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Neutron Electric Dipole Moment

A key to the Baryon Asymmetry of the Universe

Malgorzata Kasprzak
on behalf of the nEDM collaboration

Isolde Seminar, CERN, 08.03.2017

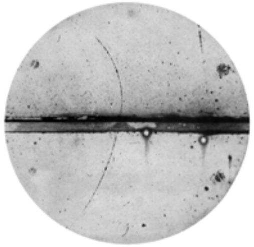
Cosmological models and Big Bang

Edwin Hubble, 1924,
Observation of the
expanding Universe

Georges Lemaitre, 1927
primeval “super-atom” theory

“…we could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass of the universe.”

1928: Paul Dirac predicts antimatter
1932: Carl Anderson discovers positrons
1955: antiproton and antineutron found at Bevatron
1957: Prove of the CPT theorem
1964: cosmic microwave background (CMB) radiation (Penzias and Wilson)



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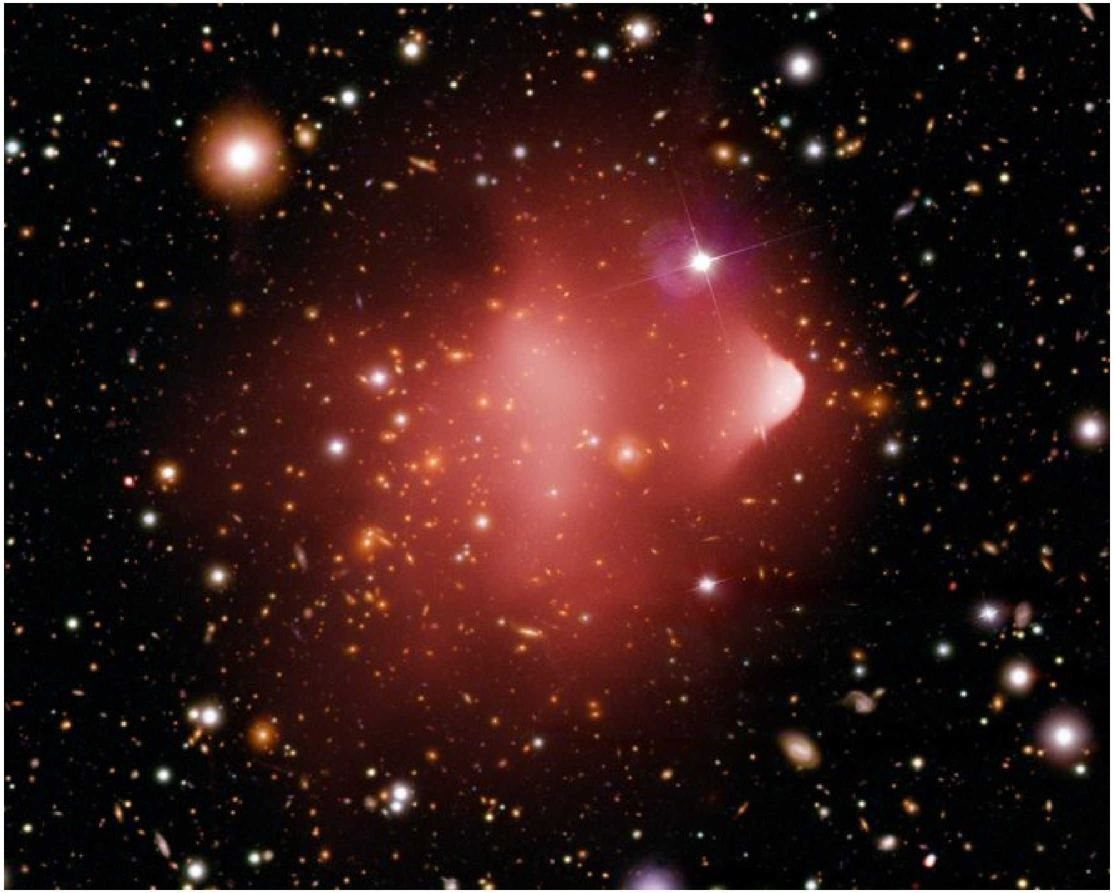
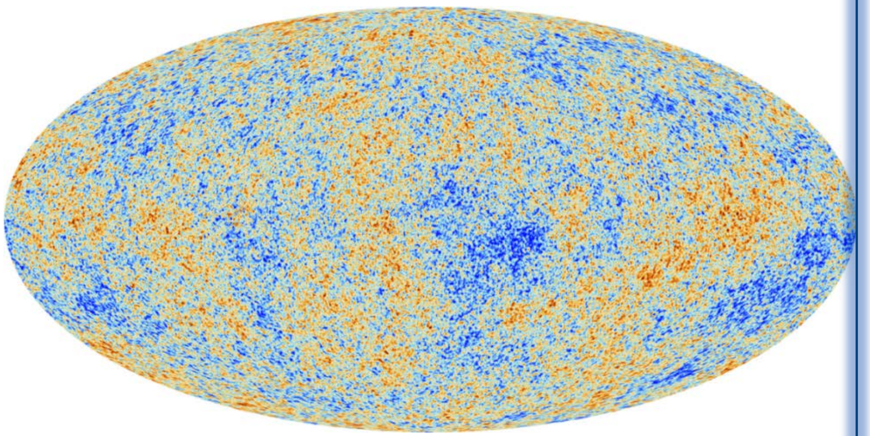
Primordial antimatter searches



Bullet Cluster, picture: NASA,

Baryon Asymmetry of the Universe (BAU)

COBE and PLACK missions precise measurements of CMB

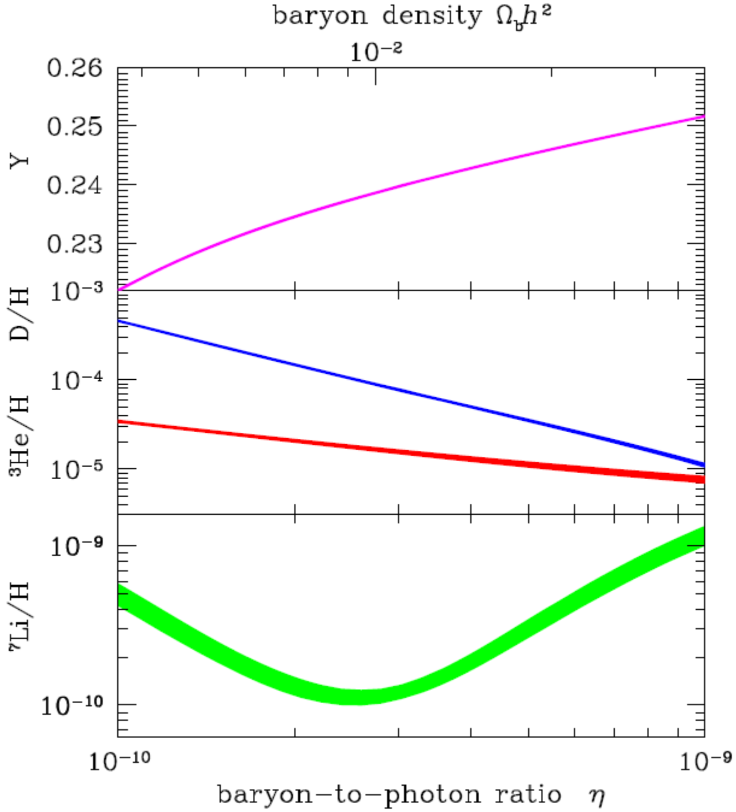


Picture: ESA and the Planck Collaboration

Baryon-to-photon ratio

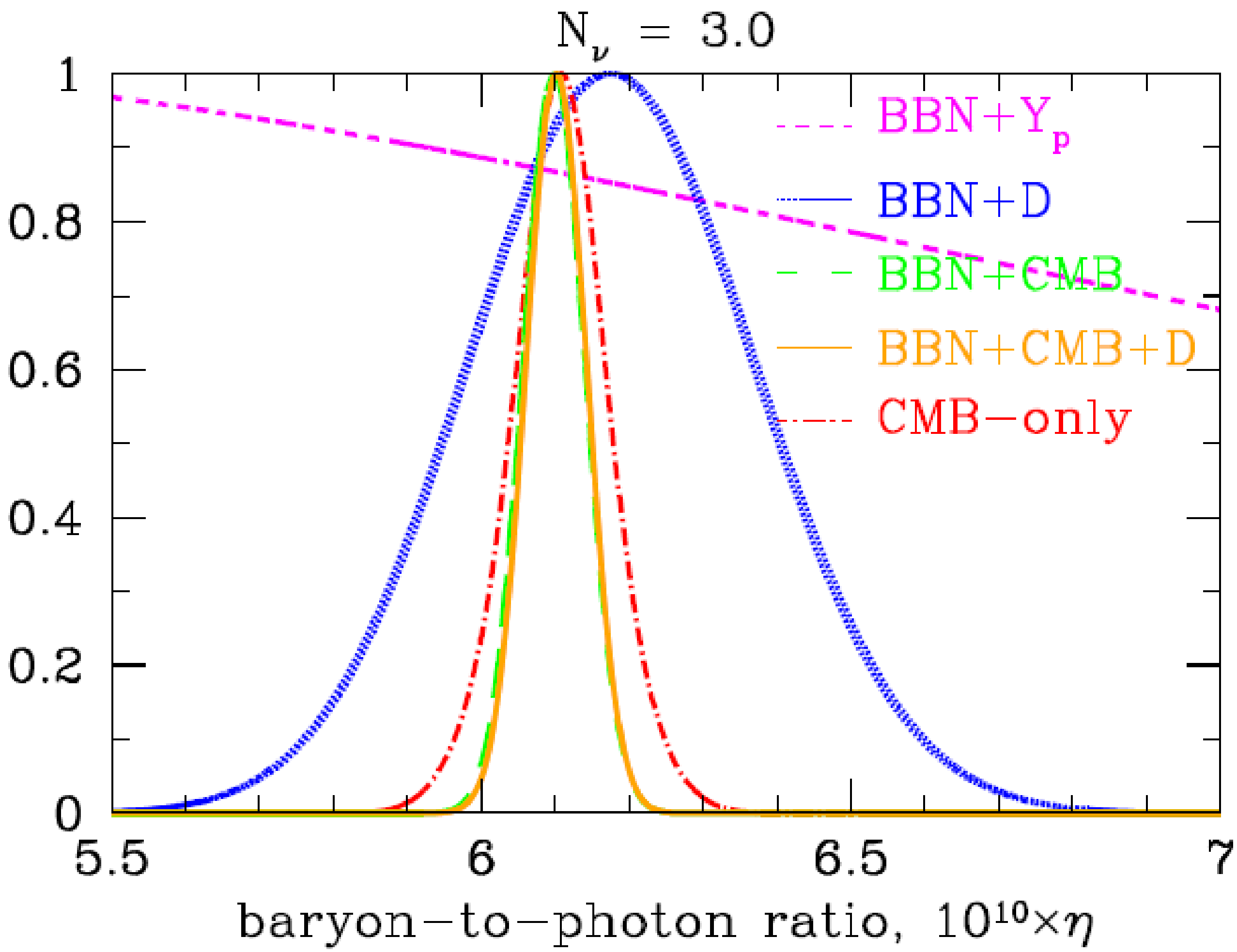
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.19 \pm 0.14)\ \times 10^{-10}$$

Big bang nucleosynthesis (BBN) and light element abundance in the intergalactic medium



R. H. Cyburt et al, Rev. Mod. Phys. 88, 015004 (2016)

Baryon Asymmetry of the Universe (BAU)



R. H. Cyburt et al, Rev. Mod. Phys. 88, 015004 (2016)

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Matter-antimatter symmetry in Universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.19 \pm 0.14)\ \times 10^{-10}$$

Perfectly symmetric Universe

$$\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} = 0$$

Theoretical predictions:

$$\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} \leq 10^{-18}$$

How to explain an excess of matter over antimatter in our universe?

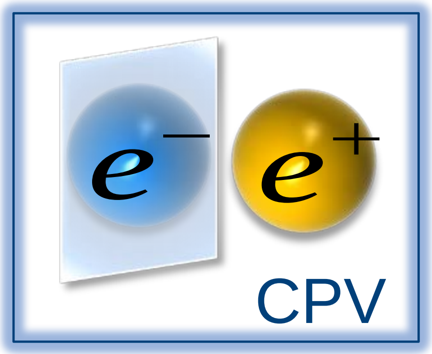
Different laws of physics for matter and for antimatter

Sakharov criteria*	SM	BSM
1. Baryon number violation	✓	✓
2. C and CP violation		✓
3. Thermal non-equilibrium		✓

*[A. D. Sakharov, JETP 5 (1967), 32]

CP violating (CPV) signatures

- High energy physics
- Electric dipole moments
- Neutrino physics



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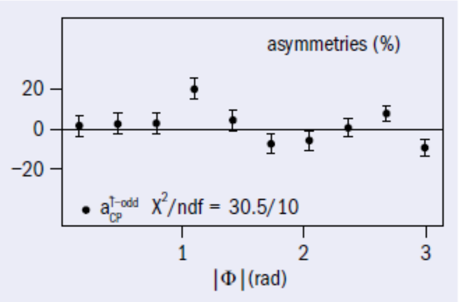
CP violation in the Standard Model (SM) and Beyond

CPV in weak interactions,
discovered by J. Cronin and V. Fitch in 1964
– too small to explain BAU

CP violating δ – term

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

First hint of CP violation in baryons (up to now only mesons) – LHCb collaboration, Nature 2017

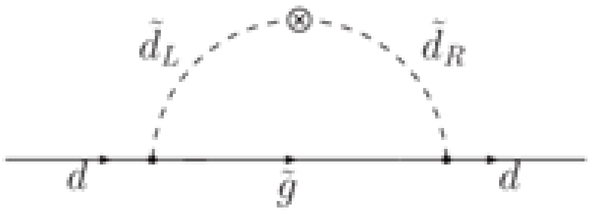


CP violation in the Standard Model (SM) and Beyond

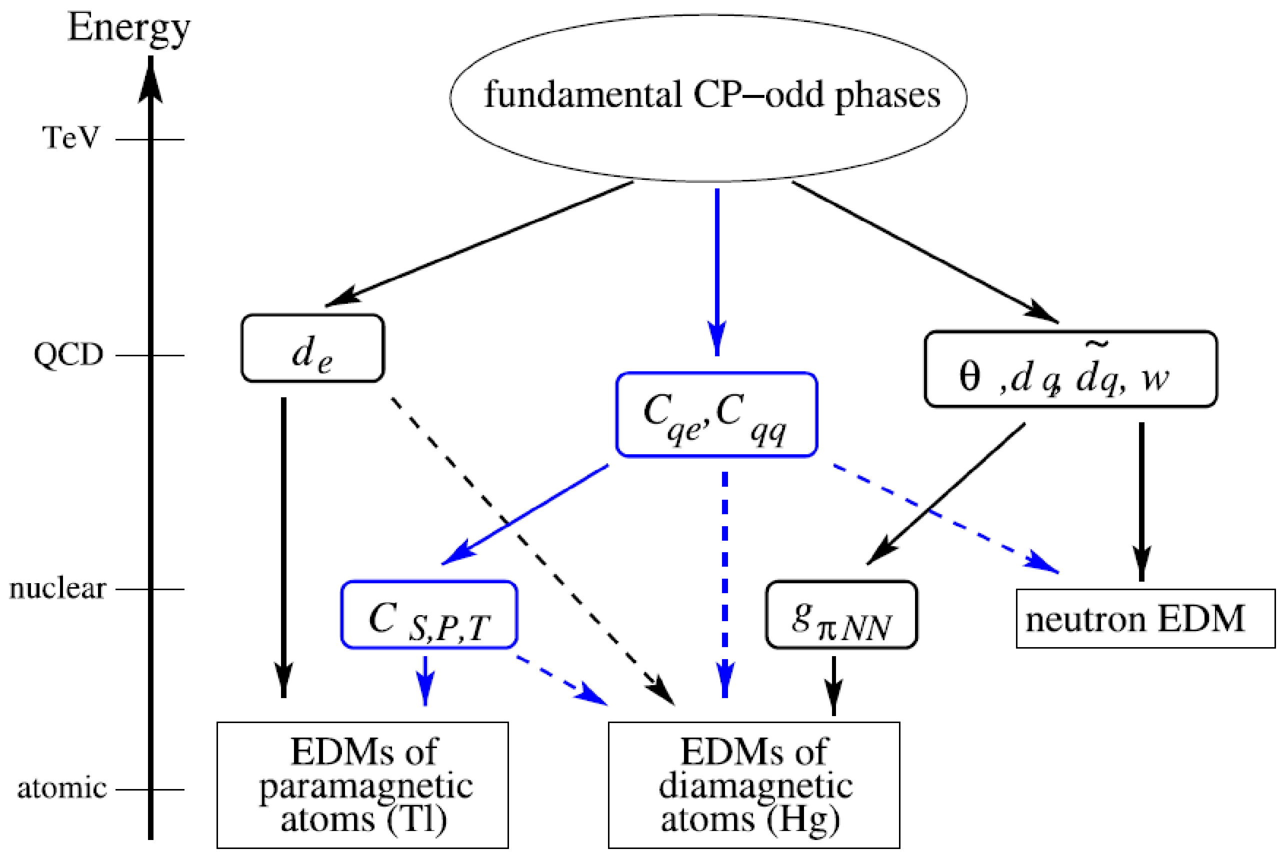
- CPV in QCD (θ term)

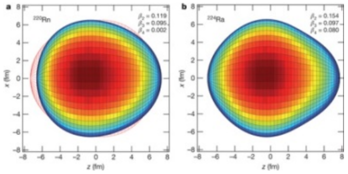
$$d_n \sim \theta \times 10^{-17} \mathrm{e \cdot cm} \qquad \theta < 10^{-9}$$

- CPV in lepton sector
- CPV in SUSY



CP violation and EDM's





CP violation and EDM's

- Current limits on EDM's and CP violating phases

Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{QCD}$	3×10^{-10}	[20]	n: 1×10^{-10} [3]
d_n (e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26} [3]
d_e (e cm)	3×10^{-27}	[21,22]	Tl: 1.6×10^{-27} [18]

[a]For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

W. C. Griffith et al, PRL 102, 101601 (2009)

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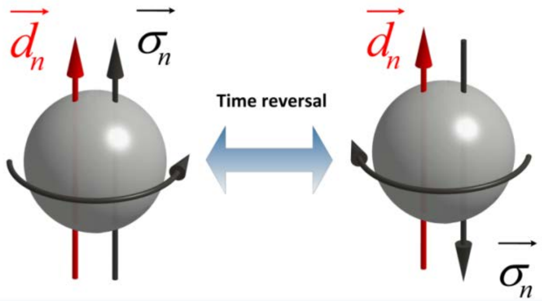
Neutron EDM and CP violation

CM



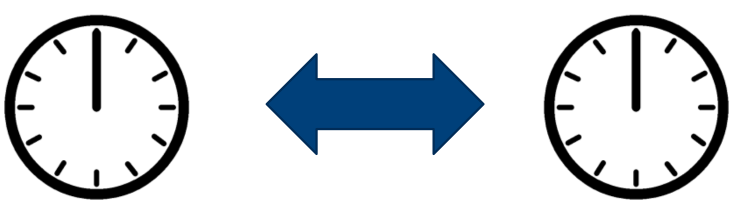
QM

$$d_n\vec{E}\cdot\frac{\vec{\sigma}}{\sigma}\overset{T}{\rightleftarrows}-d_n\vec{E}\cdot\frac{\vec{\sigma}}{\sigma}$$

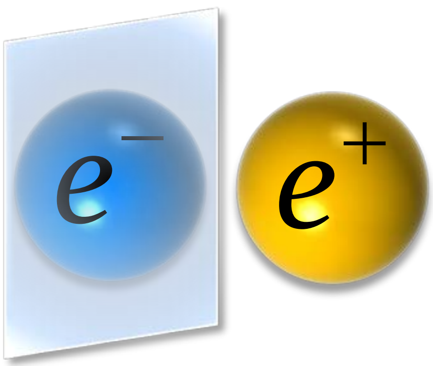
$$\vec{\sigma}\overset{T}{\rightleftarrows}-\vec{\sigma}$$

$$\vec{E}\overset{T}{\rightleftarrows}\vec{E}$$

- Time reversal violation translates into CPV if the CPT symmetry is valid



$$\overset{CPT}{\equiv}$$



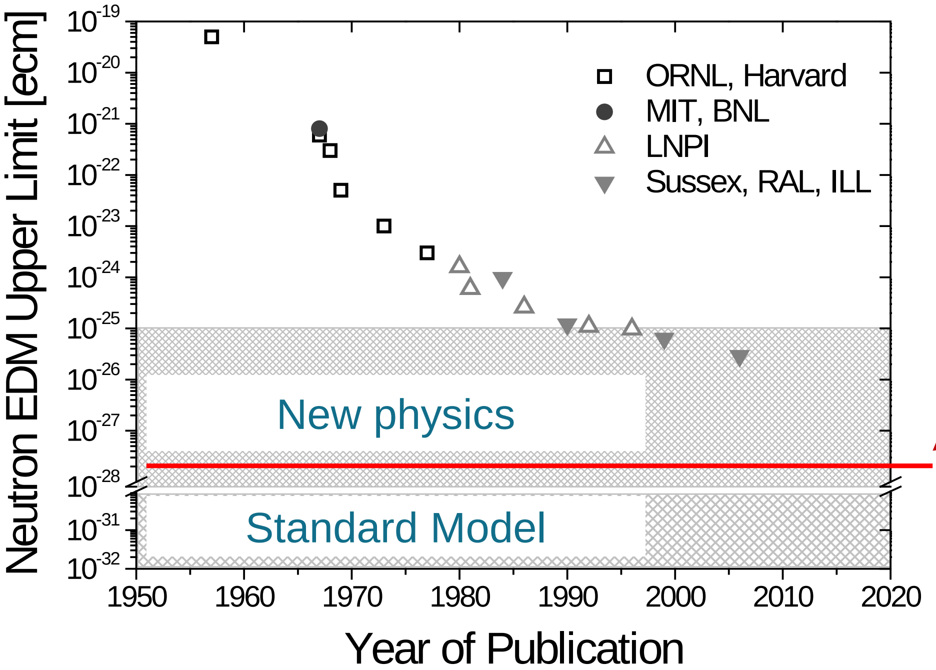
nEDM prediction and measurements

Upper limit on nEDM : $d_n < 3\times10^{-26} e\,cm$

Pendlebury et al., PRD92 (2015) 092003

Standard Model : $d_n \approx 10^{-31} e\,cm$

New Physics scenarios : $d_n \approx 10^{-27} - 10^{-28} e\,cm$



Ultimate aim of nEDM @ PSI

$d_n < 5\times10^{-28} e\,cm$

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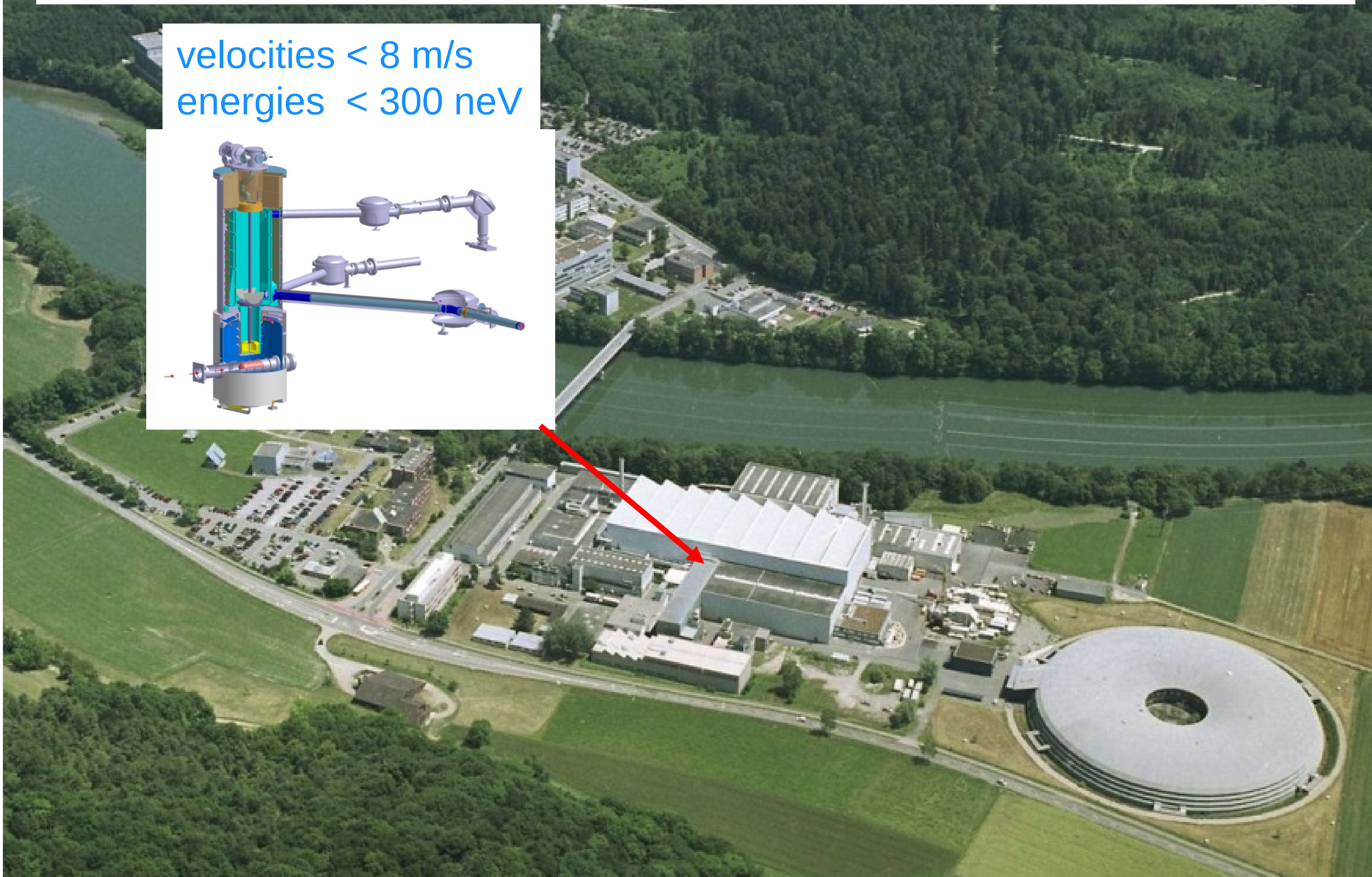
Ultracold neutron source and nEDM experiment at the Paul Scherrer Institute



Ultracold neutron source and nEDM experiment at the Paul Scherrer Institute

velocities < 8 m/s
energies < 300 neV

Neutron bottle (22 liters)

Polarized UCN
5T Magnet

Ultracold neutrons

UCN can be totally reflected from the surface of specific materials at all angles of incidence.

Ultracold neutrons

UCN can be totally reflected from the surface of specific materials at all angles of incidence.

$$\lambda_n = h/(m_n \mathrm{v})$$

$$\lambda_n > 80\ nm$$

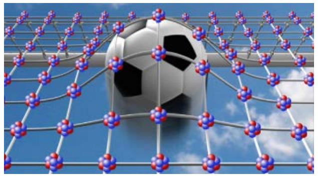
$$E_k = m_n \mathrm{v}^2/2 < 300\ \mathrm{neV}$$

Ultracold neutrons

UCN can be totally reflected from the surface of specific materials at all angles of incidence.

$$\lambda_n = h / (m_n \mathrm{v}) \qquad \lambda_n > 80\ nm \qquad E_k = m_n \mathrm{v}^2 / 2 < 300\ \mathrm{neV}$$

$$n = \sqrt{1 - \frac{V}{E_k}} \qquad \begin{cases} V_F(\vec{r}) = \dfrac{h^2 b_{coh} N}{2\pi m_n} \end{cases}$$



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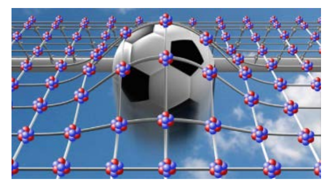

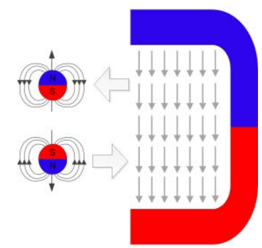

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Ultracold neutrons

UCN can be totally reflected from the surface of specific materials at all angles of incidence.

$$\lambda_n = h/(m_n \mathrm{v}) \qquad \lambda_n > 80\ nm \qquad E_k = m_n \mathrm{v}^2/2 < 300\ \mathrm{neV}$$

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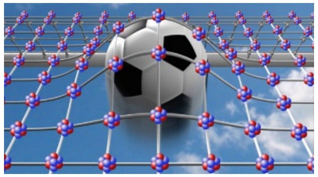

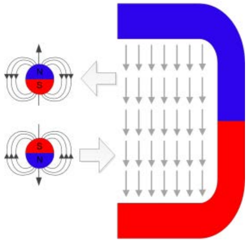

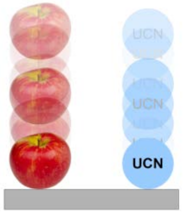

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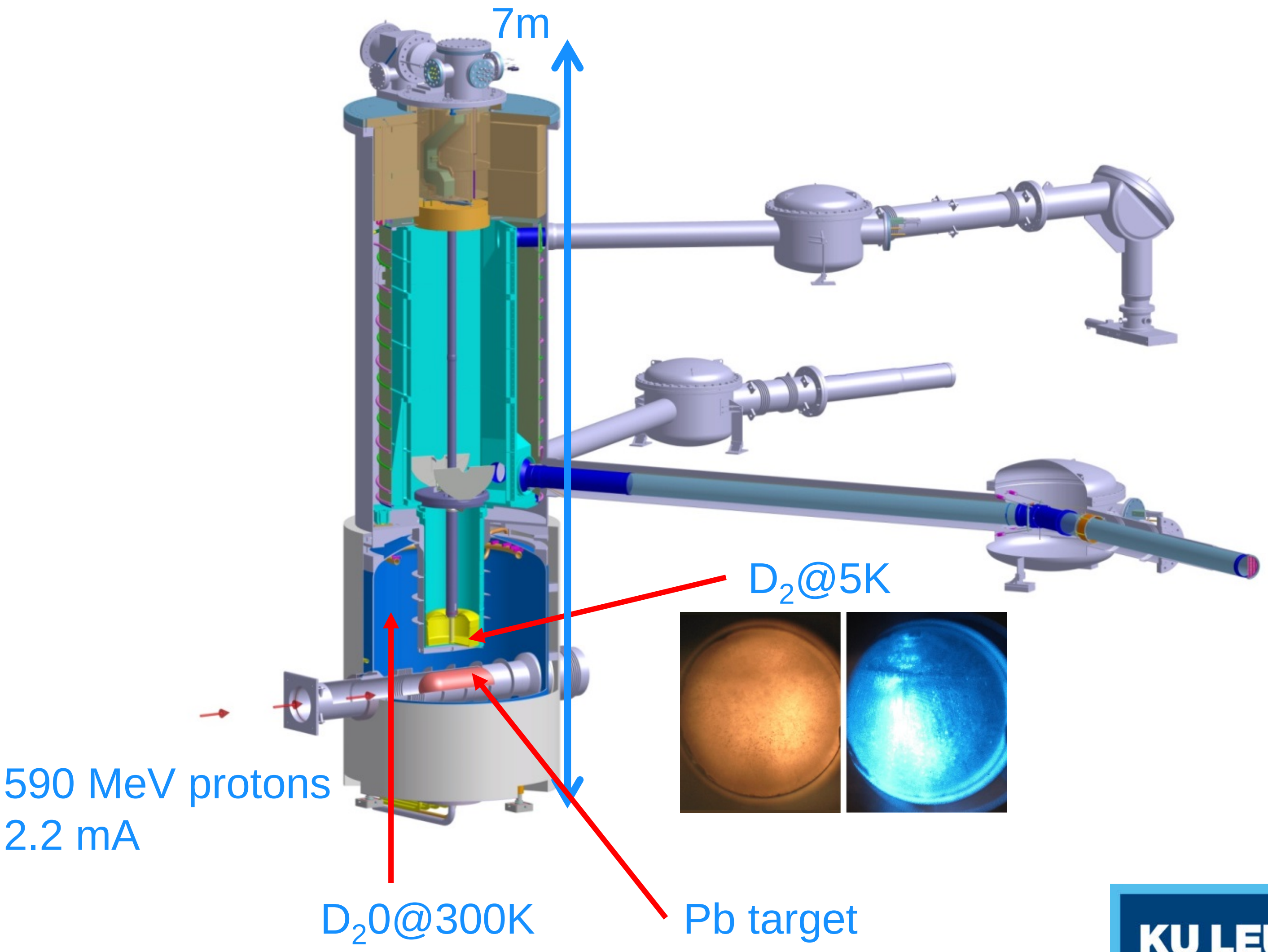
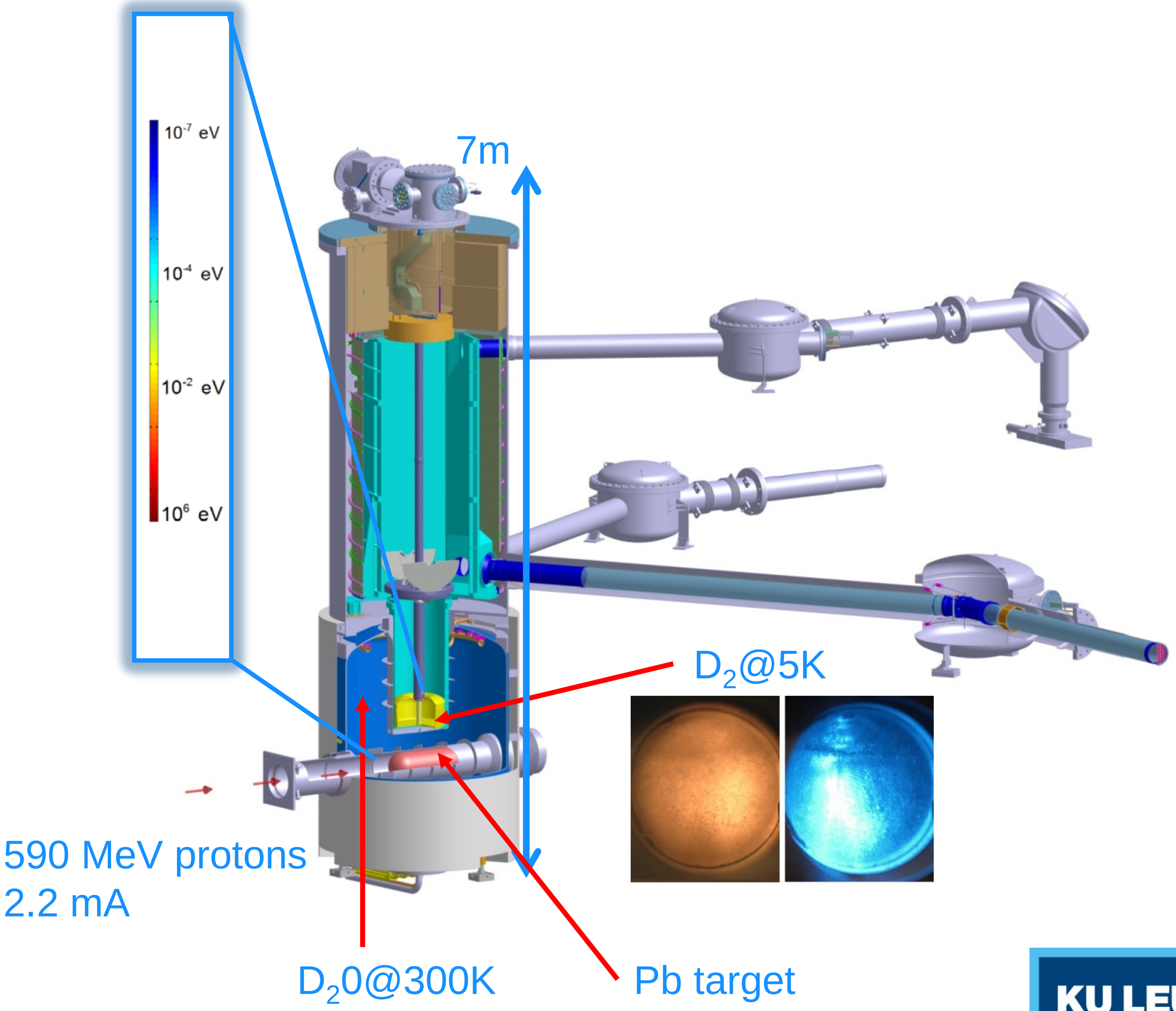
Ultracold neutron production



Ultracold neutron production



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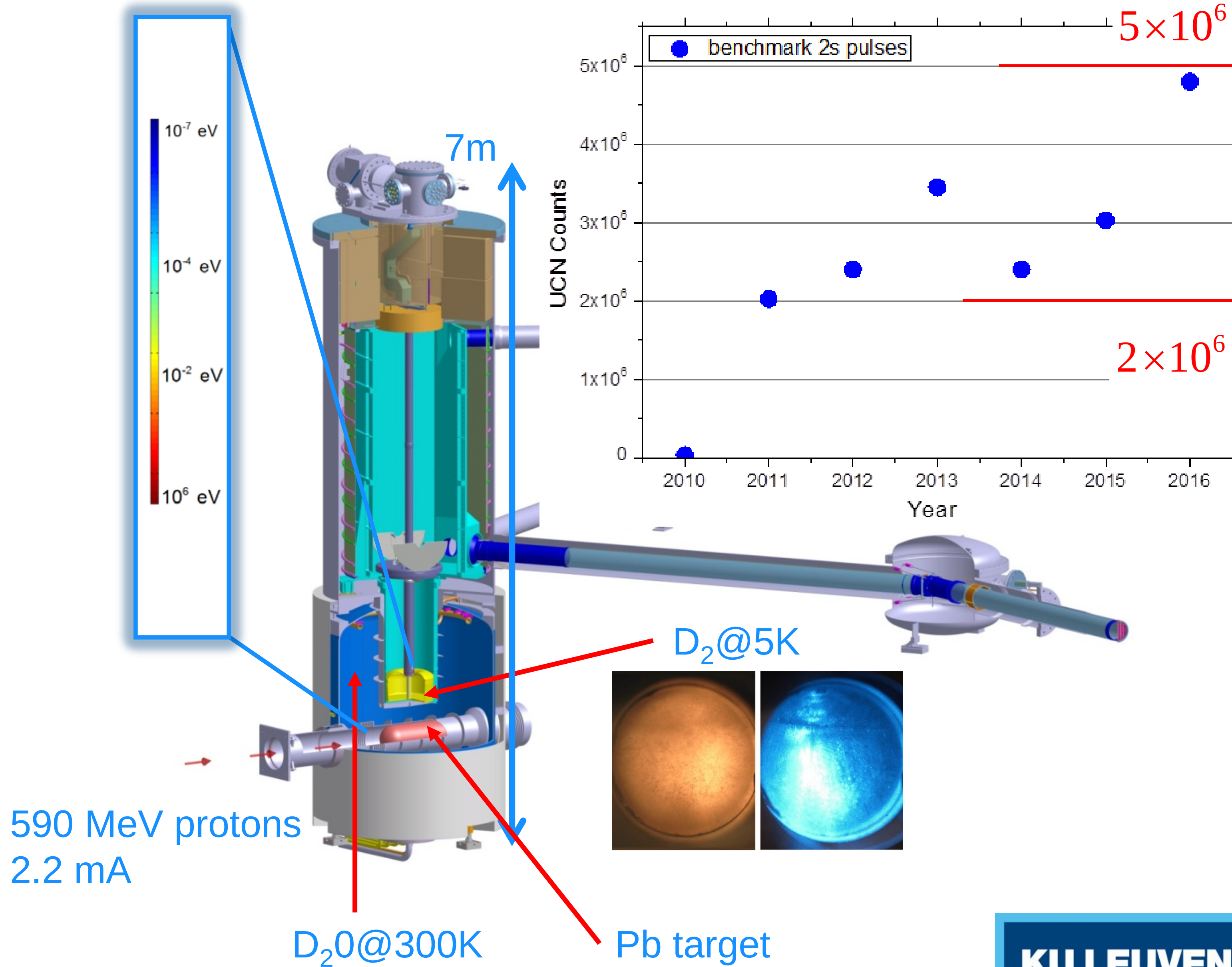
Ultracold neutron production



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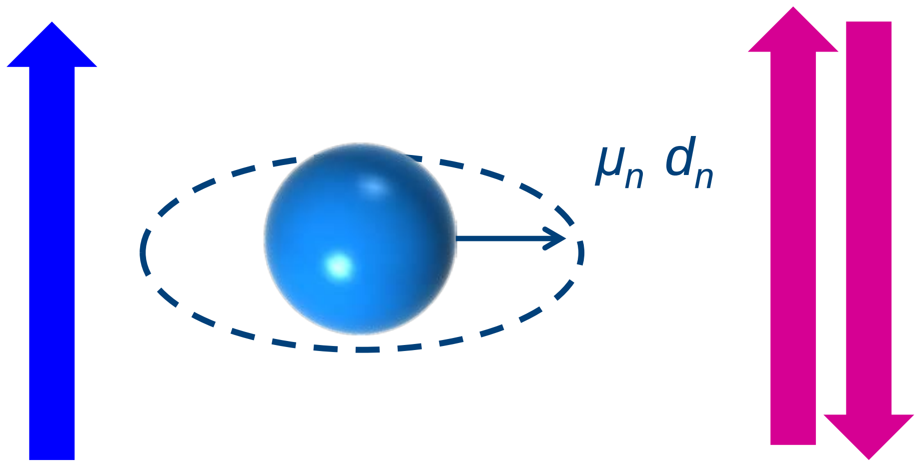
nEDM principle : Spin precession in E and B fields

$\mu_n = 60\ \text{neV/T}$

$\vec{B} = 1\ \mu\text{T}$

$\nu_B \approx 29\,\text{Hz}$



$d_n < 3\times10^{-26}\,e\,cm$

$\vec{E} = 11\ \text{kV/cm}$

$\nu_E < 160\,\text{nHz}$

High-precision measurements of magnetic field

$$\nu_n = \frac{2\mu_n}{h}\left|\vec{B}\right| \pm \frac{2d_n}{h}\left|\vec{E}\right|$$

$$\left|B_+\right| = \left|B_-\right| \Rightarrow\ d_n = \frac{h}{4\left|\vec{E}\right|}\left(\nu_n^+ - \nu_n^-\right)$$

$$\sigma_B < 10^{-14}\ \text{T (10 fT)}$$

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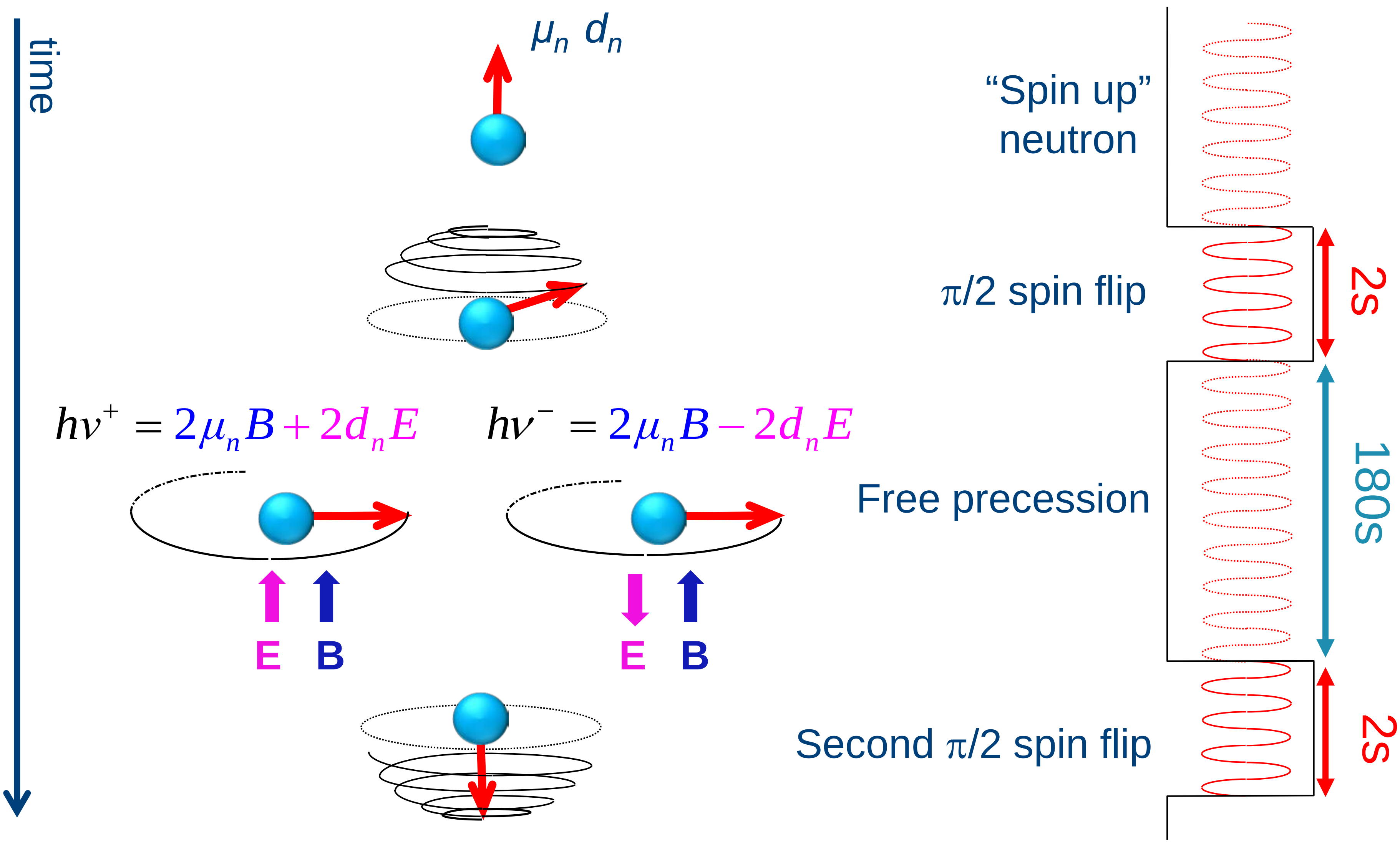
Ramsey method in time space

$$h\nu^{+} = 2\mu_n B + 2d_n E \qquad h\nu^{-} = 2\mu_n B - 2d_n E$$



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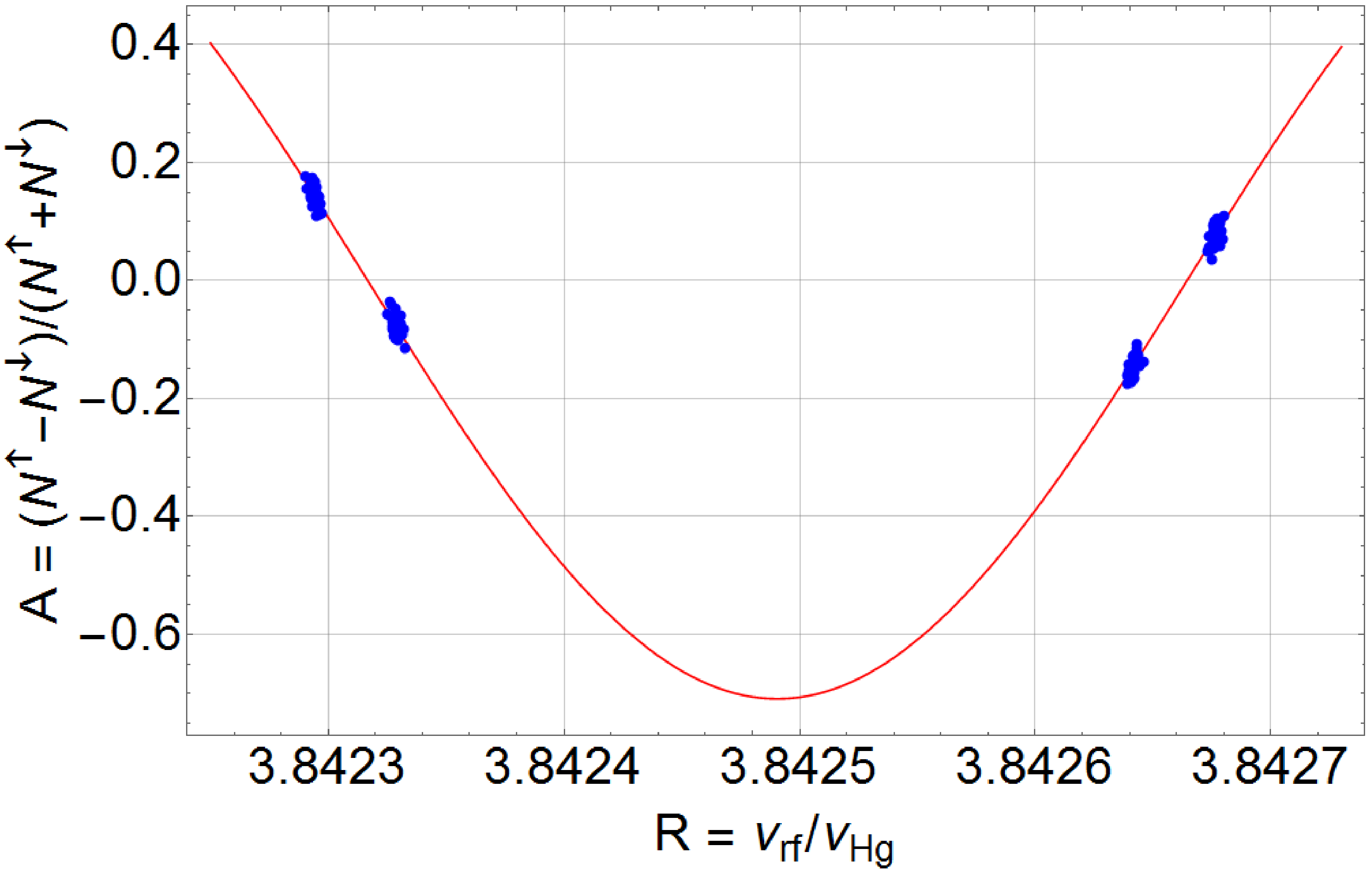
Neutron resonance frequency



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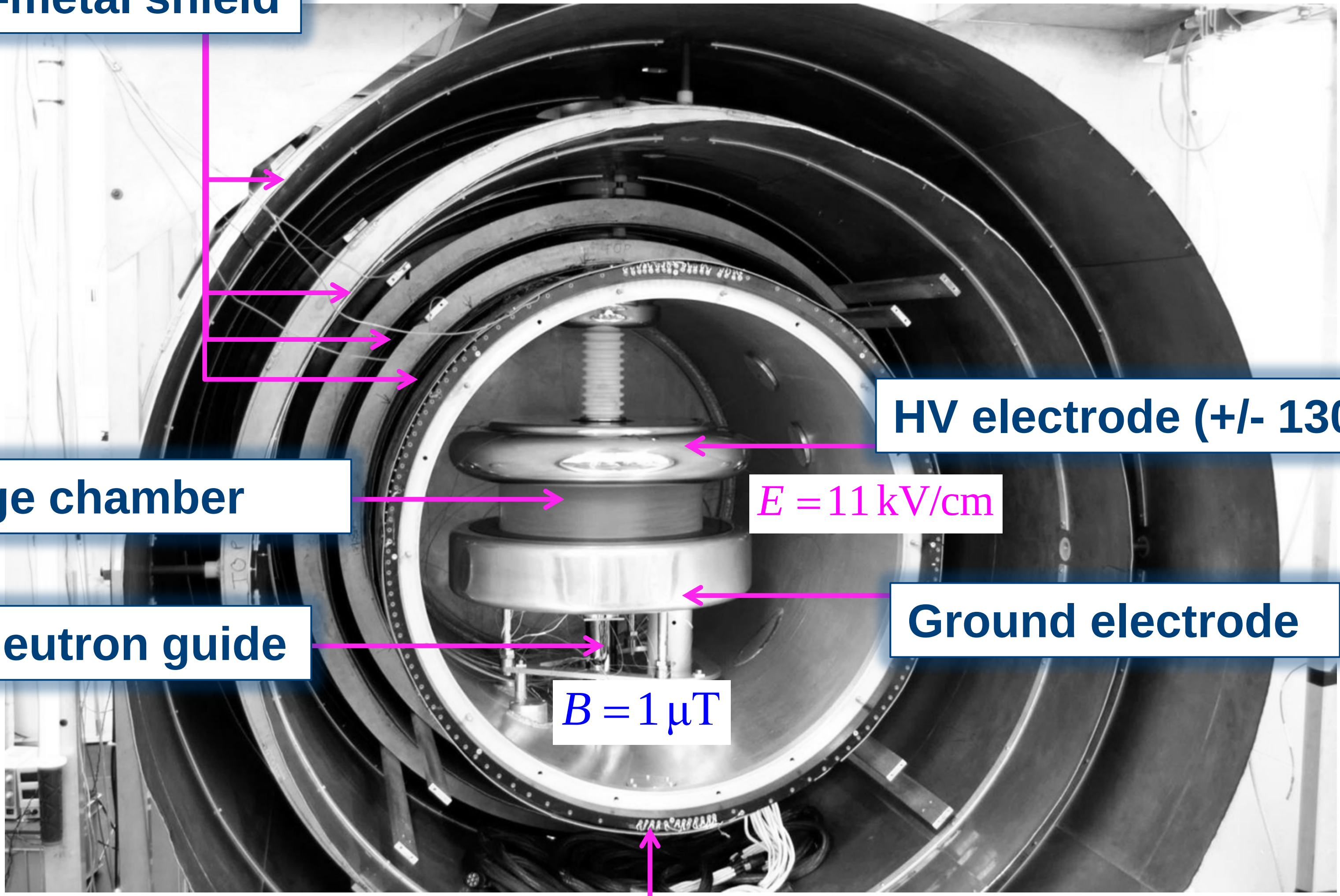
nEDM apparatus



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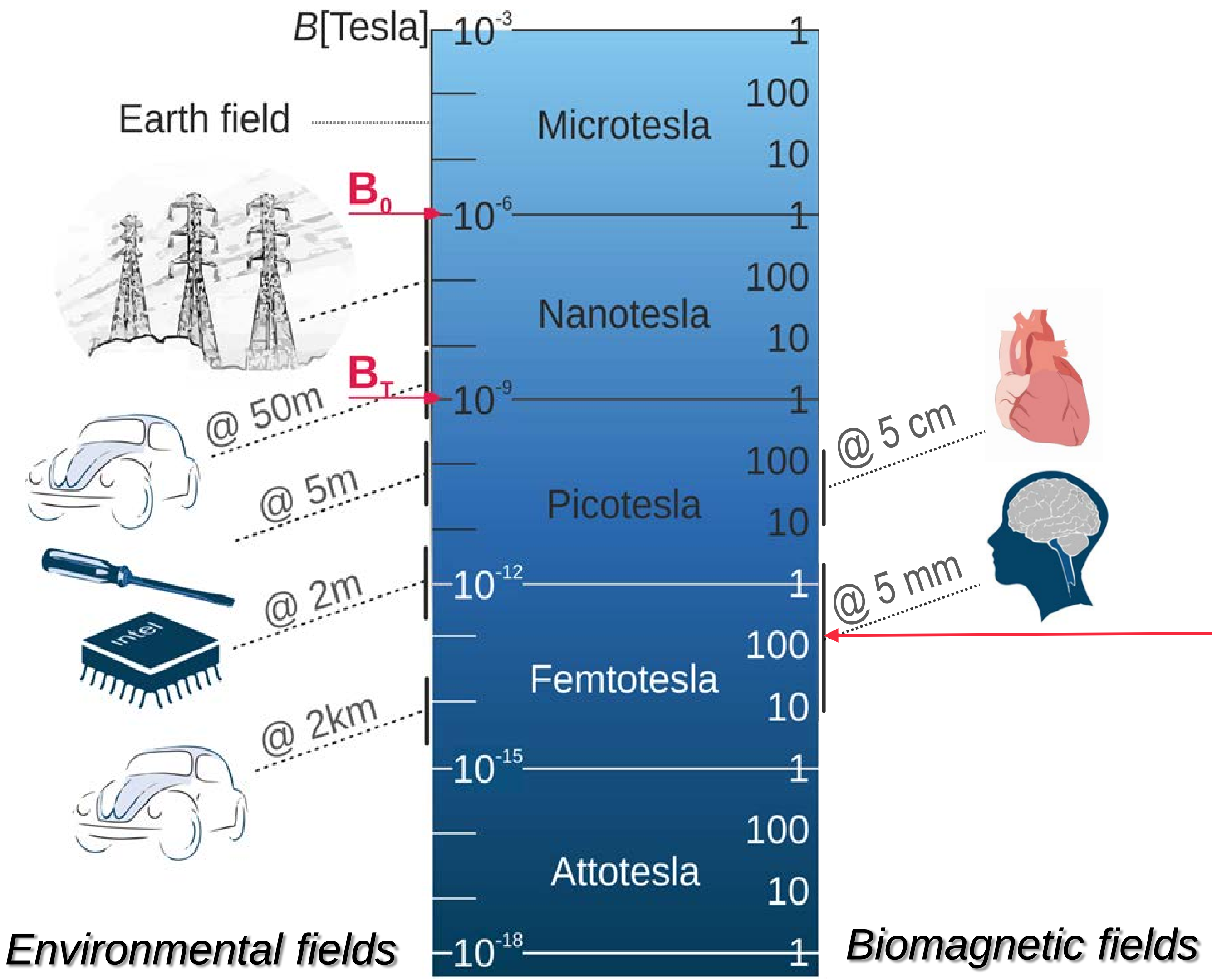
Magnetic fields



nEDM sensitivity requirement

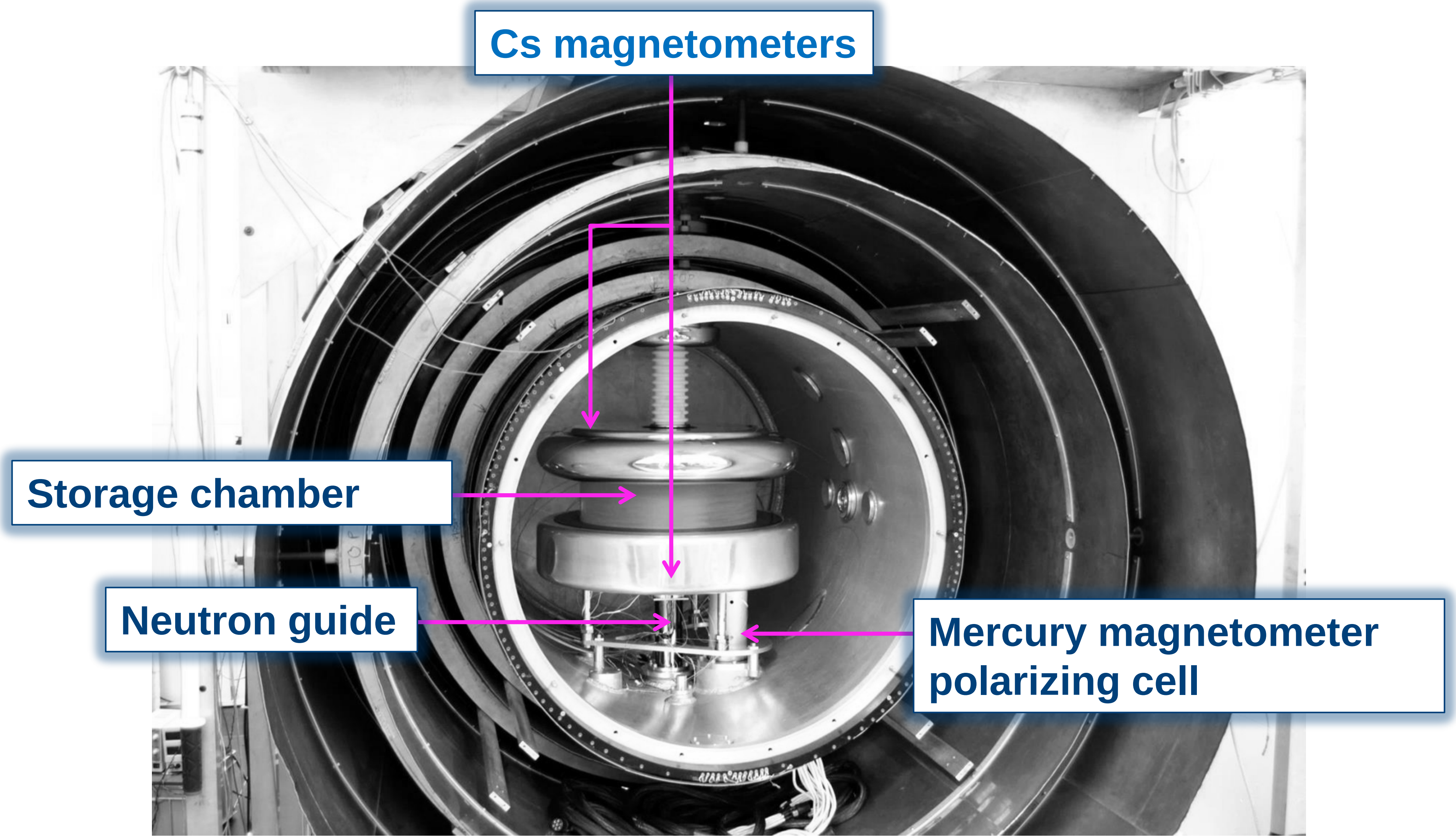
$\delta B < 170\mathrm{fT}$

Magnetometers (Cs/Hg)

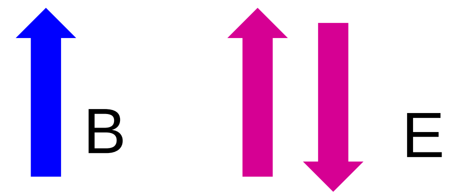
Magnetic shielding in nEDM

Magnetic shield
Surrounding field coils
Air-conditioned non–magnetic house

Magnetic field control in nEDM



Magnetic field sensitivity



$$\nu_n = \frac{2\mu_n}{h}\left|\vec{B}\right| \pm \frac{2d_n}{h}\left|\vec{E}\right|$$

$$|B_+| = |B_-| \Rightarrow \quad d_n = \frac{h}{4\left|\vec{E}\right|}\left(\nu_n^+ - \nu_n^-\right)$$

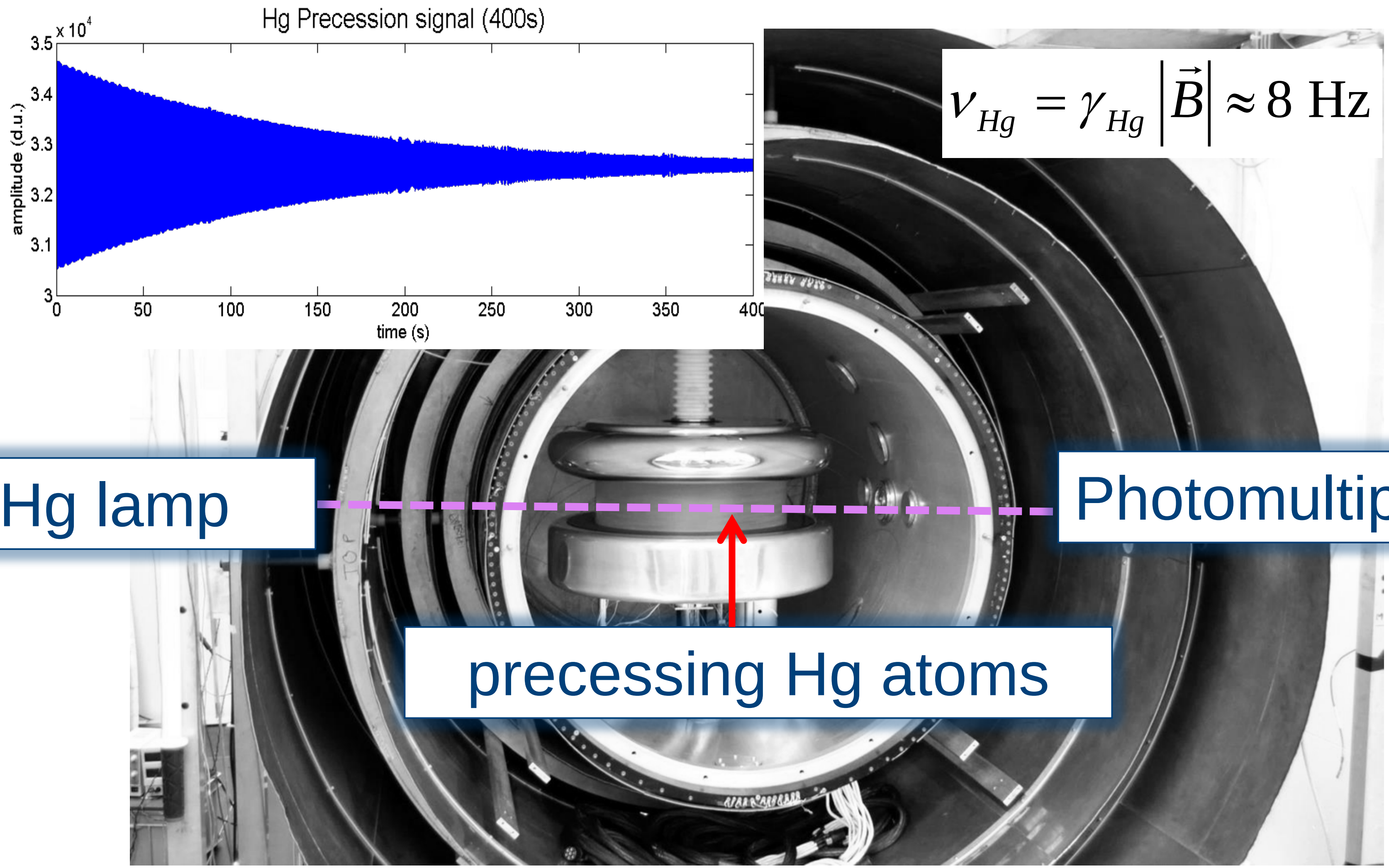
$$d_{meas} = d_n + \frac{\mu_n\left(|B_+| - |B_-|\right)}{2|E|\sqrt{m}}$$

$$\delta(\mathrm{d}_{meas}) = \frac{\hbar}{2\alpha TE\sqrt{N}}$$

$$\sigma(d_{meas}) \approx 1.1\times10^{-25}\,\mathrm{e}\cdot\mathrm{cm/day}\ \text{(288 measurements)}$$

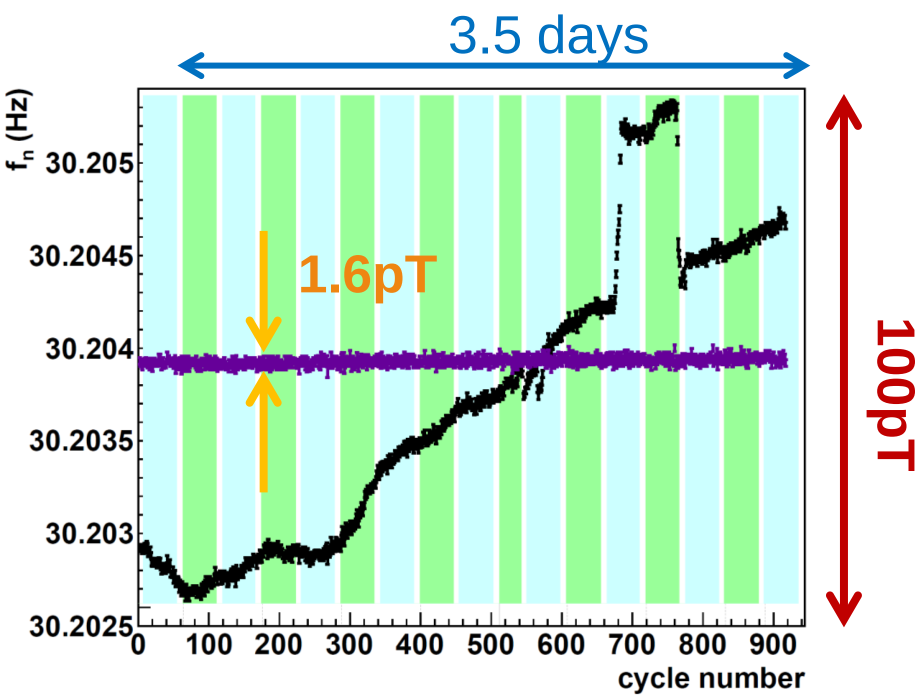
$$\sigma(B) < 170\ \mathrm{fT}\ \text{in a single measurement}$$

Hg co-magnetometer

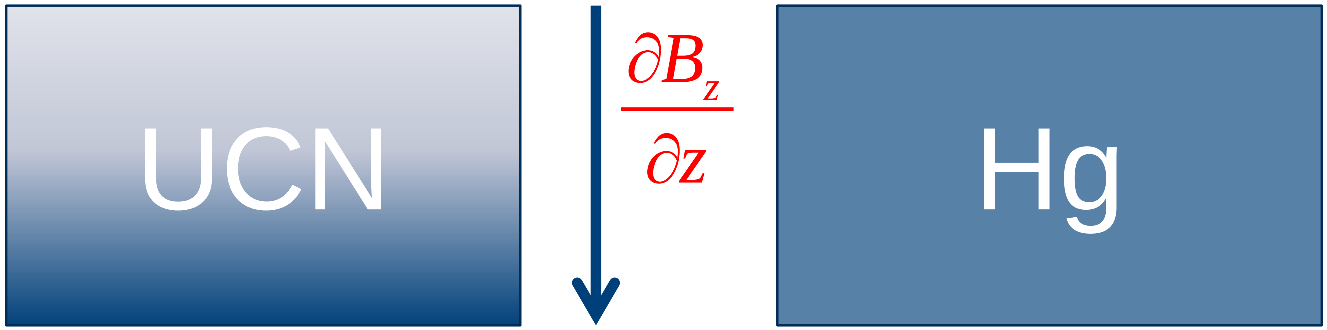


$$\nu_{Hg} = \gamma_{Hg} \left|\vec{B}\right| \approx 8 \text{ Hz}$$

Magnetic field correction



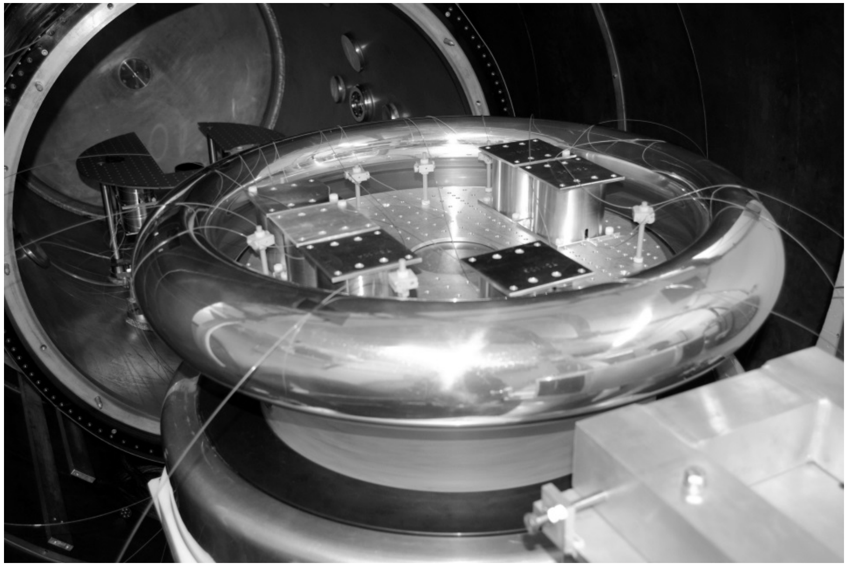
Gravitational shift

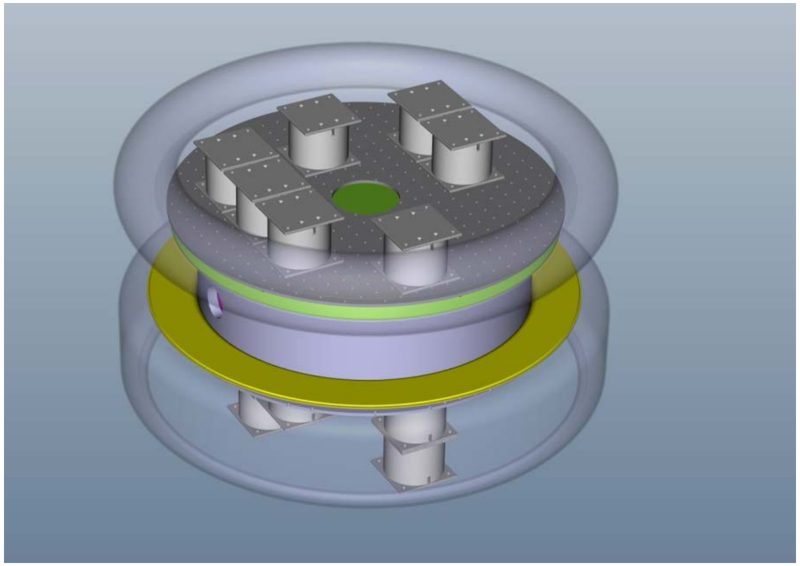


$$R \approx \frac{\nu_n}{\nu_{Hg}}\left(1 \pm \Delta h \frac{\partial B_z / \partial z}{B}\right)$$

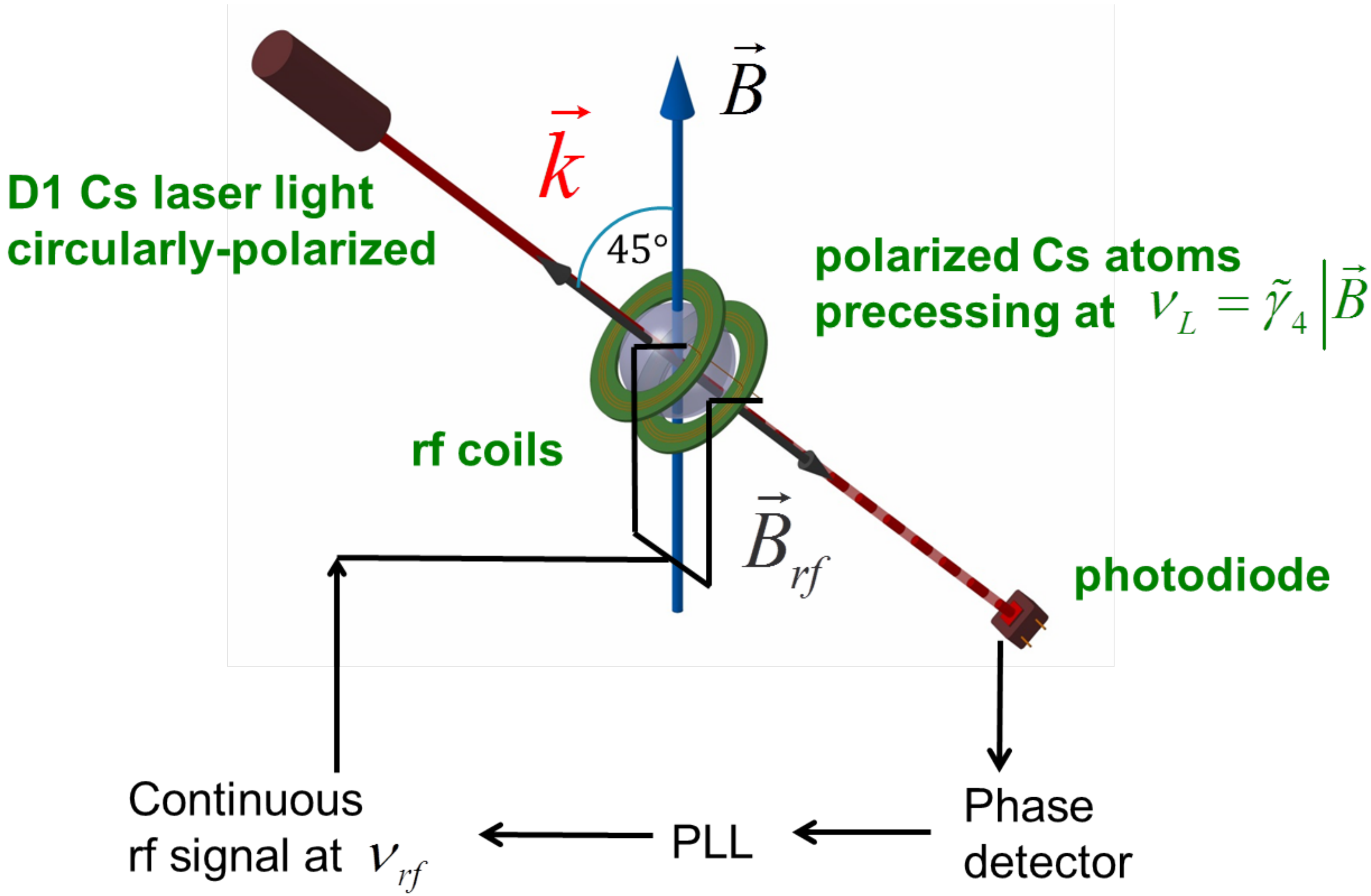
$$d_{meas} = d_n \pm k(\mathrm{R} - \mathrm{R}_0)$$

Cs magnetometers

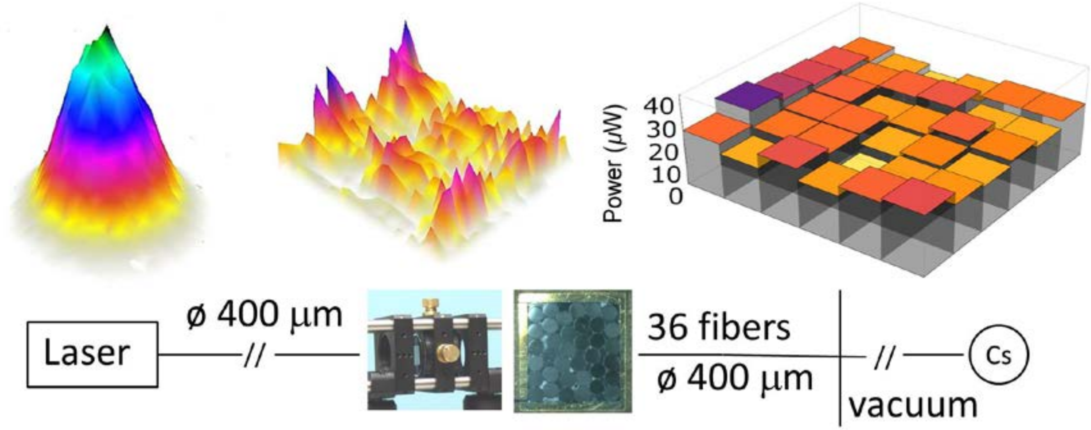


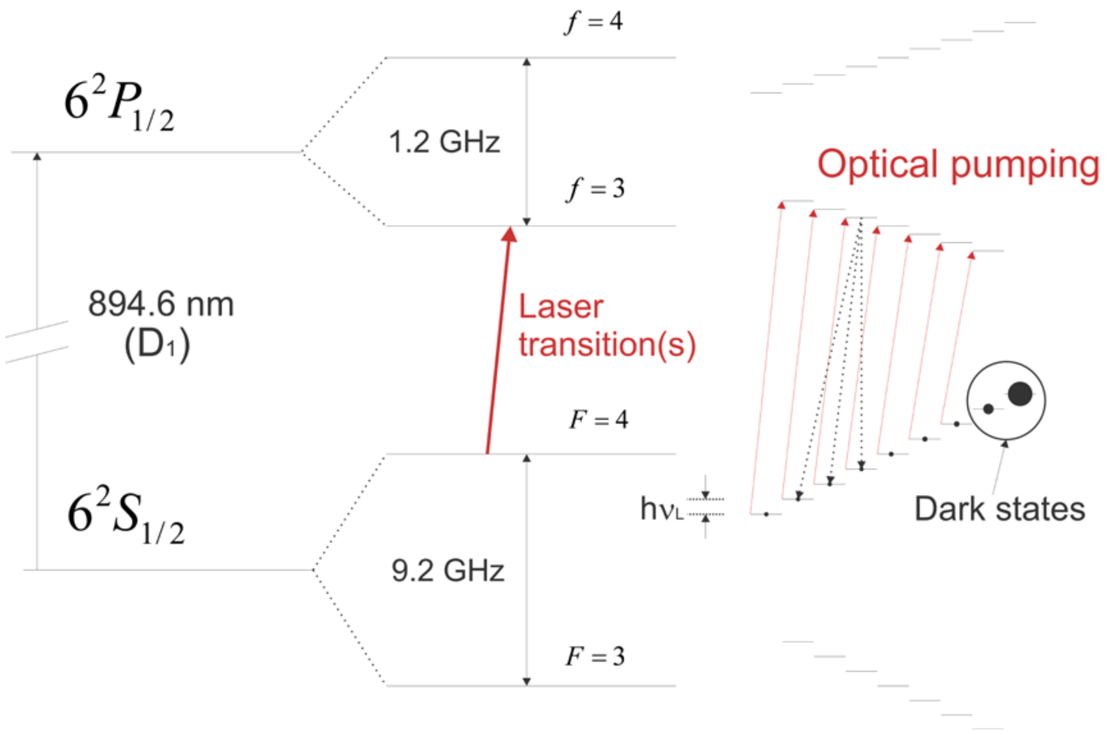


Cs magnetometers

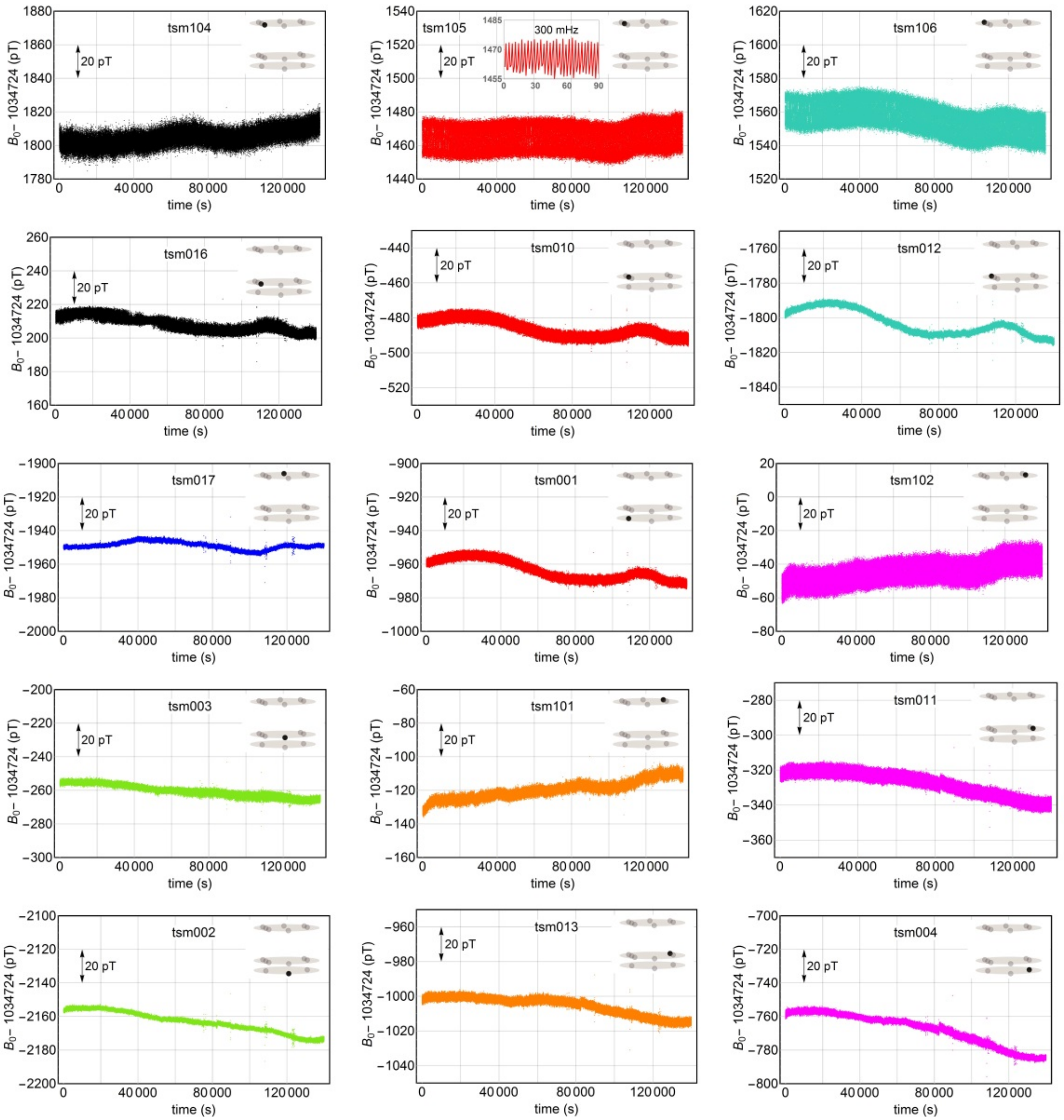


Single laser operation





Cs magnetometers

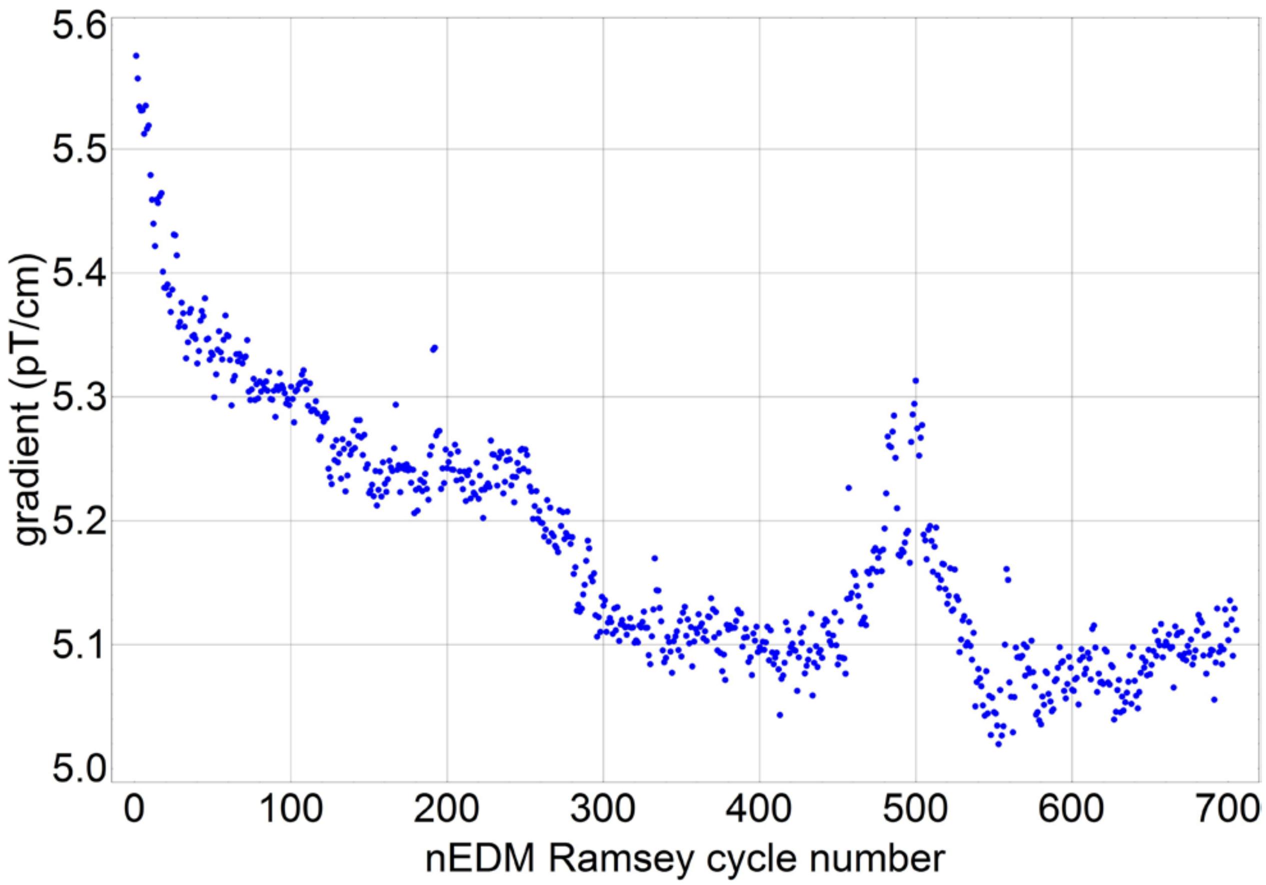


The multipole expansion of the B_z component is used with the aim of obtaining $\partial B_z / \partial z$.

The B_z measured by a [133]Cs magnetometer at the position (x,y,z) is expressed as

$$B_z(x,y,z) = B_z + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy} xy + g_{xz} xz + g_{yz} yz$$

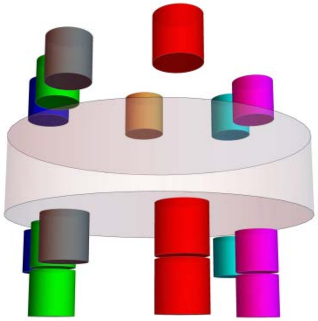
Gradient



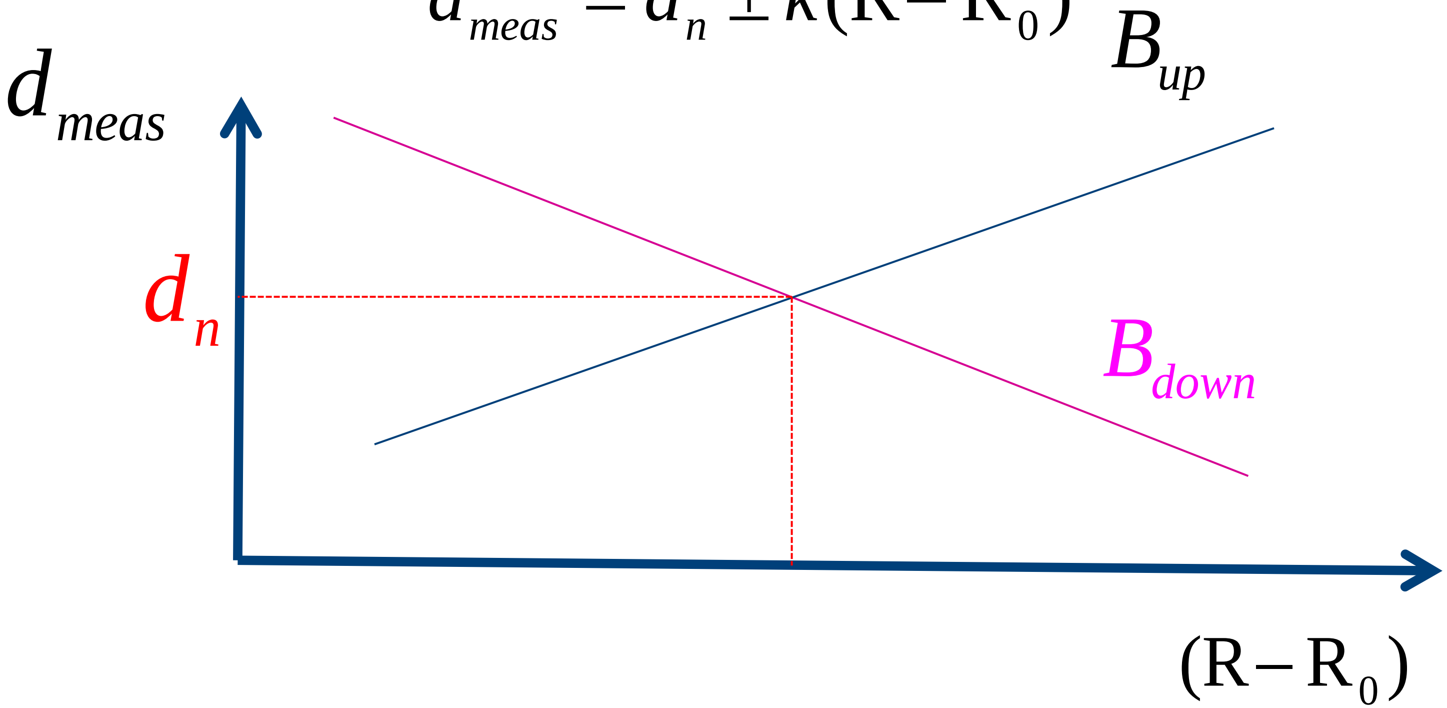
5.6
5.5
5.4
5.3
5.2
5.1
5.0
gradient (pT/cm)
0
100
200
300
400
500
600
700
nEDM Ramsey cycle number

Crossing point analysis

$$R = \frac{\nu_n}{\nu_{Hg}}\left(1 \pm \Delta h \frac{\partial B_z / \partial z}{|B|}\right)$$



$$d_{meas} = d_n \pm k(\mathrm{R} - \mathrm{R}_0)$$

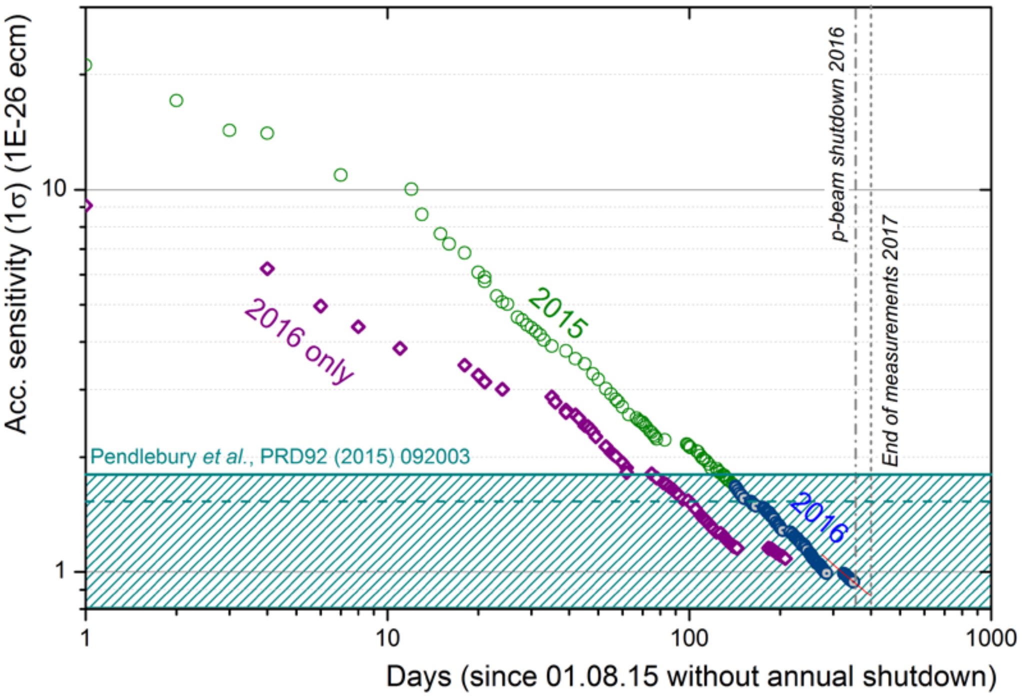


Statistical sensitivity in the running experiment

Accumulated raw sensitivity

2015: 1.7×10^{-26} ecm
2016: 1.1×10^{-26} ecm
Total: 0.94×10^{-26} ecm

(values from simple fit)



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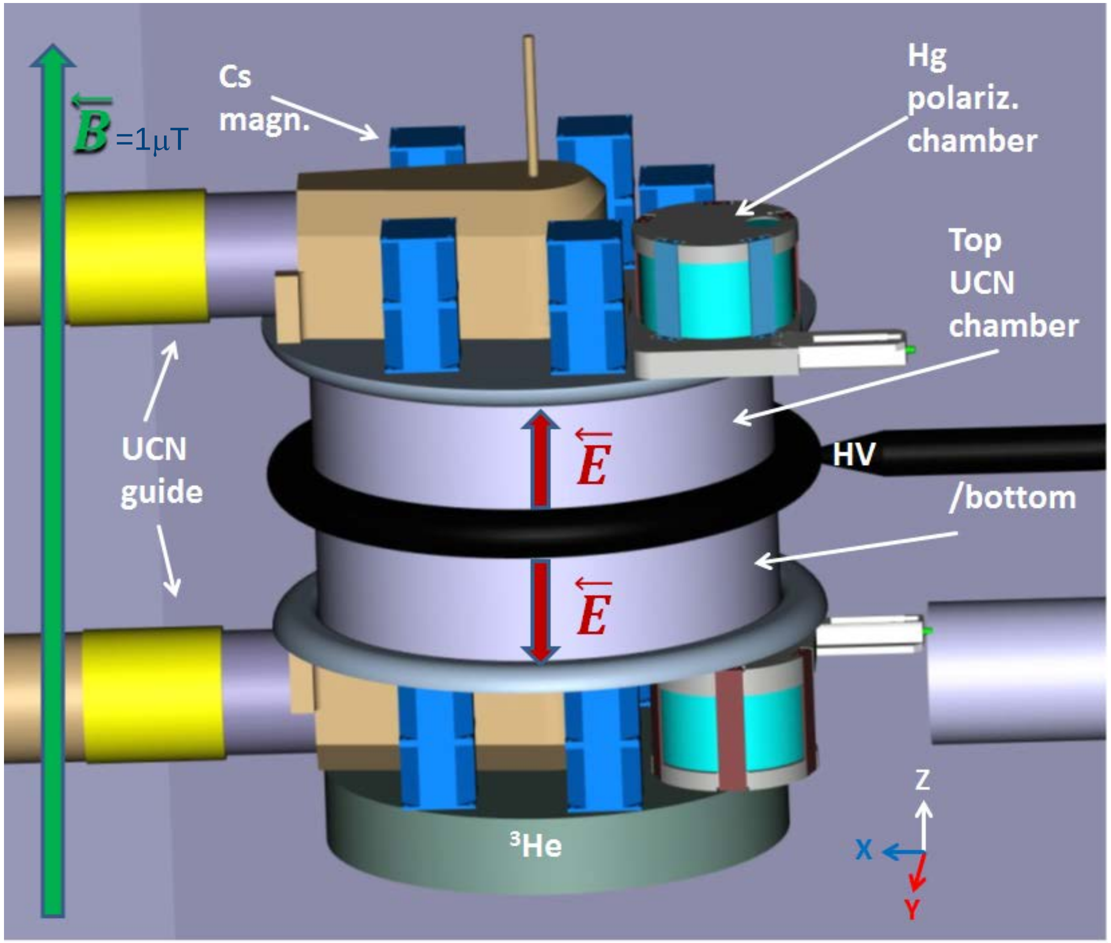
Next step: new setup and increased sensitivity



- Double precession chamber
- Better adaptation to the UCN source
- Stronger electric field
- Hg co-magnetometer in both chambers with laser read-out
- Cs arrays on ground potential (>50 sensors)

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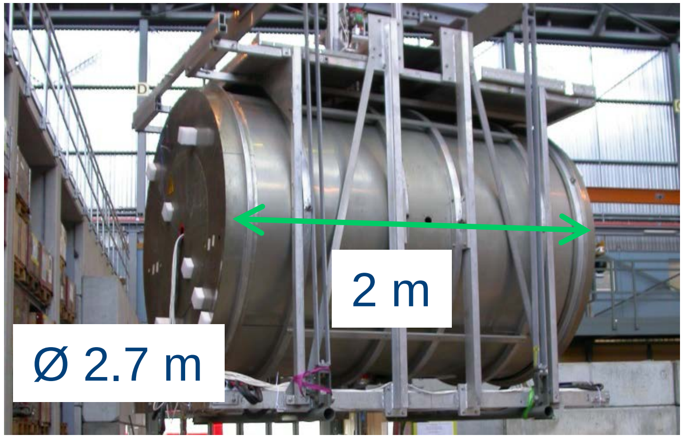
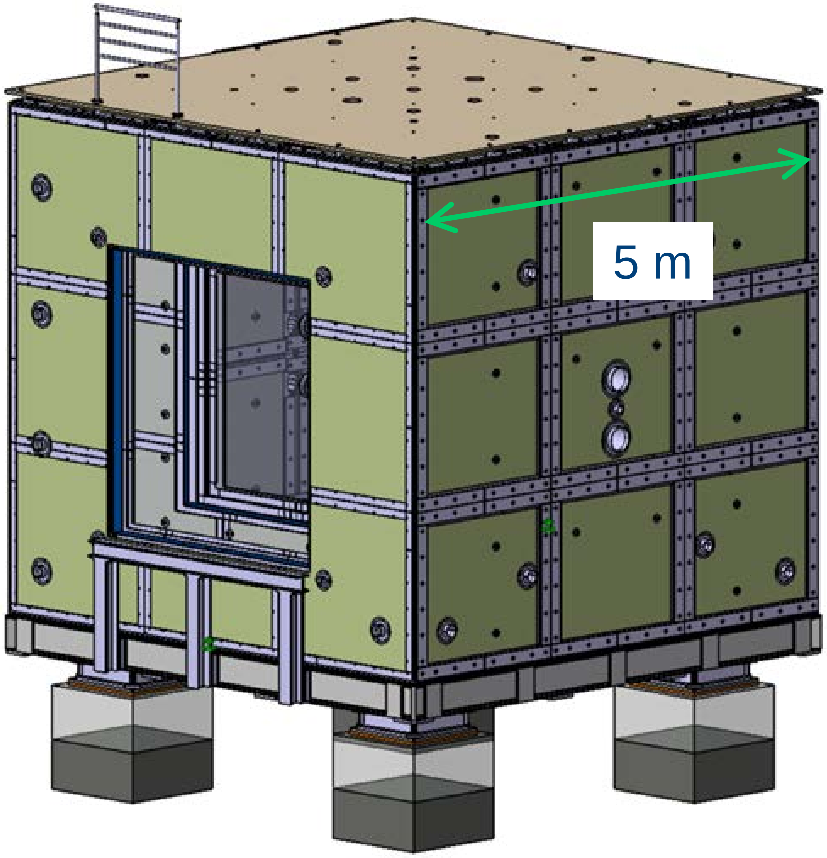
New magnetic shield





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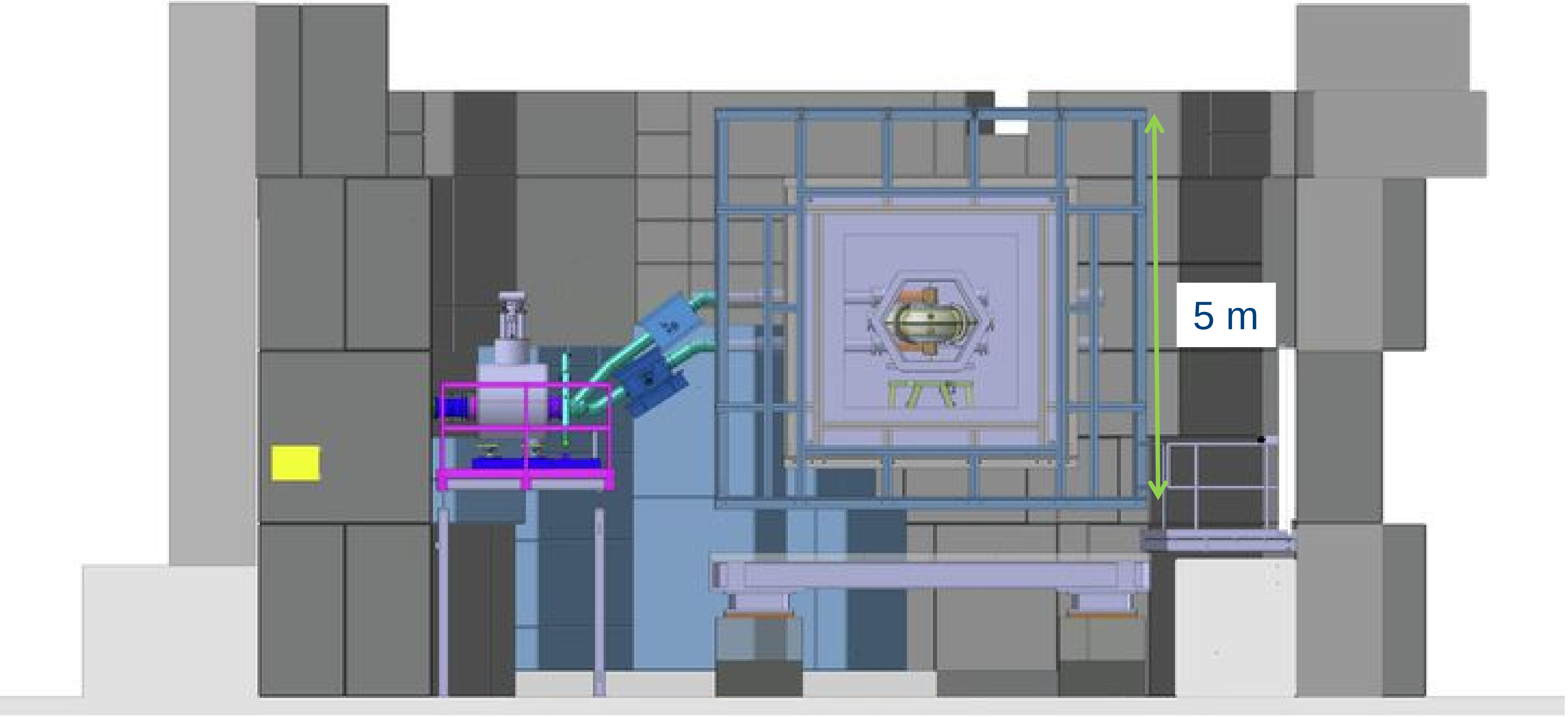
New setup inside new magnetic shield



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Conclusions

- Search for a neutron EDM probes the New Physics
- The existence of a nEDM has cosmological implications on BAU
- nEDM@PSI is running with the world's best sensitivity (accumulated sensitivity of 1.16×10^{-26} e.cm) and expecting to deliver a new nEDM upper limit soon
- Upgrade of the nEDM@PSI in the next years with an ultimate aim of 5×10^{-28} e.cm

nEDM collaboration

- ~ 50 members
- 14 institutions
- 7 countries

Thank you for your attention

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