PAUL SCHERRER INSTITUT

PSI

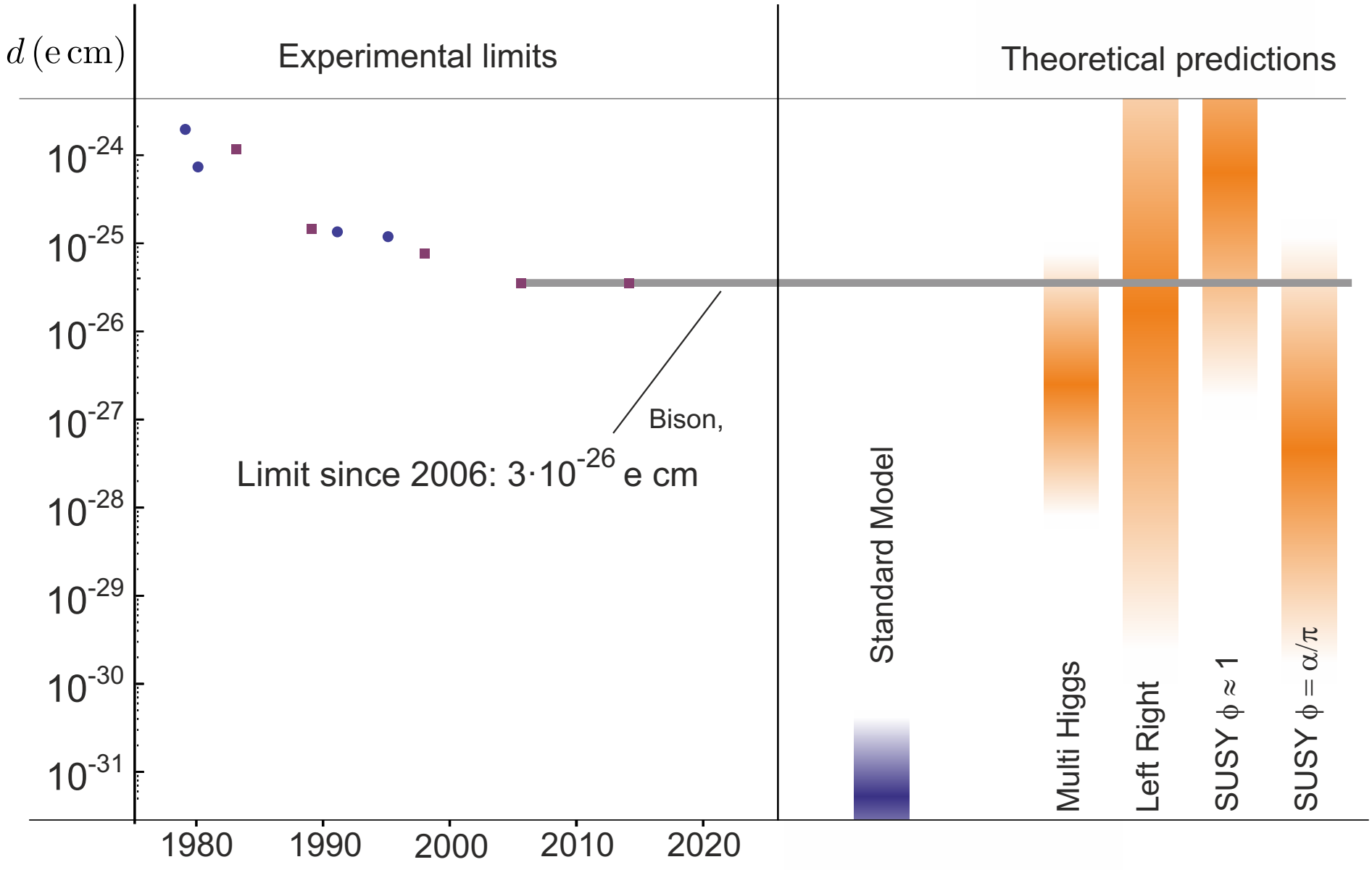
Paul Scherrer Institut

G. Bison for the nEDM collaboration

Result of the neutron EDM starch at PSI

- **Introduction & neutron EDM experiment @ PSI**
- Results
- New experiment n2EDM

History

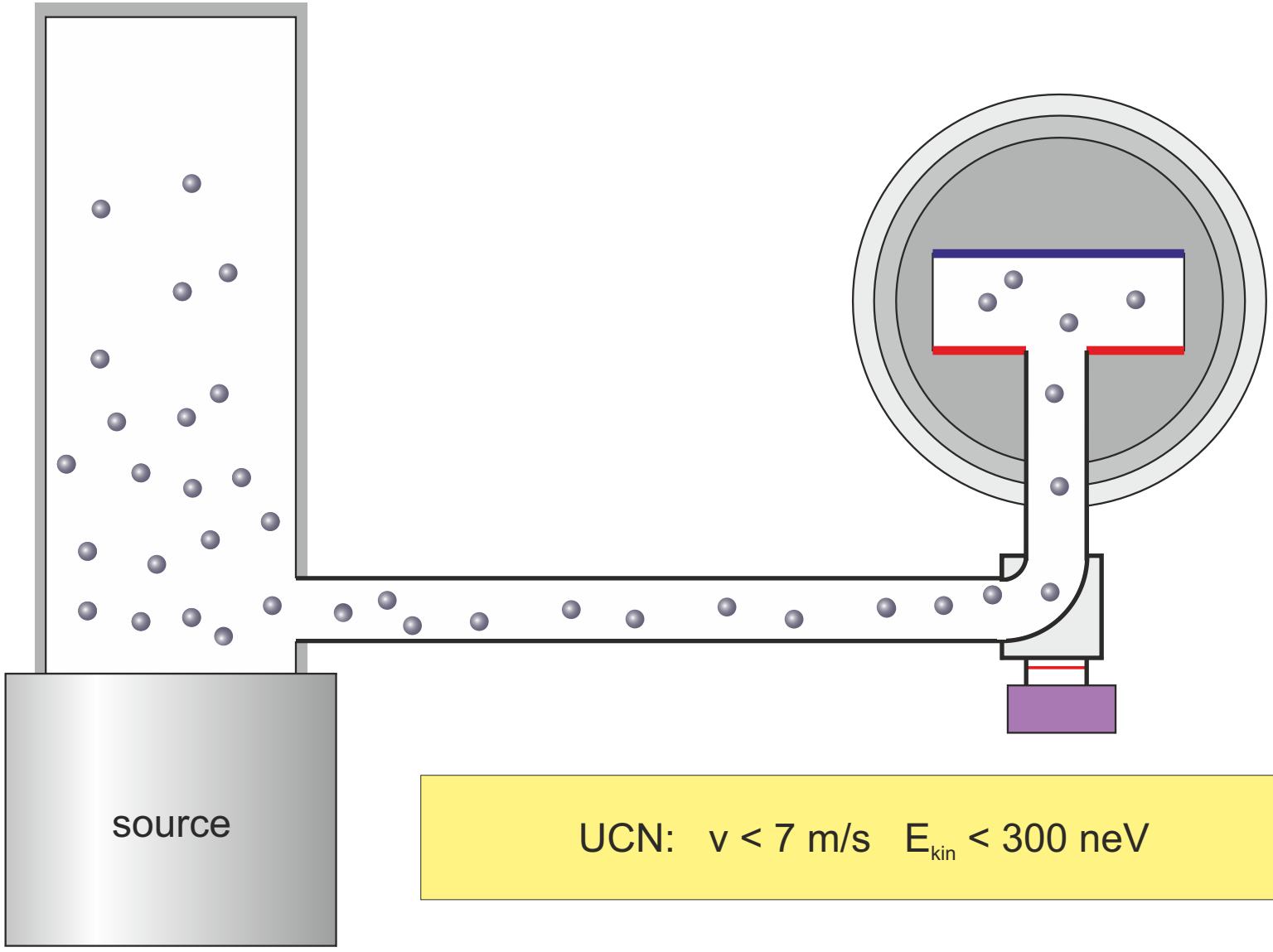


Theoretical data: «Particle electric dipole moments»
J.M. Pendlebury & E.A. Hinds, NIM A 440 (2000) 471

Ultra cold neutrons

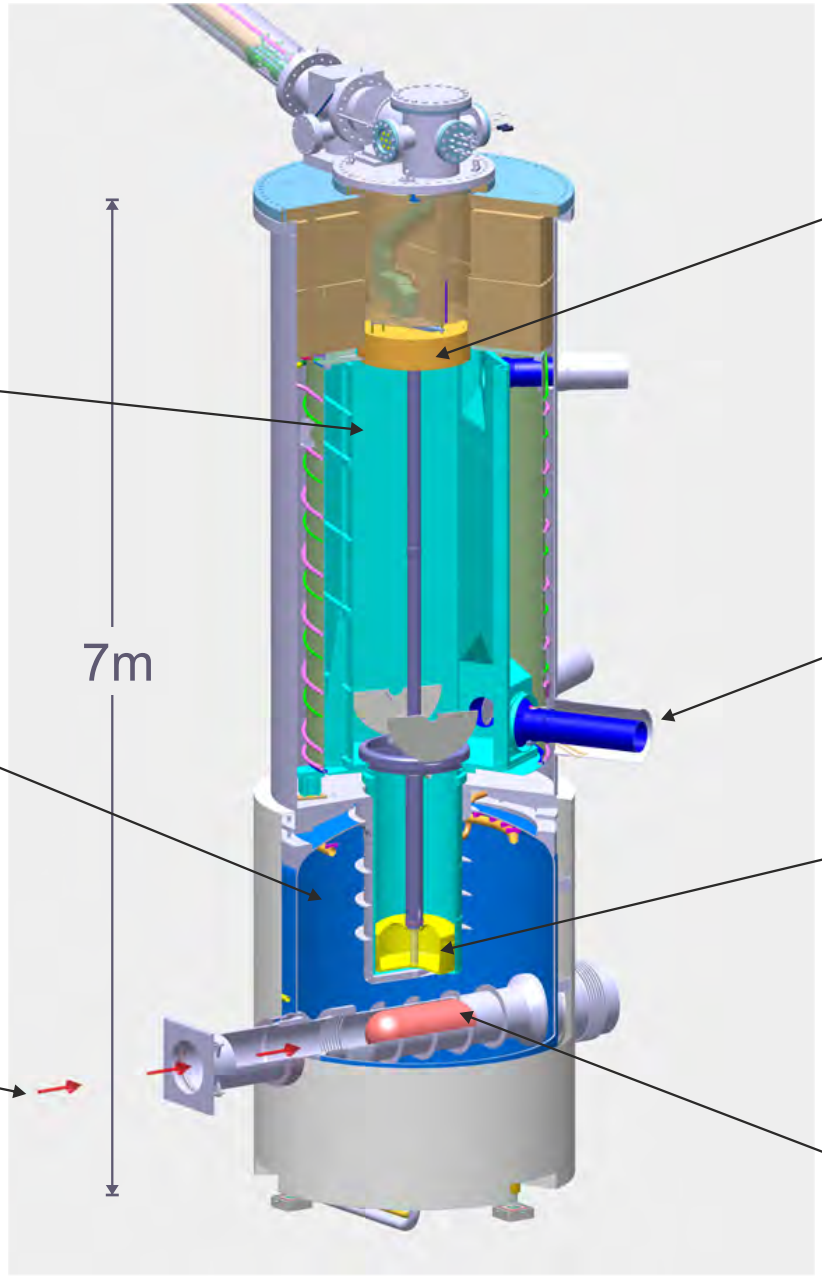
Make Ultra Cold Neutrons (UCN)

Measure Electric Dipole Moment (EDM)



UCN: $v < 7$ m/s $E_{kin} < 300$ neV

The Ultra-cold neutron (UCN) source @ PSI



cryo-pump

DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

UCN guide towards
experimental areas

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

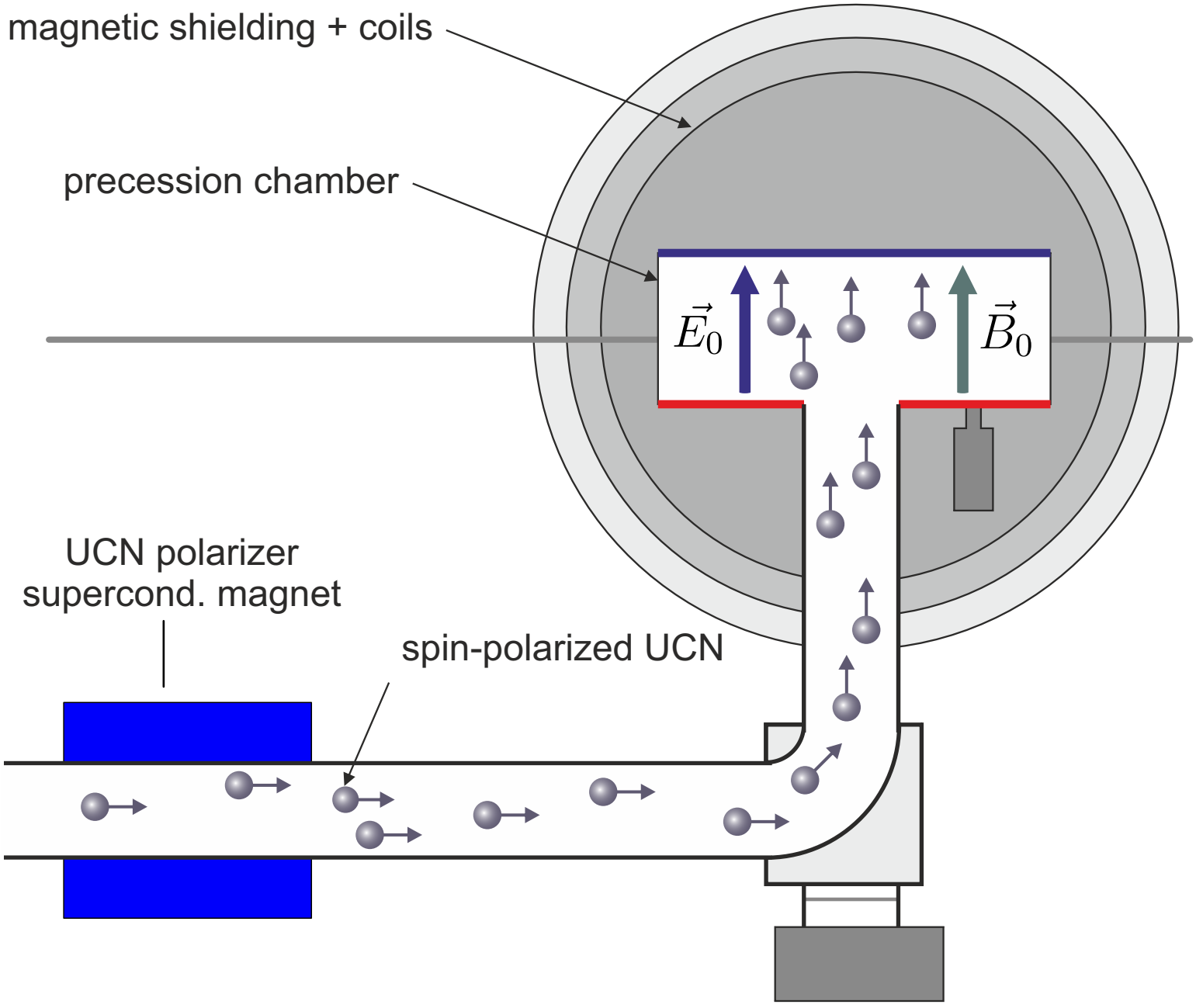
cold UCN-converter
~30l solid D2 at 5 K

pulsed 1.3 MW p-beam
600 MeV, up to 2.4 mA

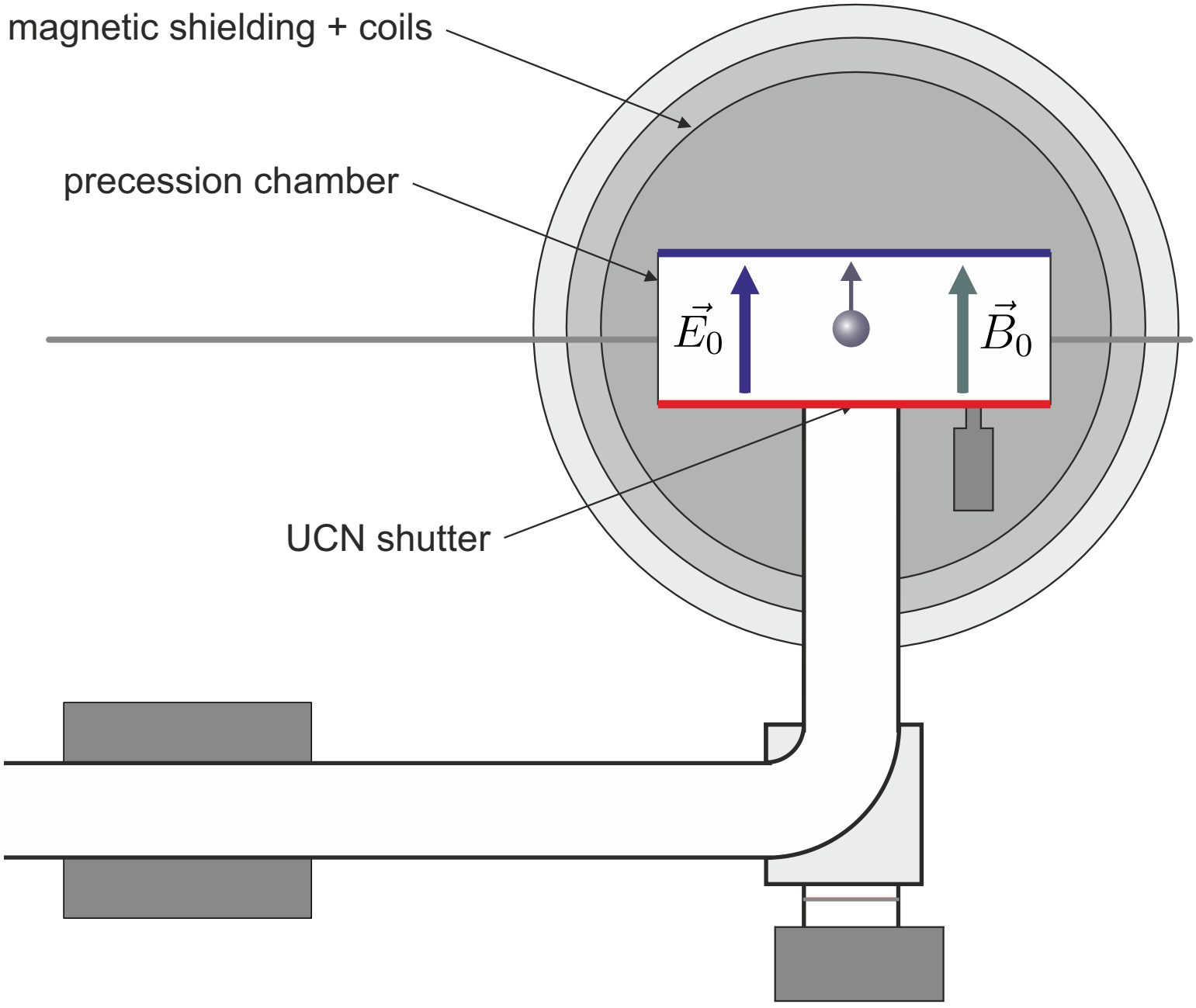
up to 60 μA average
current on target

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

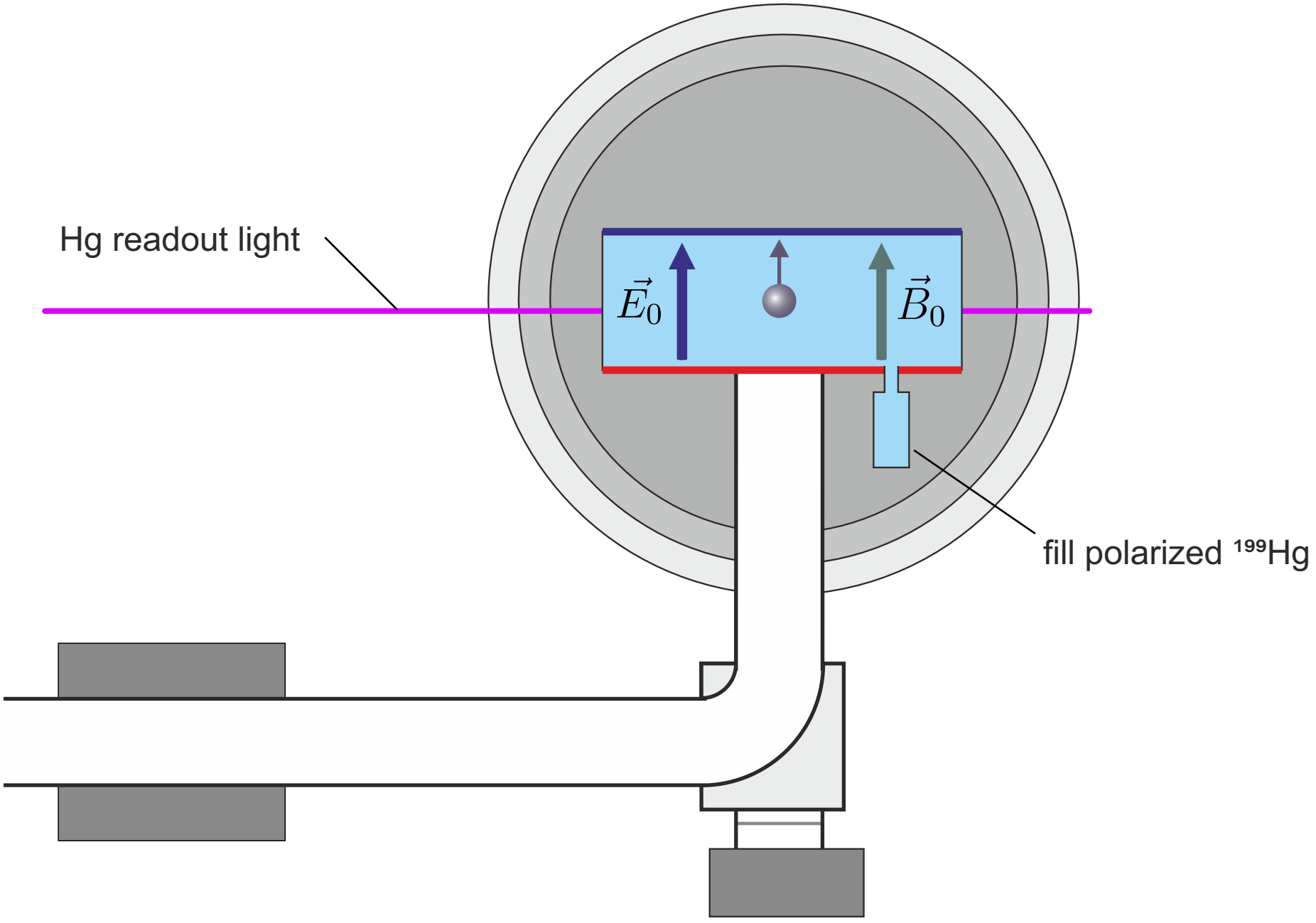
Filling the precession chamber



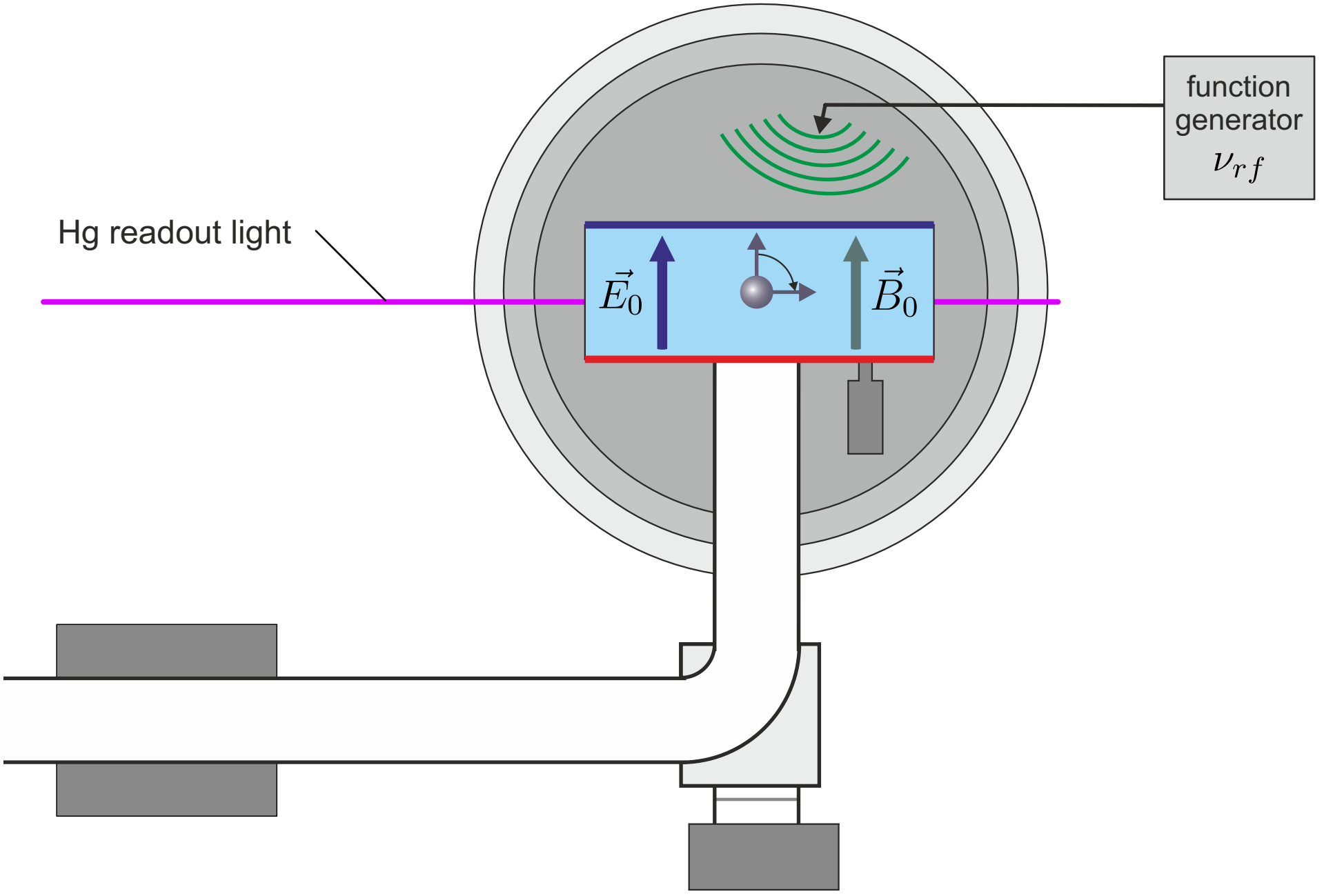
Filling the precession chamber



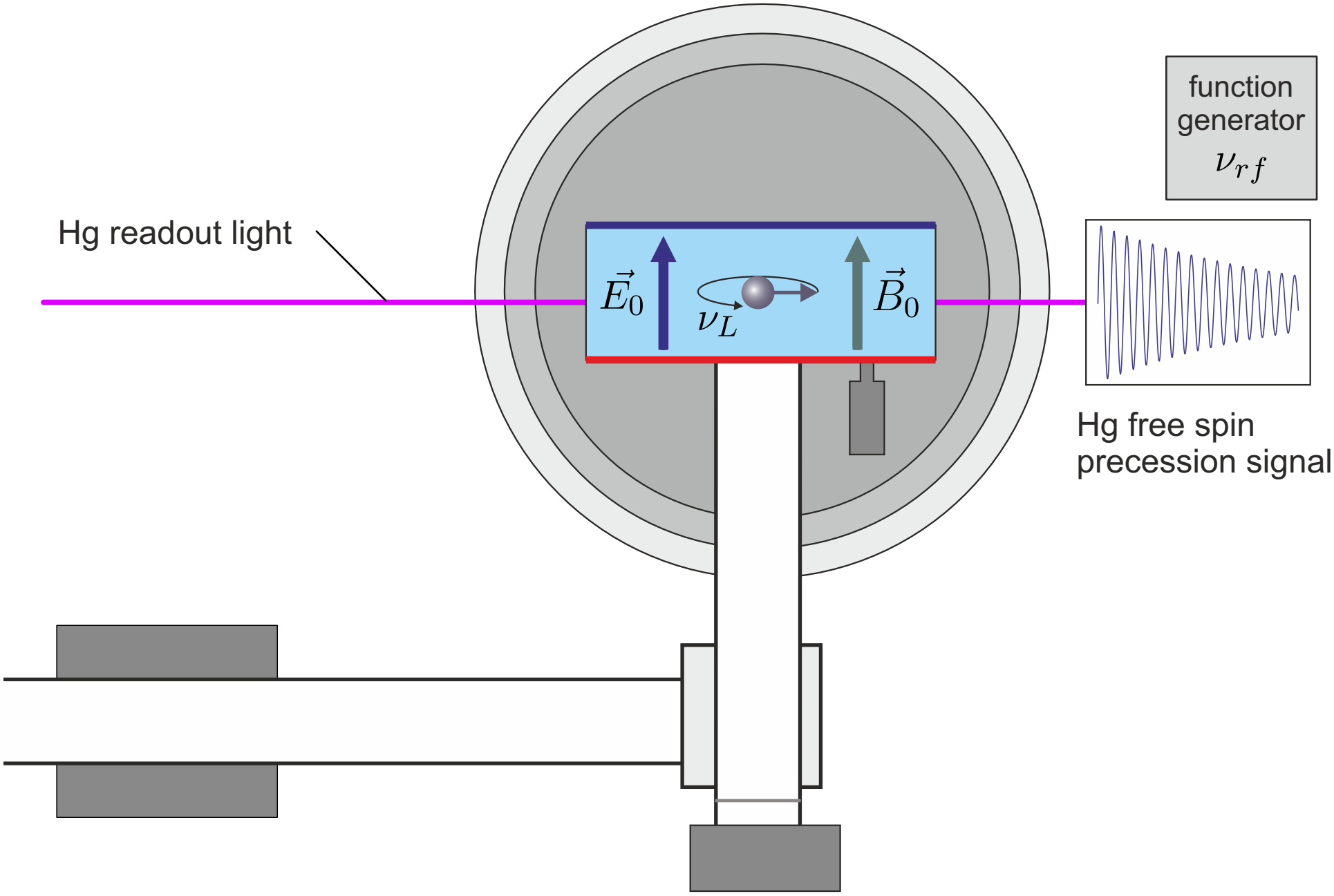
Filling the precession chamber



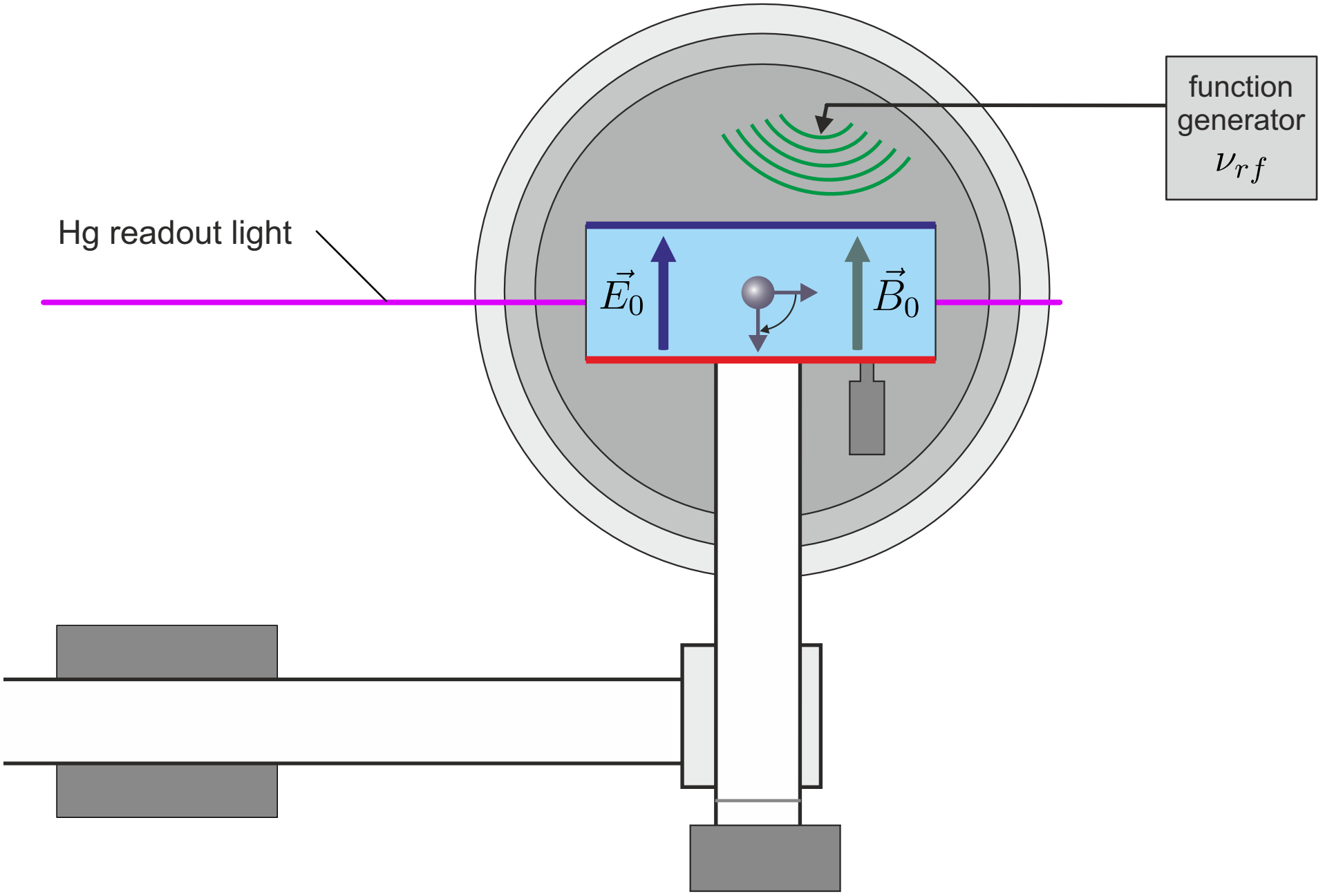
Ramsey cycle



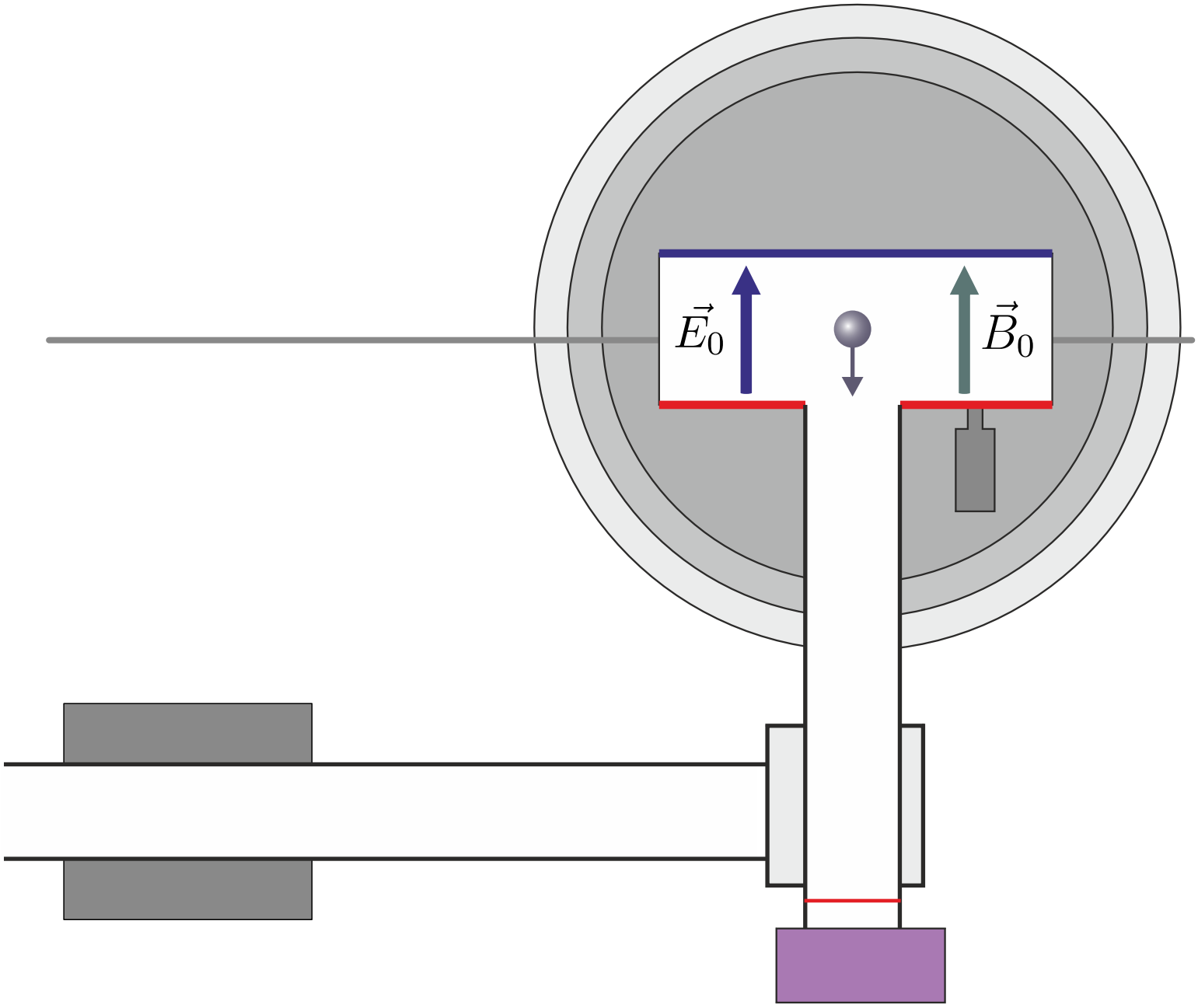
Ramsey cycle



Ramsey cycle

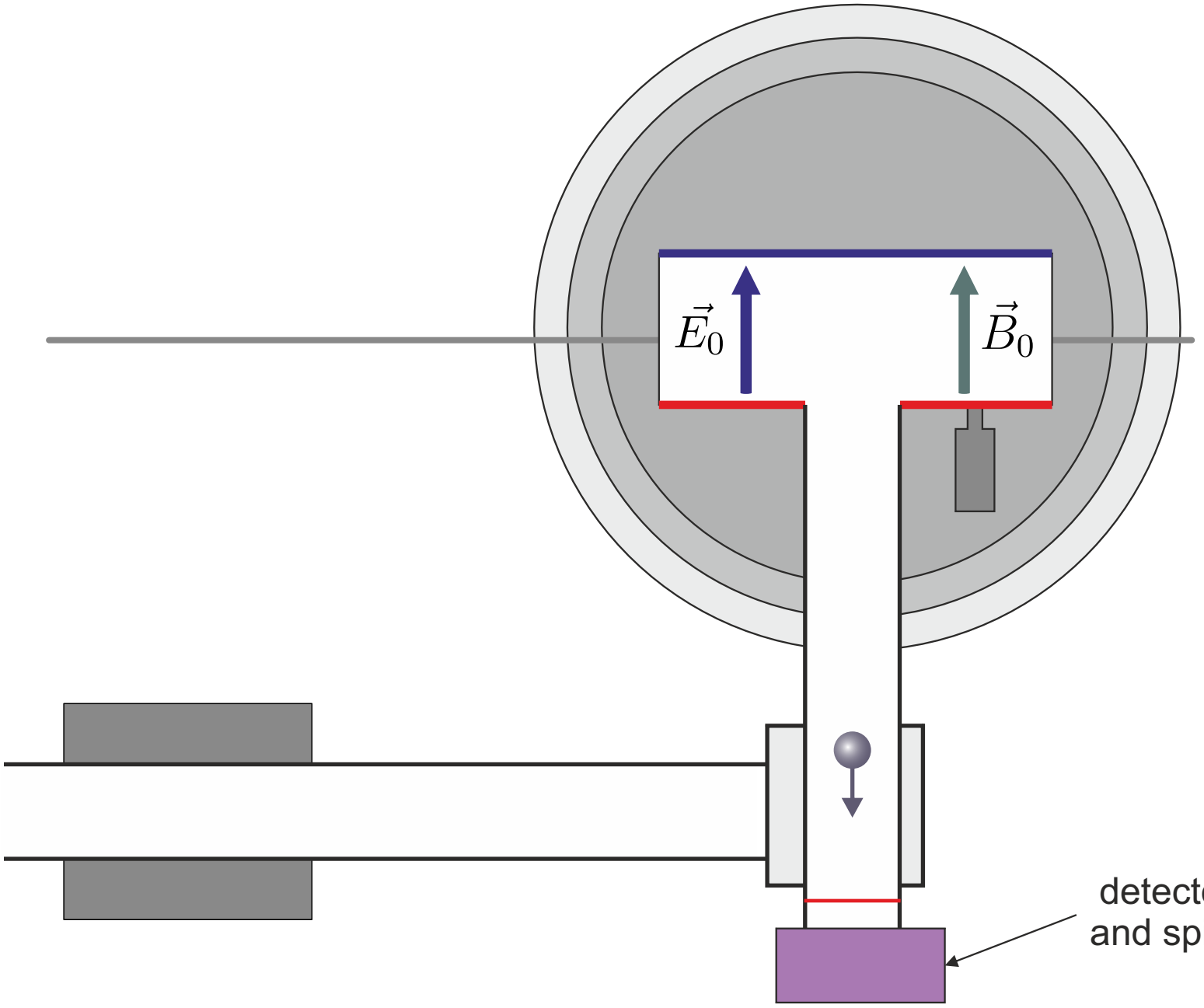


Emptying the precession chamber



function generator ν_{rf}

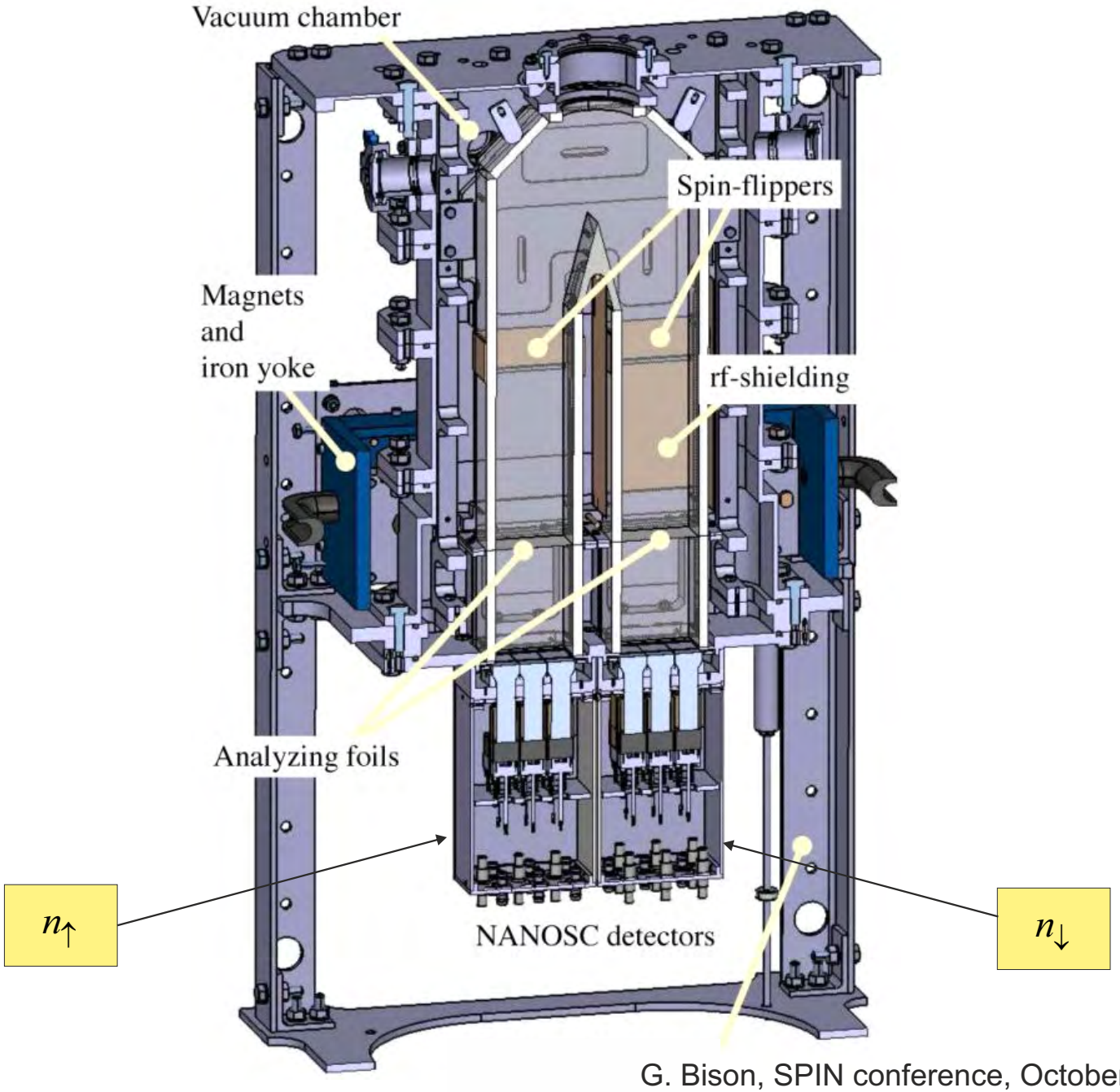
Neutron detection



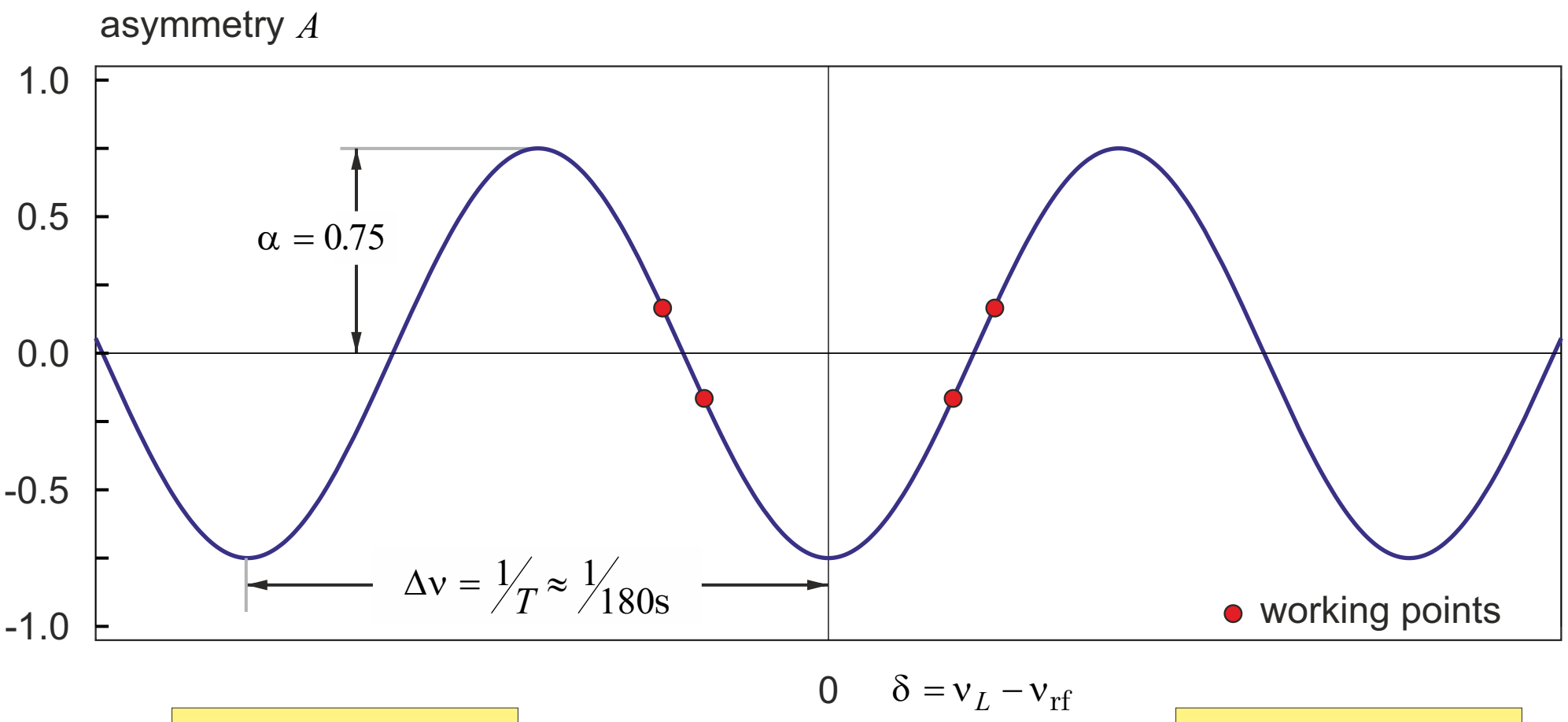
function generator ν_{rf}

detector: count spin up and spin down neutrons

Neutron Detection



Ramsey technique

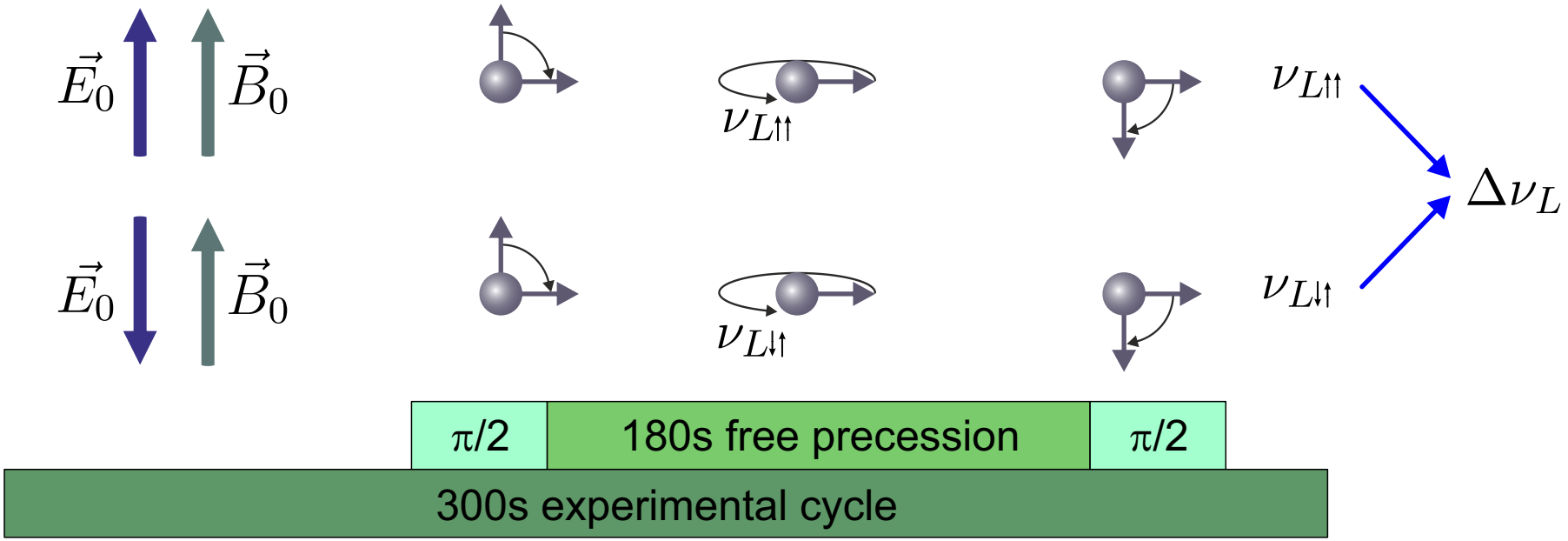


$$A = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

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

Neutron Larmor precession frequency

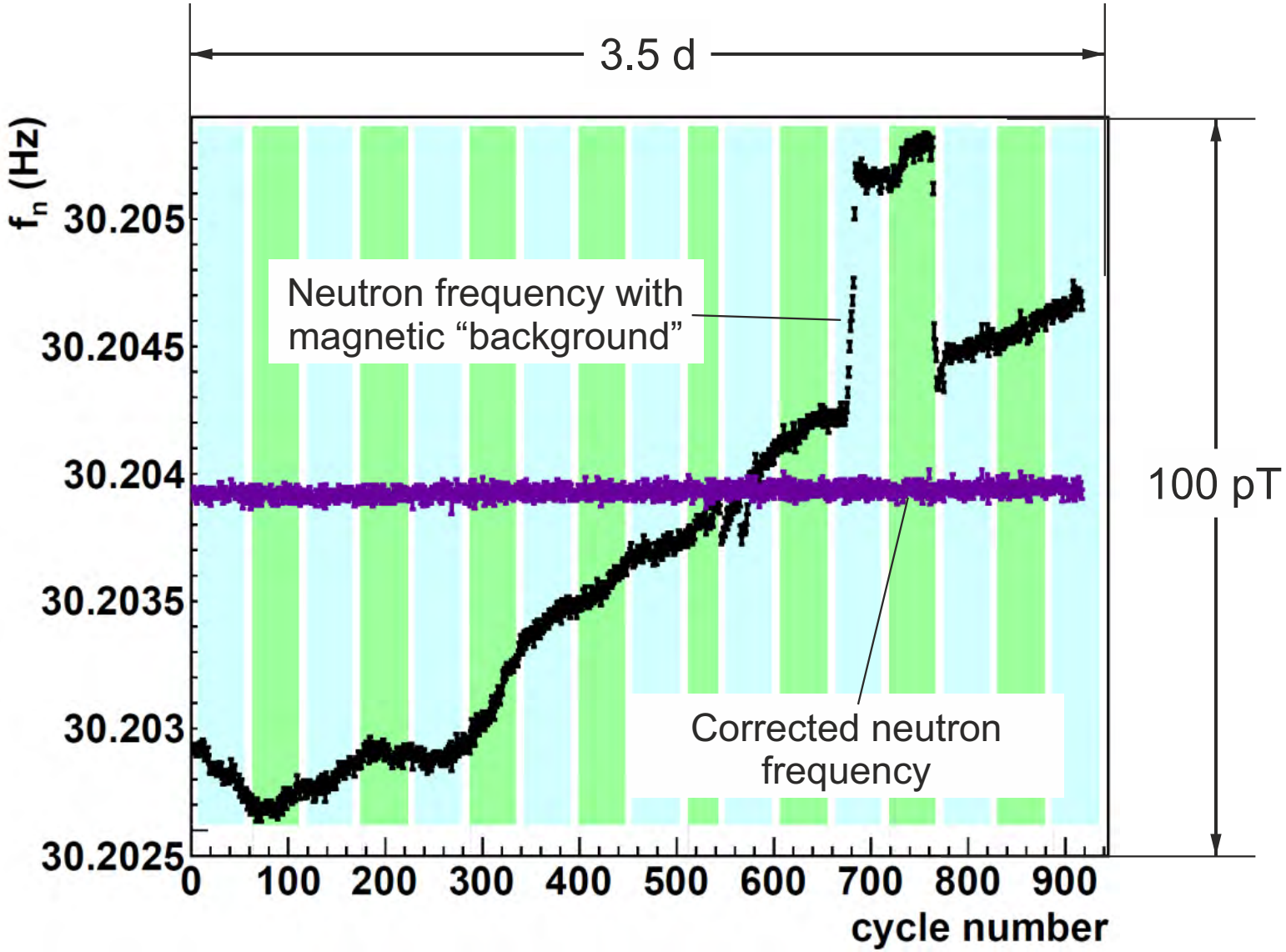
$$h\nu_L = -2\,\mu\,B_0 \pm 2\,d\,E_0$$



$$\Delta\nu_L = \frac{4\,d\,E_0}{h} + \frac{2\,\mu\,\Delta B}{h}$$

We use sensitive magnetometers to correct for this B-field dependence.

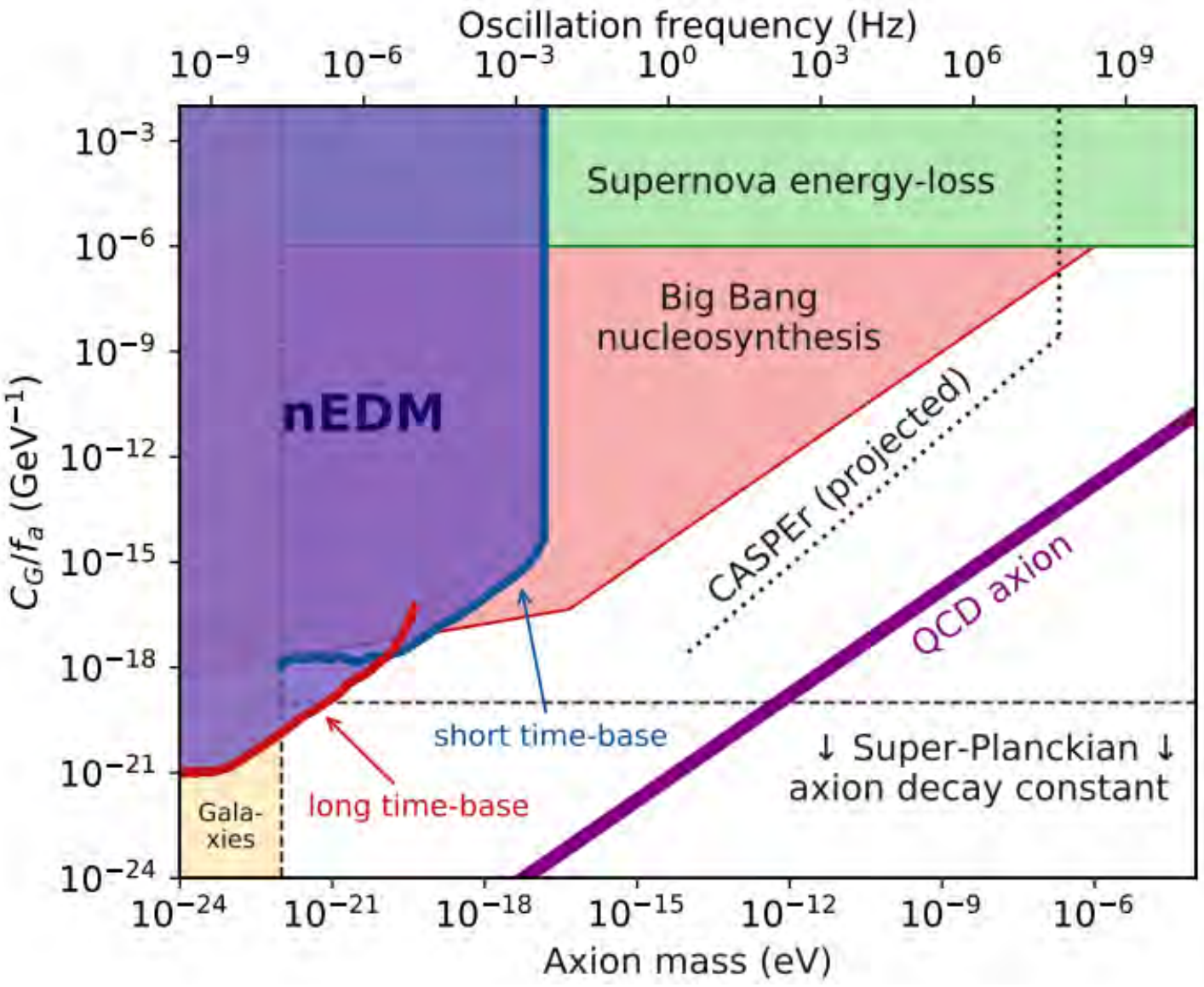
Magnetic field correction



In total we recorded >50000 cycles in two years

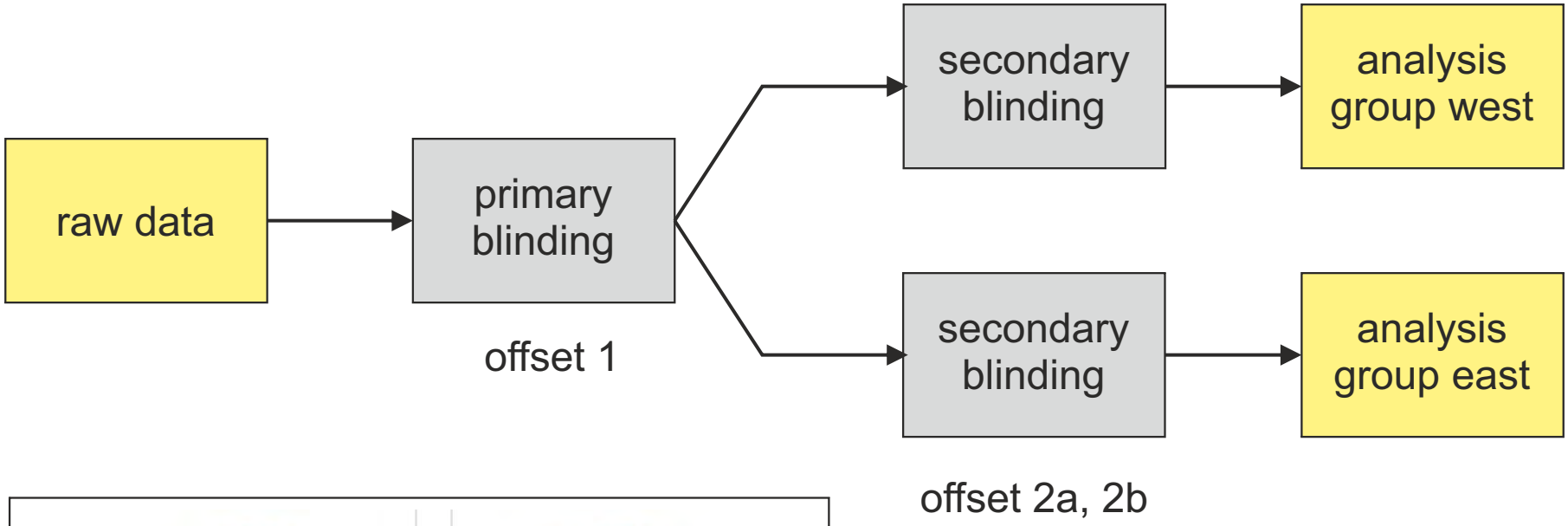
- Introduction & old neutron EDM experiment @ PSI
- **Results**
- New experiment n2EDM

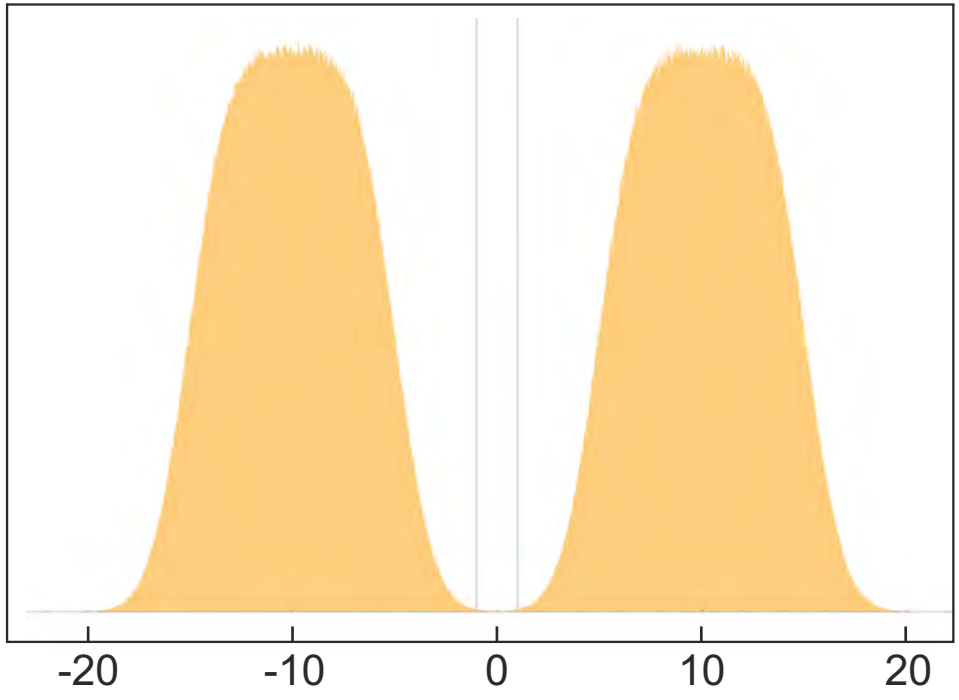
Our limit on the axion–gluon coupling



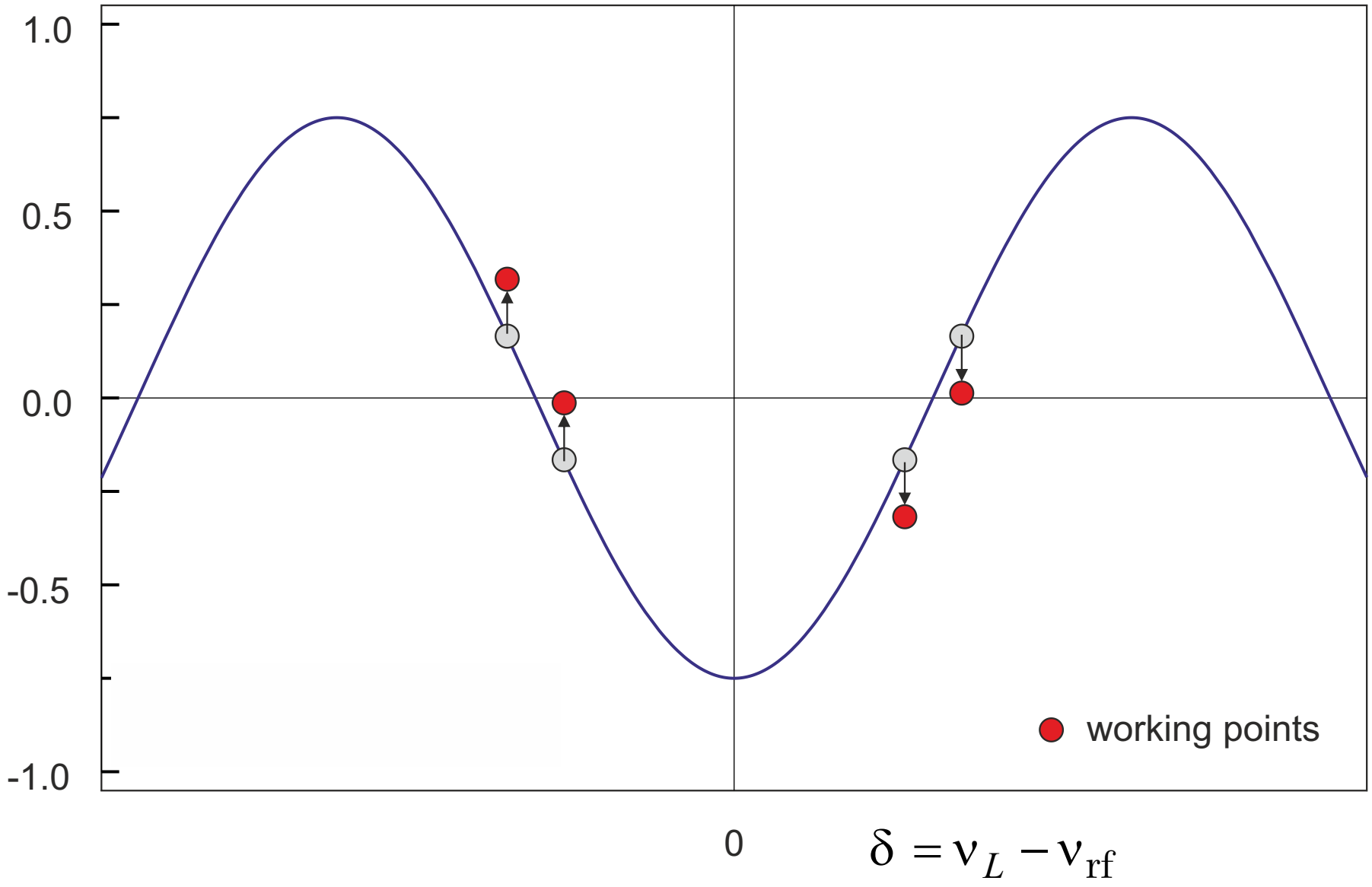
Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields, Abel et al. Phys Rev X 7,041034 (2017).

Blinding

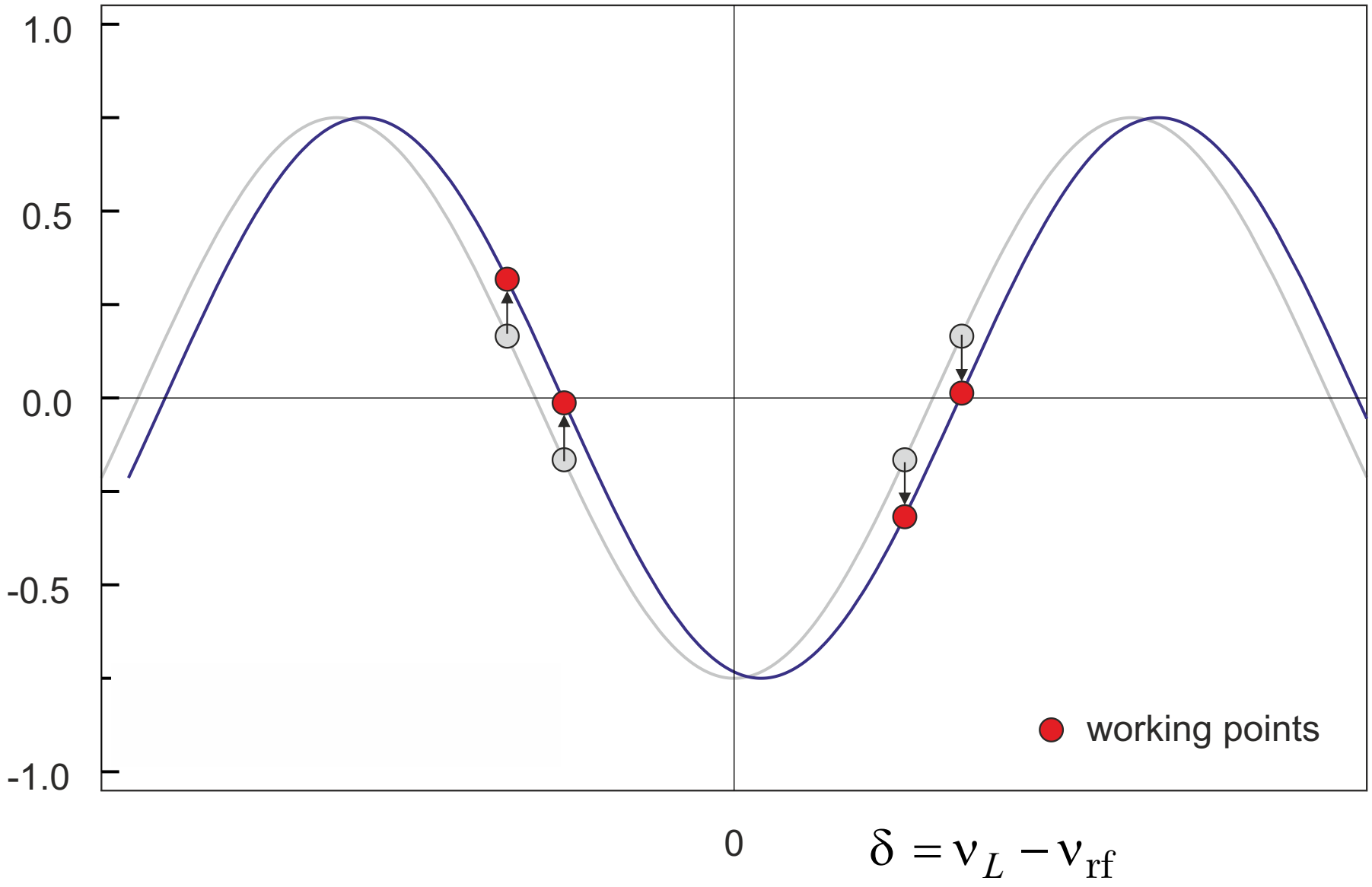

raw data
primary blinding
offset 1
secondary blinding
analysis group west
secondary blinding
analysis group east
offset 2a, 2b


-20
-10
0
10
20
blinding offset (10^{-26} e cm)

Blinding


asymmetry A
1.0
0.5
0.0
-0.5
-1.0
0
working points
$\delta = \nu_L - \nu_{\mathrm{rf}}$

Blinding


asymmetry A
1.0
0.5
0.0
-0.5
-1.0
0
working points
$\delta = \nu_L - \nu_{\mathrm{rf}}$

nEDM error budget

Effect	shift	error
Error on $\langle z \rangle$	-	7
Higher order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM[8]	-0.1	0.1
Local dipole fields	-	4
$v \times E$ UCN net motion	-	2
Quadratic $v \times E$	-	0.1
Uncompensated G drift	-	7.5
Mercury light shift	-	0.4
Inc. scattering ^{199}Hg	-	7
TOTAL	69	18

10^{-28} $e$cm

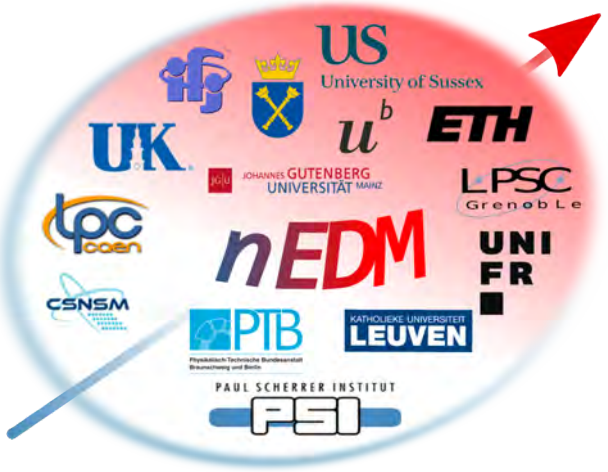
Systematic uncertainty six times smaller than before.

nEDM unblinding

Measurement of the permanent electric dipole moment of the neutron

C. Abel S. Afach, N. J. Ayres, C. A. Baker, G. Ban, G. Bison, K. Bodek, V. Bondar, M. Burghoff, E. Chanel, Z. Chowdhuri, P.-J. Chiu, B. Clement, C. B. Crawford, M. Daum, S. Emmenegger, L. Ferraris-Bouchez, M. Fertl, P. Flaux, B. Franke, A. Fratangelo, P. Geltenbort, K. Green, W. C. Griffith, M. van der Grinten, Z. D. Grujic, P. G. Harris, L. Hayen, W. Heil, R. Henneck, V. Hélaine, N. Hild, Z. Hodge, M. Horras, P. Iaydjiev, S. N. Ivanov, M. Kasprzak, Y. Kermaidic, K. Kirch, A. Knecht, P. Knowles, H.-C. Koch, P.A. Koss, S. Komposch, A. Kozela, A. Kraft, J. Krempel, M. Kuzniak, B. Lauss, T. Lefort, Y. Lemière, A. Leredde, P. Mohanmurthy, A. Mtchedlishvili, M. Musgrave, O. Naviliat-Cuncic, D. Pais, F.M. Piegsa, E. Pierre, G. Pignol, C. Plonka-Spehr, P. N. Prashanth, G. Quéméner, M. Rawlik, D. Rebreyend, I. Rienäcker, D. Ries, S. Roccia, G. Rogel, D. Rozpedzik, A. Schnabel, P. Schmidt-Wellenburg, N. Severijns, D. Shiers, R. Tavakoli, J. A. Thorne, R. Virot, J. Voigt, A. Weis, E. Wursten, G. Wyszynski, J. Zejma, J. Zenner, and G. Zsigmond,

Phys. Rev. Lett. **124,** 081803 (2020)



Public announcement: January 28 2020 during our annual accelerator meeting at PSI

$$d_{\mathrm{n}} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\, e\cdot\mathrm{cm}$$

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$10^{-28}\, e\mathrm{cm}$

Systematic uncertainty six times smaller than before.

nEDM result

$$d_{\mathrm{n}} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\, e\cdot\mathrm{cm}.$$

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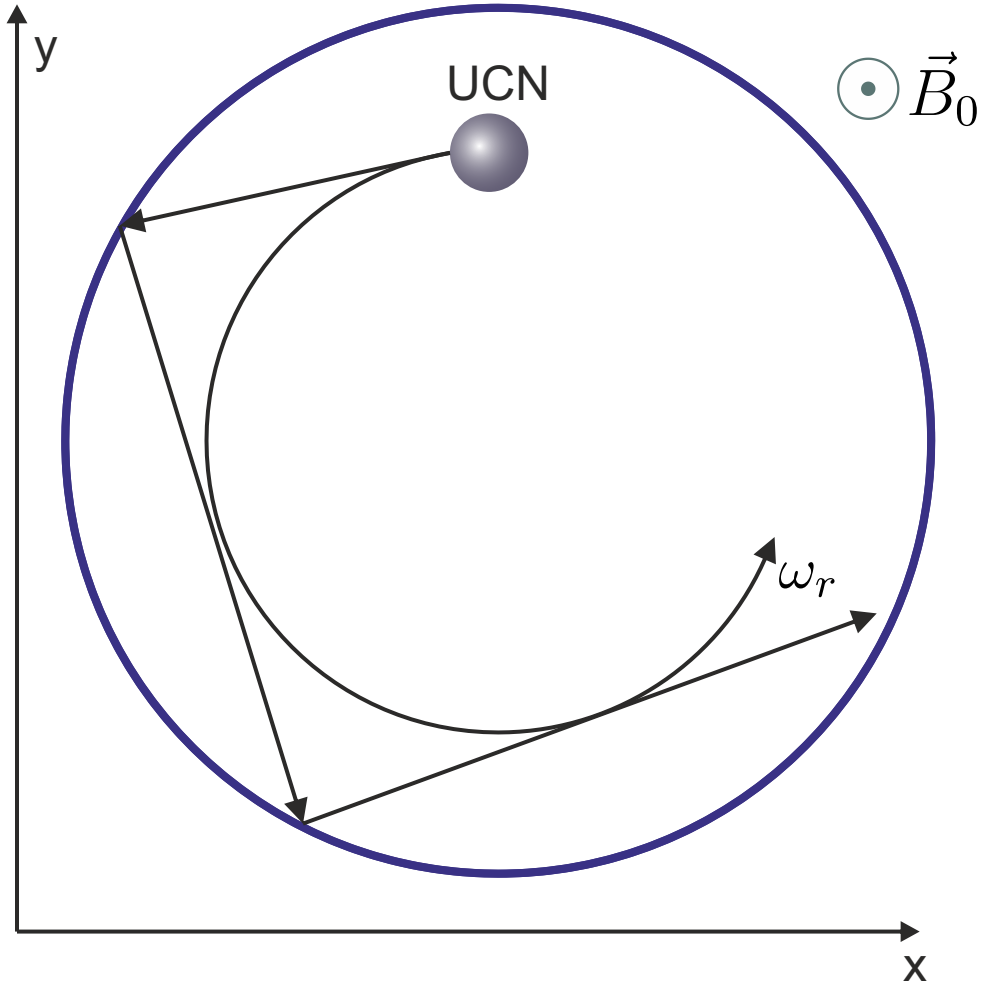
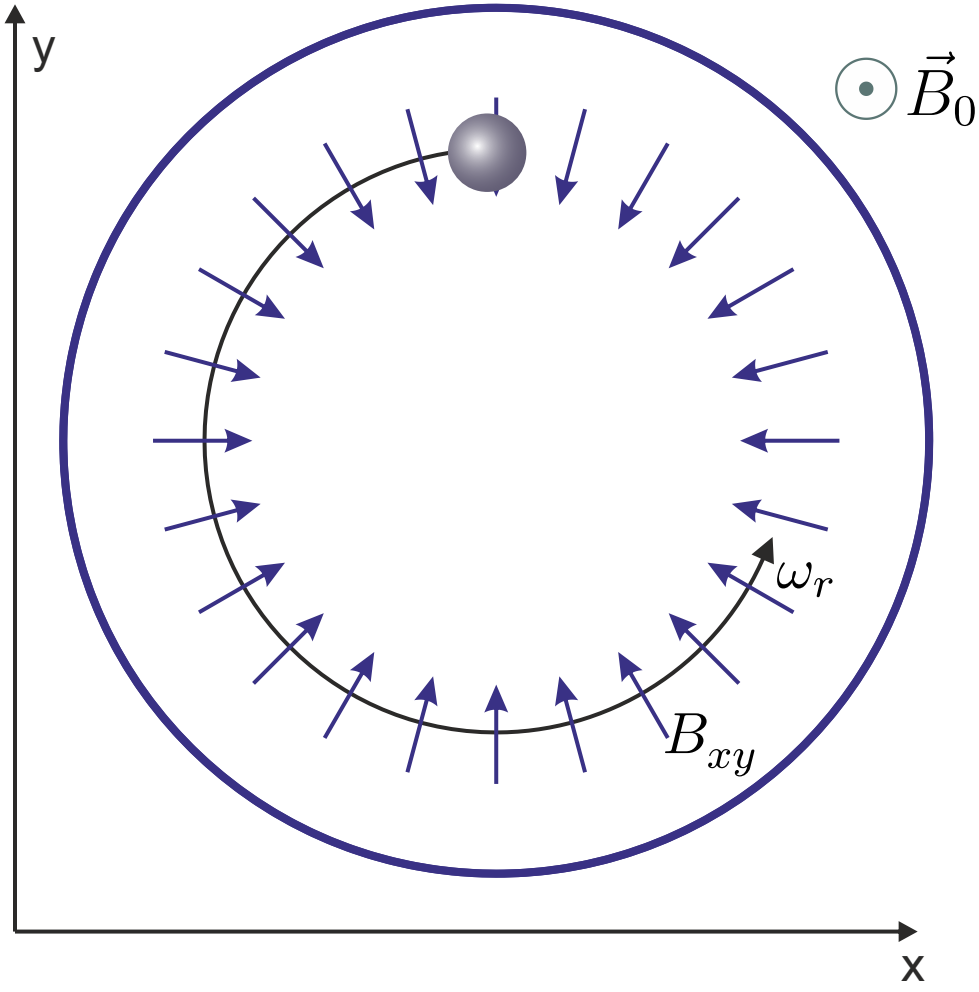
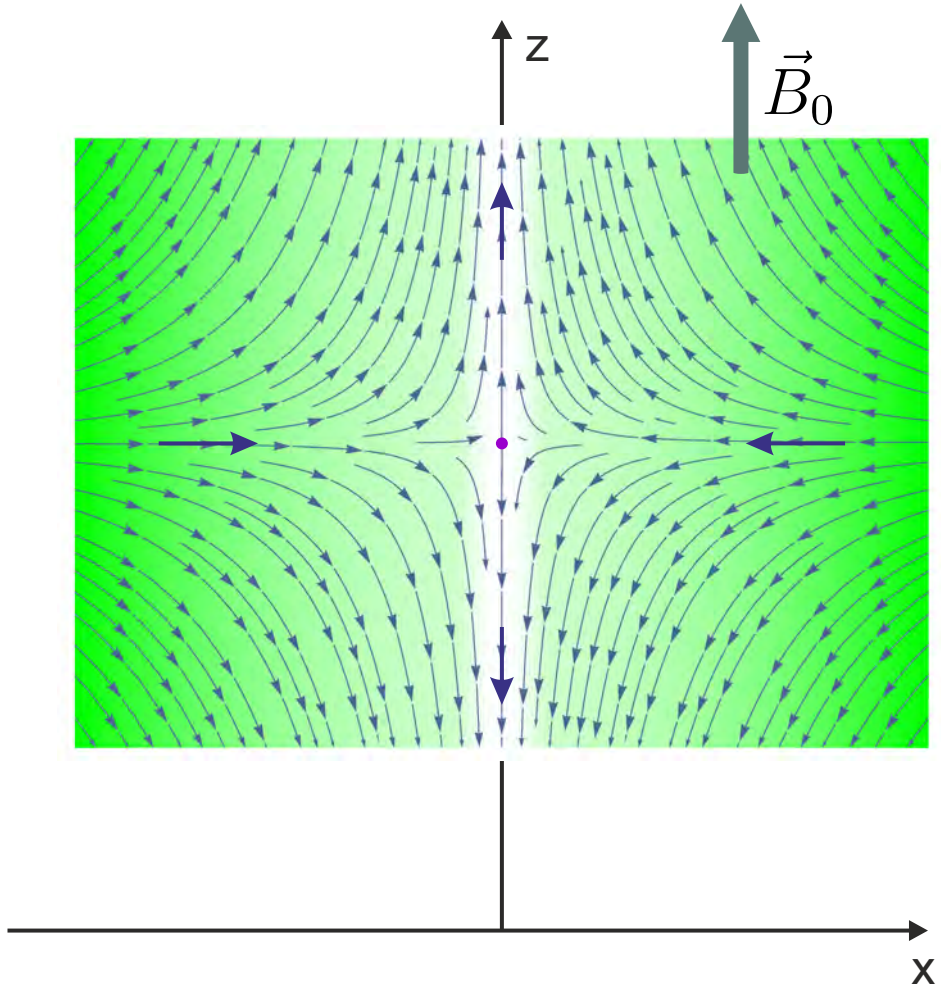
$10^{-28}\, e\mathrm{cm}$

Ramsey-Bloch-Siegert-shift



Ramsey-Bloch-Siegert-shift due to magnetic gradients

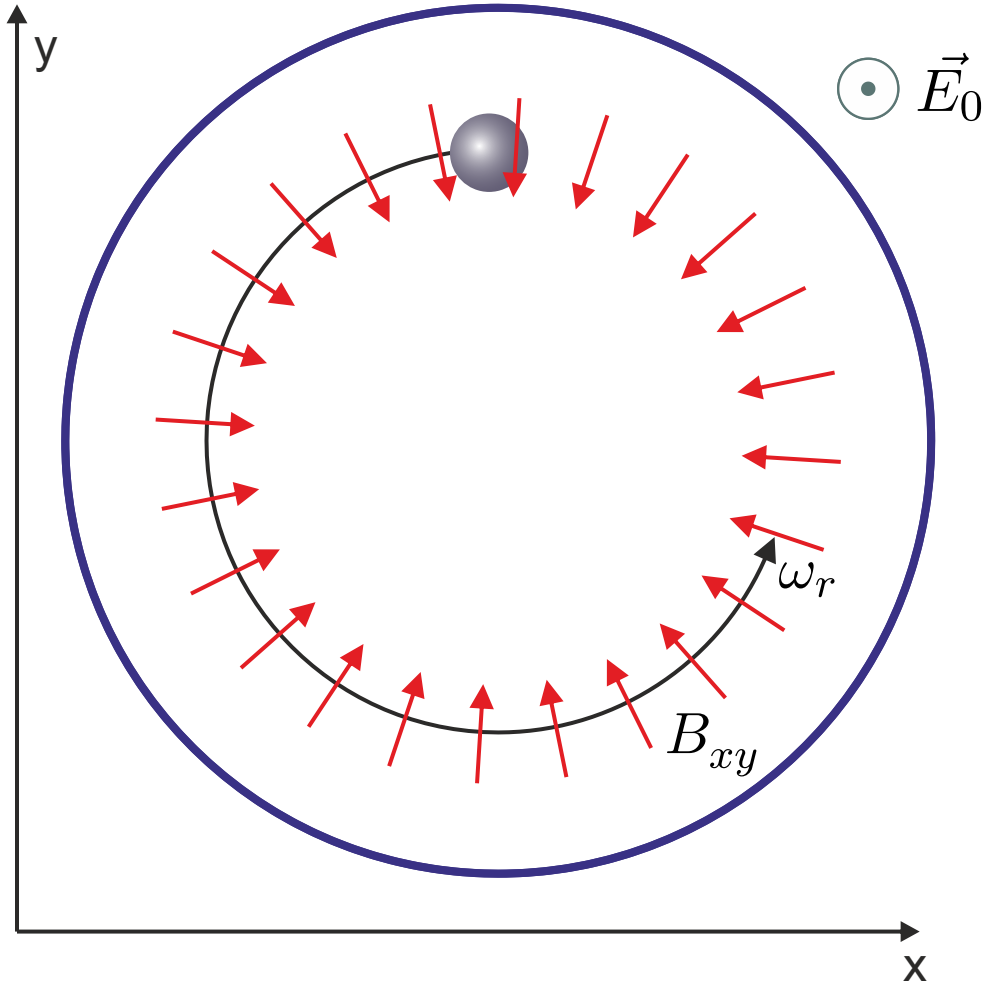


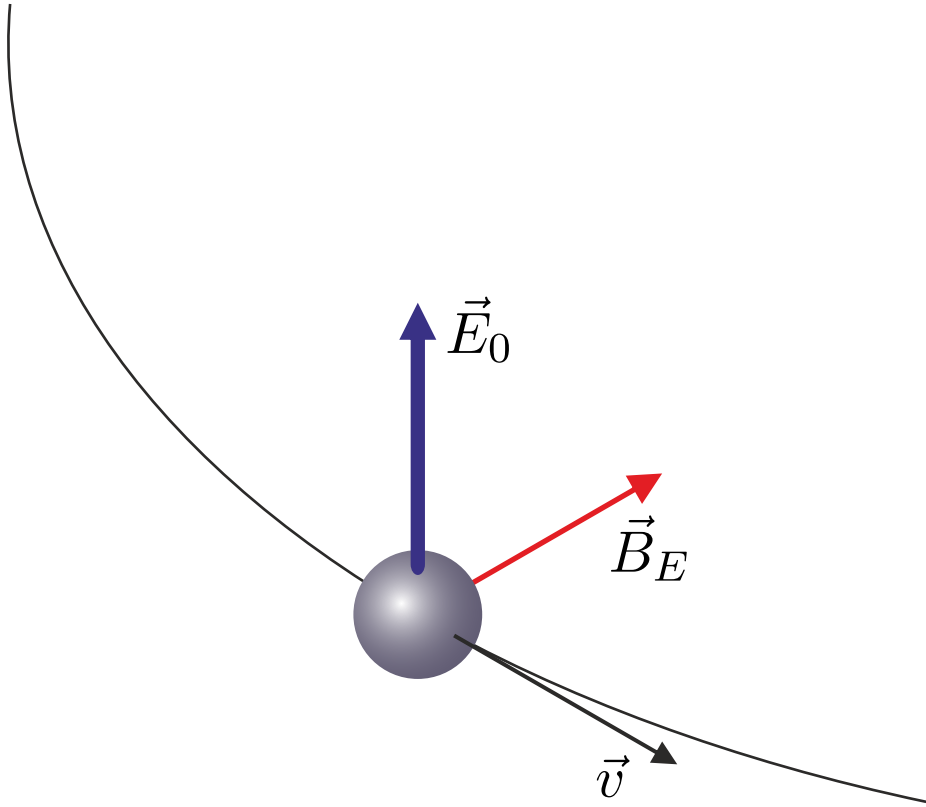


$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

$$\vec{B}_G = \frac{\partial B_z}{\partial z}\frac{\vec{r}}{2}$$

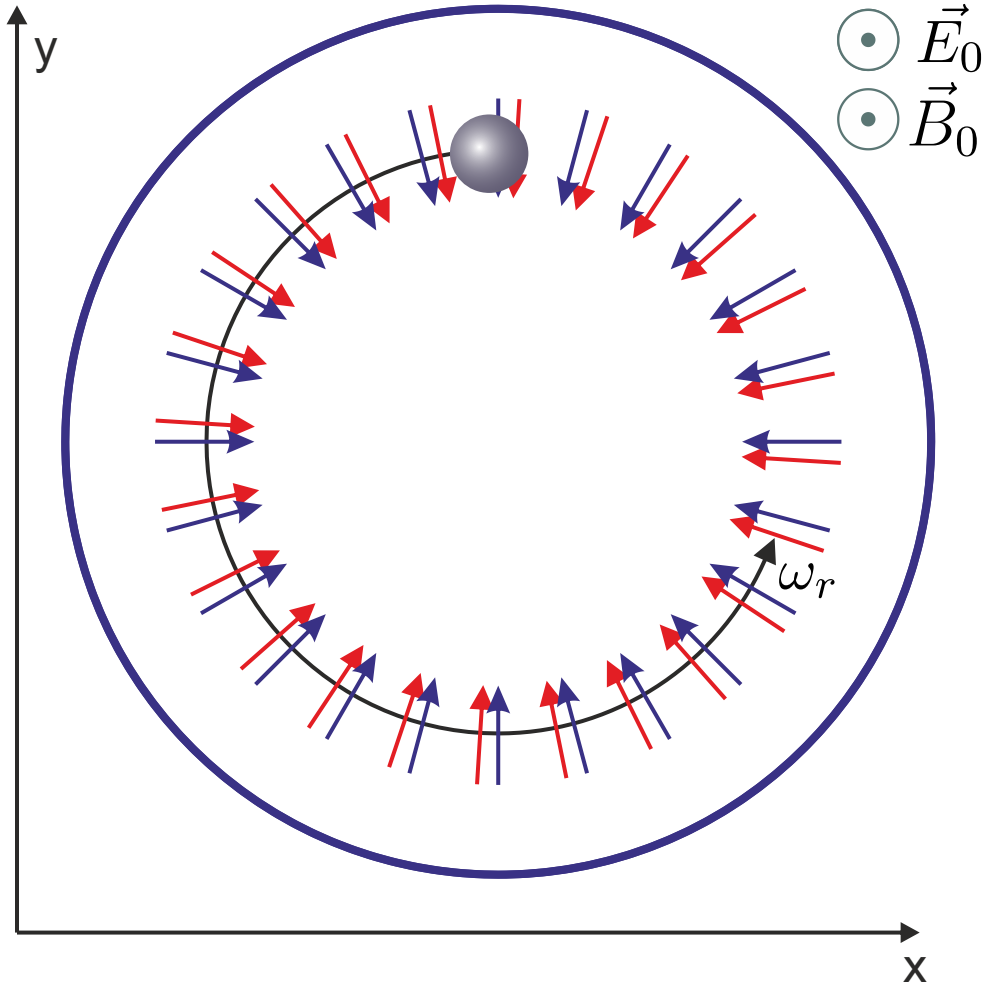
Ramsey-Bloch-Siegert-shift due to motional B-fields





$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

$$\vec{B}_E = \frac{\vec{E}_0 \times \vec{v}}{c^2}$$



$$\vec{B}_G + \vec{B}_E$$

$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

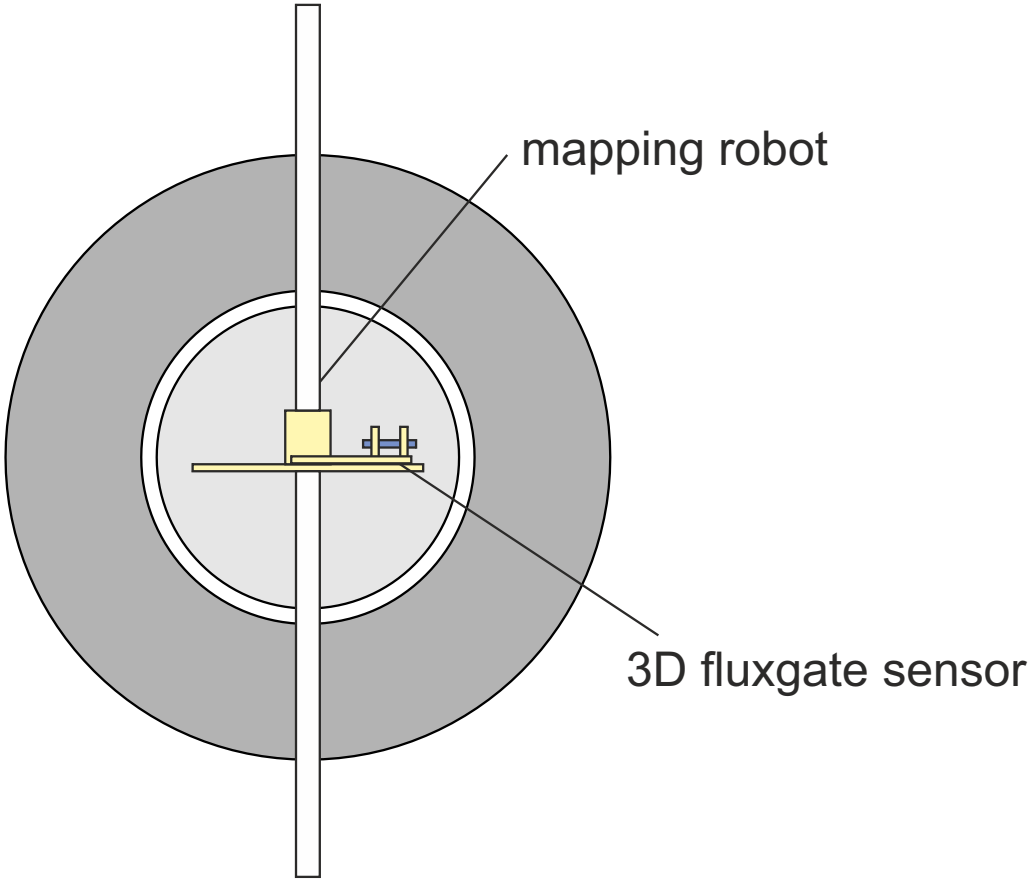
$$= \Delta\omega_{EE} + \Delta\omega_{GG} + \Delta\omega_{EG}$$

EDM-like signal: proportional to the E-field and the B-field gradient

$$d_{\text{false}} = \frac{\hbar\,\gamma_{Hg}\,\gamma_n}{2c^2}\,\langle xB_x + yB_y\rangle$$

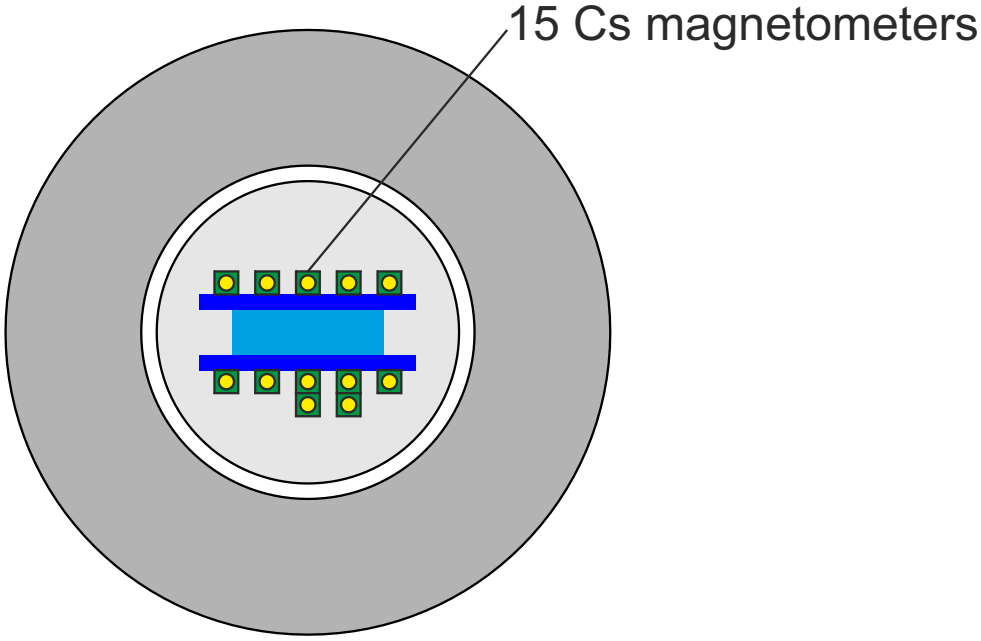
Pignol & Roccia, Phys. Rev. A 85, 042105 (2012)

Offline field mapping



Mapping of the magnetic field to correct systematic effects in a neutron electric dipole moment experiment.
C. Abel et al., 2021. arXiv: 2103.09039 [physics.ins-det].

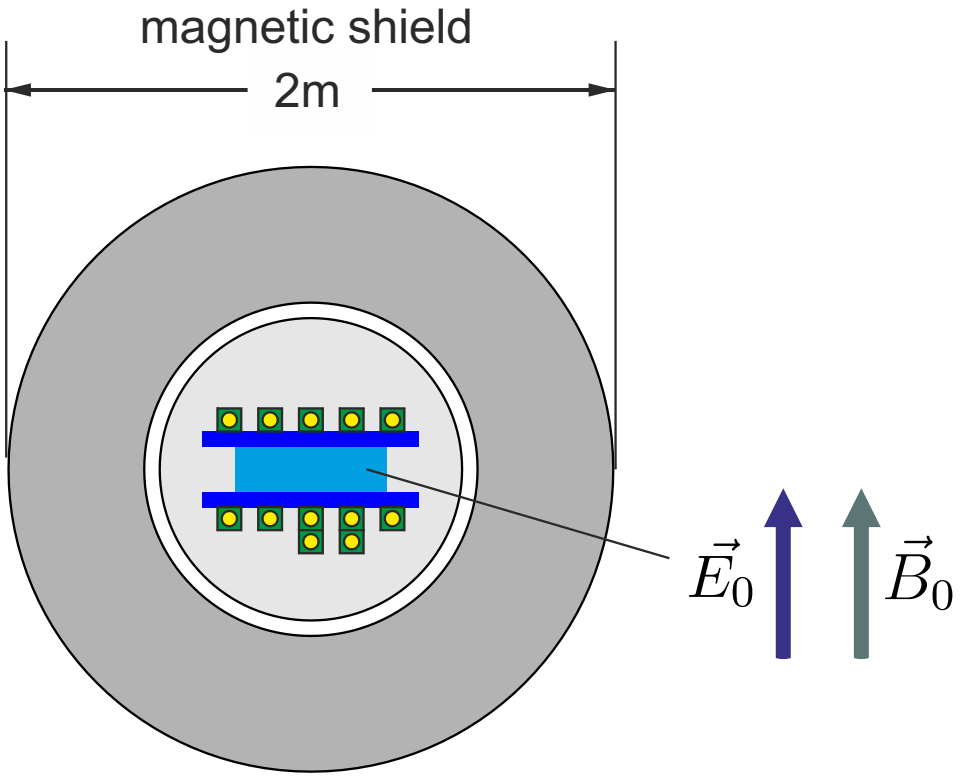
Online gradient measurements



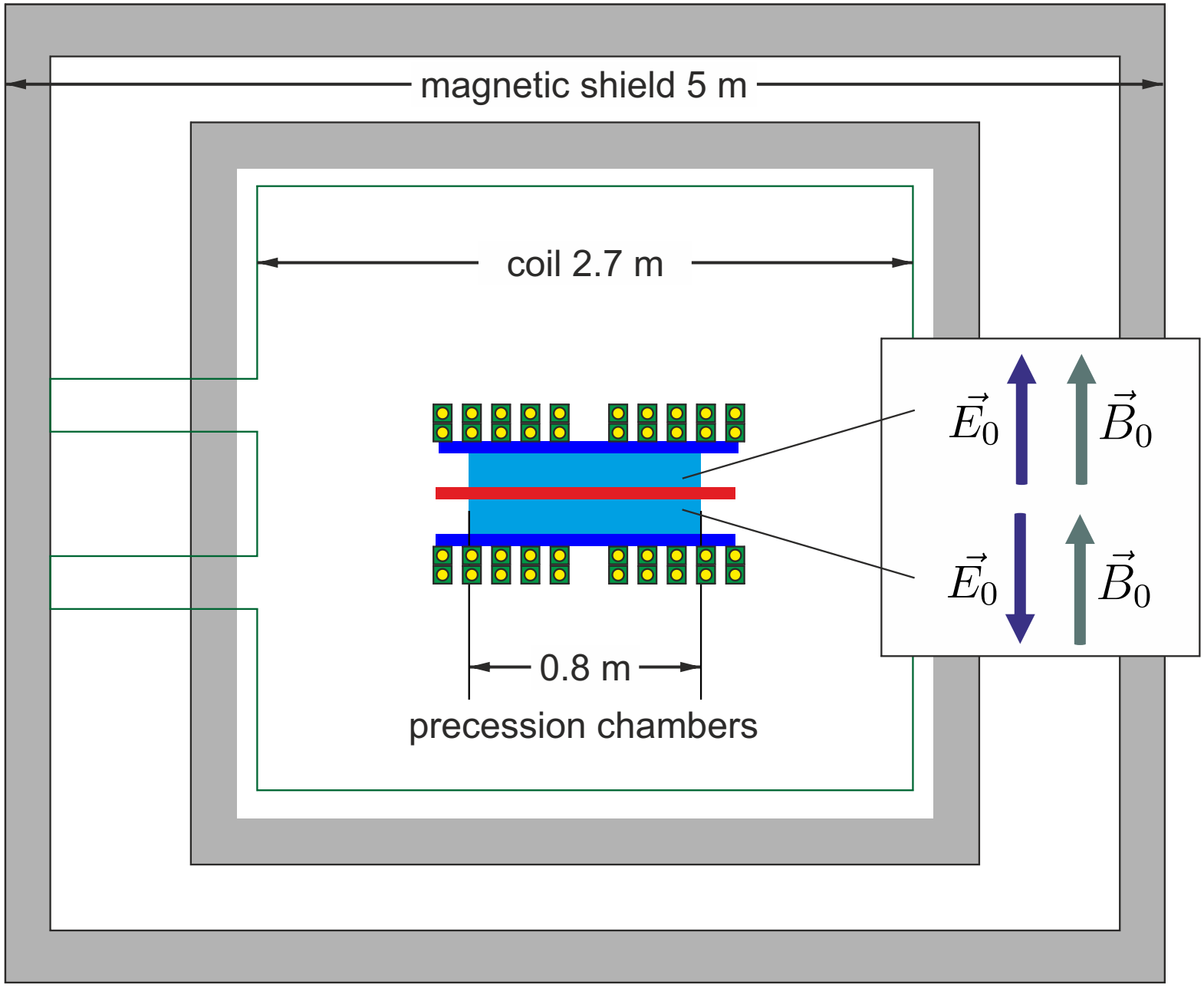
Optically pumped Cs magnetometers enabling a high-sensitivity search for the neutron electric dipole moment, C. Abel et al. PRA 101, 053419 (2020)

- Introduction & old neutron EDM experiment @ PSI
- Results
- **New experiment n2EDM**

Current nEDM experiment

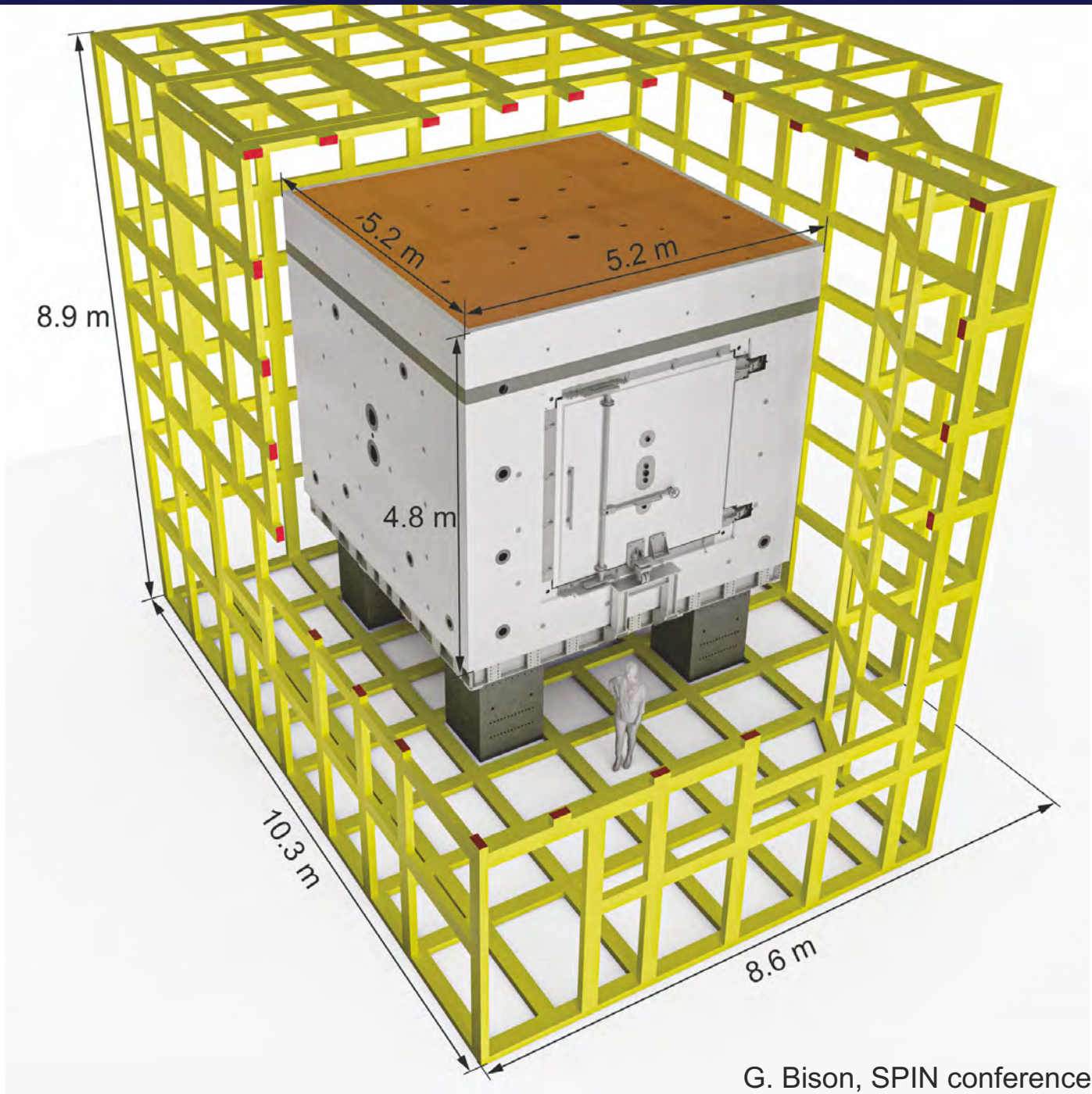


Future n2EDM experiment

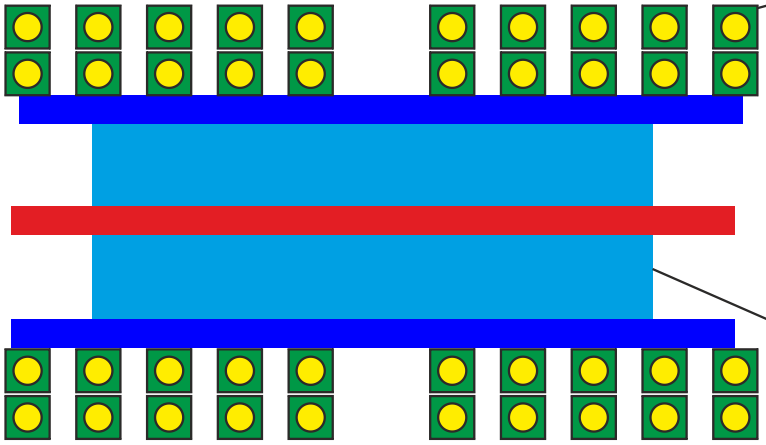


Future n2EDM experiment

Active & passive magnetic shield



Magnetometry challenges of n2EDM



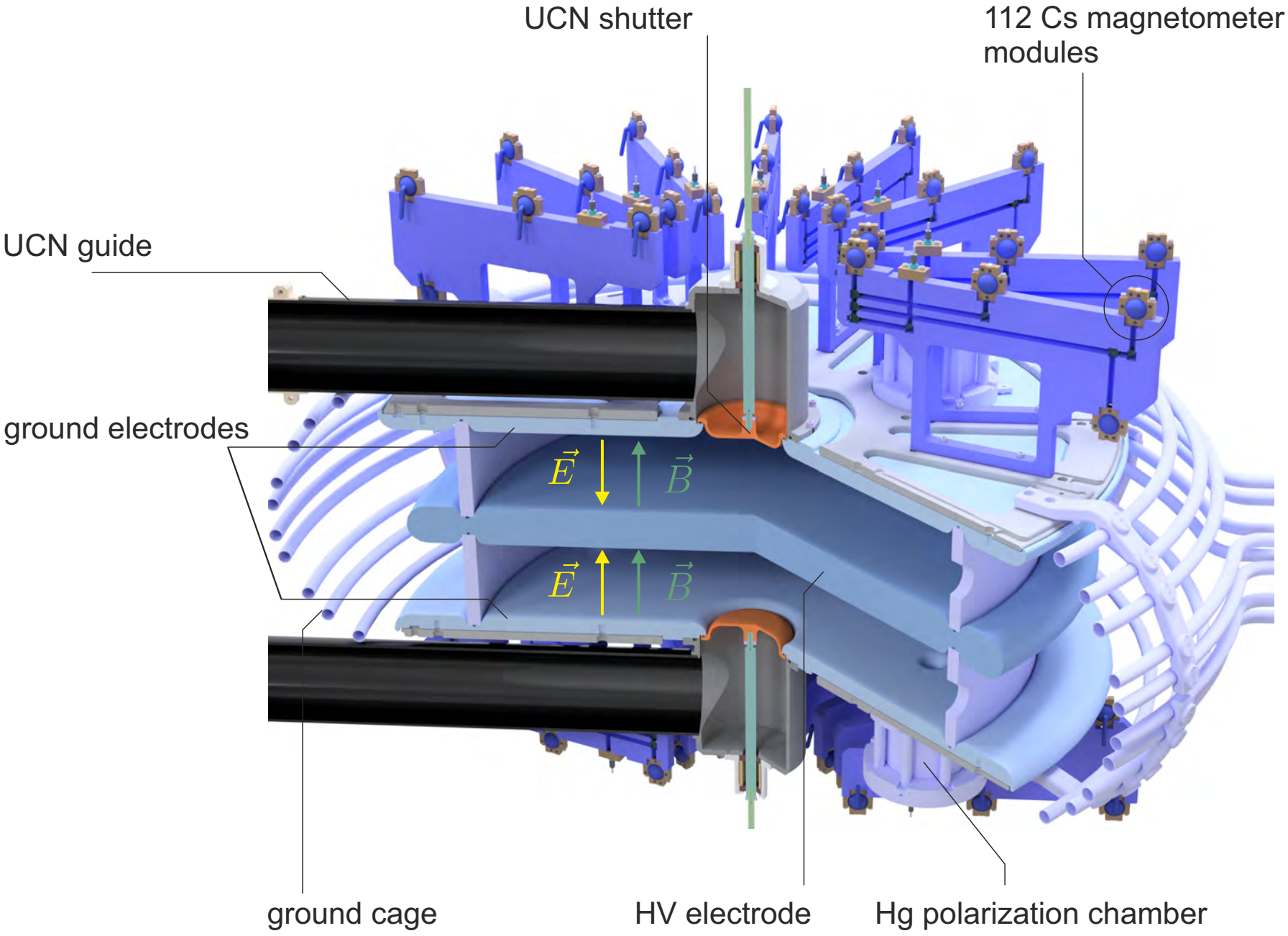
Cs magnetometer array

- field homogenization
- online gradient monitoring

Hg co-magnetometers

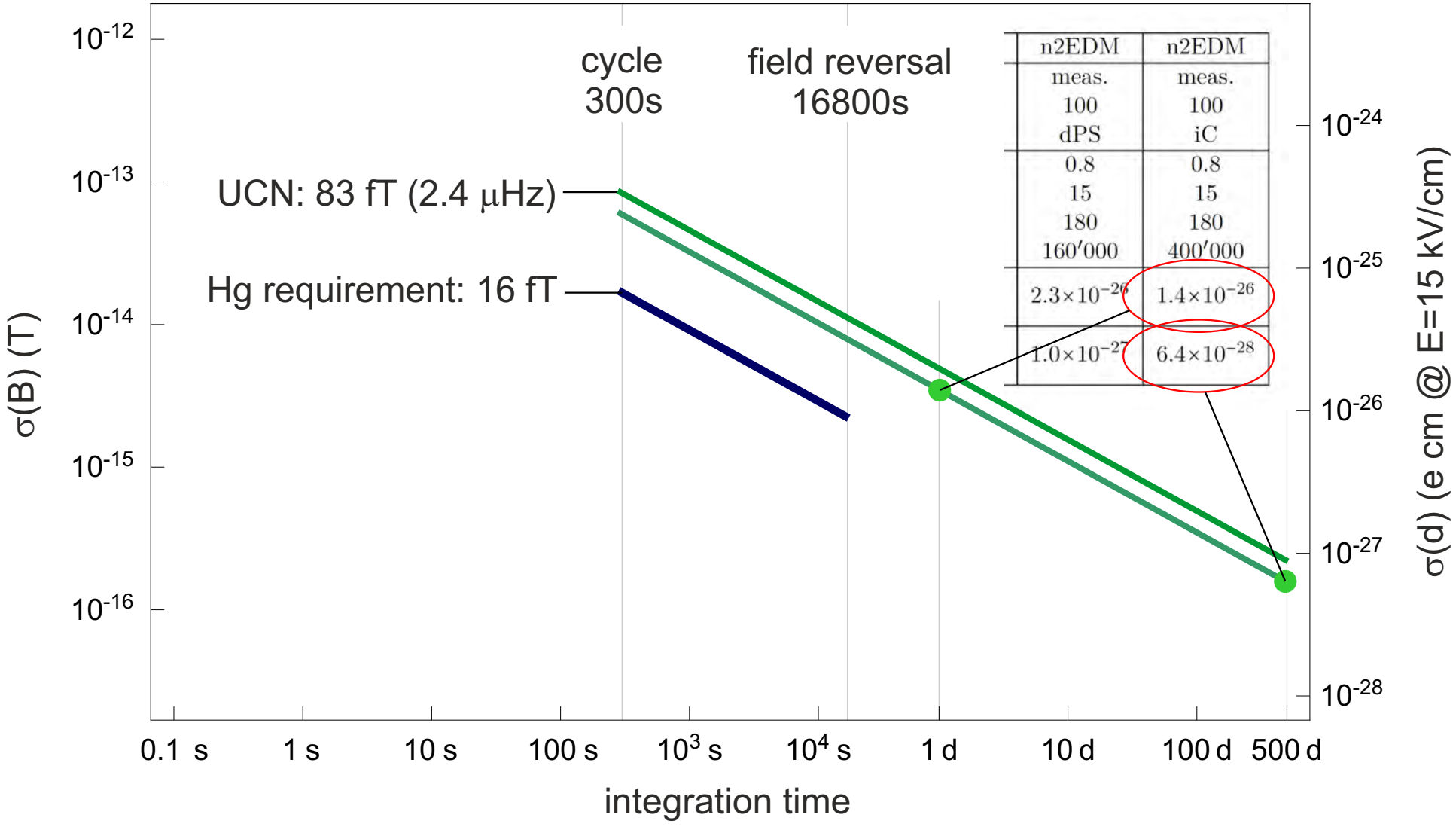
- primary magnetic correction
- online gradient monitoring

Experiment design

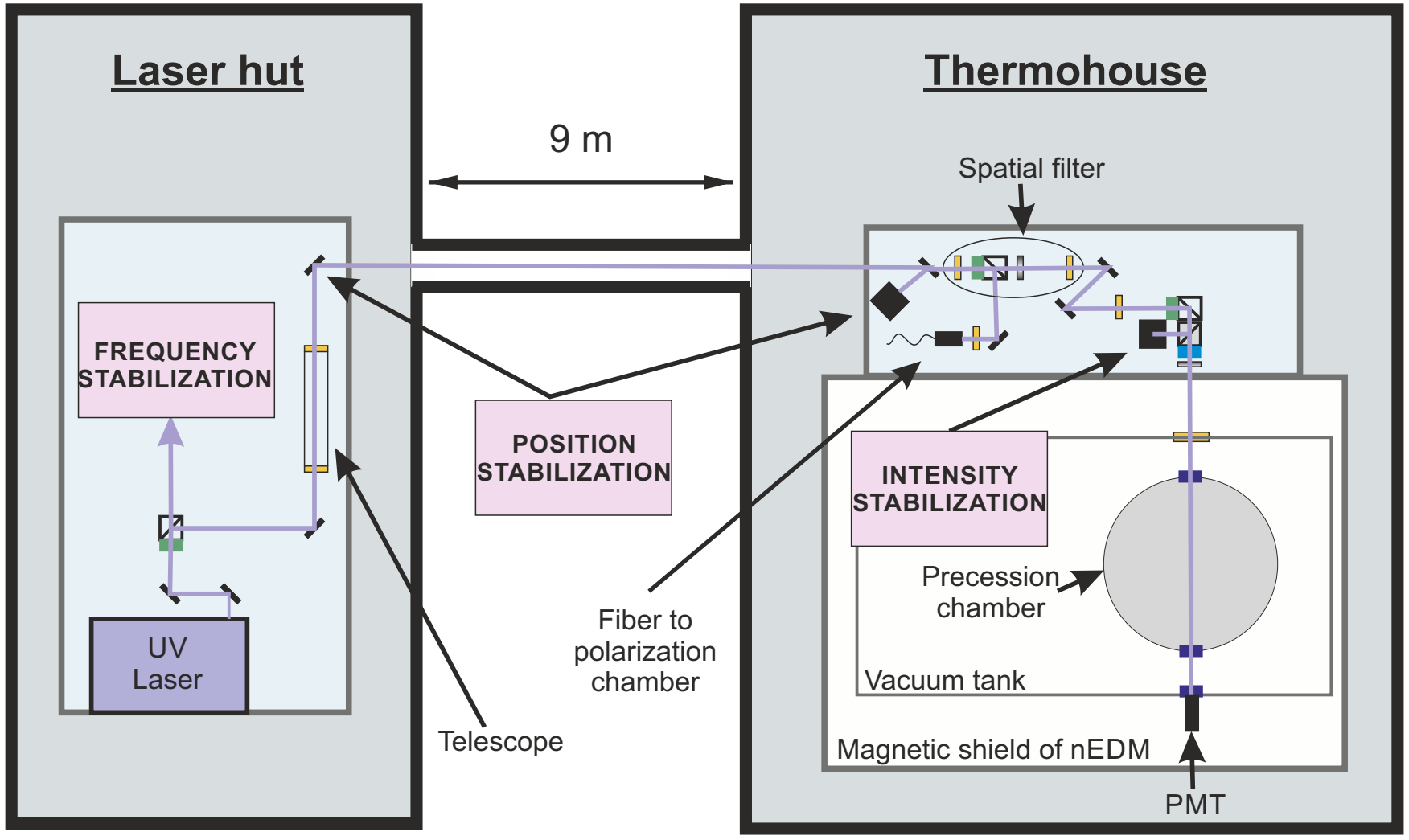


Magnetometer performance comparison

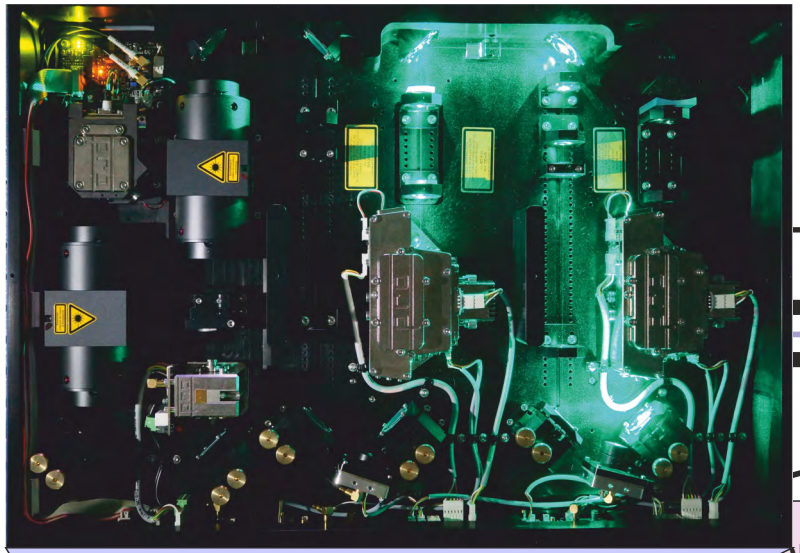
Neutron spin precession frequency $h\nu_L = -2\,\mu\,B_0 \pm 2\,d\,E_0$



Laser setup for the Hg magnetometer



Laser setup for the Hg magnetometer



Toptica FHG, 254 nm

UV Laser

Telescope

Fiber to polarization chamber

Thermohouse

Spatial filter

INTENSITY STABILIZATION

Precession chamber

Vacuum tank

Magnetic shield of nEDM

PMT

Polarizing beam splitter

Non polarizing beam splitter

Lens

UV transmitting window

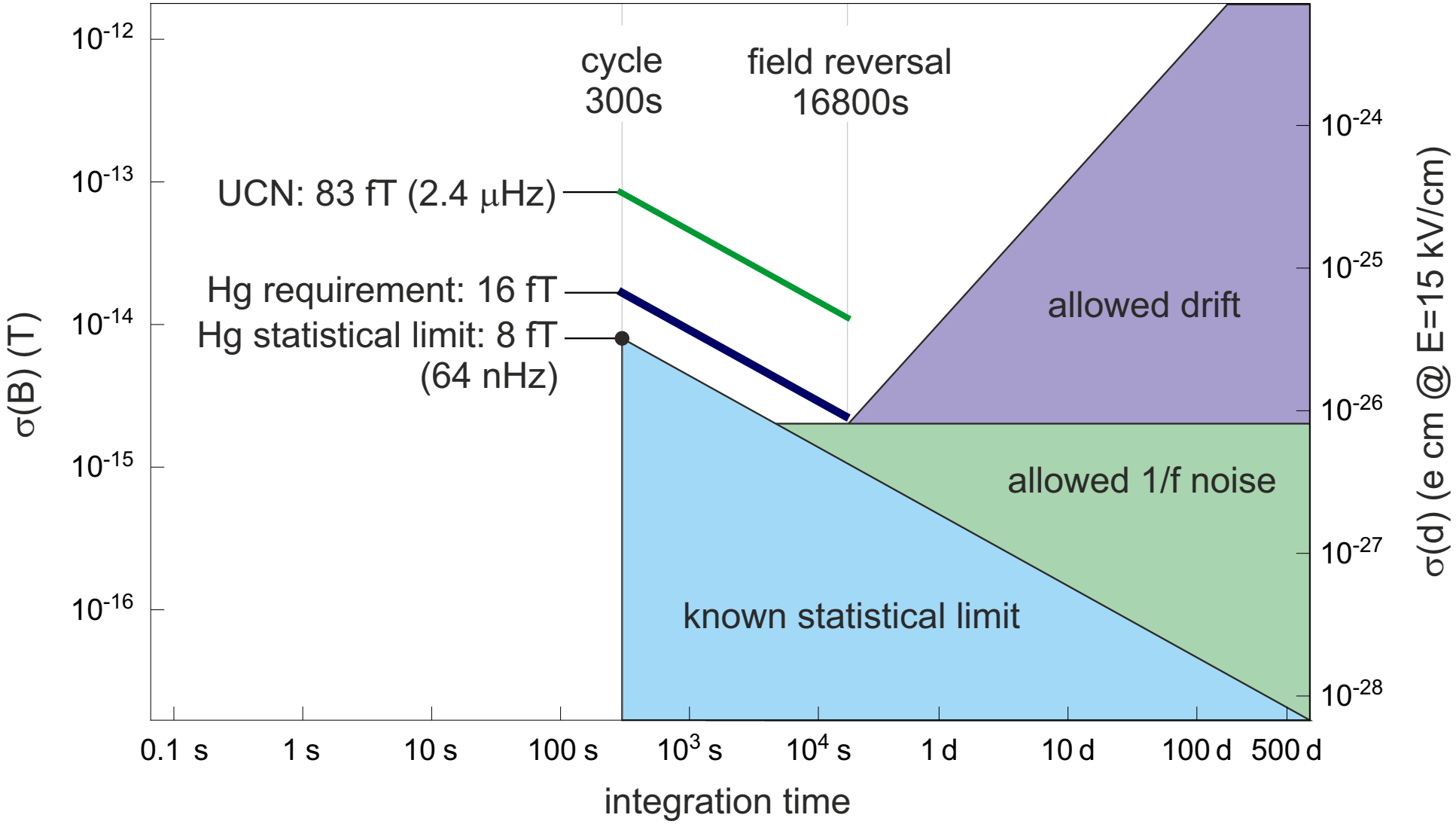
Photo detector

Mirror

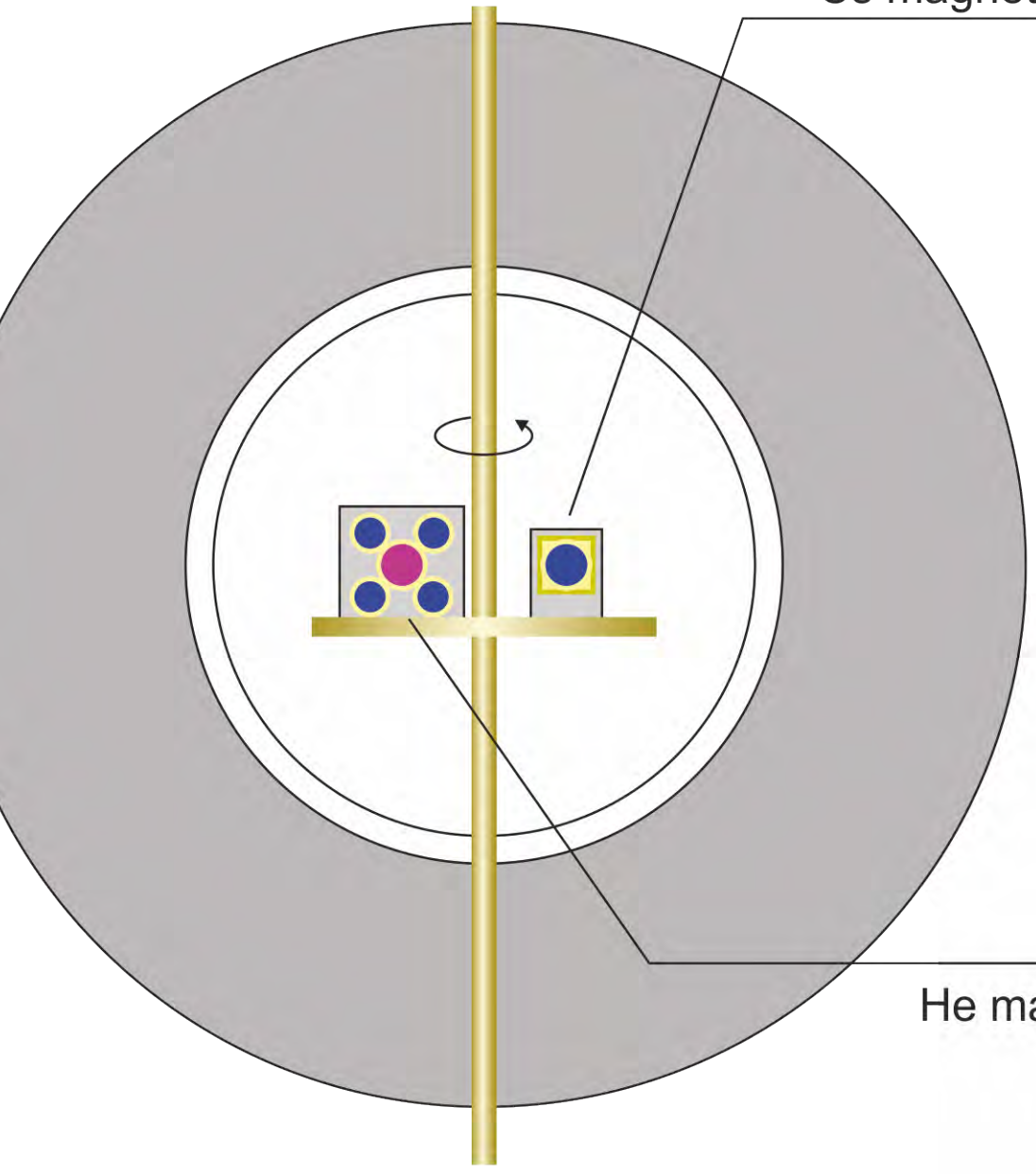
almost shot-noise limited performance @ 8 Hz

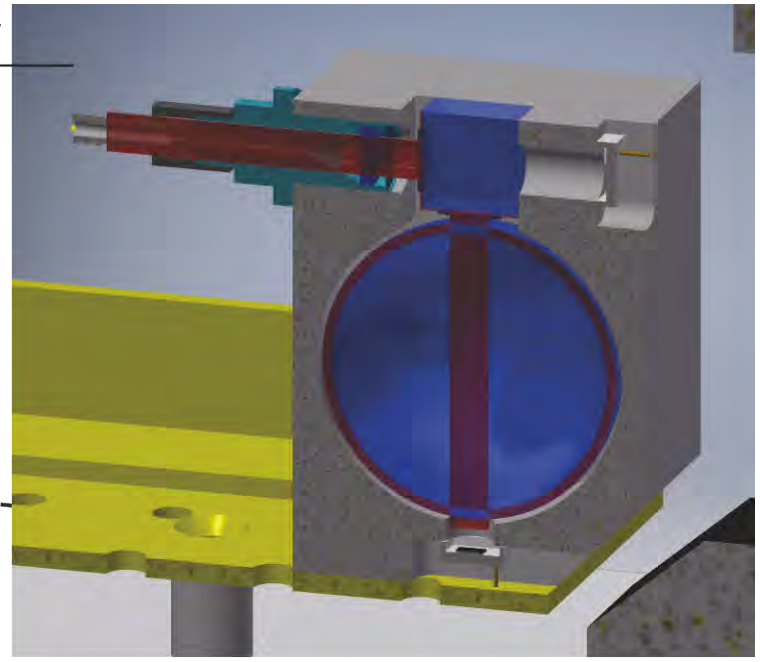
Statistical magnetometer performance

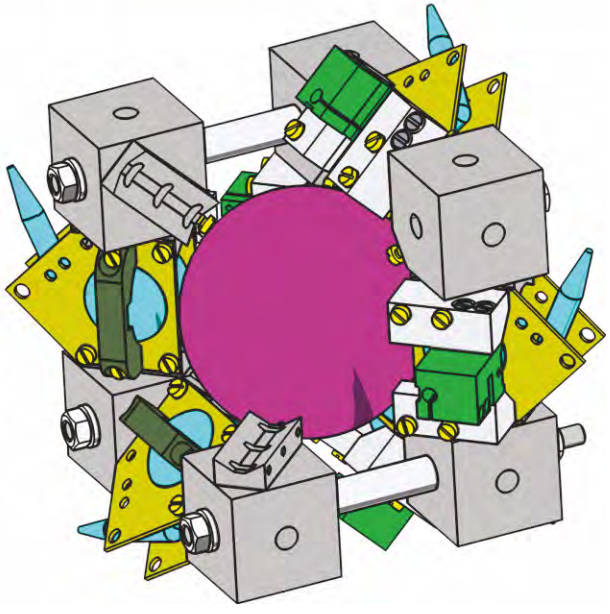
Neutron spin precession frequency $h\nu_L = -2\,\mu\,B_0 \pm 2\,d\,E_0$



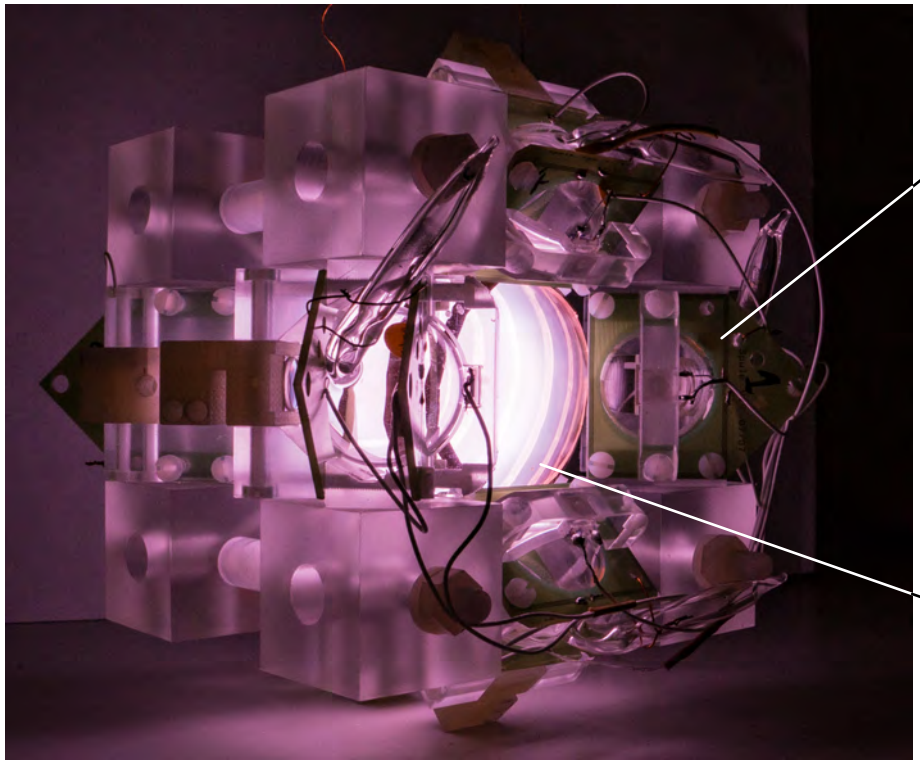
Cs magnetometer calibration



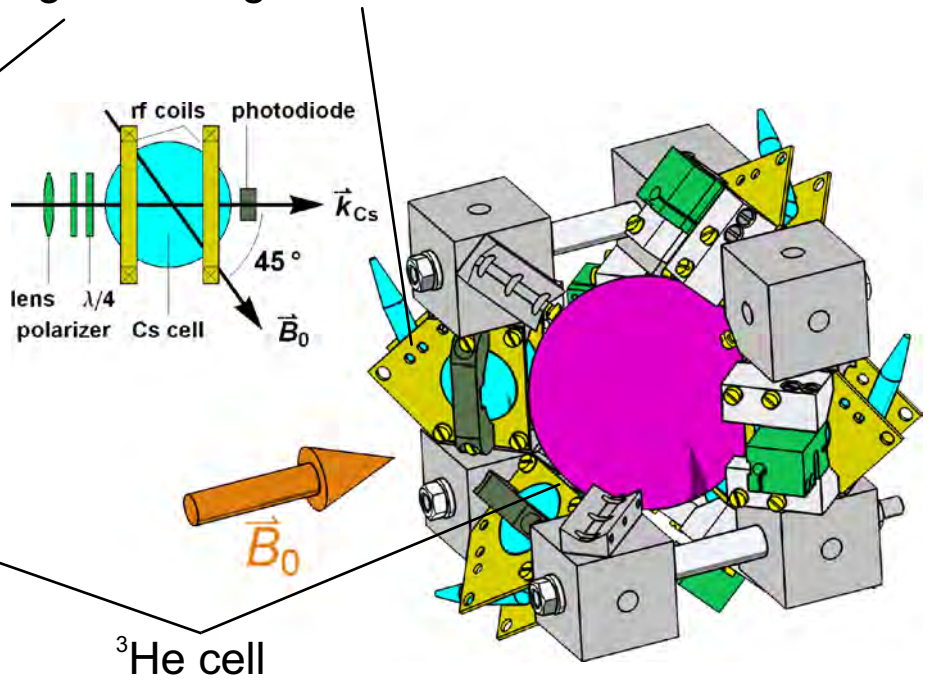




He Magnetometer



eight Cs magnetometers

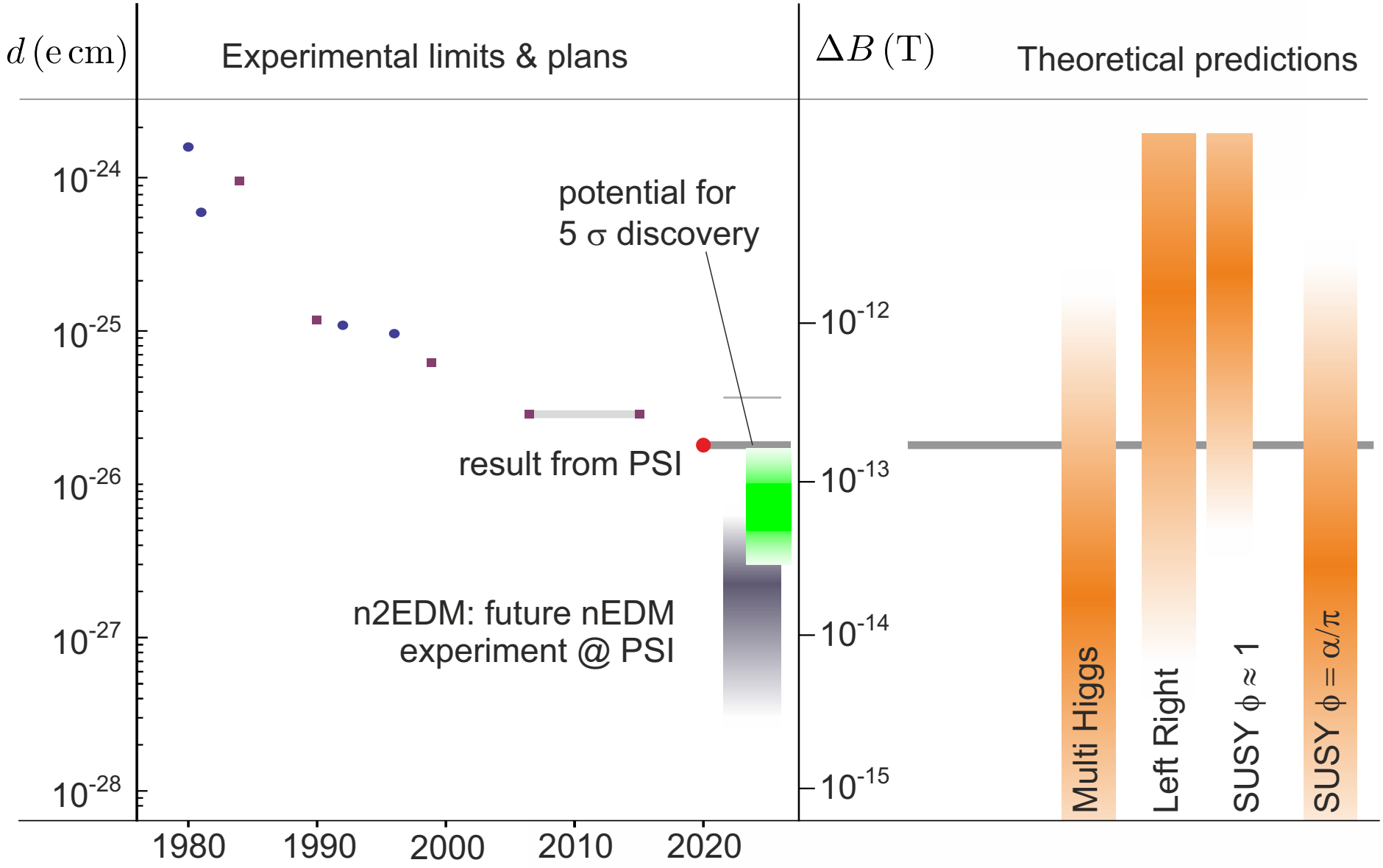


metastable exchange optical pumping

Design and performance of an absolute ^{3}He/Cs magnetometer H.-C. Koch, G. Bison, Z. D. Grujić, W. Heil, M. Kasprzak, P. Knowles, A. Kraft, A. Pazgalev, A. Schnabel, J. Voigt, A. Weis. Eur. Phys. J. D 69:202 (2015)

Investigation of the intrinsic sensitivity of a ^{3}He/Cs magnetometer. H.-C. Koch, G. Bison, Z. D. Grujić, W. Heil, M. Kasprzak, P. Knowles, A. Kraft, A. Pazgalev, A. Schnabel, J. Voigt, A. Weis Eur. Phys. J. D 69: 262 (2015).

Outlook for our n2EDM



Theoretical data from «Particle electric dipole moments»
J.M. Pendlebury & E.A. Hinds, NIM A 440 (2000) 471

The nEDM collaboration