Ultracold neutrons

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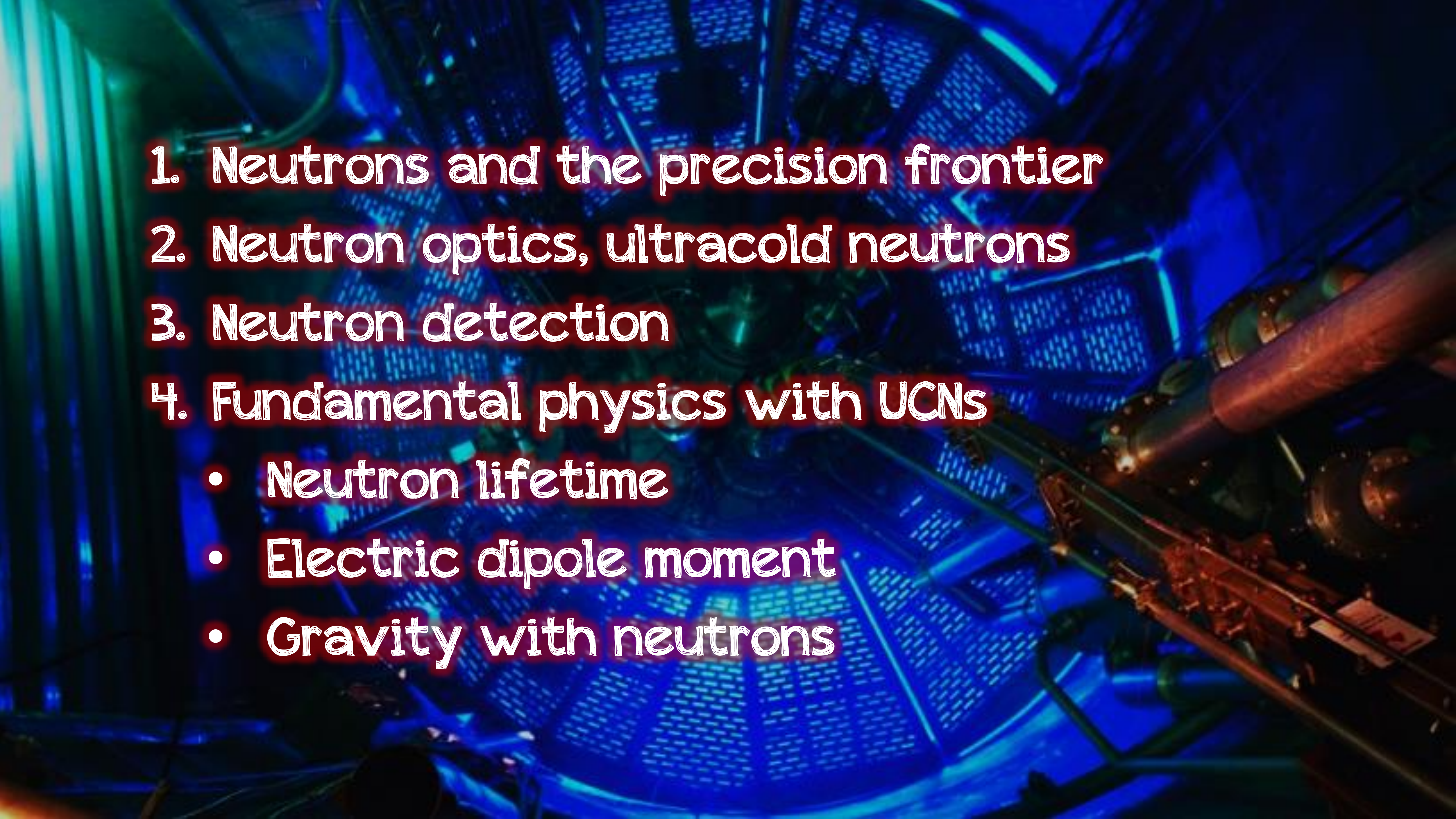
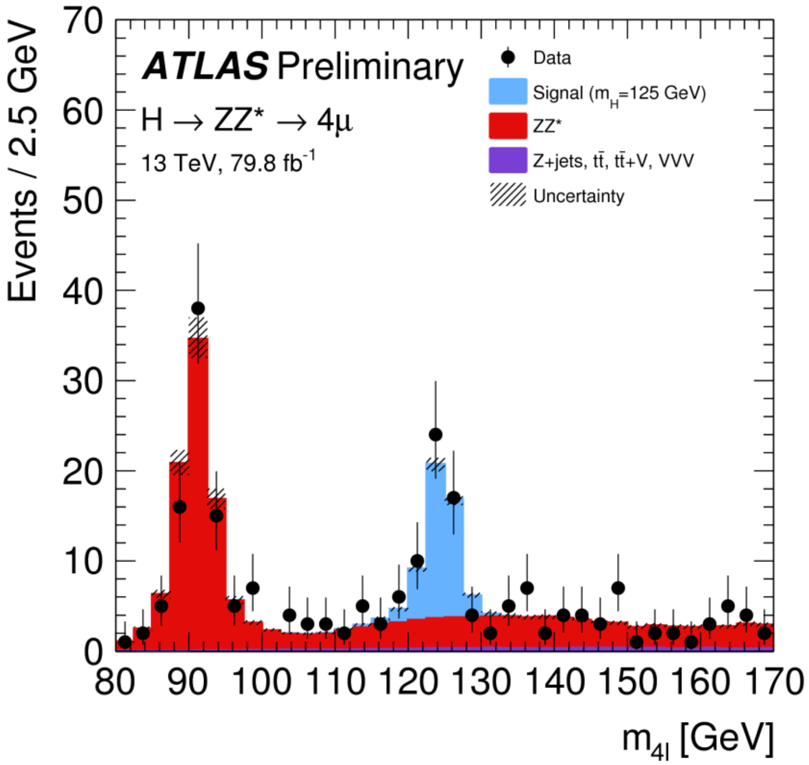


1. Neutrons and the precision frontier
2. Neutron optics, ultracold neutrons
3. Neutron detection
4. Fundamental physics with UCNs
    - Neutron lifetime
    - Electric dipole moment
    - Gravity with neutrons

Two frontiers of particle physics

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

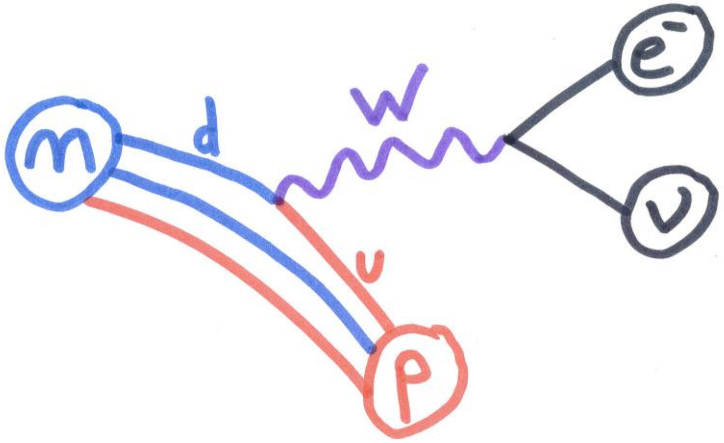
- W boson, $m_W = 80$ GeV
- Higgs boson, $m_H = 125$ GeV
- Dark matter particle?



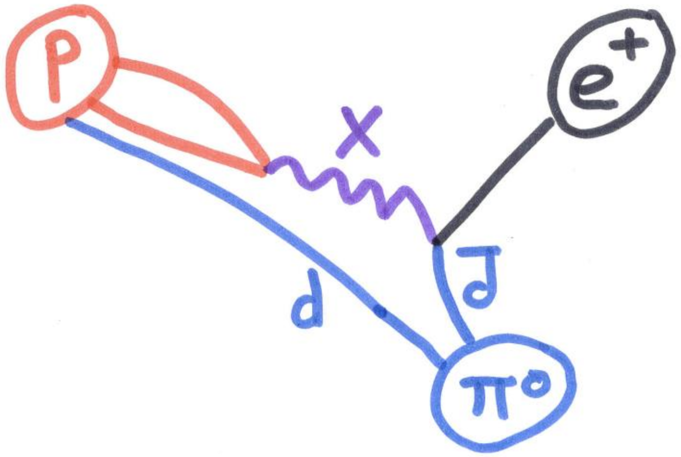
Precision frontier: detecting the effect of virtual particles.

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).



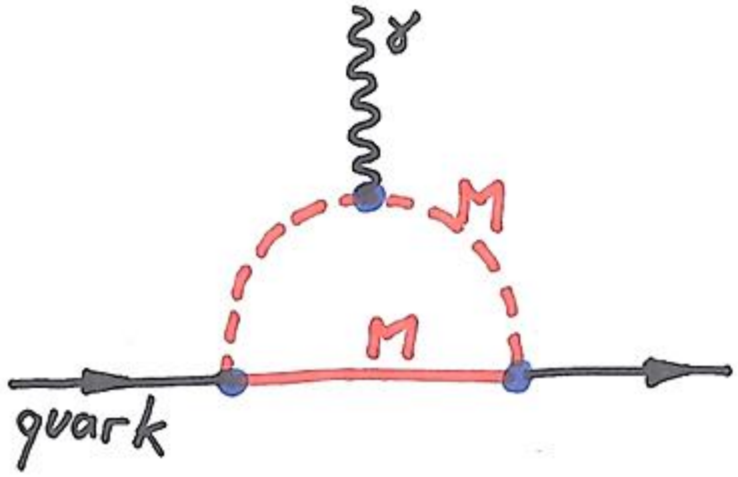
New physics at the precision/intensity frontier



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.

Detecting the neutron electric dipole moment

$$\hat{H} = -d_n \vec{E} \cdot \vec{\sigma}$$

If the neutron EDM is $d_n = 10^{-27}\, e$ cm
And the electric field is $E = 15$ kV/cm
The neutron spin will make one full turn in a time
$\frac{\pi\hbar}{d_n E} = 1.4 \times 10^6$ s $= 4$ years

In order to detect such a tiny coupling we need:

- The slowest possible neutrons
  to maximize the interaction time in the electric field
- An intense source of such neutrons
  to maximize the statistical sensitivity

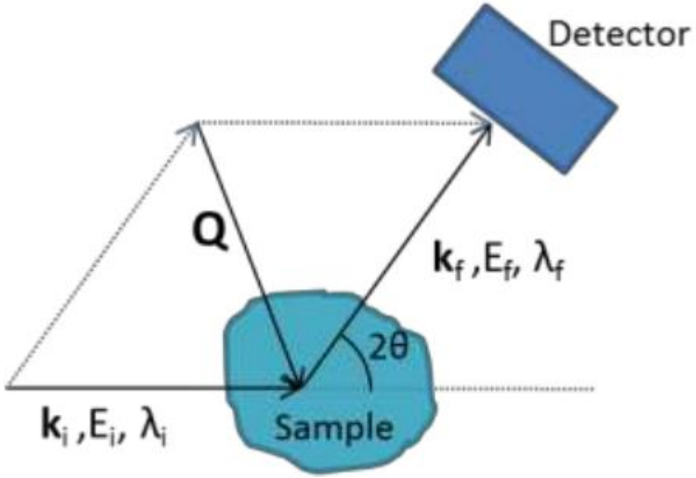
Large neutron factories

ILL high flux reactor
since 1967
Grenoble, France

Future European Spallation Source
Scheduled 2025
Lund, Sweden

multi-disciplinary facilities

Biology
Chemistry
Material sciences
Magnetism
Nuclear physics
Particle physics

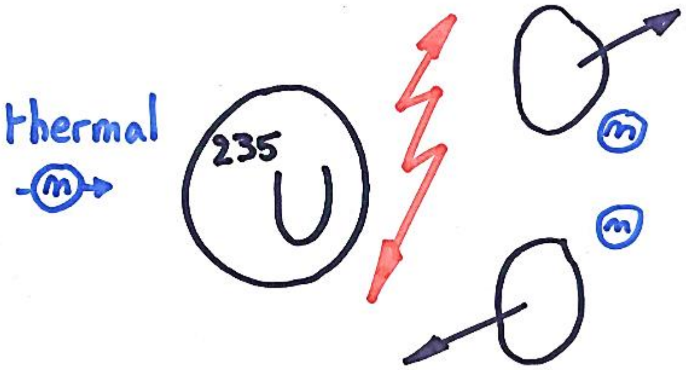


A typical neutron scattering experiment

Fission or Spallation sources

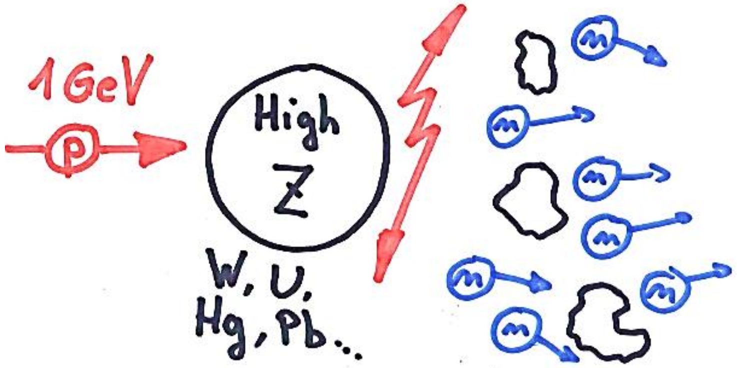
FISSION

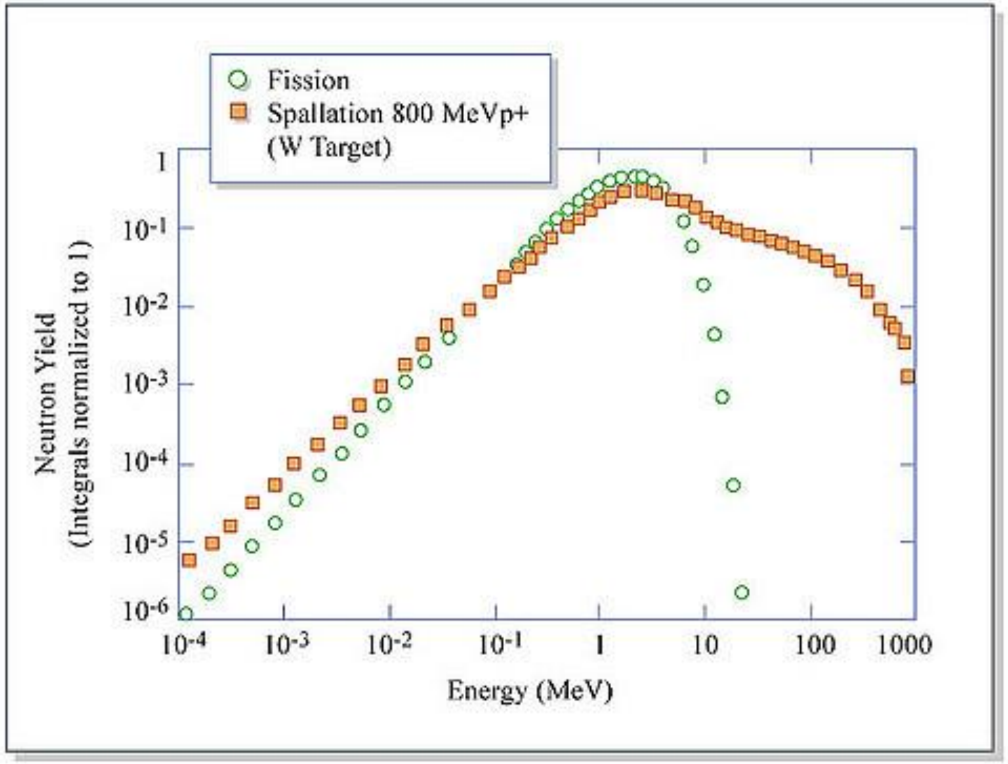
- steady chain reaction
- ~ 2 neutron/fission
- Energy ~ 2 MeV



SPALLATION

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



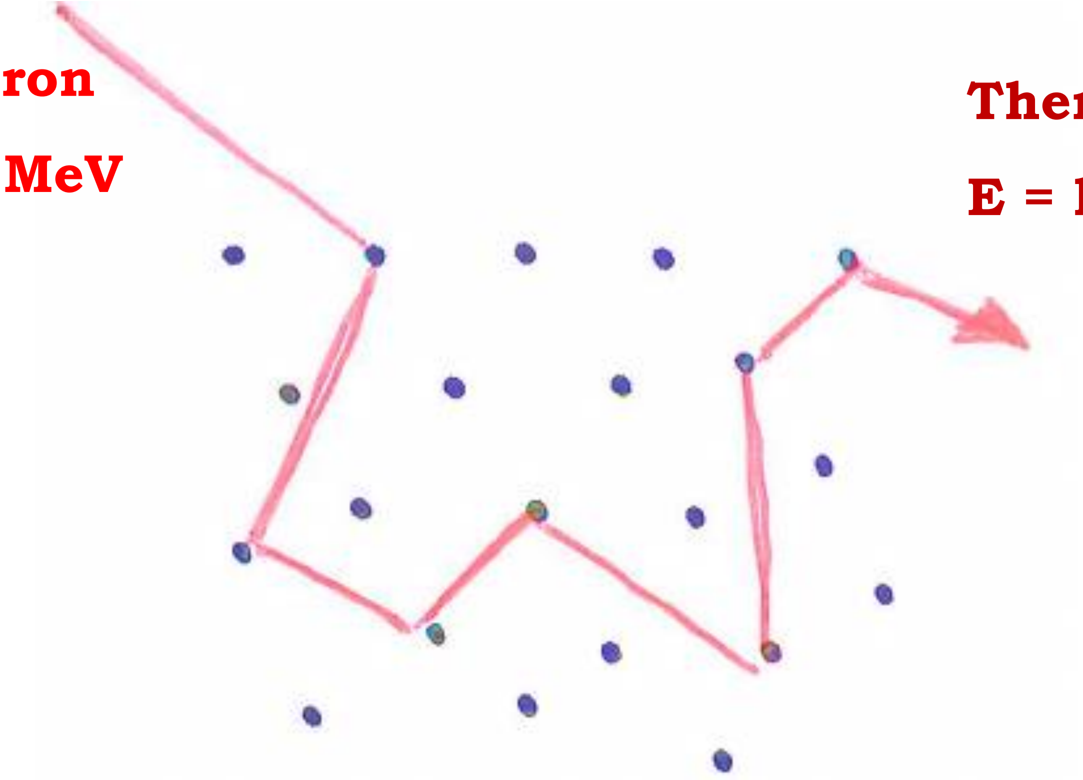


G.J. Russell, Spallation physics–an overview,
Proceedings of ICANS-XI, KEK-Report Vol. 90-25, 291–299, 1991

Thermalization of fast neutrons

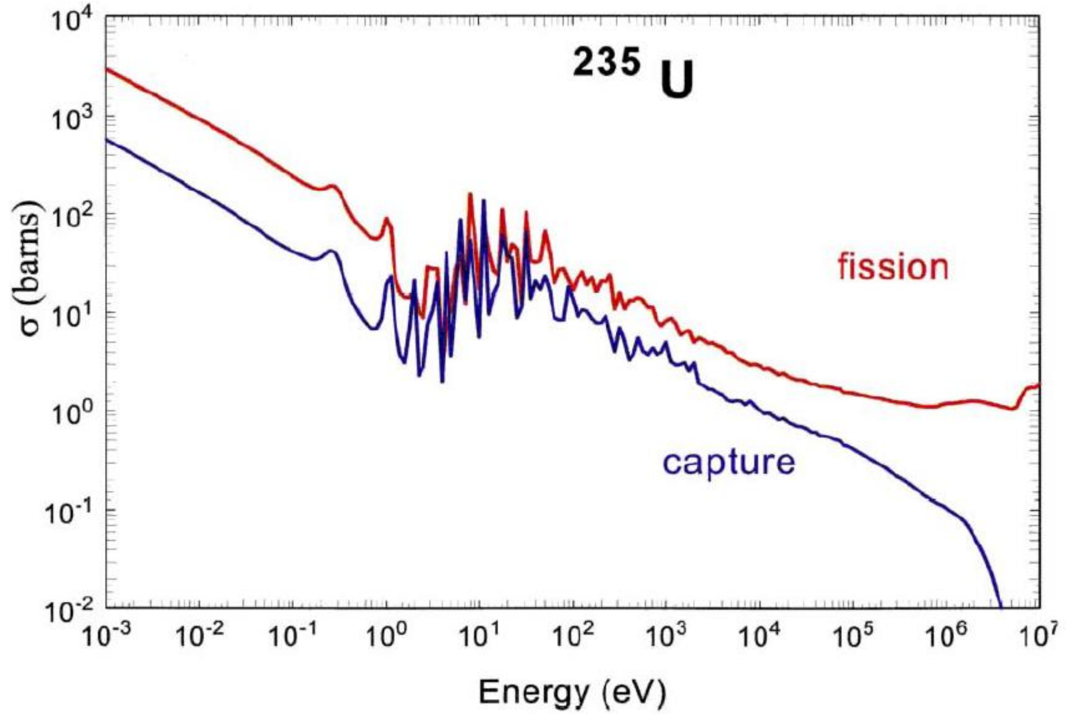
Fast neutron

E = a few MeV



Thermal neutron

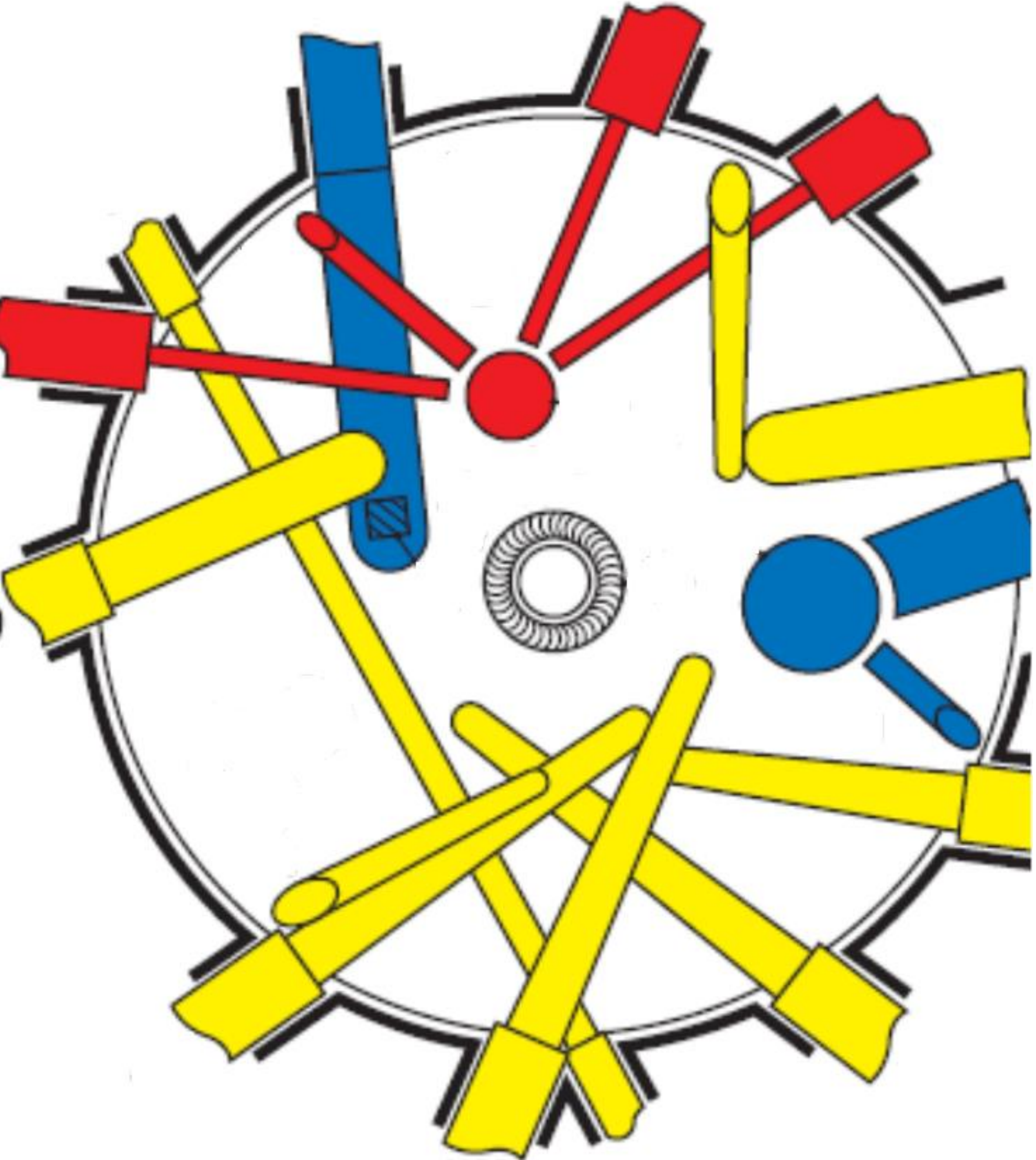
E = kT = 25 meV



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

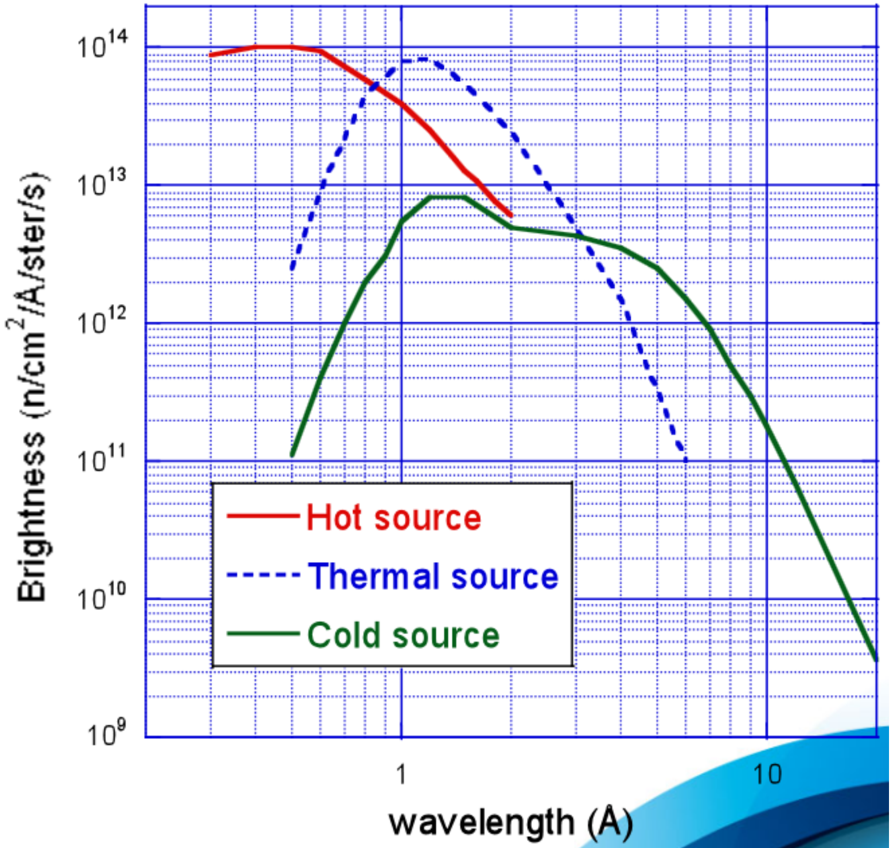


Heavy water moderator and reflector Ø2.5 m

Fuel: HEU (93.3% 235)

Hot source

Cold source: 20 L of Liquid D2 at 20K



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

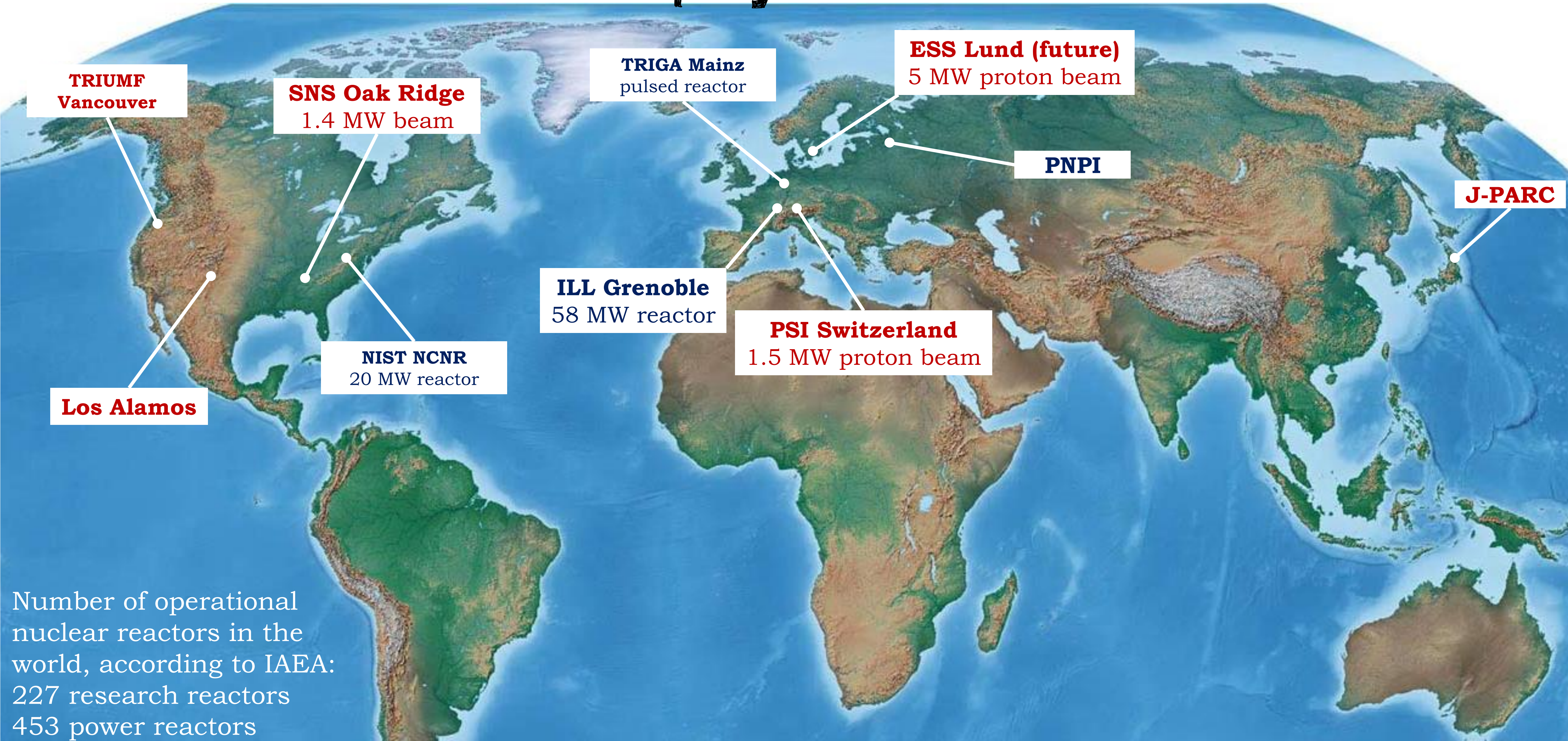
SNS pulsed source (60 Hz)

Thermal neutron flux

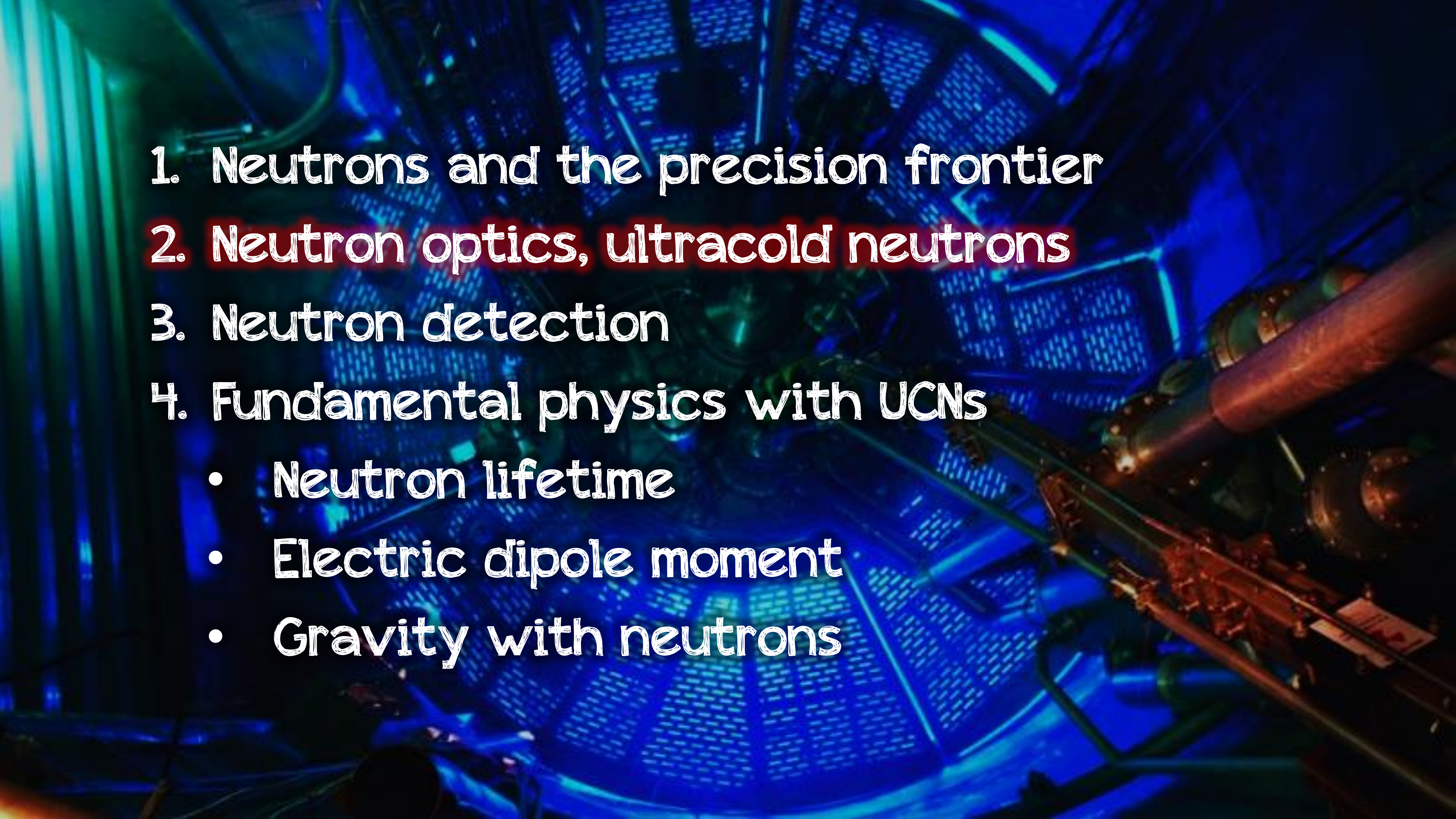
Peak ~ 3×10^{16} n/cm^2/s

Average ~ 4×10^{13} n/cm^2/s

About 10 Big neutron sources available for fundamental physics in the world



Number of operational nuclear reactors in the world, according to IAEA:
227 research reactors
453 power reactors



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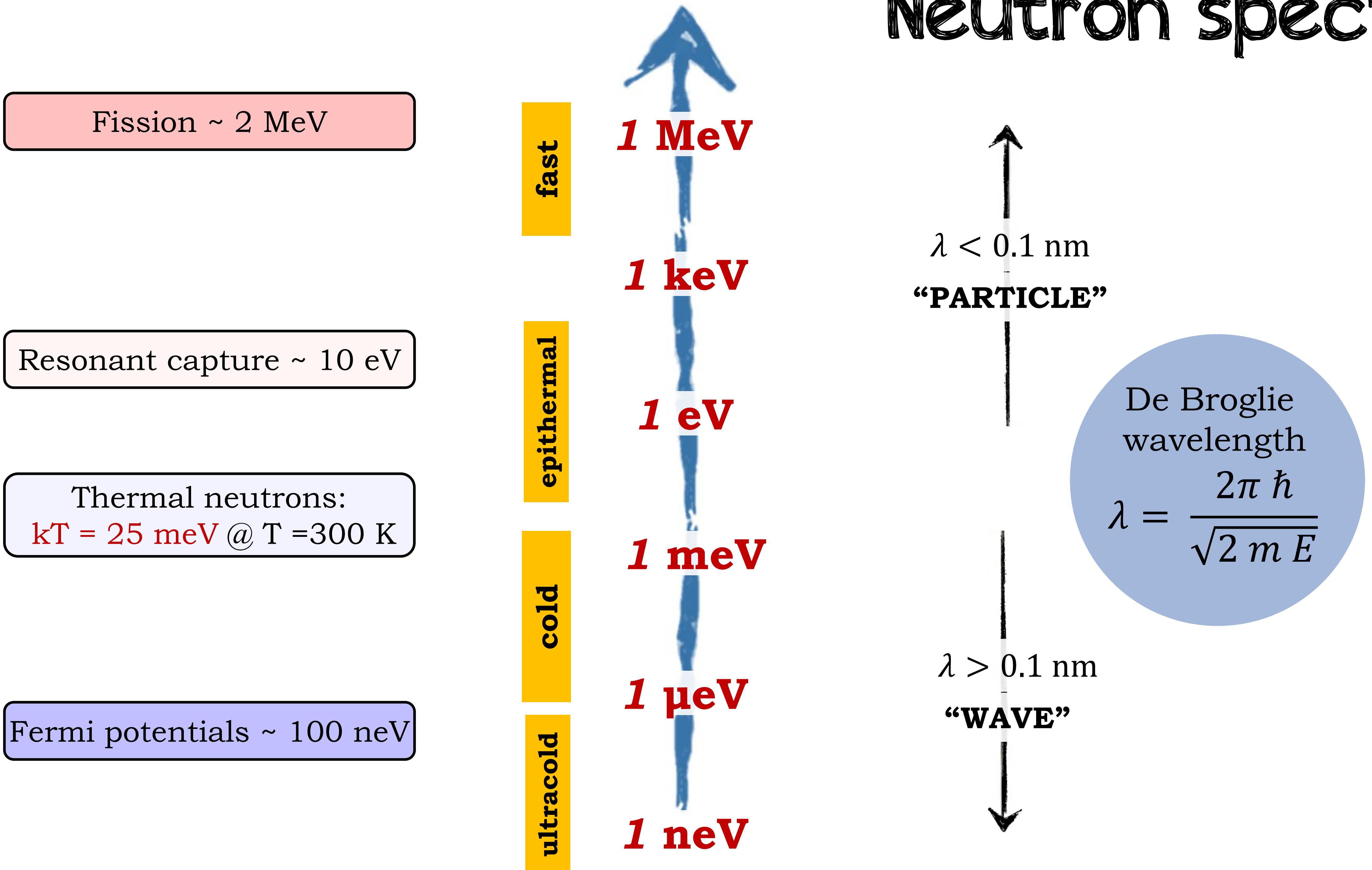
Neutron spectrum



Fission ~ 2 MeV

Resonant capture ~ 10 eV

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

Fermi potentials ~ 100 neV

$\lambda < 0.1$ nm

“PARTICLE”

De Broglie wavelength

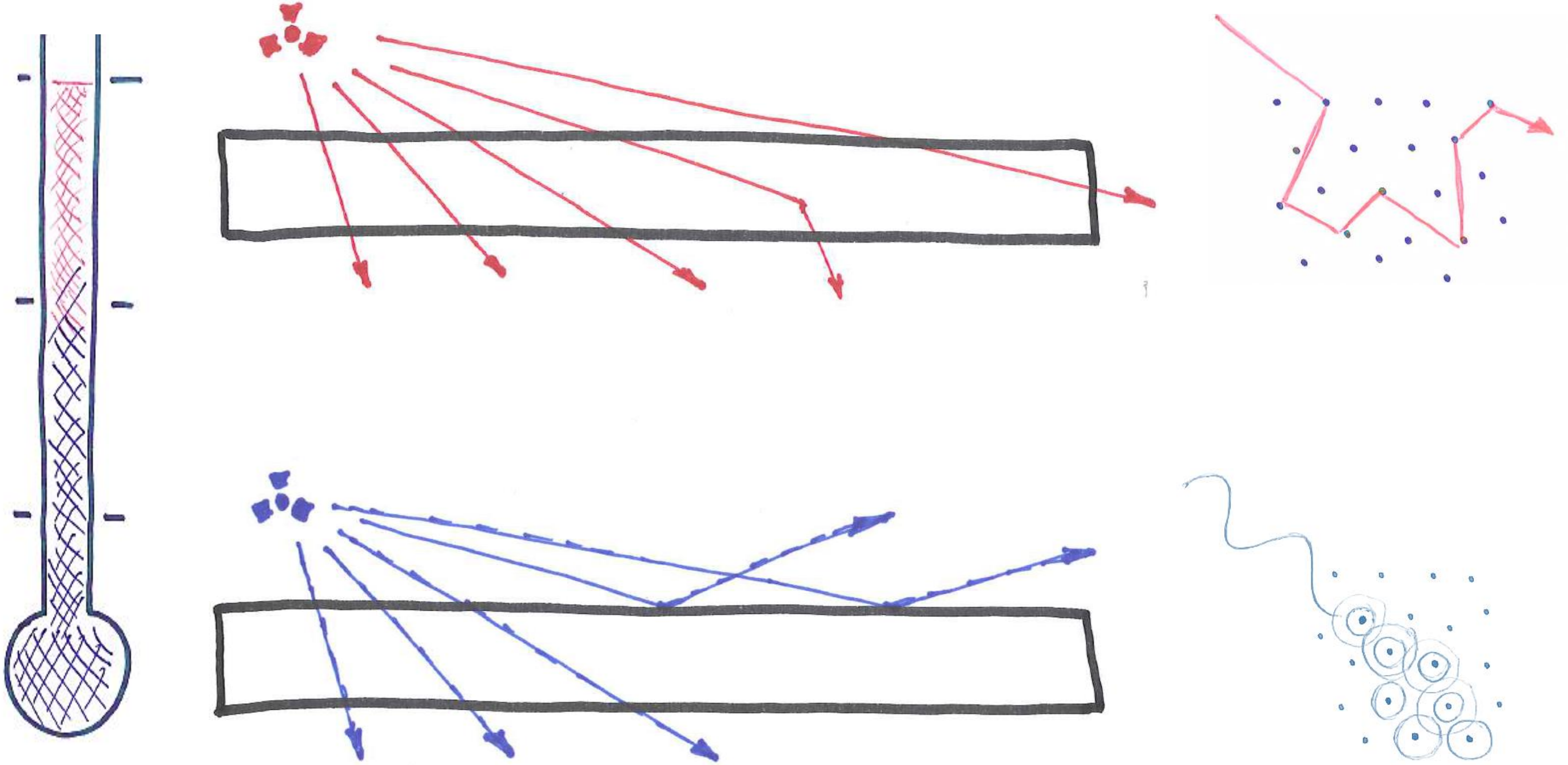
$$\lambda = \frac{2\pi\,\hbar}{\sqrt{2\,m\,E}}$$

$\lambda > 0.1$ nm

“WAVE”

Mirror effect at grazing incidence

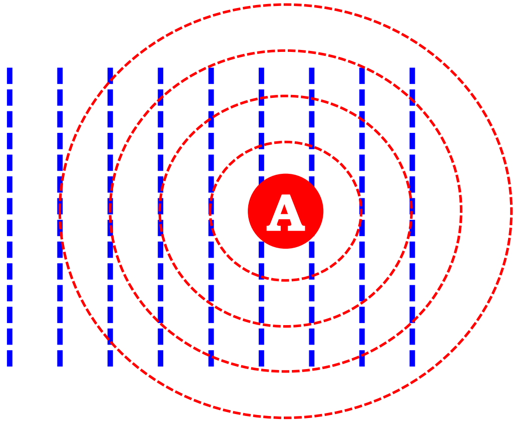
Particles and waves



Neutron interaction with a single nucleus

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

- Isotropic scattering
- Energy-independent

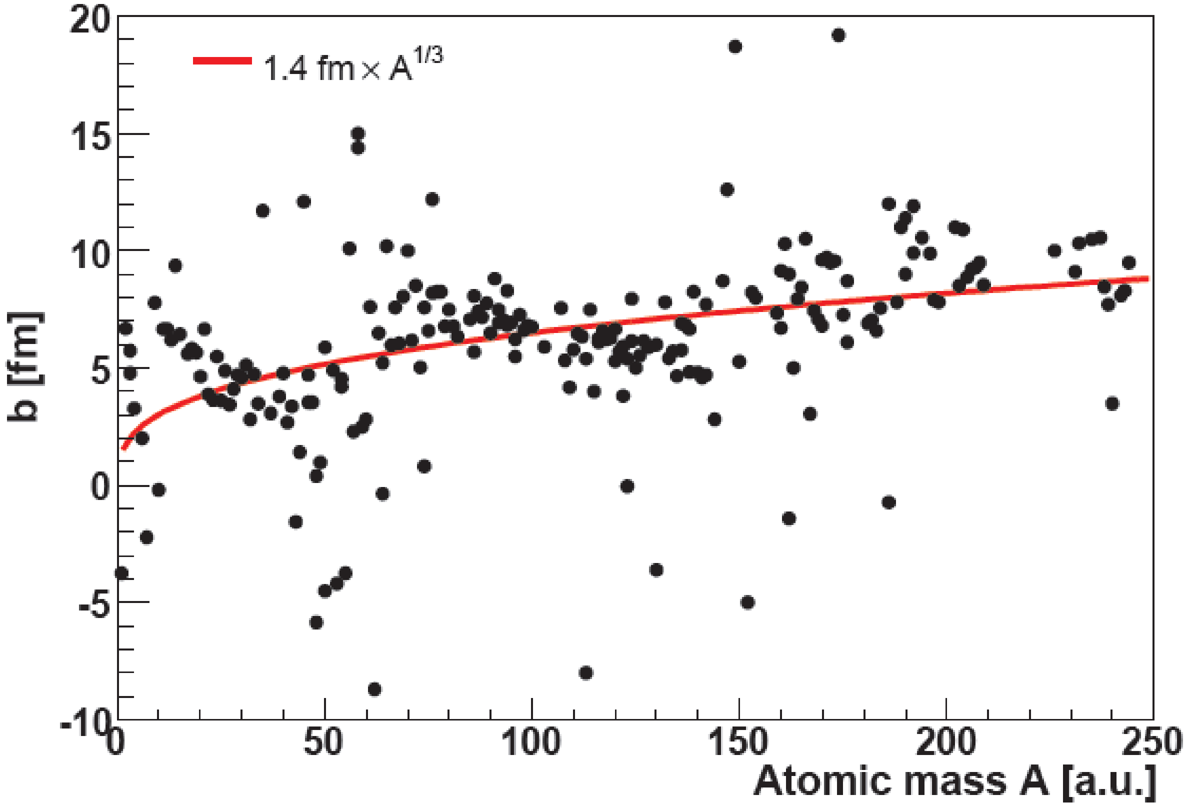


Neutron wave function corresponding to the scattering process

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

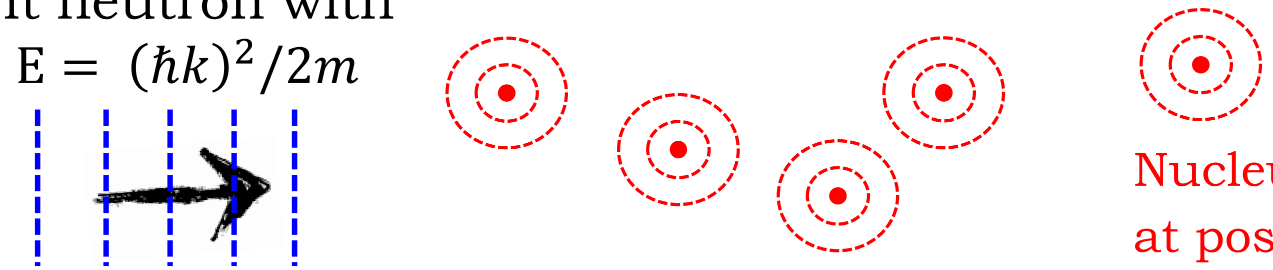
scattering X-section

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



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 = $(\hbar k)^2/2m$

Nucleus number j
at position $\overrightarrow{R_j}$

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

Neutron Fermi potential

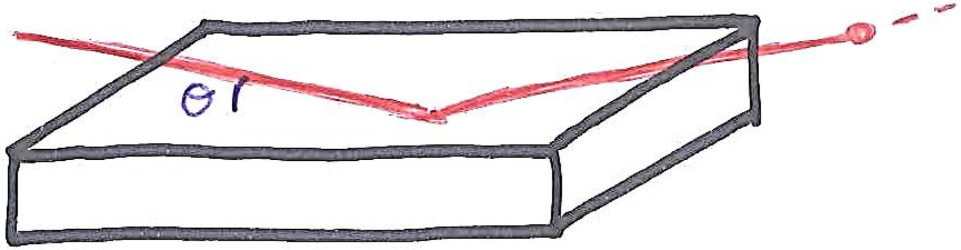
Defining the Fermi potential of a medium

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

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..).



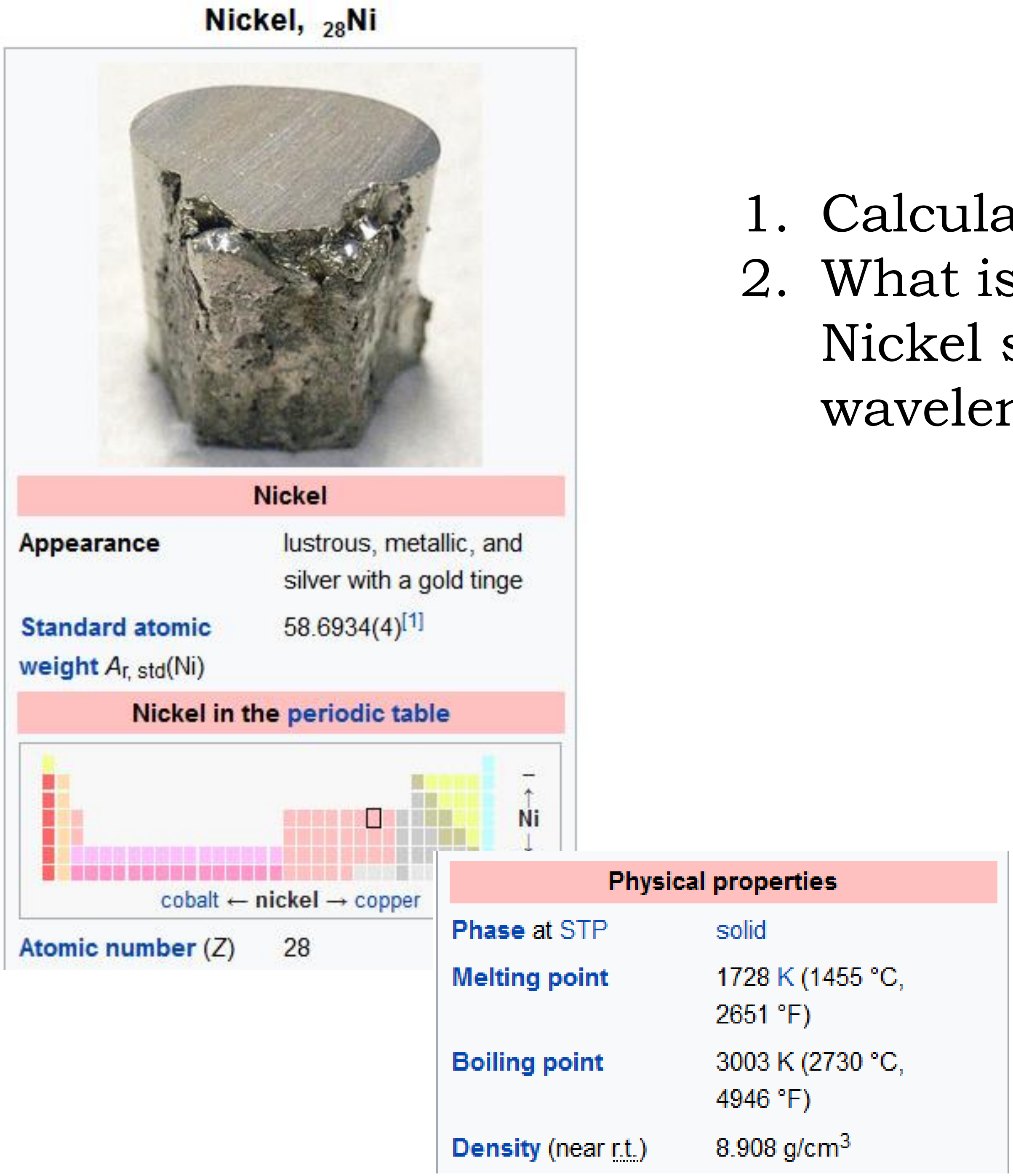
Solid matter characterized by the Fermi potential V_F

Condition for total reflection of neutrons of energy E (Fermi & Zinn 1946)

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

Exercises

1. Calculate the Fermi potential of Nickel
2. What is the maximum reflection angle on a Nickel surface for a cold neutron of wavelength 0.9 nm?



Nickel, $_{28}$Ni

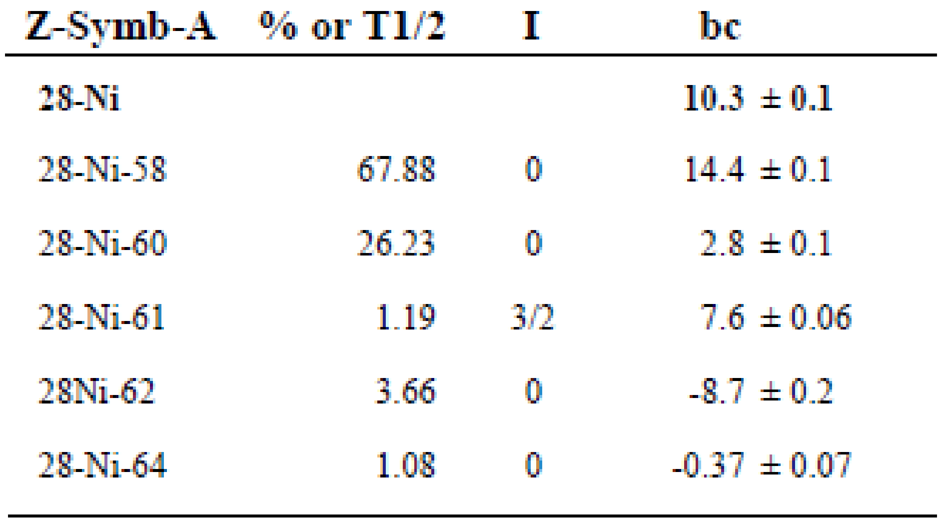
Nickel	
Appearance	lustrous, metallic, and silver with a gold tinge
Standard atomic weight $A_{r,\,\mathrm{std}}$(Ni)	58.6934(4)[1]

Nickel in the periodic table

cobalt ← **nickel** → copper

Atomic number (Z)	28

Physical properties	
Phase at STP	solid
Melting point	1728 K (1455 °C, 2651 °F)
Boiling point	3003 K (2730 °C, 4946 °F)
Density (near r.t.)	8.908 g/cm^3



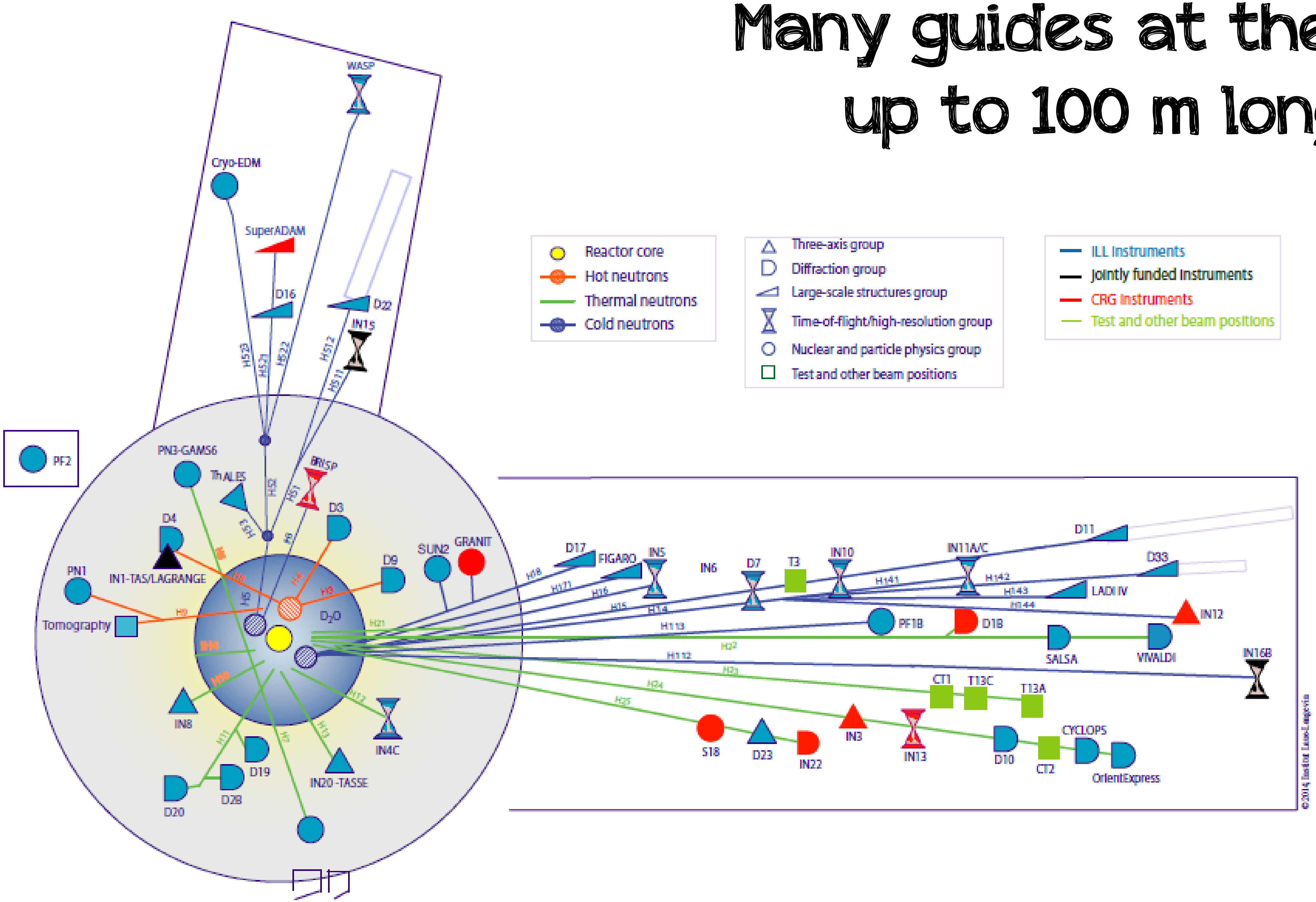
Z-Symb-A	% or T1/2	I	bc
28-Ni			10.3 ± 0.1
28-Ni-58	67.88	0	14.4 ± 0.1
28-Ni-60	26.23	0	2.8 ± 0.1
28-Ni-61	1.19	3/2	7.6 ± 0.06
28Ni-62	3.66	0	-8.7 ± 0.2
28-Ni-64	1.08	0	-0.37 ± 0.07

Application: neutron guides

ILL High Flux Reactor

Neutron distribution channel at ILL

Many guides at the ILL, up to 100 m long



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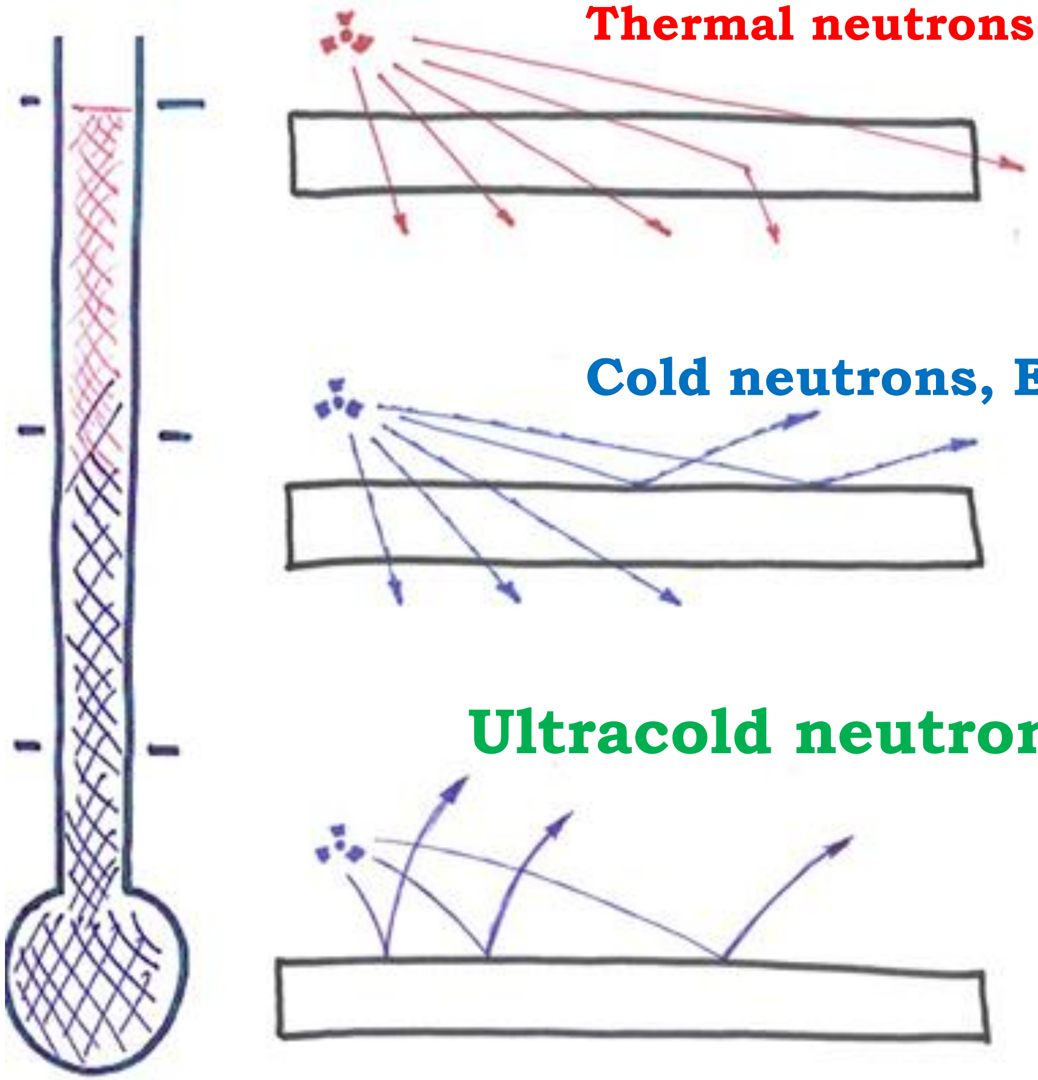
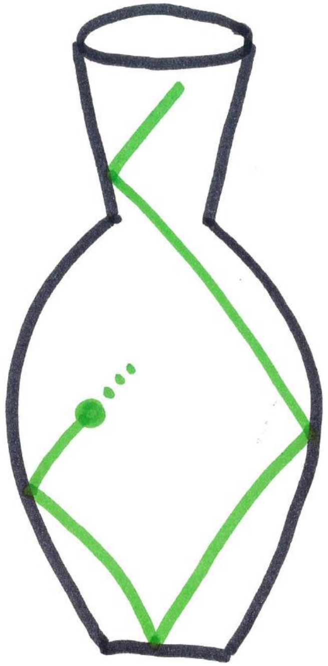
Ultracold neutrons (UCNs)



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.

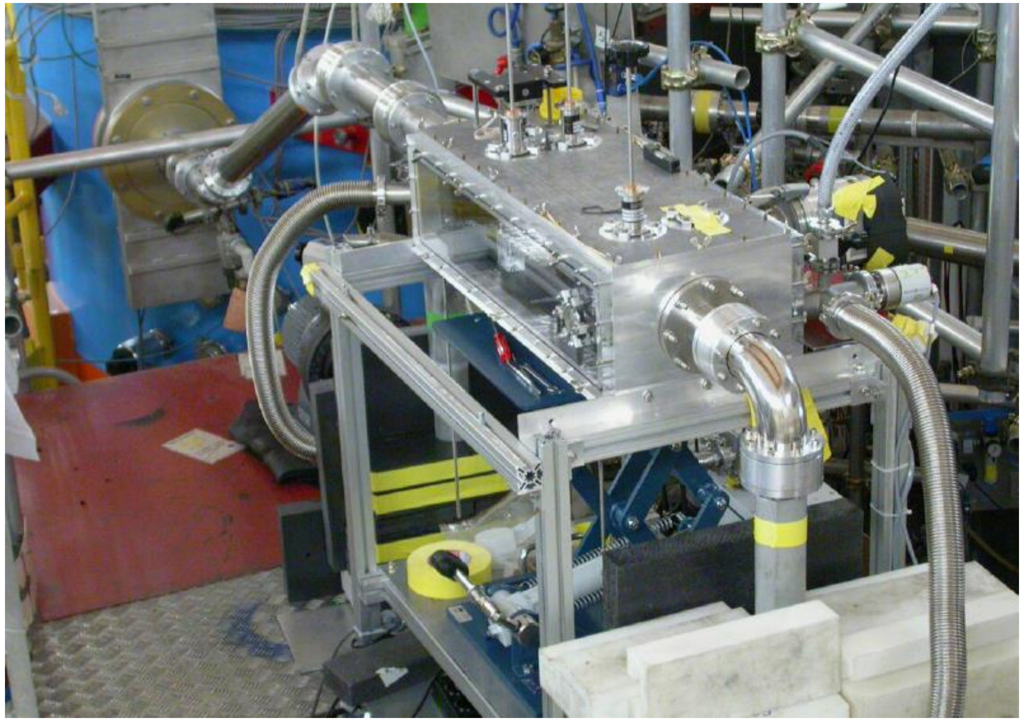
They can be stored in material bottles for long times (minutes).

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 $h = 0$?

UCN and gravity

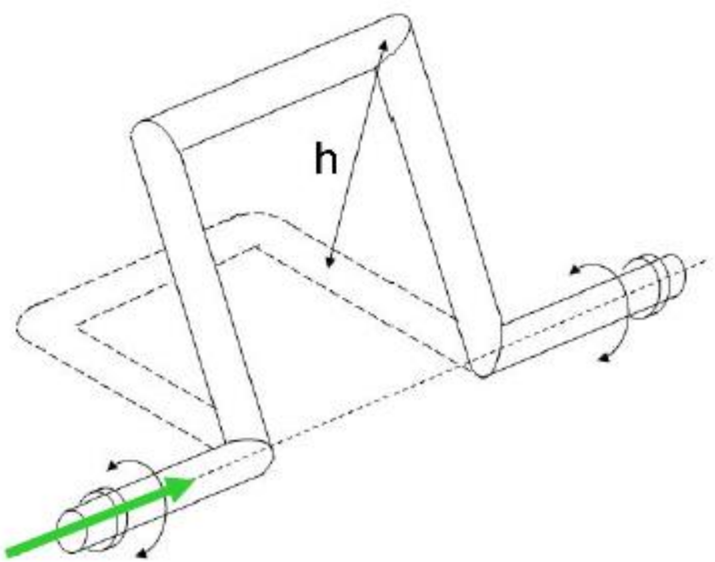
UCNs feel gravity

$$V(z) = mg\,z = 1.02\,\frac{\text{neV}}{\text{cm}} \times z$$

Very important for UCN techniques

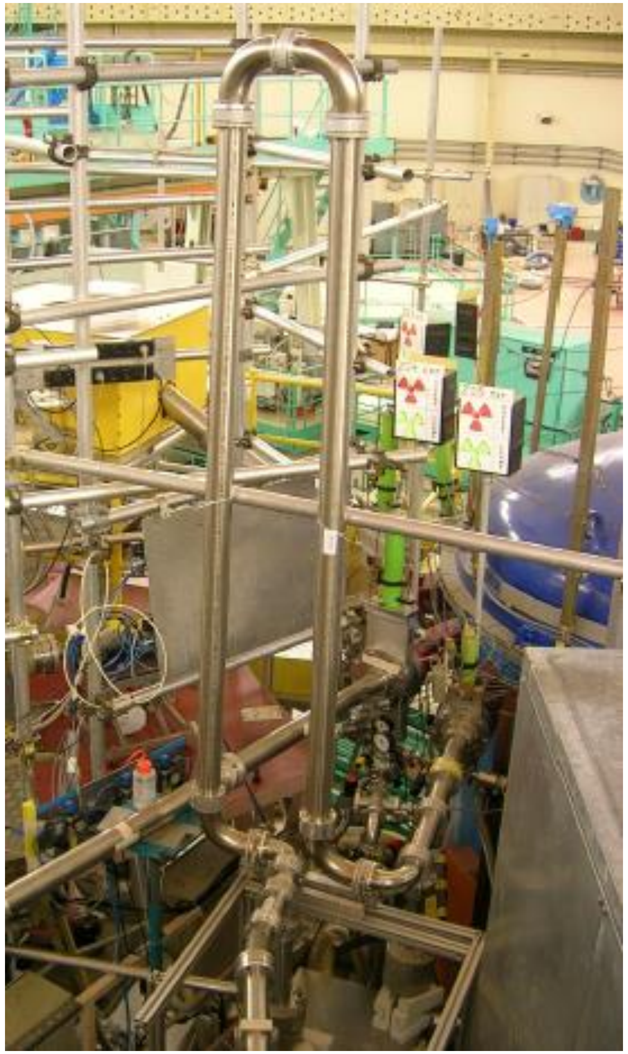
- We accelerate UCNs to detect them (otherwise they would bounce off the detector window).
- Some UCN traps do not need a roof.

Example: the “U” filter



To remove UCNs with energy E<80 neV,

Just set h = 80 cm



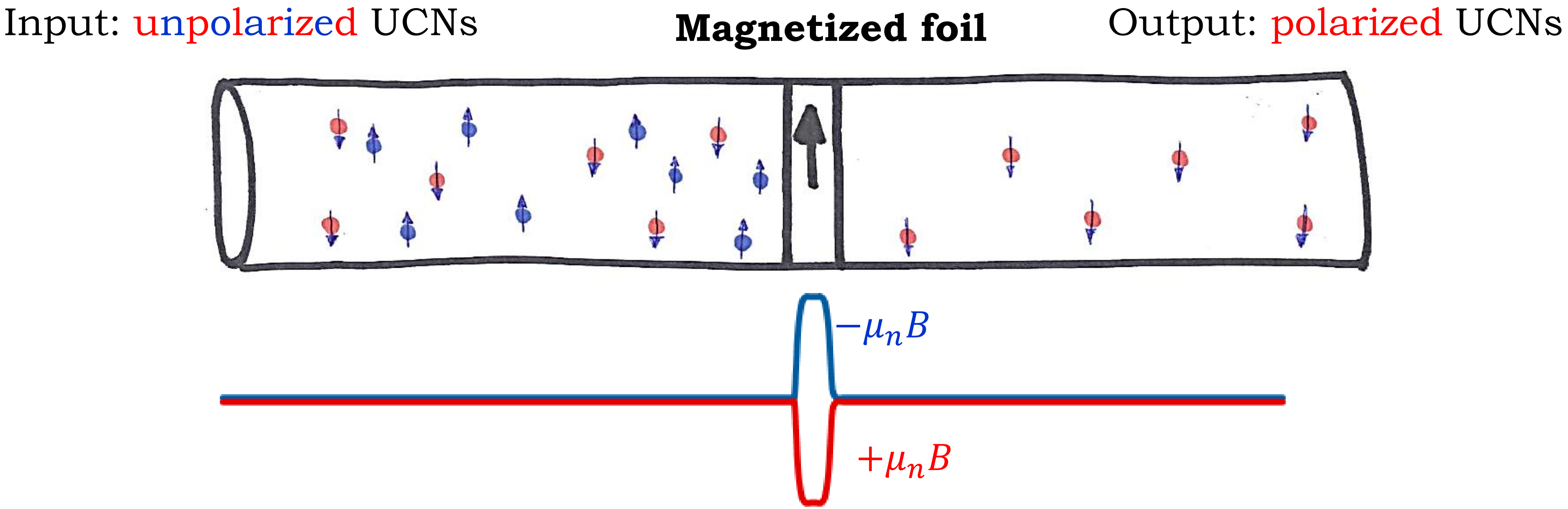
UCNs and magnetic fields

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 about UCN interactions

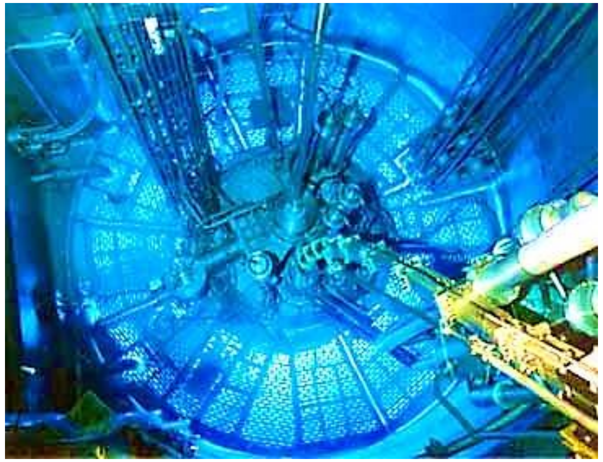
UCNs can be manipulated using

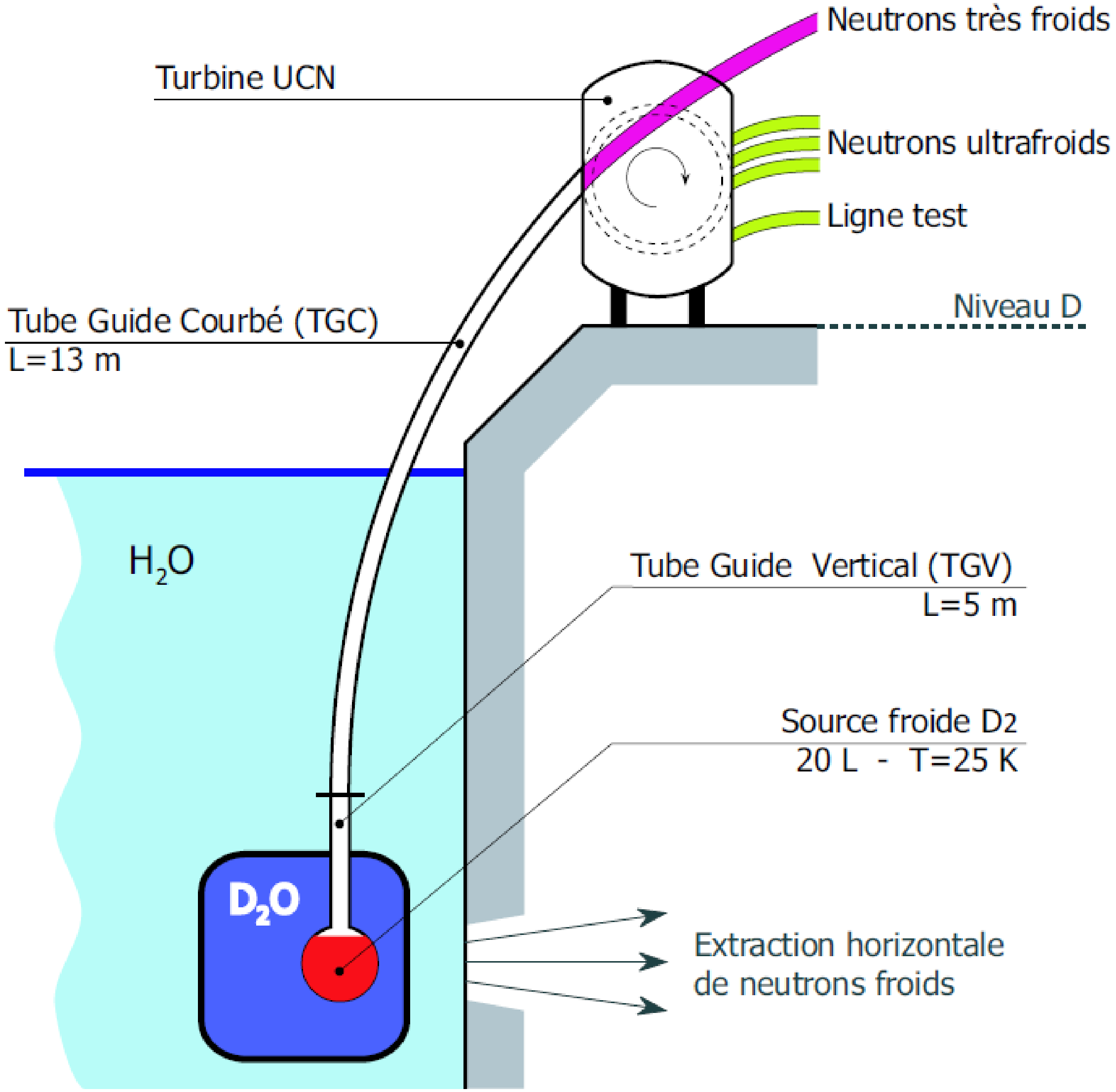
- The nuclear force (Fermi potentials ~ 100 neV)
- The gravitational force (1 m = 100 neV)
- Magnetic fields (1T = 60 neV)

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

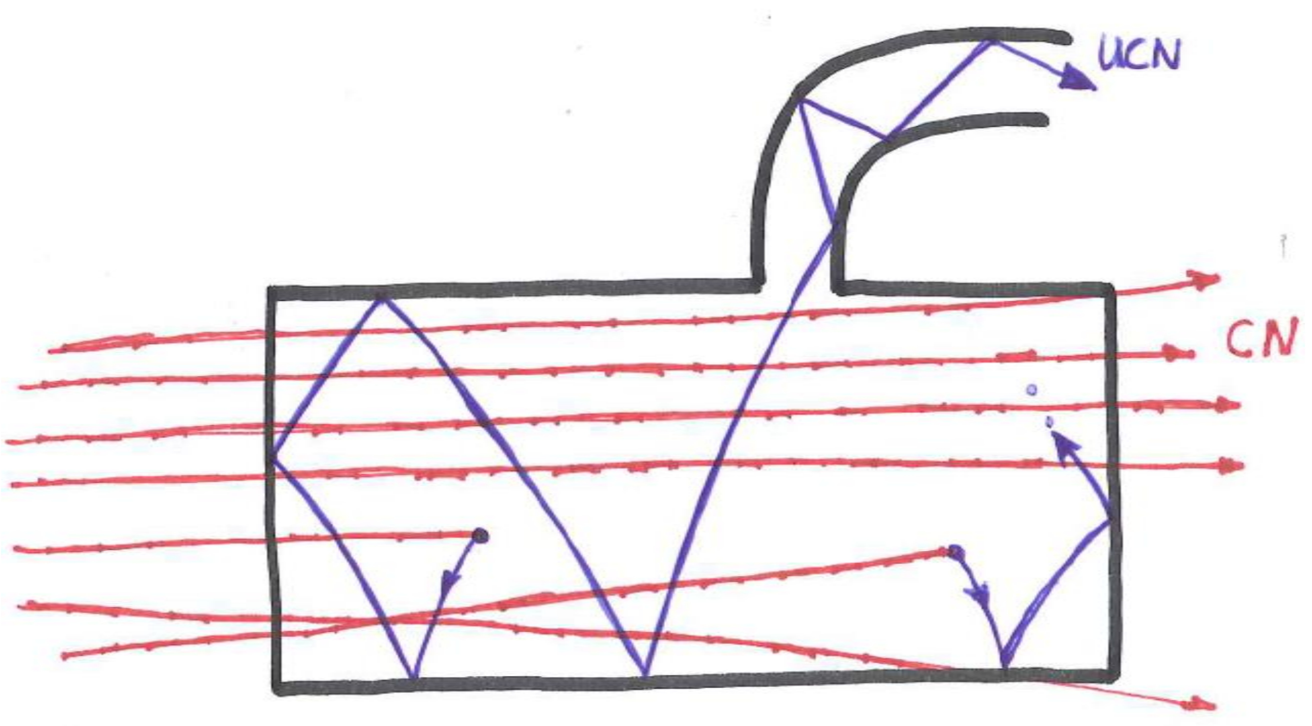
UCN source at ILL

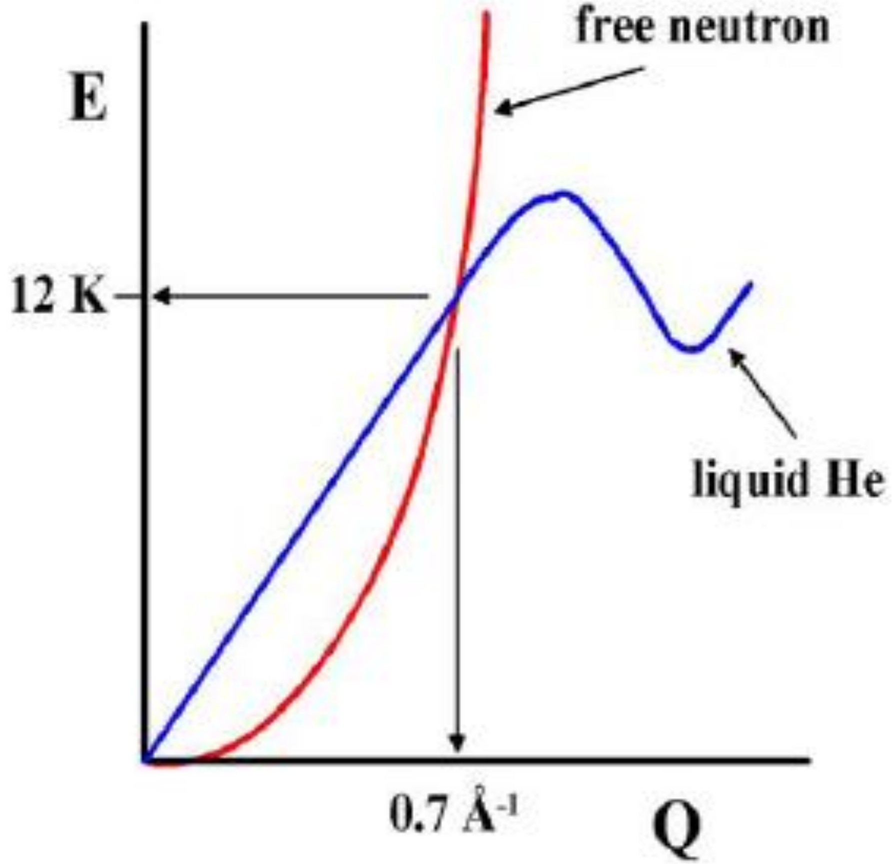




Turbine with counter rotating blades to decelerate the neutrons

Superthermal production of UCNs in superfluid He





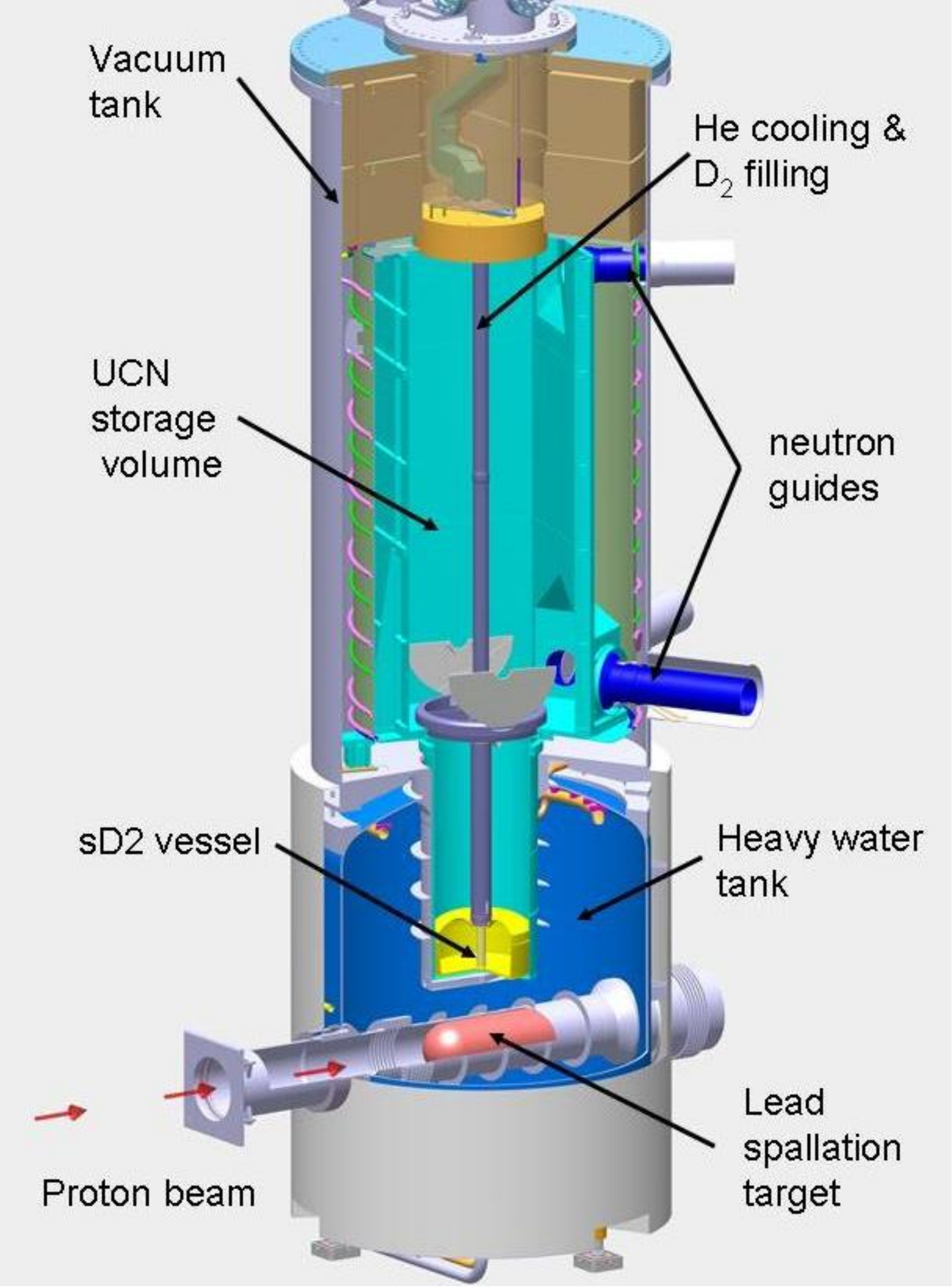
Input: intense beam of cold neutrons with a wavelength of 8.9 A

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)

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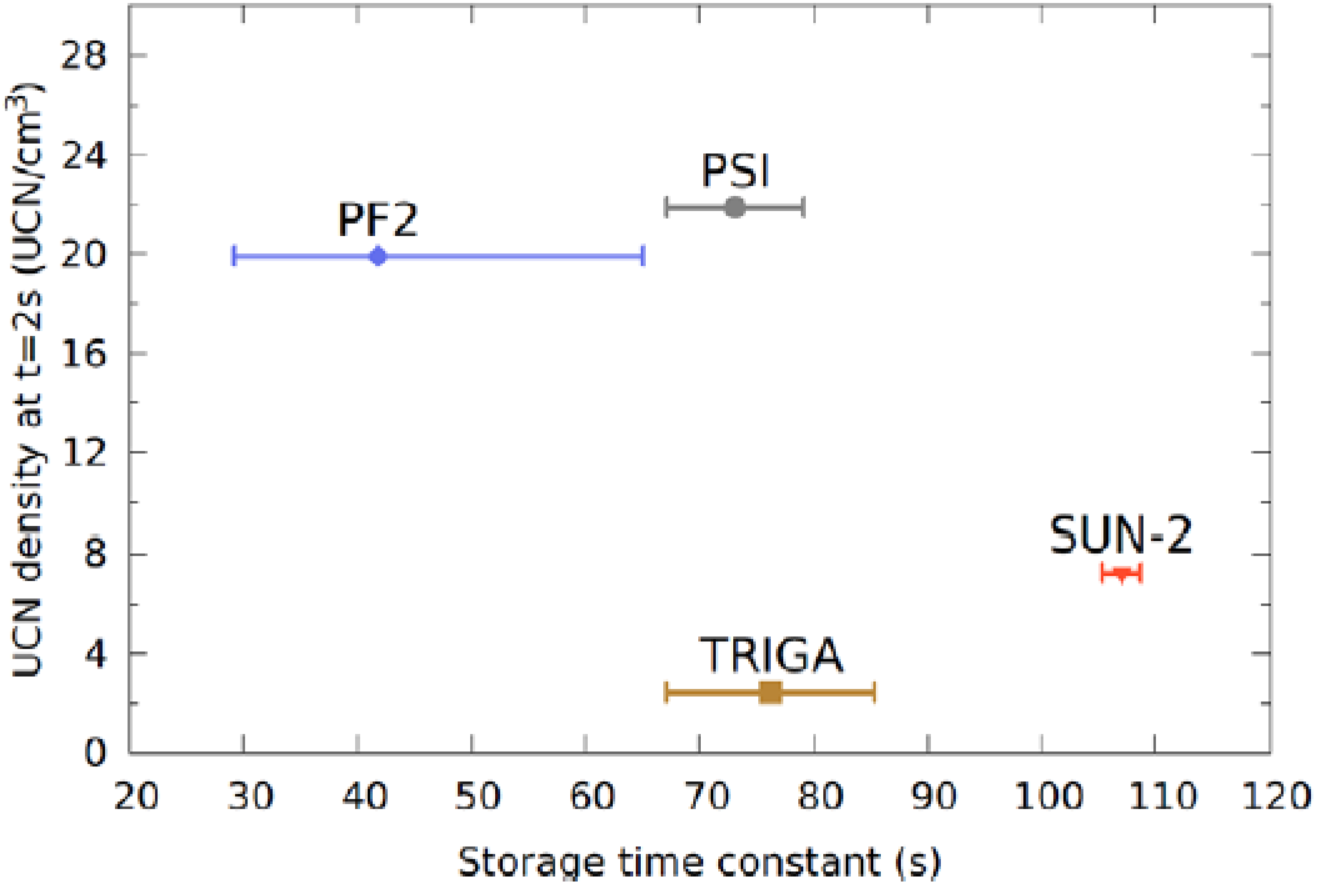
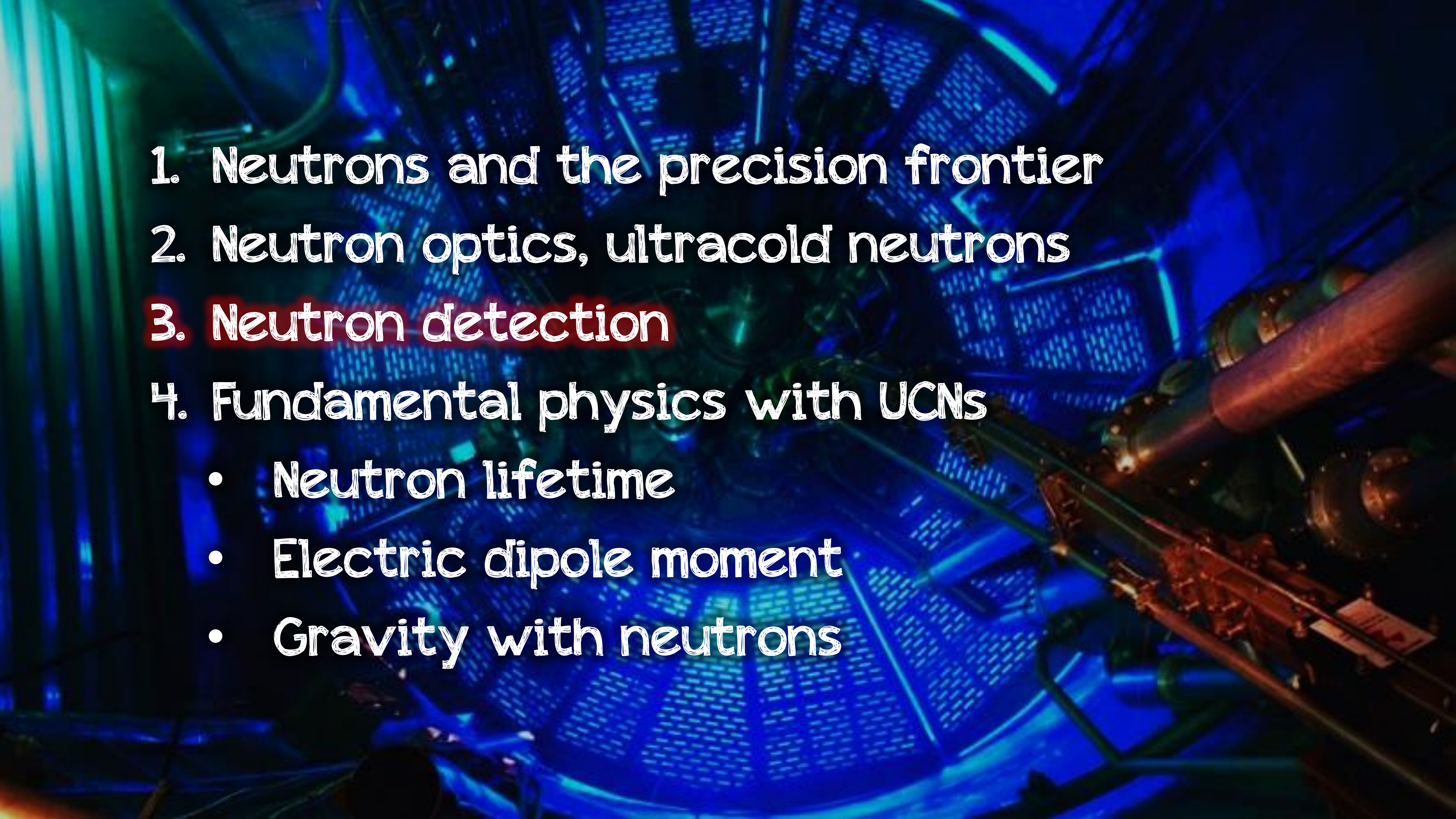
Comparison of ultracold neutron sources for fundamental physics measureme



Diter Ries standard stainless steel bottle



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Importance of neutron detection

- Monitoring in nuclear reactors
- Radiation safety
- Detection of special nuclear materials (^{233}U and ^{239}Pu)
- Cosmic ray detection, monitoring the flux
- Neutrino detectors $\nu + p \rightarrow e^{+} + n$
- Etc…

Remember: You can't directly detect neutrons…
Neutrons should be converted in a detectable particle first.

Neutron inelastic reactions

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

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

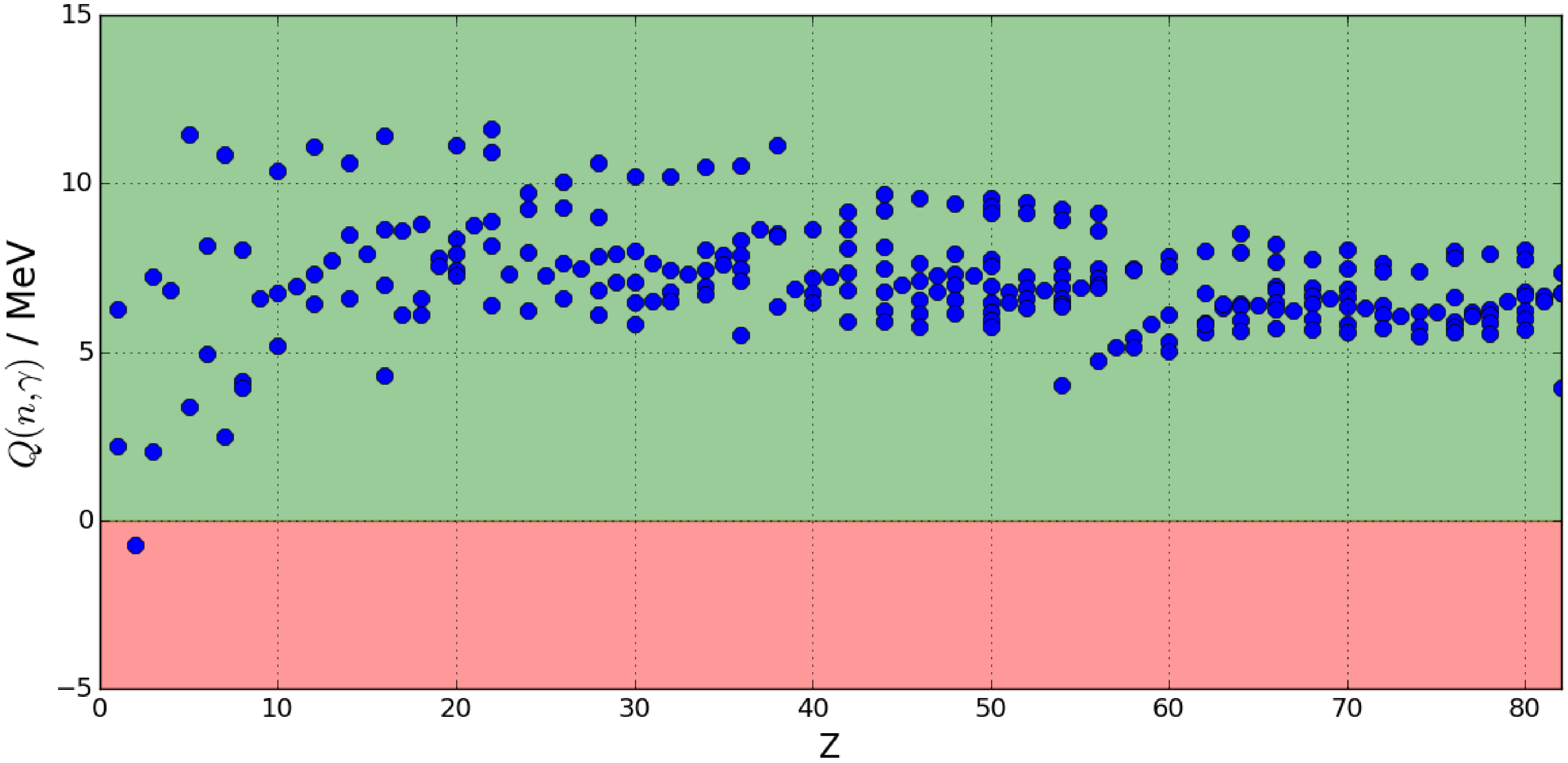
THE 1/v LAW

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

One finds in tabulated neutron data the thermal cross sections

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

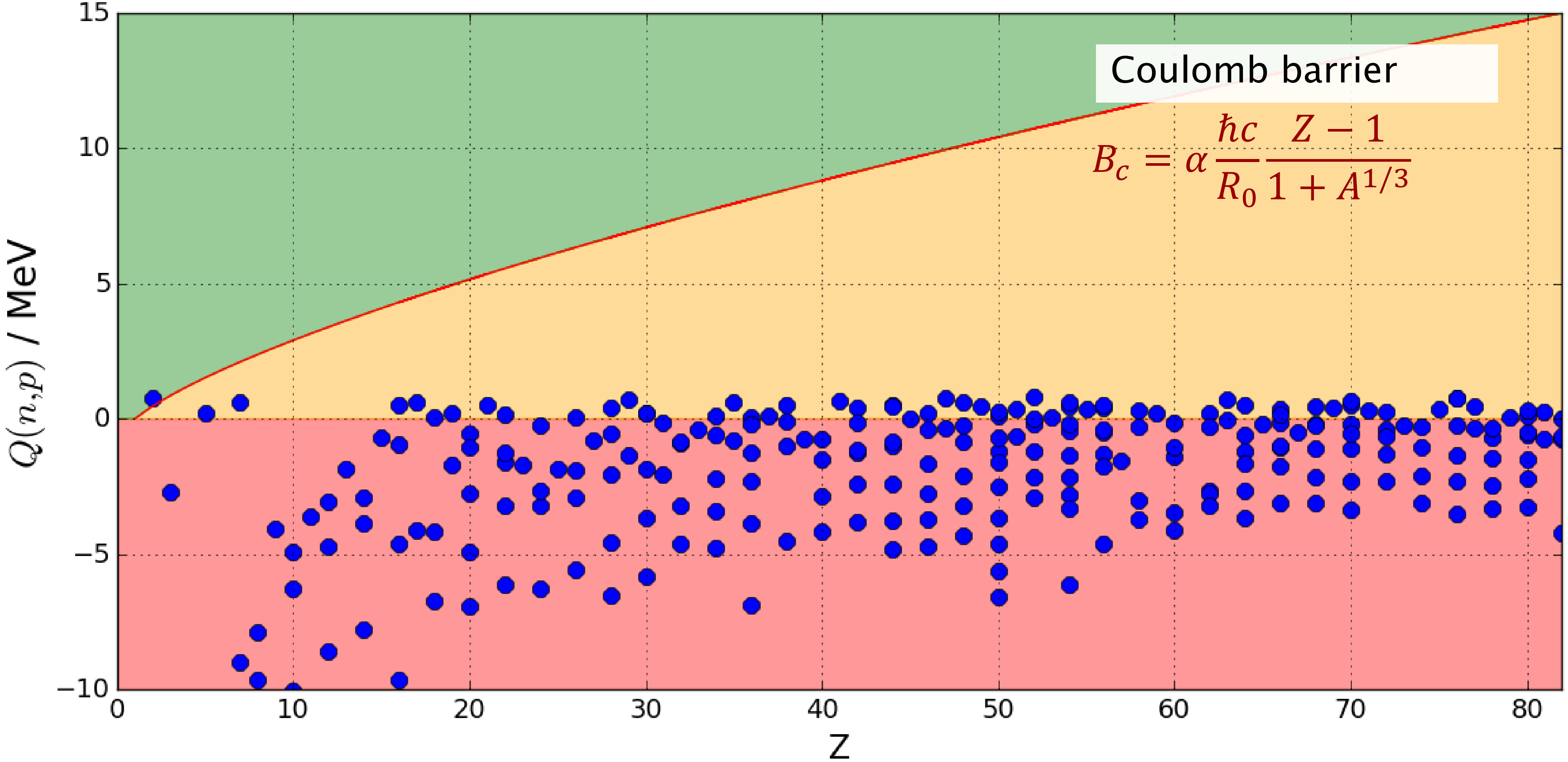
(n,γ) capture: $n + {}^{A}_{Z}\mathrm{X} \rightarrow \gamma + {}^{A+1}_{Z}\mathrm{X}$



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

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

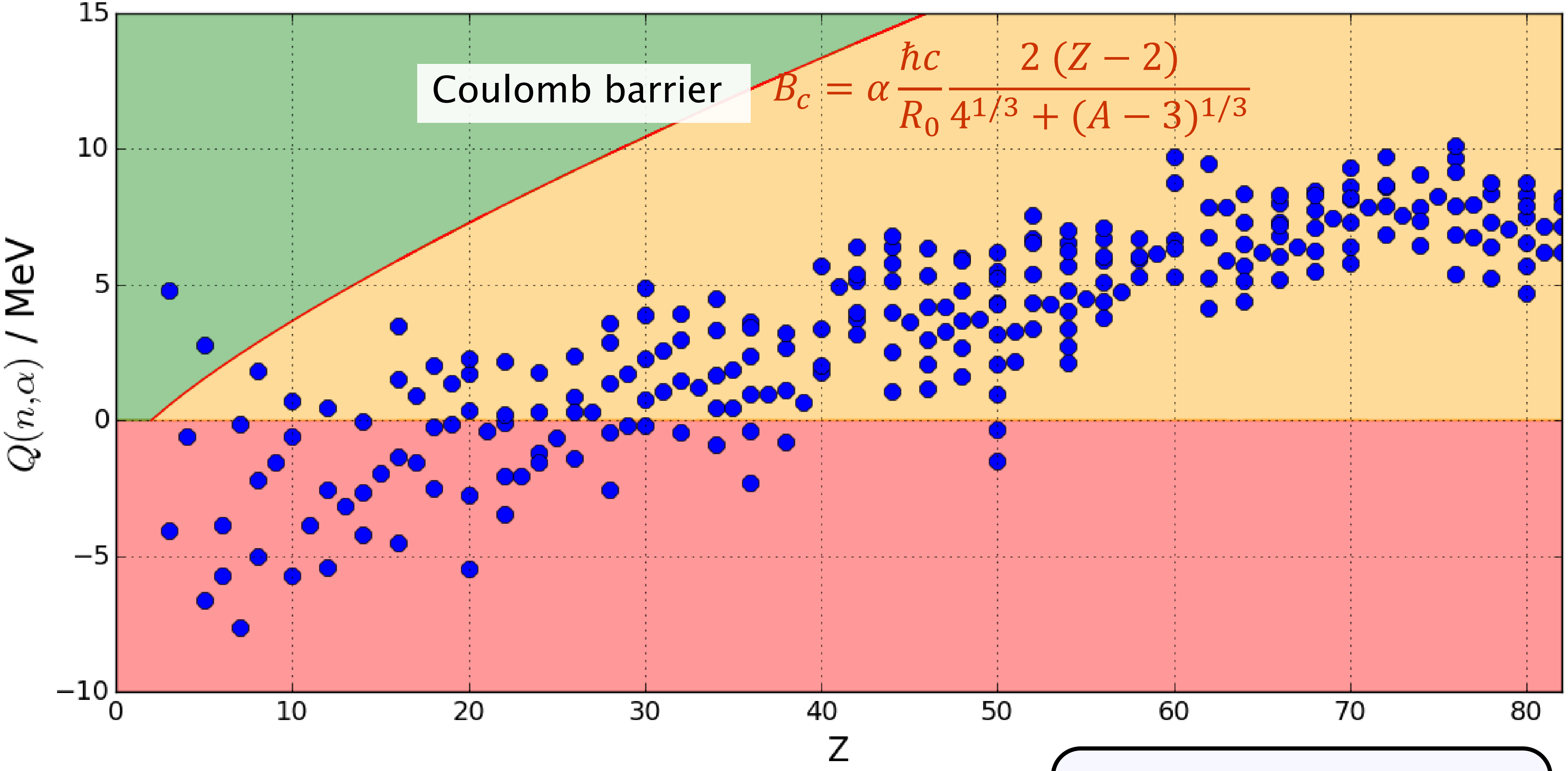


Energy release $Q = (m_X + m_n - m_p - m_Y)c^2$

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

Only one possibility
$n + 3\mathrm{He} \rightarrow p + t$

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



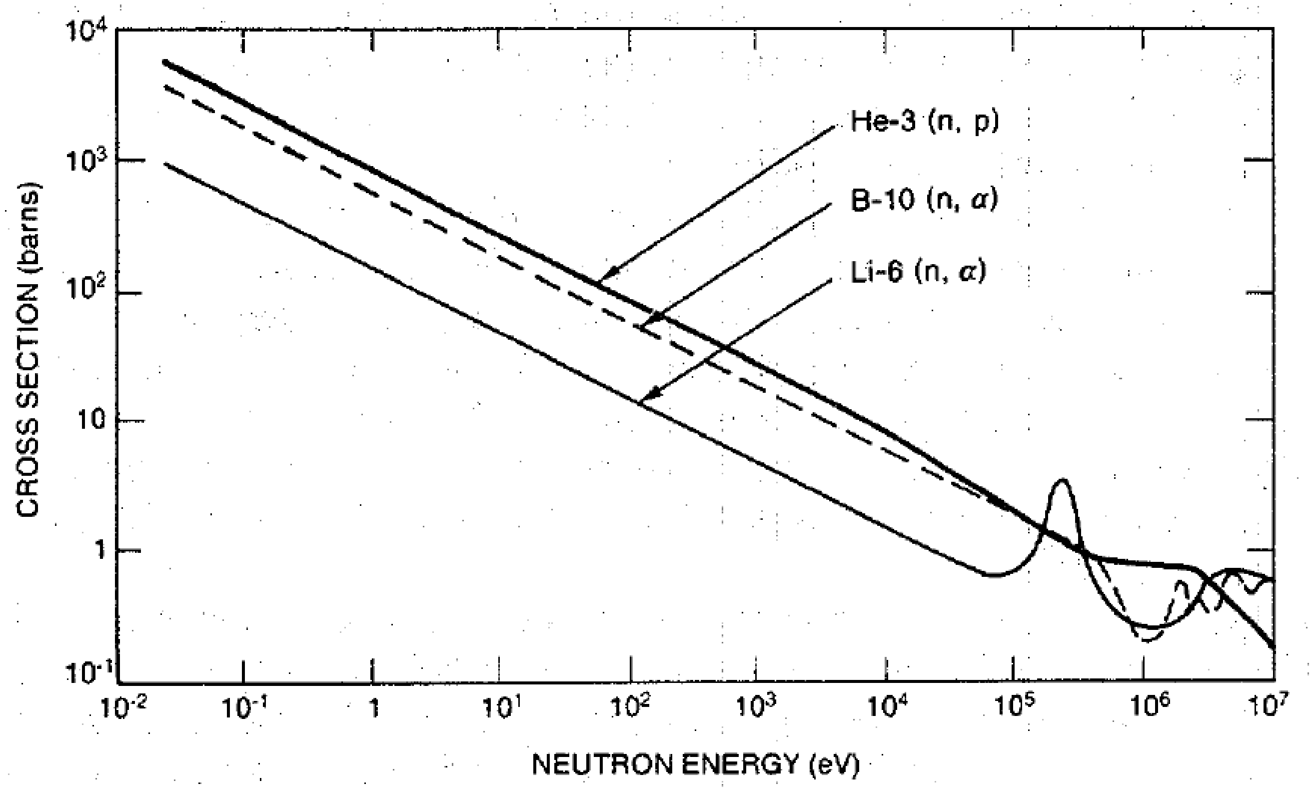
Energy release $Q = (m_X + m_n - m_\alpha - m_Z)c^2$
Slow neutrons undergo (n,α) reaction only if $Q > B_c$

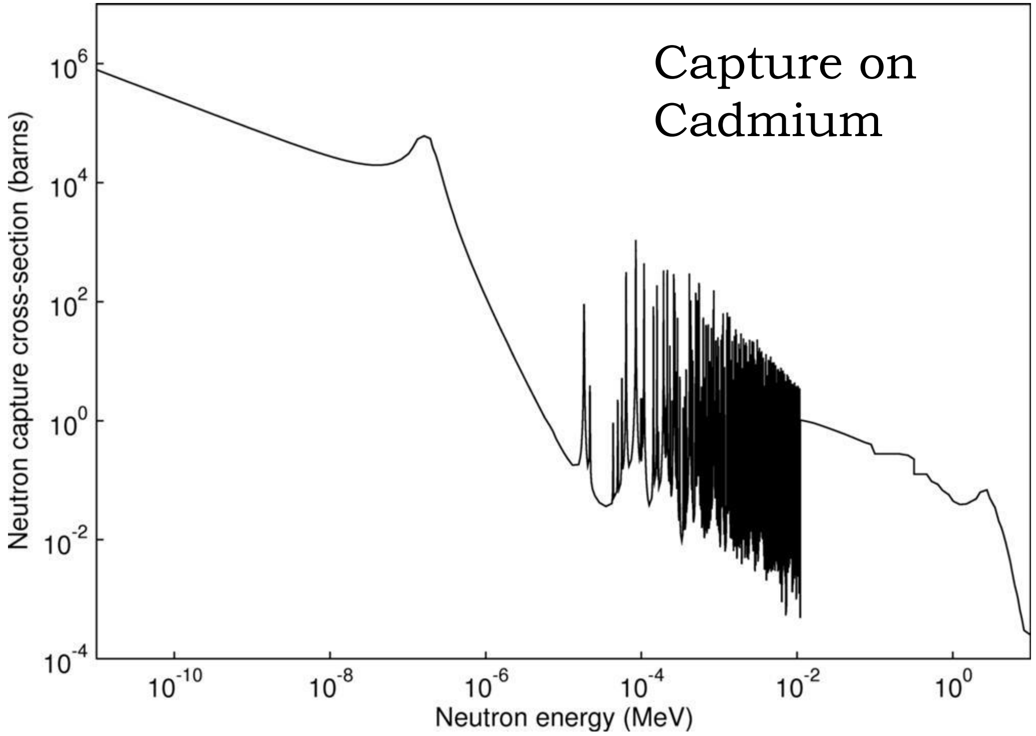
Only two possibilities

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

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

Validity of the 1/v law





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

Three possible neutron convertors

	^{3}He (n,p)	**^{6}Li (n,α)**	**^{10}B (n,α)**
Abundance	0.014 %	7.6 %	19.9 %
σ^{th}	5330 barn	937 barn	3837 barn
Kinetic energy of products	p 764 keV	**α** 2.056 MeV	**α** 1.47 MeV
	t 191 keV	t 2.728 MeV	**Li** 0.84 MeV
			γ 0.48 MeV

Gaseous detectors

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

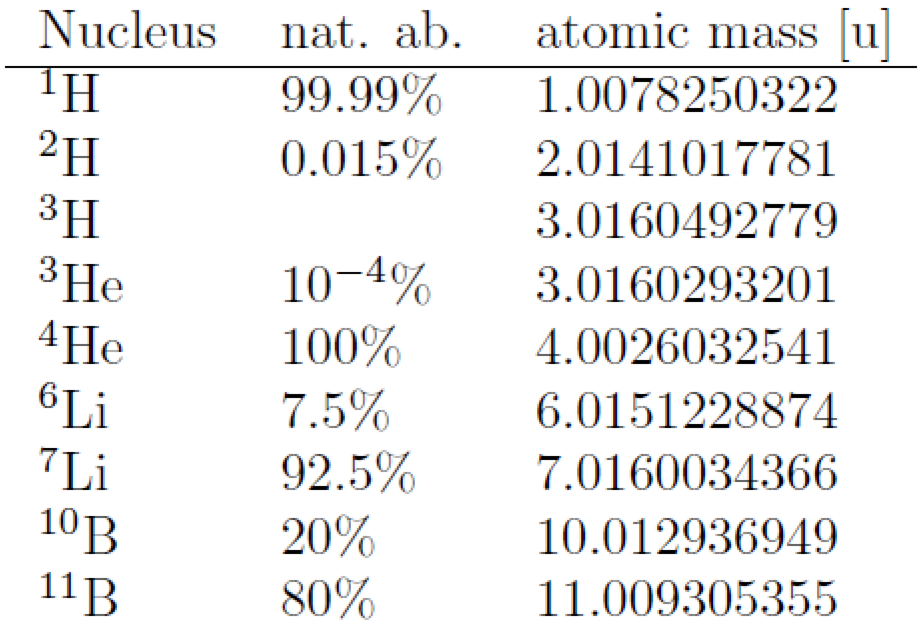
Solid detectors

scintillators **LiF**

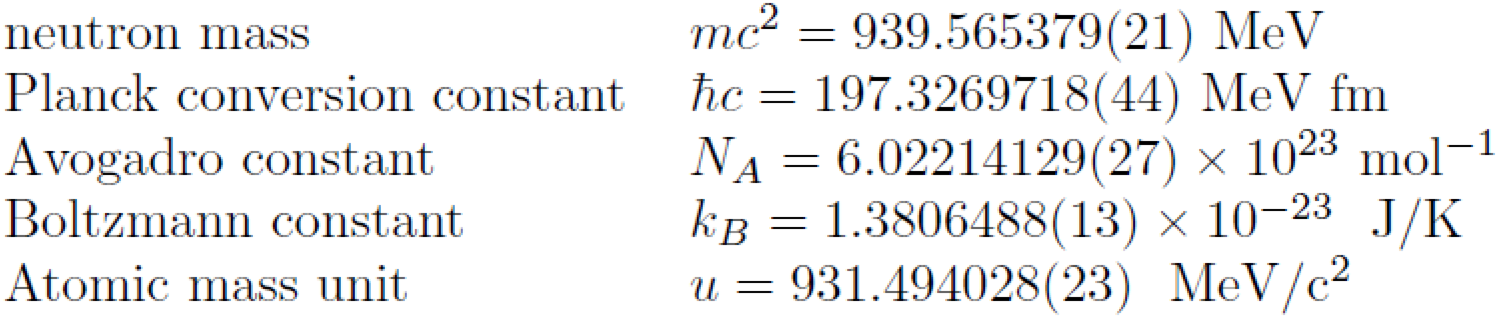
silicon detectors with Boron solid conversion layer

Exercises

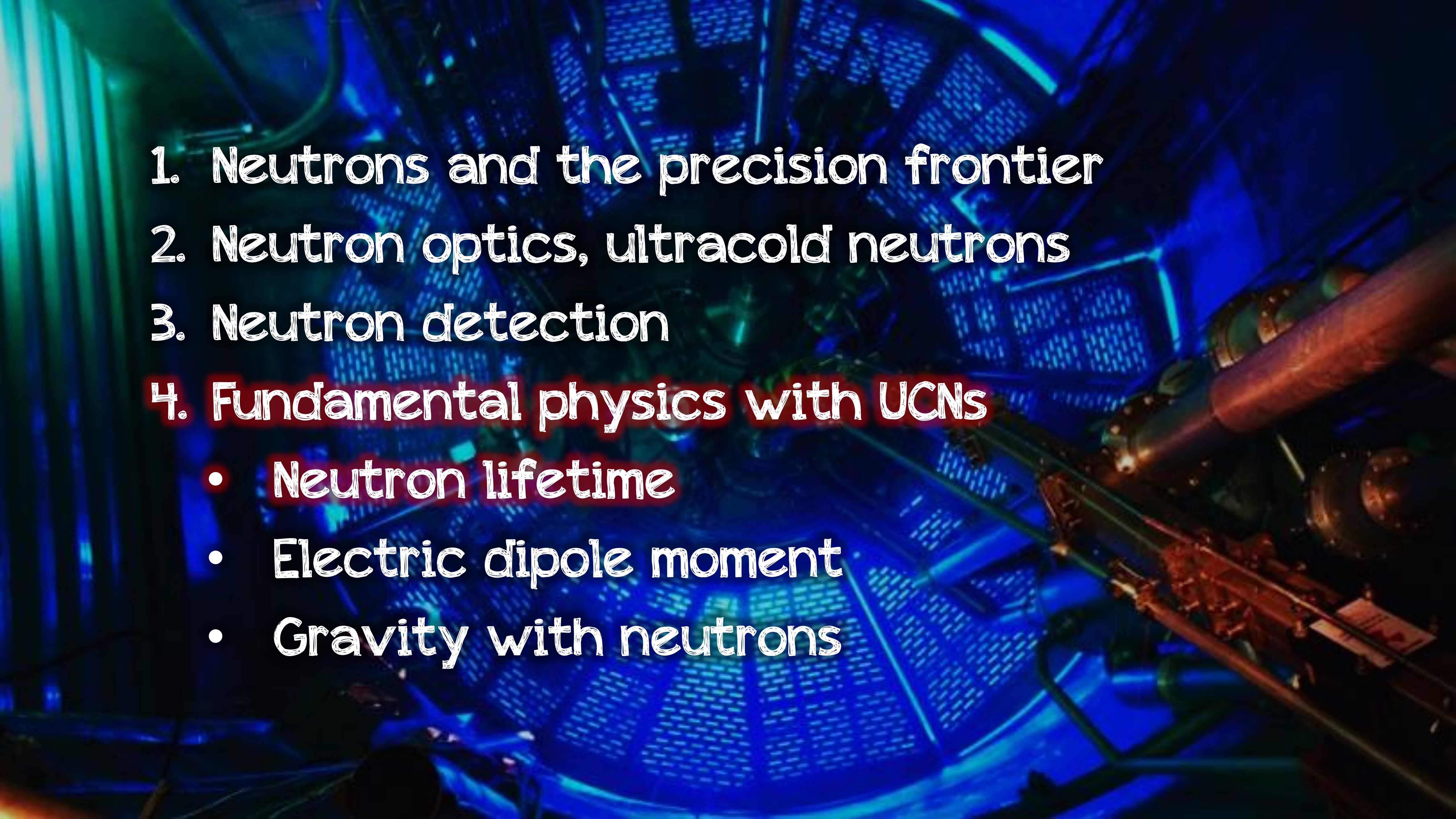
1. Calculate the kinetic energy of the products for the reaction
   $n + 3\text{He} \rightarrow t + p$
2. Consider a 1 cm thick multiwire proportional chamber filled with 1 bar of ^{3}He. What is the detection efficiency for thermal neutrons?
3. The same detector is filled with 10 mbar of ^{3}He, what is the detection efficiency for UCNs? 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



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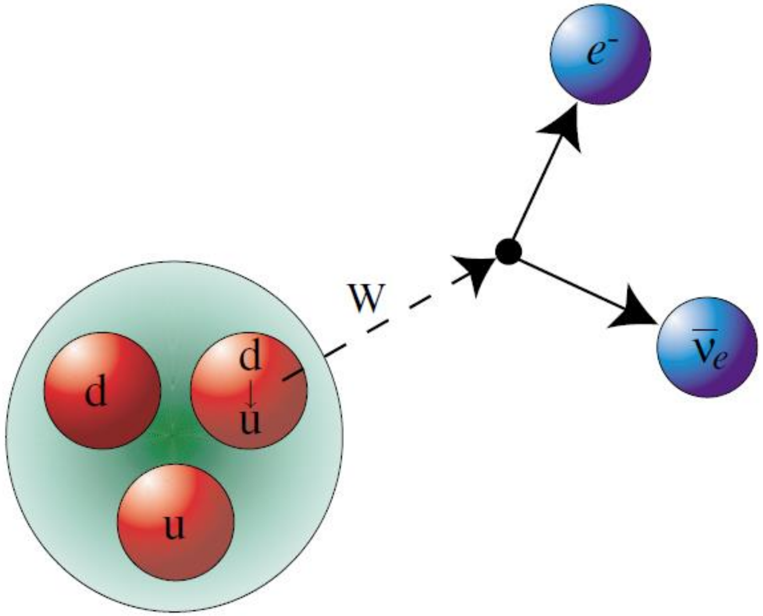
The neutron beta decay lifetime



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

Free neutron lifetime

$$\tau_n = (880.2 \pm 1.0)\ \mathrm{s}$$

[PDG 2018]

- ***Particle physics***

extracting CKM matrix element

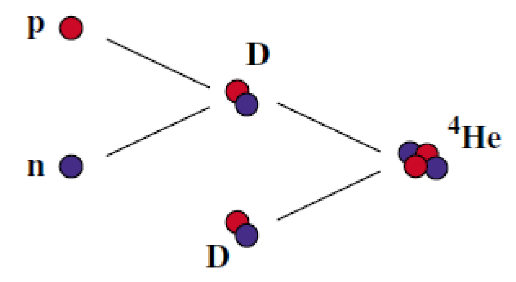
- ***Astrophysics and Neutrinos***

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.

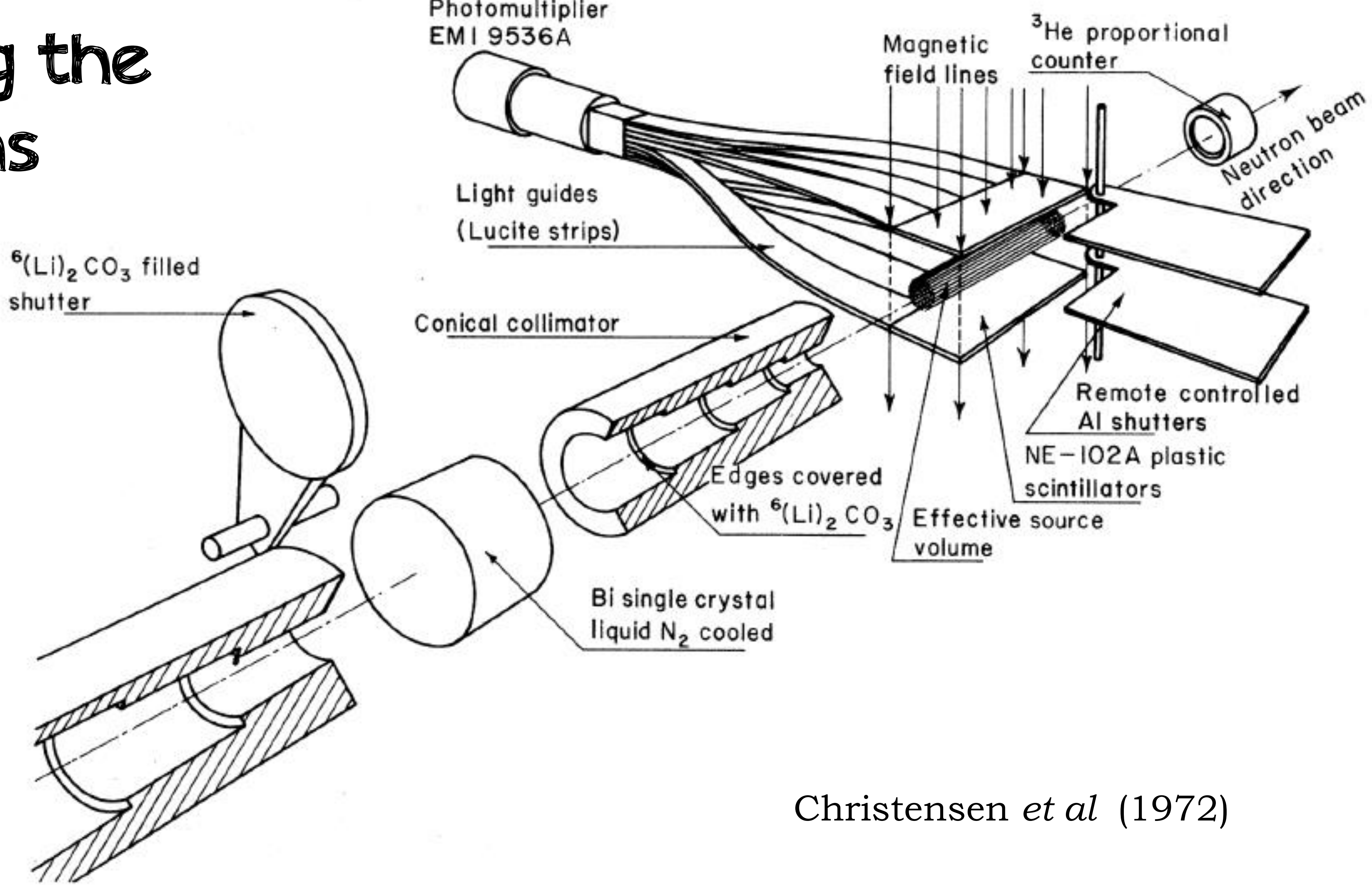
$$-\frac{dN}{dt} = \frac{N}{\tau_n}$$

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.

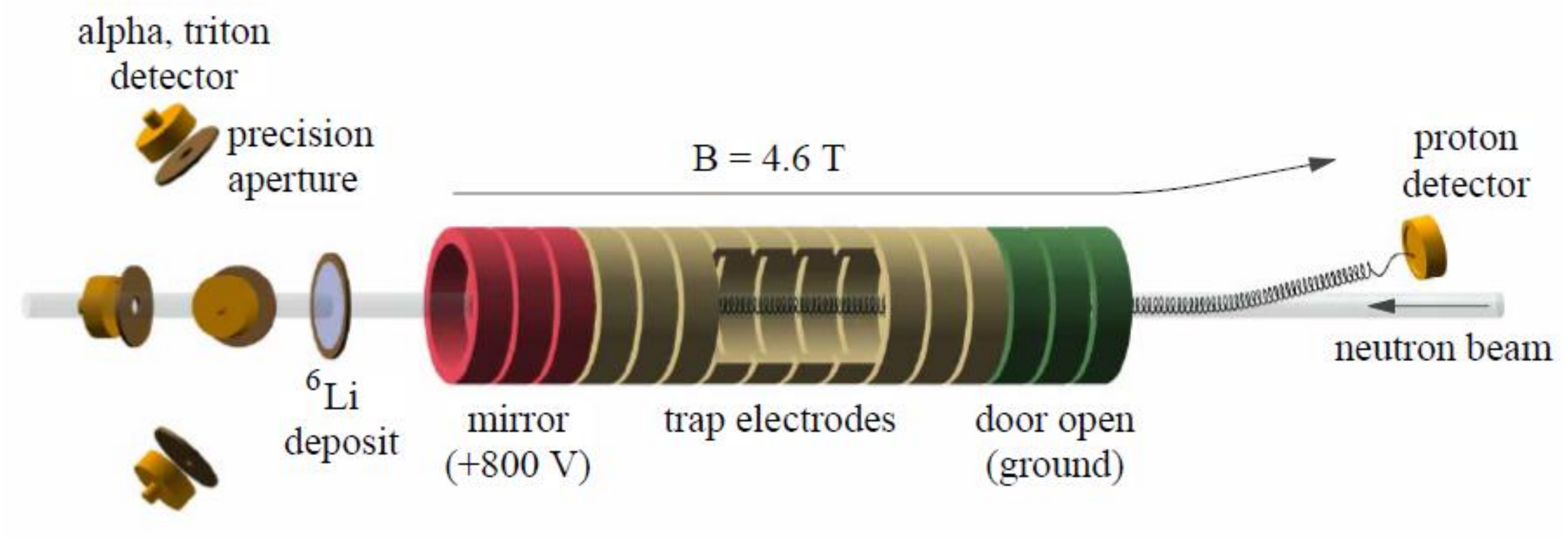
$$N(t) = N(0)e^{-t/\tau_n}$$

Early beam method: counting the electrons



Christensen *et al* (1972)

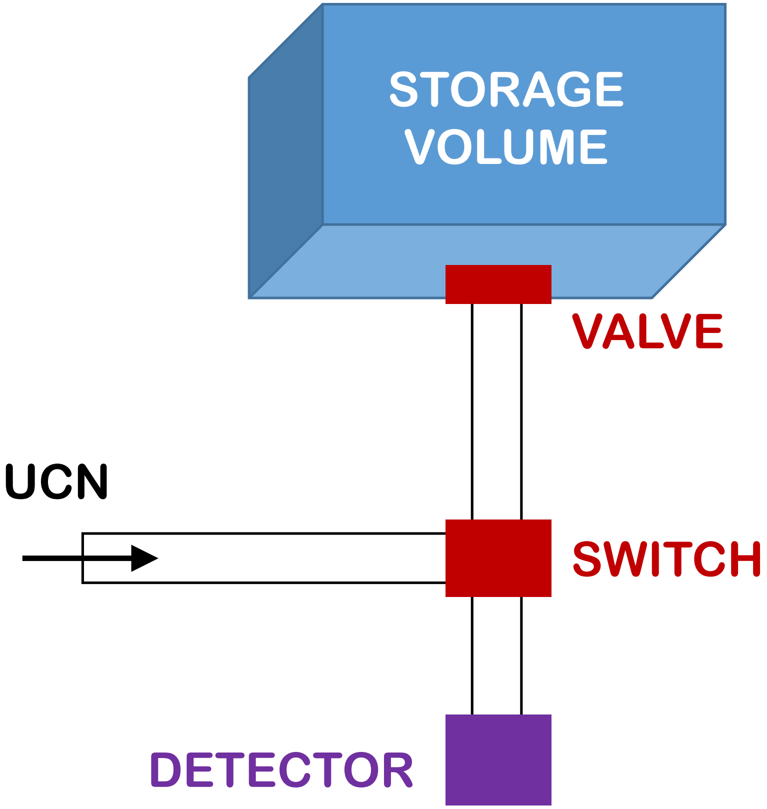
Modern beam method: counting the protons



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

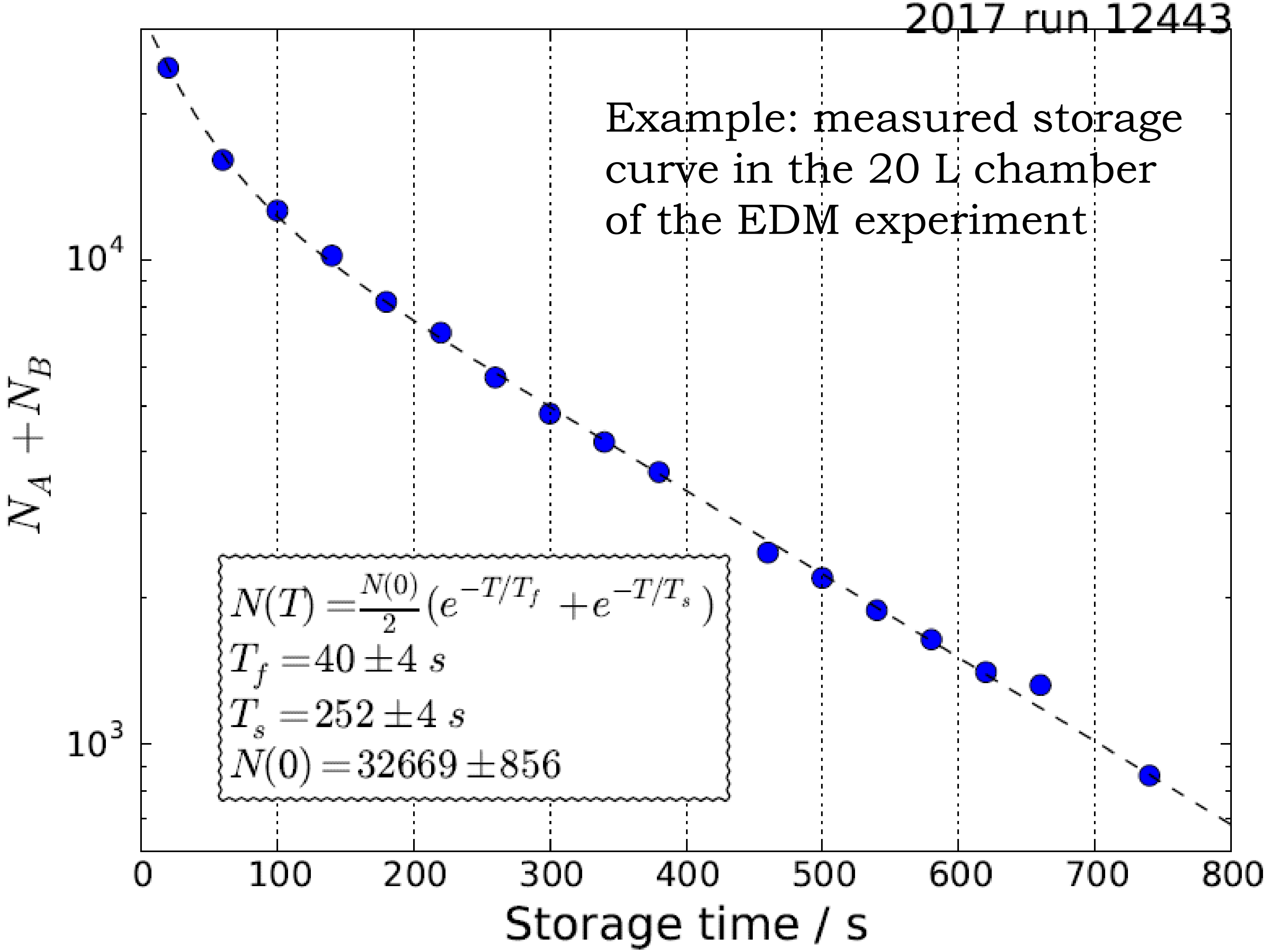


Typical sequence

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.

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

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

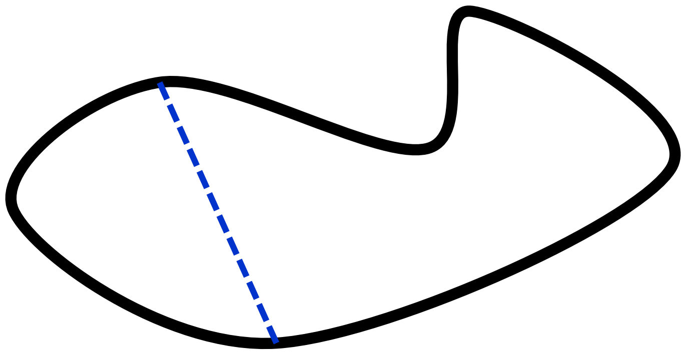
$$f = \frac{v}{\lambda} \approx 10\ \mathrm{Hz}$$

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

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

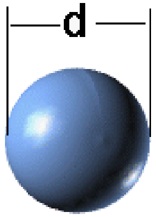
Useful Clausius law

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

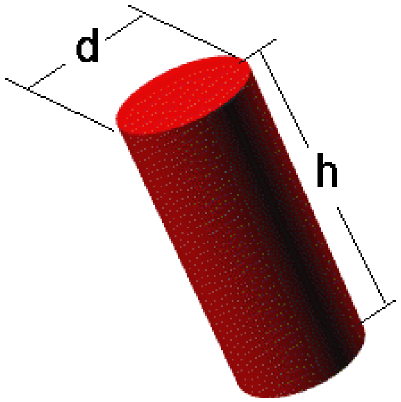


When mechanical equilibrium is achieved (isotropic velocity distribution) the mean free path between wall collisions is

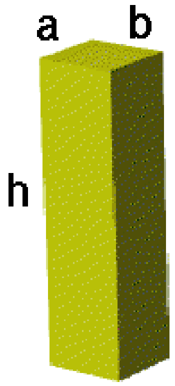
$$\lambda = \frac{4\,V}{S}$$



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



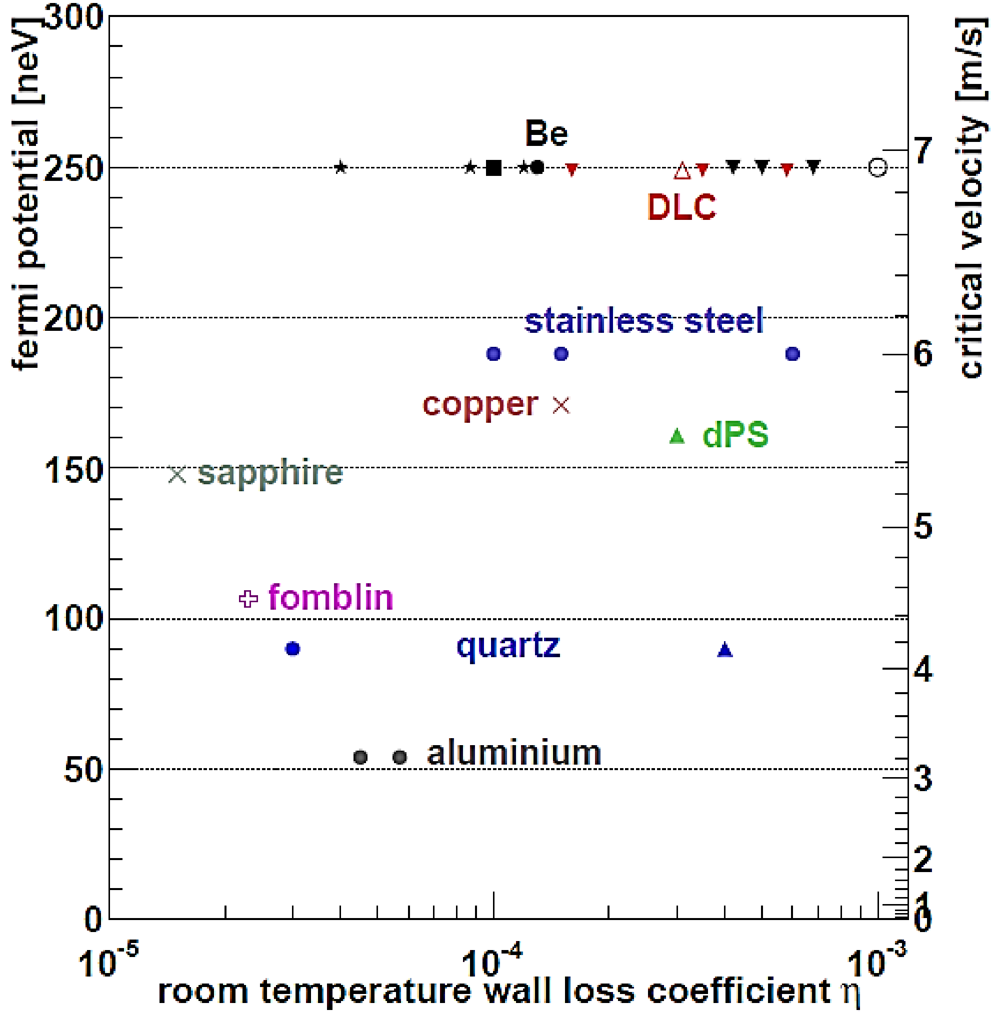
$$\lambda = \frac{dh}{d/2 + h}$$



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

Results valid without gravity!

More on wall losses (complicated topic)

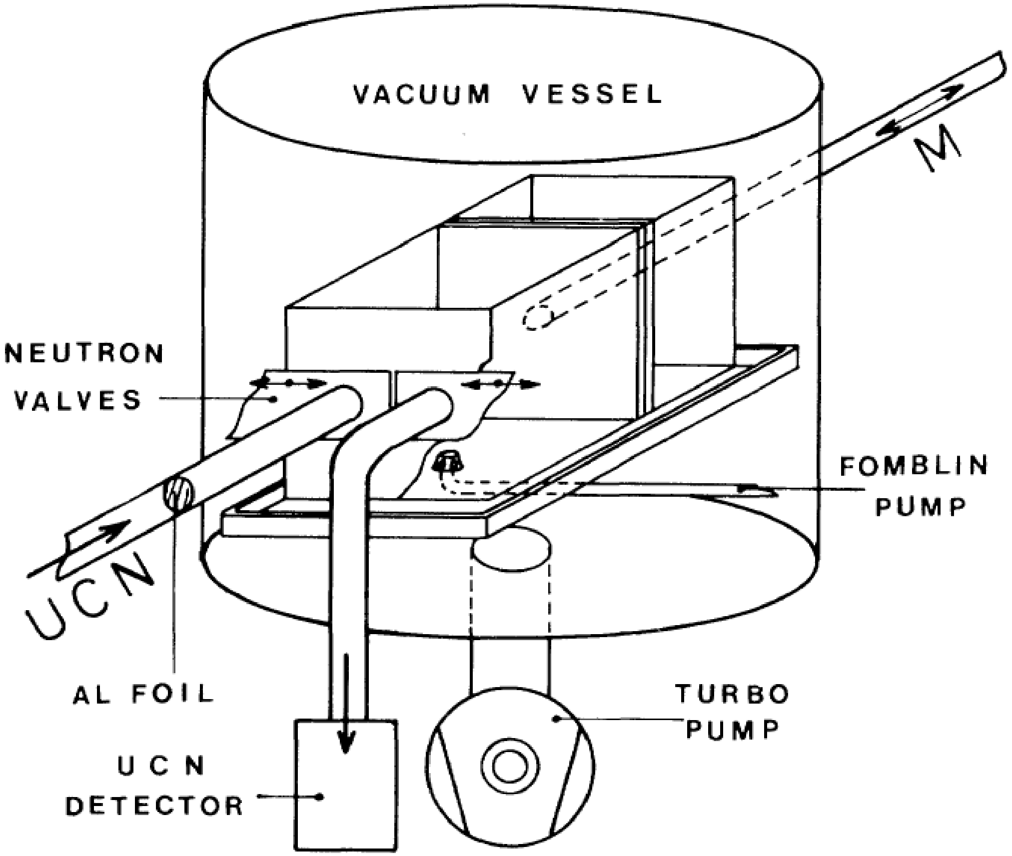


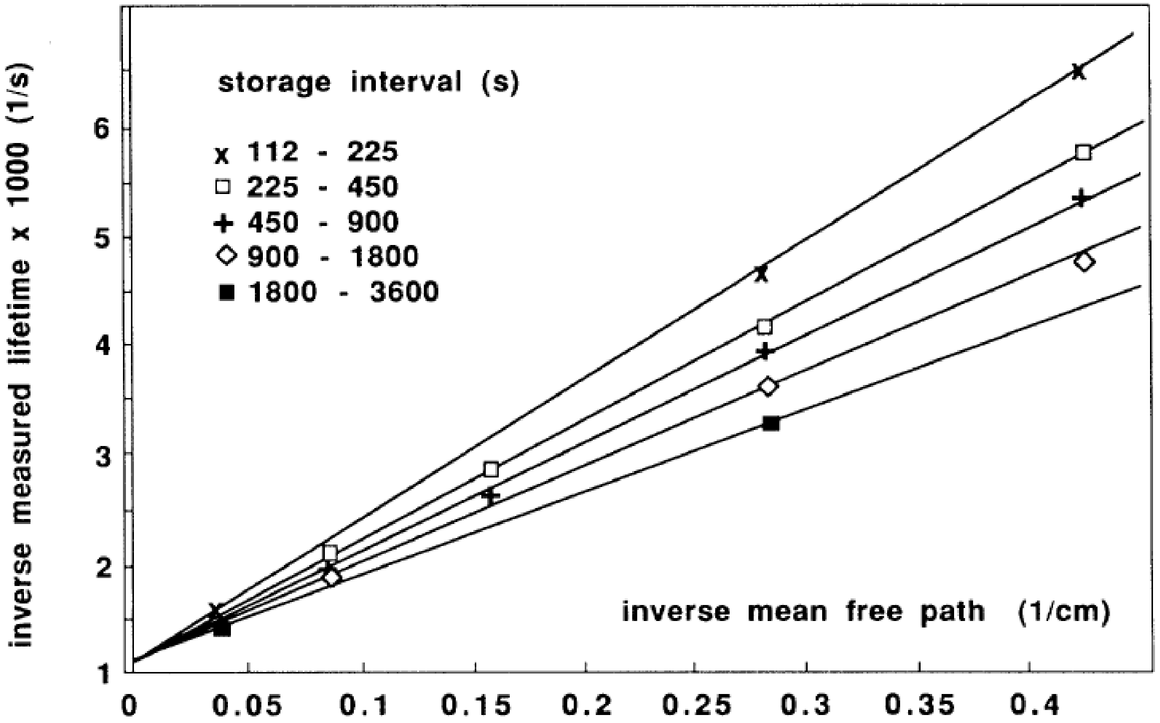
- The wall loss probability is energy-dependent

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

- 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)

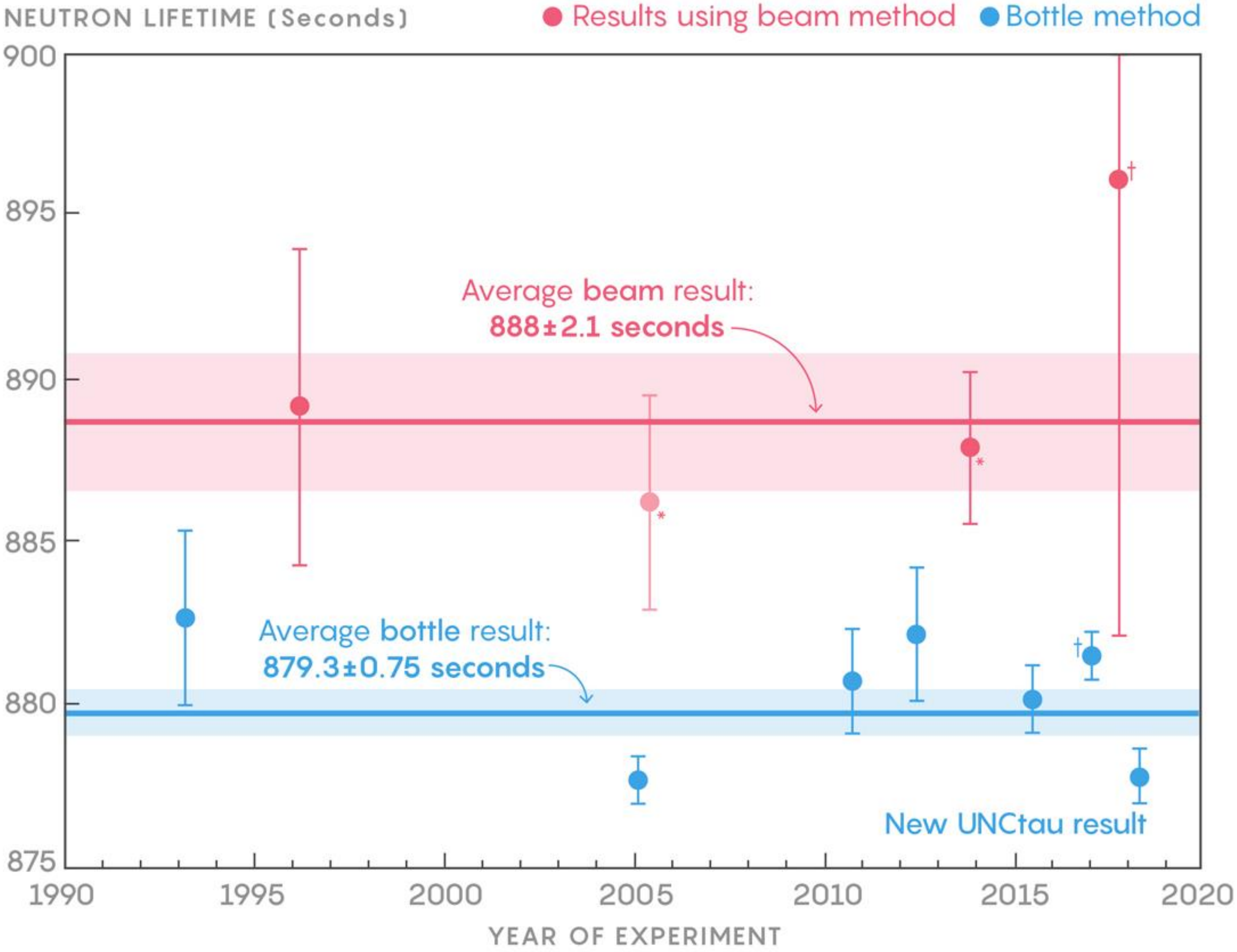
Example: MAMBO 1 (ILL, 1989)





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

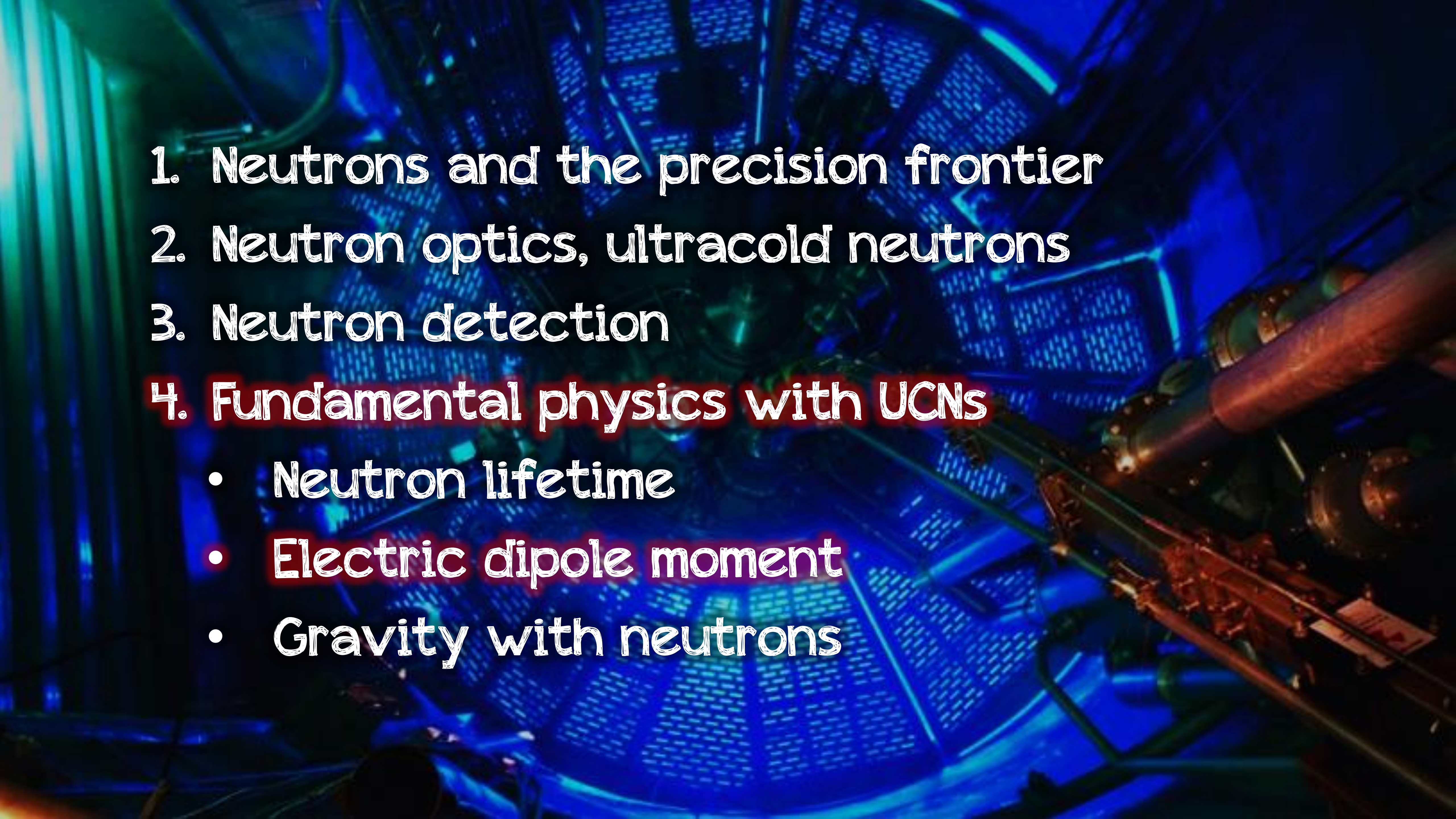
Current status on the neutron lifetime



*Nico result (2005) was superseded by an updated and improved result, Yue (2013);

There is a persisting **discrepancy of 8 s (3.9 σ)** between the bottle method combination and the beam method combination.

To be continued…



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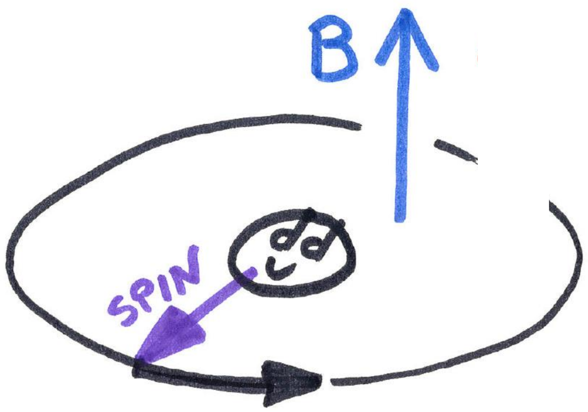
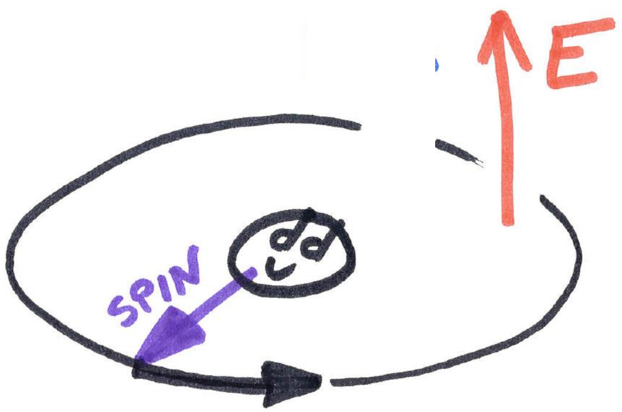
Electric and Magnetic Dipoles



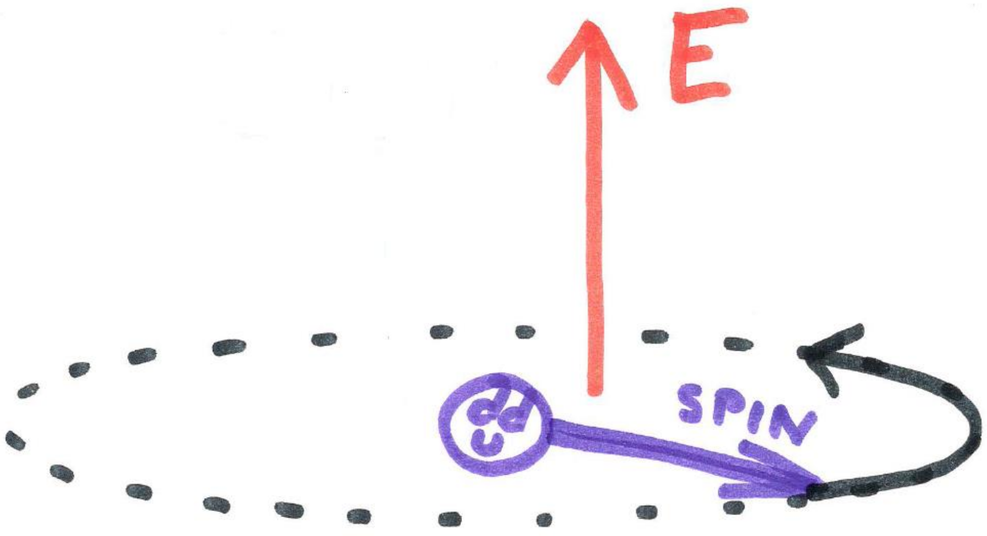
Spin precession due to the magnetic dipole μ_n

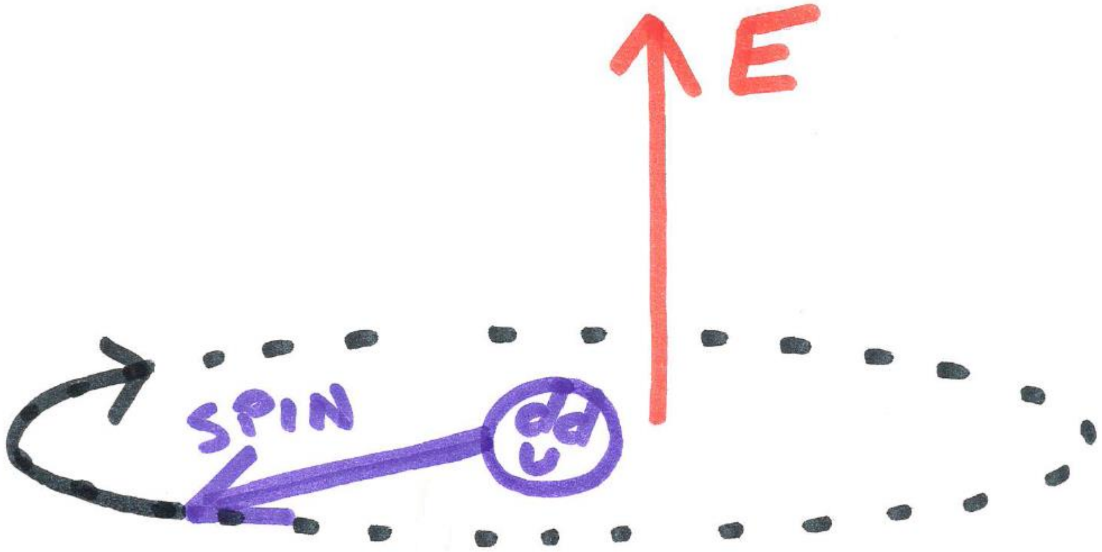


Spin precession due to the electric dipole d_n?

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

Violation of time reversal



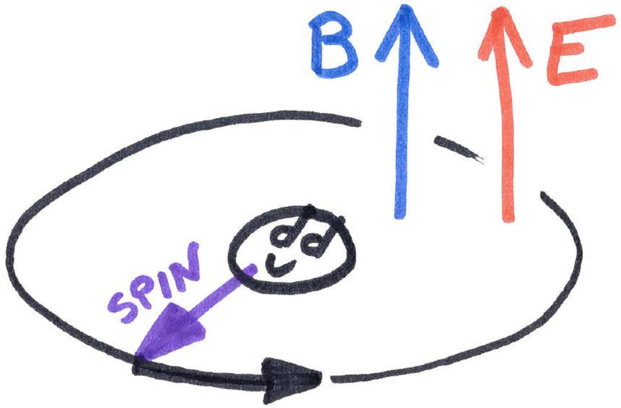


>> PLAY >>

<< REWIND <<

If $d \neq 0$ the process and its time reversed version are different. $\Rightarrow$ **Violation of T** $\xRightarrow{\text{CPT}}$ **Violation of CP**

Hunting the neutron Electric Dipole Moment

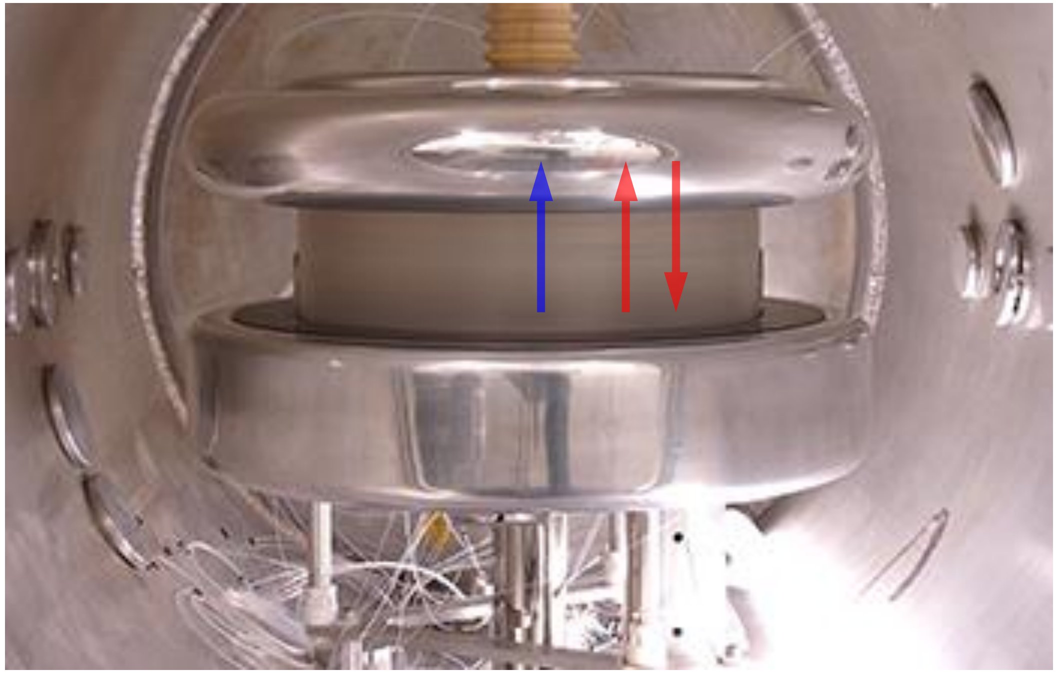


One measures the neutron Larmor precession frequency f_L in weak Bagdetic and strong Electric fields

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

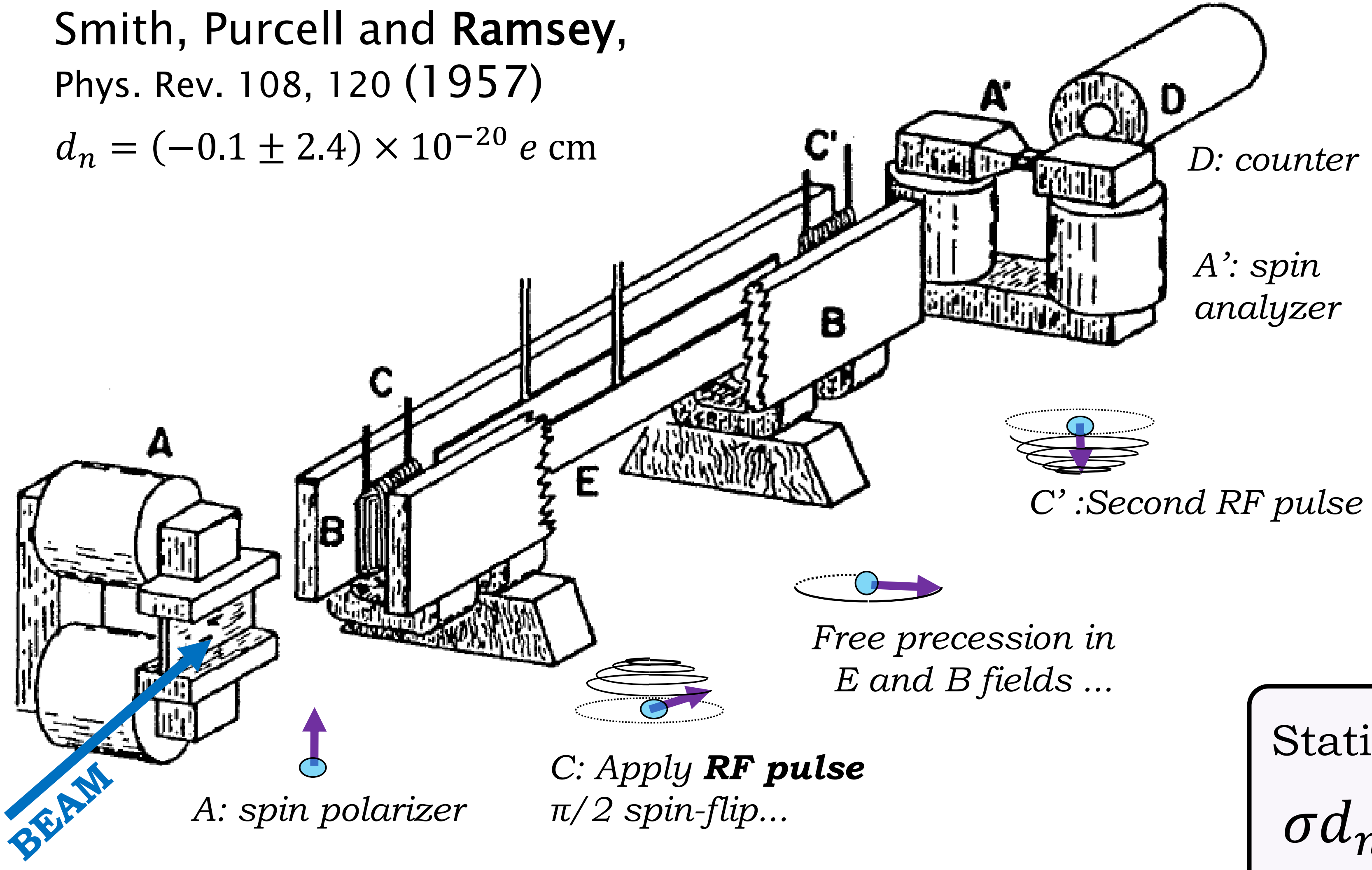
Neutron EDM

The most sensitive experiments use Ramsey’s method with polarized ultracold neutrons stored in a “precession” chamber Here a cylinder, Ø47 cm, H12 cm.



First EDM experiment with a neutron beam

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



A: spin polarizer

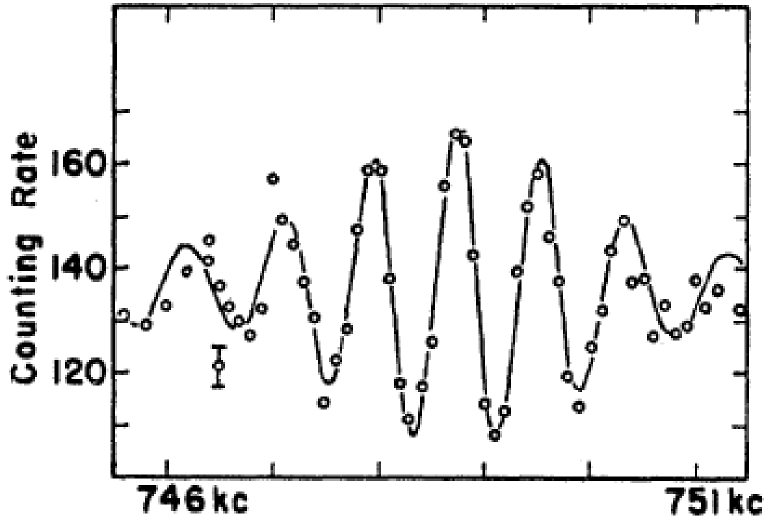
C: Apply ***RF pulse***
π/2 spin-flip…

Free precession in
E and B fields …

C' :Second RF pulse

D: counter

A': spin
analyzer



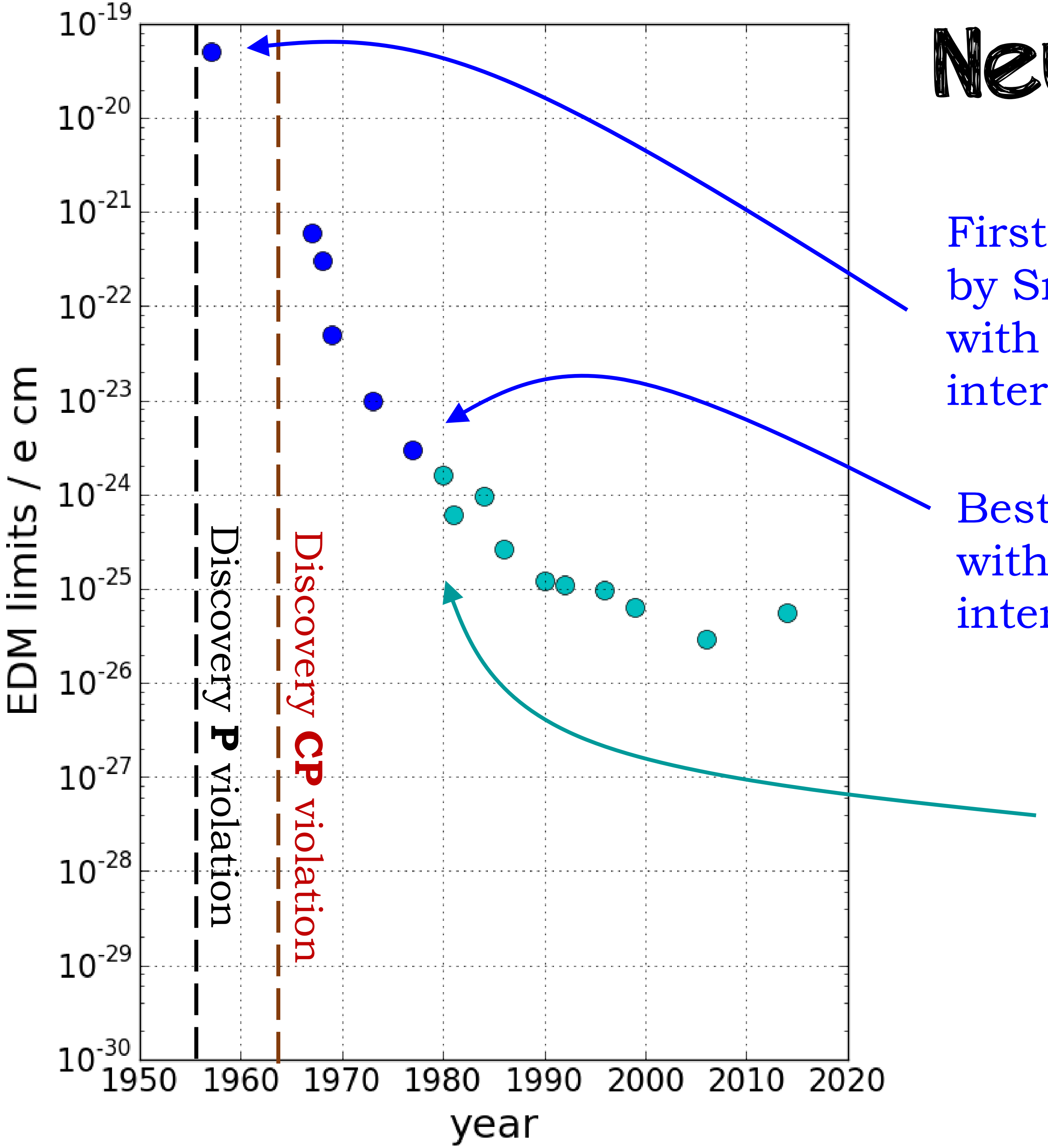
Vary the RF frequency and measure the resonance curve to extract f_L. Do it for parallel and antiparallel E and B fields.

Statistical sensitivity:

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

$T \approx 1$ ms

Neutron EDM history

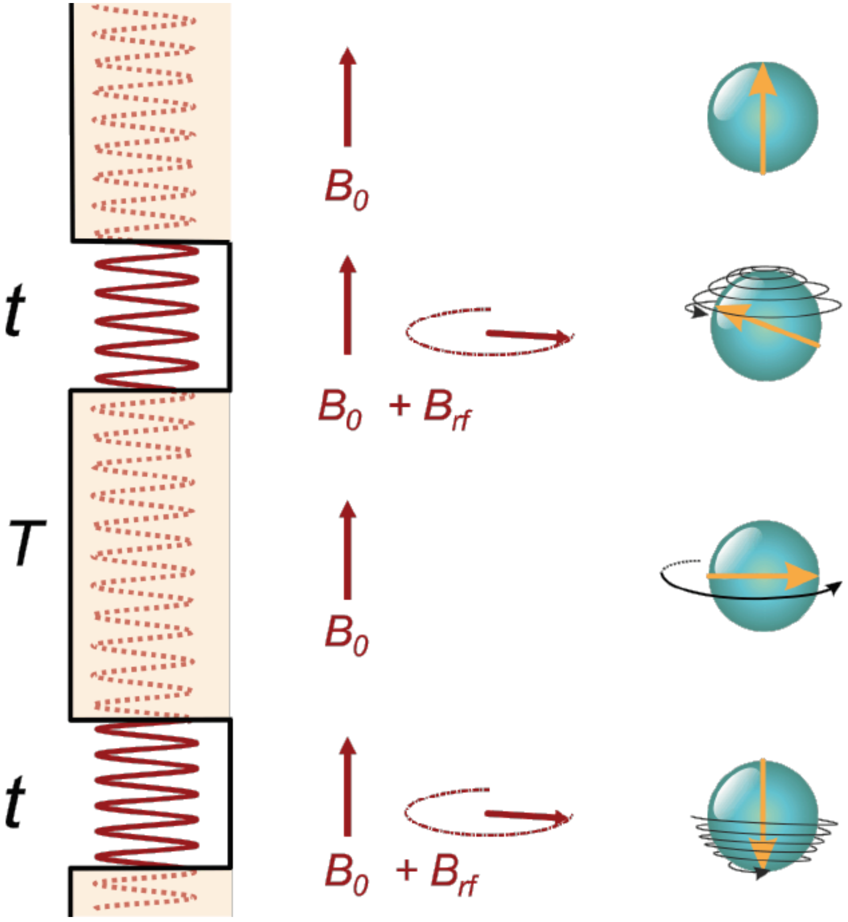


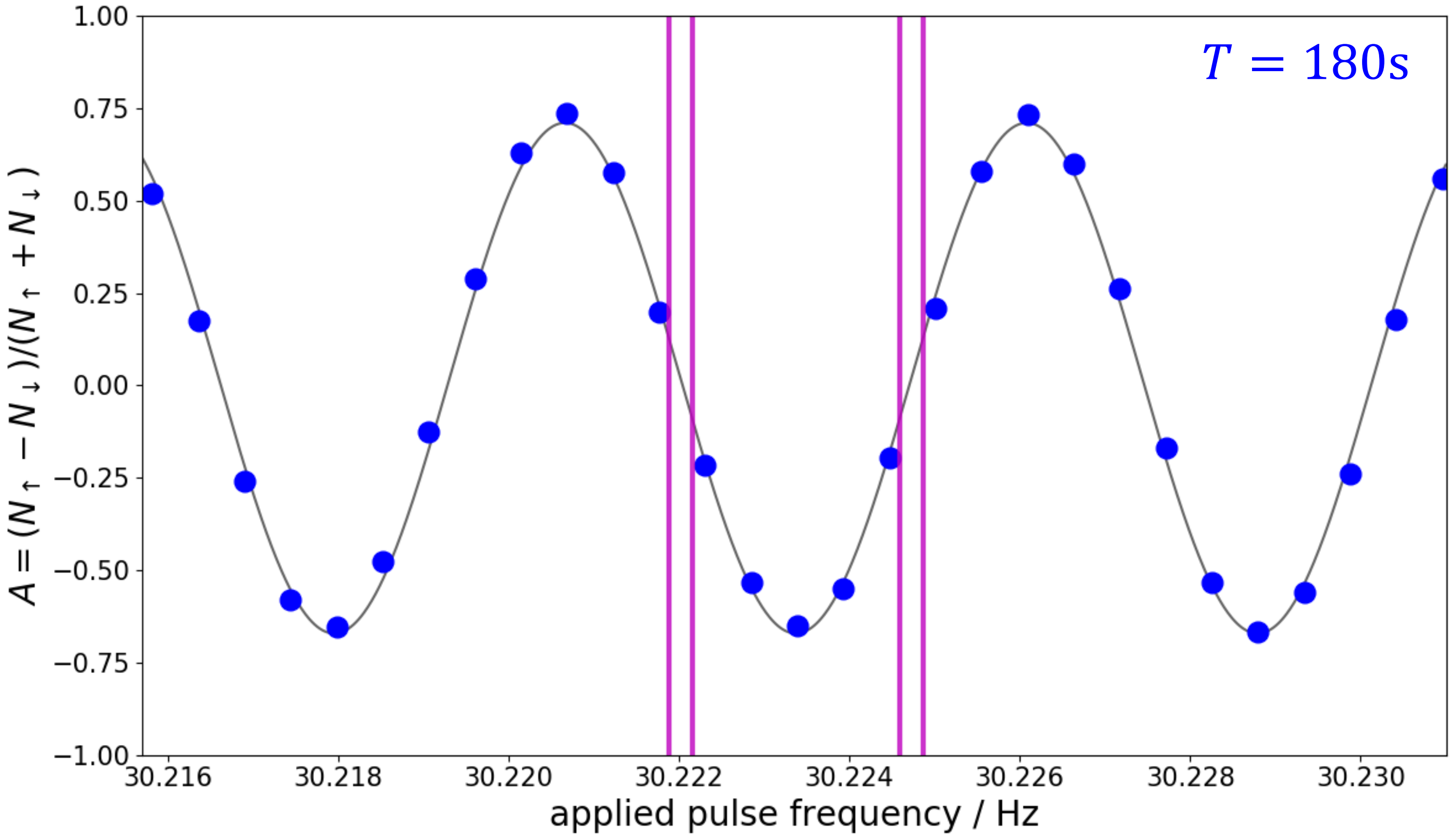
First experiment
by Smith, Purcell and Ramsey
with a **beam of thermal neutrons**,
interrogation time $T \approx 1$ ms

Best « beam » experiment in Grenoble
with **slower neutrons**,
interrogation time $T \approx 20$ ms

« Modern » experiments with
ultracold neutrons started.
interrogation time $T \approx 100$ s

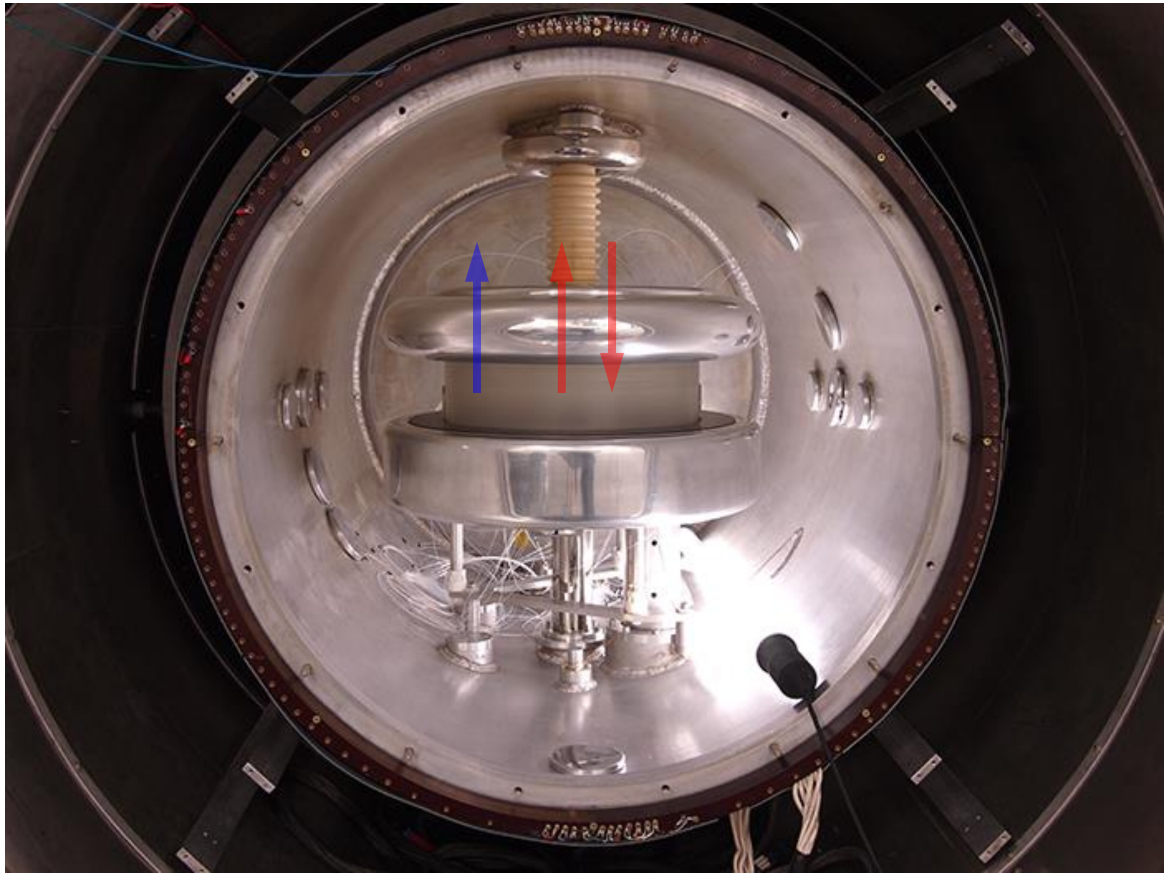
Ramsey's method





Statistical sensitivity: $\sigma d_n = \dfrac{\hbar}{2\,\alpha\, E\, T\sqrt{N}}$

UCN nEDM apparatus (Sussex/RAL/ILL)

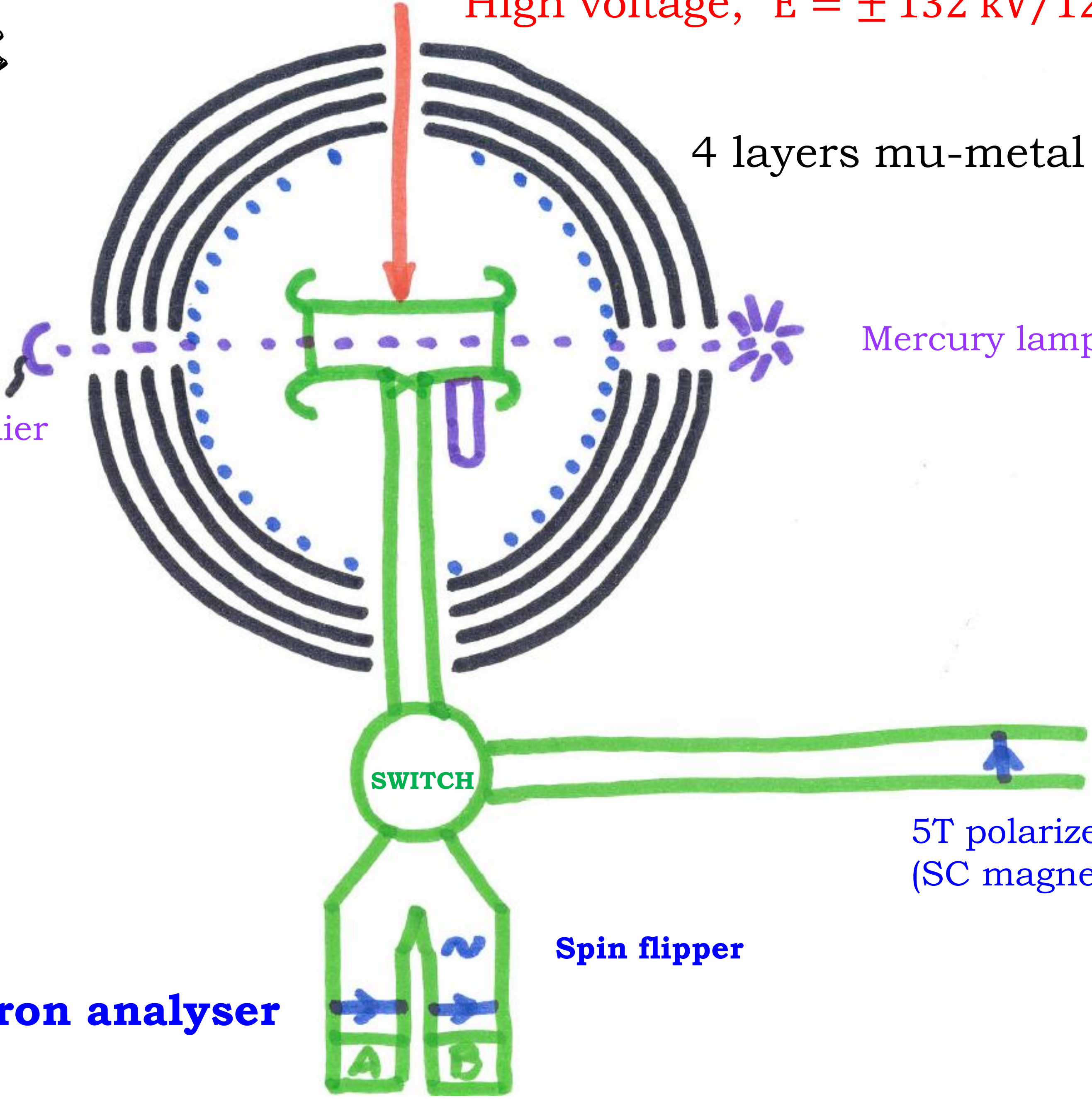


Apparatus installed at the ILL reactor Grenoble (1986-2009)

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



High voltage, $E = \pm 132\ \mathrm{kV}/12\ \mathrm{cm}$

4 layers mu-metal shield

Mercury lamp

photomultiplier

UCN source

5T polarizer
(SC magnet)

Spin flipper

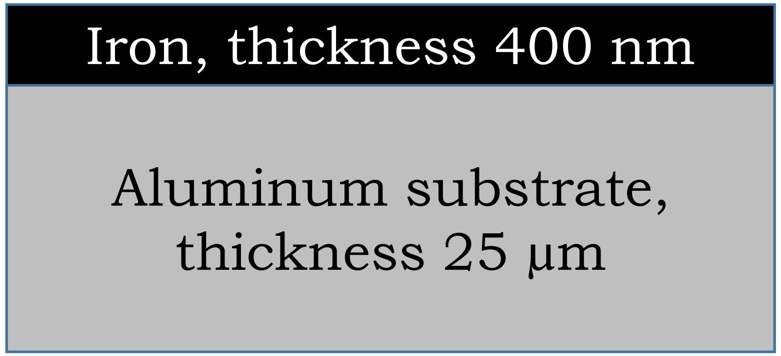
Iron analyser

Problem: the analyzing foil

What is the optimal height of the analyzing 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*.

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



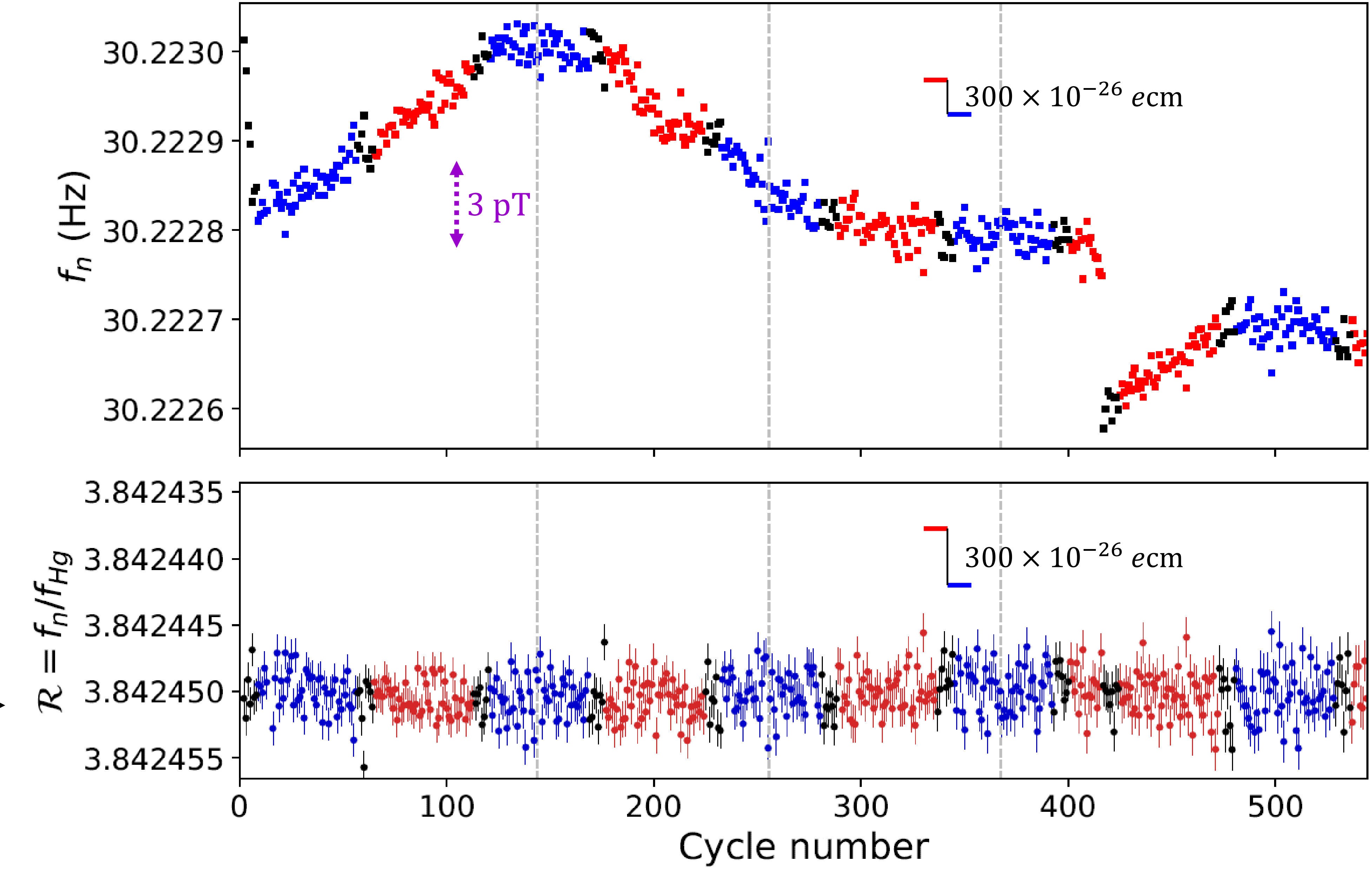
Iron, thickness 400 nm

Aluminum substrate, thickness 25 μm

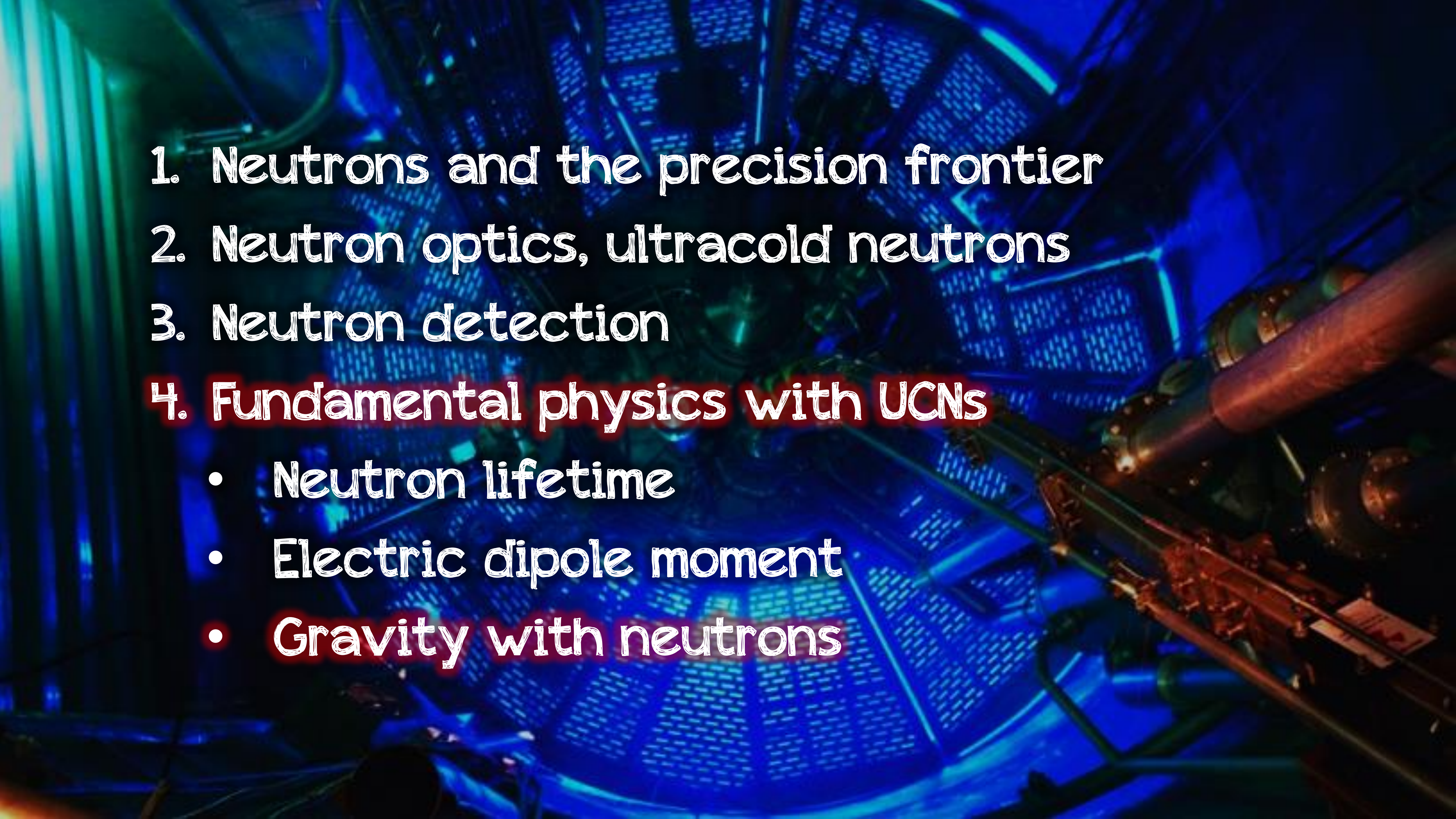
material	ρ [g/cm^3]	M [g/mol]
aluminum	2.70	27.0
boron	2.34	10.8
iron	7.87	55.8

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

A sequence of cycles (nEDM data)



B-field fluctuations (random and correlated with E) are corrected for at each cycle with the mercury magnetometer by measuring $f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$



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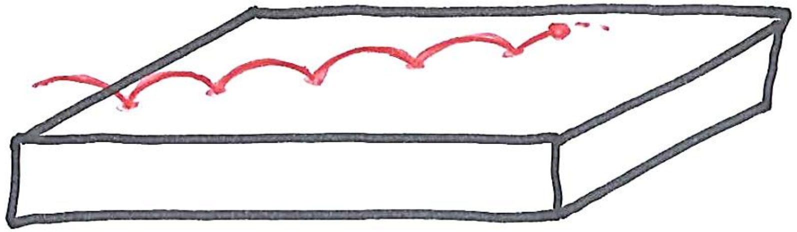
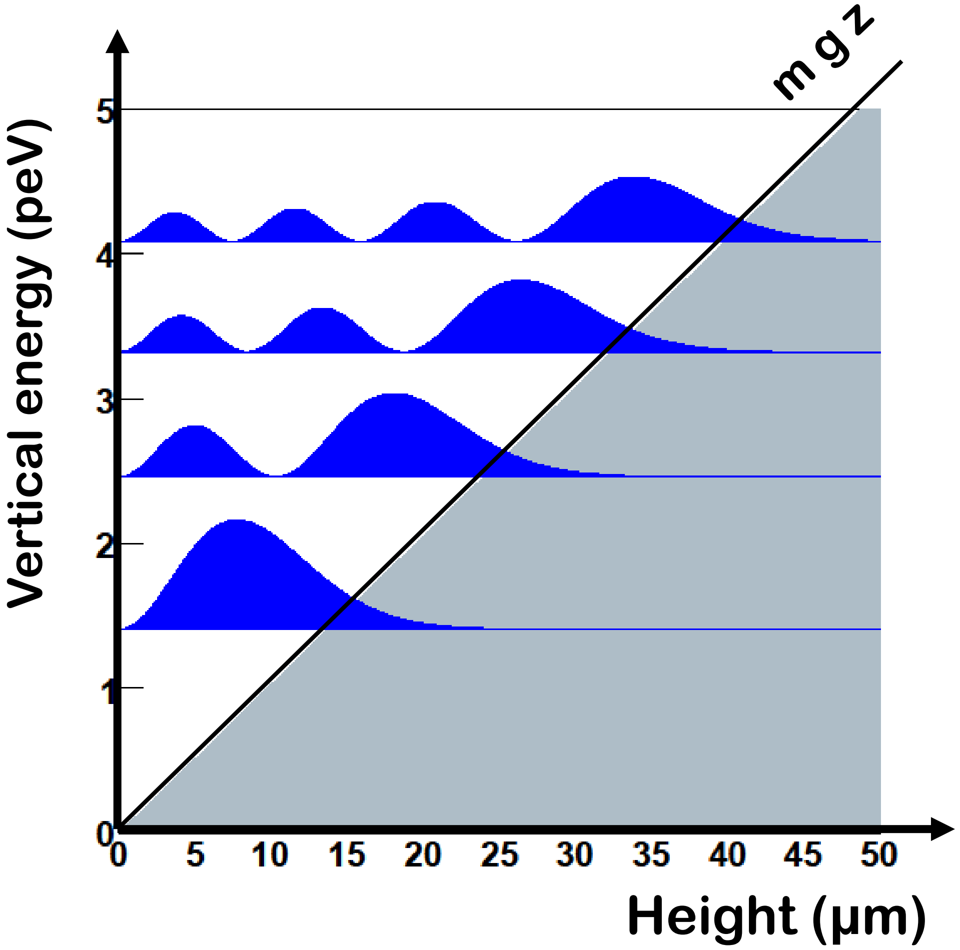
Bouncing neutrons



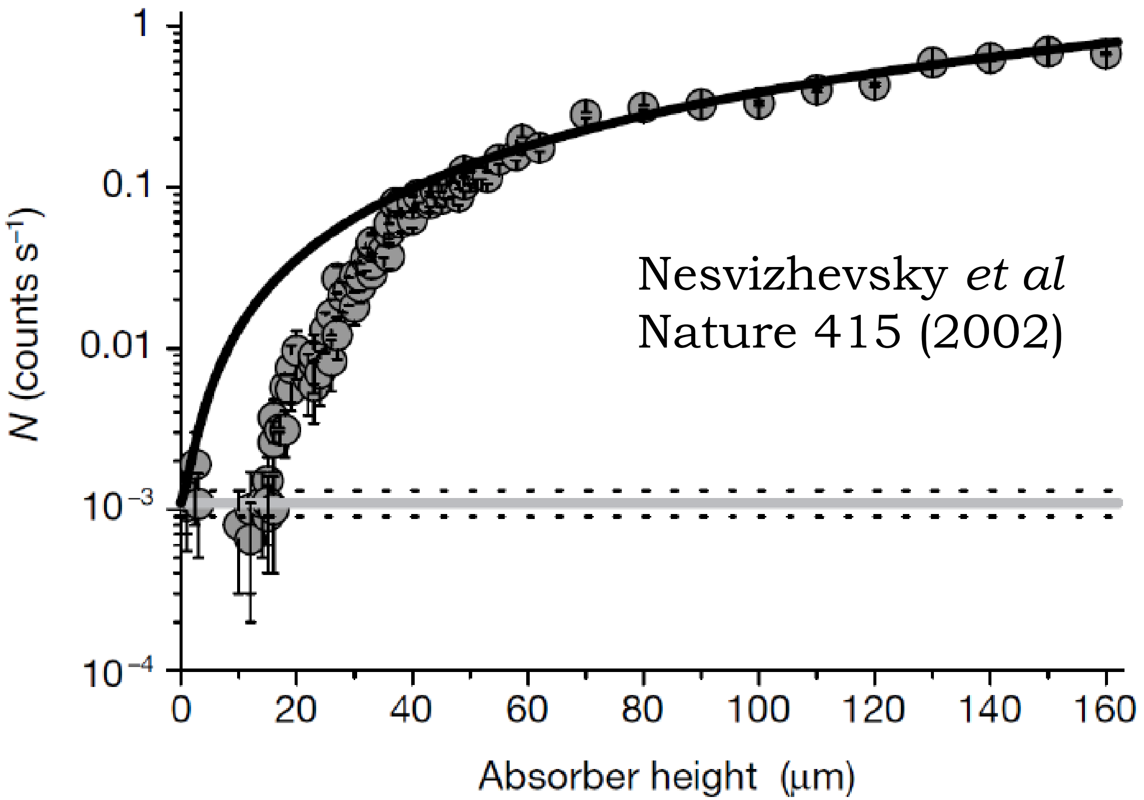
The vertical motion is a
simple quantum well problem

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

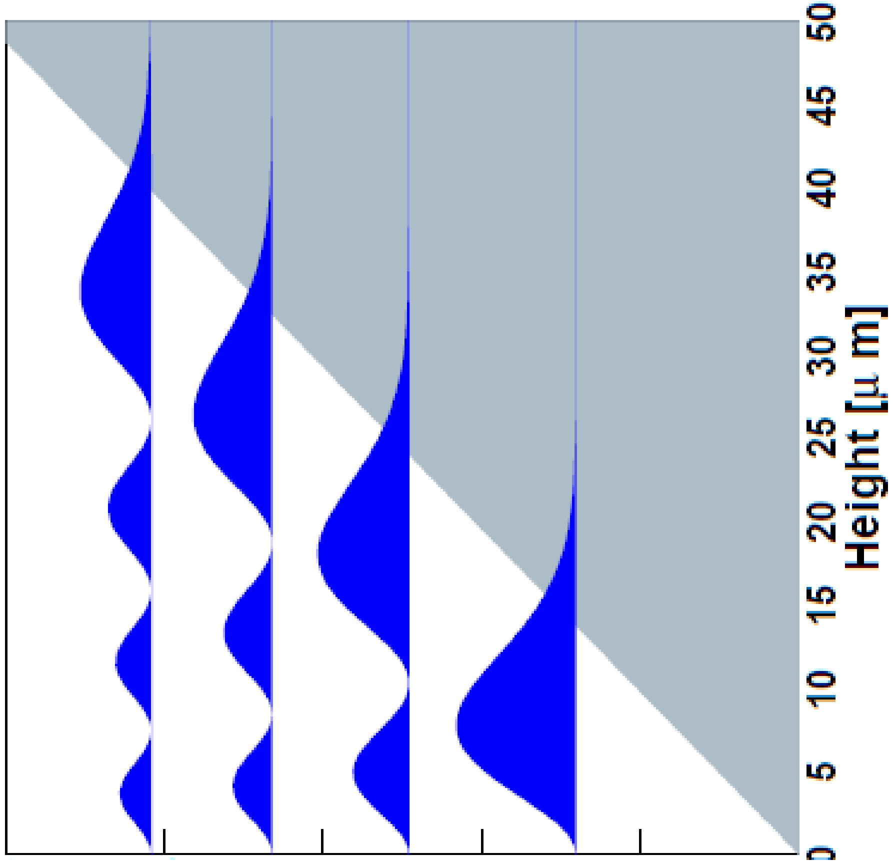
We want to test Enstein's equivalence
principle for a quantum particle in a
classical gravity field.

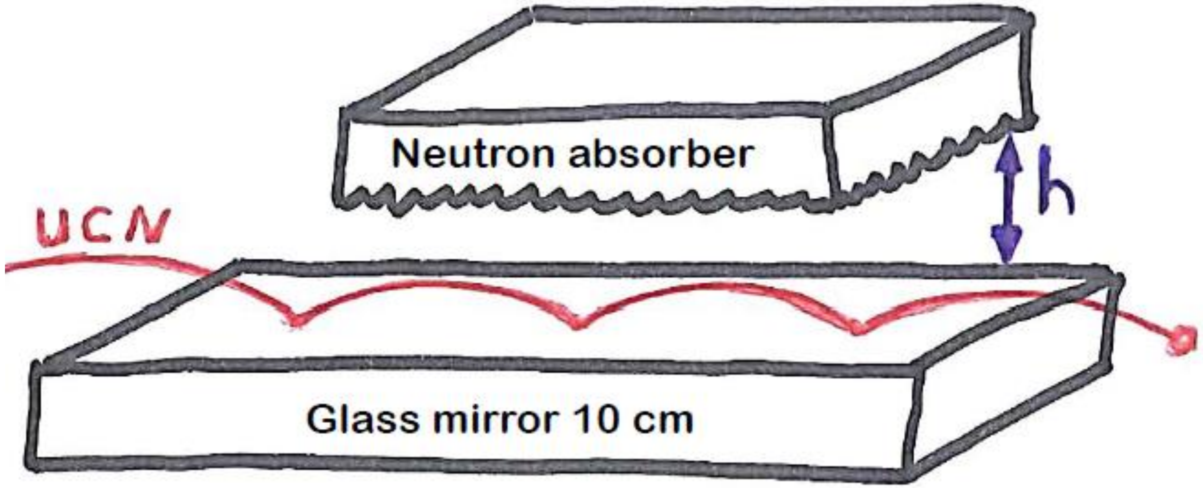


Discovery of the quantum states at ILL

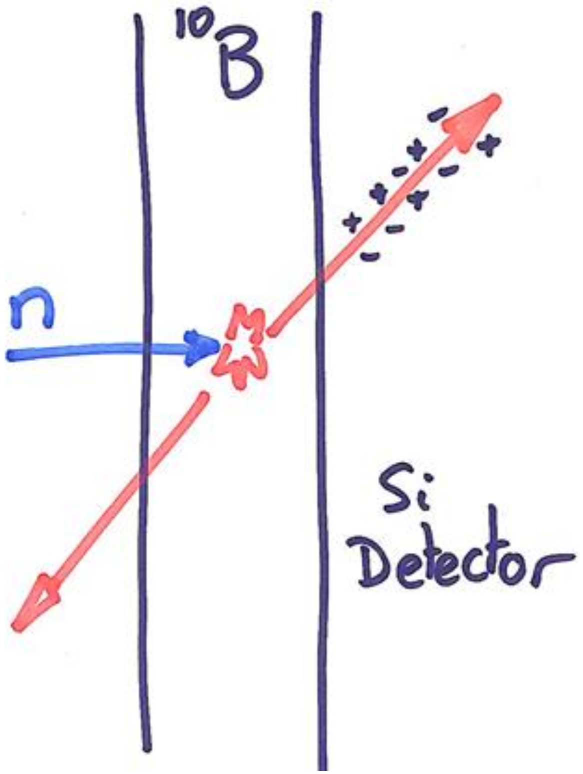


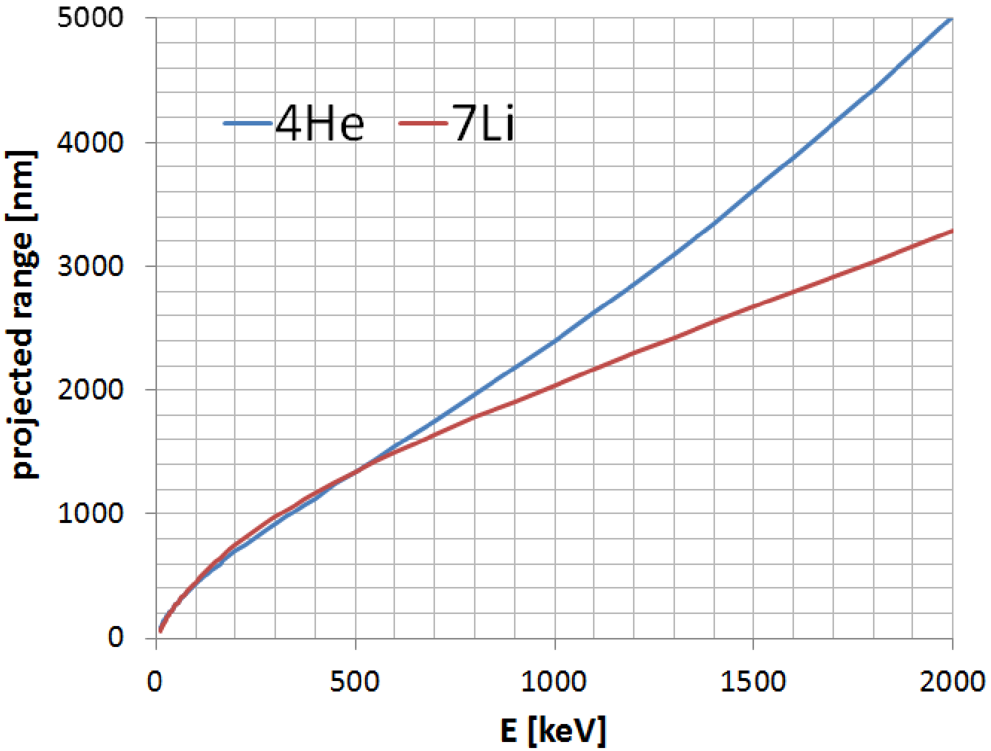
Nesvizhevsky *et al*
Nature 415 (2002)





Problem: micrometric position sensitive detector





1. Calculate the Fermi potential of (i) natural boron (ii) pure ^{10}B. 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.