SEPTEMBER 17-22, 2023
Saint-Pierre d'Oléron | FRANCE

BEYOND THE STANDARD MODEL OF WEAK INTERACTION:
nuclei, neutrons, neutrinos

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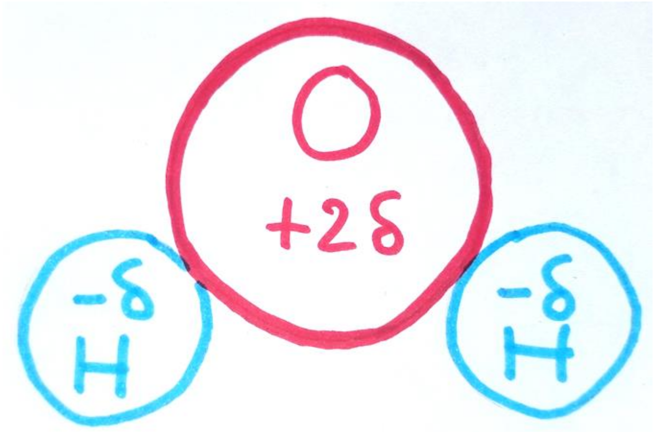
The quest for the Electric Dipole of the Neutron

Guillaume Pignol, Grenoble University

Outline of the nEDM lecture

1. nEDM: What, Why, How?
2. Neutron optics, ultracold neutrons
3. Manipulating neutron spin
4. Past, present and future experiments

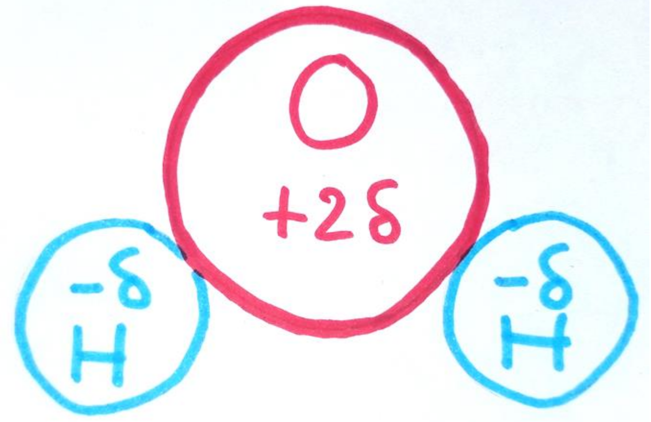
What is an Electric Dipole Moment (EDM) ?



$\vec{d}$ ↑ Electric Dipole Moment

Classical EDM: separation between positive and negative electric charges.
e.g. water molecule d = 0.4 e Å

What is an Electric Dipole Moment (EDM) ?



$\vec{d}\uparrow$ Electric Dipole Moment

Classical EDM: separation between positive and negative electric charges.
e.g. water molecule d = 0.4 e Å

Energy for a "localized" classical charge distribution $\rho(r)$

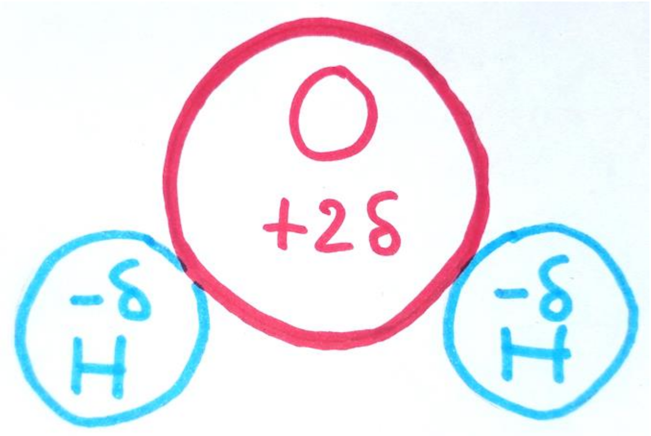
Multipole expansion

exposed to a "weak" electrostatic potential $V(r) = V + r_i \partial_i V + \frac{1}{2} r_i r_j \partial_i \partial_j V + \cdots$

$$W = \int \rho(r) V(r) dr = \left(\int \rho(r) dr \right) V + \left(\int r_i \rho(r) dr \right) \partial_i V + \left(\int \frac{1}{2} r_i r_j \rho(r) dr \right) \partial_i \partial_j V + \cdots$$

Electric charge (scalar) | EDM (vector) | Electric Quadrupole Moment (tensor)

What is an Electric Dipole Moment (EDM) ?



$\vec{d}$ ↑ Electric Dipole Moment

General definition of q, $\vec{d}$, $\vec{\vec{Q}}$, for systems not necessarily described by a classical charge distribution, like elementary particles:

Energy W in an external electric field $\vec{E} = -\vec{\nabla}V$

$$\mathrm{W} = qV - \vec{d} \cdot \vec{E} - \vec{\vec{Q}} \cdot \vec{\nabla}\vec{E} + \cdots$$

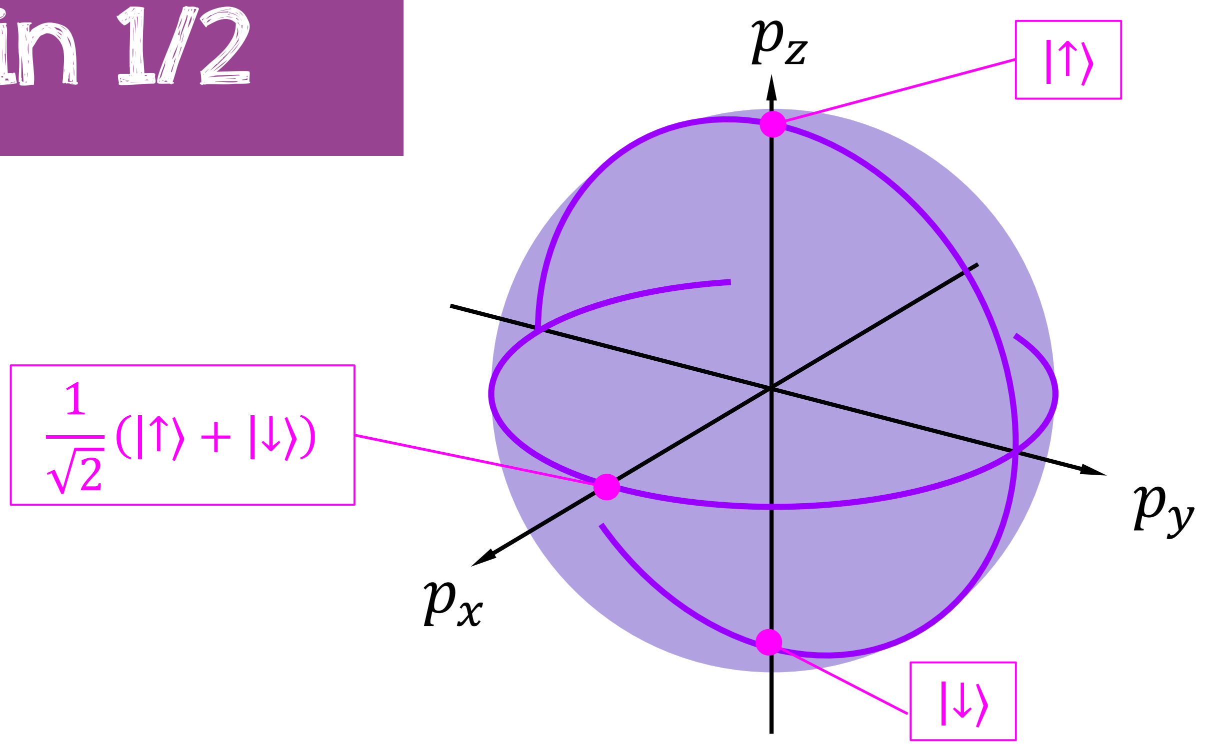
For a quantum system, $\vec{d}$ is a vector operator

What? - Basics of spin 1/2

Internal quantum state of a neutron

$$|\psi\rangle = a\,|\uparrow\rangle + b\,|\downarrow\rangle \coloneqq \begin{pmatrix} a \\ b \end{pmatrix}$$

$(|a|^2 + |b^2| = 1)$



Spin observable $\hat{\vec{S}} = \hbar/2\ \vec{\sigma}$

$\vec{\sigma}$ are the Pauli matrices

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$
$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$
$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

The polarization vector $\vec{p} = \langle\psi|\vec{\sigma}|\psi\rangle$

- describes completely the state $|\psi\rangle$

  * up to an irrelevant phase factor ** valid for spin ½ only
- belongs to the **Bloch sphere** $|\vec{p}| = 1$

  * for a pure state, spin 1/2. For a neutron ensemble $|\vec{p}| \leq 1$

What? - Interaction with E & B fields

MDM and EDM are vector operators, they must be proportional to $\vec{\sigma}$ (Wigner-Eckart theorem for spin 1/2)

$$\hat{H} = -\mu\,\vec{\sigma}\cdot\vec{B} - d\,\vec{\sigma}\cdot\vec{E}$$

Spin dynamics given by Schrödinger equation

$$i\hbar\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle$$

$$\frac{d}{dt}\begin{pmatrix}a\\b\end{pmatrix} = \left(\frac{i\mu}{\hbar}\,\vec{\sigma}\cdot\vec{B} + \frac{id}{\hbar}\,\vec{\sigma}\cdot\vec{E}\right)\begin{pmatrix}a\\b\end{pmatrix}$$

Or equivalently by the Bloch equation

$$\frac{d\vec{p}}{dt} = \vec{p}\times\left(\frac{2\mu}{\hbar}\vec{B} + \frac{2d}{\hbar}\vec{E}\right)$$

What? - Larmor precession

Case $\vec{B} = B_0 \vec{e}_z$ static, $\vec{E} = \vec{0}$

Initial condition $|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

$\gamma = \frac{2\mu}{\hbar}$ =: gyromagnetic ratio

$\omega_0 = \gamma B_0$ =: Larmor angular frequency

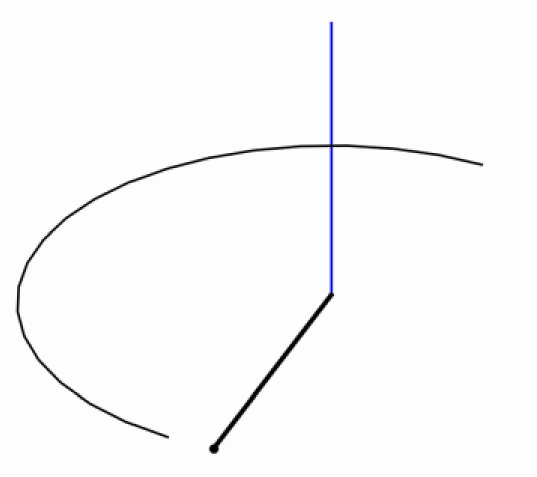
Schrödinger equation:

$$\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \frac{i}{2}\omega_0\, \sigma_z \begin{pmatrix} a \\ b \end{pmatrix}$$

Solution: $\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{i\frac{\omega_0}{2}t} \\ e^{-i\frac{\omega_0}{2}t} \end{pmatrix}$

Bloch equation: $\frac{d\vec{p}}{dt} = \gamma\, \vec{p} \times \vec{B} = \omega_0 \begin{pmatrix} p_y \\ -p_x \\ 0 \end{pmatrix}$

Solution: $\vec{p}(t) = \begin{pmatrix} \sin \omega_0 t \\ \cos \omega_0 t \\ 0 \end{pmatrix}$



Precession at angular frequency $\omega_0 = \gamma B_0$

What are the measured MDM and EDM for the neutron?

$$\hat{H} = -\mu\,\vec{\sigma}\cdot\vec{B} - d\,\vec{\sigma}\cdot\vec{E}$$

$$\mu = -1.913\,042\,7(5)\,\mu_N$$

Nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_N}$$

$$d = (0 \pm 1)\times 10^{-26}\,e\,\mathrm{cm}$$

$$= (0 \pm 1)\times 10^{-12}\times \mu_N/c$$

$$\frac{\mu_N}{c} \approx 0.1\ \mathrm{e\ fm}$$

Why is it so small?

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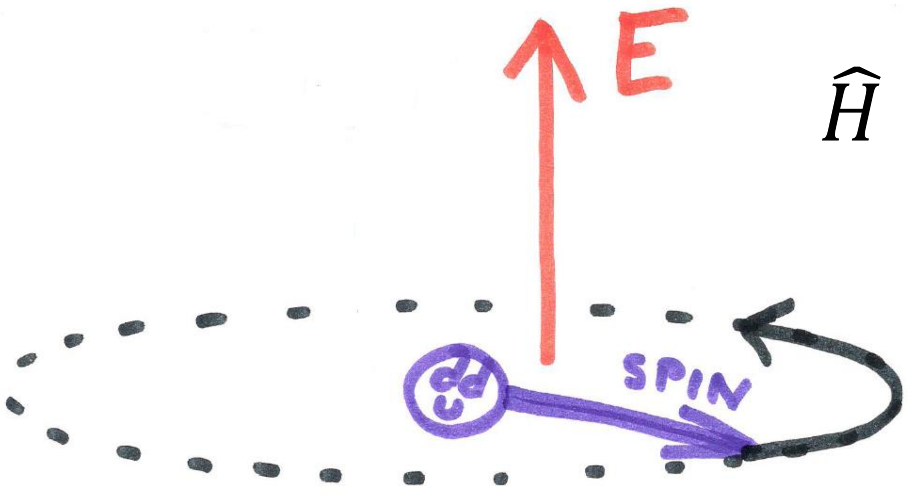
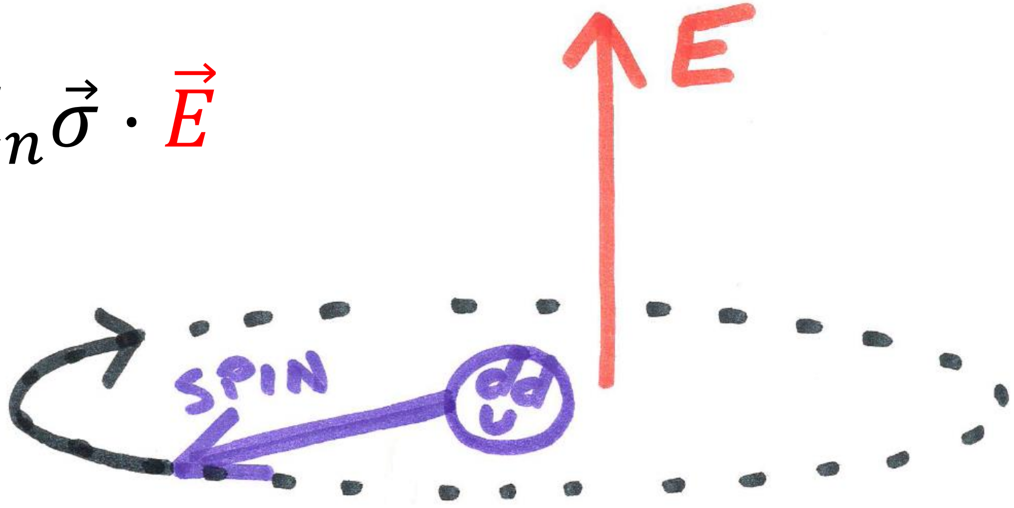
Why tiny? Because of T-symmetry

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



>> PLAY >>



<< REWIND <<

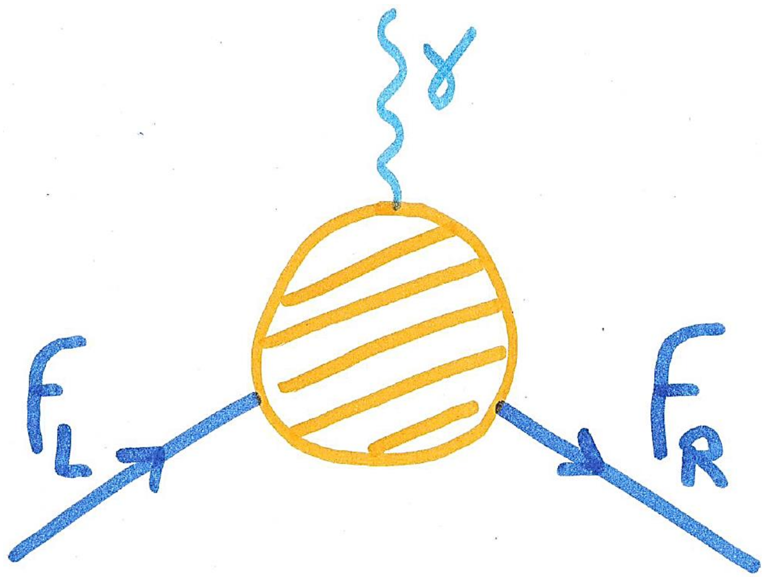
If $d_n \neq 0$ the process and its time reversed version are different.

Violation of T

Violation of CP

CPT theorem

the EDM from the point of view of a high energy theorist



Fermion-photon coupling

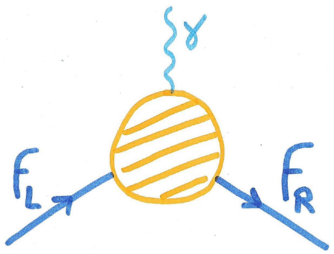
$$\mathcal{L} = \frac{1}{2}(\boldsymbol{\delta\mu} + i\boldsymbol{d})\bar{f}_L \sigma_{\mu\nu} f_R \, F^{\mu\nu} + h.c.$$

Real part = anomalous magnetic moment

Imaginary part = electric dipole moment

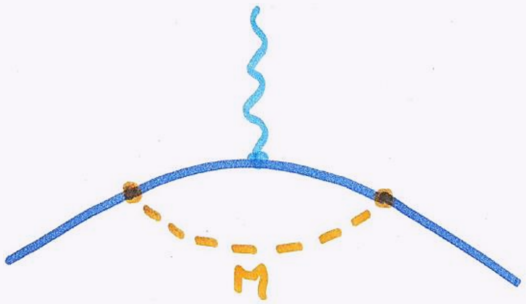
Non-relativistic limit: $\hat{H} = -\boldsymbol{\mu}\sigma B - \boldsymbol{d}\sigma E$

Sources of neutron EDM



$$\mathcal{L} = -\frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\, F^{\mu\nu} \rightarrow \hat{H} = -d\hat{\sigma}E$$

Typical 1-loop contribution for quark EDM

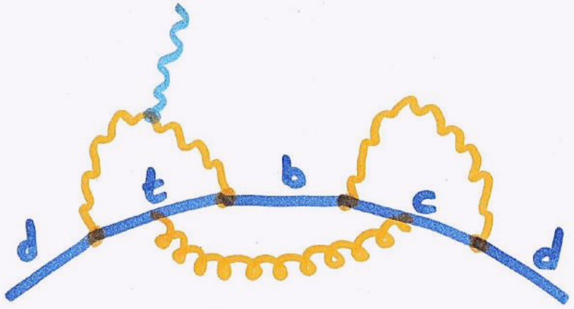


$$d_n \sim e\frac{g^2}{16\pi^2}\sin(\phi_{\text{CPV}})\frac{m_q}{M^2}$$

$\rightarrow M >$ TeV if phase ~ 1

Contribution of weak interaction

Leading order
for quark EDMs at 3 loops!
Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-18}\ \mu_N/c$

* The "long distance" contribution dominates over quark EDMs, still super-small.

The SM QCD theta term $\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$

generates a potentially enormous neutron EDM : $d_n \sim -0.02 \times \bar{\theta}\ \mu_N/c$

$\rightarrow |\bar{\theta}| < 10^{-10} \rightarrow$ « Strong CP problem »

Systematic approach: ladder of Effective Field Ths

UV complete BSM theory,

$\mathcal{L}_{\rm UV}$: Scale $= \Lambda \gg m_H \sim 100$ GeV

EFT with SM fields: quarks, leptons, gauge bosons, Higgs

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{D=5} + \sum_{a=1}^{3045} \frac{c_a}{\Lambda^2} O_a^{(6)} + \mathcal{L}_{D=7} + \cdots$$

EFT with hadrons, leptons and photons
Isospin-diagonal, CPV operators

$$-\mathcal{L}_{\rm EDM} = \frac{1}{2} d_n\, \bar{n}\sigma_{\mu\nu} i\gamma_5 n\, F^{\mu\nu} + \frac{G_F}{\sqrt{2}} C_S^0\, \bar{n}n\, \bar{e}i\gamma_5 e + \cdots$$

Observables: EDMs of nucleons, atoms, molecules…

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

European Strategy Particle Physics 1910.11775

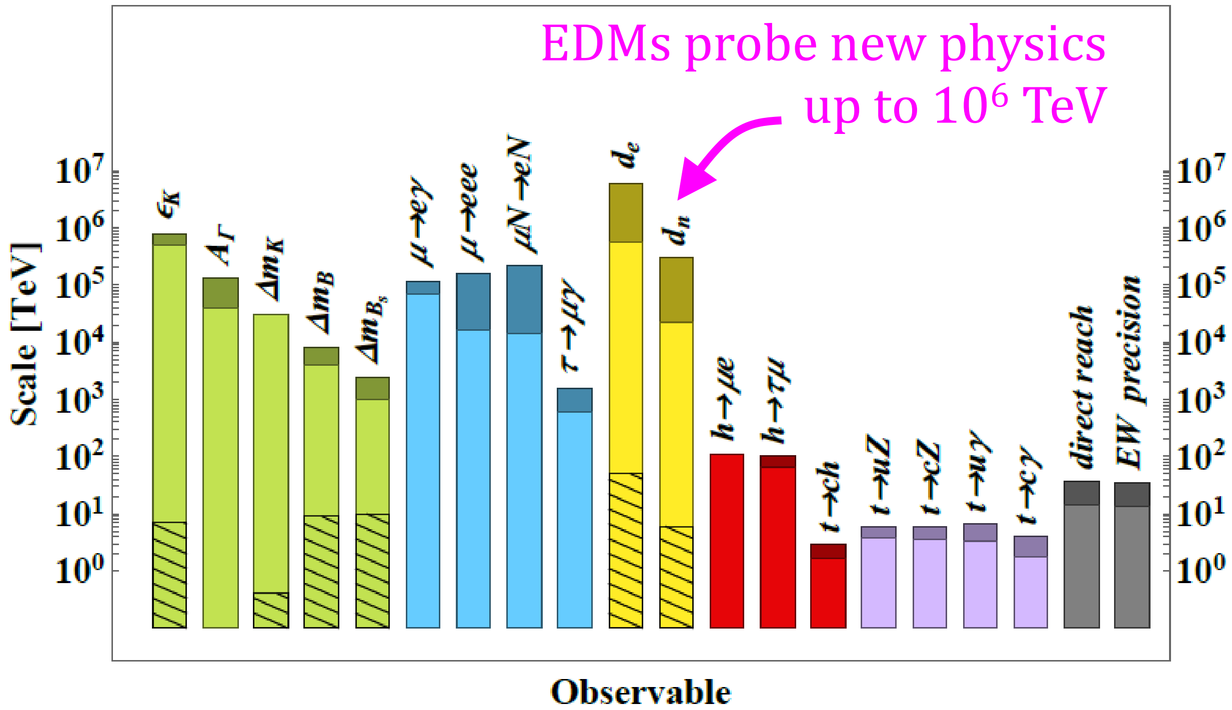


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects,

Summary on What and Why.

What is the neutron EDM?

- For elementary spin ½ particles such as the neutron or the electron, the EDM is really the magnitude of the coupling between spin and E field (don't think of a distribution of charges, it's useless).
- Experimental limit: less than 10^{-12} of the natural size μ_N/c.

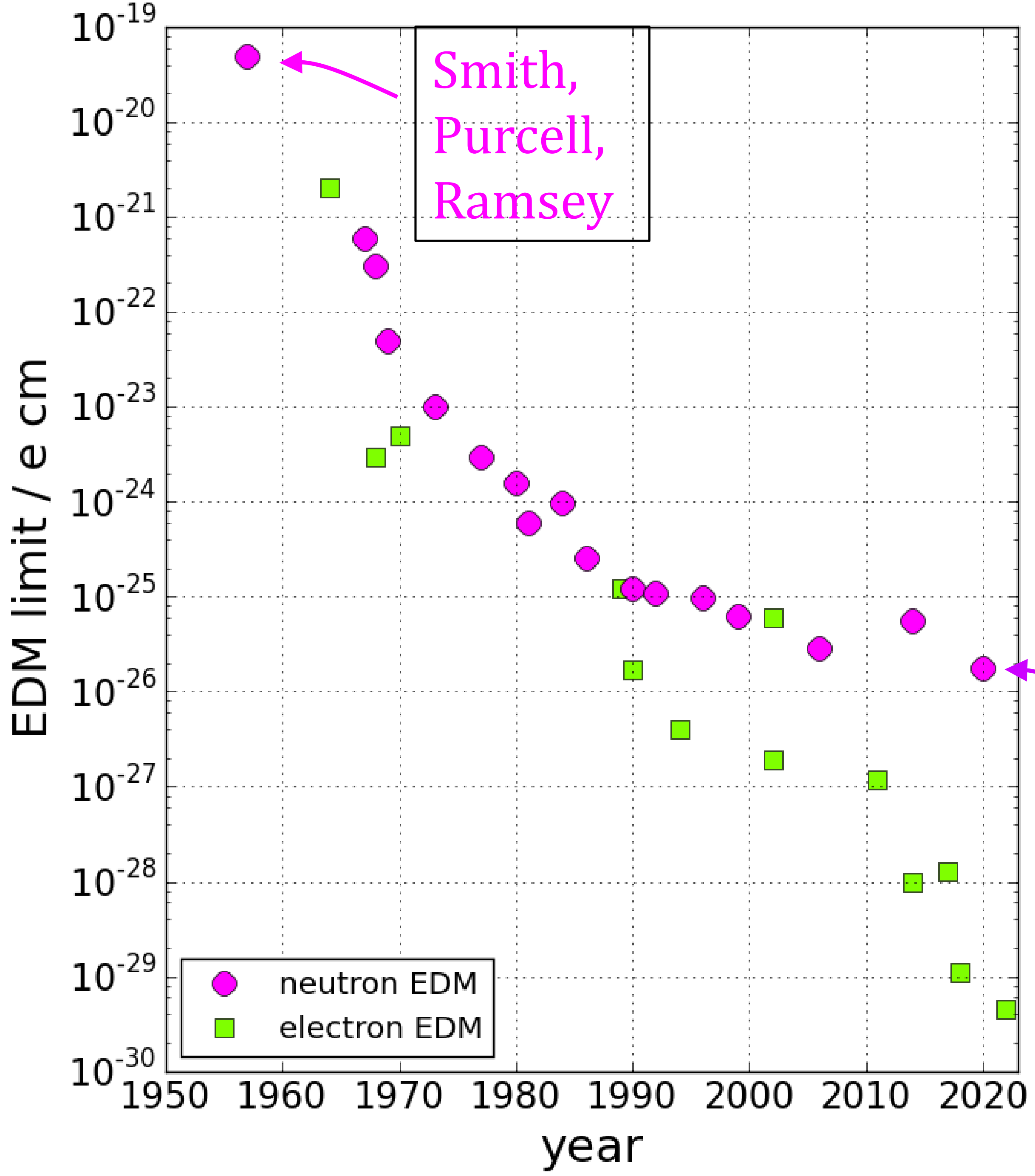
Why is it so small?

- Nonzero EDM violates P and T symmetries, therefore also CP symmetry.
- In the standard model of weak interaction, CP violation needs three generations of quarks.

Why do we continue the search?

- Sensitive probe of CP violation beyond the Standard Model.

Since when?



On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. PURCELL AND N. F. RAMSEY
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

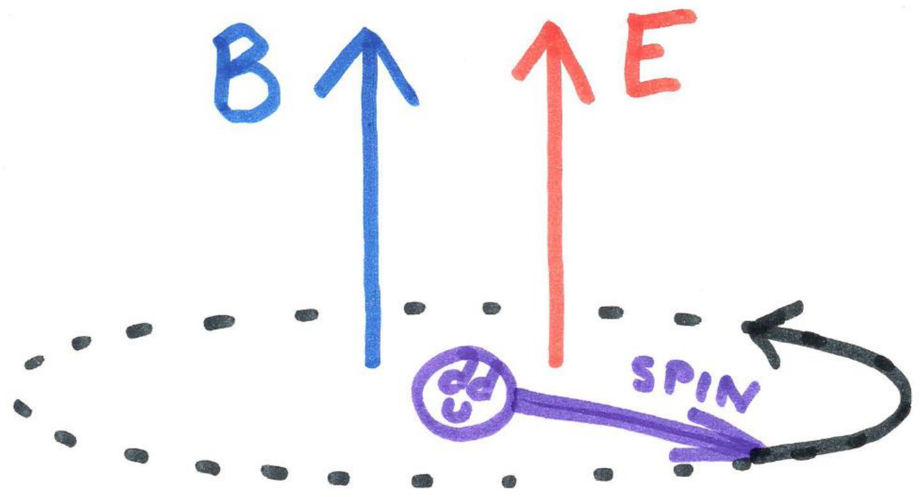
IT is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

Limit from the nEDM experiment @PSI

$$|d_n| < 1.8 \times 10^{-26}\ e$$

Abel et al, PRL (2020)

How? basics of nEDM measurement



Larmor frequency

~ 30 Hz @ $B = 1$ μT

$$2\pi f = \frac{2\mu_n}{\hbar} B \pm \frac{2d_n}{\hbar} |E|$$

If $d_n \sim 10^{-26}$ e cm and $E \sim 10$ kV/cm

duration of one full turn ~ 1 year

To detect such a minuscule coupling

- Long interaction time
- High intensity/statistics
- Control the magnetic field

- **Long interaction time**
- **High intensity/statistics**
- **Control the magnetic field**

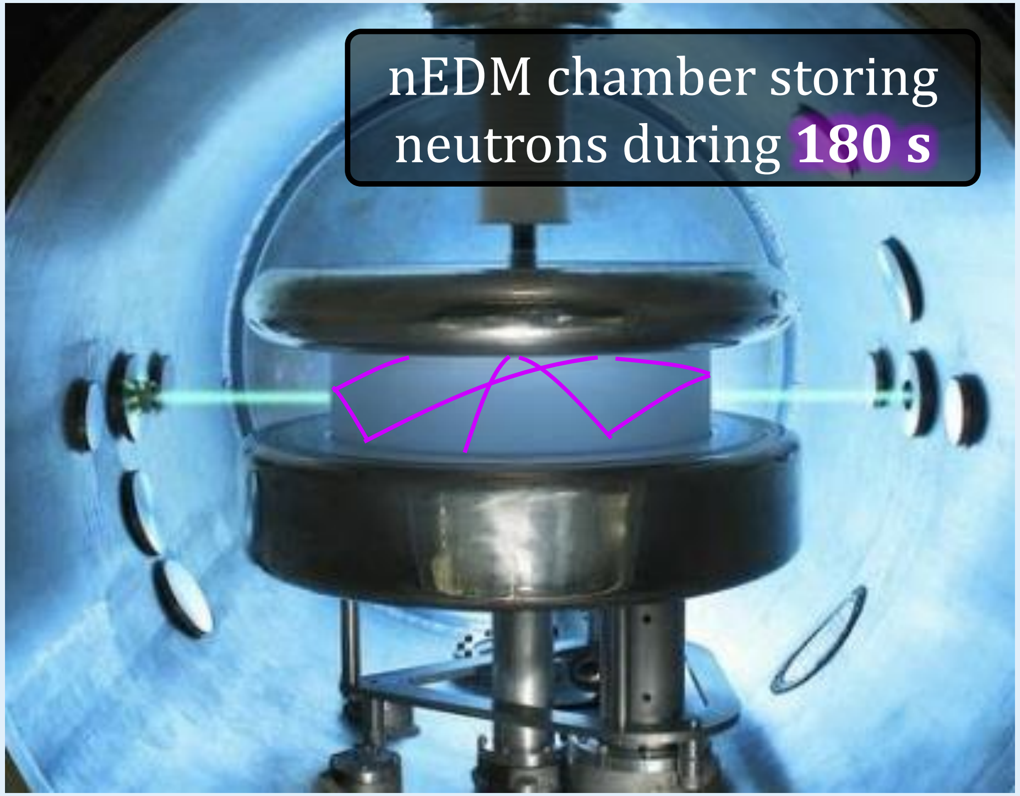
Use big magnetic shielding

+ Use quantum magnetometry

With mercury and cesium atoms

Use Ultracold neutrons

Neutrons with velocity <5m/s can undergo total reflection and be stored in material "bottles"



Abel et al, PRL (2020)

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}\, e\mathrm{cm}$$

Limited by the number of UCNs (~500 million counts)

Uniformity of the B-field

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Thermalization of fast neutrons

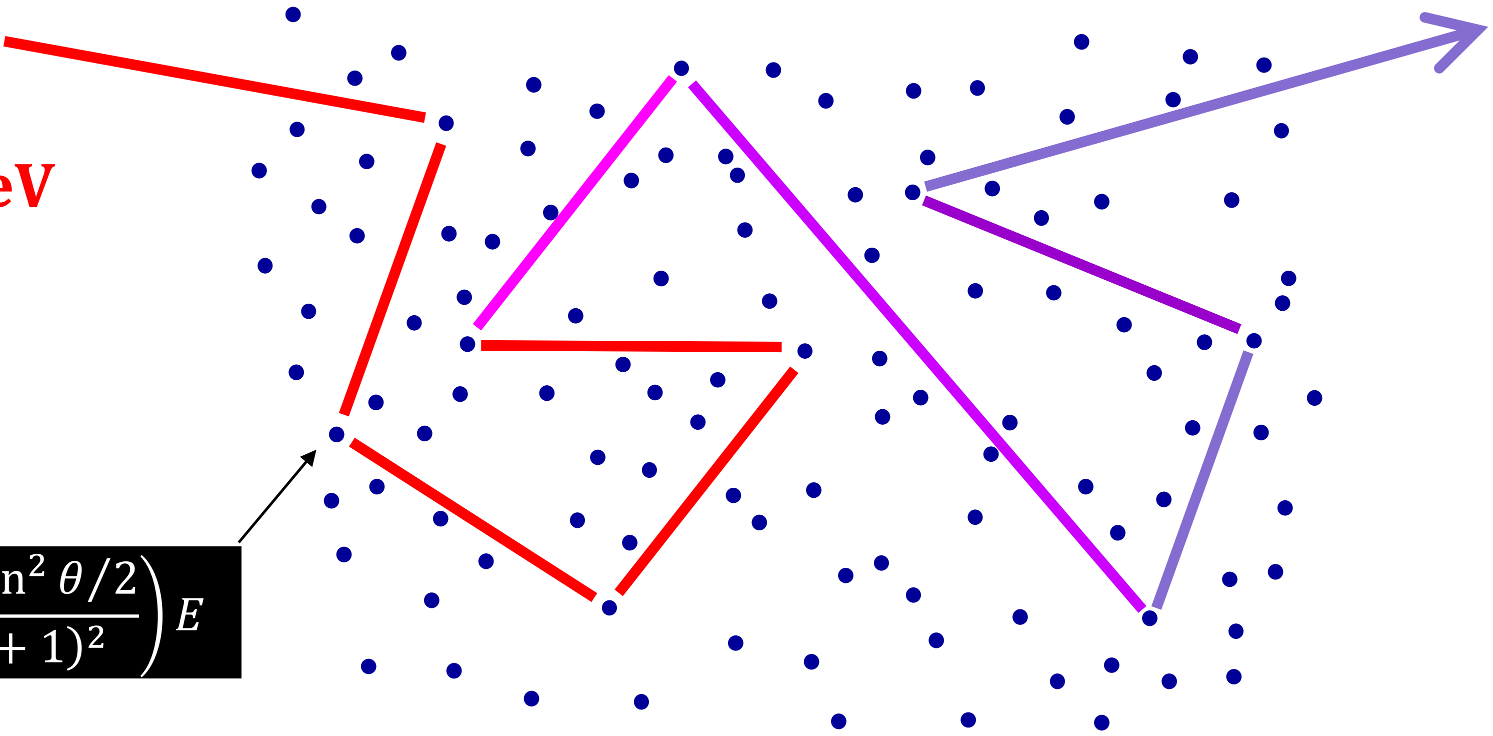
Moderator material with hydrogen or deuterium.

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

Fast neutron produced by fission or spallation

E ~ 2 -- 20 MeV

v ~ 0.1 c



Thermal neutron

E = kT = 25 meV

v = 2200 m/s

$$E' = \left(1 - \frac{4A\sin^2\theta/2}{(A+1)^2}\right)E$$

Neutron optics

De Broglie wavelength of the neutron: $\lambda = \dfrac{2\pi\hbar}{mv}$

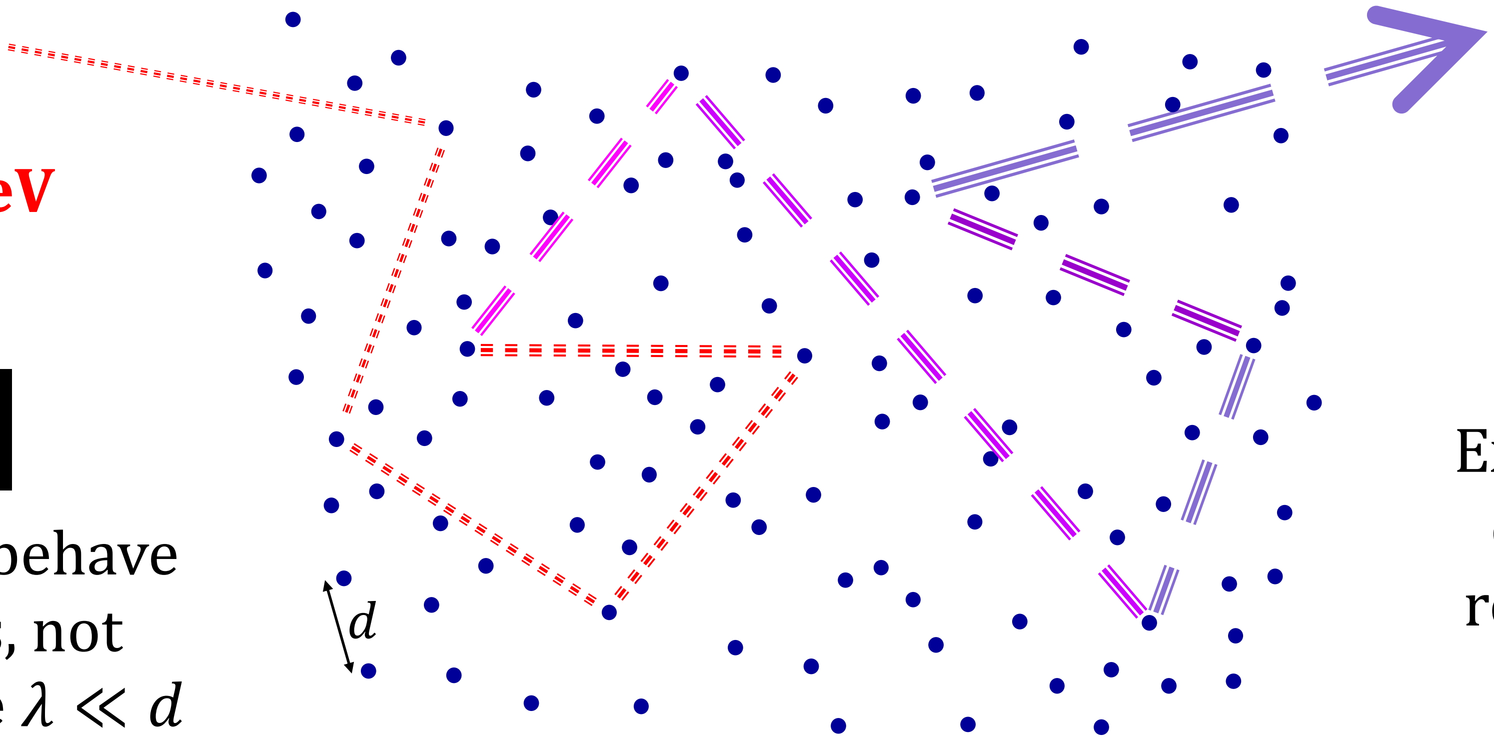
Fast neutron produced by fission or spallation

E ~ 2 -- 20 MeV

v ~ 0.1 c

$\lambda \sim 10$ fm

Fast neutrons behave like particles, not waves, because $\lambda \ll d$



Thermal neutron

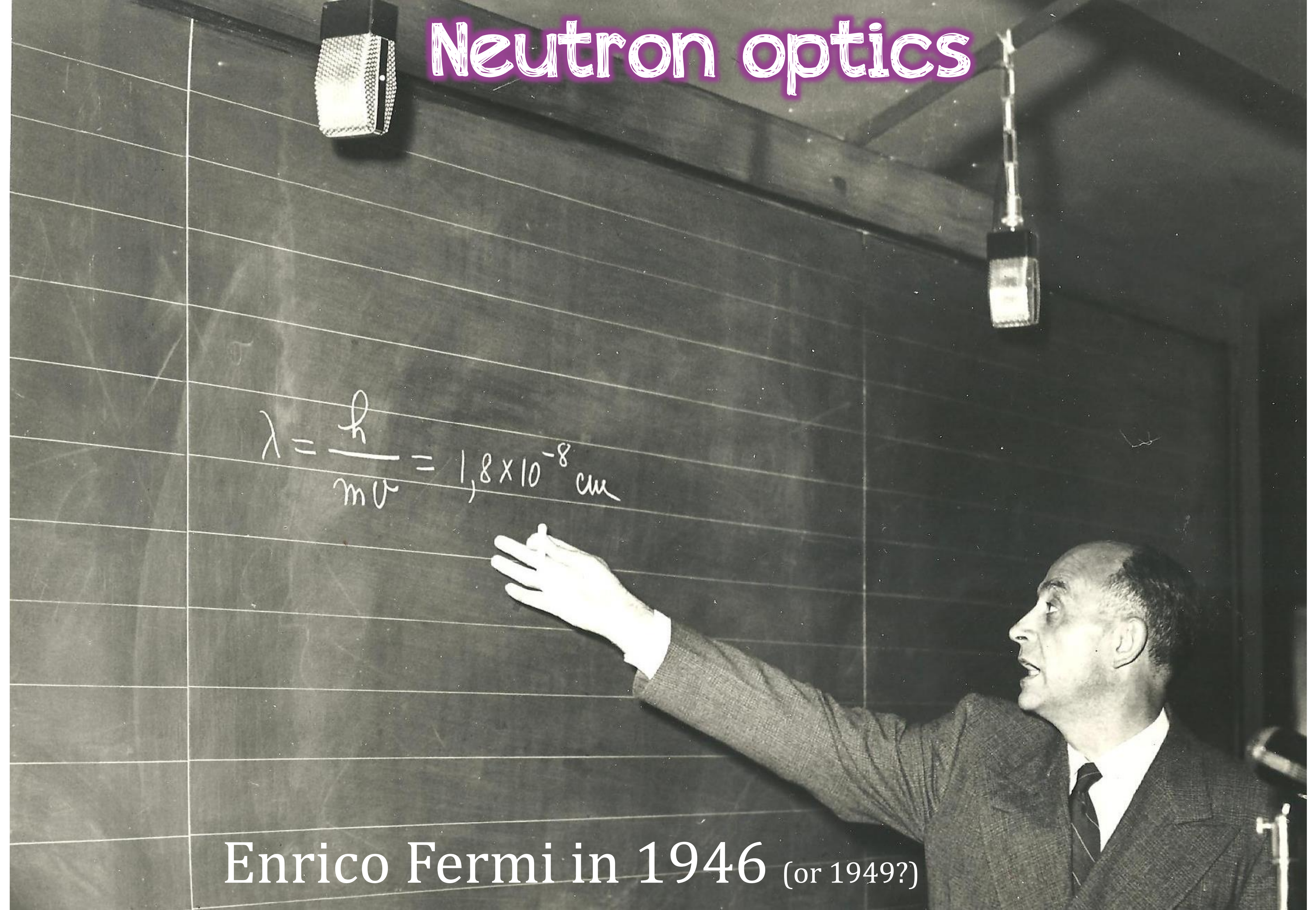
E = kT = 25 meV

v = 2200 m/s

$\lambda = 0.2$ nm

Expect significant wave effects (interference, refraction) for thermal and cold neutrons because $\lambda \approx d$

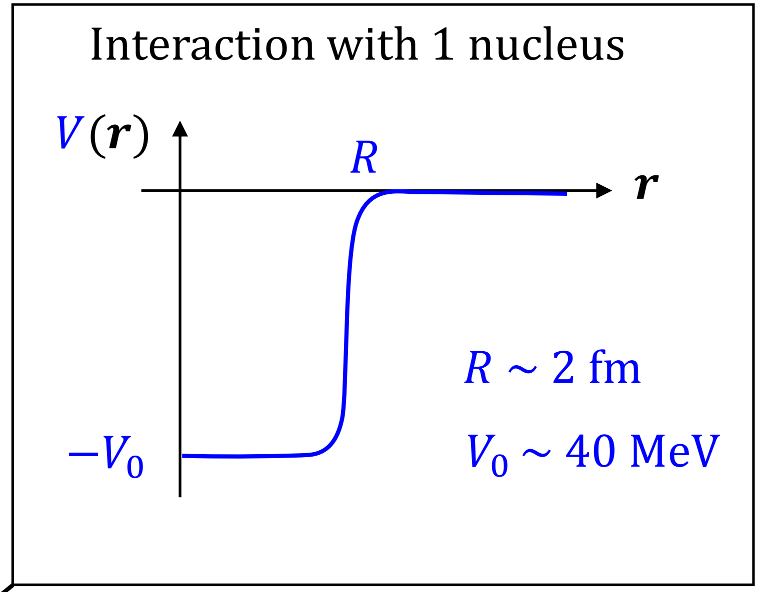
Neutron optics

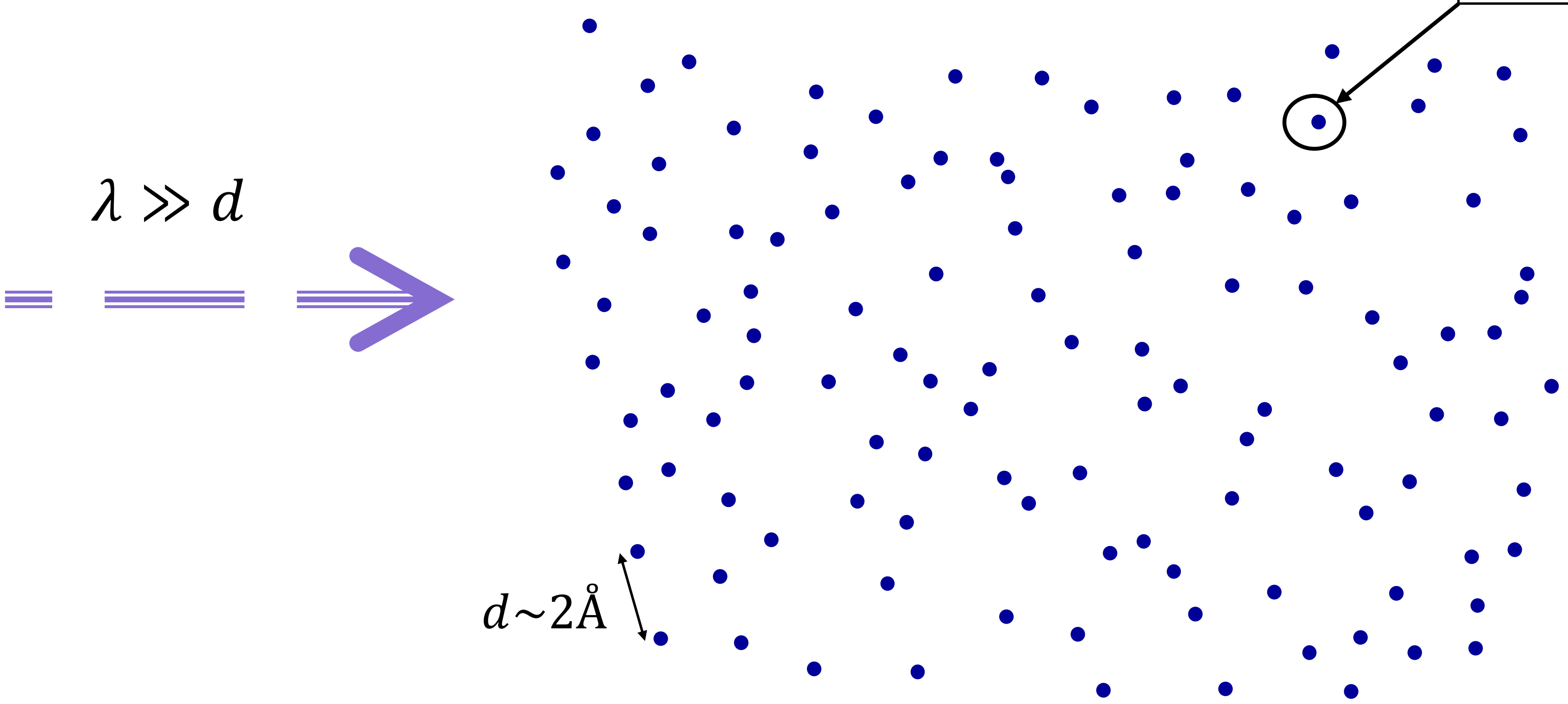


Enrico Fermi in 1946 (or 1949?)

Naïve picture of neutron optics

In this case: wrong.





Smearing of the nuclear potential by simple volume average:

$$\langle V\rangle \;=\; -V_0\frac{4\pi}{3}\left(\frac{R}{d}\right)^3$$
$$\sim\; -200\ \text{neV}$$

Predicts negative « optical » potential.

Scattering of the neutron wave … correct approach

Quantum theory of non-relativistic collisions describes an incident neutron wave with $\lambda = 2\pi/k$ scattered by a single nucleus localized at $\vec{0}$

$$\psi(\vec{r}) = e^{i\,k\,x} + f(\theta)\,\frac{e^{ik|\vec{r}|}}{|\vec{r}|}$$

For slow neutrons, nuclei look point-like ($kR \ll 1$), the scattering amplitude $f(\theta)$ is isotropic and energy-independent:

$f(\theta) = \text{cst} =: -b$ $\quad$ b = neutron scattering length for a given nucleus.

the minus sign is a convention decided by the pope

Multiple scattering on a collection of nuclei localized at positions $\vec{r_j}$

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

Approximation valid for $\lambda \gg d$

$n(\vec{r}')$ = number density of targets

$$\psi(\vec{r}) = e^{i\,k\,x} - \int \psi(\vec{r}')\, b\, \frac{e^{ik|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}\, n(\vec{r}')\, d^3\vec{r}'$$

Scattering of the neutron wave, $\lambda \gg d$

implicit equation on $\psi(\vec{r})$ valid for $\lambda \gg d$

$$\psi(\vec{r}) = e^{i\,k\,x} - \int \psi(\vec{r}\,')\,b\,\frac{e^{ik|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|}\,n(\vec{r}\,')\,d^3\vec{r}\,'$$

Apply $\Delta + k^2$ on both sides and recall that

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

$$(\Delta + k^2)\psi(\vec{r}) = 0 + 4\pi b n(\vec{r})\psi(\vec{r})$$

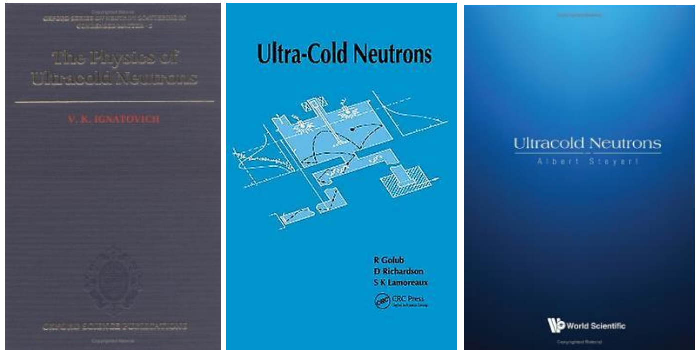
takes the form of a Schrödinger equation

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

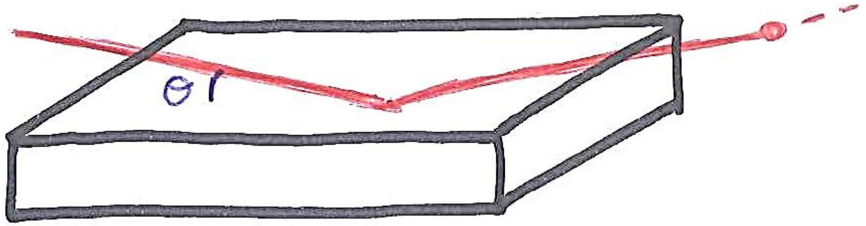
Optical Fermi potential

$$V_F(\vec{r}) = \frac{2\pi\hbar^2}{m} b n(\vec{r})$$

There is more on this, see textbooks



Repulsive optical potential? Neutron mirrors??



For positive b,
the optical potential of the material is repulsive

=> total reflection of neutrons for $E \sin^2 \theta < V_F$

COLLIMATION OF NEUTRON BEAM FROM THERMAL COLUMN OF CP–3 AND THE INDEX OF REFRACTION FOR THERMAL NEUTRONS

E. FERMI and W. H. ZINN
Excerpt from Report CP–1965 for Month Ending July 29, 1944.

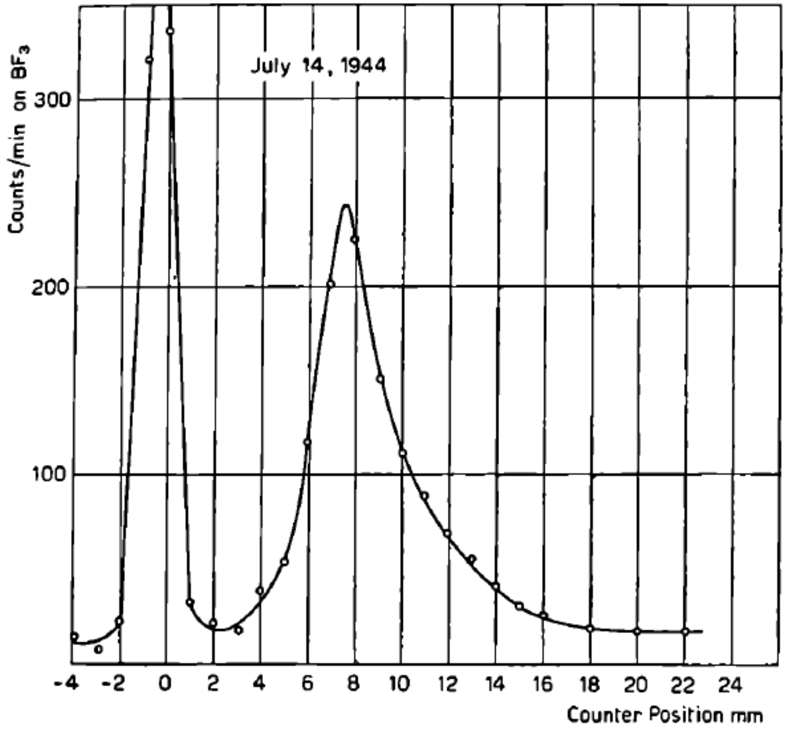


Fig. 1. – Graphite mirror. Glancing angle 3 minutes. Refected beam displaced 0.8 cm.

Interference Phenomena of Slow Neutrons

E. Fermi and L. Marshall
Argonne National Laboratory and University of Chicago, Chicago, Illinois
(Received February 7, 1947)

Various experiments involving interference of slow neutrons have been performed in order to determine the phase of the scattered neutron wave with respect to the primary neutron wave. Theoretically this phase change is very close to either 0° or 180°. The experiments show that with few exceptions the latter is the case.

$b < 0$ $b > 0$

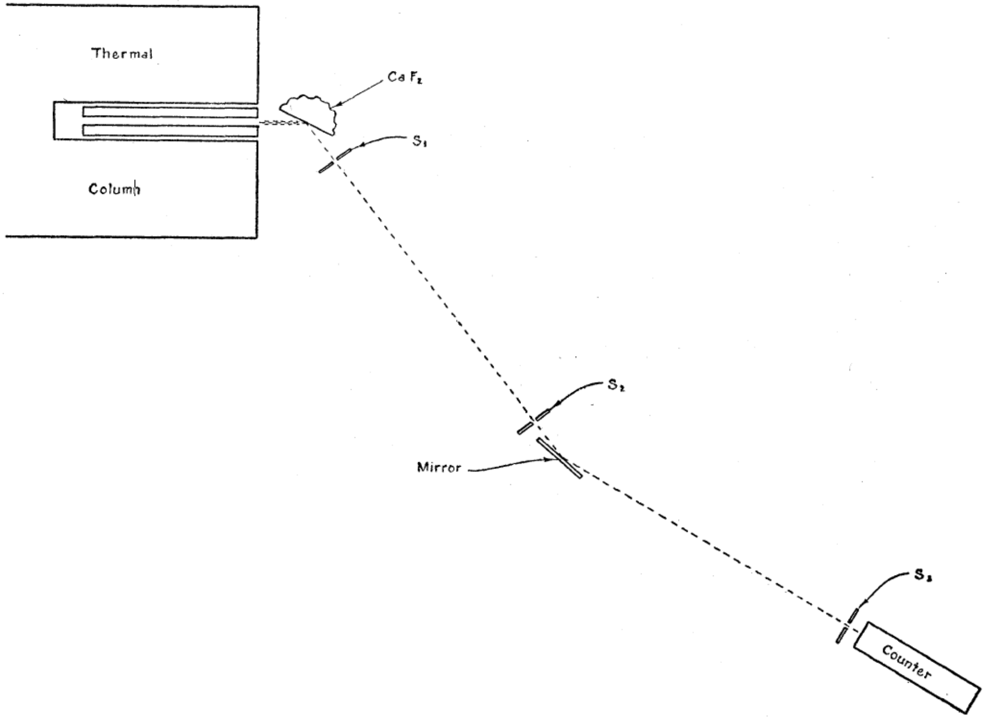


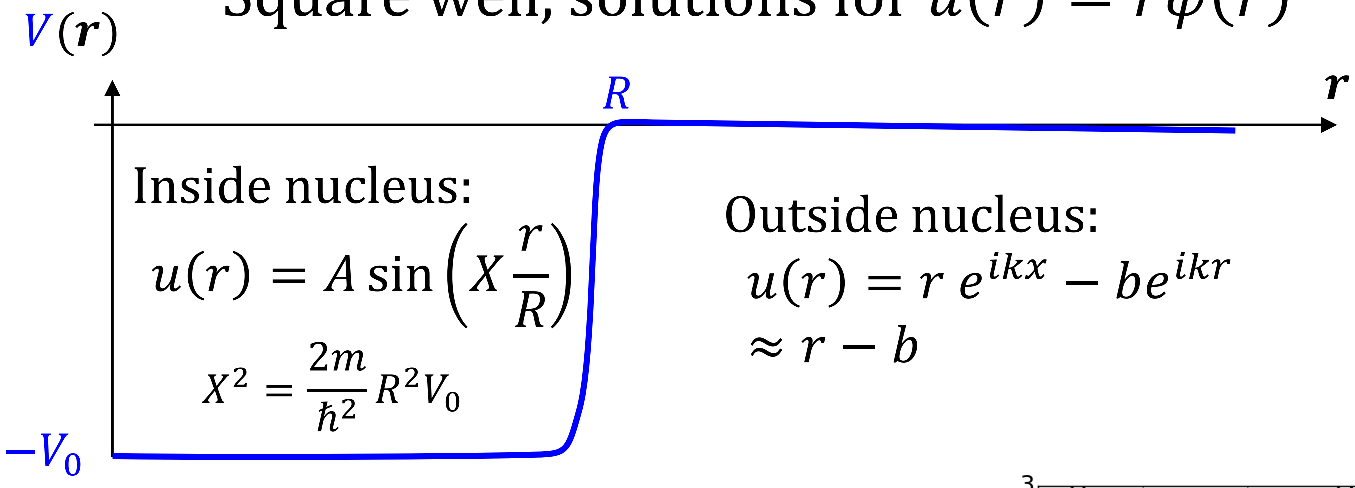
Fig. 4. Monochromatic total reflection on mirrors.

Table VI. Limiting angle for total reflection of neutrons of 1.873A.

Mirror	Limiting angle (minutes) Observed	Calculated
Be	12.0	11.1
C (graphite)	10.5	8.4
Fe	10.7	10.0
Ni	11.5	11.8
Zn	7.1	6.9
Cu	9.5	9.5

Understanding positive scattering lengths

Square well, solutions for $u(r) = r\psi(r)$



Inside nucleus:

$$u(r) = A\sin\left(X\frac{r}{R}\right)$$

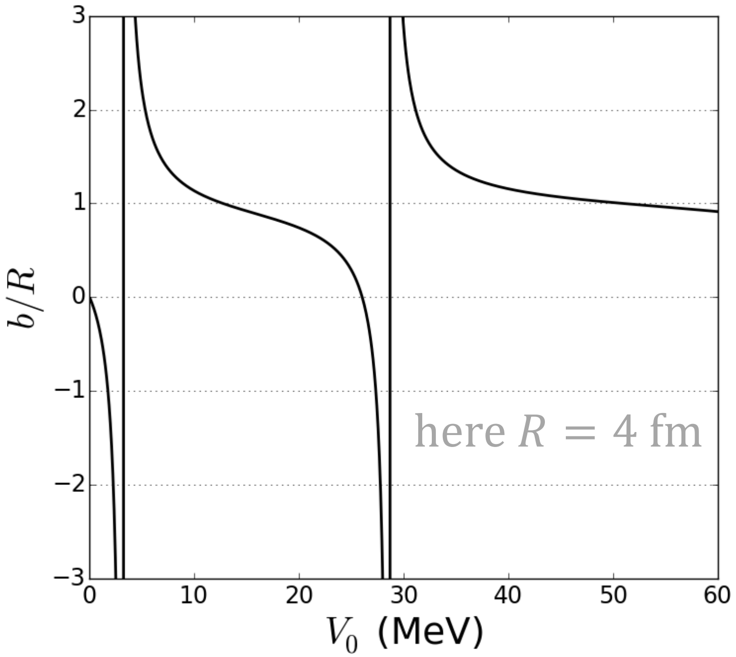
$$X^2 = \frac{2m}{\hbar^2}R^2V_0$$

Outside nucleus:

$$u(r) = r\,e^{ikx} - be^{ikr}$$
$$\approx r - b$$

Continuity of u and u' at the nuclear surface:

$$b = R\left(1 - \frac{\tan X}{X}\right)$$



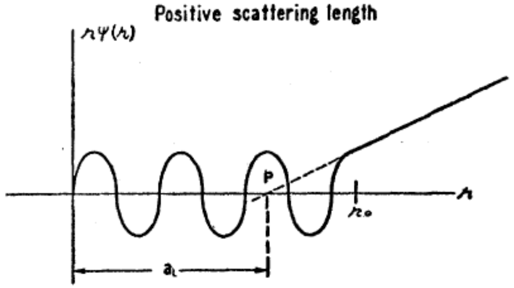


FIG. 1A. Positive scattering length.

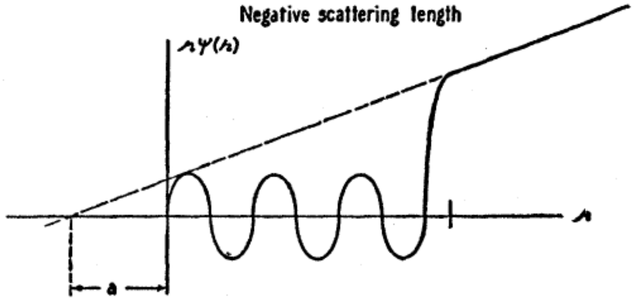


FIG. 1B. Negative scattering length.

Measured scattering lengths, from
www.ncnr.nist.gov/resources/n-lengths

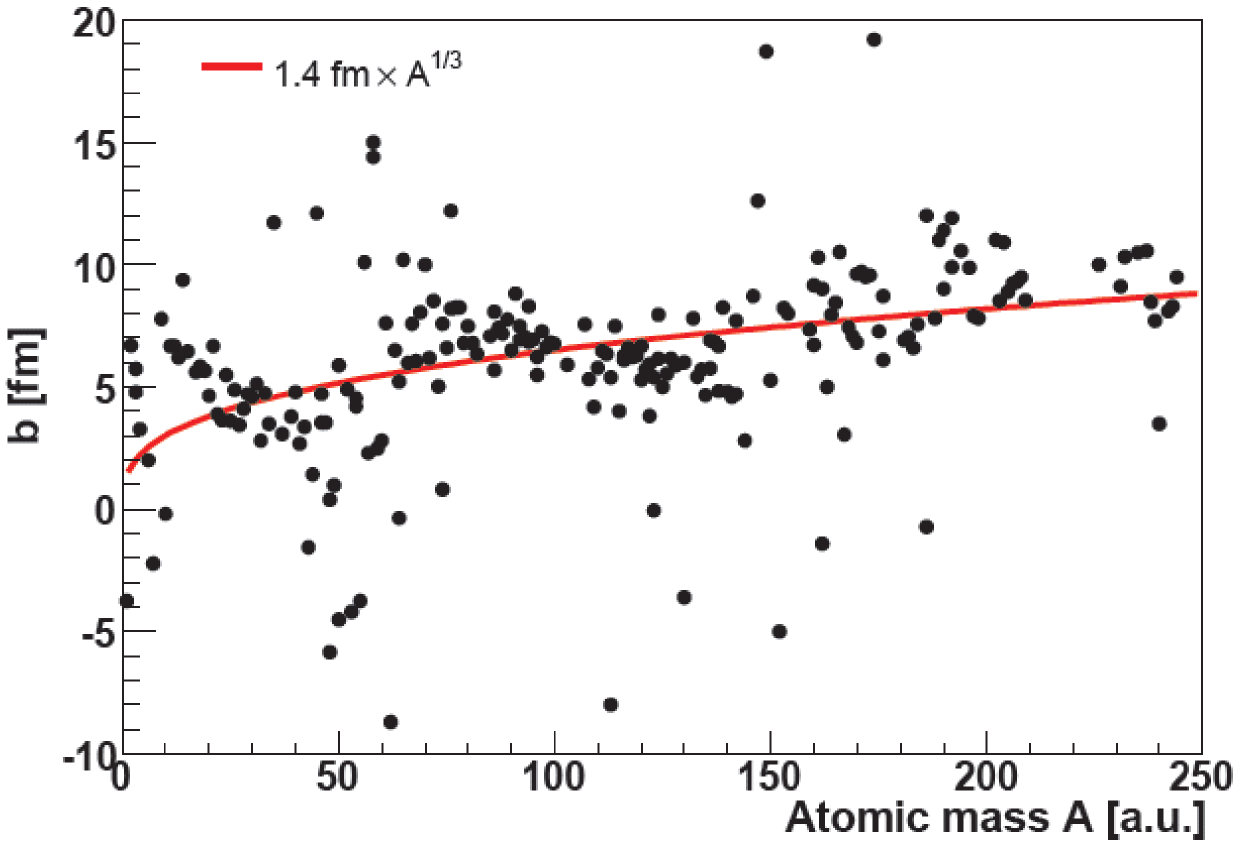
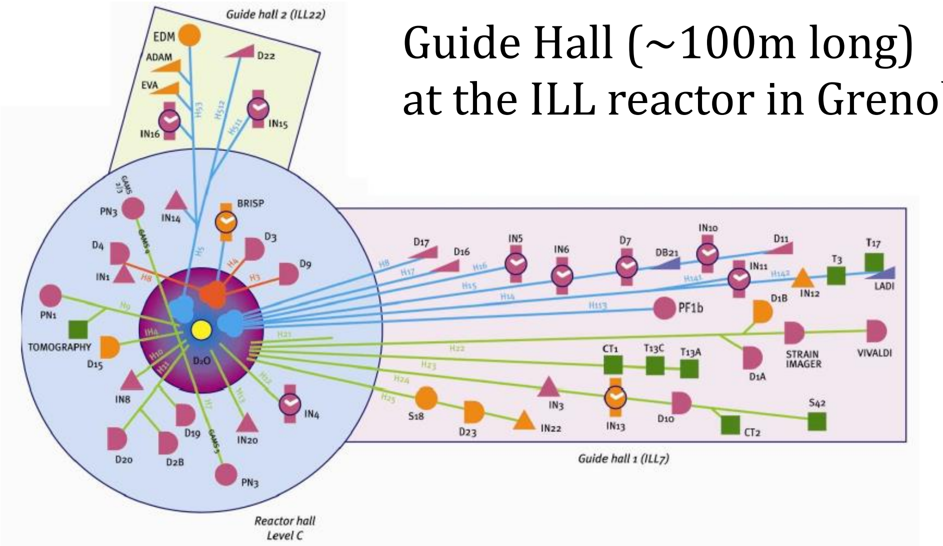


Table of optical Fermi potentials for common materials

Element	$\rho_{g/cc}$	$N_{form/cc}$ $\times 10^{22}$	$\sum_{form} a_{coh}^{bound}$ $\times 10^{-13}$ cm	V_{neV}
Ni^{58}	8.8	9.0	14.4	335
BeO	3.0	7.25	13.6	261
Ni	8.8	9.0	10.6	252
Be	1.83	12.3	7.75	252
Cu^{65}	8.5	8.93	11.0	244
Fe	7.9	8.5	9.7	210
C	2.0	10.0	6.6	180
Cu	8.5	8.93	7.6	168
PTFE (Teflon)	2.2	2.65	17.6	123
Pb	11.3	3.29	9.6	83
Al	2.7	6.02	3.45	54
Perspex $(CH_2H_3O)_n$	1.18	1.65	7.88	33.9
V	6.11	7.1	−0.382	−7.2
Polyethylene $(CH_2)_n$	0.92	3.9	−0.84	−8.7
H_2O	1.0	3.34	−1.68	−14.7
Ti	4.54	5.6	−3.34	−48

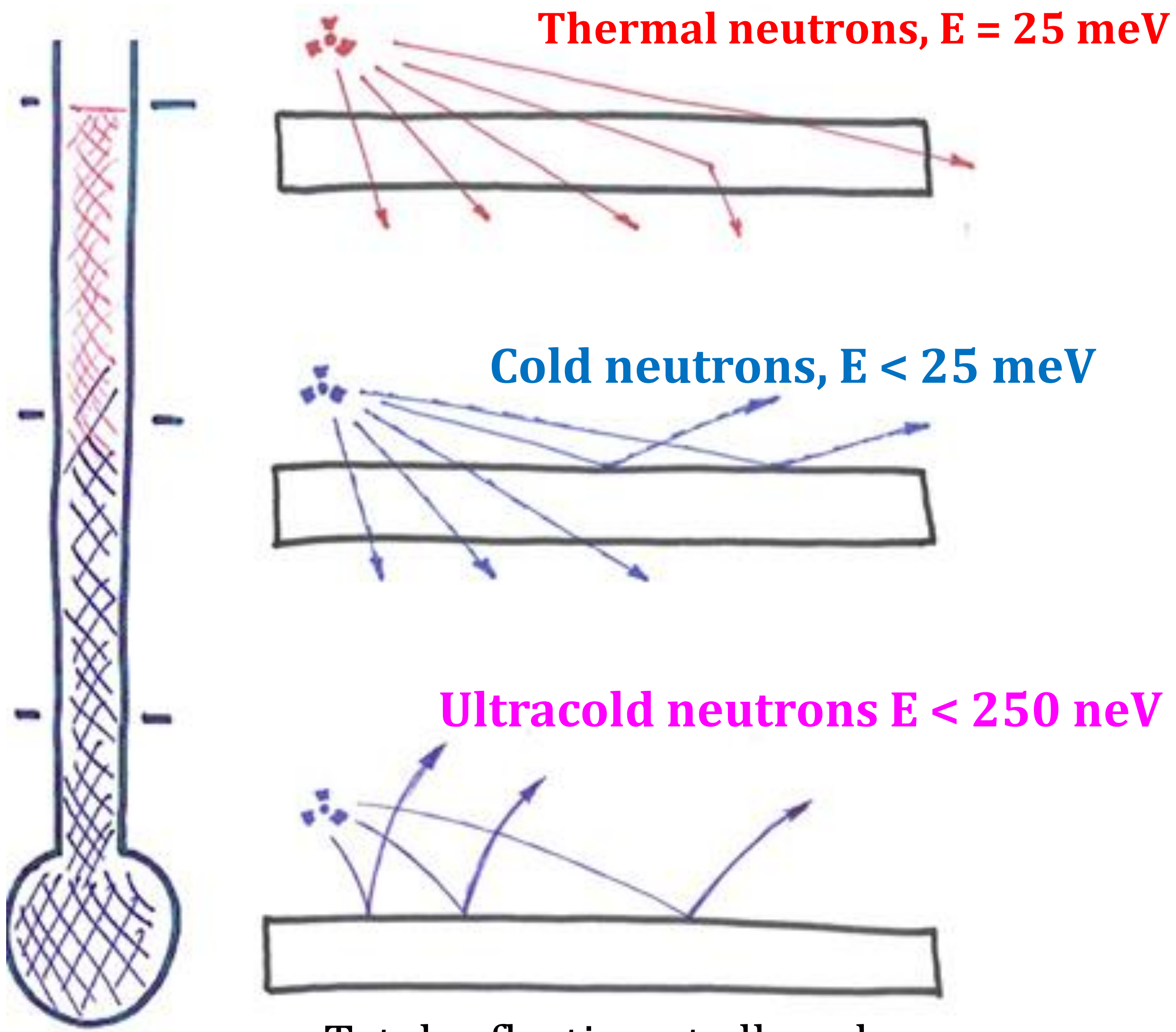
Application of neutron mirrors: neutron guides



Guide Hall (~100m long)
at the ILL reactor in Grenoble

“simply” evacuated rectangular pipes of nickel (or more fancy multilayer surfaces called super-mirrors) to transport thermal and cold neutrons from the reactor core to instruments.

Ultracold neutrons



Total reflection at all angles
(for suitable surfaces
such as nickel, steel, DLC, glass…)

Definition:
UCN = neutron with energy < 250 neV
= **neutron storable in material chambers**

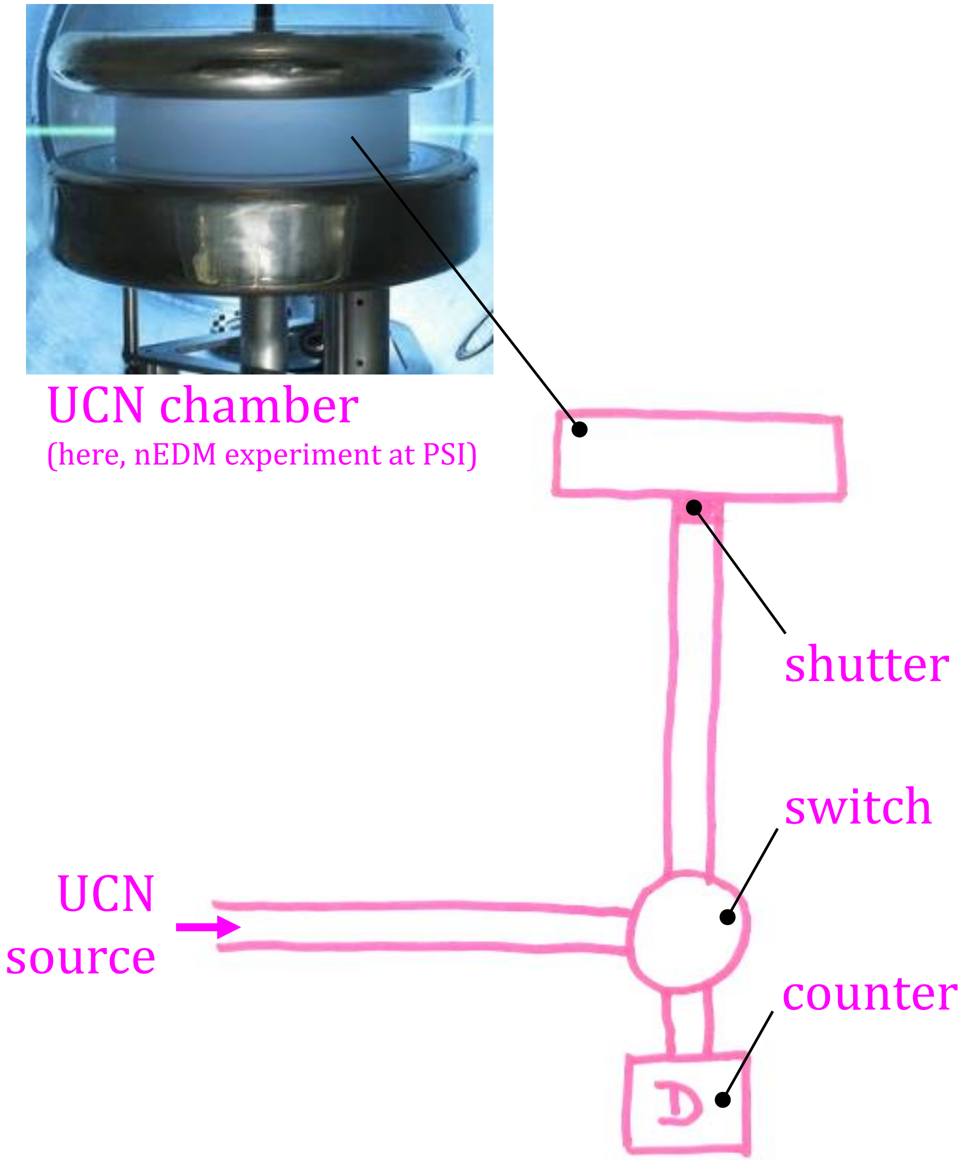
History:

- Predicted by Zeldovich in 1959
- Experimental realization in 1969
  by two groups in Dubna and Munich.

Properties:

- velocity < 7 m/s
- wavelength > 60 nm
- In Earth gravity : 1 cm <-> 1 neV

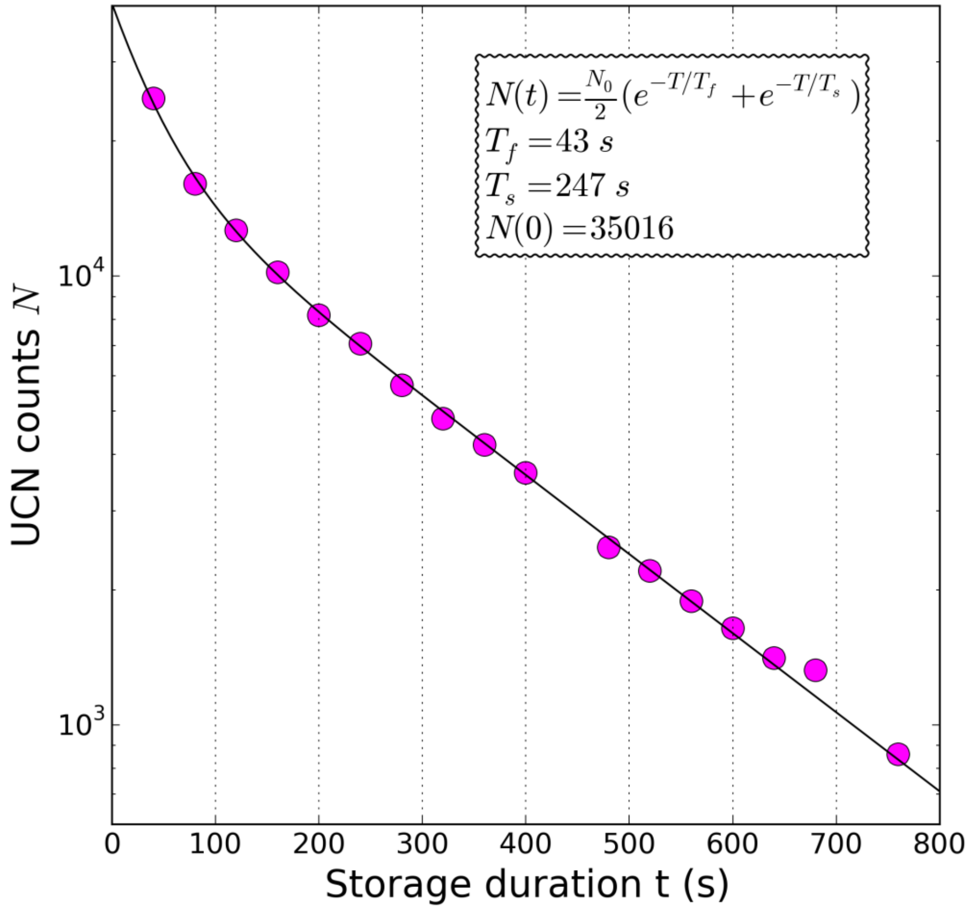
Storage of ultracold neutrons in chambers



Typical sequence:

1. Move switch to FILL position, Wait for neutrons.
2. Fill chamber for 30s, Close shutter.
3. Wait duration **t** . While waiting, Move switch to EMPTY
4. Open shutter, count neutrons for 30 s

Repeat, change **t**



Outline of the nEDM lecture

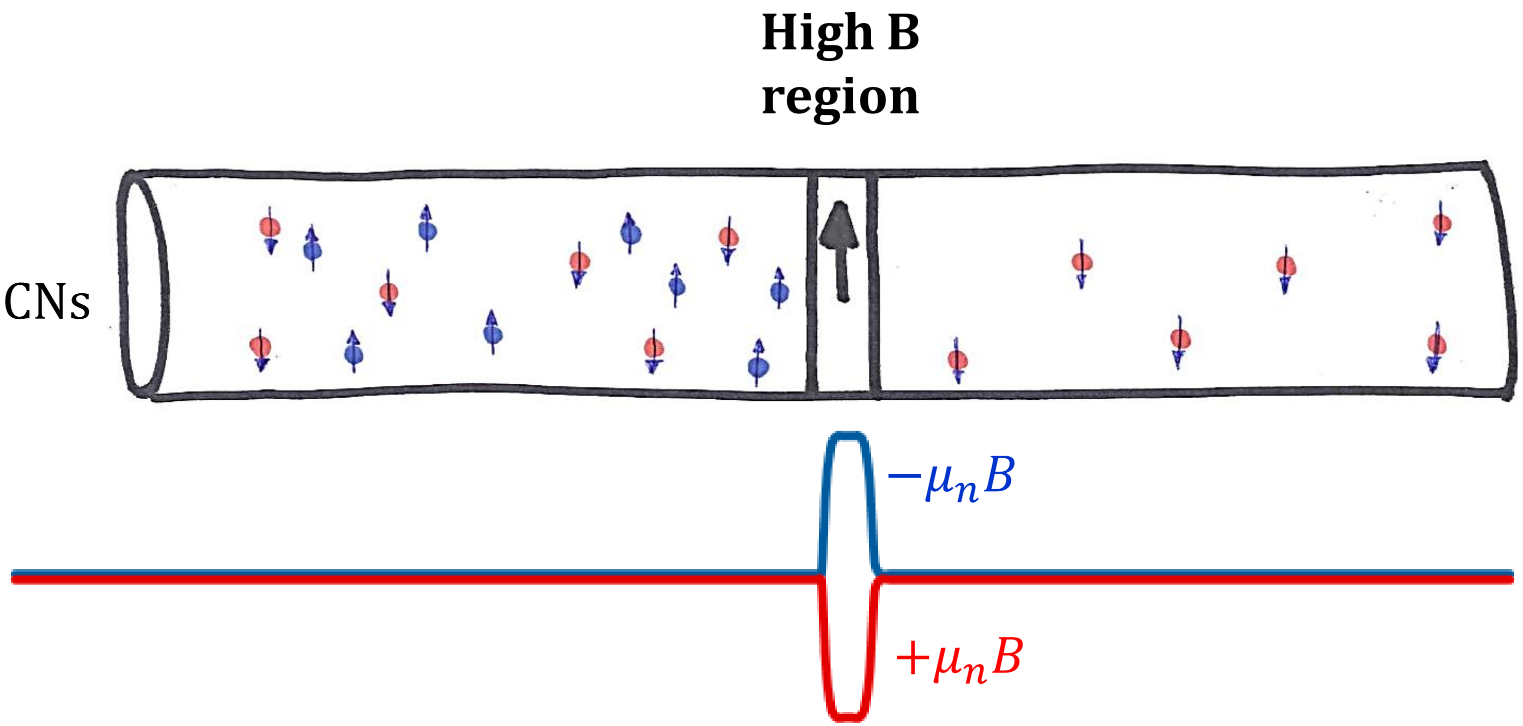
1. nEDM: What, Why? How?
2. Neutron optics, ultracold neutrons
3. Manipulating neutron spin
4. Past, present and future experiments

Basic principle to polarize / analyze UCNs

Recall the magnetic potential

$$\hat{H} = -\mu_n \, \vec{\sigma} \cdot \vec{B}$$
$$\mu_n = -60 \text{ neV/T}$$

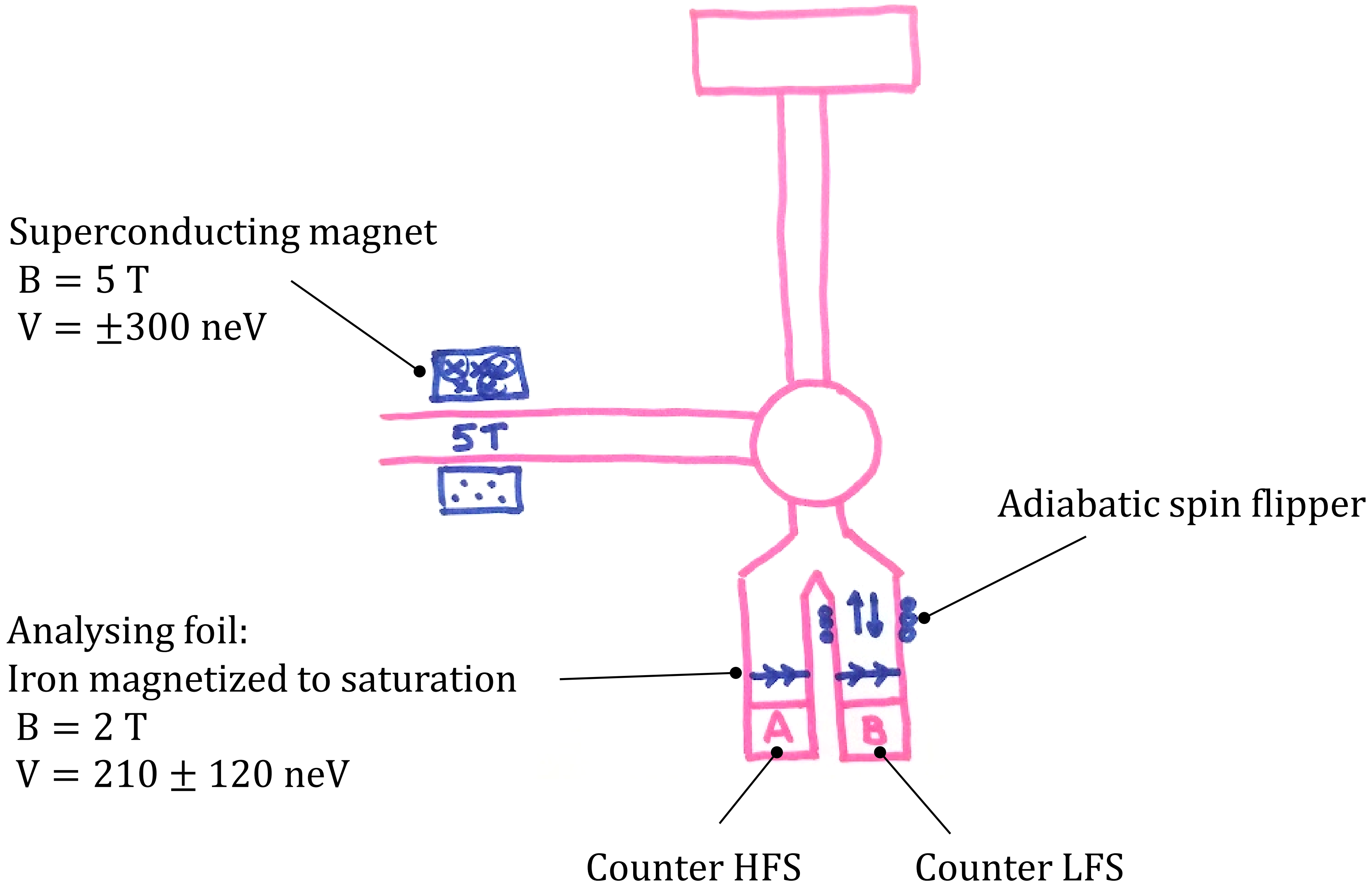
Input:
unpolarized UCNs



Output: polarized UCNs

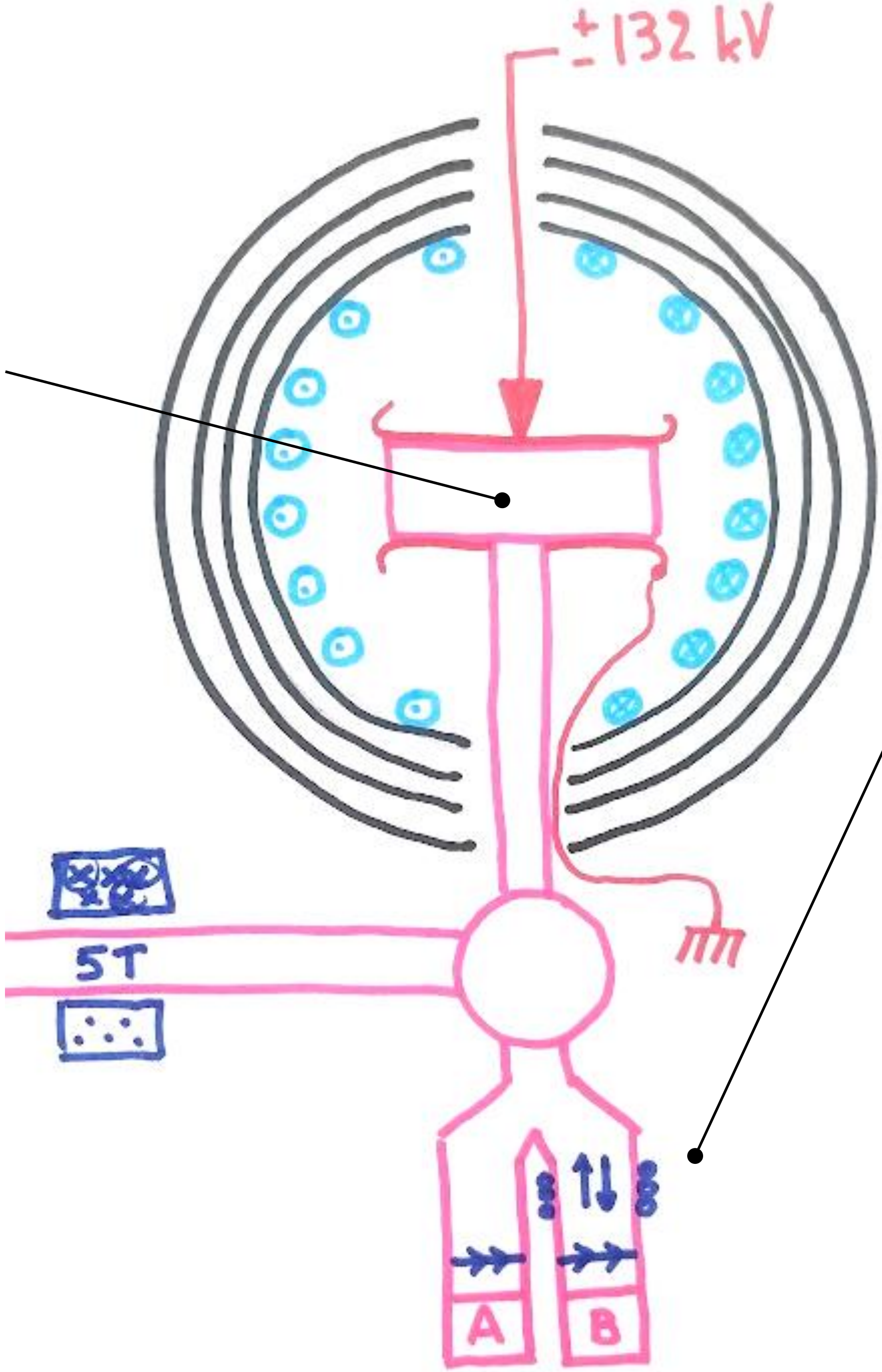
Only the "high field seekers" are transmitted.
The "low field seekers" are reflected back.

Polarizer - analyze scheme



At this stage of the story:

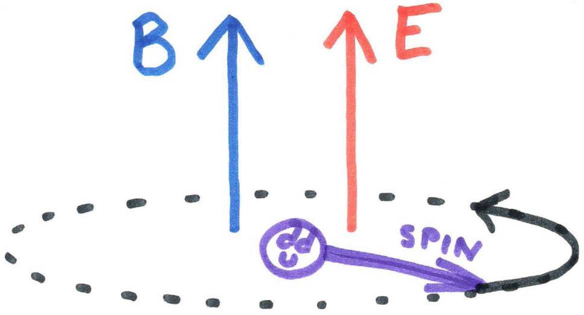
we get polarized ultracold neutrons exposed to vertical B and E fields there.



At the end, we can analyze the spin by counting

N_A and N_B

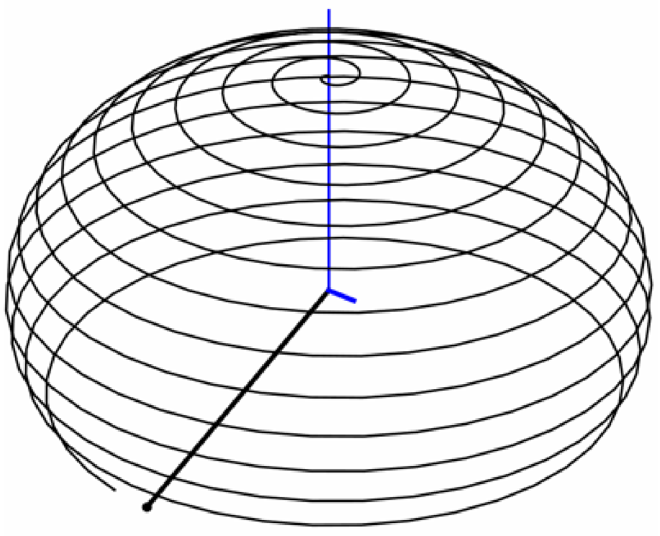
Now: how can we measure the Larmor frequency ??



$$2\pi f = \frac{2\mu_n}{\hbar} B \pm \frac{2d_n}{\hbar} |E|$$

Rabi oscillation

Apply a rotating transverse field
$\vec{B}(t) = B_0 \overrightarrow{e_z} + B_1 (\cos \omega t\, \overrightarrow{e_x} + \sin \omega t\, \overrightarrow{e_y})$
at resonance $\omega = \omega_0$



Bloch equation in the lab frame

$$\frac{d\vec{p}}{dt} = \gamma\, \vec{p} \times \vec{B}$$

Precession at the Larmor frequency

$$\frac{\omega_0}{2\pi} = \frac{\gamma B_0}{2\pi}$$

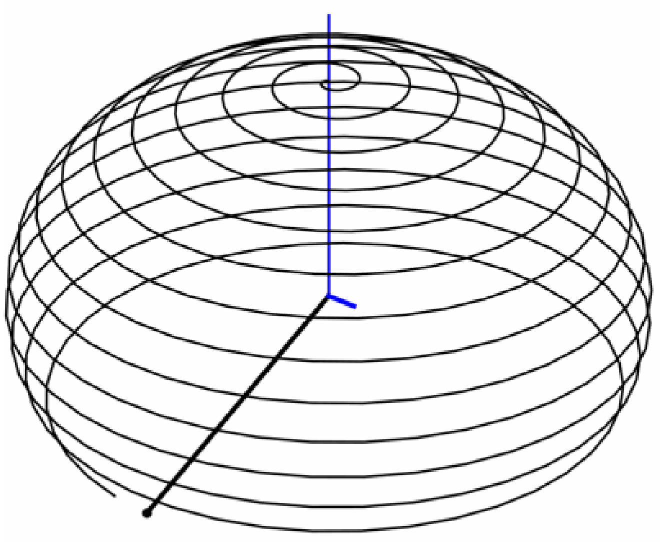
Nutation at the Rabi frequency

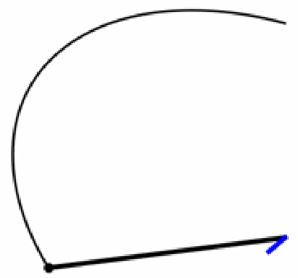
$$\frac{\Omega}{2\pi} = \frac{\gamma B_1}{2\pi}$$

**Formula for the out-of resonance case
$\Omega^2 = (\gamma B_1)^2 + (\omega_0 - \omega)^2$

Rabi oscillation

Apply a rotating transverse field
$\vec{B}(t) = B_0\vec{e_z} + B_1(\cos\omega t\,\vec{e_x} + \sin\omega t\,\vec{e_y})$
at resonance $\omega = \omega_0$





Bloch equation in the lab frame

$$\frac{d\vec{p}}{dt} = \gamma\,\vec{p} \times \vec{B}$$

Bloch equation in the rotating frame

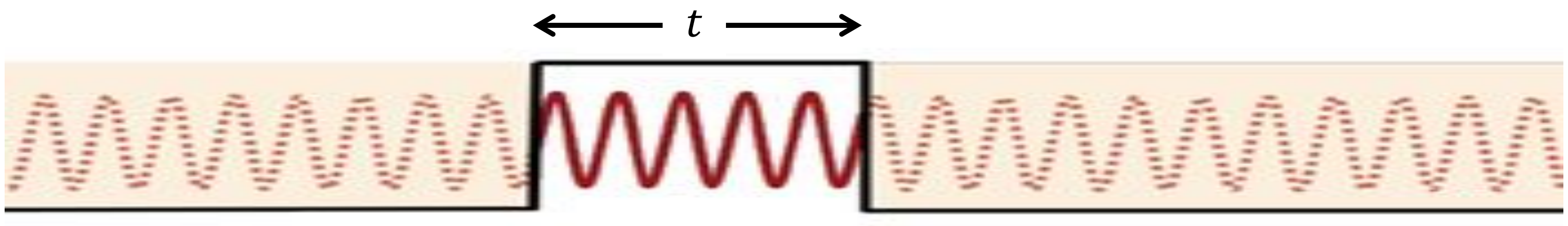
$$\frac{d\vec{p}\prime}{dt} = \gamma\,\vec{p}' \times \left(\vec{B}' - \frac{\vec{\omega}}{\gamma}\right)$$

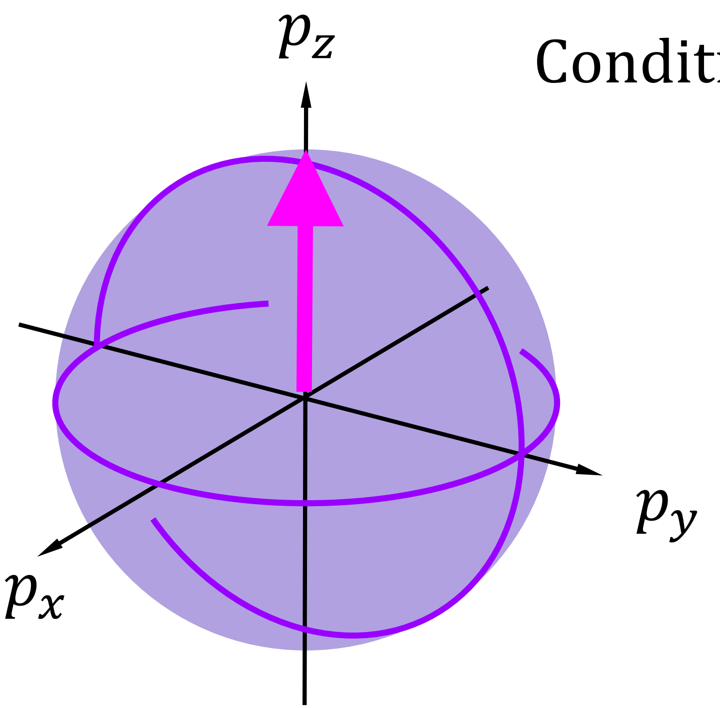
$\vec{B}'(t) = B_0\vec{e_z} + B_1\vec{e_x}'$

Inertial field

The pi/2 pulse

B_1

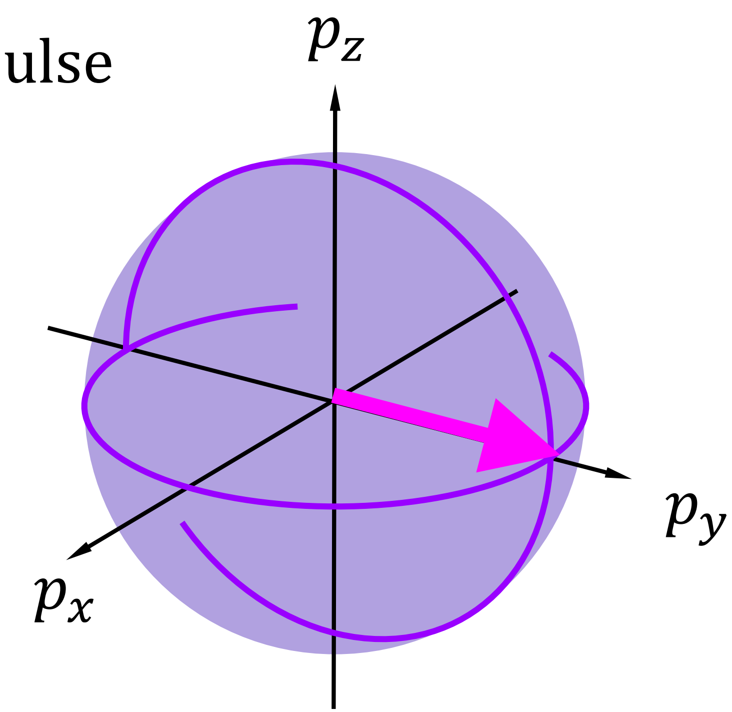




Before pulse

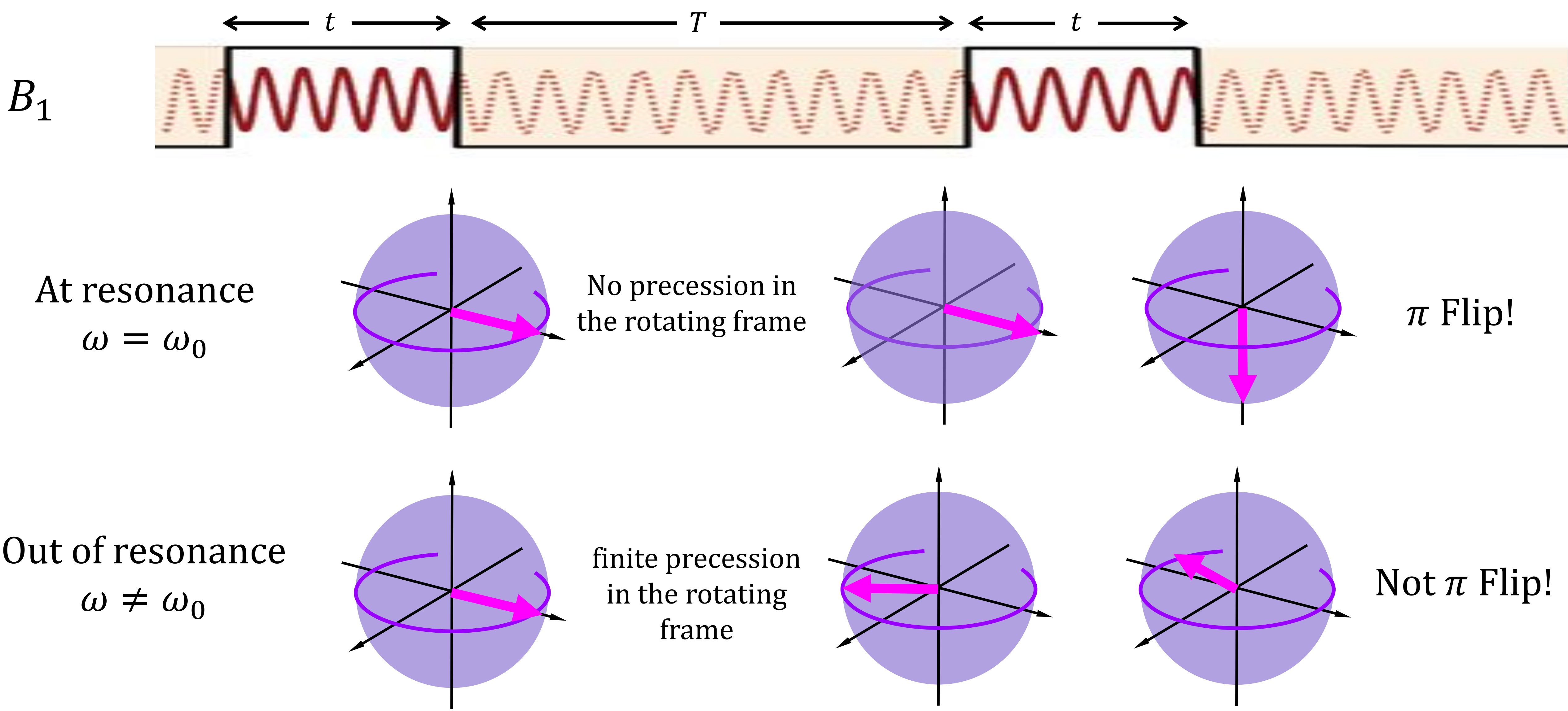
Condition for $\pi/2$ pulse

$$\gamma B_1 t = \frac{\pi}{2}$$



After pulse
In the rotating frame

Ramsey's method of separated oscillating fields



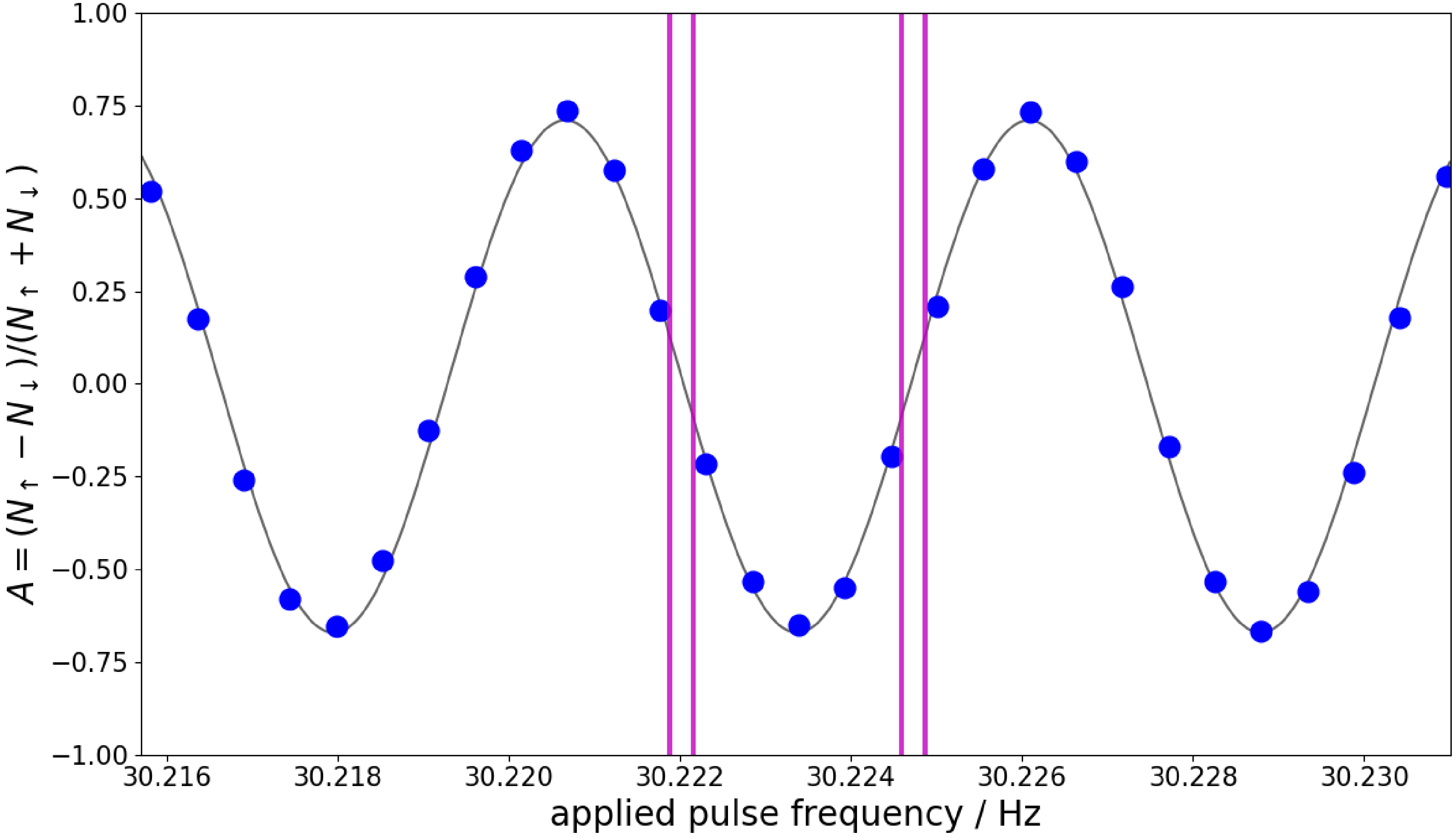
Ramsey's method of separated oscillating fields

$$A = -\alpha \cos\left(\pi \frac{f_{RF} - f_n}{\Delta\nu}\right) \qquad \frac{1}{\Delta\nu} = 2T + 8t/\pi$$

Ramsey scan measured with the nEDM apparatus at PSI in 2017

$T = 180$ s
$t = 2$ s

$B_0 \approx 1\ \mu T$
$f_n = \frac{\gamma B_0}{2\pi} \approx 30$ Hz



From UCN counts to EDM

$$A = -\alpha \cos\left(\pi \frac{(f_{\mathrm{RF}} - f_n)}{\Delta\nu}\right) \rightarrow f_n = f_{\mathrm{RF}} \mp \frac{\Delta\nu}{\pi} \arccos\left(\frac{N_\uparrow - N_\downarrow}{\alpha N_{\mathrm{tot}}}\right)$$

$$f_n = \left|\frac{\gamma B_0}{2\pi}\right| \mp \frac{d_n}{\pi\hbar}|E|$$

Exercise :
propagate the statistical errors from UCN counts to EDM

Solution: $\sigma d_n = \dfrac{\hbar}{2\ \alpha\ E\ T\ \sqrt{N}}$ (statistical error per cycle)

In the real life α<1, why?

The “visibility” or “contrast” of the Ramsey resonance

$$\alpha(T) = \boxed{\alpha_0} \times 1 \times \boxed{\frac{\alpha(T)}{\alpha_0}}$$

α_0 analyzing power of the detection system
$\alpha_0 = 0.86$ in the nEDM experiment

Loss of polarization during UCN transport negligible If adiabaticity condition fulfilled

Depolarization during UCN storage

Depolarization during storage, simplified

Simplified case: consider a group of monoenergetic UCNs

$$\frac{\alpha(T)}{\alpha_0} = \exp\left(-\frac{T}{T_2}\right) \qquad \frac{1}{T_2} = \frac{1}{T_{2,\text{wall}}} + \frac{1}{T_{2,\text{mag}}}$$

Depolarization due to wall collisions

$$\frac{1}{T_{2,\text{wall}}} = \nu\,\beta$$

Rate of wall collisions (ν) $\approx 50/\text{s}$

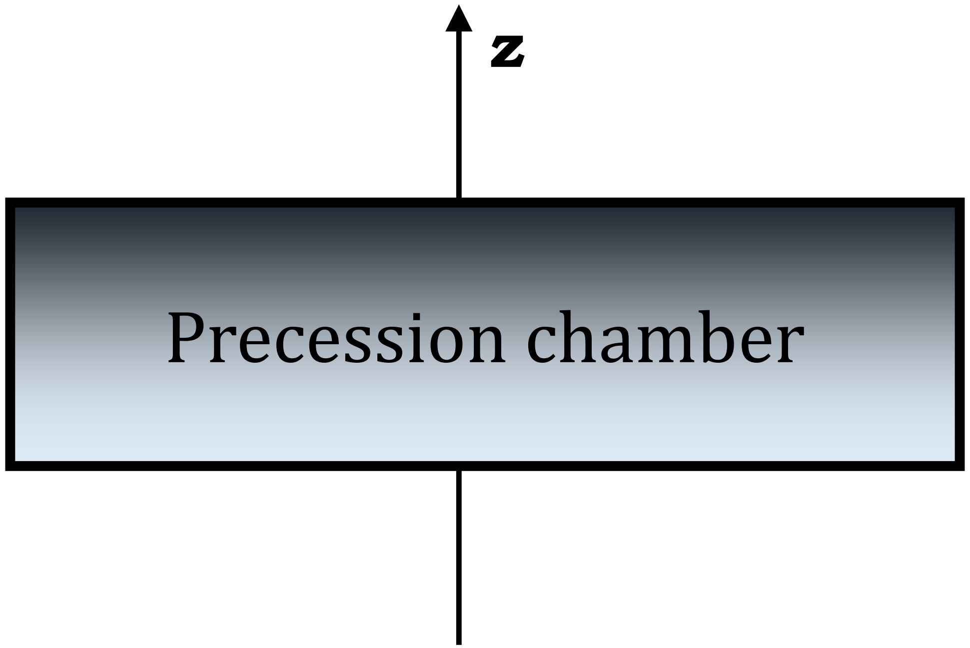
Depolarization probability (β) $\approx 3 \times 10^{-6}$

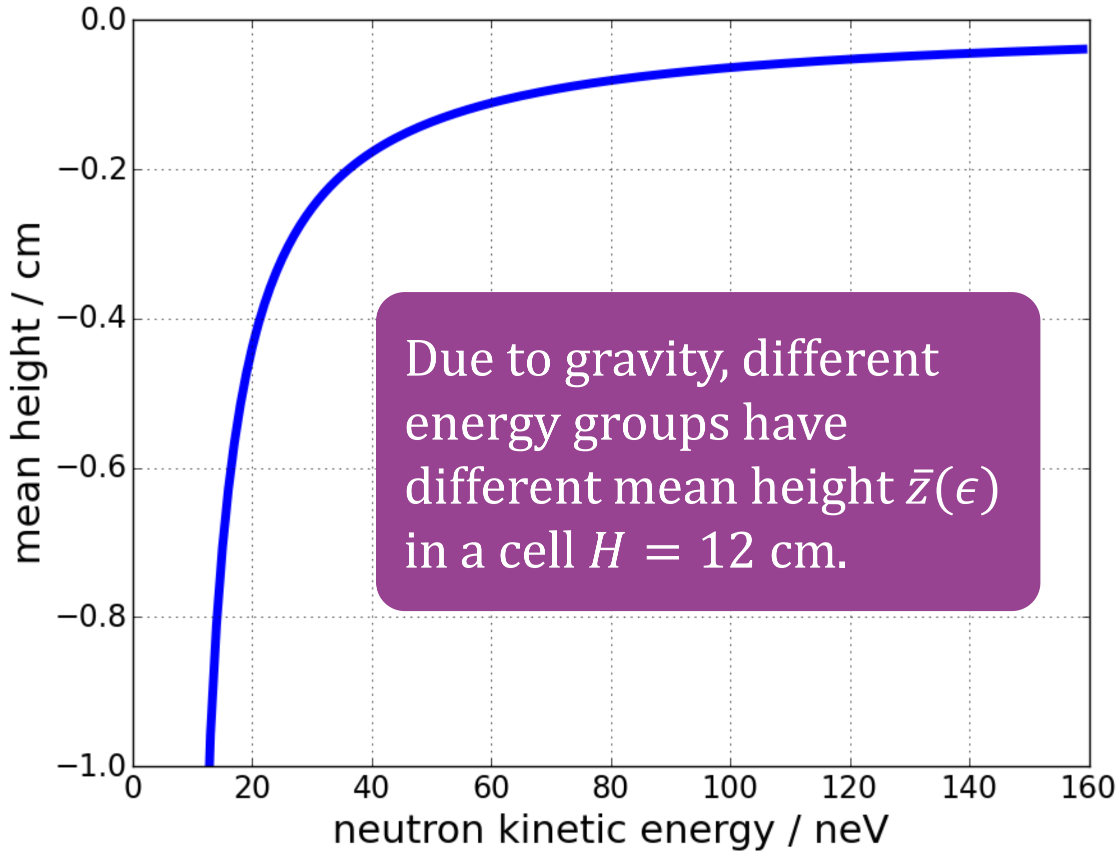
Intrinsic depolarization due to magnetic gradients

$$\frac{1}{T_{2,\text{mag}}} = \gamma^2 \int_0^\infty \langle B_z(t) B_z(t+\tau)\rangle\, d\tau$$

Autocorrelation function of the field

Gravitationally enhanced depolarization





Phase for the group of energy ϵ

$$\varphi(\epsilon) = \gamma_n \, G \, (\bar{z}(\epsilon) - \langle z \rangle) T$$

Vertical field gradient

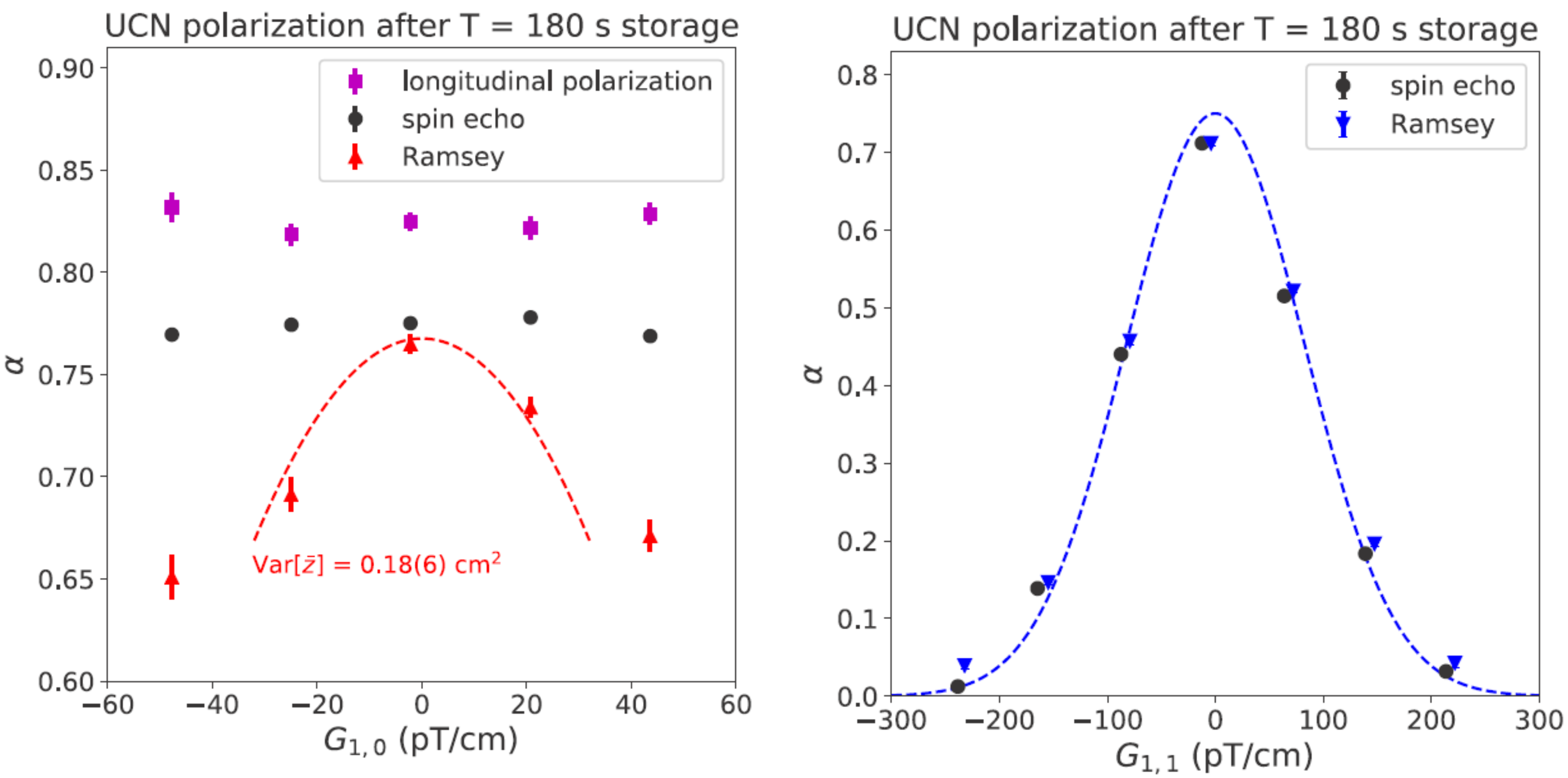
UCN depolarization: complete picture

$$\alpha(T) = \alpha_0 \int n(\epsilon) d\epsilon \exp\left(-\frac{T}{T_2(\epsilon)}\right) \cos(\gamma_n G(\bar{z}(\epsilon) - \langle z \rangle) T)$$

For details see

Magnetic-field uniformity in neutron electric-dipole-moment experiments

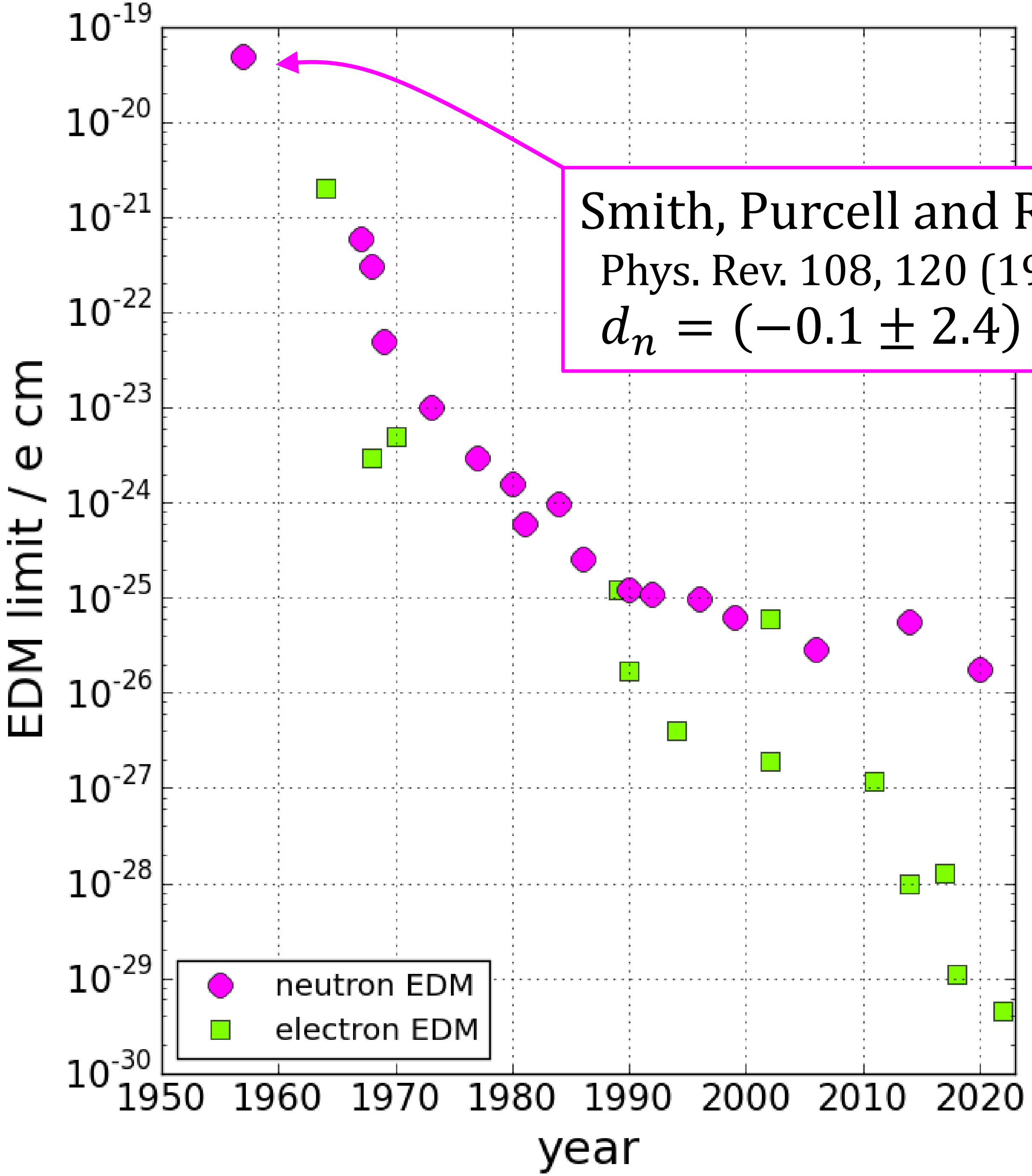
Phys. Rev.A **99**, 042112 (2019)



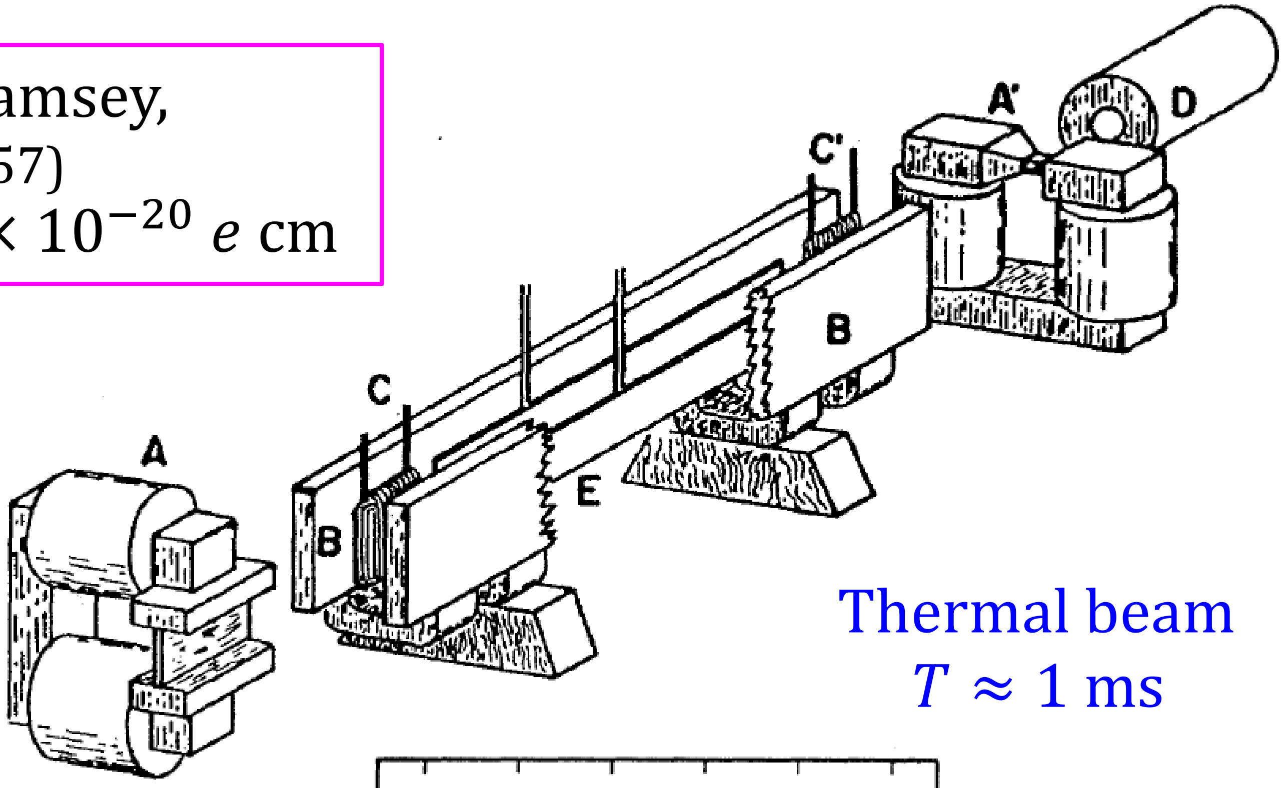
Outline of the nEDM lecture

1. nEDM: What, Why? How?
2. Neutron optics, ultracold neutrons
3. Manipulating neutron spin
4. **Past, present and future experiments**

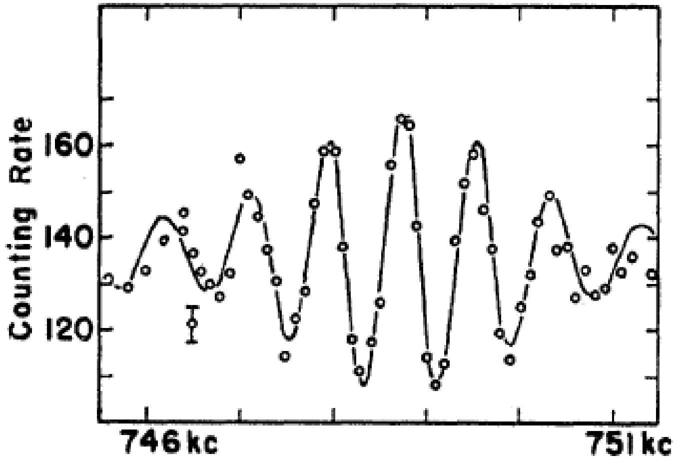
First nEDM experiment



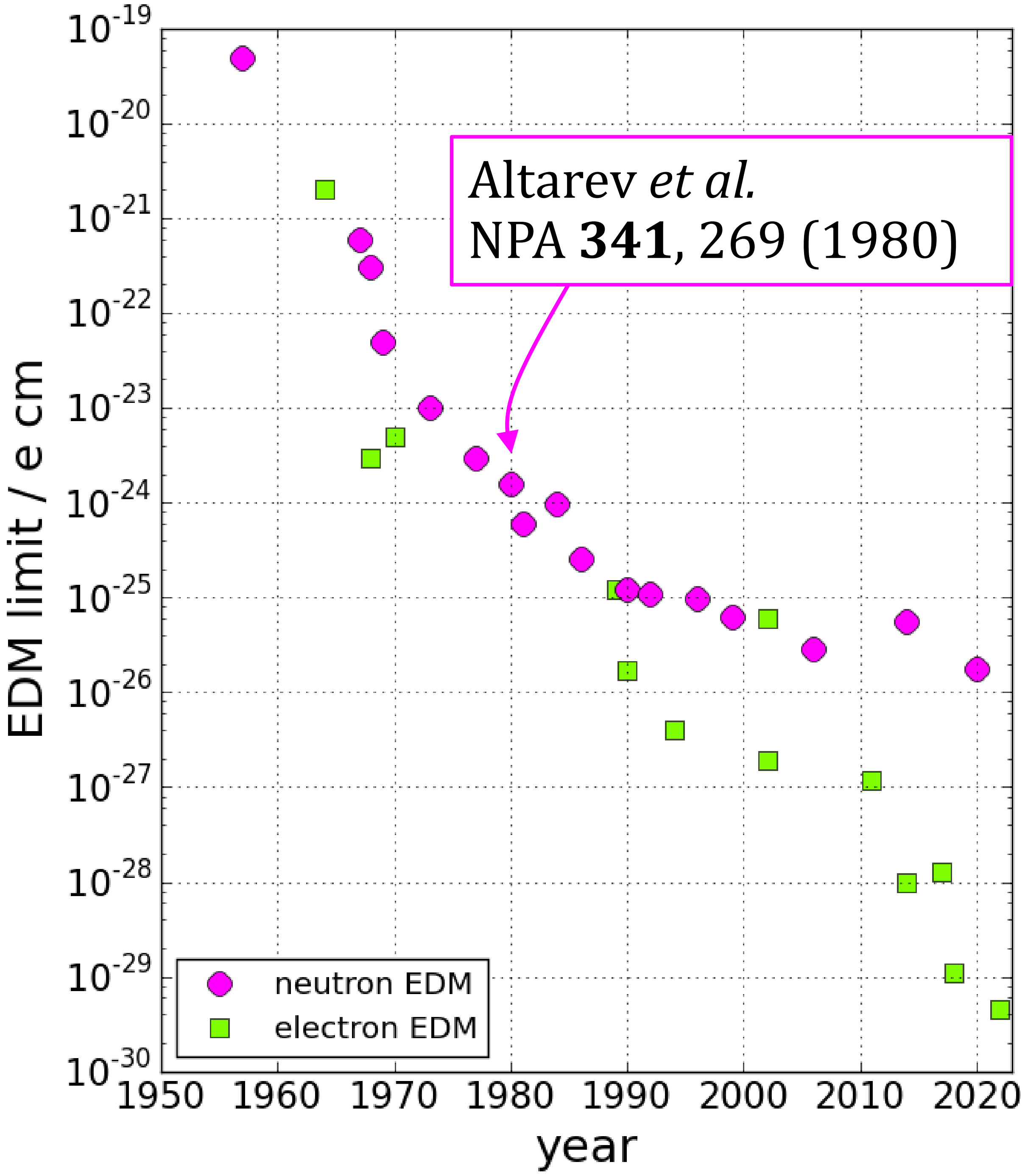
Smith, Purcell and Ramsey,
Phys. Rev. 108, 120 (1957)
$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ e\ \mathrm{cm}$



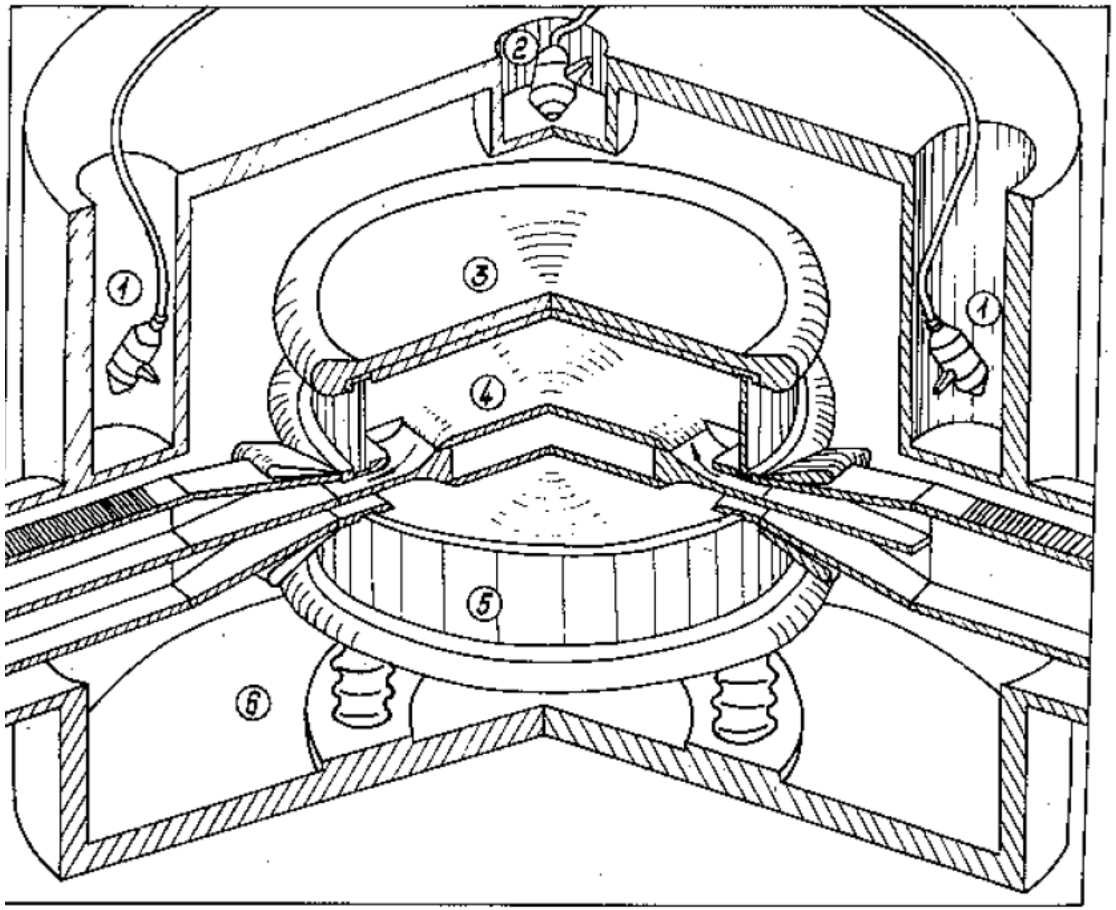
Thermal beam
$T \approx 1$ ms

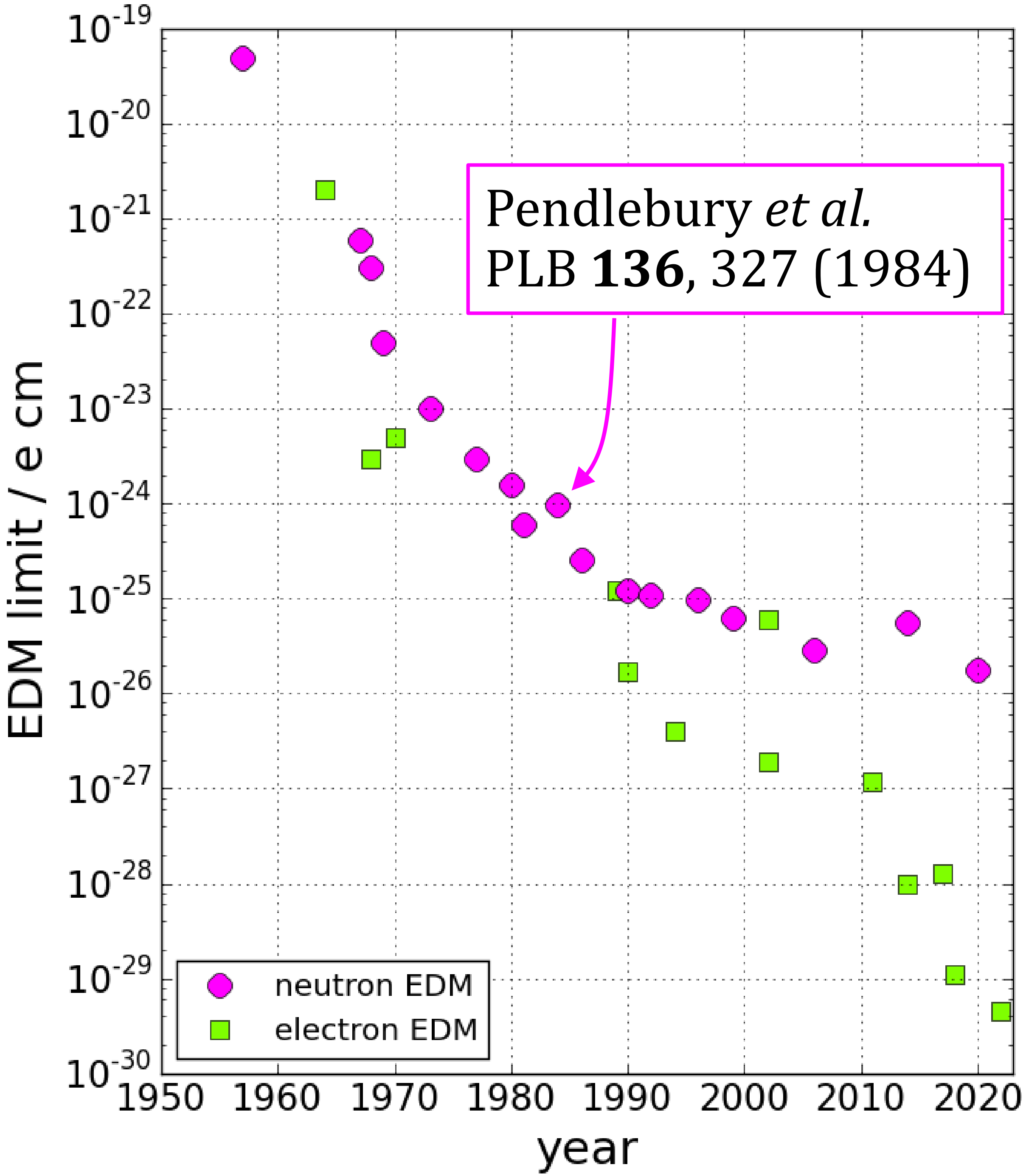


First UCN nEDM experiment



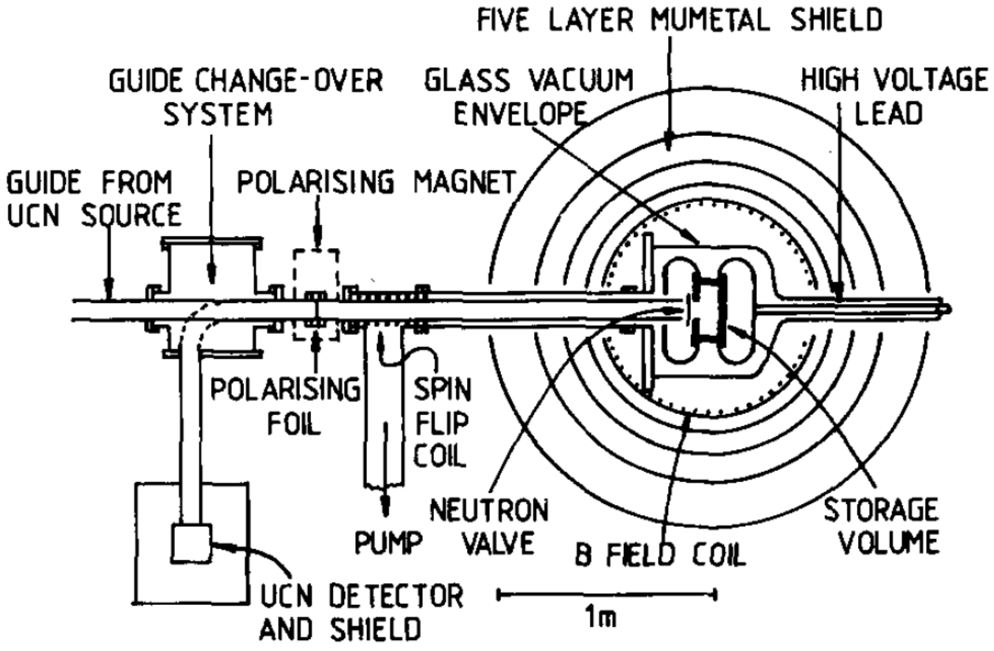
UCN flow through,
double chamber, $T \approx 5\ s$

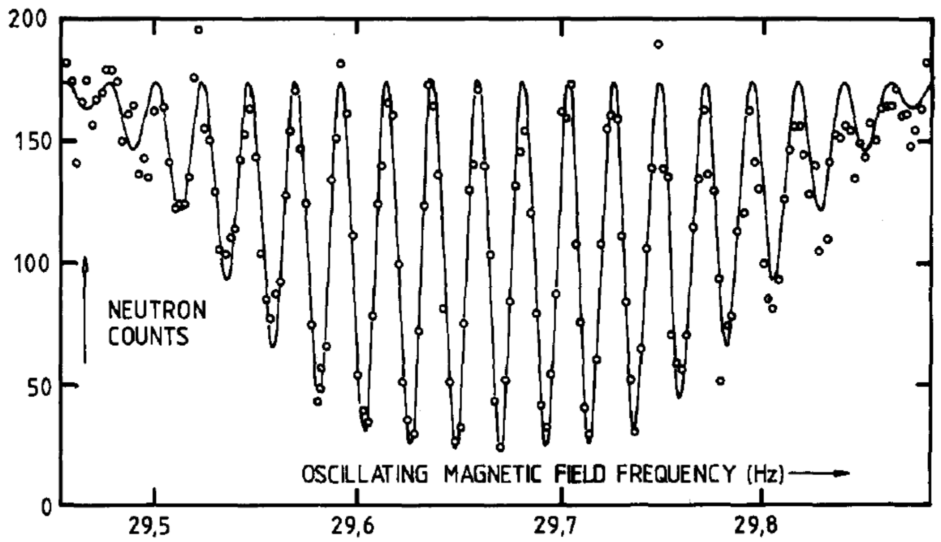




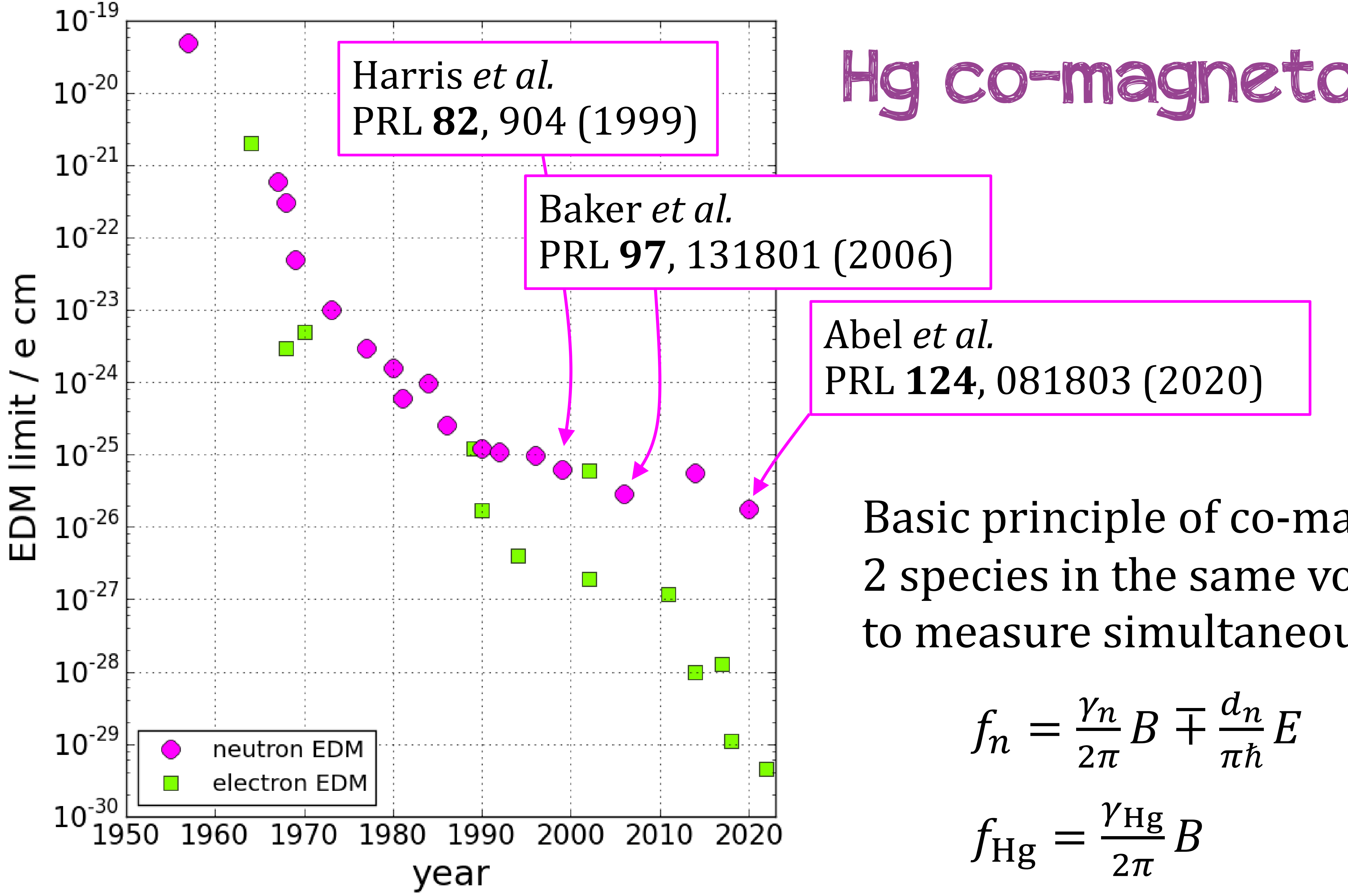
Stored UCNs

$T = 60$ s





Hg co-magnetometry

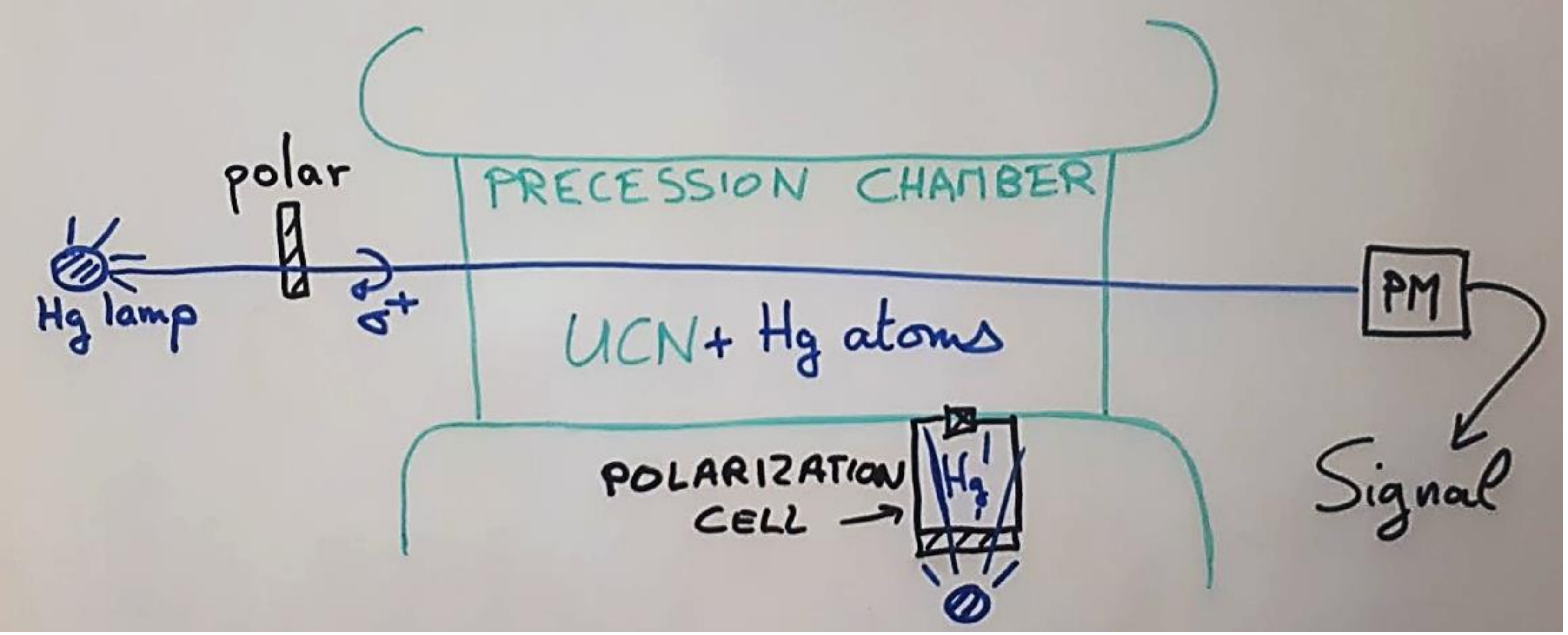


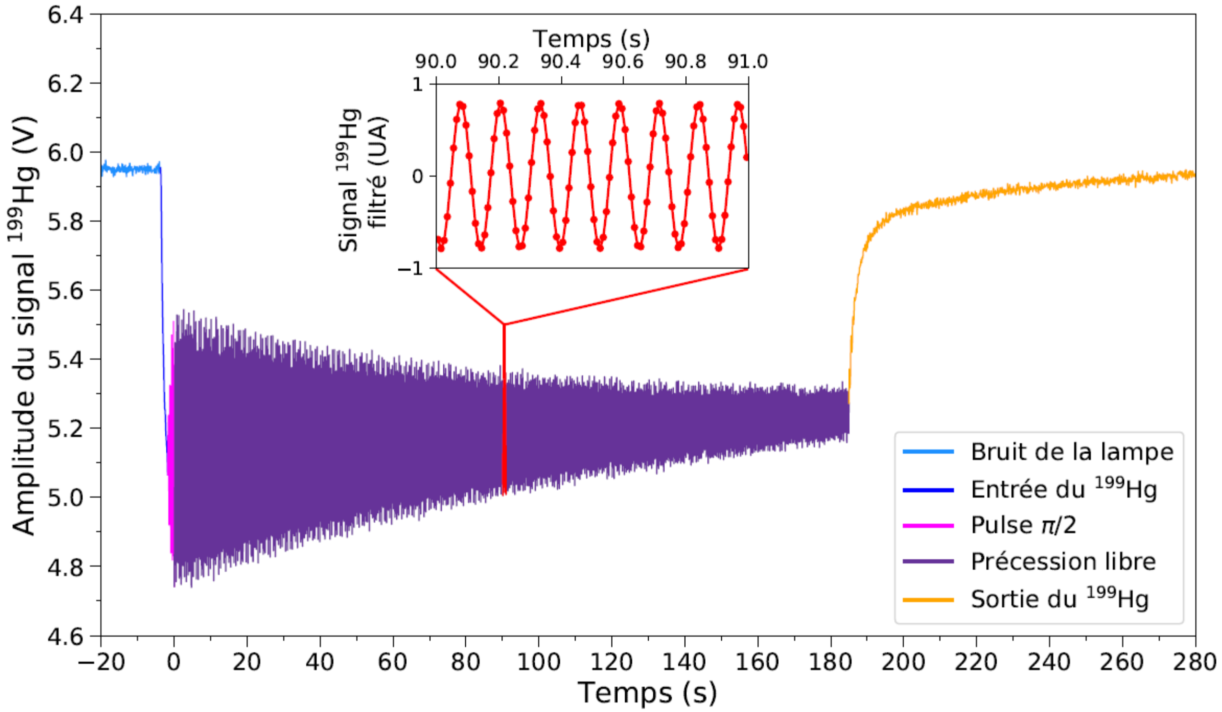
Basic principle of co-magnetometry:
2 species in the same volume
to measure simultaneously

$$f_n = \frac{\gamma_n}{2\pi} B \mp \frac{d_n}{\pi\hbar} E$$

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

Atomic comagnetometry with ^{199}Hg





Principle of **optical reading** of the precession:

photon spin → atom spin → : absorption of light forbidden by angular momentum conservation

photon spin → atom spin ← : absorption of light allowed

Guess who is the best atom?

$_{1}$H $^{2}S_{1/2}$																	$_{2}$He $^{1}S_{0}$
$_{3}$Li $^{2}S_{1/2}$	$_{4}$Be $^{1}S_{0}$											$_{5}$B $^{2}P_{1/2}$	$_{6}$C $^{3}P_{0}$	$_{7}$N $^{4}S_{3/2}$	$_{8}$O $^{3}P_{2}$	$_{9}$F $^{2}P_{3/2}$	$_{10}$Ne $^{1}S_{0}$
$_{11}$Na $^{2}S_{1/2}$	$_{12}$Mg $^{1}S_{0}$											$_{13}$Al $^{2}P_{1/2}$	$_{14}$Si $^{3}P_{0}$	$_{15}$P $^{4}S_{3/2}$	$_{16}$S $^{3}P_{2}$	$_{17}$Cl $^{2}P_{3/2}$	$_{18}$Ar $^{1}S_{0}$
$_{19}$K $^{2}S_{1/2}$	$_{20}$Ca $^{1}S_{0}$	$_{21}$Sc $^{2}D_{3/2}$	$_{22}$Ti $^{3}F_{2}$	$_{23}$V $^{4}F_{3/2}$	$_{24}$Cr $^{7}S_{3}$	$_{25}$Mn $^{6}S_{5/2}$	$_{26}$Fe $^{5}D_{4}$	$_{27}$Co $^{4}F_{9/2}$	$_{28}$Ni $^{3}F_{4}$	$_{29}$Cu $^{2}S_{1/2}$	$_{30}$Zn $^{1}S_{0}$	$_{31}$Ga $^{2}P_{1/2}$	$_{32}$Ge $^{3}P_{0}$	$_{33}$As $^{4}S_{3/2}$	$_{34}$Se $^{3}P_{2}$	$_{35}$Br $^{2}P_{3/2}$	$_{36}$Kr $^{1}S_{0}$
$_{37}$Rb $^{2}S_{1/2}$	$_{38}$Sr $^{1}S_{0}$	$_{39}$Y $^{2}D_{3/2}$	$_{40}$Zr $^{3}F_{2}$	$_{41}$Nb $^{6}D_{1/2}$	$_{42}$Mo $^{7}S_{3}$	$_{43}$Tc $^{6}S_{5/2}$	$_{44}$Ru $^{5}F_{5}$	$_{45}$Rh $^{4}F_{9/2}$	$_{46}$Pd $^{1}S_{0}$	$_{47}$Ag $^{2}S_{1/2}$	$_{48}$Cd $^{1}S_{0}$	$_{49}$In $^{2}P_{1/2}$	$_{50}$Sn $^{3}P_{0}$	$_{51}$Sb $^{4}S_{3/2}$	$_{52}$Te $^{3}P_{2}$	$_{53}$I $^{2}P_{3/2}$	$_{54}$Xe $^{1}S_{0}$
$_{55}$Cs $^{2}S_{1/2}$	$_{56}$Ba $^{1}S_{0}$	$_{71}$Lu $^{2}D_{3/2}$	$_{72}$Hf $^{3}F_{2}$	$_{73}$Ta $^{4}F_{3/2}$	$_{74}$W $^{5}D_{0}$	$_{75}$Re $^{6}S_{5/2}$	$_{76}$Os $^{5}D_{4}$	$_{77}$Ir $^{4}F_{9/2}$	$_{78}$Pt $^{3}D_{3}$	$_{79}$Au $^{2}S_{1/2}$	$_{80}$Hg $^{1}S_{0}$	$_{81}$Tl $^{2}P_{1/2}$	$_{82}$Pb $^{3}P_{0}$	$_{83}$Bi $^{4}S_{3/2}$	$_{84}$Po $^{3}P_{2}$	$_{85}$At $^{2}P_{3/2}$	$_{86}$Rn $^{1}S_{0}$

$_{57}$La $^{2}D_{3/2}$	$_{58}$Ce $^{1}G_{4}$	$_{59}$Pr $^{4}I_{9/2}$	$_{60}$Nd $^{5}I_{4}$	$_{61}$Pm $^{6}H_{5/2}$	$_{62}$Sm $^{7}F_{0}$	$_{63}$Eu $^{8}S_{7/2}$	$_{64}$Gd $^{9}D_{2}$	$_{65}$Tb $^{6}H_{15/2}$	$_{66}$Dy $^{5}I_{8}$	$_{67}$Ho $^{4}I_{15/2}$	$_{68}$Er $^{3}H_{6}$	$_{69}$Tm $^{2}F_{7/2}$	$_{70}$Yb $^{1}S_{0}$

- **We want a diamagnetic atom J = 0 (*)**

(*) J = total electronic angular momentum
For diamagnetic atoms, $\gamma \sim \gamma_n$. Paramagnetic atoms have a larger (~x1000) gyromagnetic ratio, they precess faster (fine) and depolarize faster (not ok to preserve the atomic polar for 3 min).

$_{1}$H $^{2}S_{1/2}$																	$_{2}$He $^{1}S_{0}$
$_{3}$Li $^{2}S_{1/2}$	$_{4}$Be $^{1}S_{0}$											$_{5}$B $^{2}P_{1/2}$	$_{6}$C $^{3}P_{0}$	$_{7}$N $^{4}S_{3/2}$	$_{8}$O $^{3}P_{2}$	$_{9}$F $^{2}P_{3/2}$	$_{10}$Ne $^{1}S_{0}$
$_{11}$Na $^{2}S_{1/2}$	$_{12}$Mg $^{1}S_{0}$											$_{13}$Al $^{2}P_{1/2}$	$_{14}$Si $^{3}P_{0}$	$_{15}$P $^{4}S_{3/2}$	$_{16}$S $^{3}P_{2}$	$_{17}$Cl $^{2}P_{3/2}$	$_{18}$Ar $^{1}S_{0}$
$_{19}$K $^{2}S_{1/2}$	$_{20}$Ca $^{1}S_{0}$	$_{21}$Sc $^{2}D_{3/2}$	$_{22}$Ti $^{3}F_{2}$	$_{23}$V $^{4}F_{3/2}$	$_{24}$Cr $^{7}S_{3}$	$_{25}$Mn $^{6}S_{5/2}$	$_{26}$Fe $^{5}D_{4}$	$_{27}$Co $^{4}F_{9/2}$	$_{28}$Ni $^{3}F_{4}$	$_{29}$Cu $^{2}S_{1/2}$	$_{30}$Zn $^{1}S_{0}$	$_{31}$Ga $^{2}P_{1/2}$	$_{32}$Ge $^{3}P_{0}$	$_{33}$As $^{4}S_{3/2}$	$_{34}$Se $^{3}P_{2}$	$_{35}$Br $^{2}P_{3/2}$	$_{36}$Kr $^{1}S_{0}$
$_{37}$Rb $^{2}S_{1/2}$	$_{38}$Sr $^{1}S_{0}$	$_{39}$Y $^{2}D_{3/2}$	$_{40}$Zr $^{3}F_{2}$	$_{41}$Nb $^{6}D_{1/2}$	$_{42}$Mo $^{7}S_{3}$	$_{43}$Tc $^{6}S_{5/2}$	$_{44}$Ru $^{5}F_{5}$	$_{45}$Rh $^{4}F_{9/2}$	$_{46}$Pd $^{1}S_{0}$	$_{47}$Ag $^{2}S_{1/2}$	$_{48}$Cd $^{1}S_{0}$	$_{49}$In $^{2}P_{1/2}$	$_{50}$Sn $^{3}P_{0}$	$_{51}$Sb $^{4}S_{3/2}$	$_{52}$Te $^{3}P_{2}$	$_{53}$I $^{2}P_{3/2}$	$_{54}$Xe $^{1}S_{0}$
$_{55}$Cs $^{2}S_{1/2}$	$_{56}$Ba $^{1}S_{0}$	$_{71}$Lu $^{2}D_{3/2}$	$_{72}$Hf $^{3}F_{2}$	$_{73}$Ta $^{4}F_{3/2}$	$_{74}$W $^{5}D_{0}$	$_{75}$Re $^{6}S_{5/2}$	$_{76}$Os $^{5}D_{4}$	$_{77}$Ir $^{4}F_{9/2}$	$_{78}$Pt $^{3}D_{3}$	$_{79}$Au $^{2}S_{1/2}$	$_{80}$Hg $^{1}S_{0}$	$_{81}$Tl $^{2}P_{1/2}$	$_{82}$Pb $^{3}P_{0}$	$_{83}$Bi $^{4}S_{3/2}$	$_{84}$Po $^{3}P_{2}$	$_{85}$At $^{2}P_{3/2}$	$_{86}$Rn $^{1}S_{0}$

$_{57}$La $^{2}D_{3/2}$	$_{58}$Ce $^{1}G_{4}$	$_{59}$Pr $^{4}I_{9/2}$	$_{60}$Nd $^{5}I_{4}$	$_{61}$Pm $^{6}H_{5/2}$	$_{62}$Sm $^{7}F_{0}$	$_{63}$Eu $^{8}S_{7/2}$	$_{64}$Gd $^{9}D_{2}$	$_{65}$Tb $^{6}H_{15/2}$	$_{66}$Dy $^{5}I_{8}$	$_{67}$Ho $^{4}I_{15/2}$	$_{68}$Er $^{3}H_{6}$	$_{67}$Tm $^{2}F_{7/2}$	$_{68}$Yb $^{1}S_{0}$

- We want a diamagnetic atom J = 0 (*)
- **We want a stable isotope, nuclear spin 1/2**

Spin 0 excluded (absence of magnetic moment, no precession).
Spins larger than ½ not great, complications due to the existence of electric quadrupole.

$_{1}$H $^{2}S_{1/2}$																	^{3}He $^{1}S_{0}$
$_{3}$Li $^{2}S_{1/2}$	$_{4}$Be $^{1}S_{0}$											$_{5}$B $^{2}P_{1/2}$	^{13}C $^{3}P_{0}$	$_{7}$N $^{4}S_{3/2}$	$_{8}$O $^{3}P_{2}$	$_{9}$F $^{2}P_{3/2}$	$_{10}$Ne $^{1}S_{0}$
$_{11}$Na $^{2}S_{1/2}$	$_{12}$Mg $^{1}S_{0}$											$_{13}$Al $^{2}P_{1/2}$	^{29}Si $^{3}P_{0}$	$_{15}$P $^{4}S_{3/2}$	$_{16}$S $^{3}P_{2}$	$_{17}$Cl $^{2}P_{3/2}$	$_{18}$Ar $^{1}S_{0}$
$_{19}$K $^{2}S_{1/2}$	$_{20}$Ca $^{1}S_{0}$	$_{21}$Sc $^{2}D_{3/2}$	$_{22}$Ti $^{3}F_{2}$	$_{23}$V $^{4}F_{3/2}$	$_{24}$Cr $^{7}S_{3}$	$_{25}$Mn $^{6}S_{5/2}$	$_{26}$Fe $^{5}D_{4}$	$_{27}$Co $^{4}F_{9/2}$	$_{28}$Ni $^{3}F_{4}$	$_{29}$Cu $^{2}S_{1/2}$	$_{30}$Zn $^{1}S_{0}$	$_{31}$Ga $^{2}P_{1/2}$	$_{32}$Ge $^{3}P_{0}$	$_{33}$As $^{4}S_{3/2}$	$_{34}$Se $^{3}P_{2}$	$_{35}$Br $^{2}P_{3/2}$	$_{36}$Kr $^{1}S_{0}$
$_{37}$Rb $^{2}S_{1/2}$	$_{38}$Sr $^{1}S_{0}$	$_{39}$Y $^{2}D_{3/2}$	$_{40}$Zr $^{3}F_{2}$	$_{41}$Nb $^{6}D_{1/2}$	$_{42}$Mo $^{7}S_{3}$	$_{43}$Tc $^{6}S_{5/2}$	$_{44}$Ru $^{5}F_{5}$	$_{45}$Rh $^{4}F_{9/2}$	$_{46}$Pd $^{1}S_{0}$	$_{47}$Ag $^{2}S_{1/2}$	^{111}Cd $^{1}S_{0}$	$_{49}$In $^{2}P_{1/2}$	^{119}Sn $^{3}P_{0}$	$_{51}$Sb $^{4}S_{3/2}$	$_{52}$Te $^{3}P_{2}$	$_{53}$I $^{2}P_{3/2}$	^{129}Xe $^{1}S_{0}$
$_{55}$Cs $^{2}S_{1/2}$	$_{56}$Ba $^{1}S_{0}$	$_{71}$Lu $^{2}D_{3/2}$	$_{72}$Hf $^{3}F_{2}$	$_{73}$Ta $^{4}F_{3/2}$	$_{74}$W $^{5}D_{0}$	$_{75}$Re $^{6}S_{5/2}$	$_{76}$Os $^{5}D_{4}$	$_{77}$Ir $^{4}F_{9/2}$	$_{78}$Pt $^{3}D_{3}$	$_{79}$Au $^{2}S_{1/2}$	^{199}Hg $^{1}S_{0}$	$_{81}$Tl $^{2}P_{1/2}$	^{207}Pb $^{3}P_{0}$	$_{83}$Bi $^{4}S_{3/2}$	$_{84}$Po $^{3}P_{2}$	$_{85}$At $^{2}P_{3/2}$	$_{86}$Rn $^{1}S_{0}$

$_{57}$La $^{2}D_{3/2}$	$_{58}$Ce $^{1}G_{4}$	$_{59}$Pr $^{4}I_{9/2}$	$_{60}$Nd $^{5}I_{4}$	$_{61}$Pm $^{6}H_{5/2}$	$_{62}$Sm $^{7}F_{0}$	$_{63}$Eu $^{8}S_{7/2}$	$_{64}$Gd $^{9}D_{2}$	$_{65}$Tb $^{6}H_{15/2}$	$_{66}$Dy $^{5}I_{8}$	$_{67}$Ho $^{4}I_{15/2}$	$_{68}$Er $^{3}H_{6}$	$_{68}$Tm $^{2}F_{7/2}$	^{171}Yb $^{1}S_{0}$

- We want a diamagnetic atom J = 0 (*)
- We want a stable isotope, nuclear spin ½
- **Gas or liquid at room temperature**

$_{1}$H $^{2}S_{1/2}$																	^{3}He $^{1}S_{0}$
$_{3}$Li $^{2}S_{1/2}$	$_{4}$Be $^{1}S_{0}$											$_{5}$B $^{2}P_{1/2}$	^{13}C $^{3}P_{0}$	$_{7}$N $^{4}S_{3/2}$	$_{8}$O $^{3}P_{2}$	$_{9}$F $^{2}P_{3/2}$	$_{10}$Ne $^{1}S_{0}$
$_{11}$Na $^{2}S_{1/2}$	$_{12}$Mg $^{1}S_{0}$											$_{13}$Al $^{2}P_{1/2}$	^{29}Si $^{3}P_{0}$	$_{15}$P $^{4}S_{3/2}$	$_{16}$S $^{3}P_{2}$	$_{17}$Cl $^{2}P_{3/2}$	$_{18}$Ar $^{1}S_{0}$
$_{19}$K $^{2}S_{1/2}$	$_{20}$Ca $^{1}S_{0}$	$_{21}$Sc $^{2}D_{3/2}$	$_{22}$Ti $^{3}F_{2}$	$_{23}$V $^{4}F_{3/2}$	$_{24}$Cr $^{7}S_{3}$	$_{25}$Mn $^{6}S_{5/2}$	$_{26}$Fe $^{5}D_{4}$	$_{27}$Co $^{4}F_{9/2}$	$_{28}$Ni $^{3}F_{4}$	$_{29}$Cu $^{2}S_{1/2}$	$_{30}$Zn $^{1}S_{0}$	$_{31}$Ga $^{2}P_{1/2}$	$_{32}$Ge $^{3}P_{0}$	$_{33}$As $^{4}S_{3/2}$	$_{34}$Se $^{3}P_{2}$	$_{35}$Br $^{2}P_{3/2}$	$_{36}$Kr $^{1}S_{0}$
$_{37}$Rb $^{2}S_{1/2}$	$_{38}$Sr $^{1}S_{0}$	$_{39}$Y $^{2}D_{3/2}$	$_{40}$Zr $^{3}F_{2}$	$_{41}$Nb $^{6}D_{1/2}$	$_{42}$Mo $^{7}S_{3}$	$_{43}$Tc $^{6}S_{5/2}$	$_{44}$Ru $^{5}F_{5}$	$_{45}$Rh $^{4}F_{9/2}$	$_{46}$Pd $^{1}S_{0}$	$_{47}$Ag $^{2}S_{1/2}$	^{111}Cd $^{1}S_{0}$	$_{49}$In $^{2}P_{1/2}$	^{119}Sn $^{3}P_{0}$	$_{51}$Sb $^{4}S_{3/2}$	$_{52}$Te $^{3}P_{2}$	$_{53}$I $^{2}P_{3/2}$	^{129}Xe $^{1}S_{0}$
$_{55}$Cs $^{2}S_{1/2}$	$_{56}$Ba $^{1}S_{0}$	$_{71}$Lu $^{2}D_{3/2}$	$_{72}$Hf $^{3}F_{2}$	$_{73}$Ta $^{4}F_{3/2}$	$_{74}$W $^{5}D_{0}$	$_{75}$Re $^{6}S_{5/2}$	$_{76}$Os $^{5}D_{4}$	$_{77}$Ir $^{4}F_{9/2}$	$_{78}$Pt $^{3}D_{3}$	$_{79}$Au $^{2}S_{1/2}$	^{199}Hg $^{1}S_{0}$	$_{81}$Tl $^{2}P_{1/2}$	^{207}Pb $^{3}P_{0}$	$_{83}$Bi $^{4}S_{3/2}$	$_{84}$Po $^{3}P_{2}$	$_{85}$At $^{2}P_{3/2}$	$_{86}$Rn $^{1}S_{0}$

$_{57}$La $^{2}D_{3/2}$	$_{58}$Ce $^{1}G_{4}$	$_{59}$Pr $^{4}I_{9/2}$	$_{60}$Nd $^{5}I_{4}$	$_{61}$Pm $^{6}H_{5/2}$	$_{62}$Sm $^{7}F_{0}$	$_{63}$Eu $^{8}S_{7/2}$	$_{64}$Gd $^{9}D_{2}$	$_{65}$Tb $^{6}H_{15/2}$	$_{66}$Dy $^{5}I_{8}$	$_{67}$Ho $^{4}I_{15/2}$	$_{68}$Er $^{3}H_{6}$	$_{68}$Tm $^{2}F_{7/2}$	^{171}Yb $^{1}S_{0}$

- We want a diamagnetic atom J = 0 (*)
- We want a stable isotope, nuclear spin ½
- Gas or liquid at room temperature
- **Existence of optical transition**

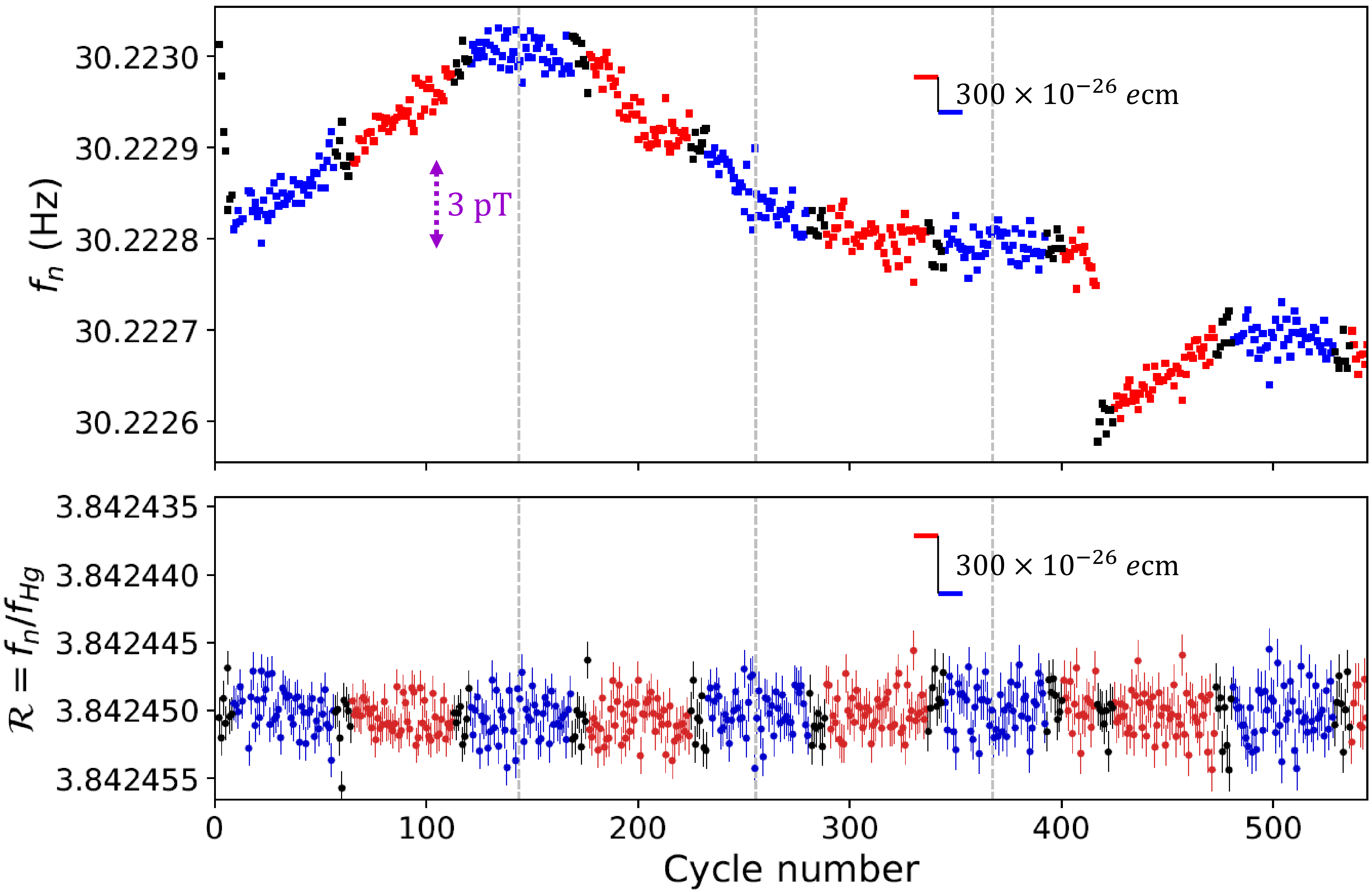
$_{1}$H $^{2}S_{1/2}$																	^{3}He $^{1}S_{0}$
$_{3}$Li $^{2}S_{1/2}$	$_{4}$Be $^{1}S_{0}$											$_{5}$B $^{2}P_{1/2}$	^{13}C $^{3}P_{0}$	$_{7}$N $^{4}S_{3/2}$	$_{8}$O $^{3}P_{2}$	$_{9}$F $^{2}P_{3/2}$	$_{10}$Ne $^{1}S_{0}$
$_{11}$Na $^{2}S_{1/2}$	$_{12}$Mg $^{1}S_{0}$											$_{13}$Al $^{2}P_{1/2}$	^{29}Si $^{3}P_{0}$	$_{15}$P $^{4}S_{3/2}$	$_{16}$S $^{3}P_{2}$	$_{17}$Cl $^{2}P_{3/2}$	$_{18}$Ar $^{1}S_{0}$
$_{19}$K $^{2}S_{1/2}$	$_{20}$Ca $^{1}S_{0}$	$_{21}$Sc $^{2}D_{3/2}$	$_{22}$Ti $^{3}F_{2}$	$_{23}$V $^{4}F_{3/2}$	$_{24}$Cr $^{7}S_{3}$	$_{25}$Mn $^{6}S_{5/2}$	$_{26}$Fe $^{5}D_{4}$	$_{27}$Co $^{4}F_{9/2}$	$_{28}$Ni $^{3}F_{4}$	$_{29}$Cu $^{2}S_{1/2}$	$_{30}$Zn $^{1}S_{0}$	$_{31}$Ga $^{2}P_{1/2}$	$_{32}$Ge $^{3}P_{0}$	$_{33}$As $^{4}S_{3/2}$	$_{34}$Se $^{3}P_{2}$	$_{35}$Br $^{2}P_{3/2}$	$_{36}$Kr $^{1}S_{0}$
$_{37}$Rb $^{2}S_{1/2}$	$_{38}$Sr $^{1}S_{0}$	$_{39}$Y $^{2}D_{3/2}$	$_{40}$Zr $^{3}F_{2}$	$_{41}$Nb $^{6}D_{1/2}$	$_{42}$Mo $^{7}S_{3}$	$_{43}$Tc $^{6}S_{5/2}$	$_{44}$Ru $^{5}F_{5}$	$_{45}$Rh $^{4}F_{9/2}$	$_{46}$Pd $^{1}S_{0}$	$_{47}$Ag $^{2}S_{1/2}$	^{111}Cd $^{1}S_{0}$	$_{49}$In $^{2}P_{1/2}$	^{119}Sn $^{3}P_{0}$	$_{51}$Sb $^{4}S_{3/2}$	$_{52}$Te $^{3}P_{2}$	$_{53}$I $^{2}P_{3/2}$	^{129}Xe $^{1}S_{0}$
$_{55}$Cs $^{2}S_{1/2}$	$_{56}$Ba $^{1}S_{0}$	$_{71}$Lu $^{2}D_{3/2}$	$_{72}$Hf $^{3}F_{2}$	$_{73}$Ta $^{4}F_{3/2}$	$_{74}$W $^{5}D_{0}$	$_{75}$Re $^{6}S_{5/2}$	$_{76}$Os $^{5}D_{4}$	$_{77}$Ir $^{4}F_{9/2}$	$_{78}$Pt $^{3}D_{3}$	$_{79}$Au $^{2}S_{1/2}$	^{199}Hg $^{1}S_{0}$	$_{81}$Tl $^{2}P_{1/2}$	^{207}Pb $^{3}P_{0}$	$_{83}$Bi $^{4}S_{3/2}$	$_{84}$Po $^{3}P_{2}$	$_{85}$At $^{2}P_{3/2}$	$_{86}$Rn $^{1}S_{0}$

$_{57}$La $^{2}D_{3/2}$	$_{58}$Ce $^{1}G_{4}$	$_{59}$Pr $^{4}I_{9/2}$	$_{60}$Nd $^{5}I_{4}$	$_{61}$Pm $^{6}H_{5/2}$	$_{62}$Sm $^{7}F_{0}$	$_{63}$Eu $^{8}S_{7/2}$	$_{64}$Gd $^{9}D_{2}$	$_{65}$Tb $^{6}H_{15/2}$	$_{66}$Dy $^{5}I_{8}$	$_{67}$Ho $^{4}I_{15/2}$	$_{68}$Er $^{3}H_{6}$	$_{68}$Tm $^{2}F_{7/2}$	^{171}Yb $^{1}S_{0}$

A sequence of cycles (nEDM data 2015-2016)

Magnetic fluctuations (random and correlated with E) are corrected for at each cycle with the Hg magnetometer by measuring

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

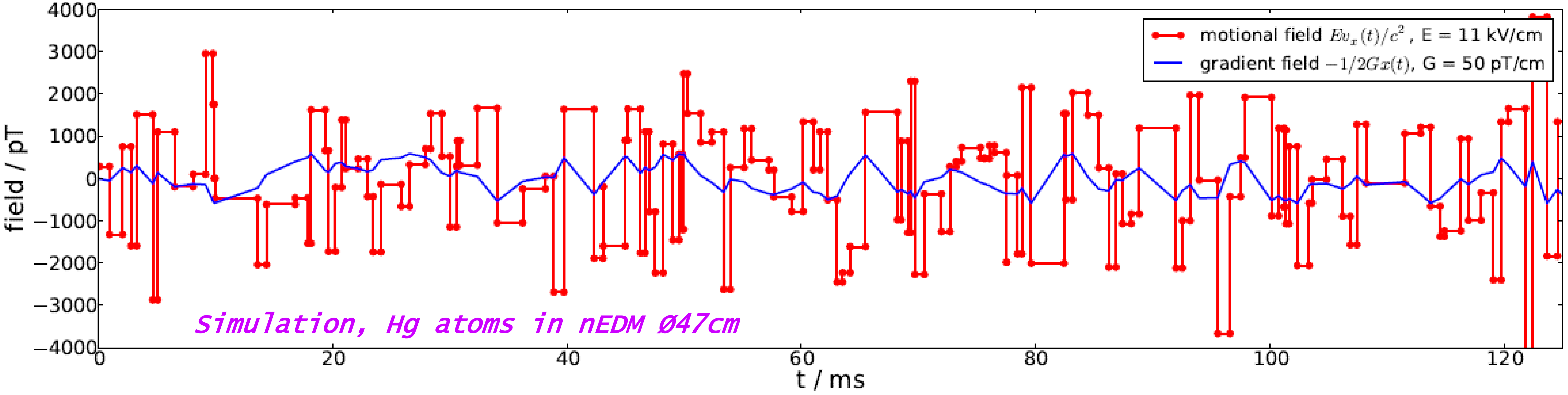


The co-magnetometer problem: $E\times v/c^2$

Transverse "noise" on a mercury atom in random motion

Nonuniform field — relativistic motional field

$$b(t) = \left(\vec{B}(t) + \frac{1}{c^2}\vec{E}\times\vec{v}(t) \right)\cdot\left(\vec{e_x} + i\vec{e_y}\right)$$



False EDM (low frequency limit): $d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = -\frac{\hbar|\gamma_n\gamma_{\mathrm{Hg}}|}{2c^2}\langle xB_x + yB_y\rangle$

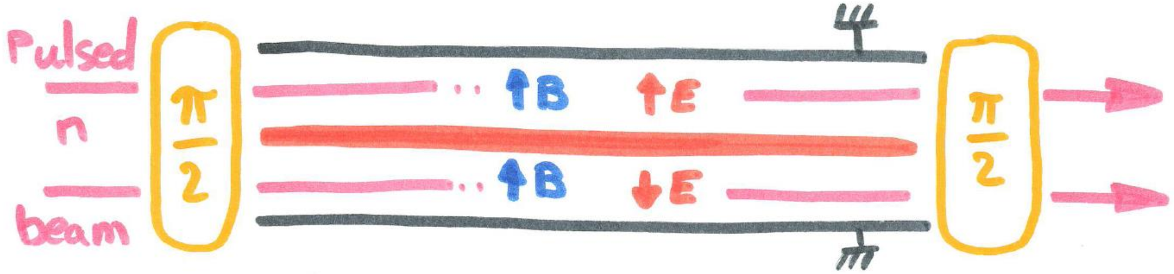
Outline of the lecture

1. nEDM: What, Why, How?
2. Neutron optics, ultracold neutrons
3. Manipulating neutron spin
4. Past, present and **future experiments**

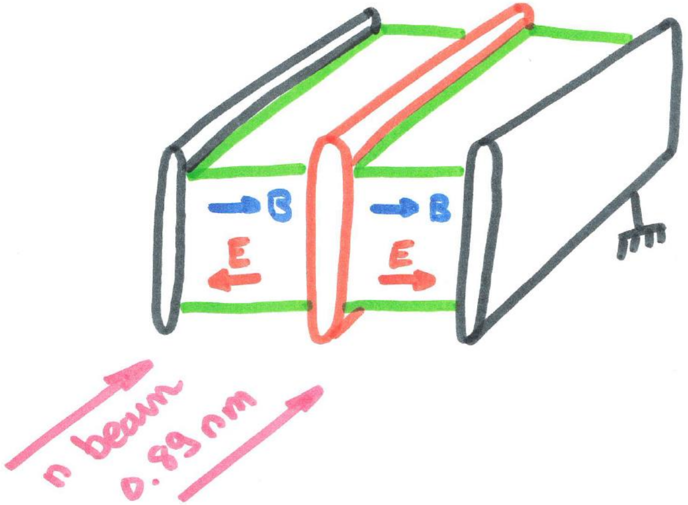
Next generation nEDM experiments

Topics discussed at the nEDM2021 workshop

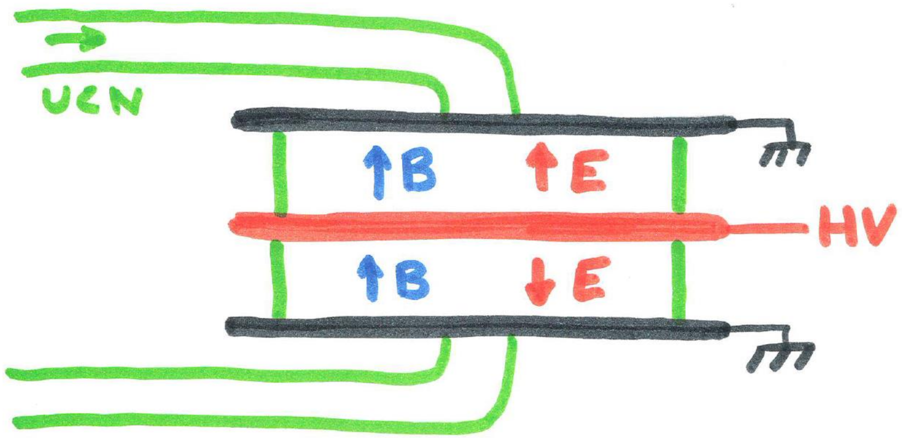
Revival of nEDM with a neutron beam



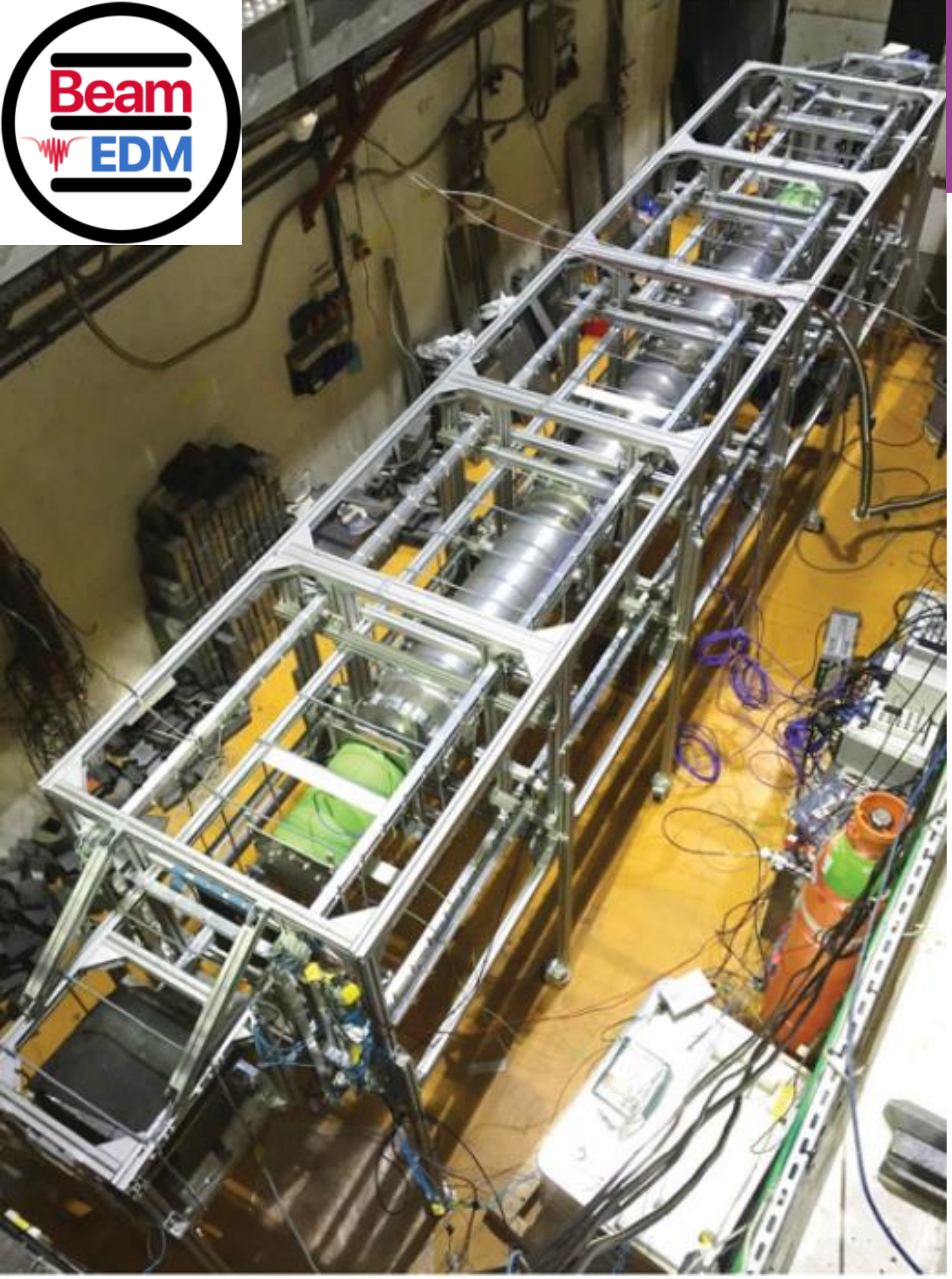
nEDM in superfluid helium



Double-chamber UCN @room temperature

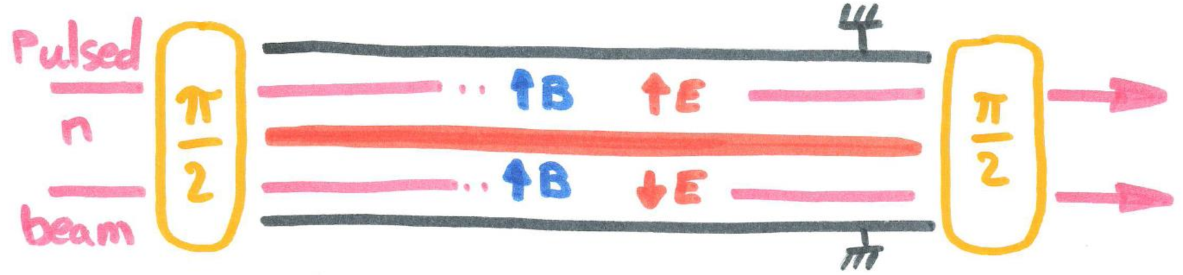


BeamEDM project



4 m long apparatus at ILL

Revival of nEDM with a neutron beam

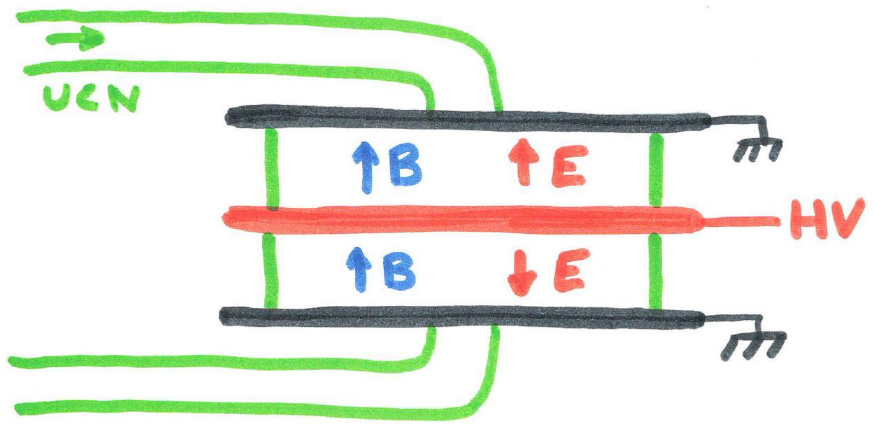


- Proof of principle measurements have been performed at the PSI, and at the ILL in Grenoble.
- Projected sensitivity at the ESS with a 50 m long apparatus: 5×10^{-26} e cm in one day of measurement.

E. Chanel et al. EPJ Web Conf., 219, 2004 (2019)

One concept, four competing projects

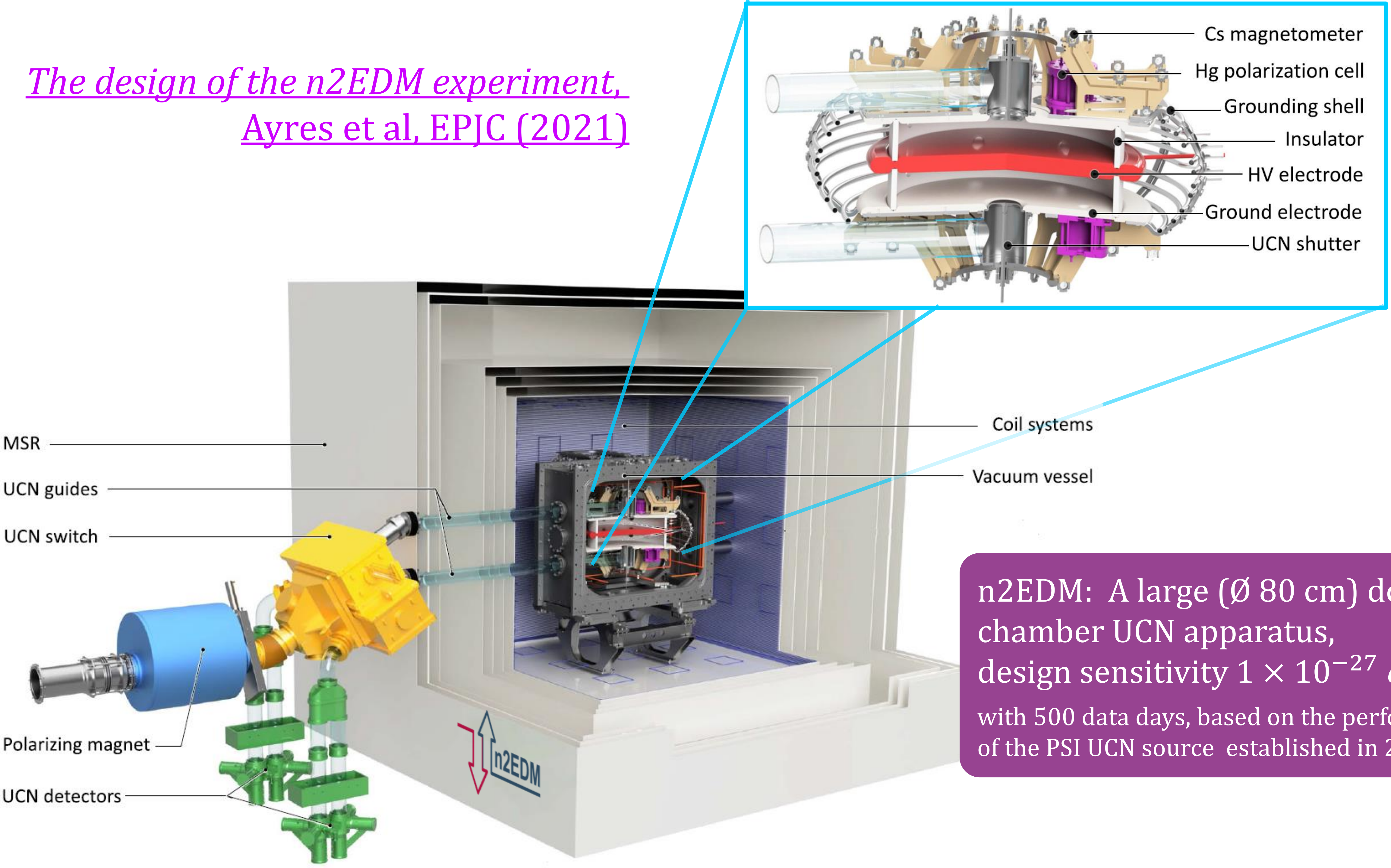
Double-chamber UCN @room temperature



+ atomic co-magnetometry in the UCN cells
+ External magnetometers
+ Complex B0 coil
+ Magnetic Shield

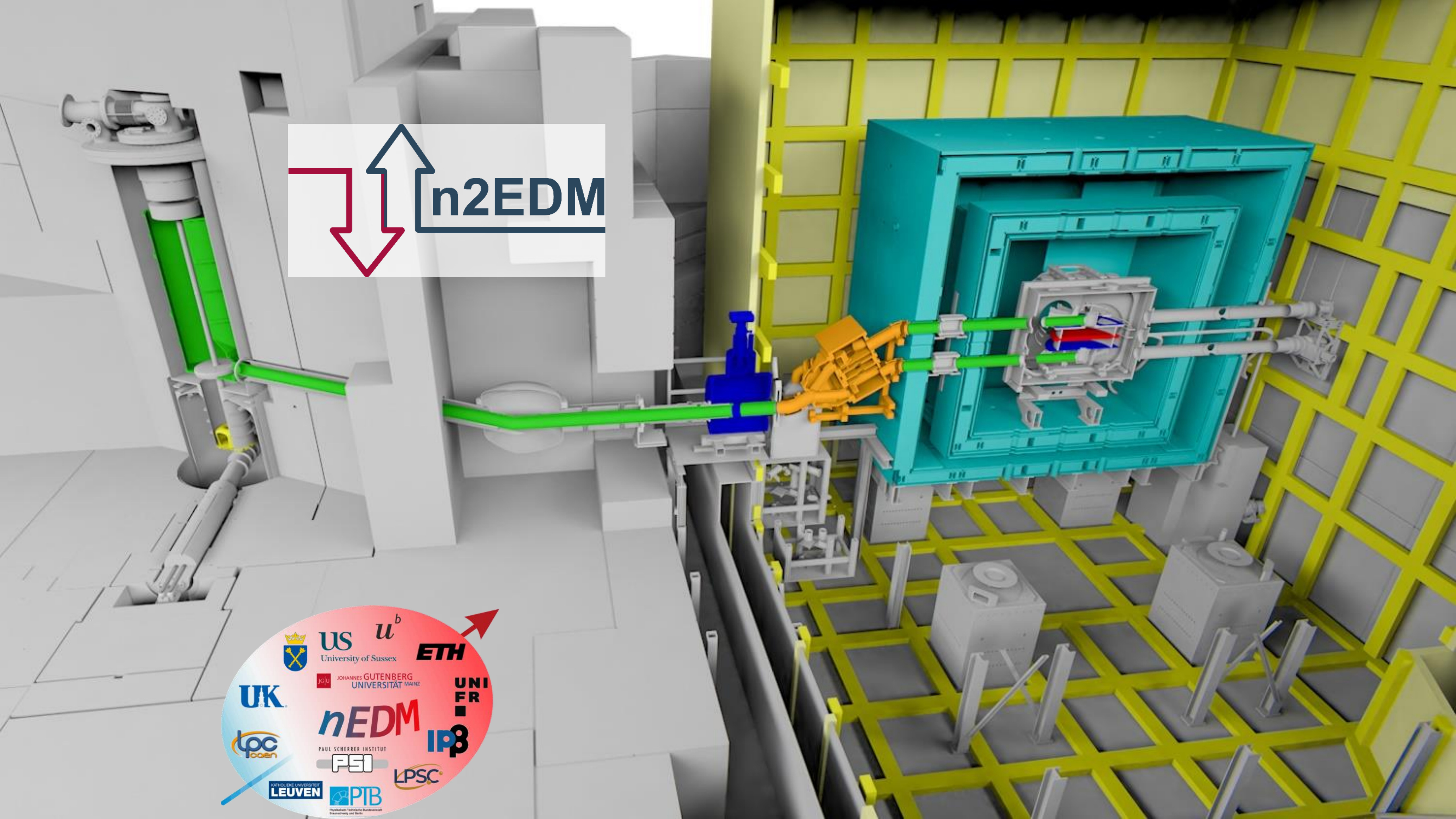
Place	Neutron source	Concept	Stage/Readiness
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber with Hg comagnetometers + Cs mag	Source under construction, experiment in design phase
LANL	Spallation + sD2 UCN source	double Ramsey chamber with Hg comagnetometers + commertial OPMs	Source running, experiment under construction
ILL	Reactor + superfluid He UCN source	panEDM: double Ramsey chamber, no comagnetometers + Hg&Cs mag	Source (supersun) and experiment under construction
PSI	Spallation + sD2 UCN source	n2EDM: large double Ramsey chamber with Hg comagnetometers + Cs mag	Source running, experiment under construction

[*The design of the n2EDM experiment, Ayres et al, EPJC (2021)*]

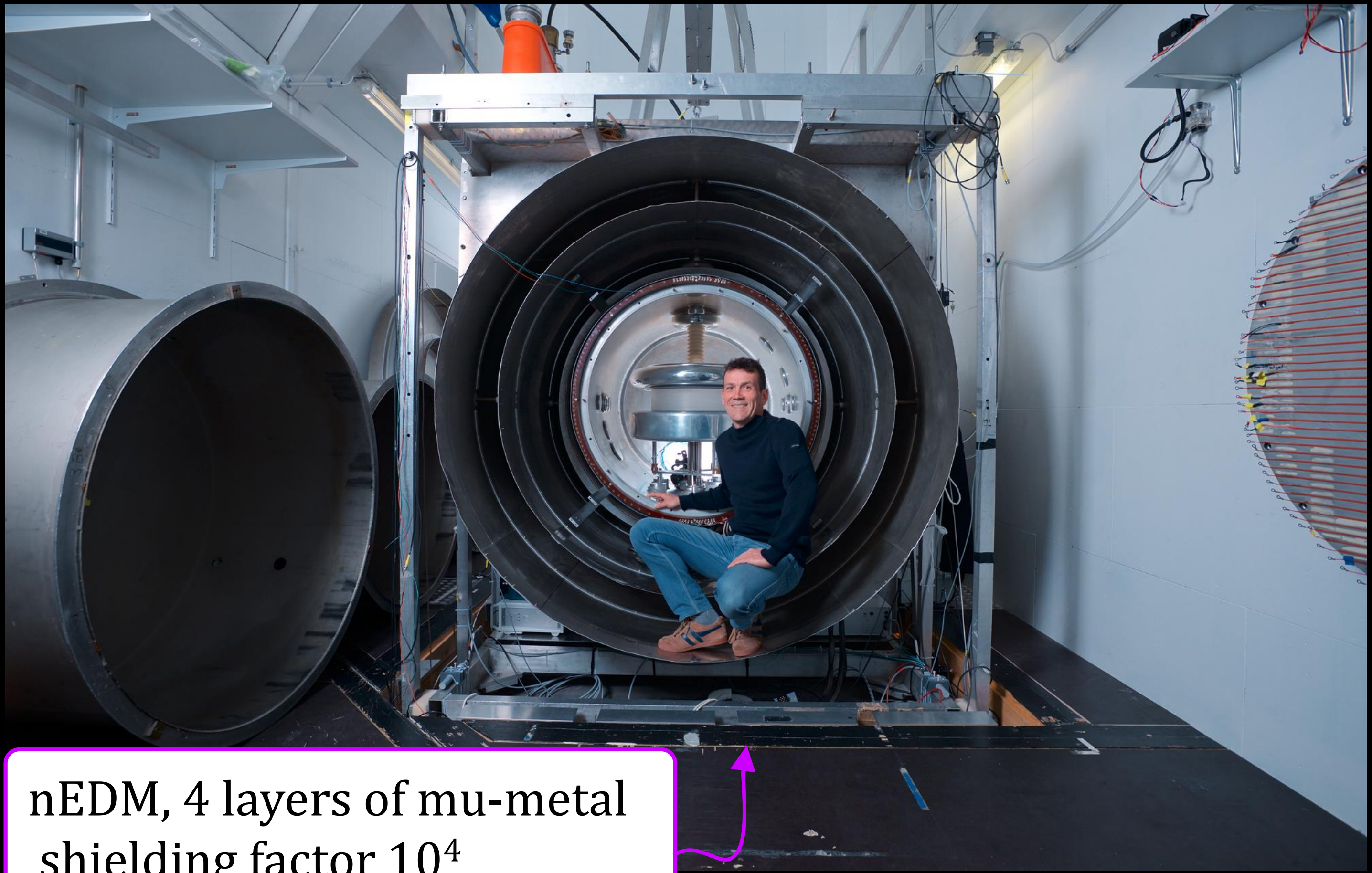


n2EDM: A large (Ø 80 cm) double-chamber UCN apparatus, design sensitivity 1×10^{-27} e cm

with 500 data days, based on the performance of the PSI UCN source established in 2016


n2EDM
US
University of Sussex
ETH
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
UK
UNI FR
nEDM
PAUL SCHERRER INSTITUT
PSI
LPSC
KATHOLIEKE UNIVERSITEIT LEUVEN
PTB

Bigger magnetic shields...

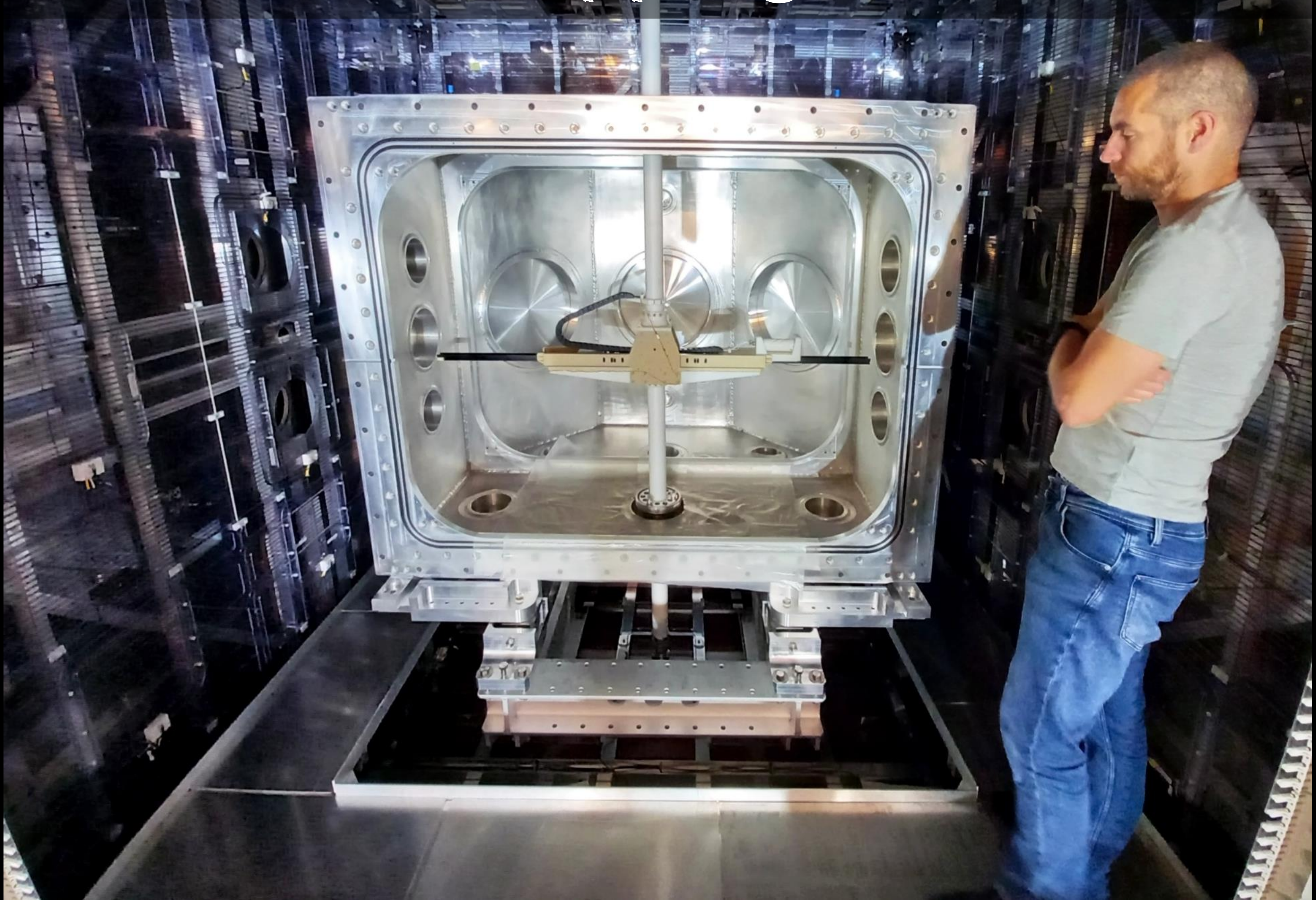


nEDM, 4 layers of mu-metal
shielding factor 10^4

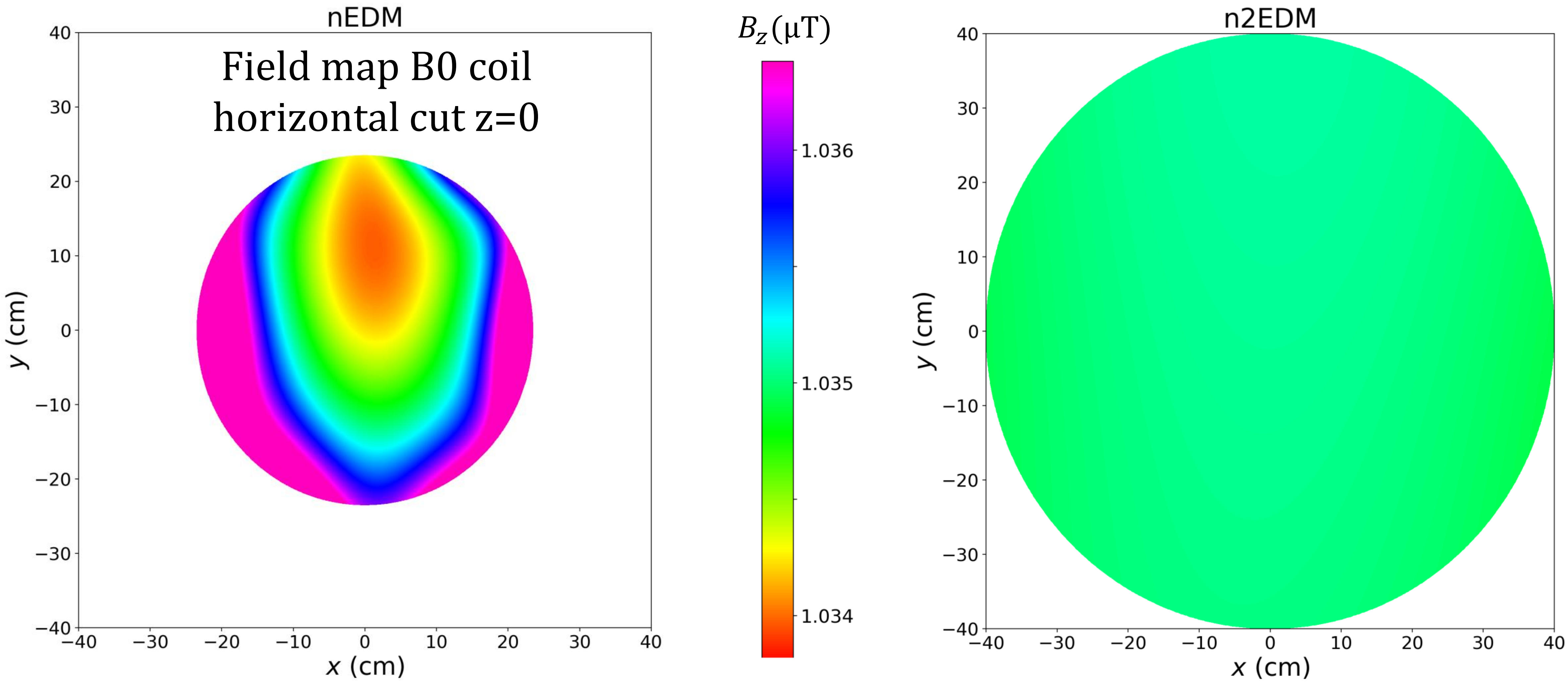
n2EDM 6 layers, shielding factor 10^5

[*The very large n2EDM magnetically shielded room*
Review of Scientific Instruments 93, 095105 (2022)]

B-field mapping 2022



Record uniformity of the vertical B-field



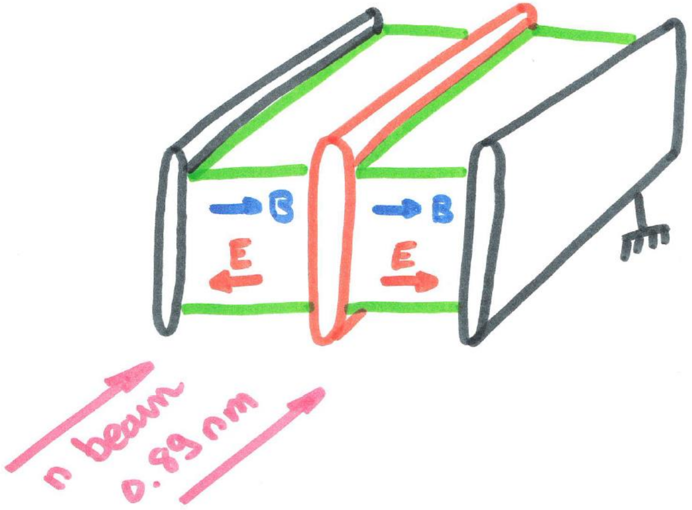
nEDM 2017 $\sigma(B_z) = 900\ \mathrm{pT}$

In the precession chamber Ø 47 cm

n2EDM 2022 $\sigma(B_z) = 50\ \mathrm{pT}$

In one chamber Ø 80 cm

nEDM in superfluid helium



Golub-Lamoreaux concept:

- In-situ UCN production in superfluid helium-4 @ 0.5K
- Precession of polarized neutrons and helium-3 in the cells
- Measure the scintillation light of 3He$(n, p)t$ which is spin-dependent

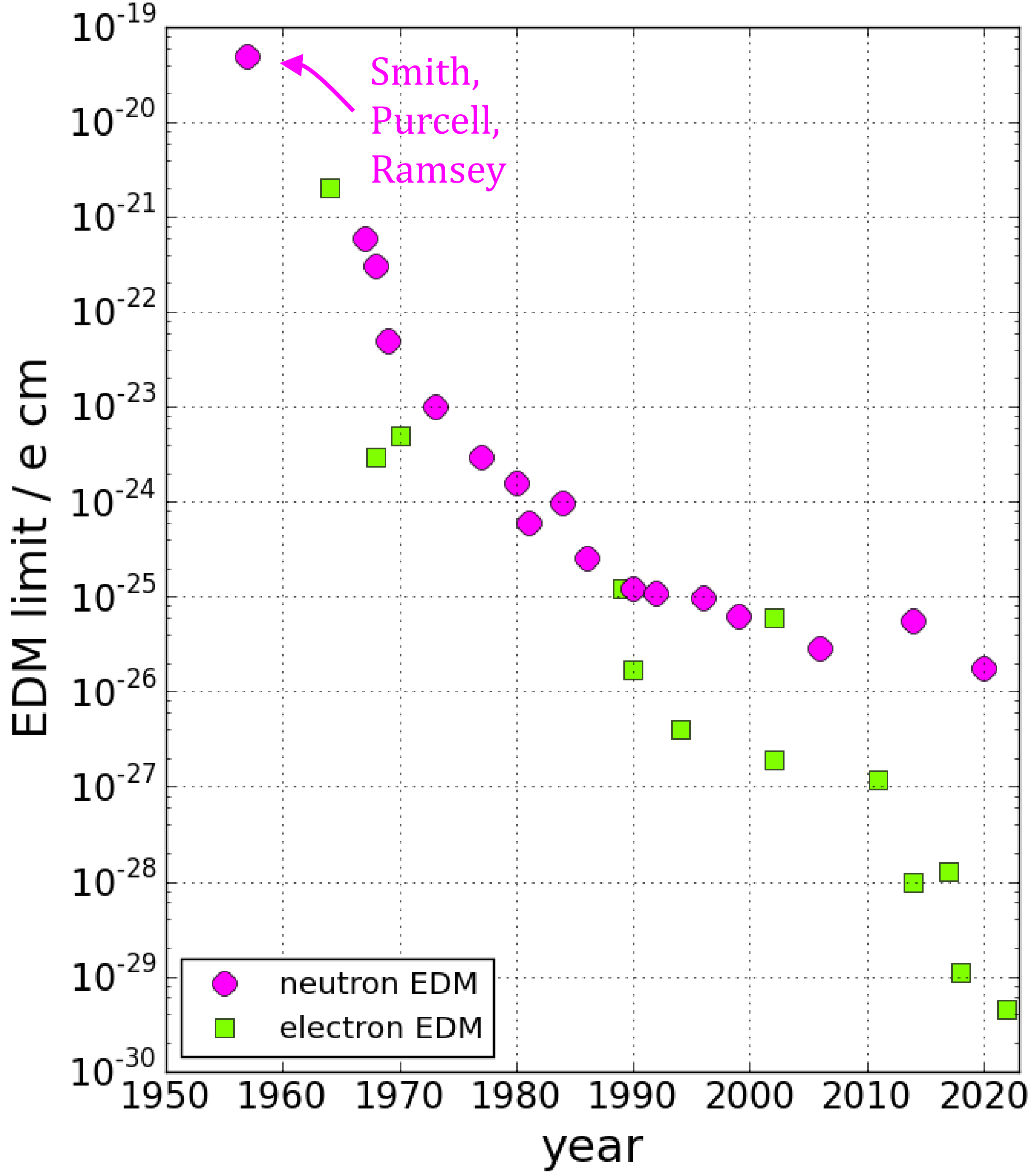
nEDM @SNS

Precision goal of 2×10^{-28} e cm

Baseline start date 2028

M.W. Ahmed et al, J. Inst., 14, P11017 (2019)

Some large final components



The end...
Not quite yet...

Design sensitivity of 4 new experiments:

n2EDM@PSI + panEDM@ILL + LANL + TUCAN@TRIUMF

Design sensitivity cryogenic nEDM@SNS

Ultimate conceivable reach with present neutron sources

CKM background uncertain, possibly 10^{-31} e cm