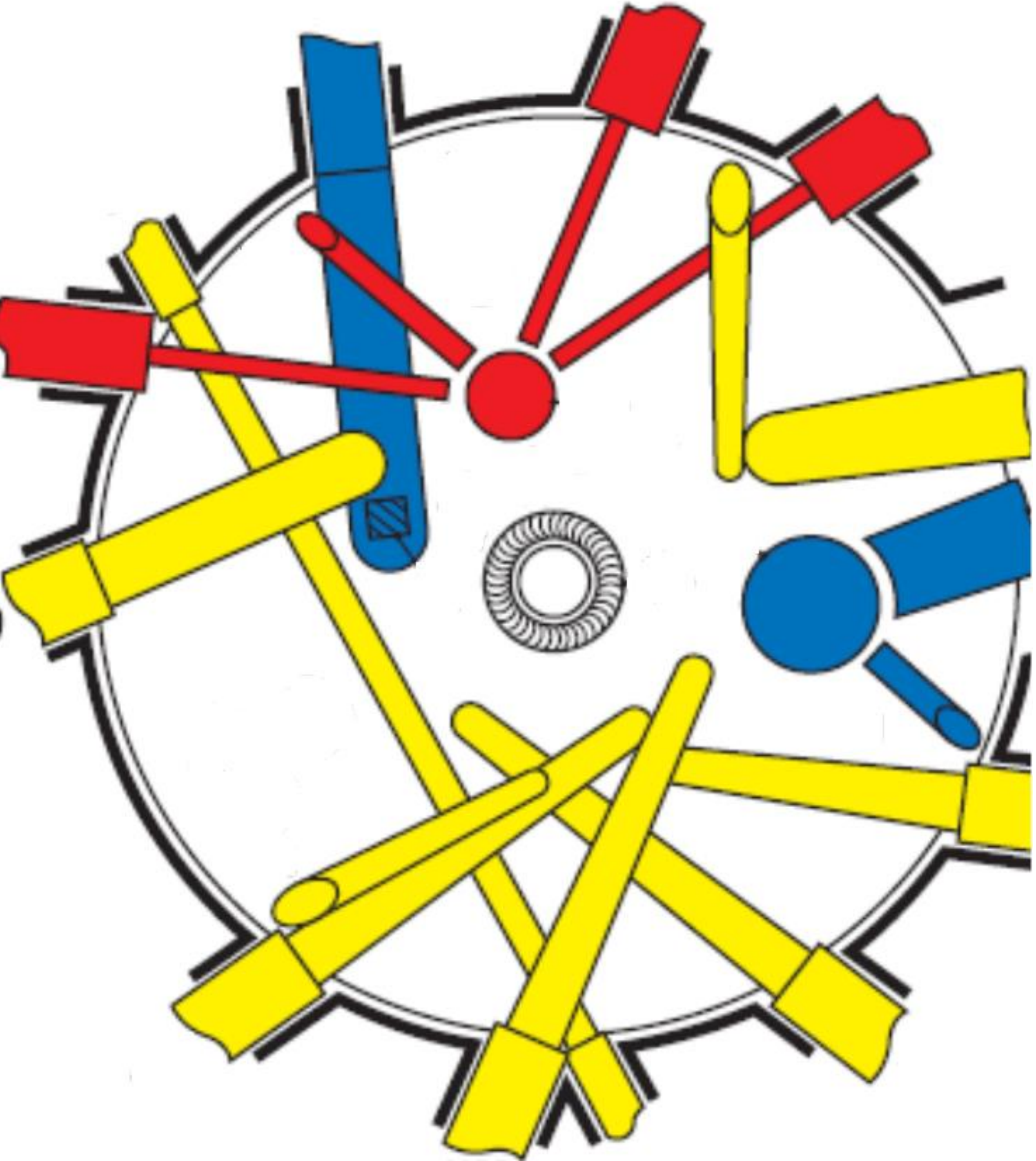
E = kT = 25 meV



Moderator material with hydrogen or deuterium.

In heavy water the mean free path is about 2 cm and it takes about 35 collision to thermalize.

ILL reactor

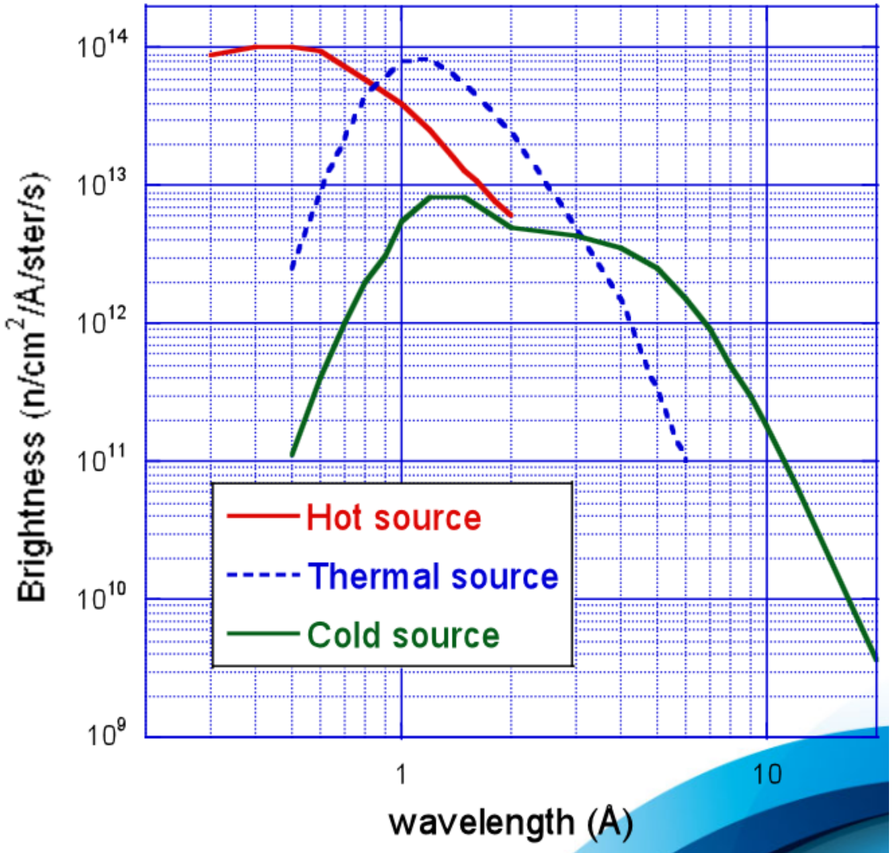


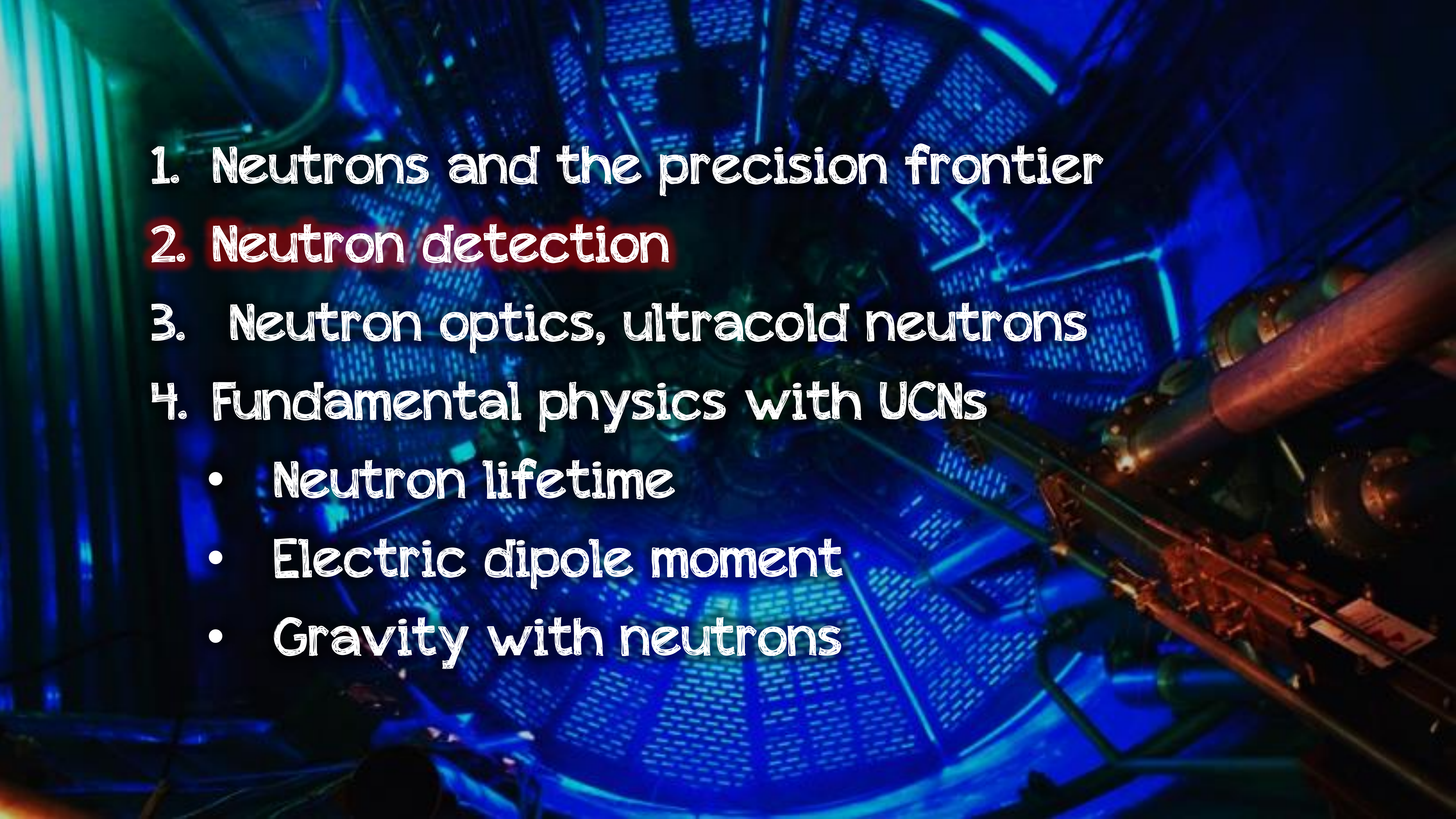
Heavy water moderator and reflector Ø2.5 m

Fuel: HEU (93.3% 235)

Hot source

Cold source: 20 L of Liquid D2 at 20K




1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. Fundamental physics with UCNs
• Neutron lifetime
• Electric dipole moment
• Gravity with neutrons

Importance of neutron detection

- 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…
Neutrons should be converted in a detectable particle first.

Neutron inelastic reactions

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

  $n + {}^{A}\mathrm{X} \rightarrow \alpha + {}^{A-3}\mathrm{Y}$ a.k.a. $\mathrm{X}(n,\alpha)\mathrm{Y}$
- Fission $n + {}^{235}\mathrm{U} \rightarrow PF_1 + PF_2 + \nu\, n$ a.k.a. $\mathrm{U}(n,f)$

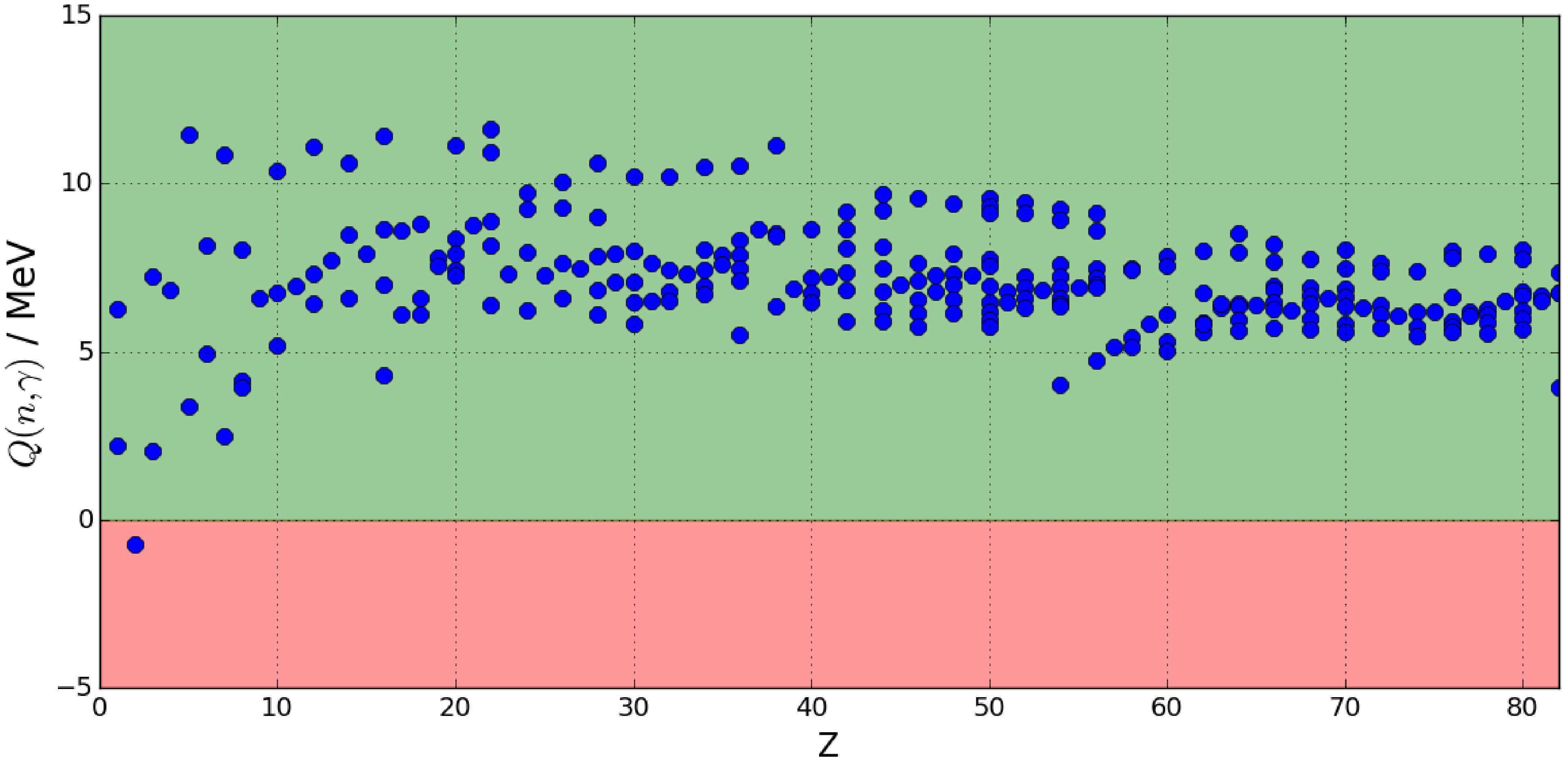
THE 1/v LAW

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

One finds in tabulated neutron data the thermal cross sections

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

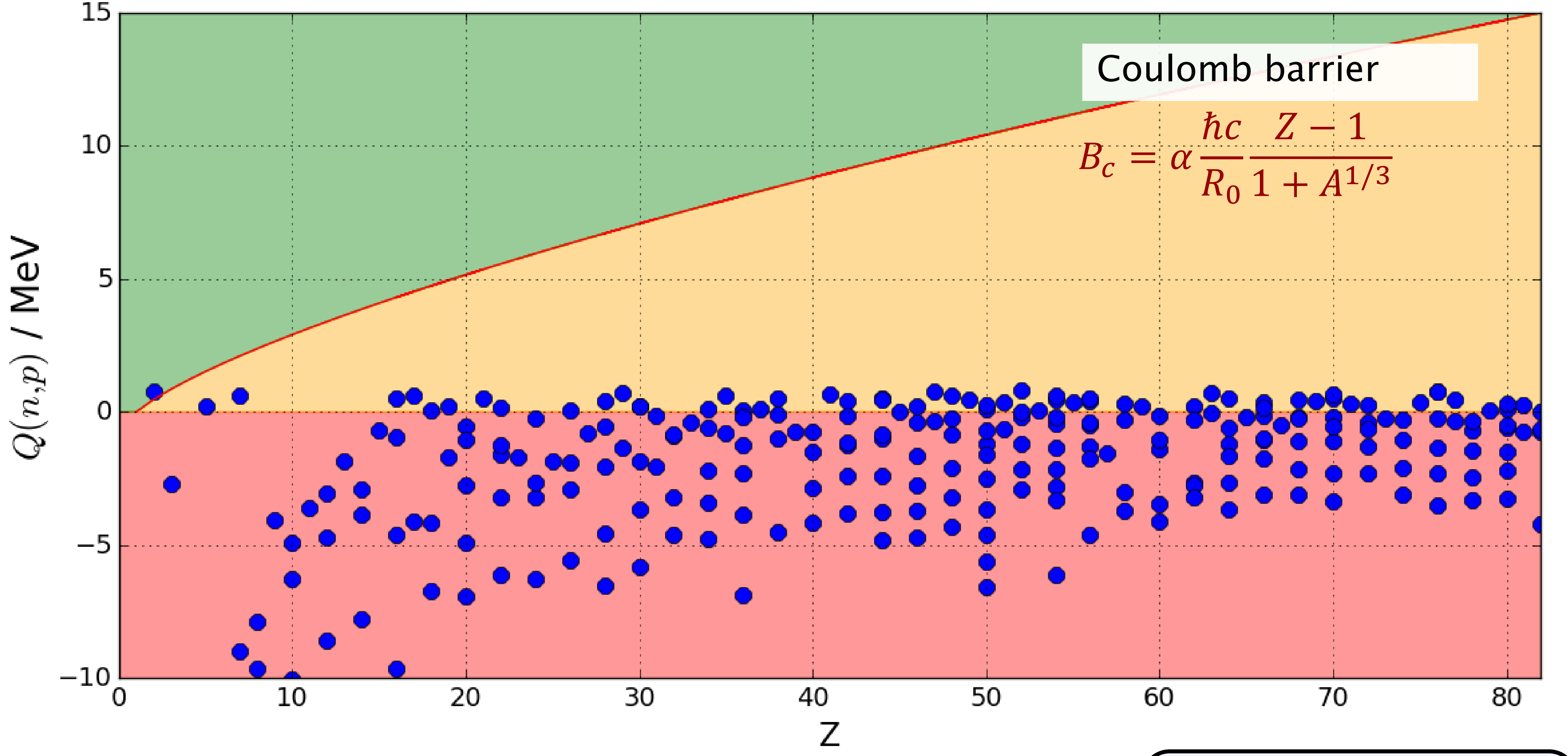
(n,γ) capture: $n + {}^{A}_{Z}\mathrm{X} \rightarrow \gamma + {}^{A+1}_{Z}\mathrm{X}$



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}**He**.
Thus, ^{4}**He** is the only stable element with zero capture cross section for slow neutrons.

(n,p) reaction $n + {}^{A}_{Z}\mathrm{X} \rightarrow p + {}_{Z-1}{}^{A}\mathrm{Y}$



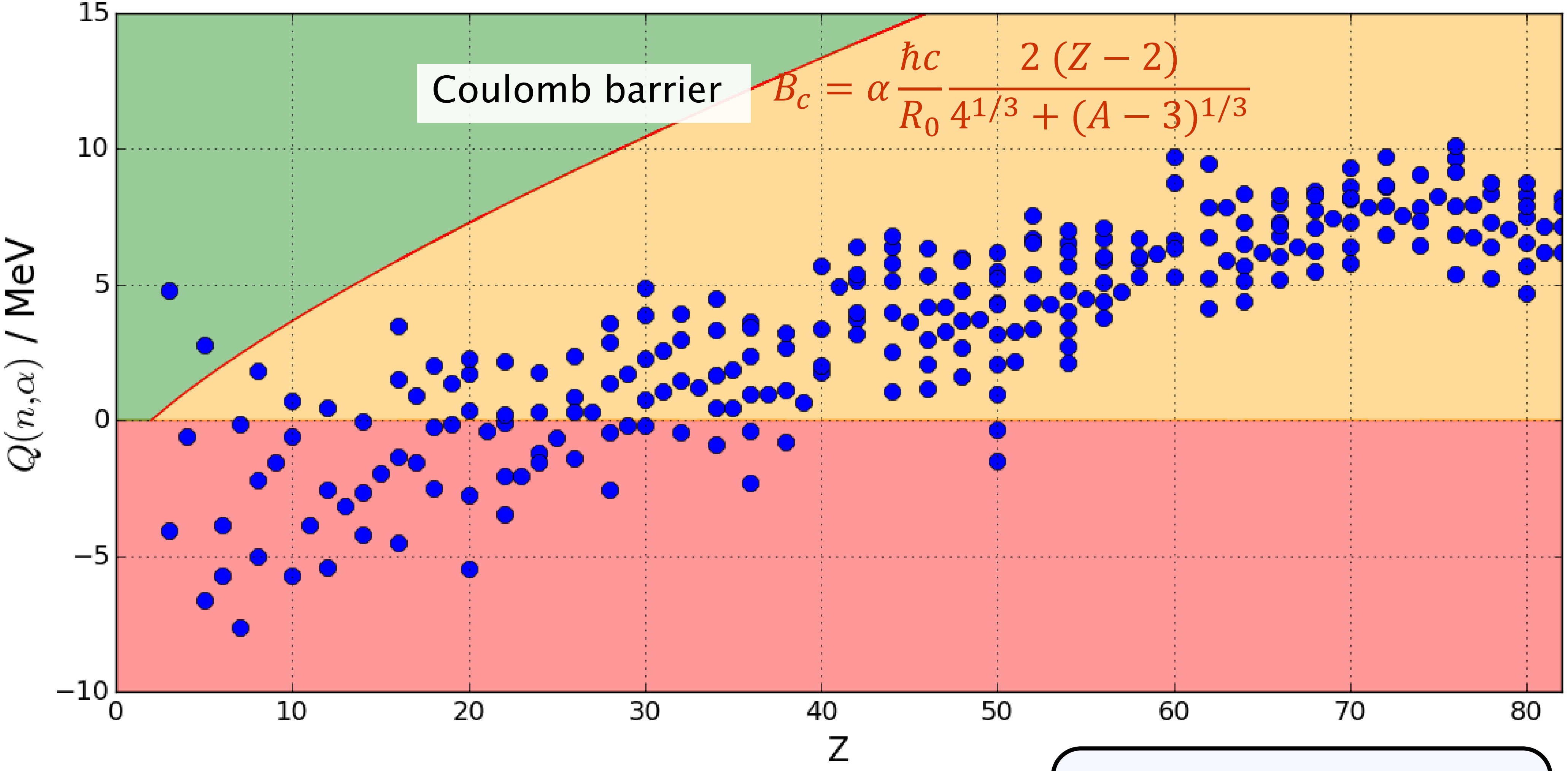
Energy release $Q = (m_X + m_n - m_p - m_Y)c^2$

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

Only one possibility

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

(n,α) reaction $n + {}^{A}_{Z}\mathrm{X} \rightarrow \alpha + {}^{A-3}_{Z-2}\mathrm{Y}$



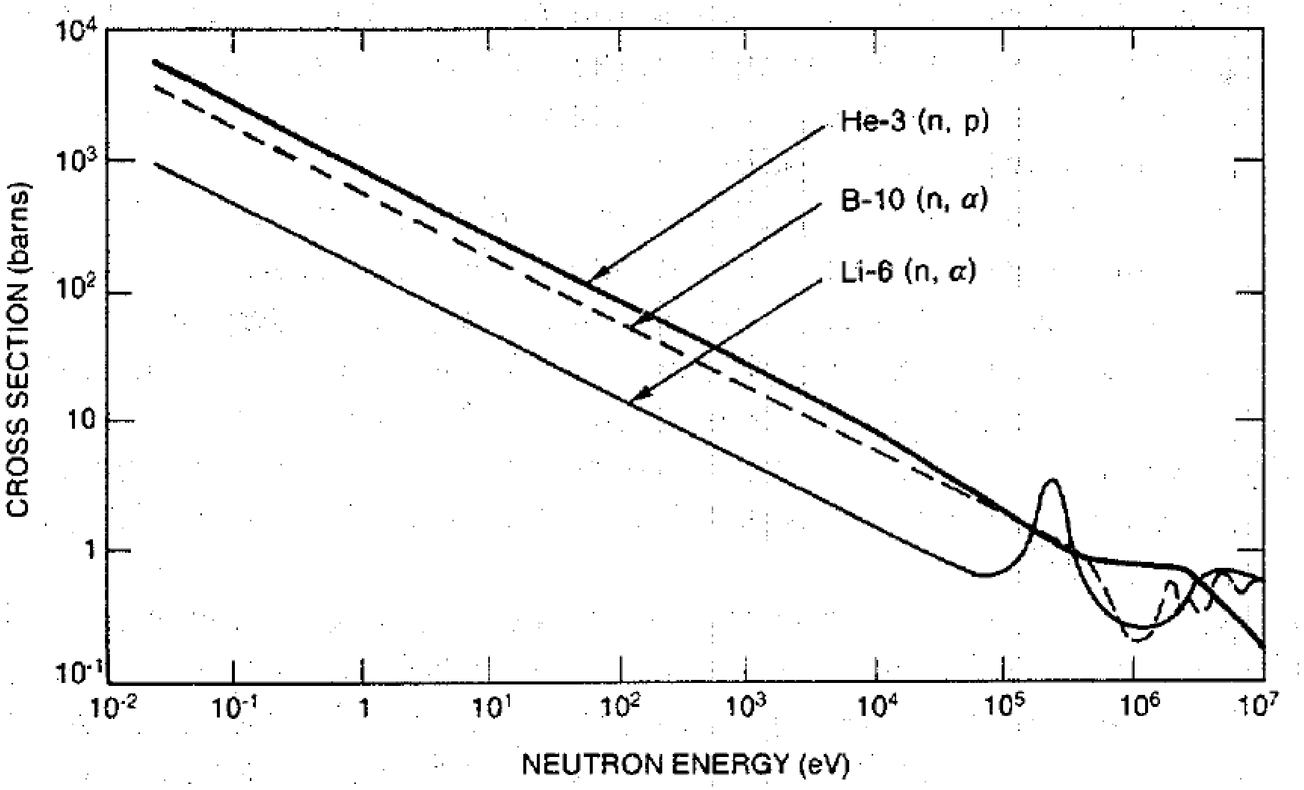
Energy release $Q = (m_X + m_n - m_\alpha - m_Z)c^2$
Slow neutrons undergo (n,α) reaction only if $Q > B_c$

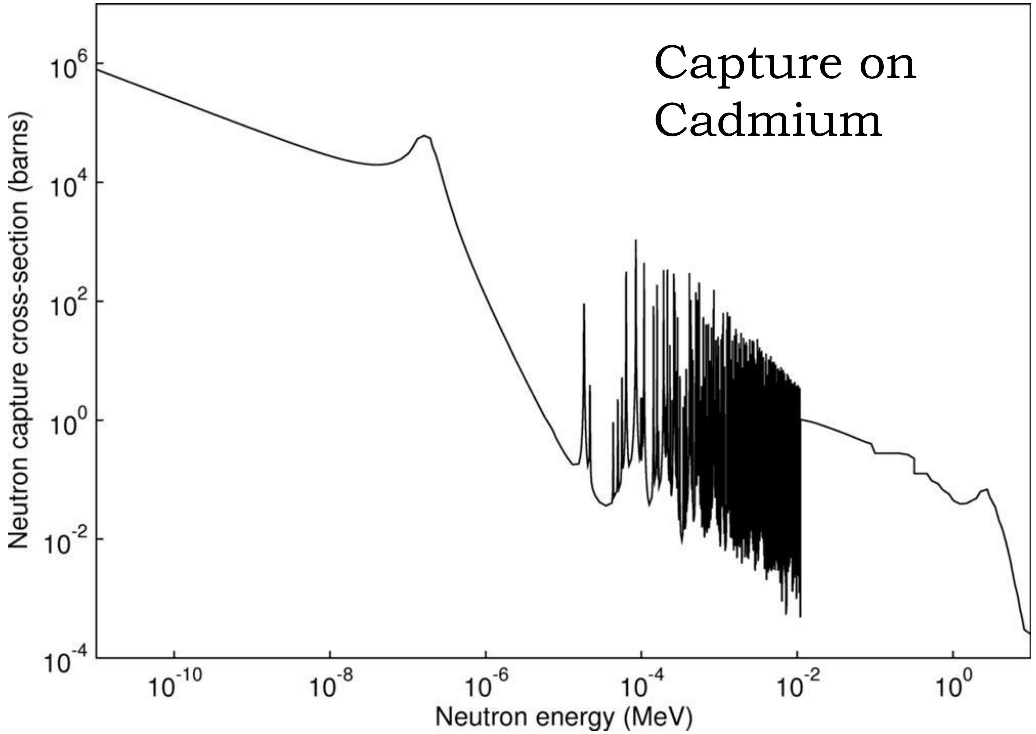
Only two possibilities

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

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

Validity of the 1/v law





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

Three possible neutron convertors

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

Gaseous detectors

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

Solid detectors

scintillators **LiF**

silicon detectors with Boron solid conversion layer

Exercises

1. Calculate the kinetic energy of the products for the following reactions induced by slow neutrons.

$$n + {}^{3}\text{He} \rightarrow t + p$$
$$n + {}^{6}\text{Li} \rightarrow \alpha + t$$

2. Consider a 1 mm thick LiF scintillating plate (density 2.63). What is the detection efficiency for thermal neutrons?

3. Consider a 1 cm thick multiwire proportional chamber filled with 1 bar of 3He. What is the detection efficiency for thermal neutrons?

Nucleus	nat. ab.	atomic mass [u]
^{1}H	99.99%	1.0078250322
^{2}H	0.015%	2.0141017781
^{3}H		3.0160492779
^{3}He	10^{-4}%	3.0160293201
^{4}He	100%	4.0026032541
^{6}Li	7.5%	6.0151228874
^{7}Li	92.5%	7.0160034366
^{10}B	20%	10.012936949
^{11}B	80%	11.009305355

neutron mass	$mc^2 = 939.565379(21)$ MeV
Planck conversion constant	$\hbar c = 197.3269718(44)$ MeV fm
Avogadro constant	$N_A = 6.02214129(27) \times 10^{23}$ mol^{-1}
Boltzmann constant	$k_B = 1.3806488(13) \times 10^{-23}$ J/K
Atomic mass unit	$u = 931.494028(23)$ MeV/c^2

1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. Fundamental physics with UCNs
    - Neutron lifetime
    - Electric dipole moment
    - Gravity with neutrons

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”

De Broglie wavelength

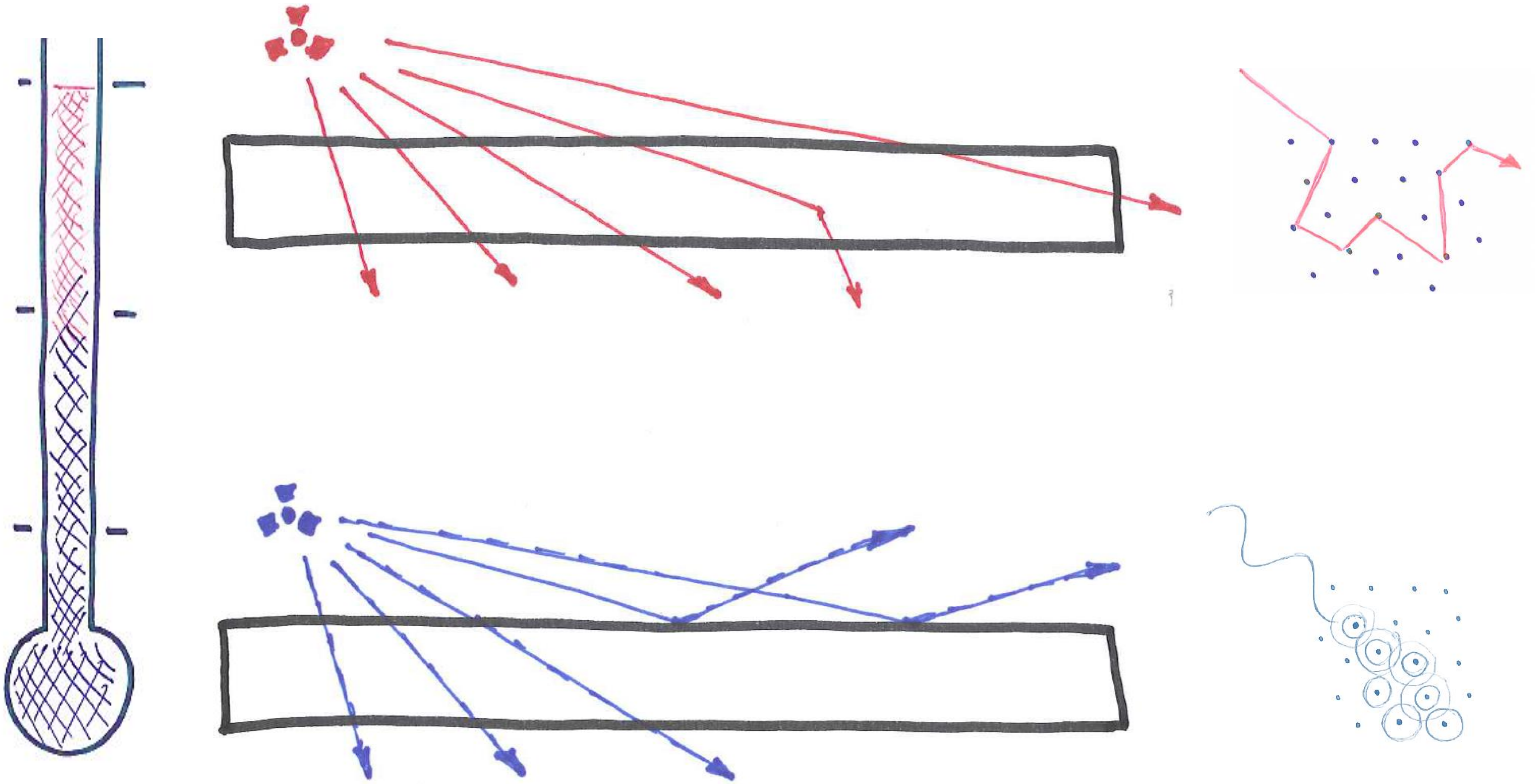
$$\lambda = \frac{2\pi\hbar}{\sqrt{2\,m\,E}}$$

$\lambda > 0.1$ nm

“WAVE”

Mirror effect at grazing incidence

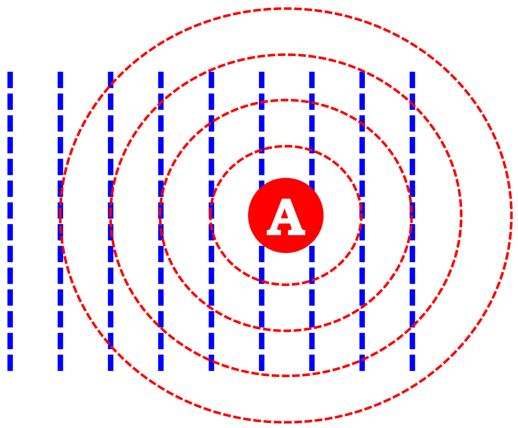
Particles and waves

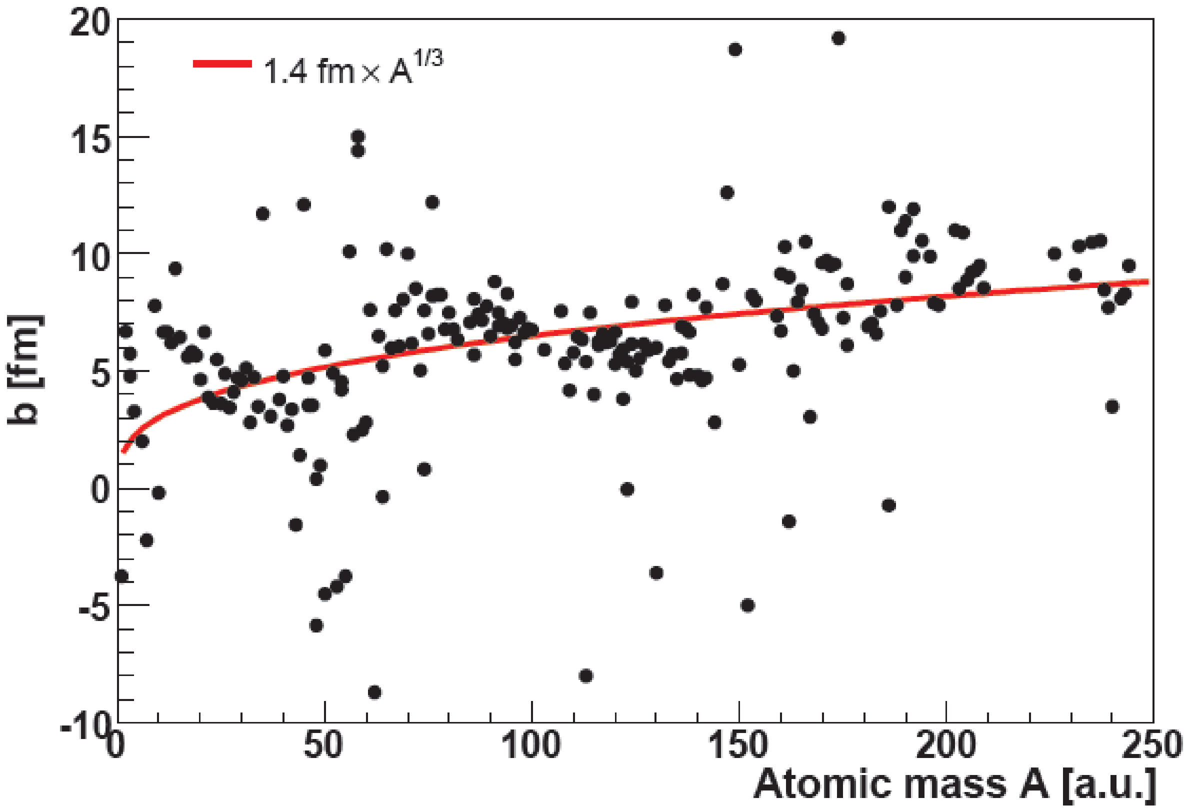


Neutron interaction with a single nucleus

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

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

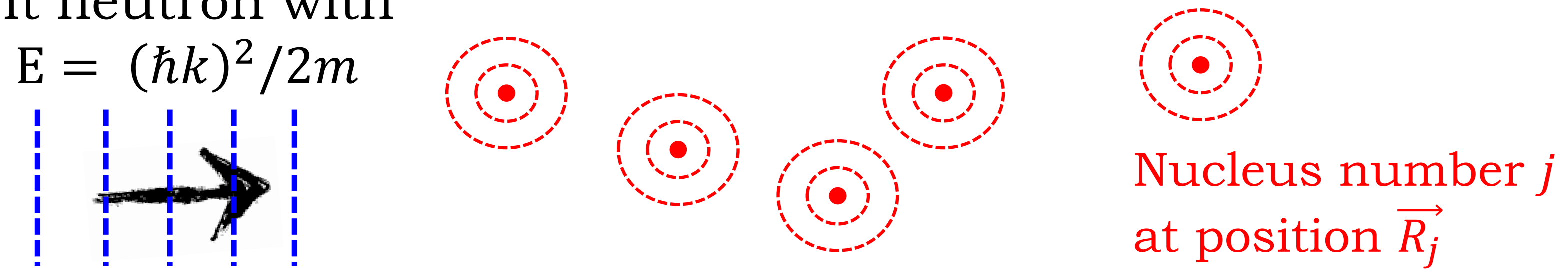
scattering X-section

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

For a catalog, see
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 $E = (\hbar k)^2/2m$



Self consistency of the wave function $$\psi(\vec{r}) = e^{i\,k\,x} - \sum_j \psi(\overrightarrow{R_j})\, b\, \frac{e^{ik|\vec{r}-\overrightarrow{R_j}|}}{|\vec{r}-\overrightarrow{R_j}|}$$

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

We find the wave equation $$(\Delta + k^2)\psi(\vec{r}) = 4\pi\, b \sum_j \delta(\vec{r} - \overrightarrow{R_j})\, \psi(\vec{r}) \approx 4\pi\, b\, n\, \psi(\vec{r})$$

n is the nuclear density of the medium

Neutron 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..).

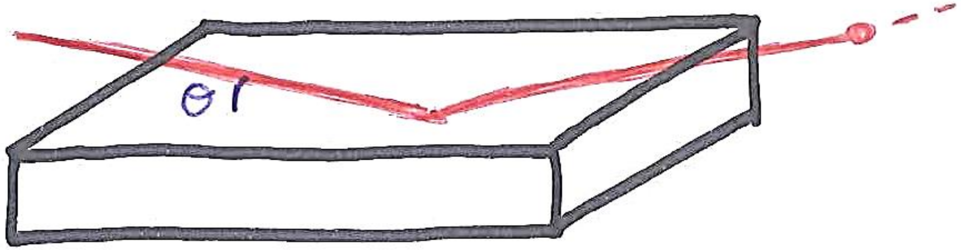
Examples

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, 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

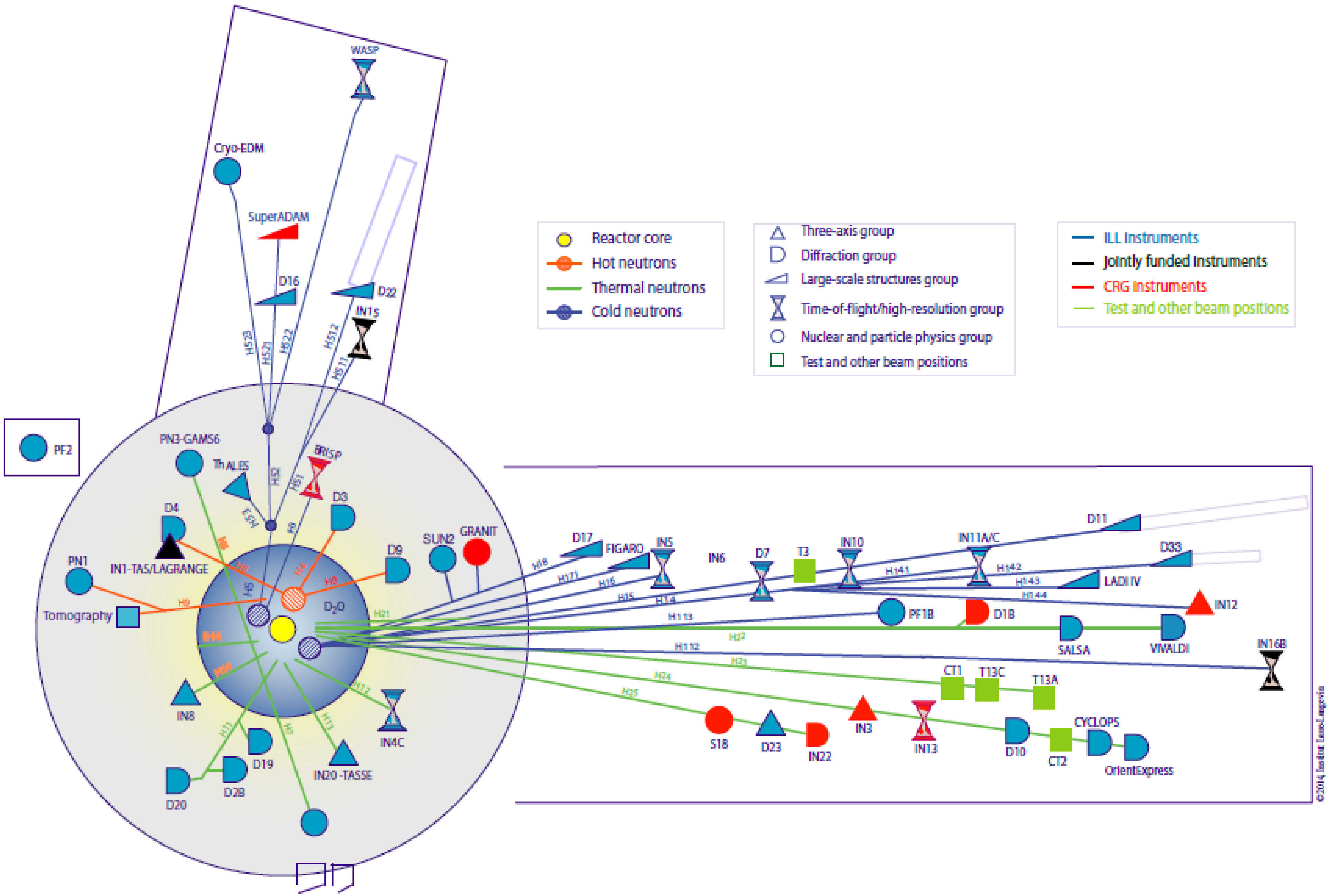
$$\theta < 0.2°$$

Application: neutron guides

ILL High Flux Reactor

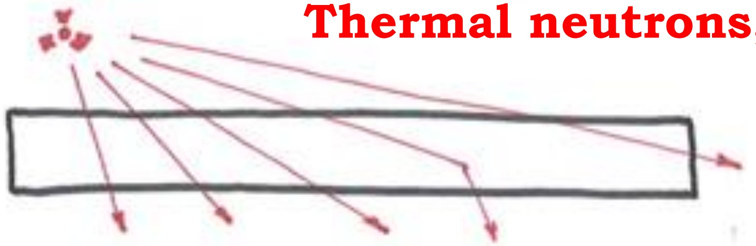
Neutron distribution channel at ILL

Many guides at the ILL, up to 100 m long

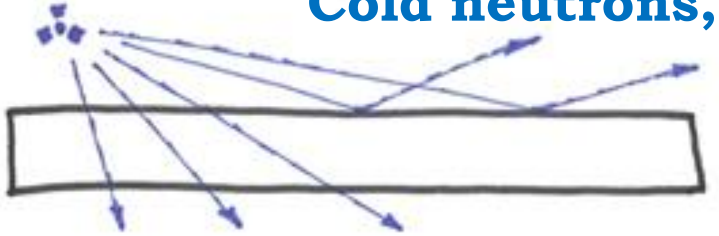


Ultracold neutrons (UCNs)

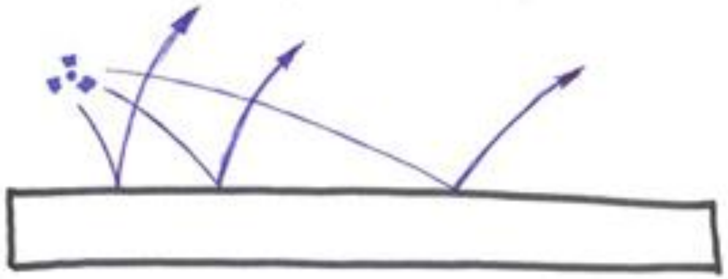
Thermal neutrons, E=25 meV

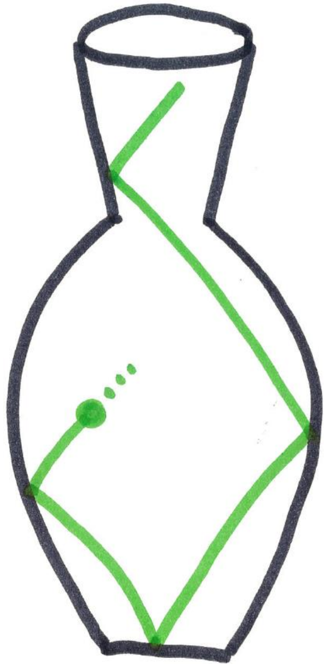


Cold neutrons, E<25 meV



Ultracold neutrons E< 200 neV





Neutrons with energy < 200 neV, are totally reflected by material walls.

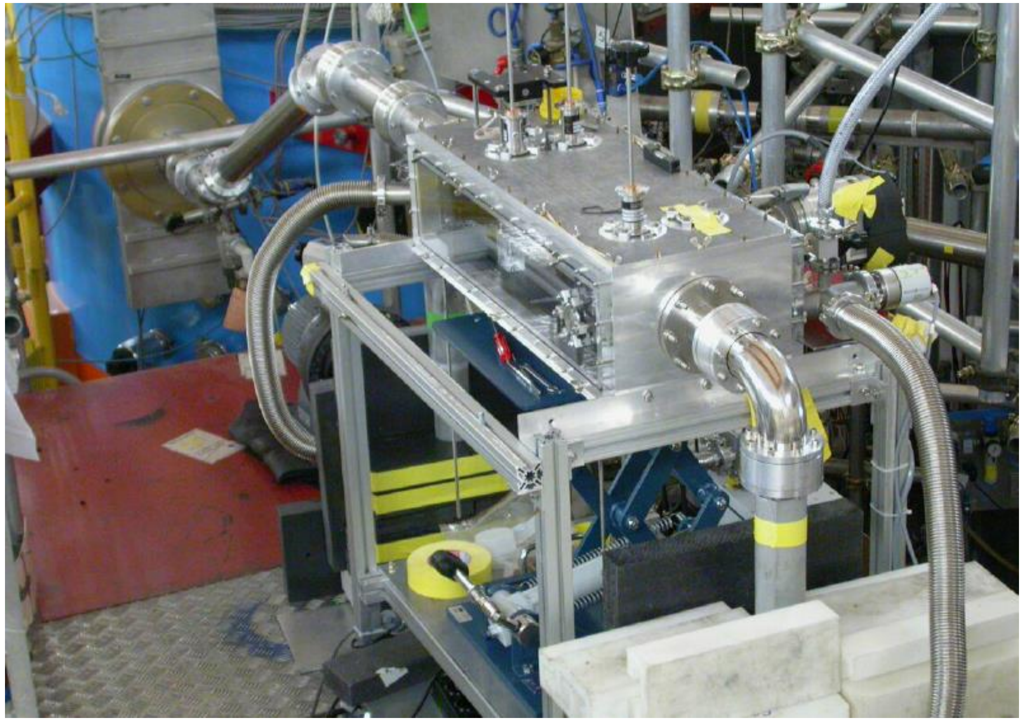
They can be stored in material bottles for long times (minutes).

They are significantly affected by gravity.

UCN plumbing

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

Losses are generally percents/meter



Exercises

1. Calculate the velocity for an UCN with an energy of 200 neV
2. Calculate the De-Broglie wavelength of the same UCN
3. What is the proportion of UCNs (say $E < 300$ neV) in a Maxwell spectrum of thermal neutrons at 300 K?
4. A neutron is dropped at rest from a height of $h = 1$ m. What is the kinetic energy of that neutron when hitting the ground at $h = 0$?

UCNs and magnetic fields

Neutron magnetic moment

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

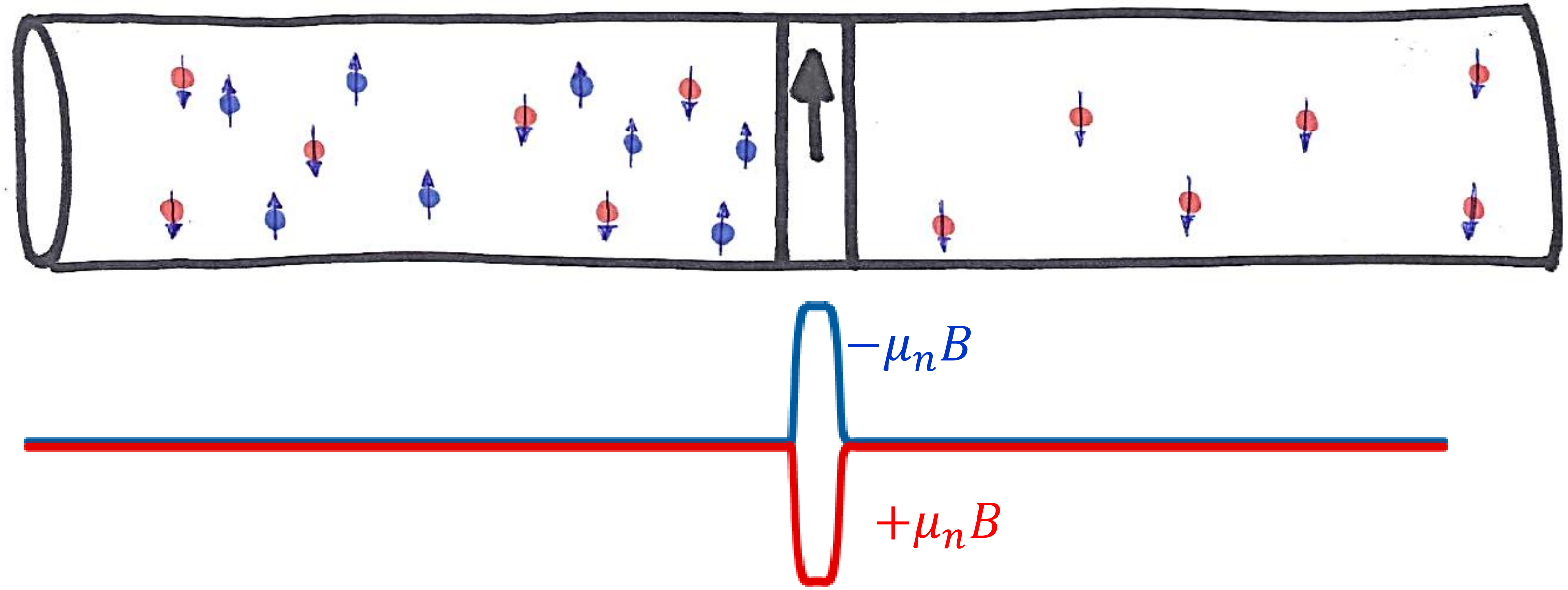
Magnetic fields act on the spin ½ neutron

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

Input: unpolarized UCNs

Magnetized foil

Output: polarized UCNs



Summary about UCN interactions

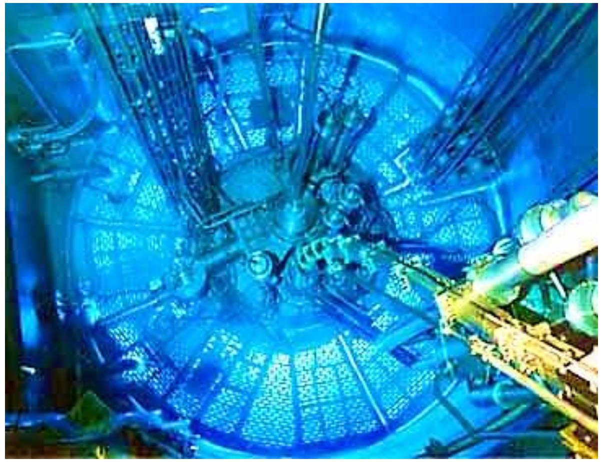
UCNs can be manipulated using

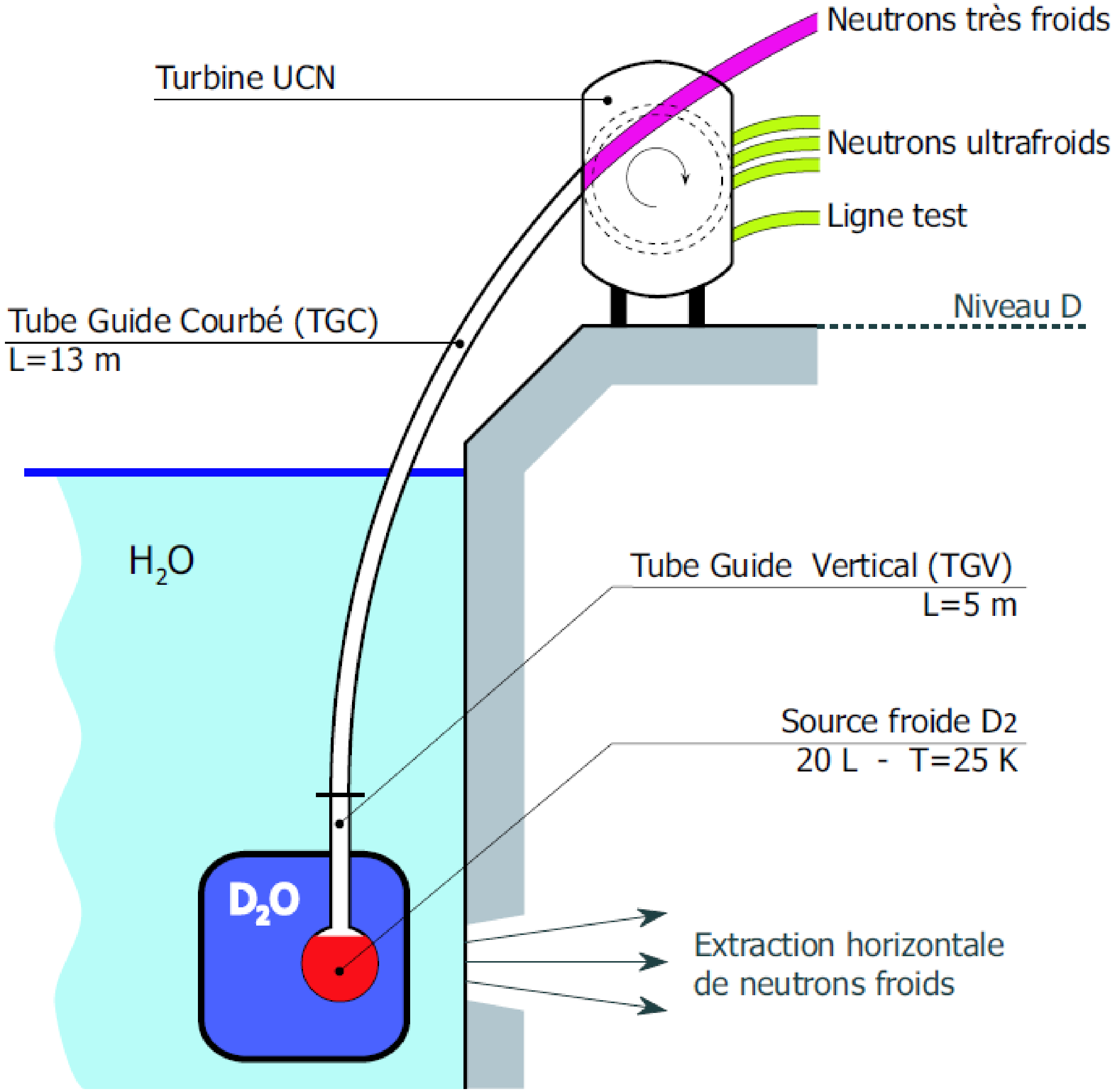
- The nuclear force (Fermi potentials ~ 100 neV)
- The gravitational force (1 m = 100 neV)
- Magnetic fields (1T = 60 neV)

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

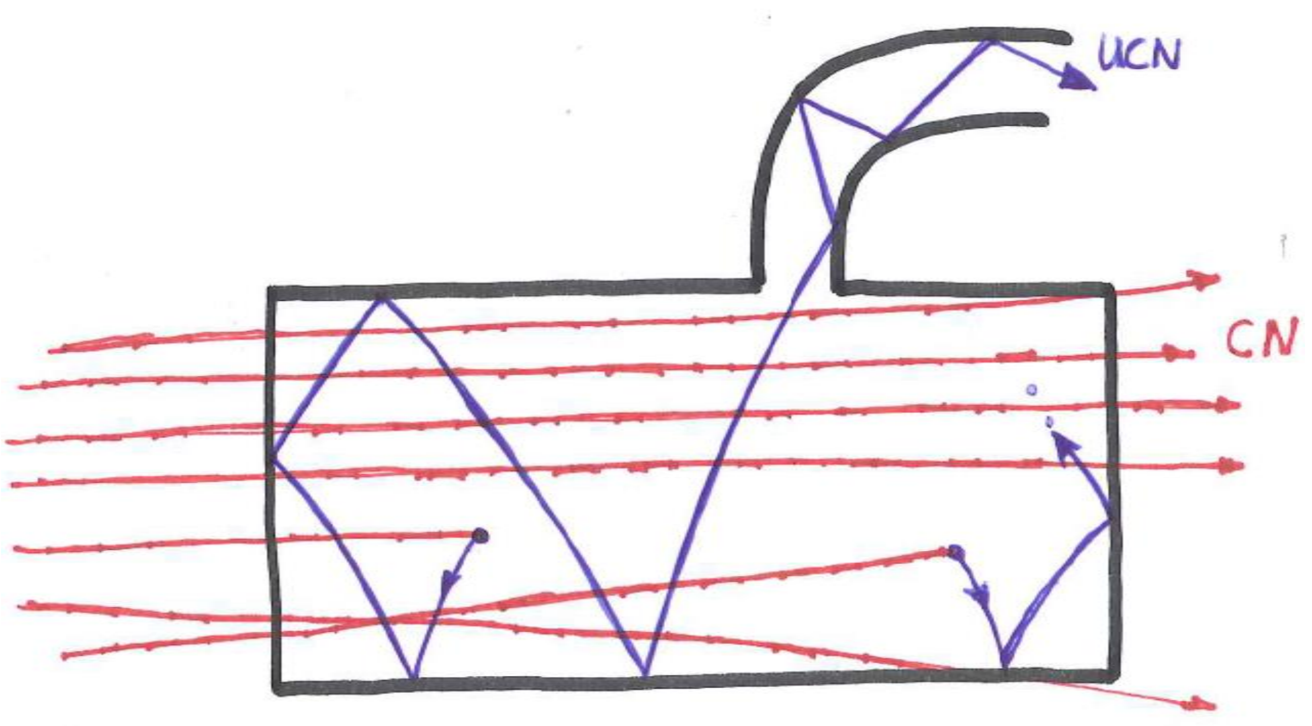
UCN source at ILL

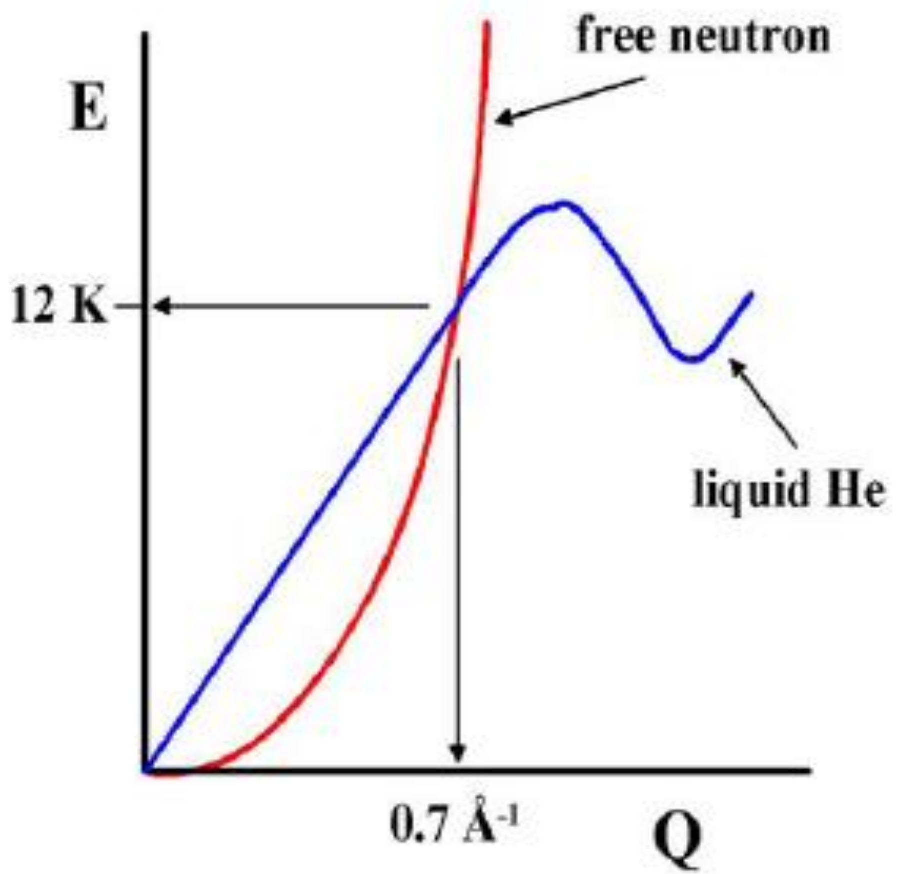




Turbine with counter rotating blades to decelerate the neutrons

Superthermal production of UCNs in superfluid He





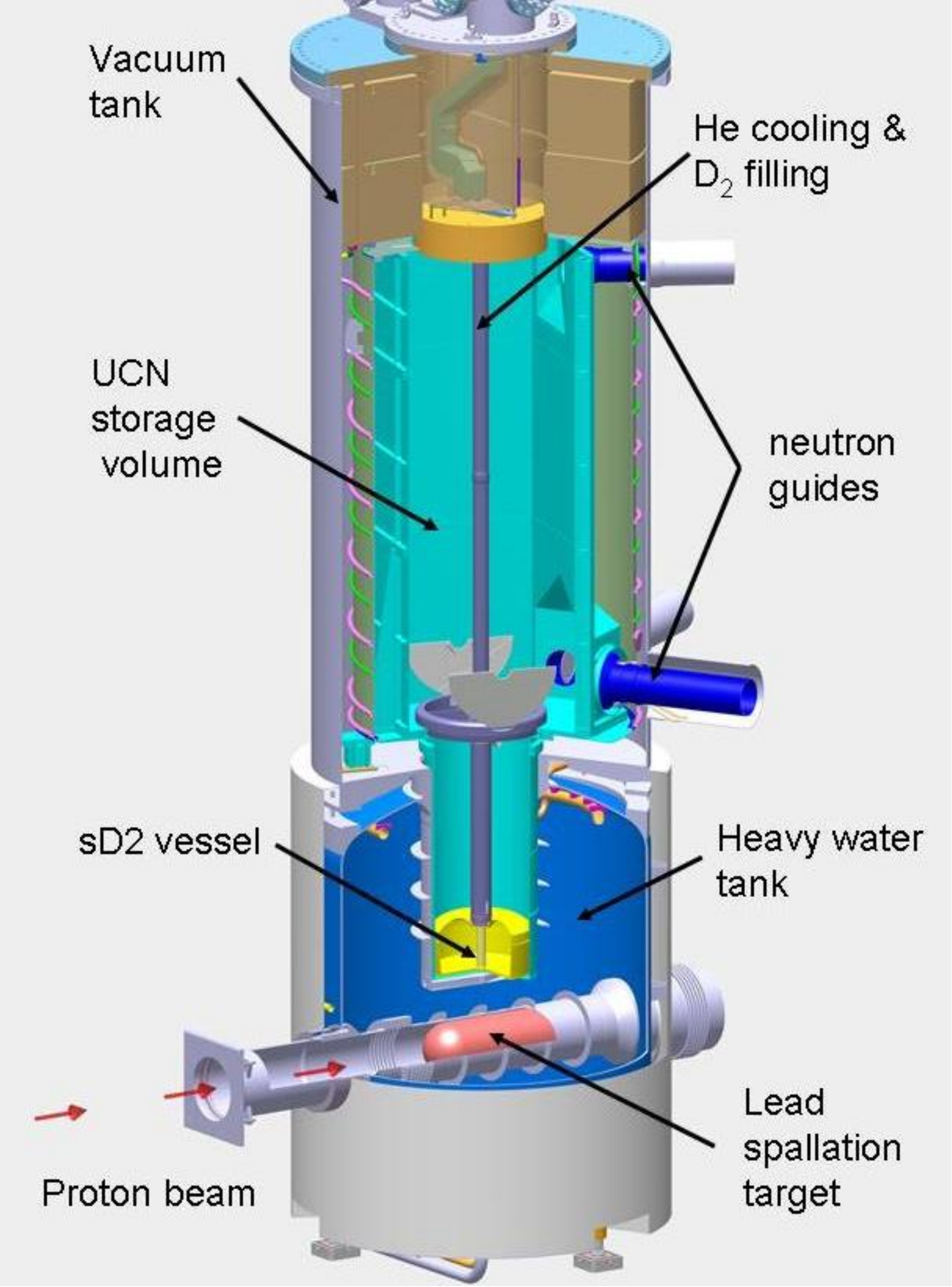
Input: intense beam of cold neutrons with a wavelength of 8.9 A

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

600 MeV
2.2 mA



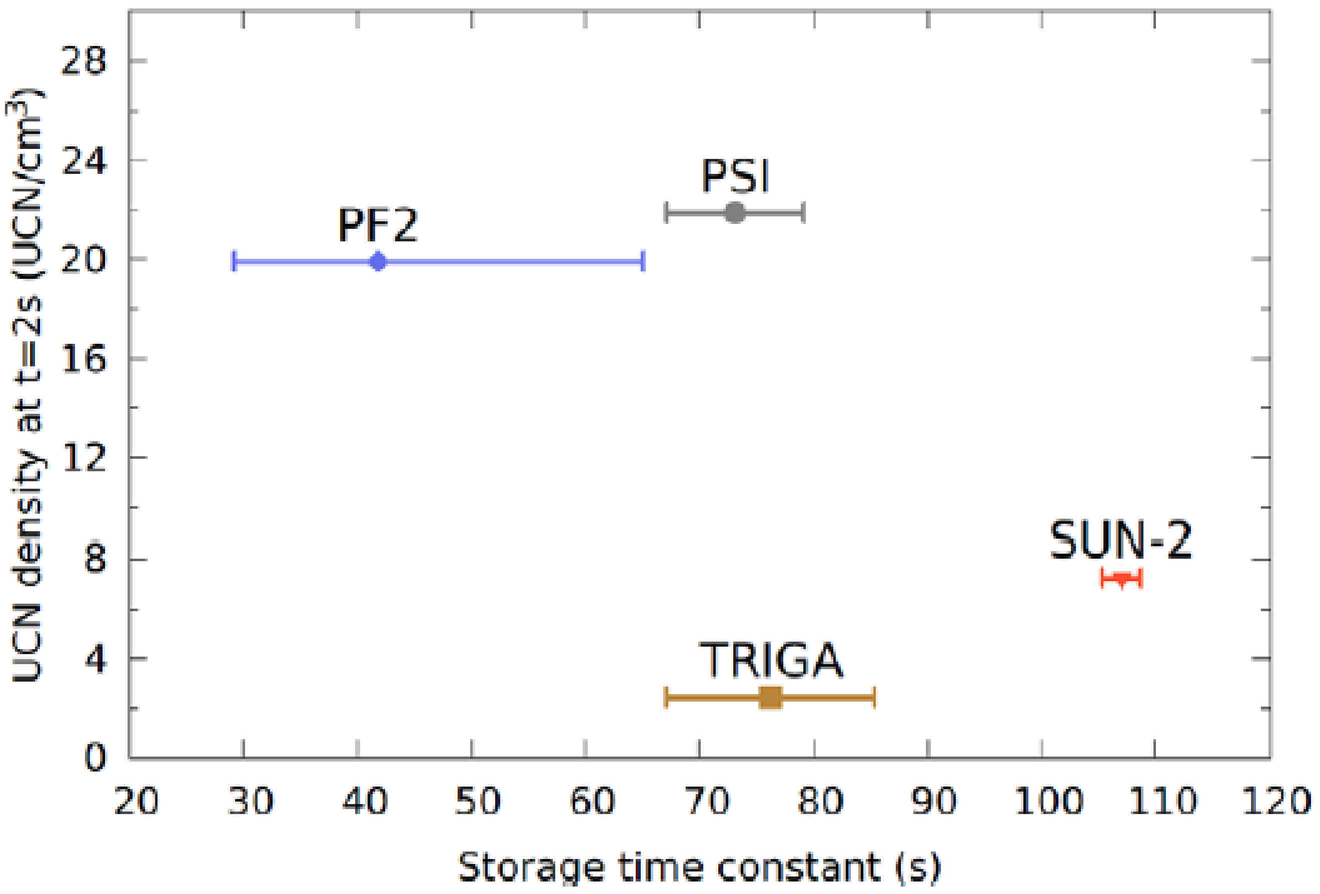
Worldwide comparison of UCN sources

3 techniques

- **selection out of a thermal flux**
  ILL PF2 source
- **Superthermal production and accumulation in superfluid He**
  ILL SUN-2, ILL GRANIT, TRIUMF
- **Superthermal production in solid deuterium**
  PSI, Los Alamos, Mainz (TRIGA)

PHYSICAL REVIEW C 95, 045503 (2017)

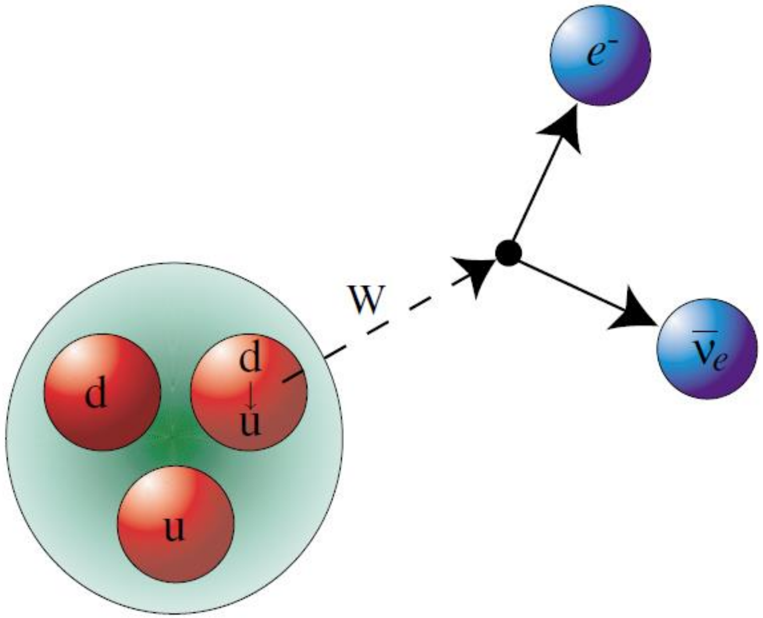
Comparison of ultracold neutron sources for fundamental physics measureme



Diter Ries standard stainless steel bottle

1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. Fundamental physics with UCNs
    - Neutron lifetime
    - Electric dipole moment
    - Gravity with neutrons

The neutron beta decay lifetime



$$n \rightarrow p + e^{-} + \bar{\nu}_e + 782\ \text{keV}$$

Free neutron lifetime

$$\tau_n = 880.0(9)\ \text{s}$$

[PDG 2013]

- ***Particle physics***

extracting CKM matrix element

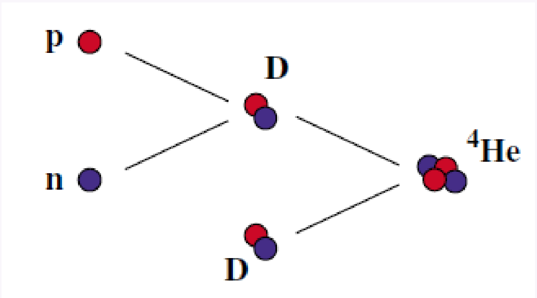
- ***Astrophysics and Neutrinos***

Calculating weak semi-leptonic processes like

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

- ***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.

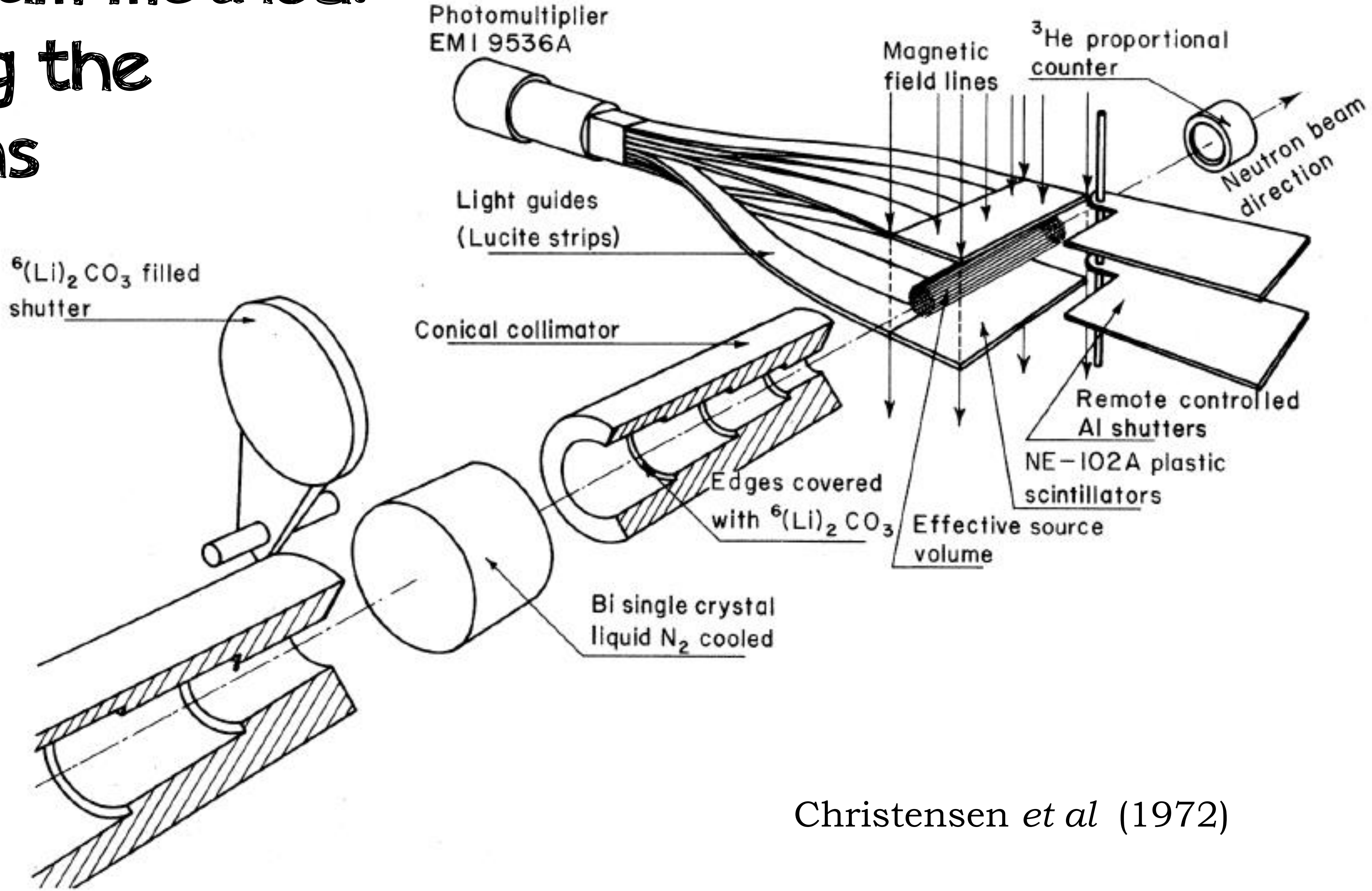
$$-\frac{dN}{dt} = \frac{N}{\tau_n}$$

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.

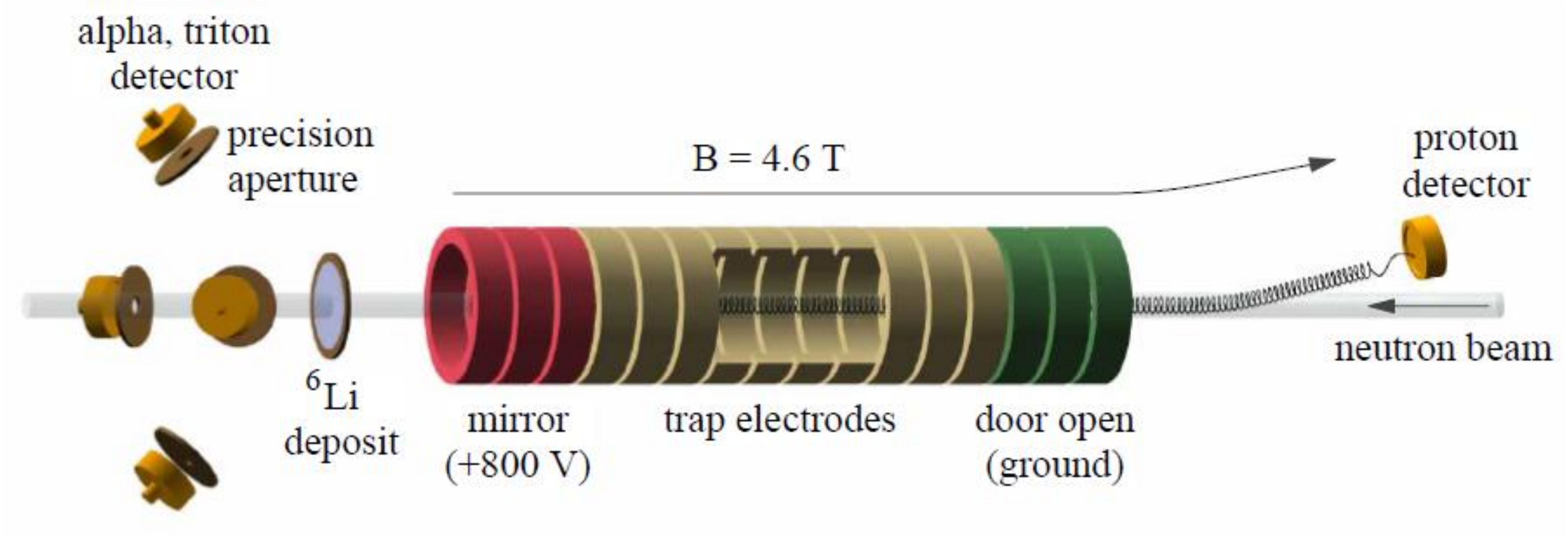
$$N(t) = N(0)e^{-t/\tau_n}$$

Early beam method: counting the electrons



Christensen *et al* (1972)

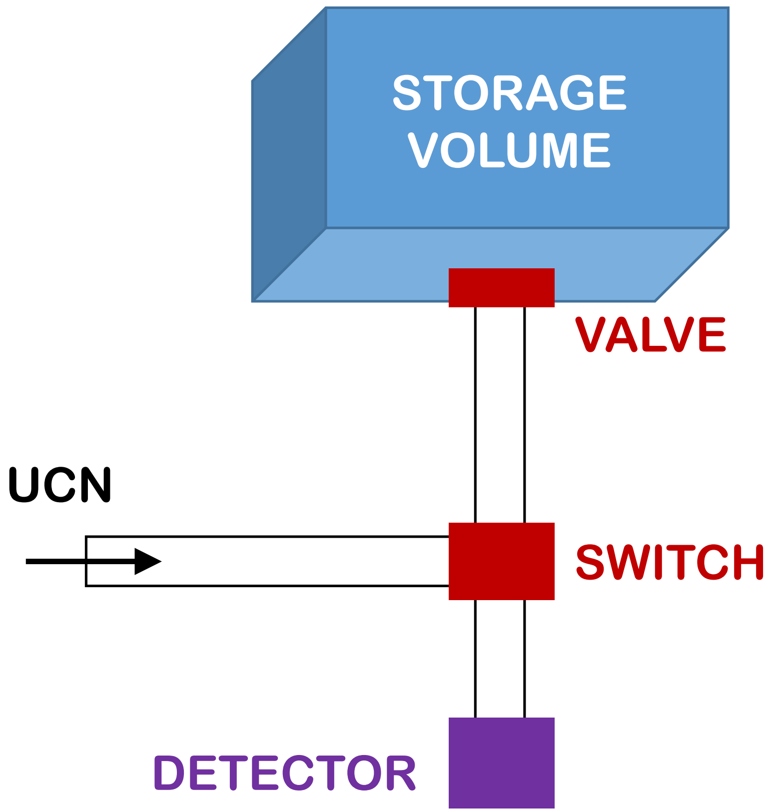
Modern beam method: counting the protons



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



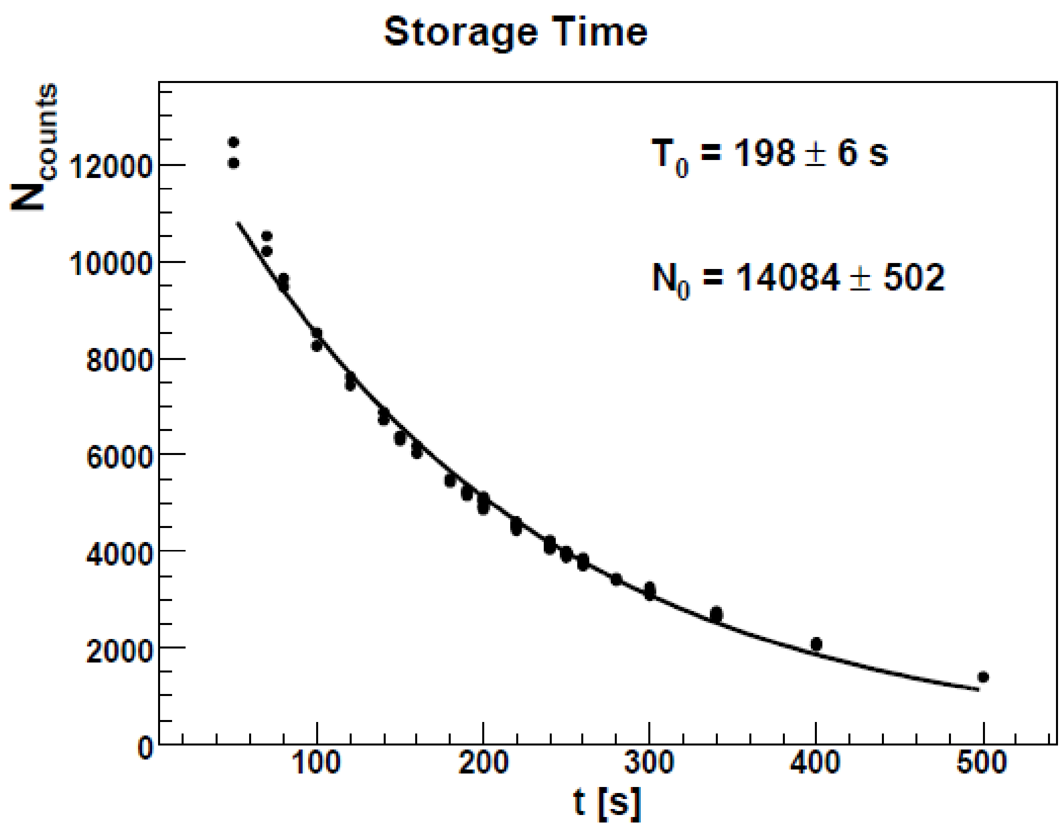
Typical sequence

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

UCN storage curve

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

$$\lambda \approx 30 \text{ cm}$$

The frequency of wall collisions for a velocity of 3 m/s is of the order of

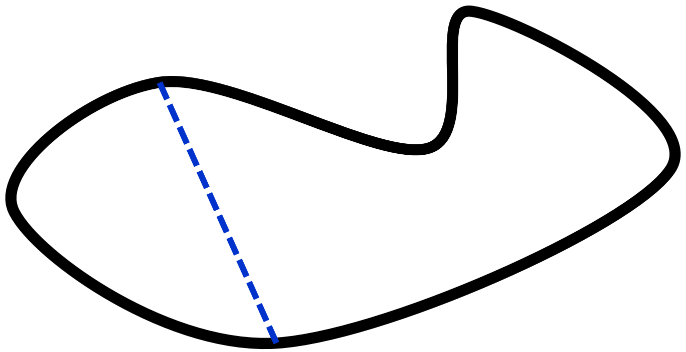
$$f = \frac{v}{\lambda} \approx 10 \text{ Hz}$$

The partial lifetime due to wall losses is thus of the order of

$$\tau_{wall} = \frac{1}{f\mu} \approx 1000 \text{ s}$$

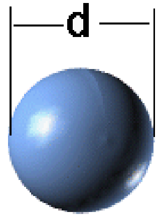
Useful Clausius law

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

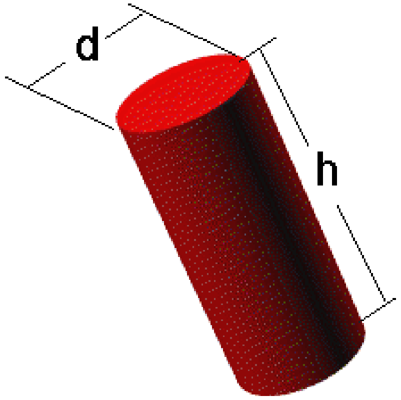


When mechanical equilibrium is achieved (isotropic velocity distribution) the mean free path between wall collisions is

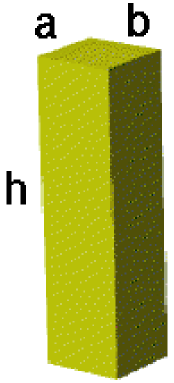
$$\lambda = \frac{4\,V}{S}$$



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



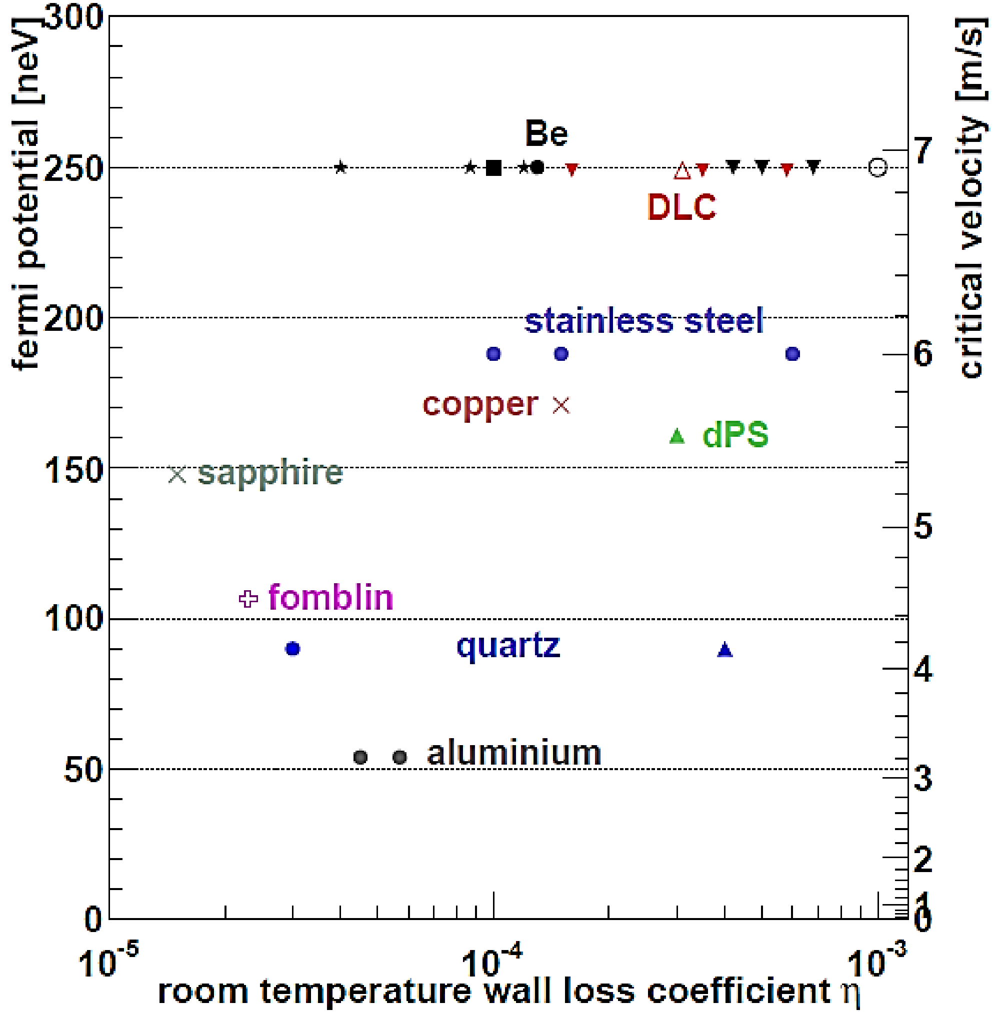
$$\lambda = \frac{dh}{d/2 + h}$$



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

Results valid without gravity!

More on wall losses (complicated topic)

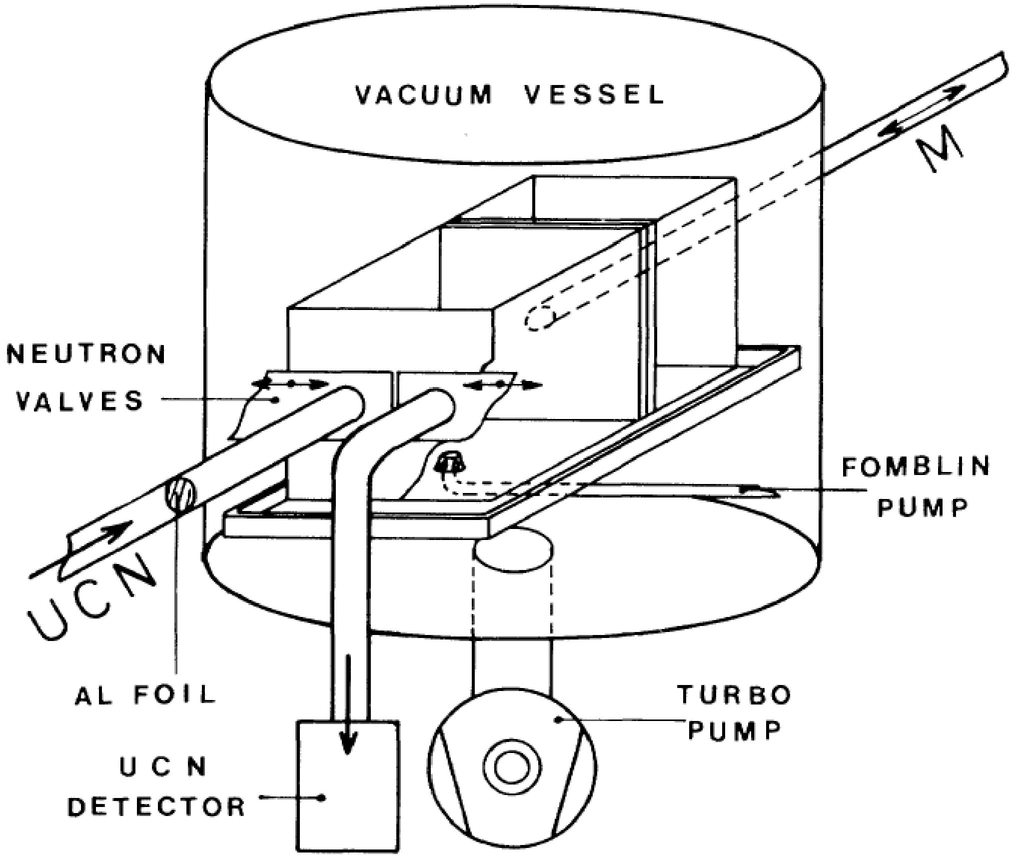


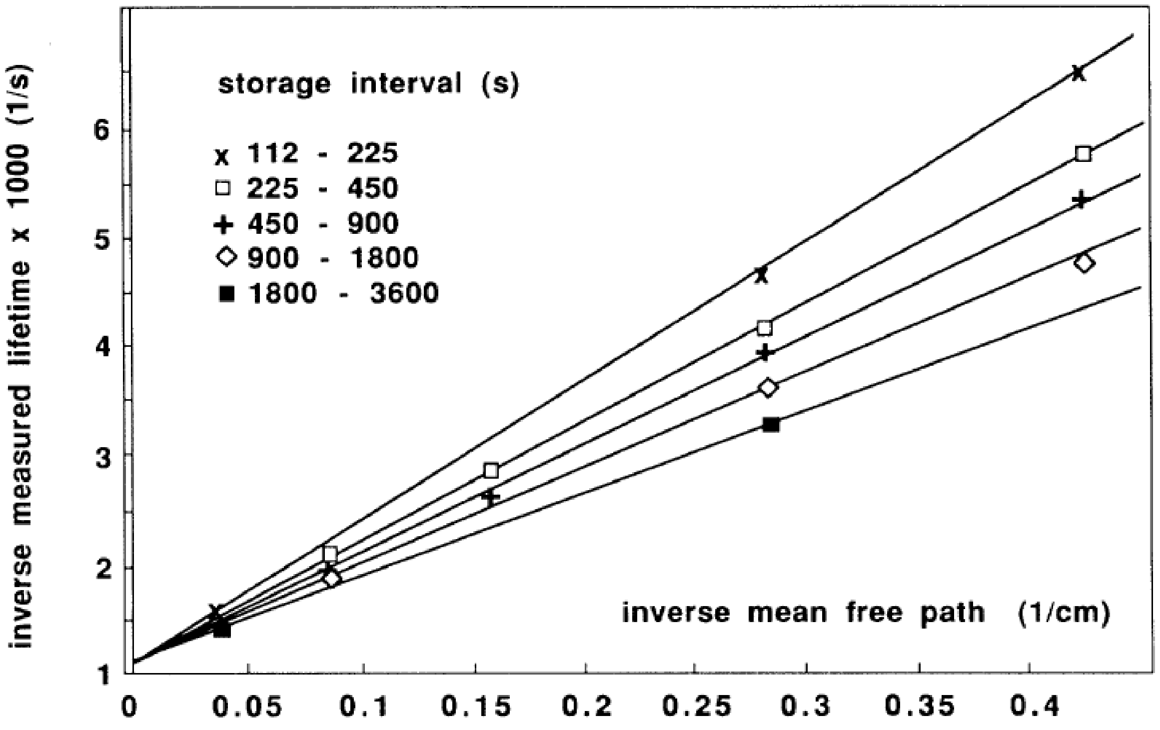
- The wall loss probability is energy-dependent

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

- 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)

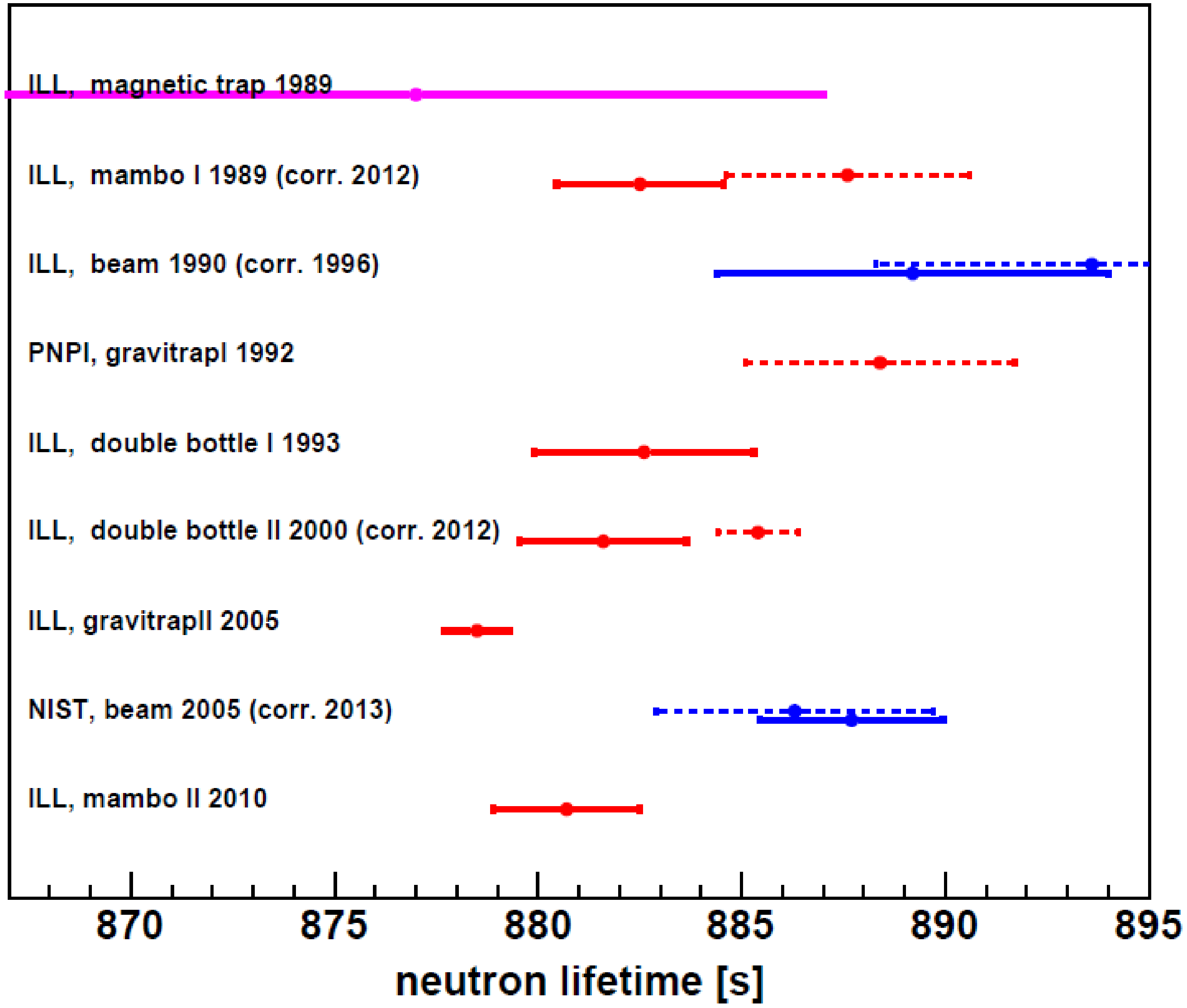
Example: MAMBO 1 (ILL, 1989)





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

Current status on the neutron lifetime



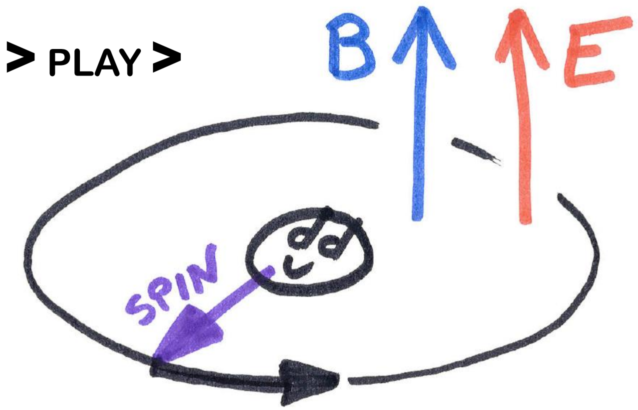
The current situation

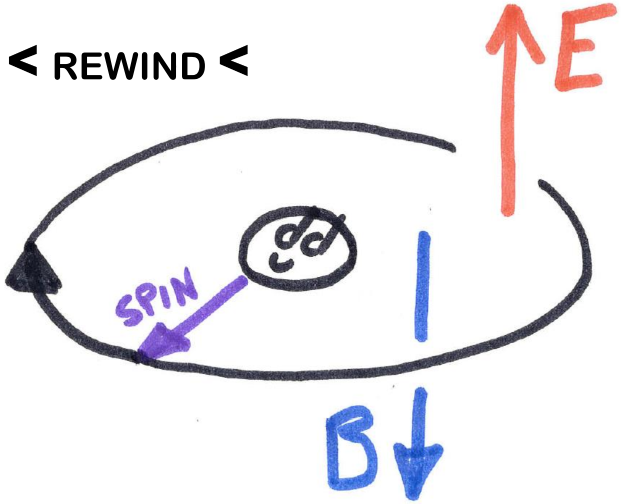
There is a 3.8 **σ** discrepancy between the bottle method combination and the beam method combination.

To be continued…

1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. **Fundamental physics with UCNs**
    - Neutron lifetime
    - **Electric dipole moment**
    - Gravity with neutrons

Electric Dipole Moments and T symmetry





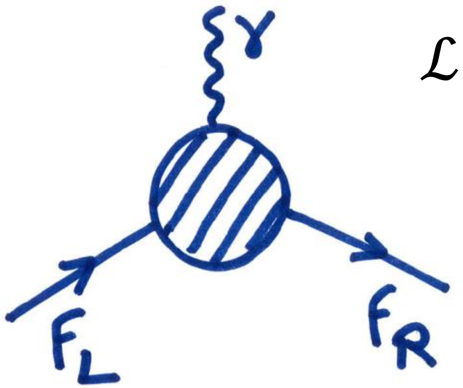
$$\hat{H} = -\mu_n \, B \, \hat{\sigma}_z - d_n \, E \, \hat{\sigma}_z$$

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

The existence of an electric dipole violates the T symmetry and therefore the CP symmetry

Electric dipoles & CP symmetry

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



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

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

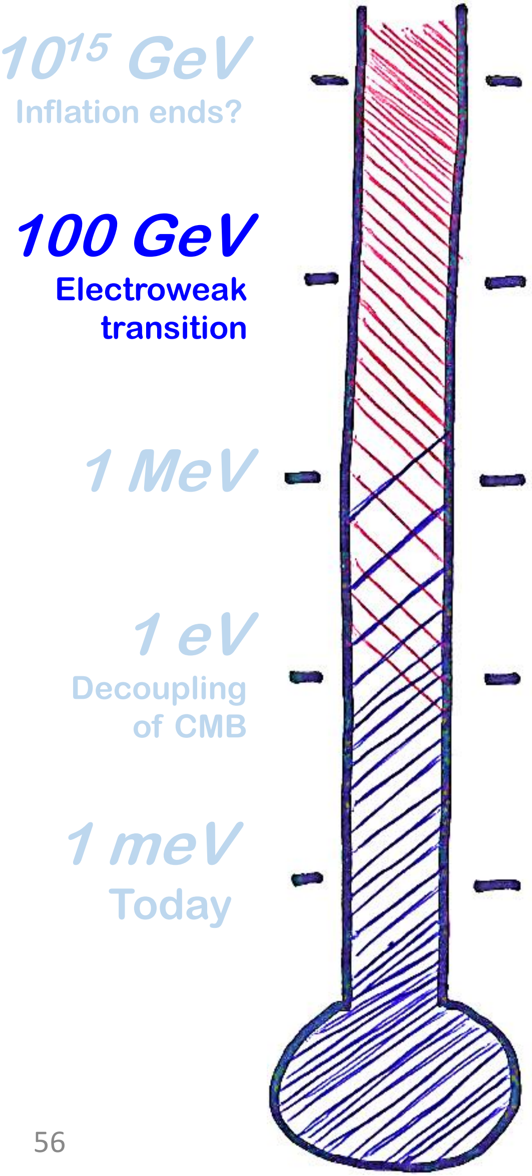
$d_n < 300 \times 10^{-28}\ e\ \text{cm}$ (Grenoble, 2006)

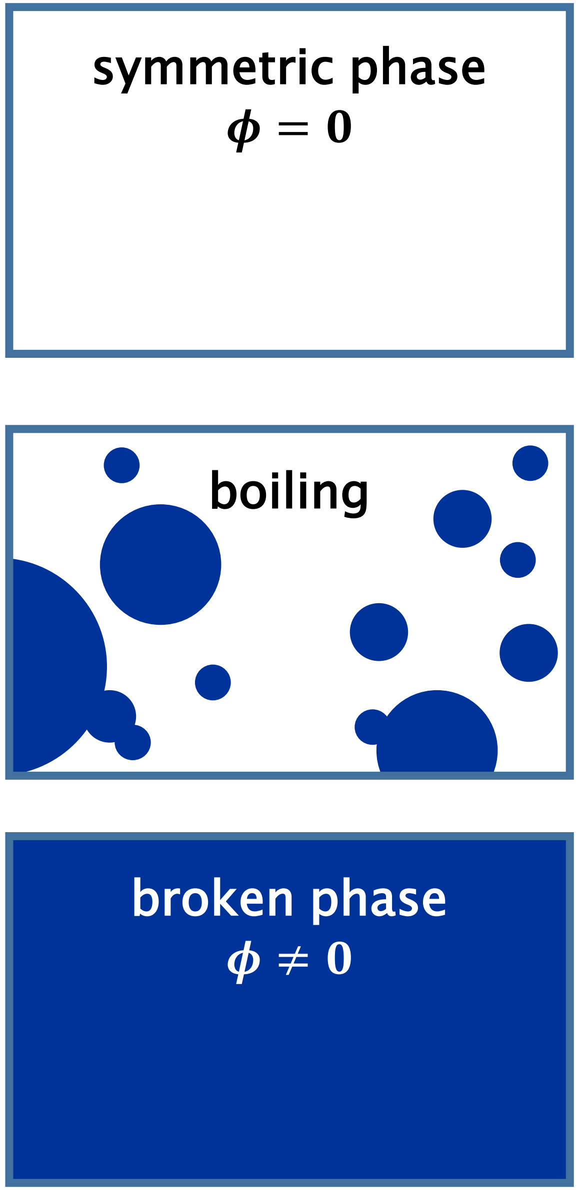
$d_p < 2000 \times 10^{-28}\ e\ \text{cm}$ (Seattle, 2016)

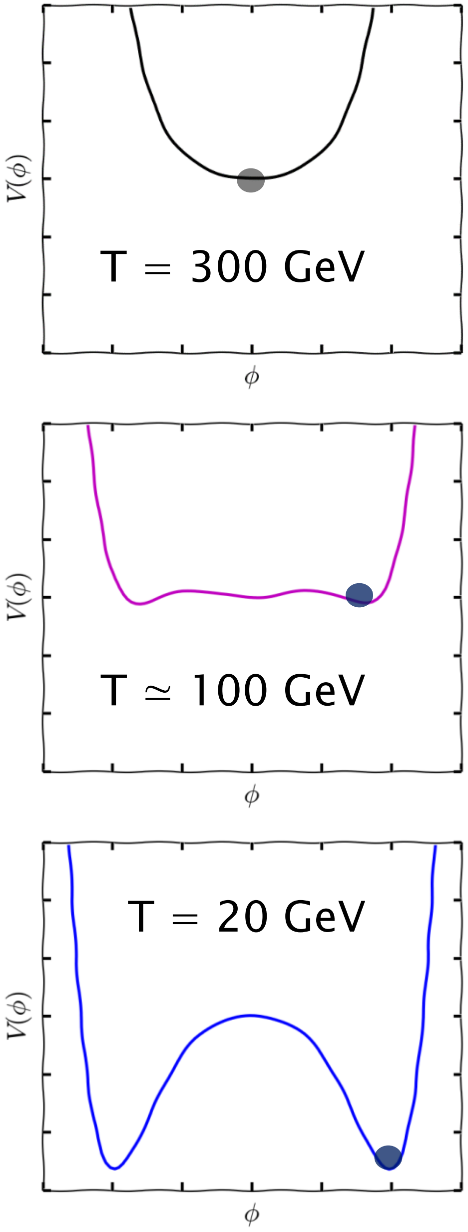
$d_e < 0.9 \times 10^{-28}\ e\ \text{cm}$ (Harvard, 2014)

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

CP violation and baryogenesis







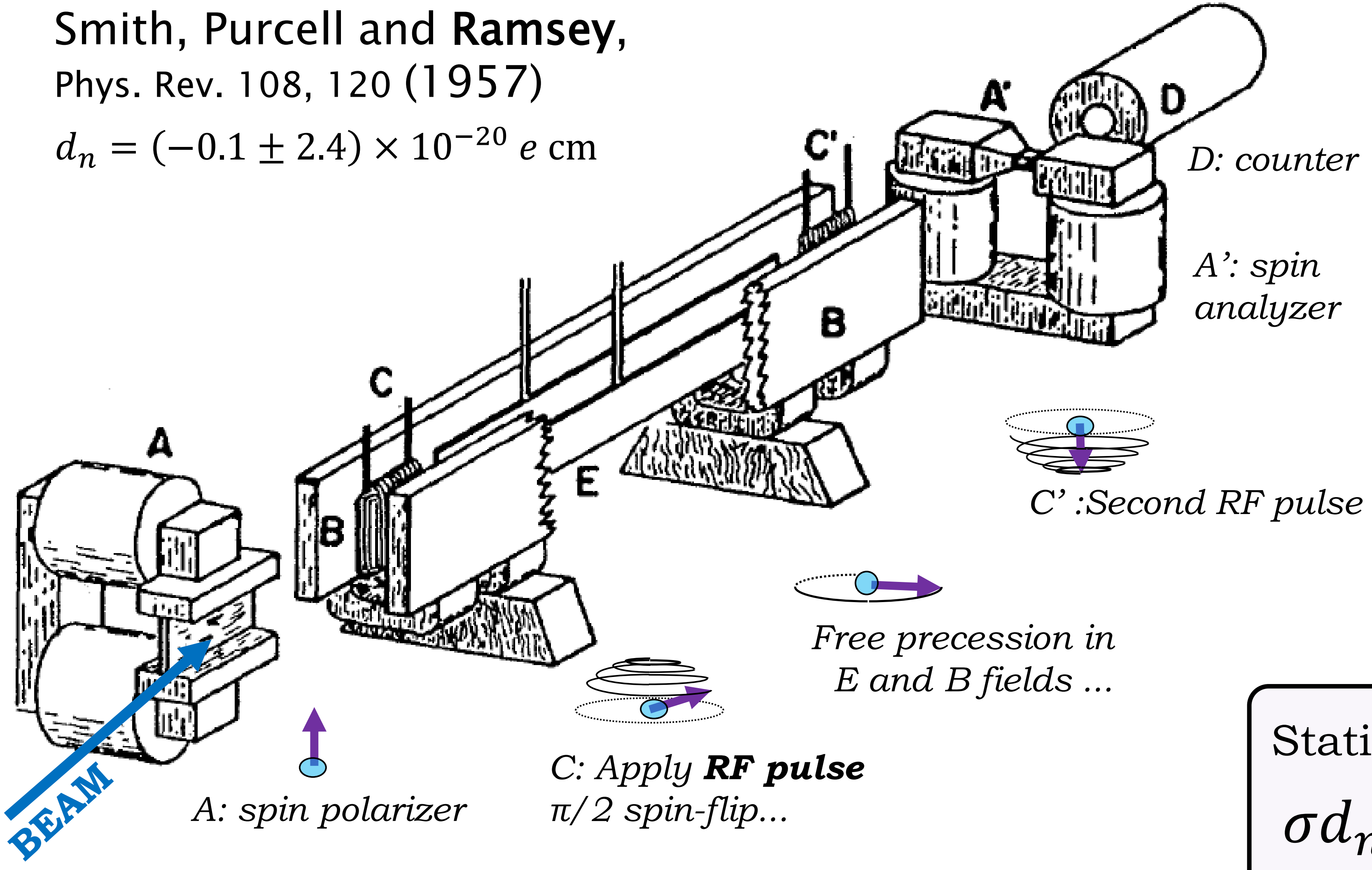
Sakharov's Baryogenesis recipe (1967)

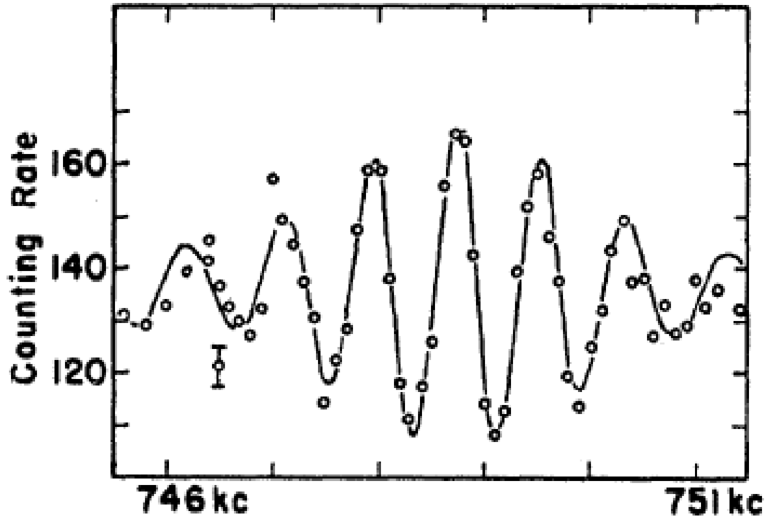
- Baryon number not conserved -> sphalerons
- Universe out of equilibrium
  - > Higgs self coupling
- **Violation of CP symmetry**
  - **> nEDM, pEDM**

Current nEDM bound constrains many scenarios of BSM electroweak baryogenesis

First EDM experiment with a neutron beam

Smith, Purcell and **Ramsey**,
Phys. Rev. 108, 120 (1957)
$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ e\ \text{cm}$



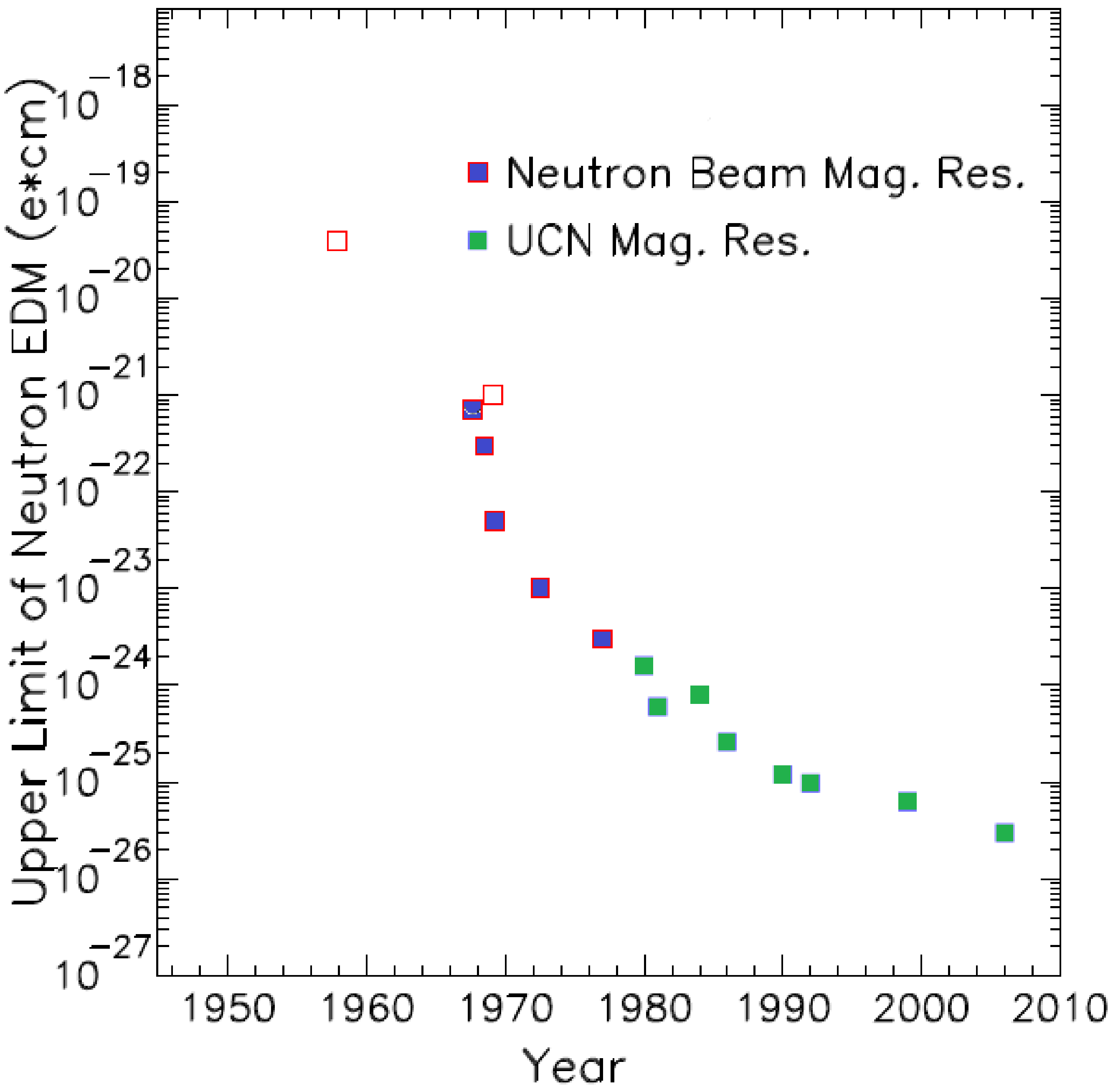


Vary the RF frequency and measure the resonance curve to extract f_L. Do it for parallel and antiparallel E and B fields.

Statistical sensitivity:

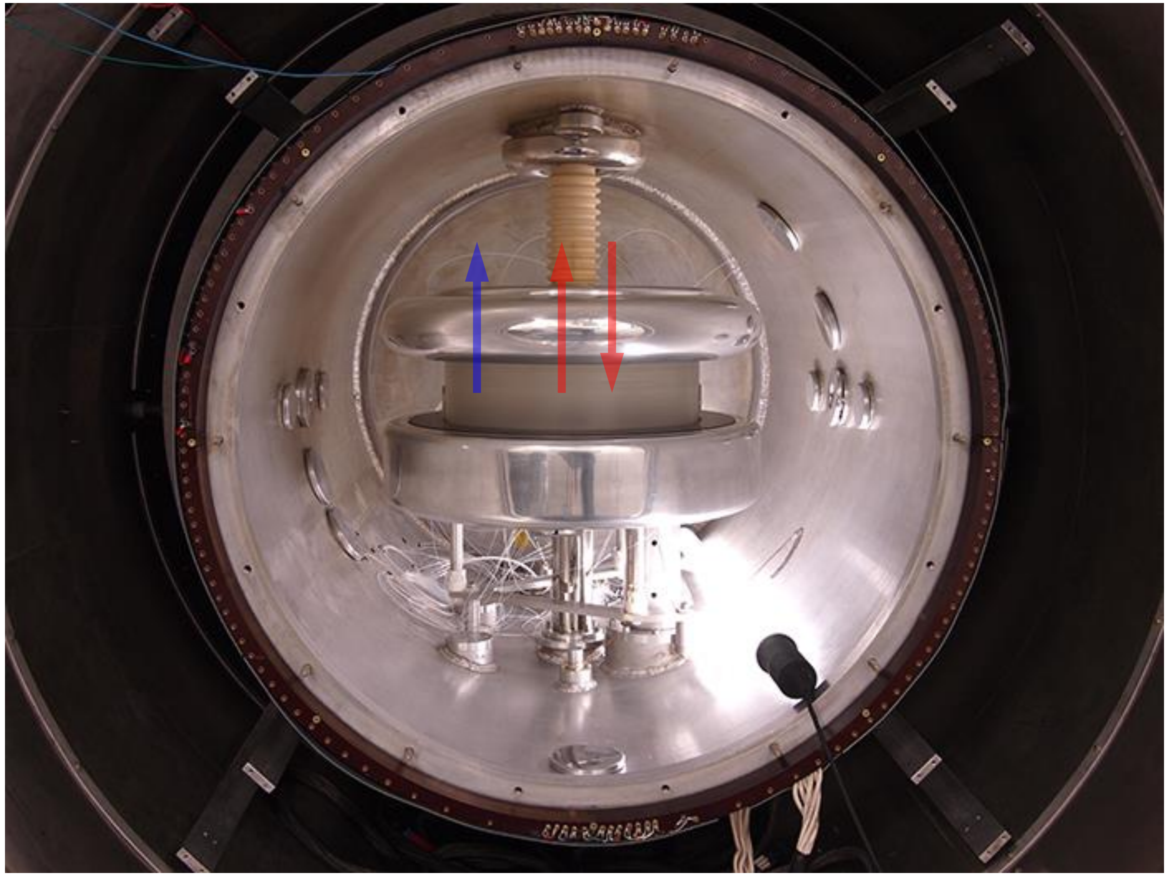
$$\sigma d_n = \frac{\hbar}{2\,\alpha\, E\, T \sqrt{N}}$$

$T \approx 1$ ms



The slower,
the better...

UCN nEDM apparatus (Sussex/RAL/ILL)

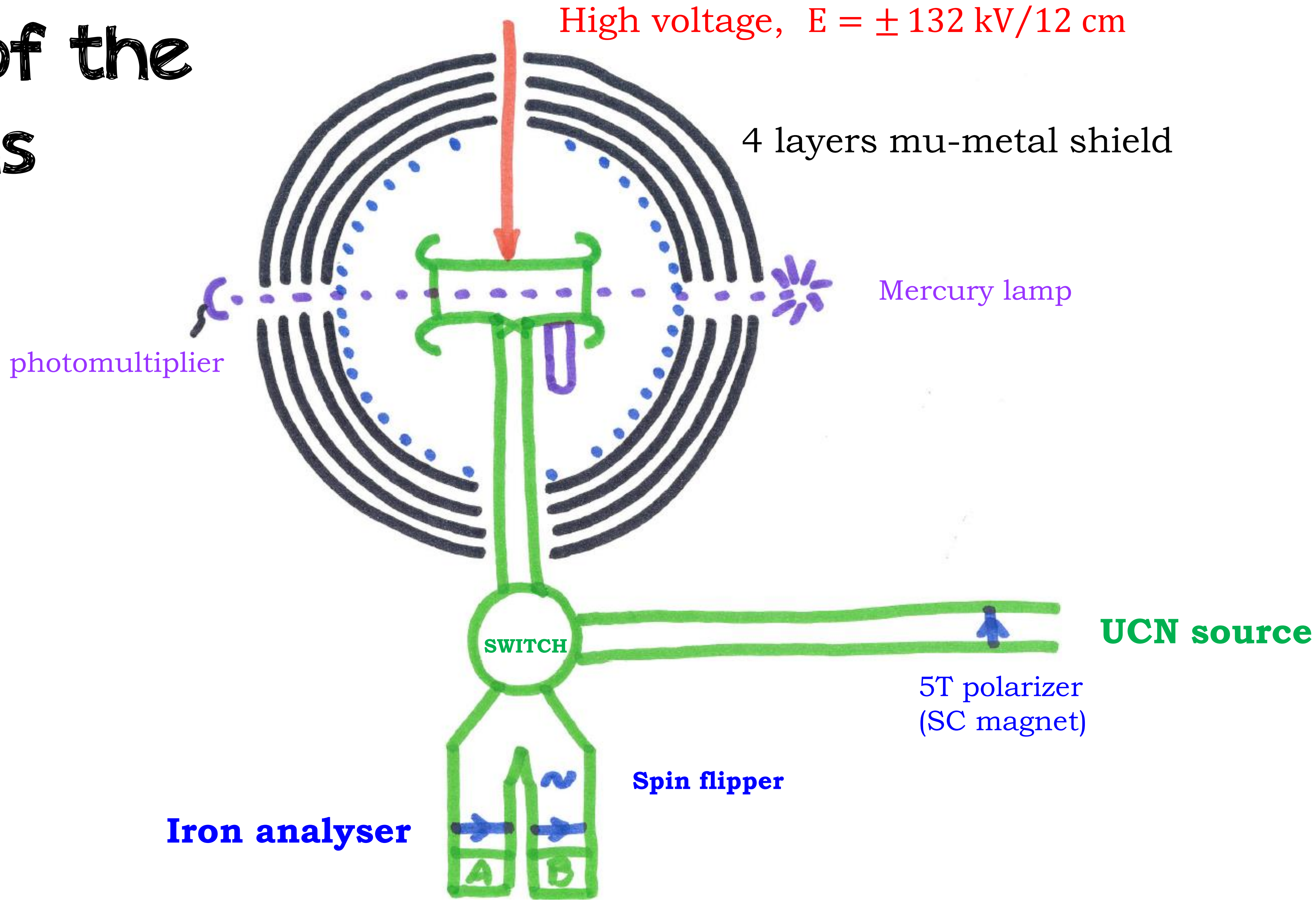


Apparatus installed at the ILL reactor Grenoble (1986-2009)

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)]

Scheme of the apparatus at PSI



Problem: the analyzing foil

What is the optimal height of the analysing foil in the nEDM experiment?

The analyzing foil consists of a thin layer of magnetized iron. The precession chamber, situated at height H above the analyzing foil, stores neutrons in the energy range 0 < E < 120 neV. Calculate the Fermi potential of non-magnetized iron. Suppose now that the foil is magnetized to a saturation field of Bs = 2 T. Neutrons with spin aligned with the magnetic field are dubbed *low field seekers*, those with spin anti-parallel with the magnetic field are dubbed *high field seekers*.

- Calculate the Fermi potential of the magnetized foil for high and low field seekers.
- Discuss the optimal height H to maximize the spin-analysis efficiency.
- Estimate the transmission of the foil.

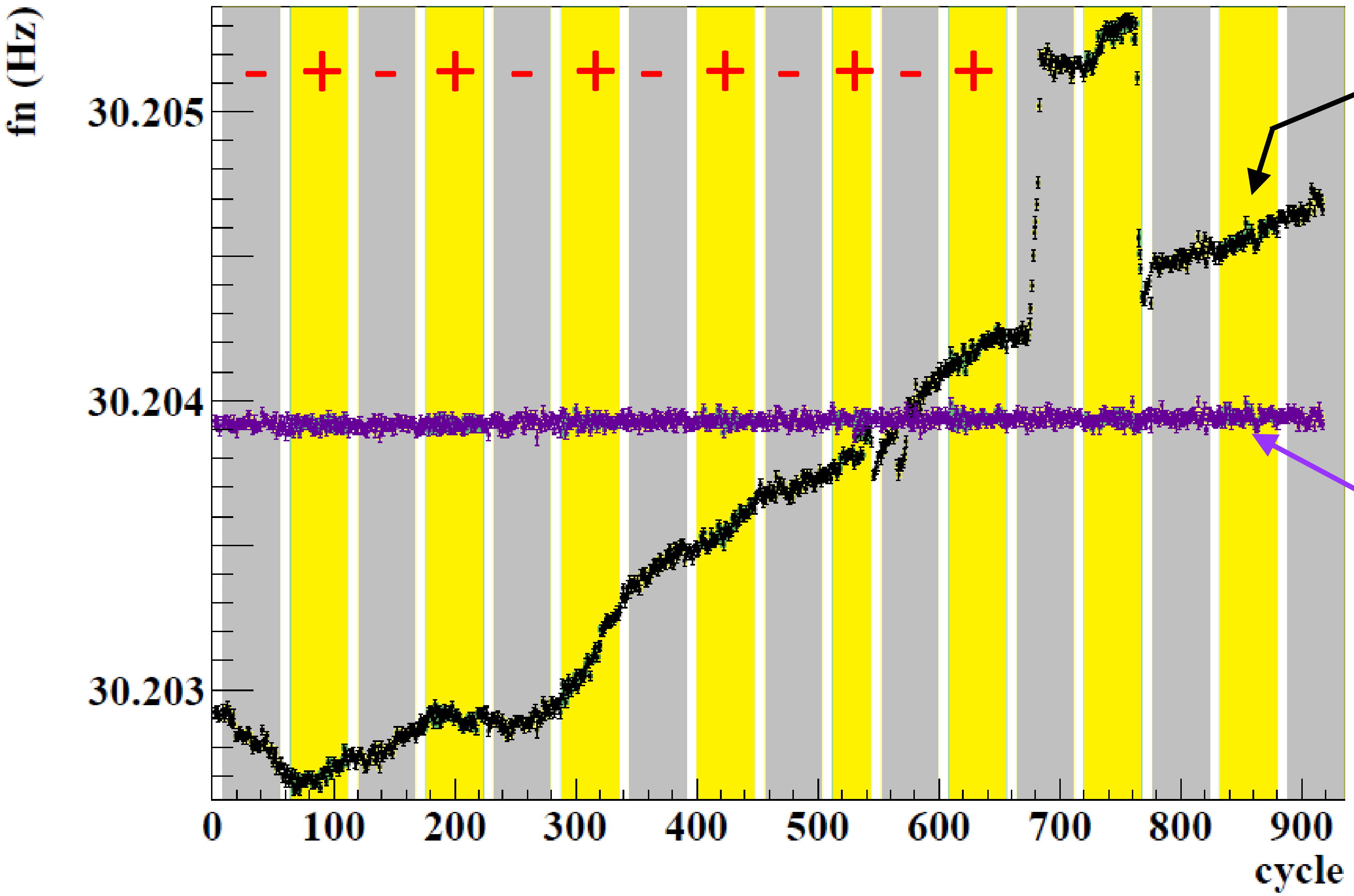
Iron, thickness 400 nm

Aluminum substrate, thickness 25 μm

material	ρ [g/cm^3]	M [g/mol]
aluminum	2.70	27.0
boron	2.34	10.8
iron	7.87	55.8

Nucleus	nat. ab.	b [fm]	σ_a^{th} [barn]	atomic mass [u]
^{27}Al	100%	3.449	0.231	26.981538531
^{54}Fe	5.8%	4.2	2.25	53.9396105
^{56}Fe	91.7%	9.94	2.59	55.934936326
^{57}Fe	2.2%	2.3	2.48	56.935394

Typical measurement sequence at PSI, 1 cycle every 5 minutes



Uncorrected neutron frequency

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

Mercury-corrected neutron frequency

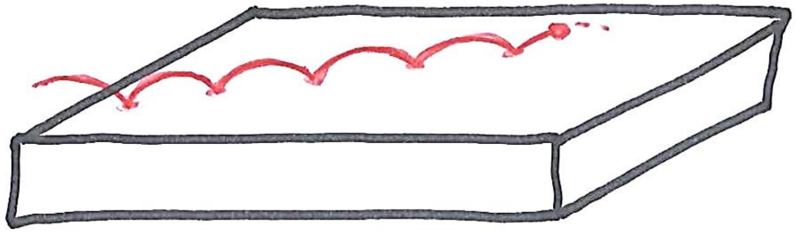
$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$

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

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

1. Neutrons and the precision frontier
2. Neutron detection
3. Neutron optics, ultracold neutrons
4. **Fundamental physics with UCNs**
    - Neutron lifetime
    - Electric dipole moment
    - **Gravity with neutrons**

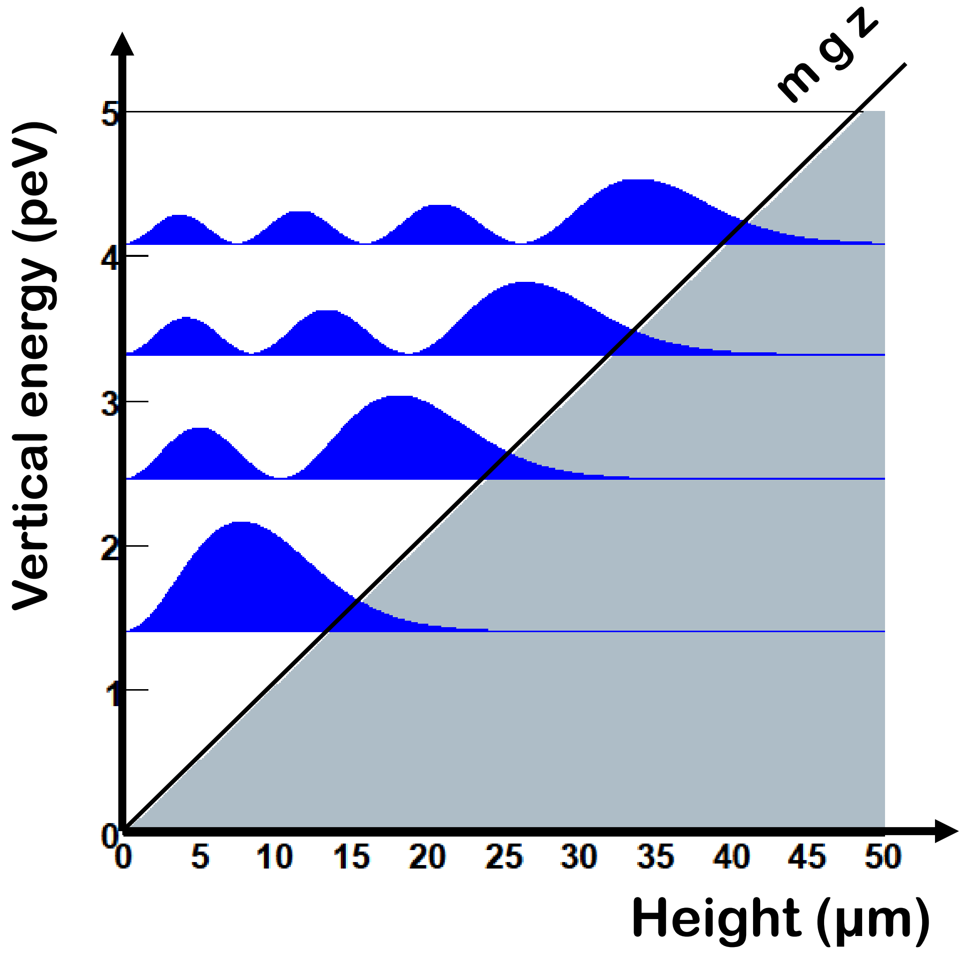
Bouncing neutrons



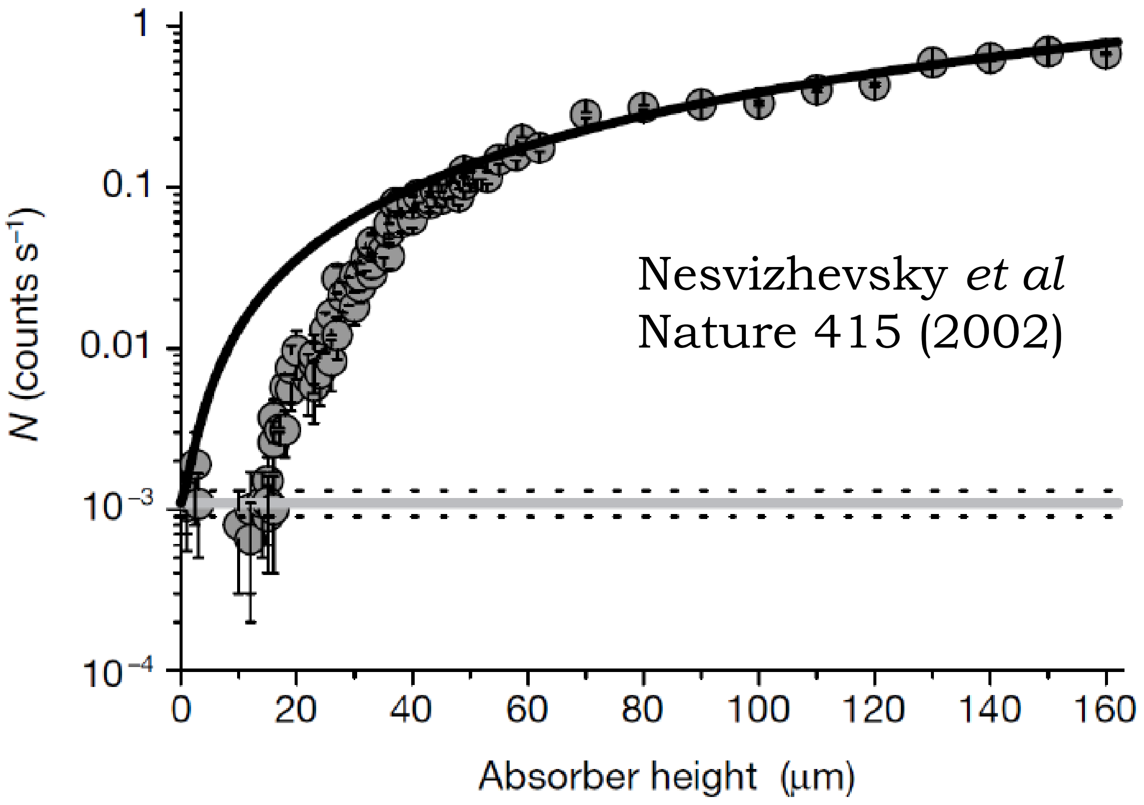
The vertical motion is a simple quantum well problem

$$-\frac{\hbar^2}{2m_i}\frac{d^2\psi}{dz^2} + m_g g z\,\psi = E\,\psi$$

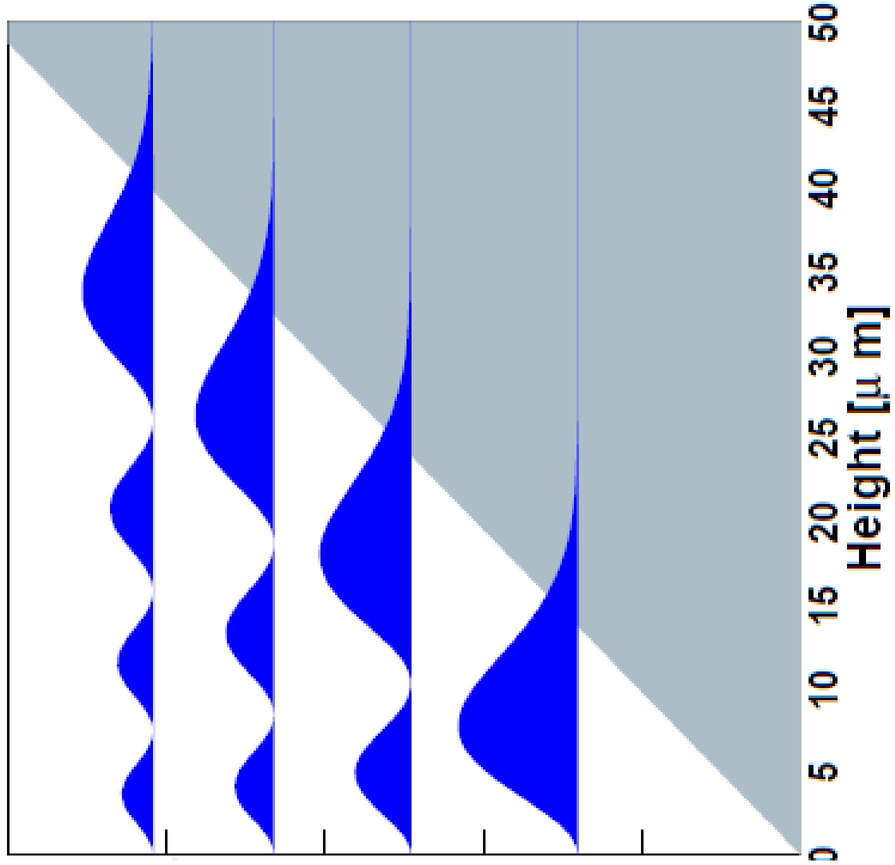
We want to test Enstein's equivalence principle for a quantum particle in a classical gravity field.

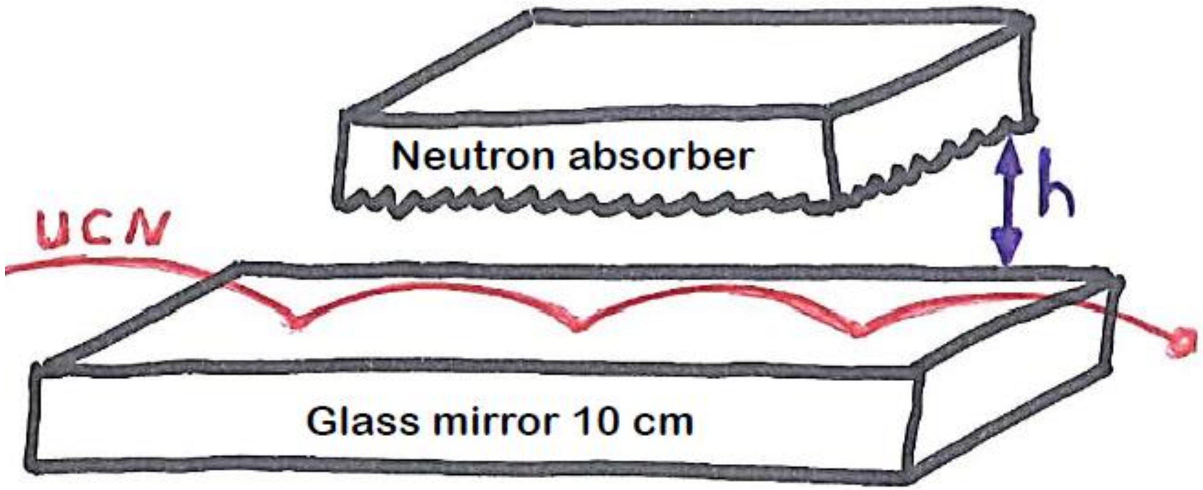


Discovery of the quantum states at ILL

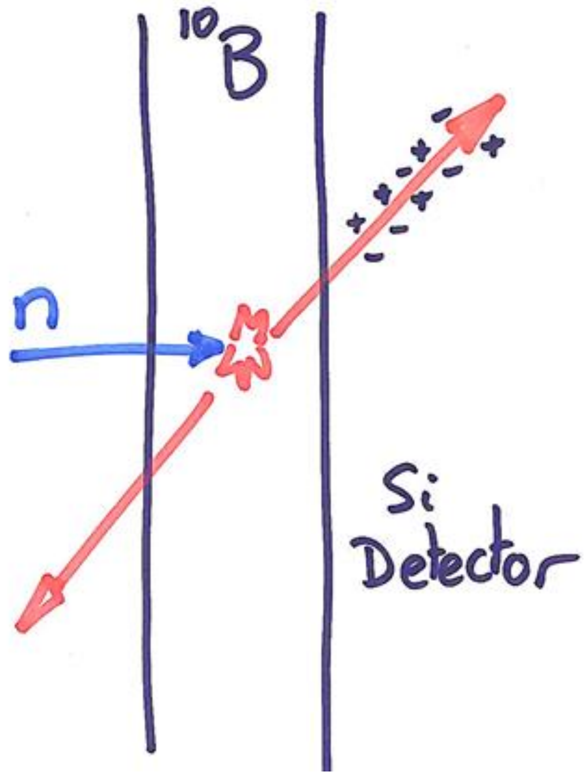


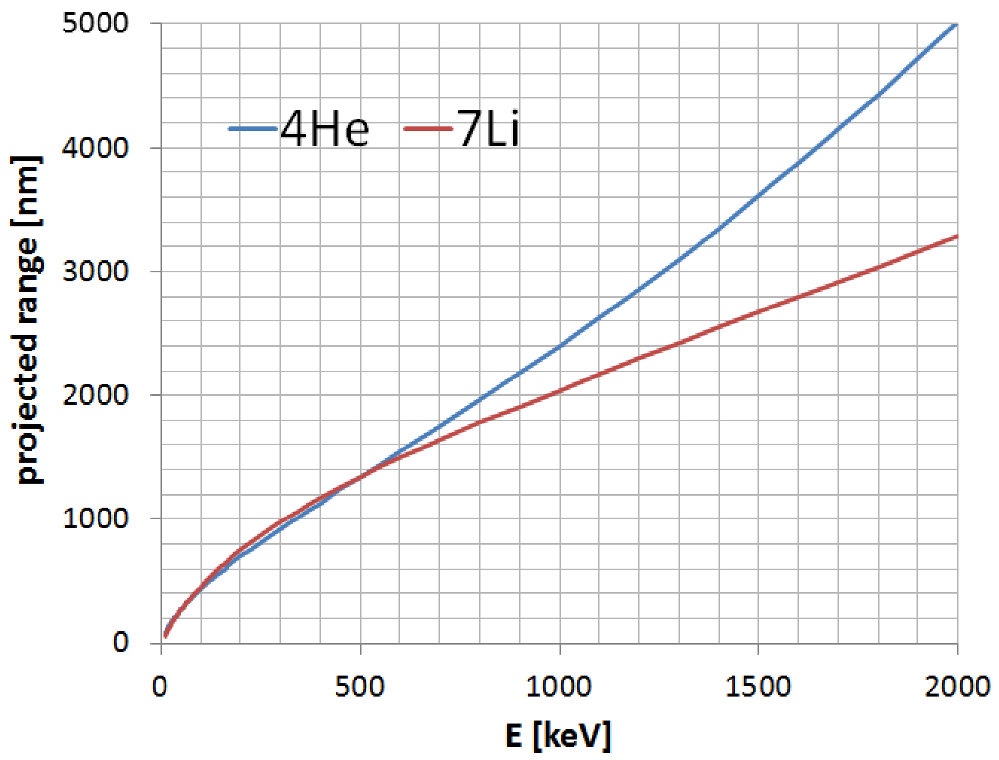
Nesvizhevsky *et al*
Nature 415 (2002)





Problem: micrometric position sensitive detector





1. Calculate the Fermi potential of (i) natural boron (ii) pure 10B. Why do we have to use isotopically pure boron?

2. We choose a boron layer thickness of 200 nm. Discuss this choice in terms of neutron conversion efficiency (for UCNs of velocity 3 m/s), Si detector efficiency and spatial resolution.