PAUL SCHERRER INSTITUT

PSI

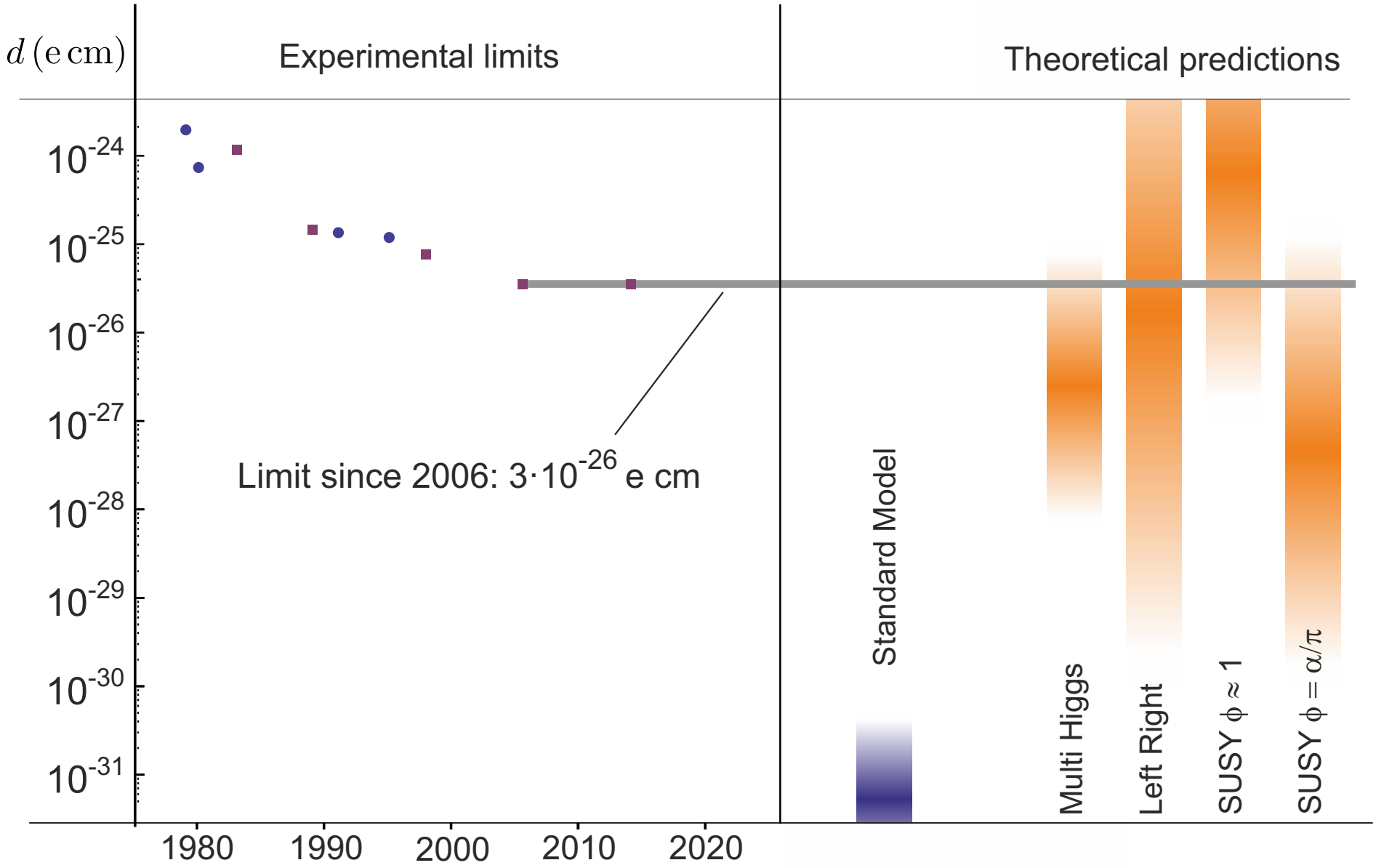
Paul Scherrer Institut

G. Bison for the nEDM collaboration

Searching for new physics with ultra-cold neutrons

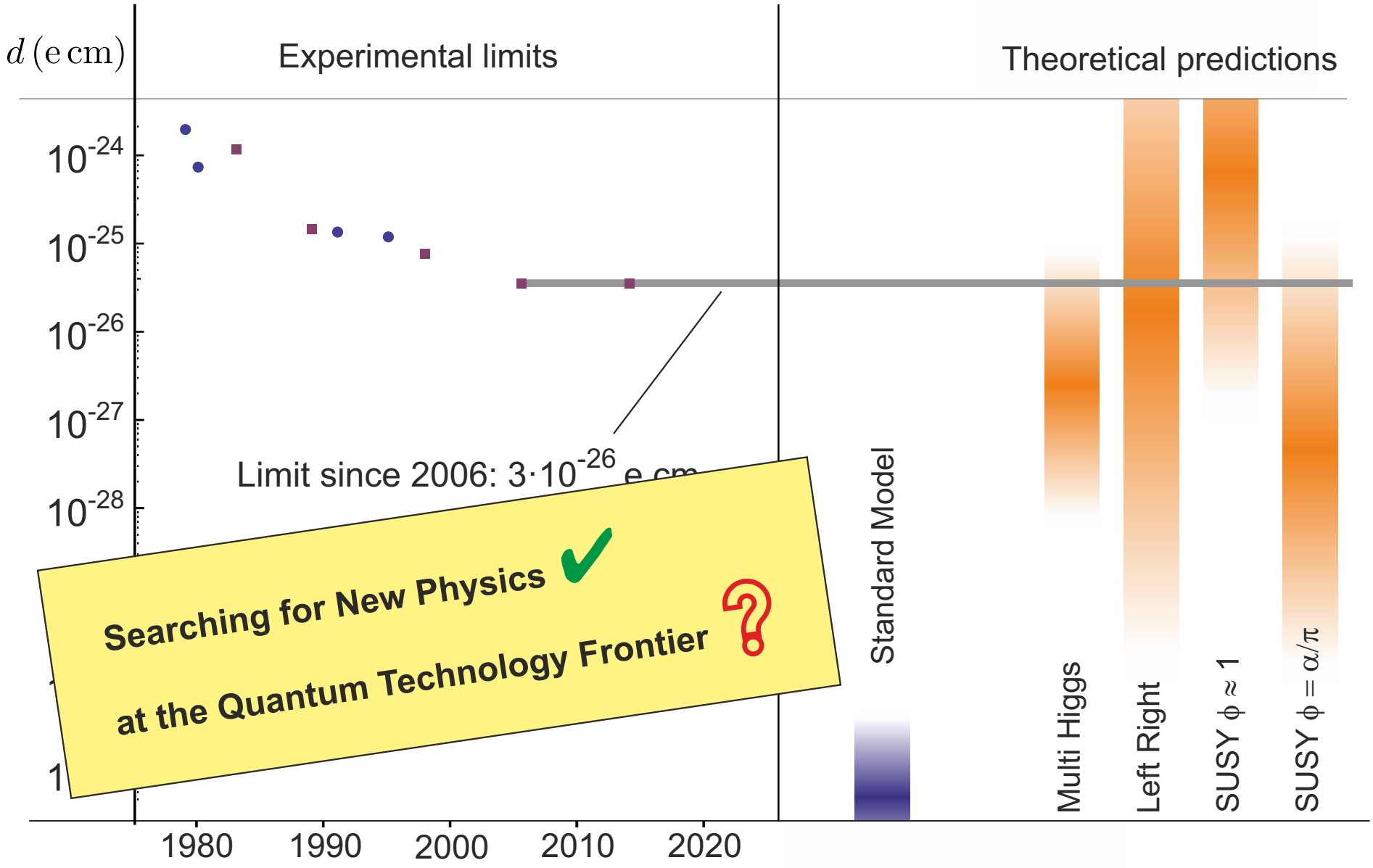
- **Introduction & neutron EDM experiment @ PSI**
- Results
- New experiment n2EDM

History



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

History



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

External Interaction Hamiltonian

$$H_{\text{ext}} = -2\,\mu_z\,B_0 \pm 2\,d_z\,E_0 = h\nu_L$$

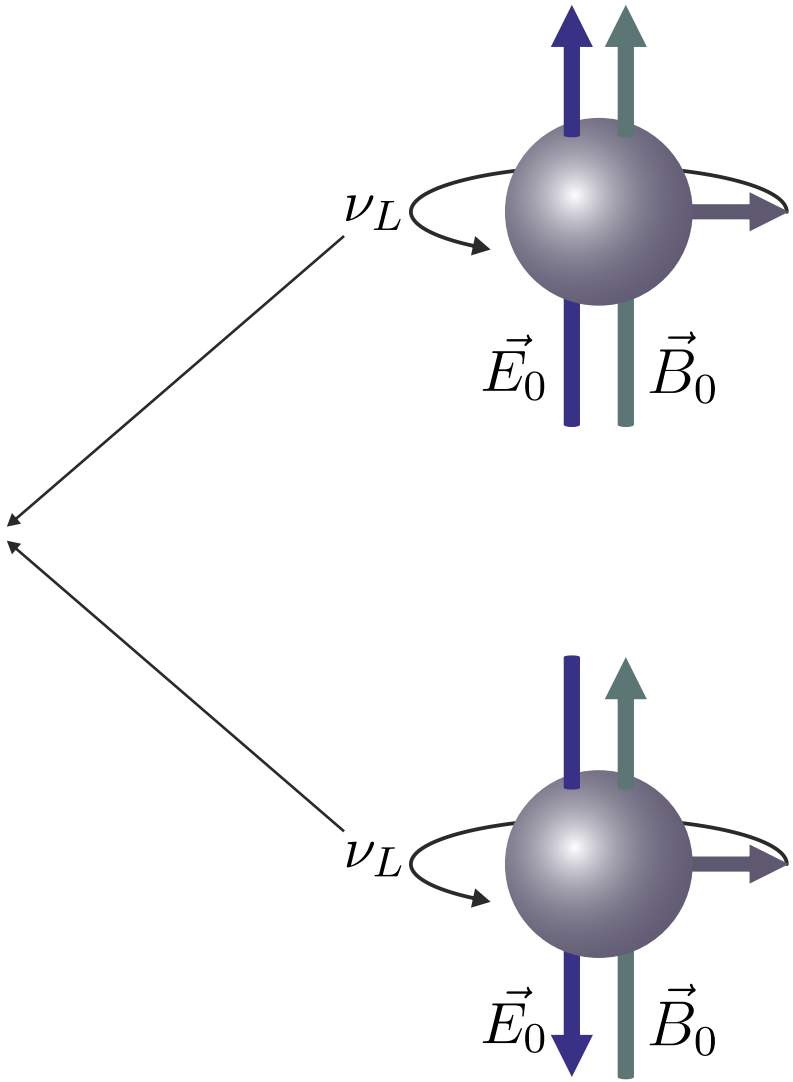
Extracting d from two measurements

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

$$d_z = \frac{h\,\Delta\nu_L}{4\,E_0}$$

is valid if

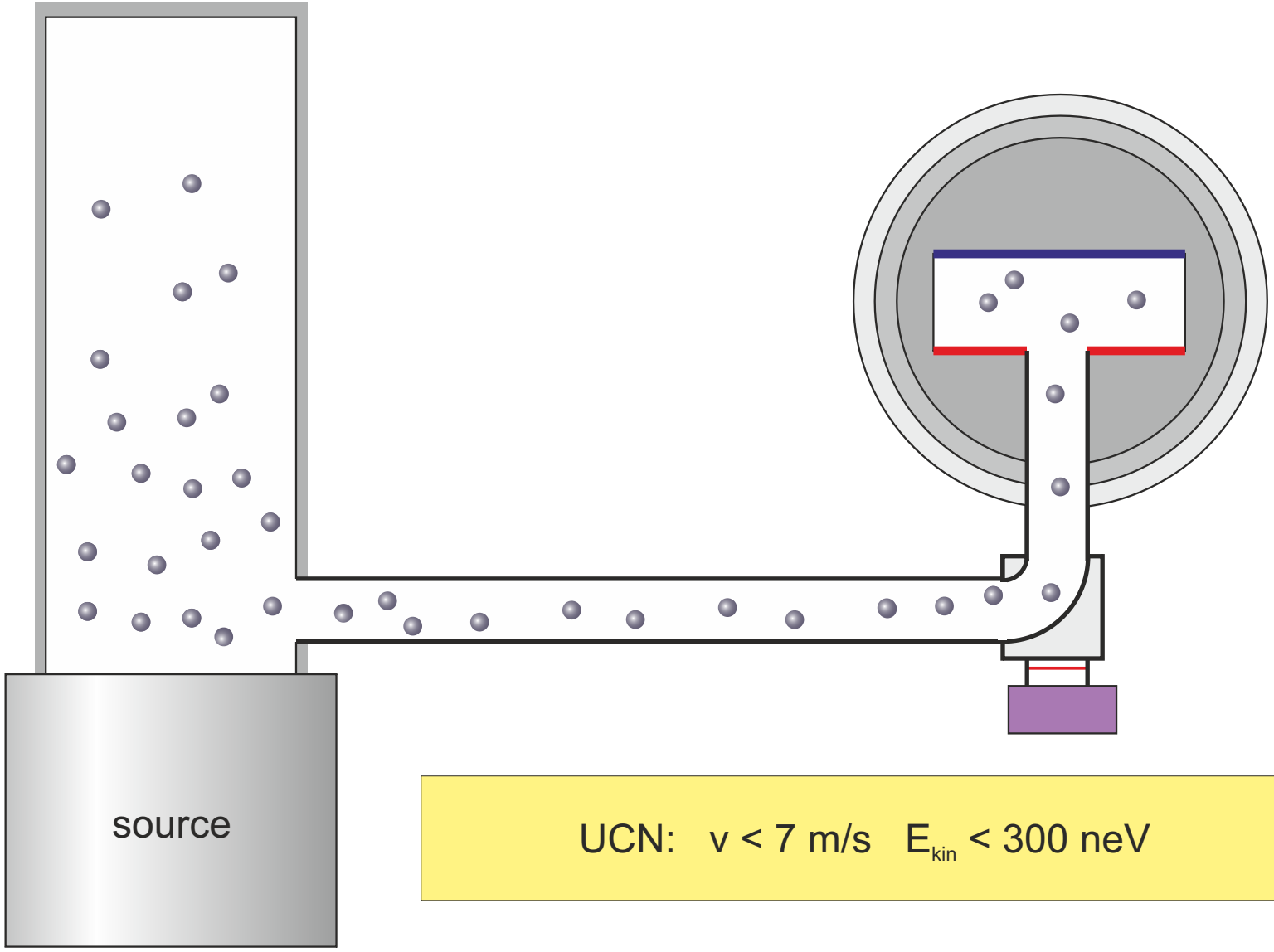
$$\Delta B \ll \frac{2\,d_z E_0}{\mu_z} \quad \cdots$$



Ultra cold neutrons

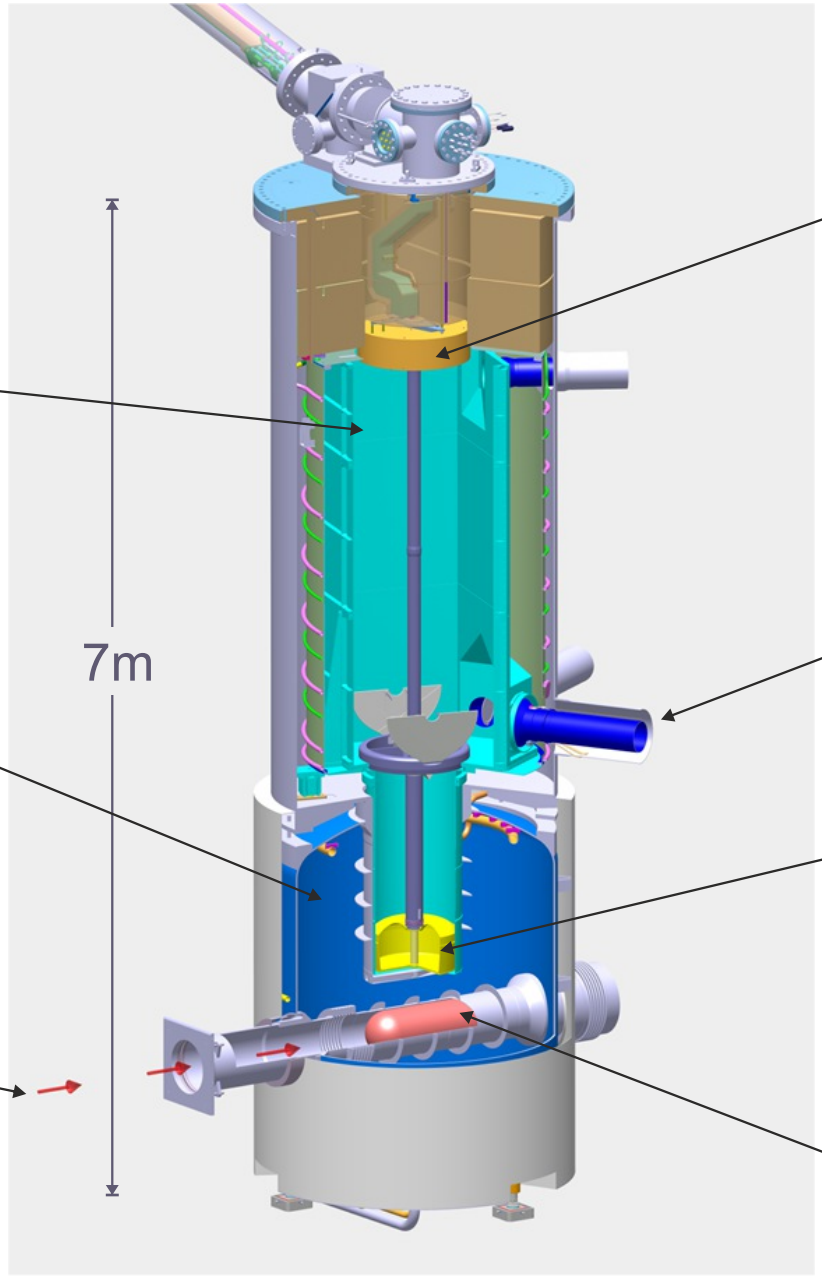
Make Ultra Cold Neutrons (UCN)

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

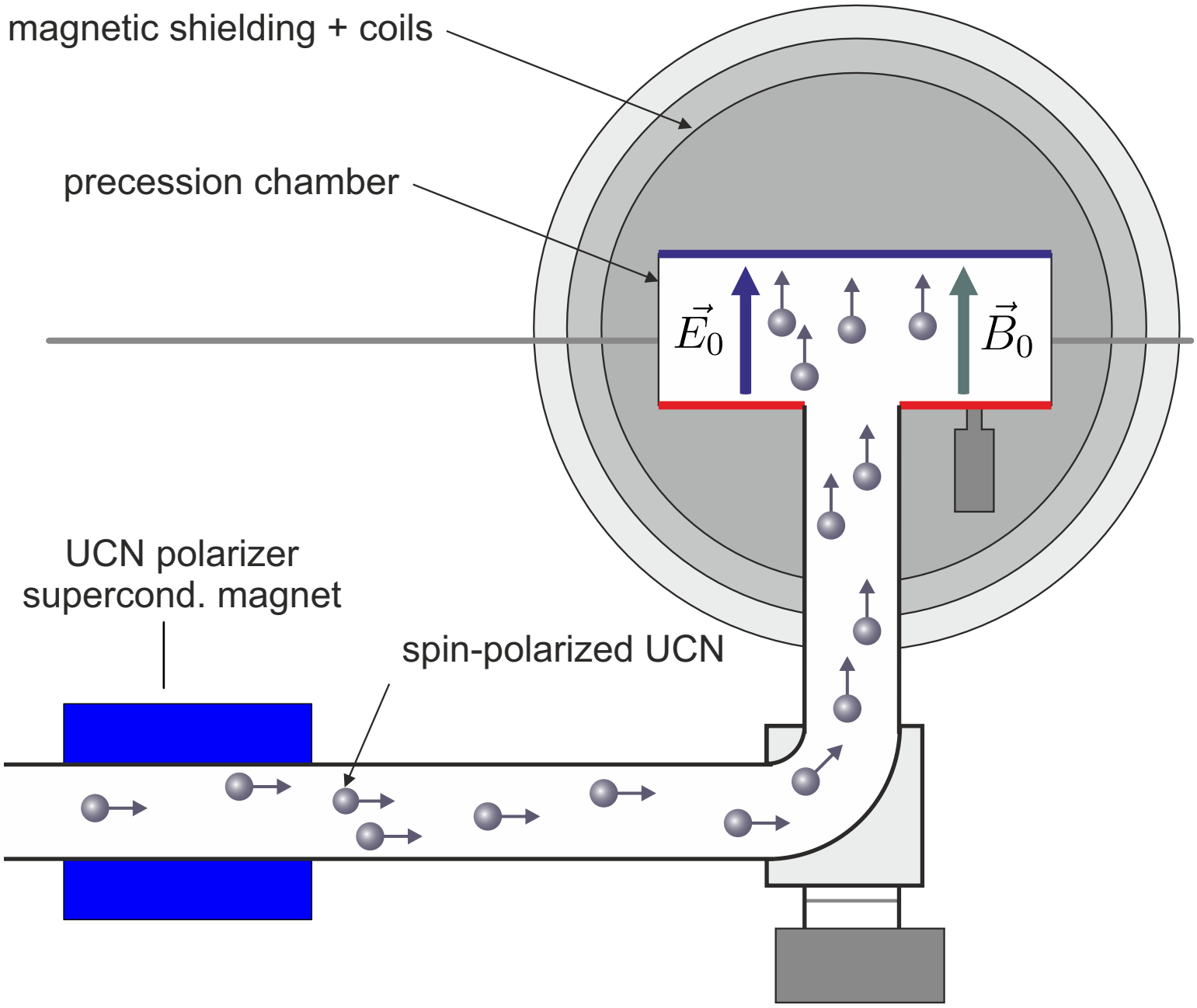
cold UCN-converter
~30l solid D2 at 5 K

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

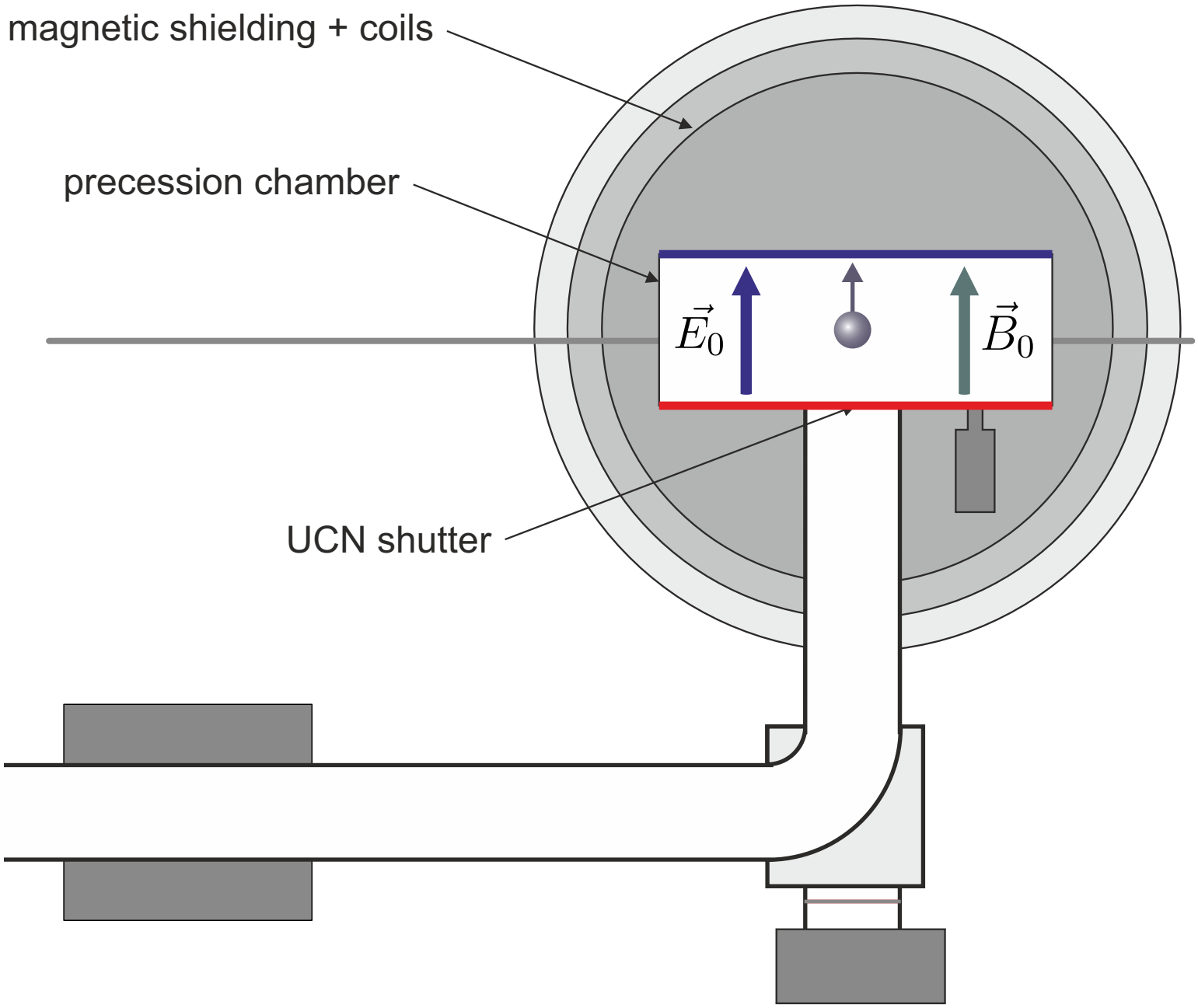
up to 60 μA average
current on target

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

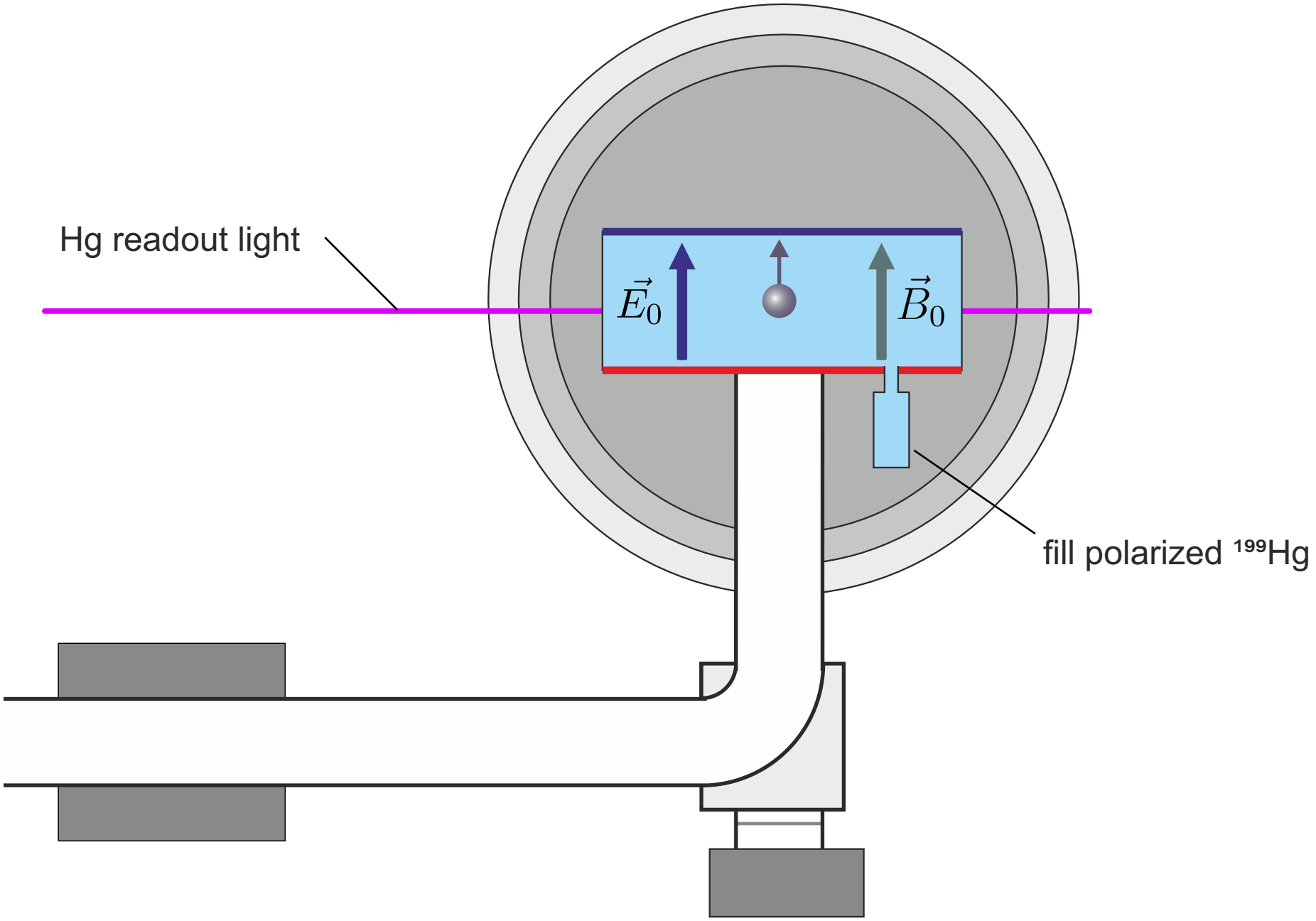
Filling the precession chamber



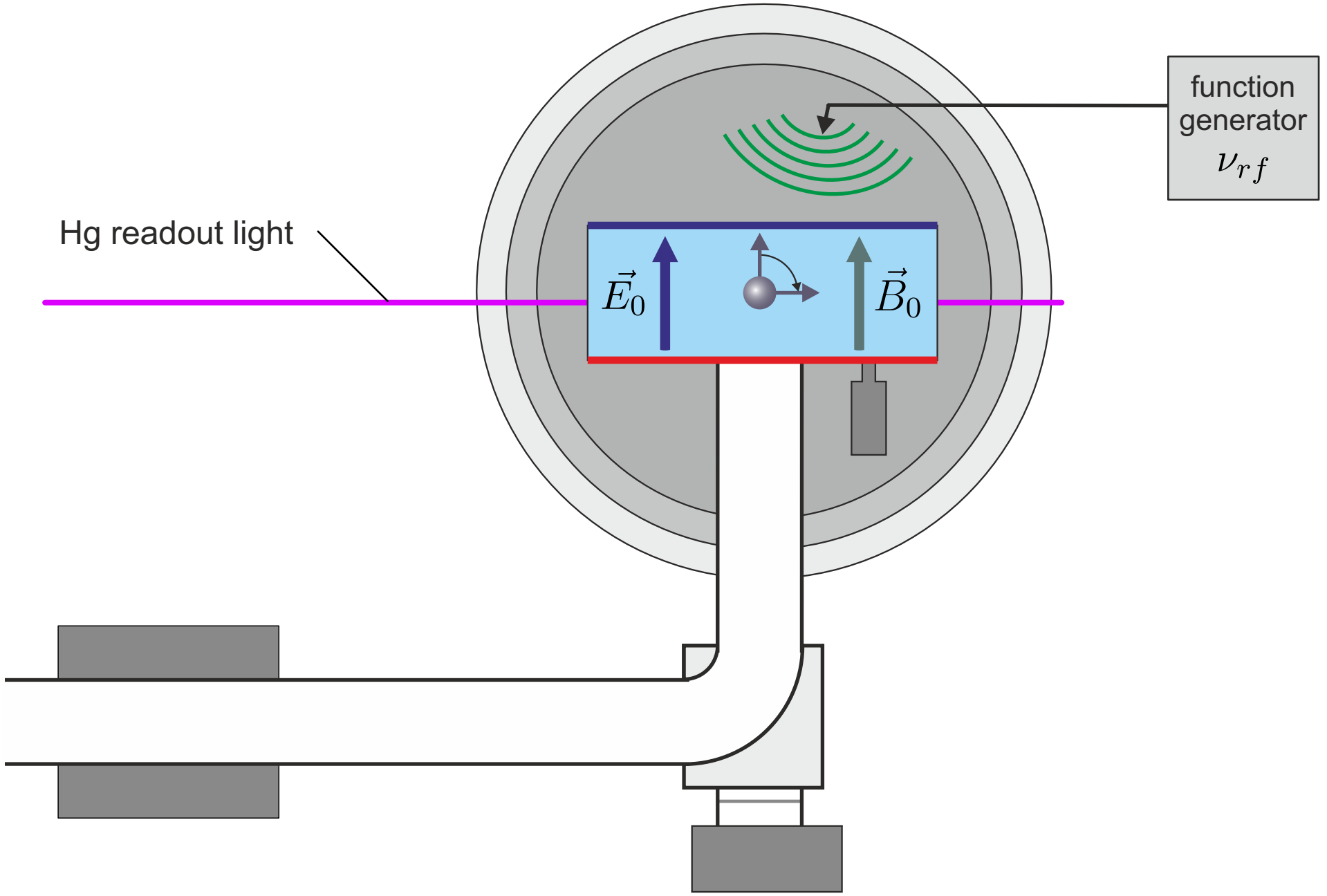
Filling the precession chamber



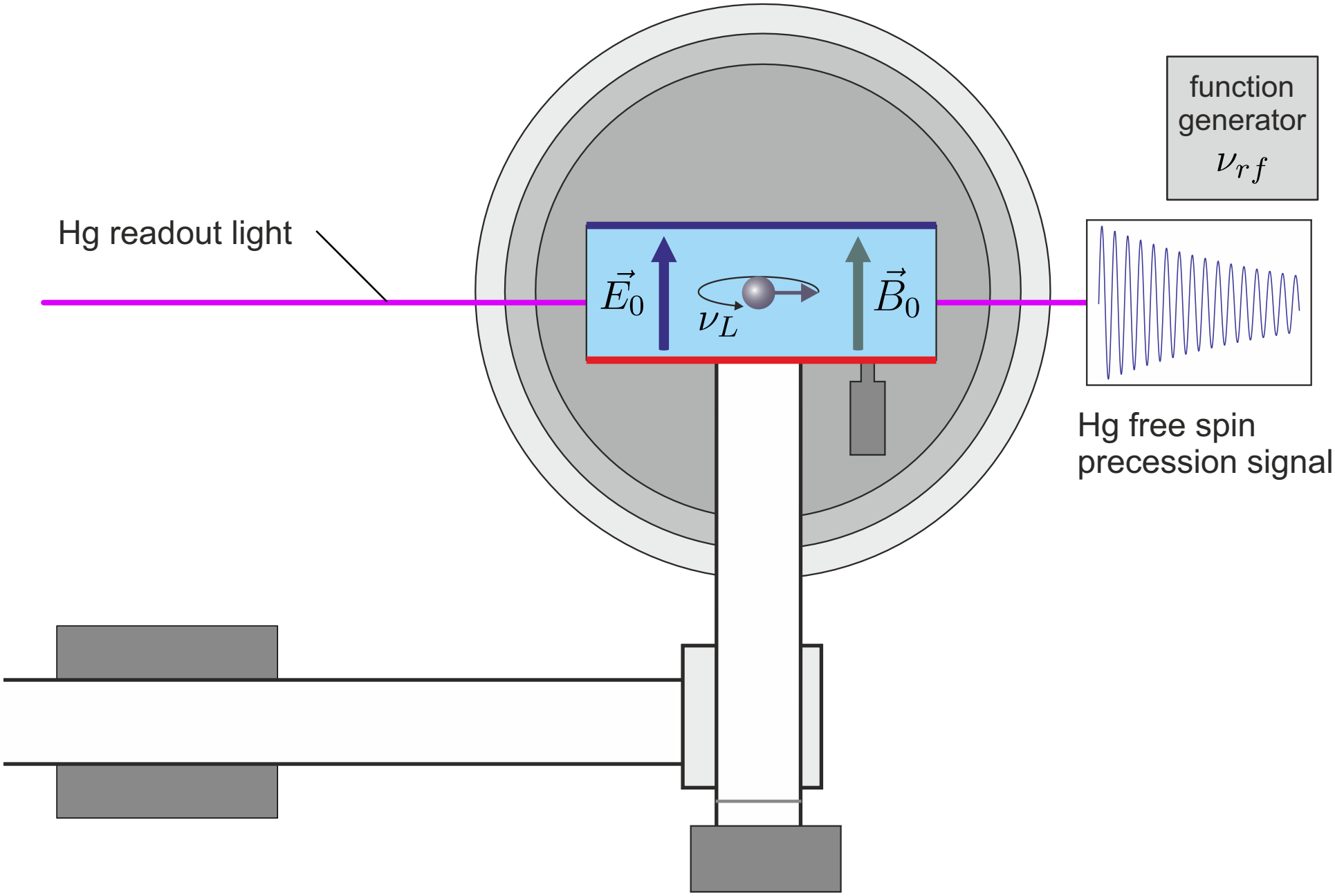
Filling the precession chamber



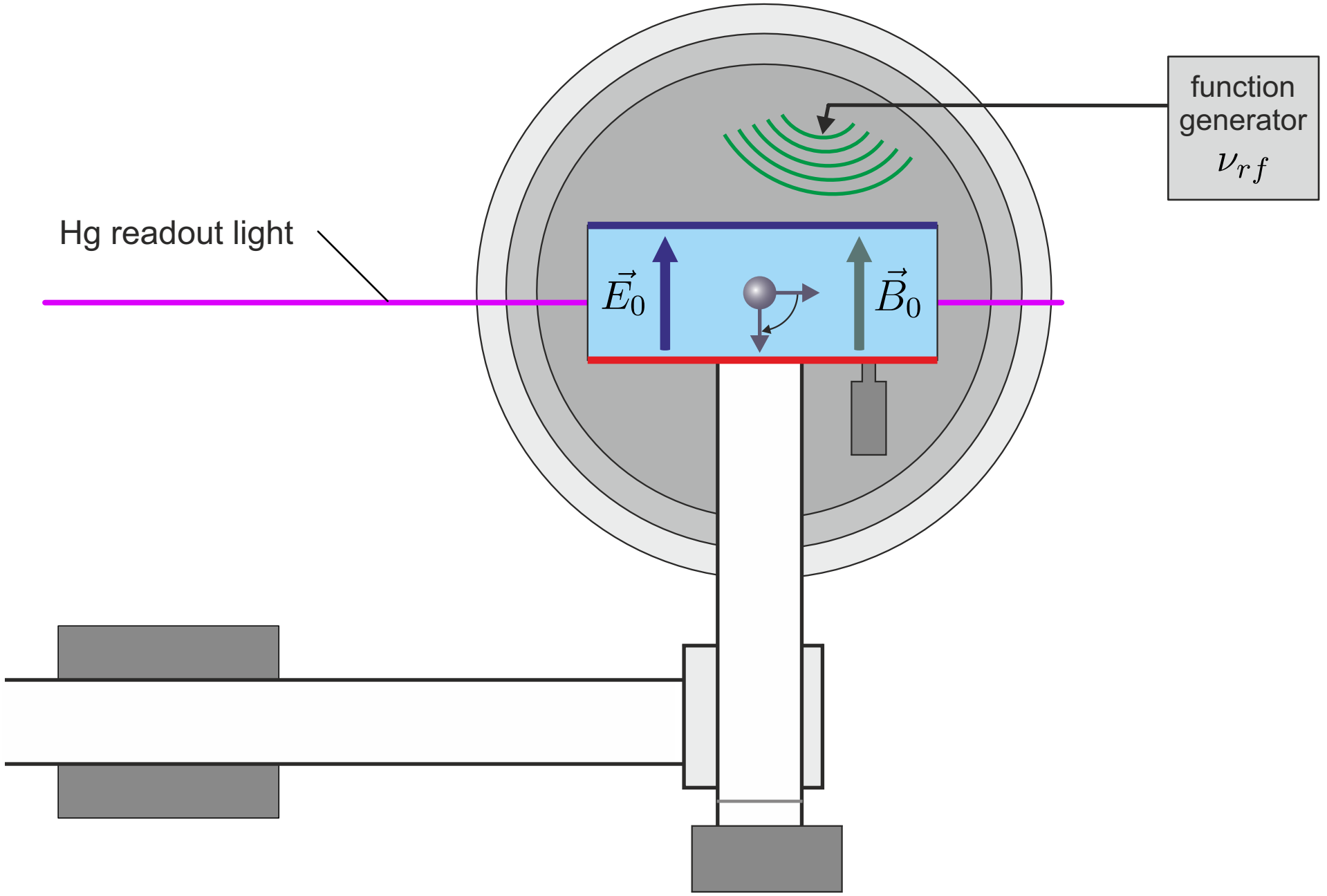
Ramsey cycle



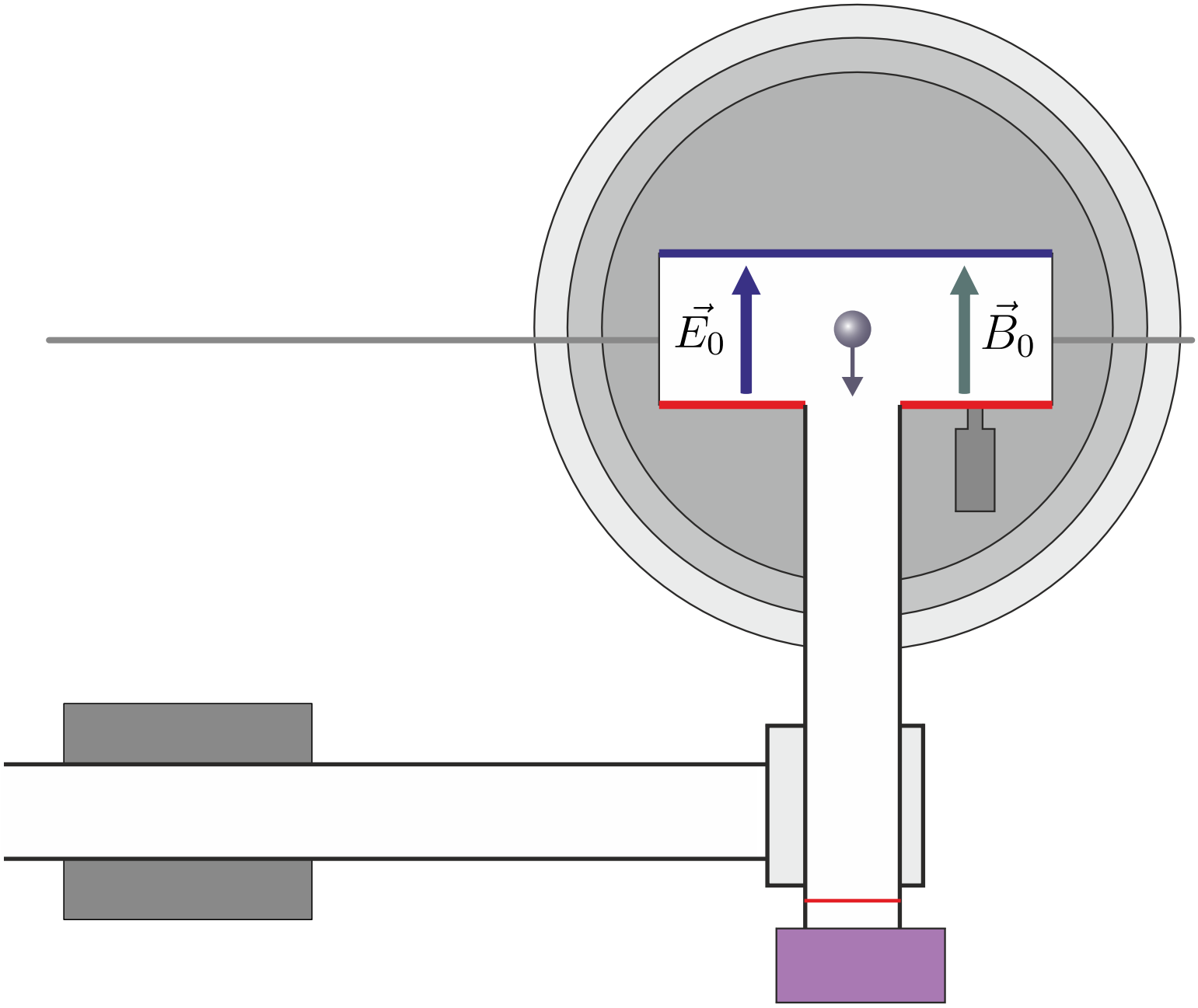
Ramsey cycle



Ramsey cycle

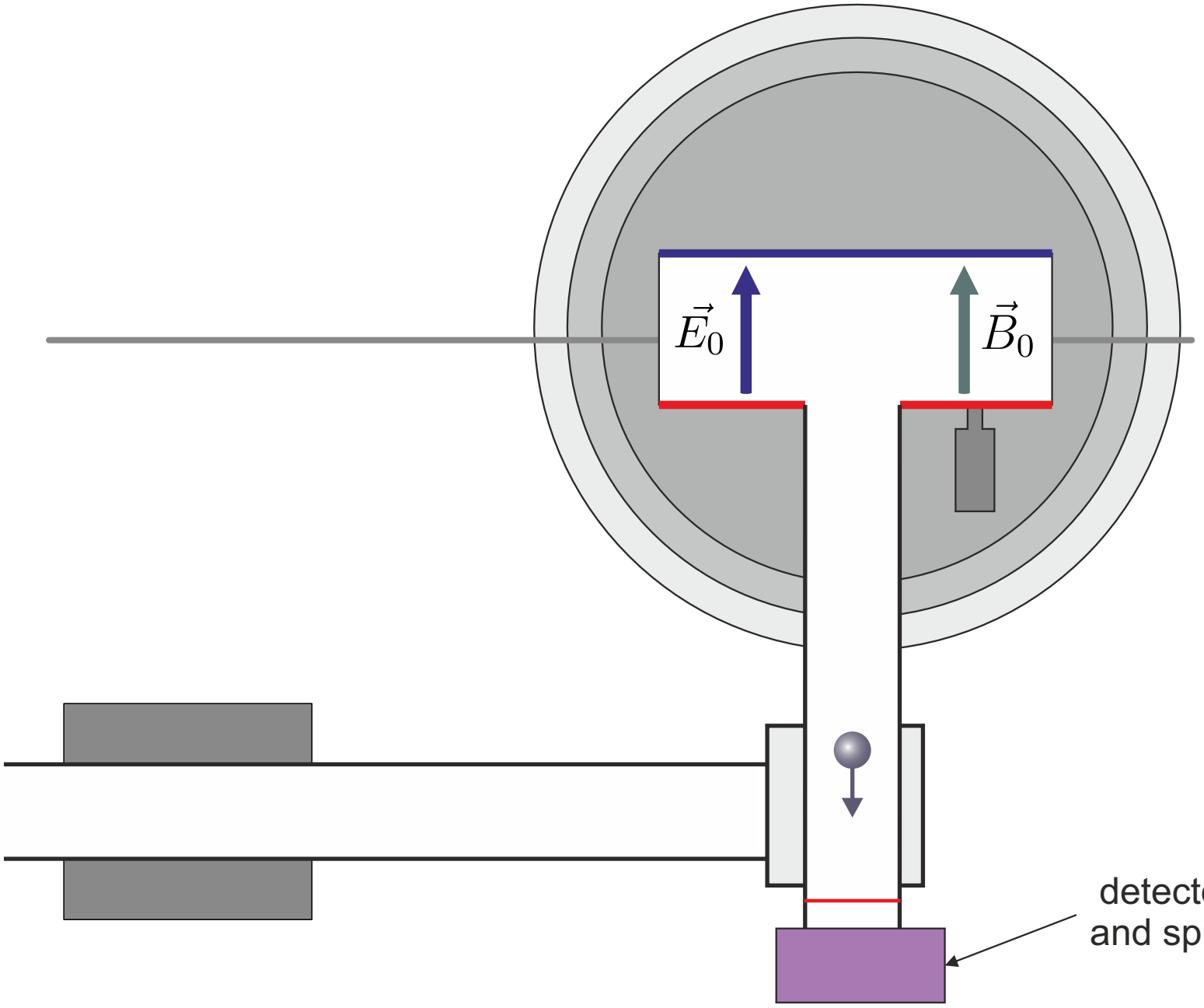


Emptying the precession chamber



function generator
ν_{rf}

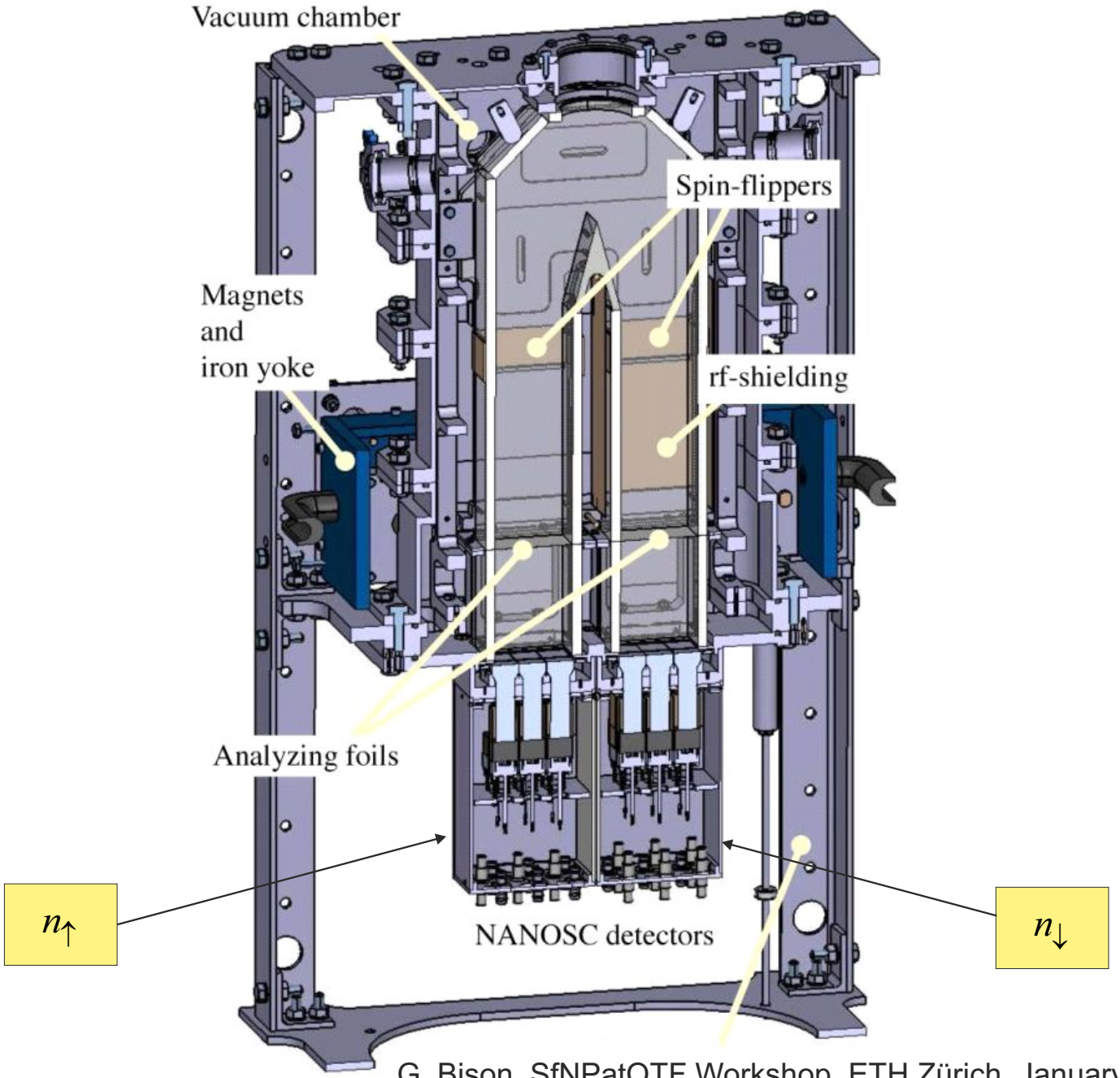
Neutron detection



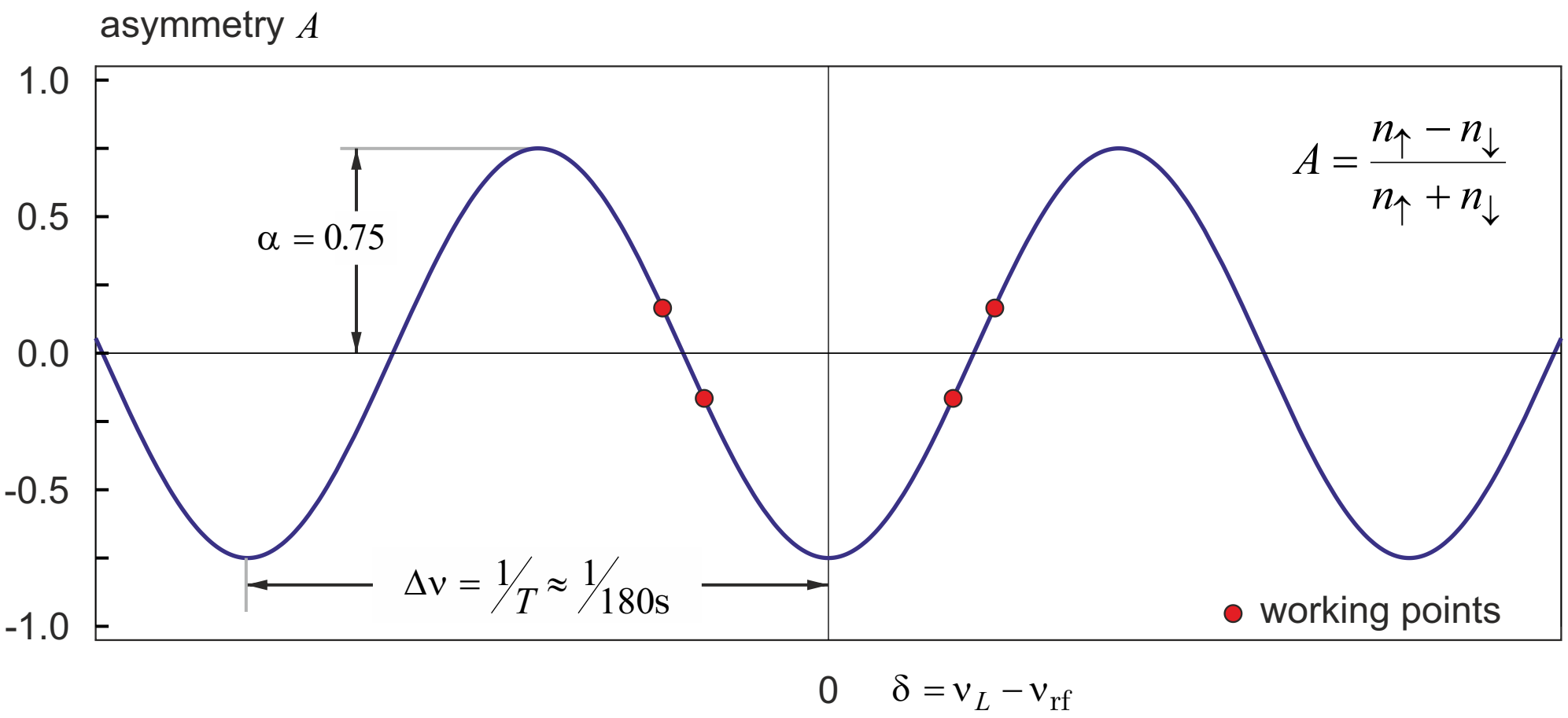
function generator ν_{rf}

detector: count spin up and spin down neutrons

Neutron Detection



Ramsey technique



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

Classical counting statistics:

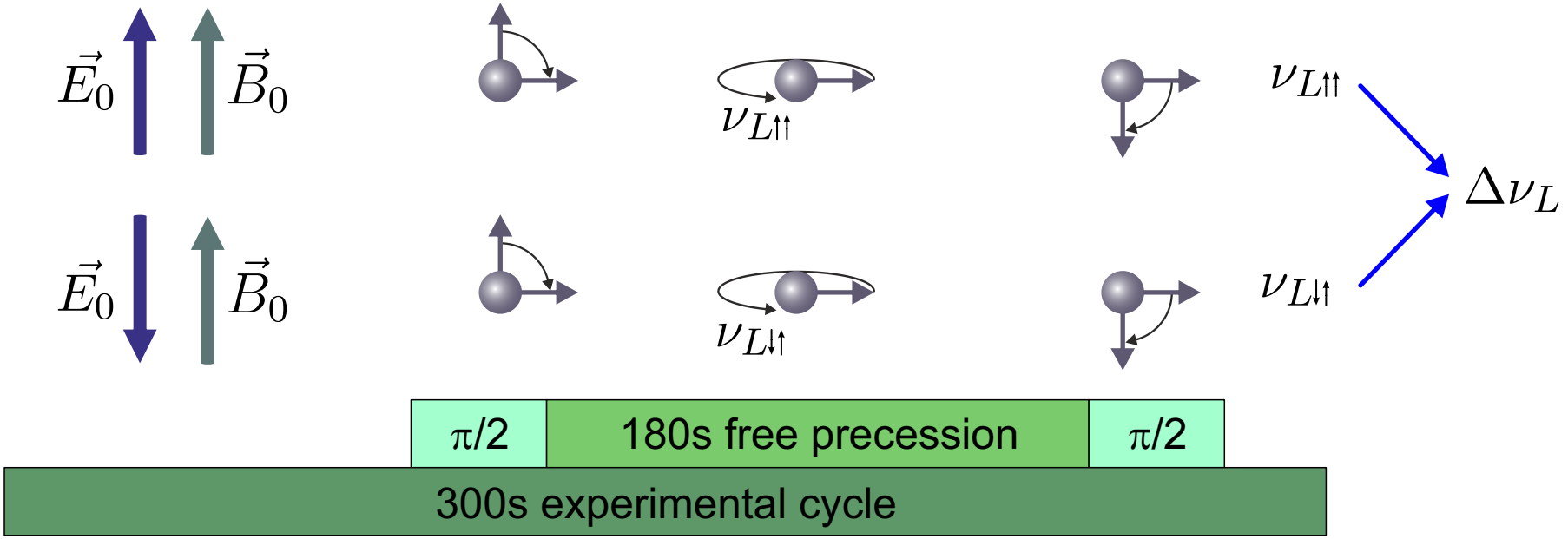
Equivalent to spin projection noise?

Can we do better

Ramsey technique

Neutron Larmor precession frequency

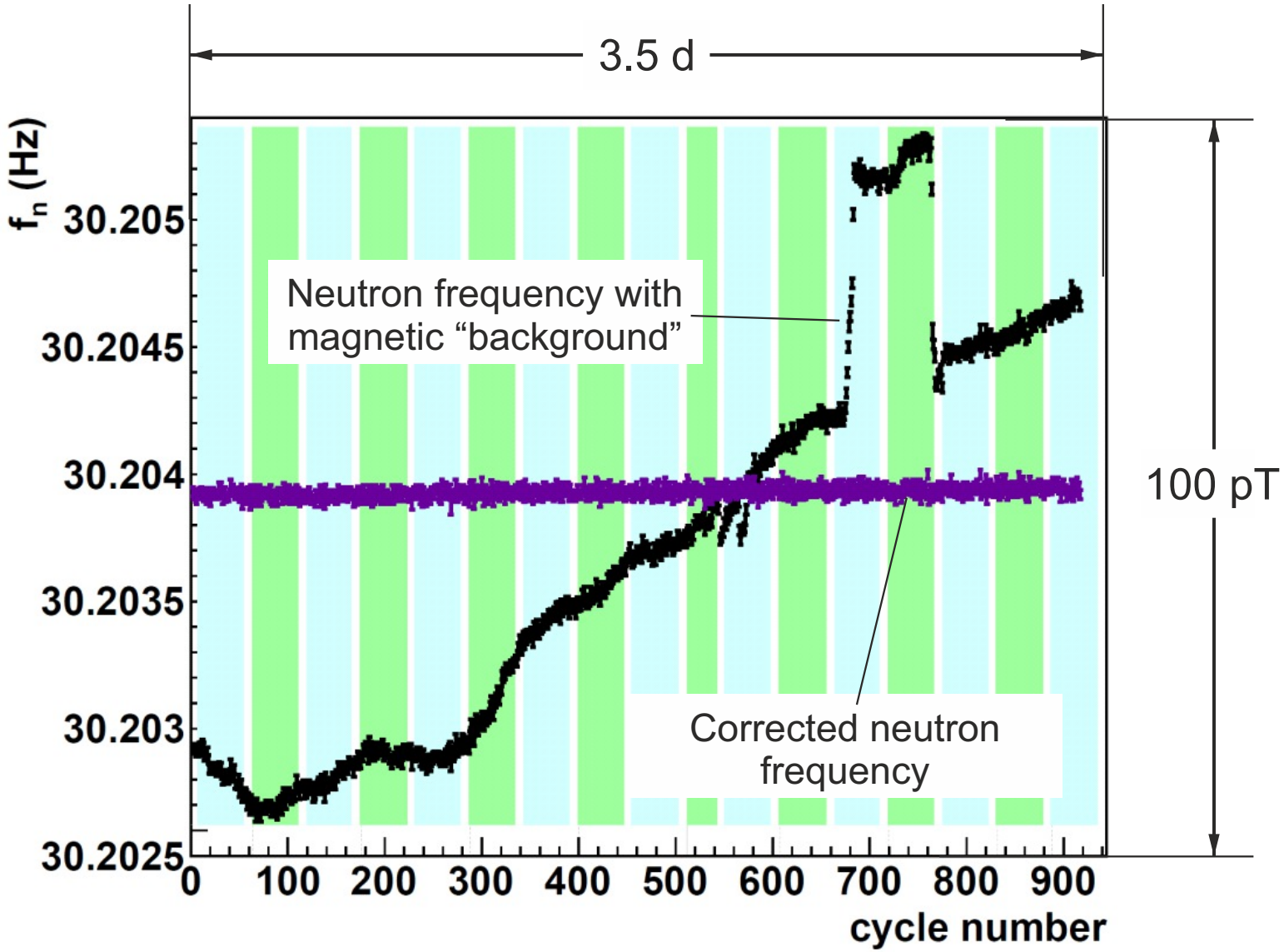
$$h\nu_L = -2\,\mu\,B_0 \pm 2\,d\,E_0$$



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

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

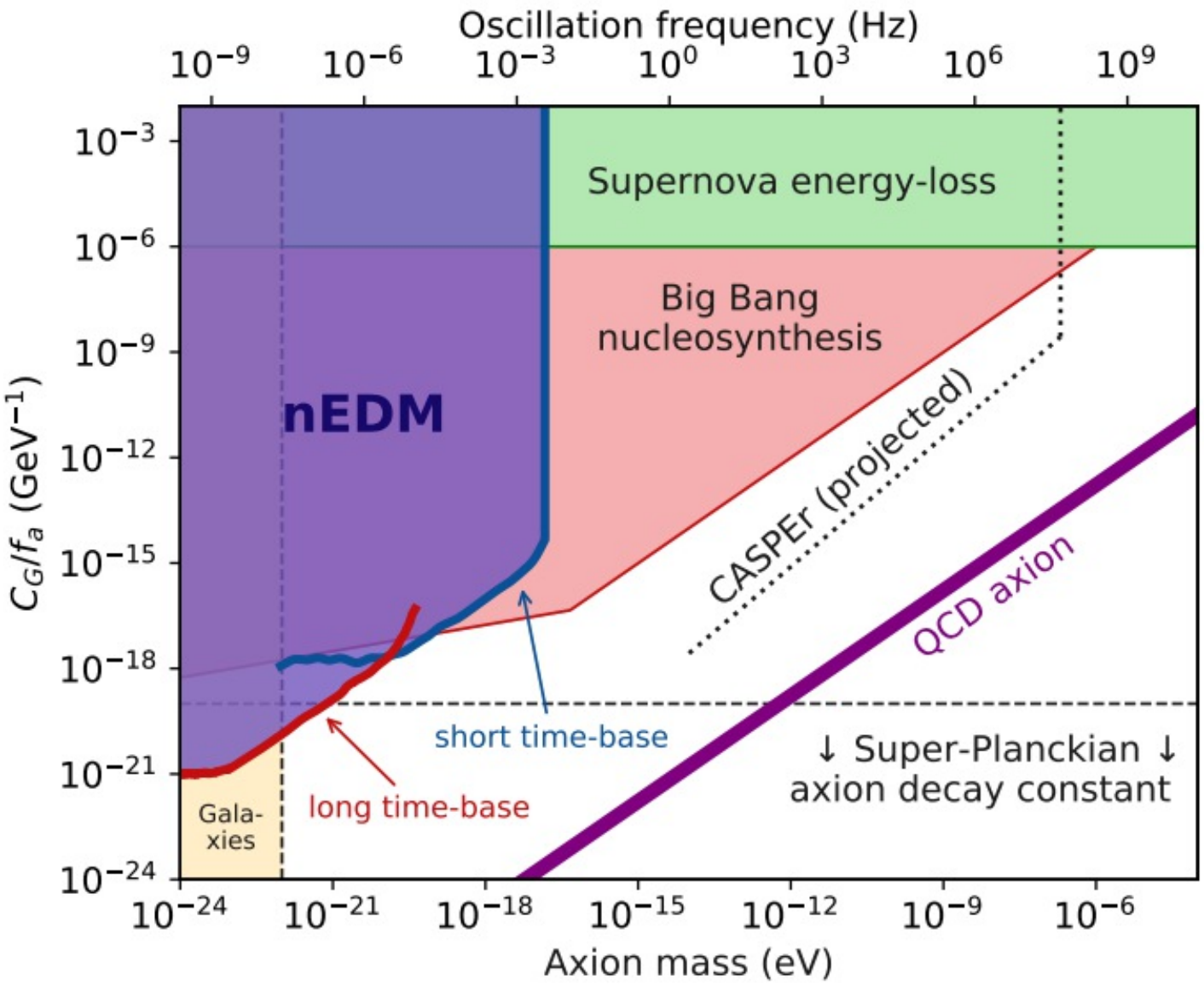
Magnetic field correction



In total we recorded >50000 cycles in two years

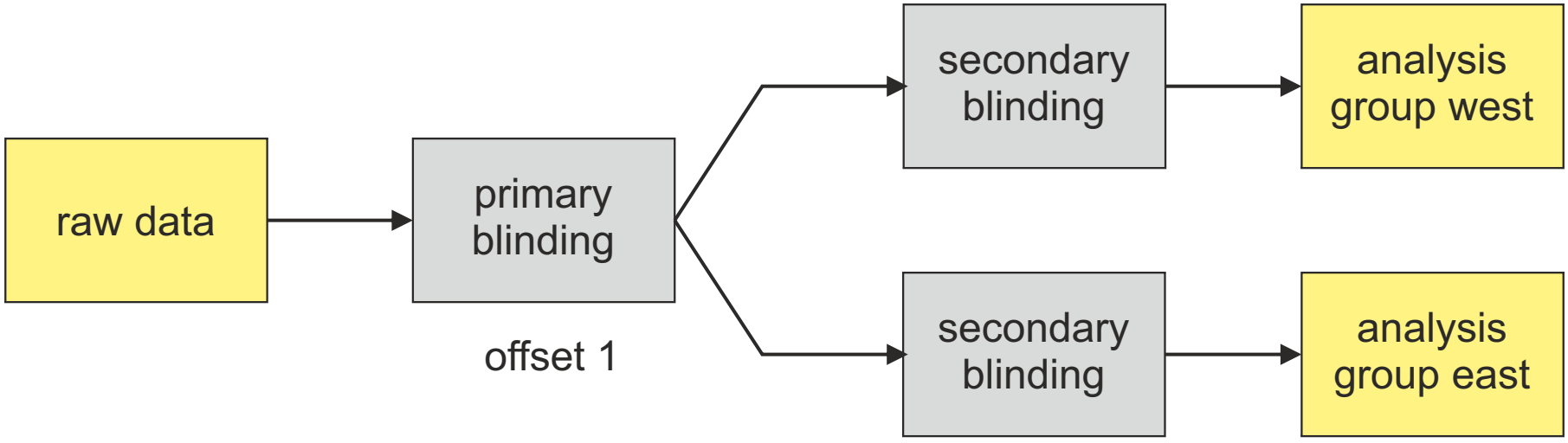
- Introduction & old neutron EDM experiment @ PSI
- **Results**
- New experiment n2EDM

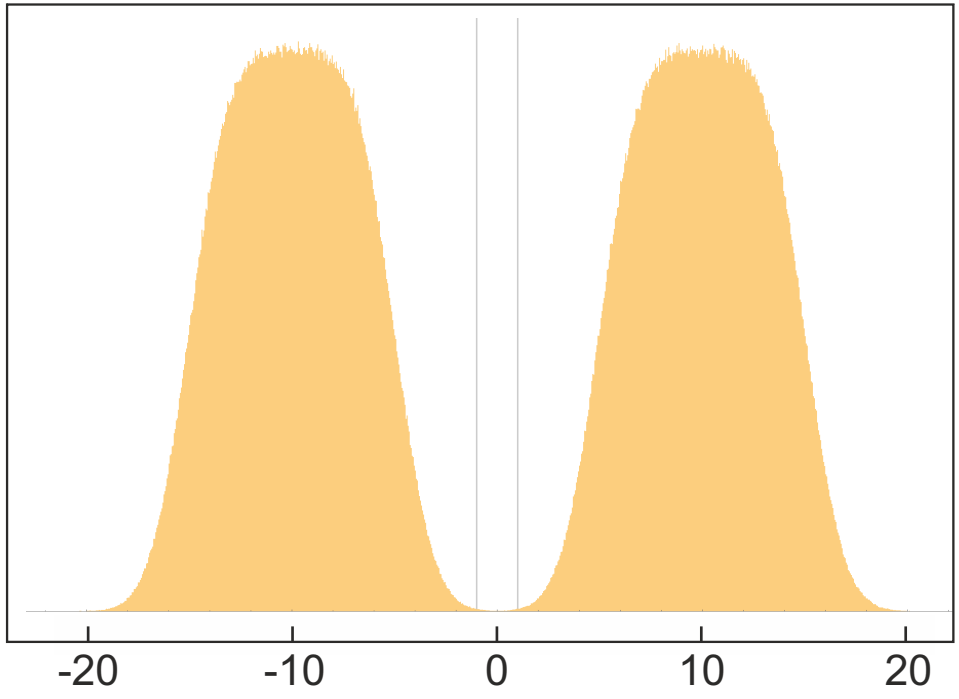
Our limit on the axion–gluon coupling



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)

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

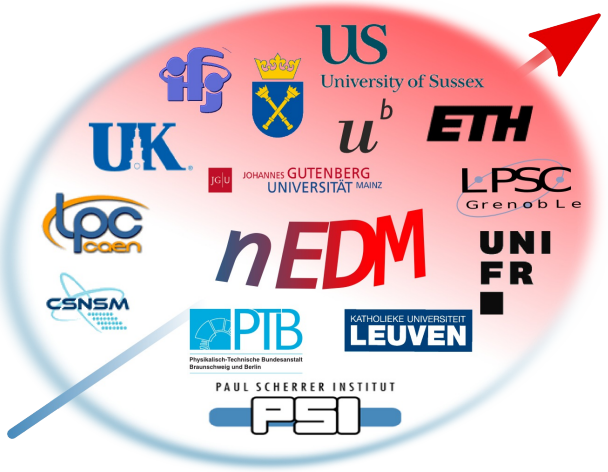
Systematic uncertainty six times smaller than before.

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

nEDM result

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

Effect	shift	error
Error on $\langle z \rangle$	-	7
Higher order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_{\mathrm{T}}^2 \rangle$	0	5
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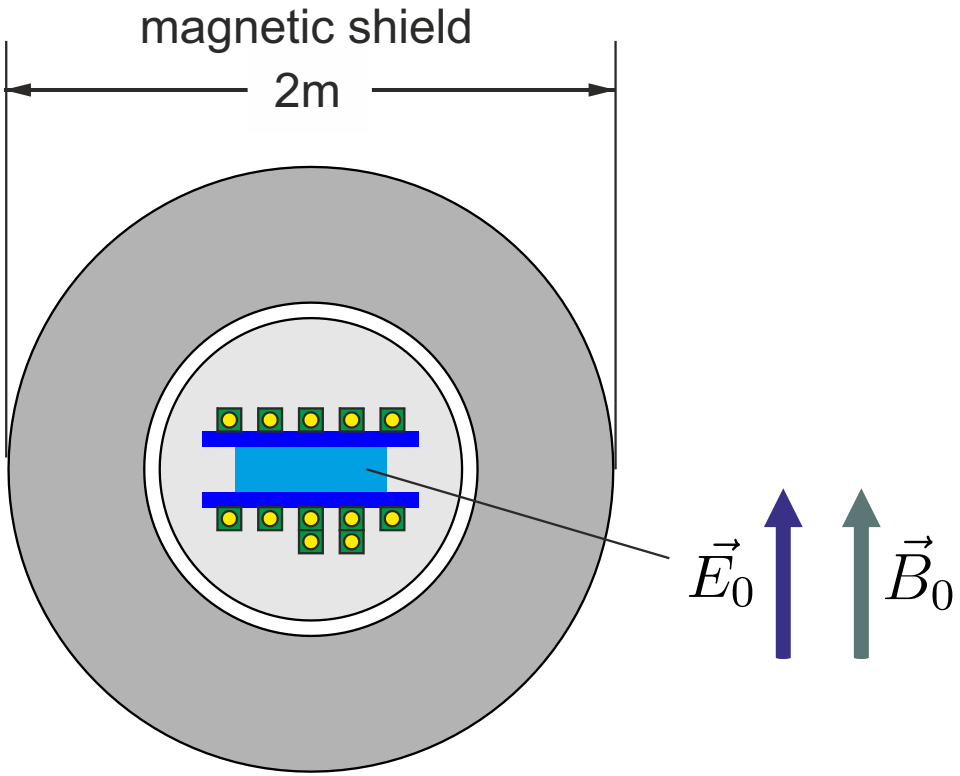
TOTAL	69	18

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

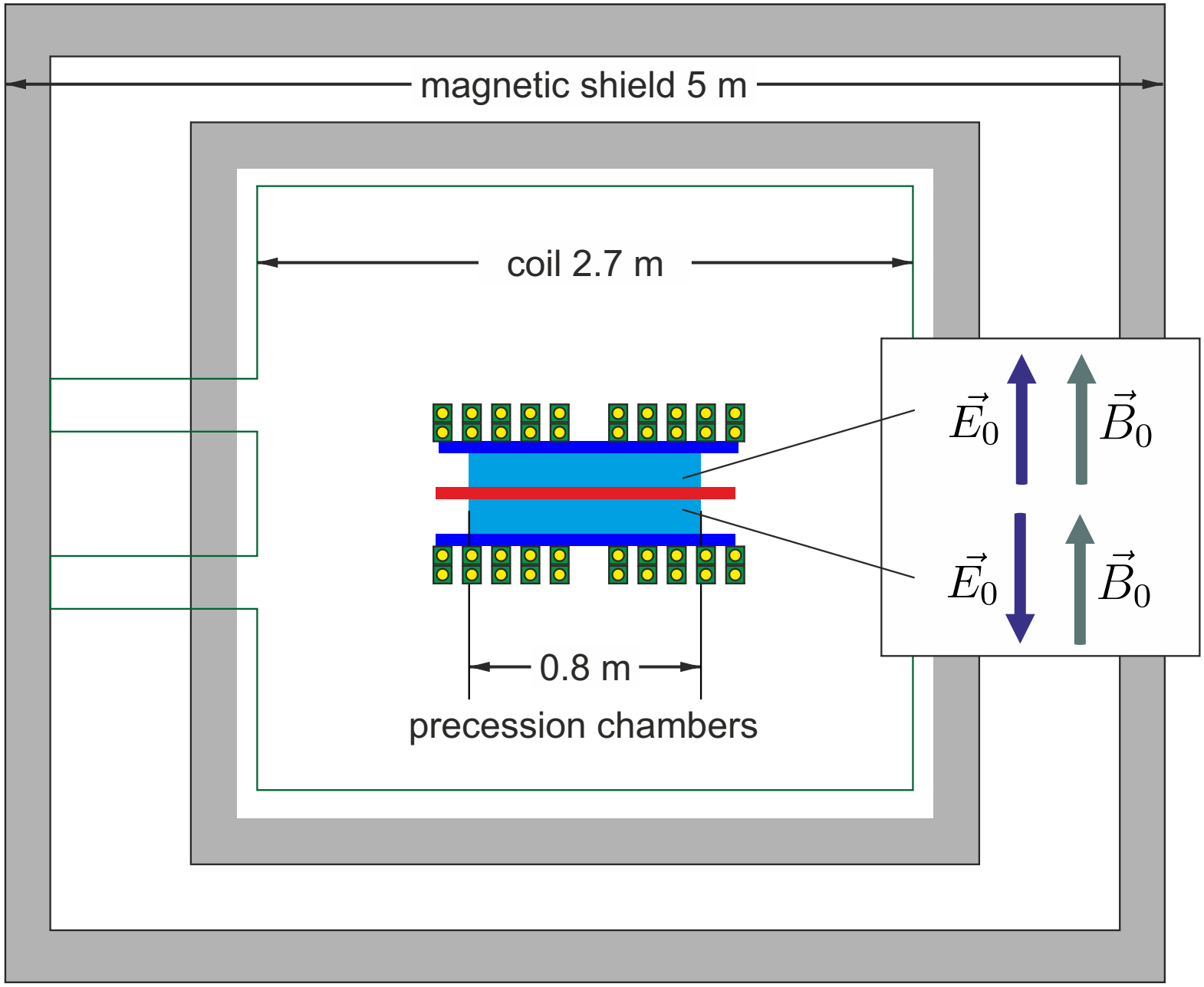
Systematic uncertainty six times smaller than before.

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

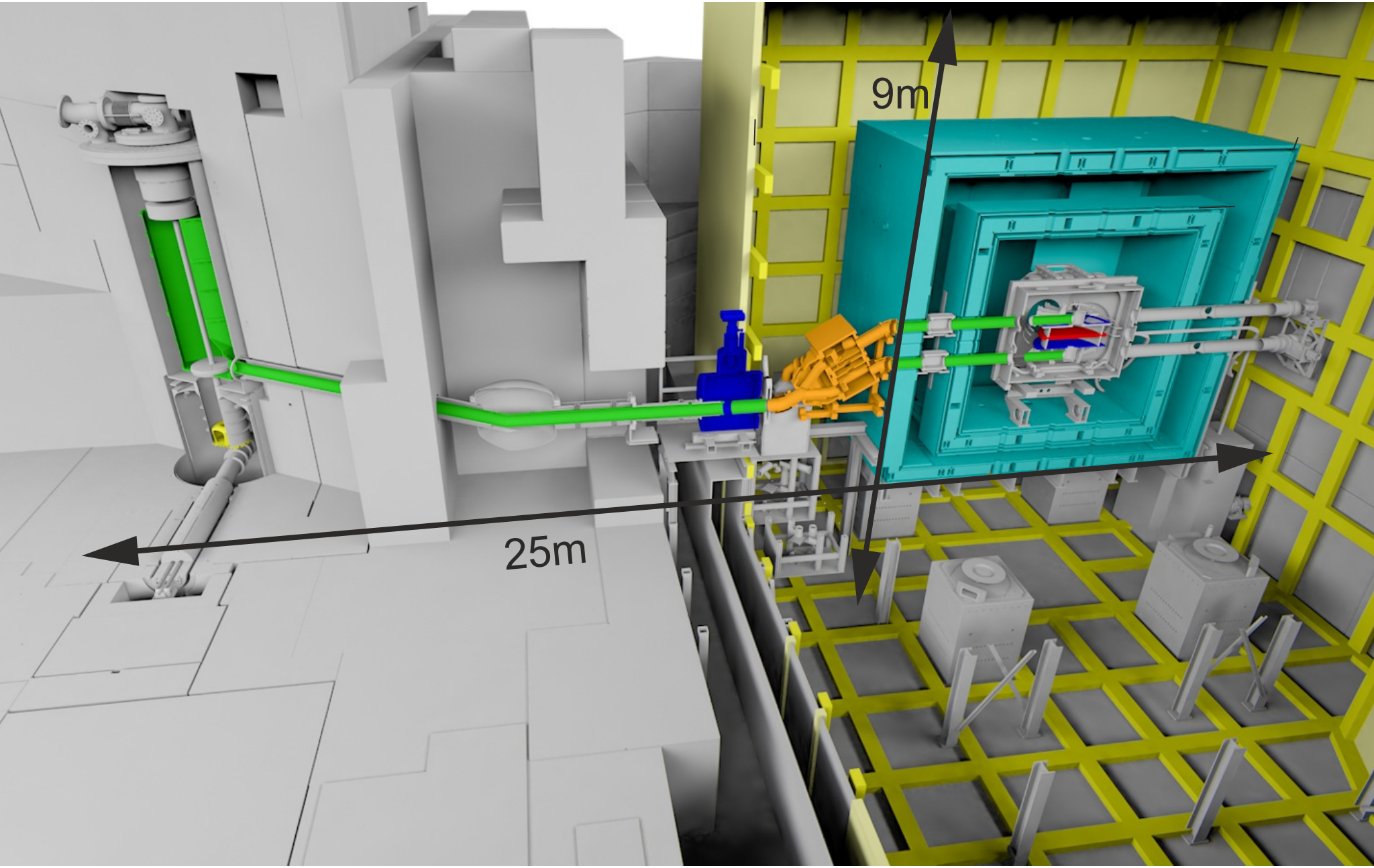
Current nEDM experiment



Future n2EDM experiment

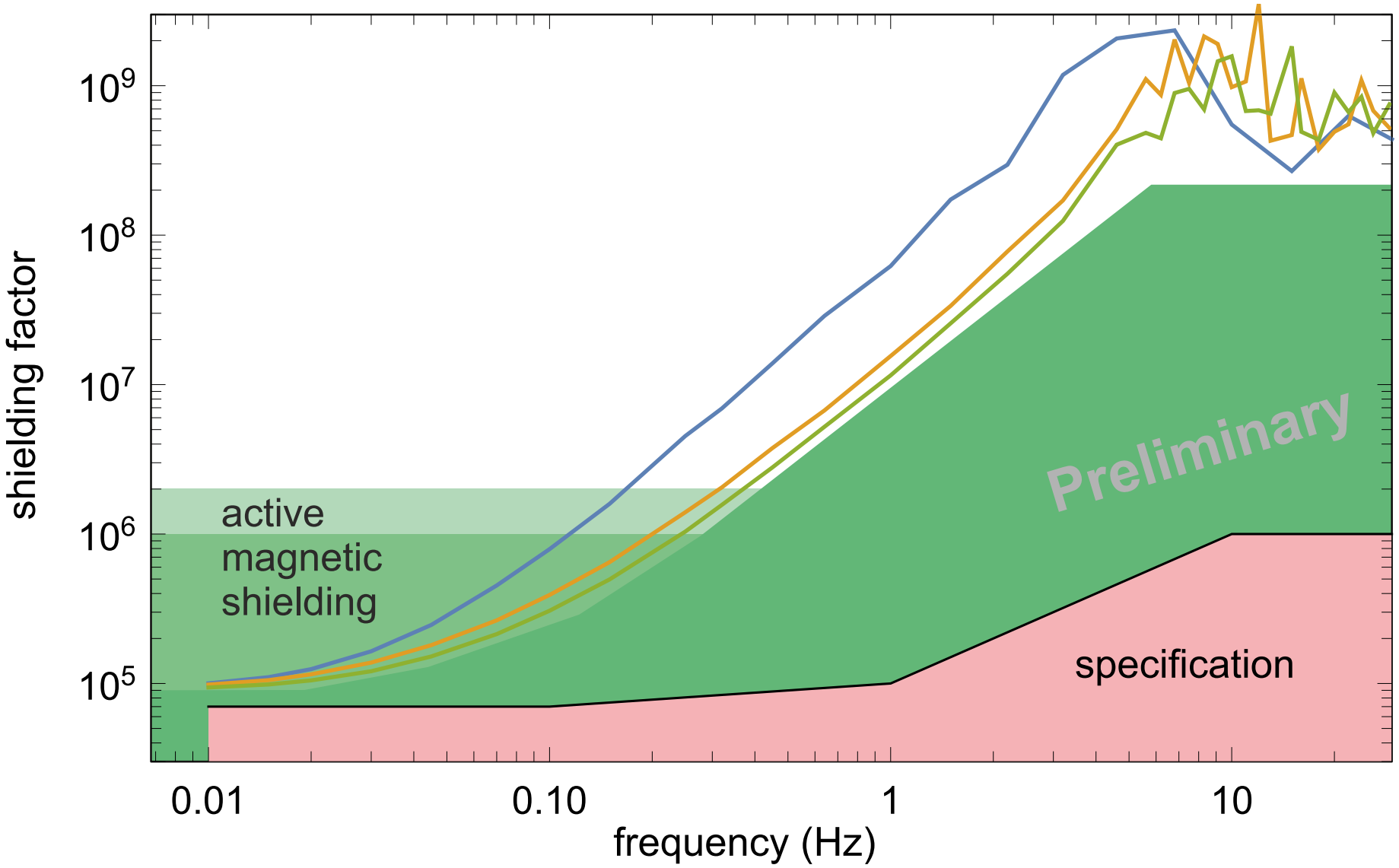


Future n2EDM experiment

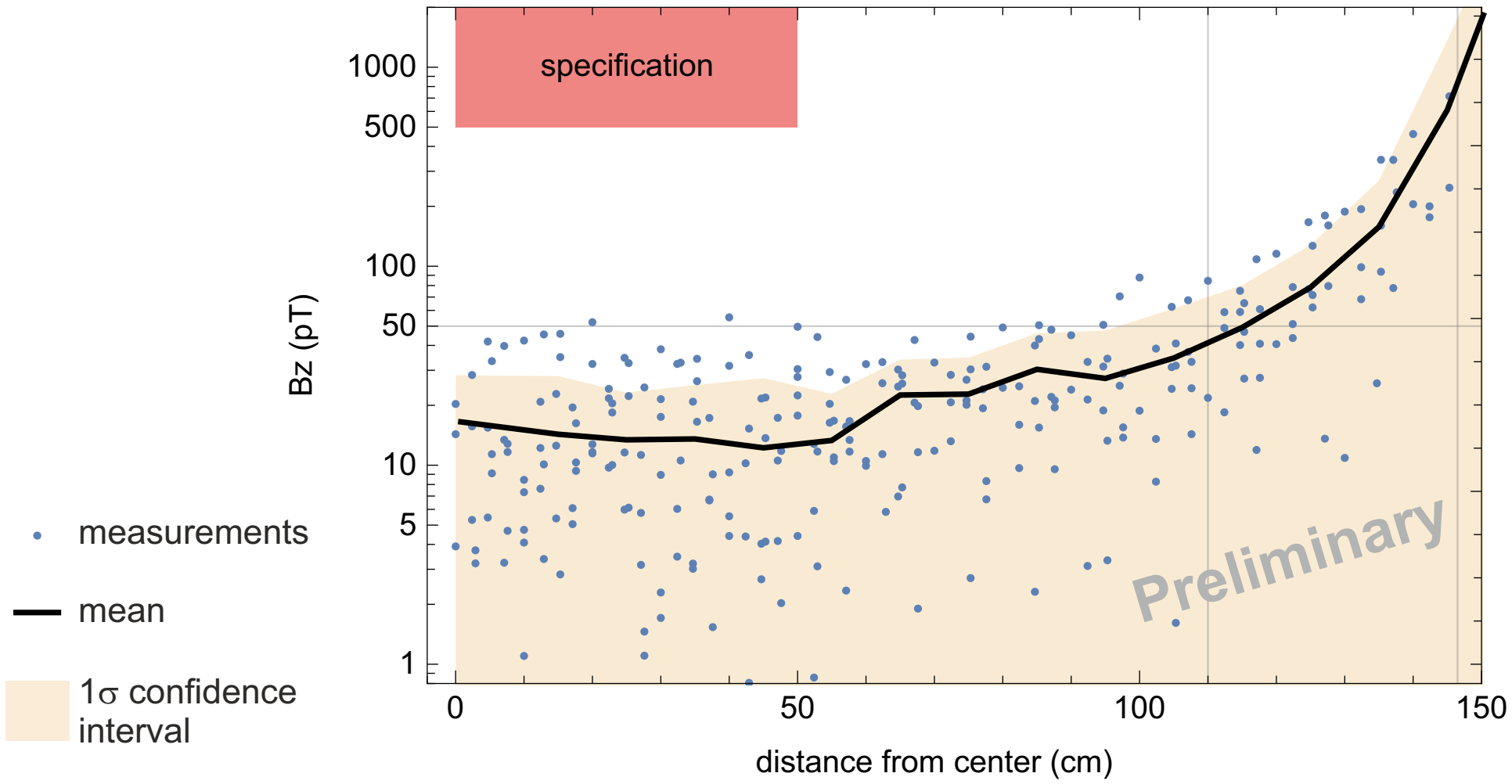


Future n2EDM experiment

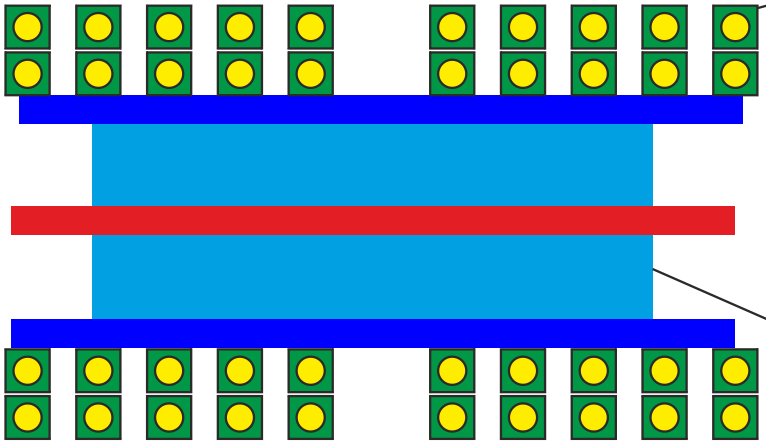
Shielding factor



Residual field Bz



Magnetometry challenges of n2EDM



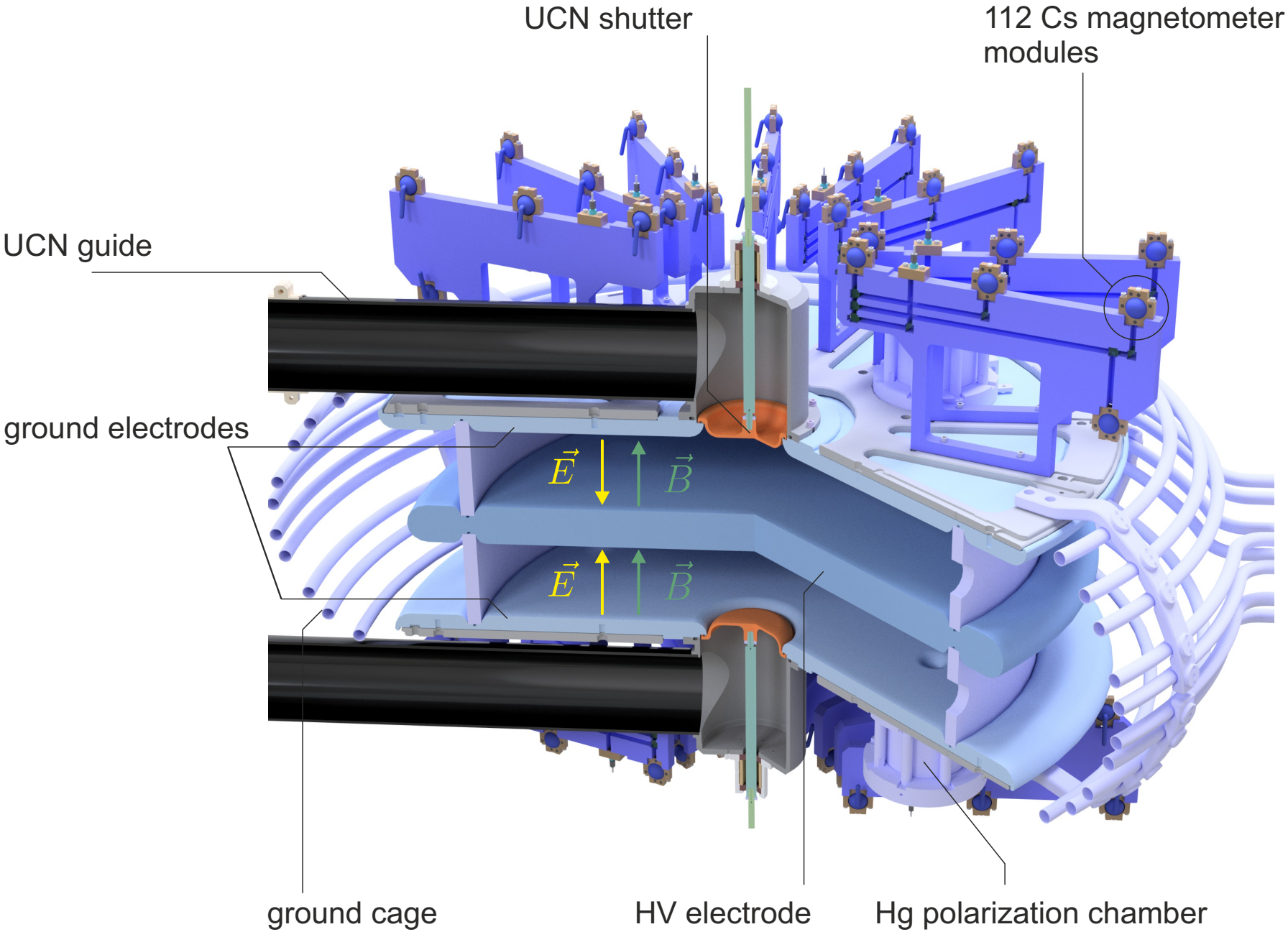
Cs magnetometer array

- field homogenization
- online gradient monitoring

Hg co-magnetometers

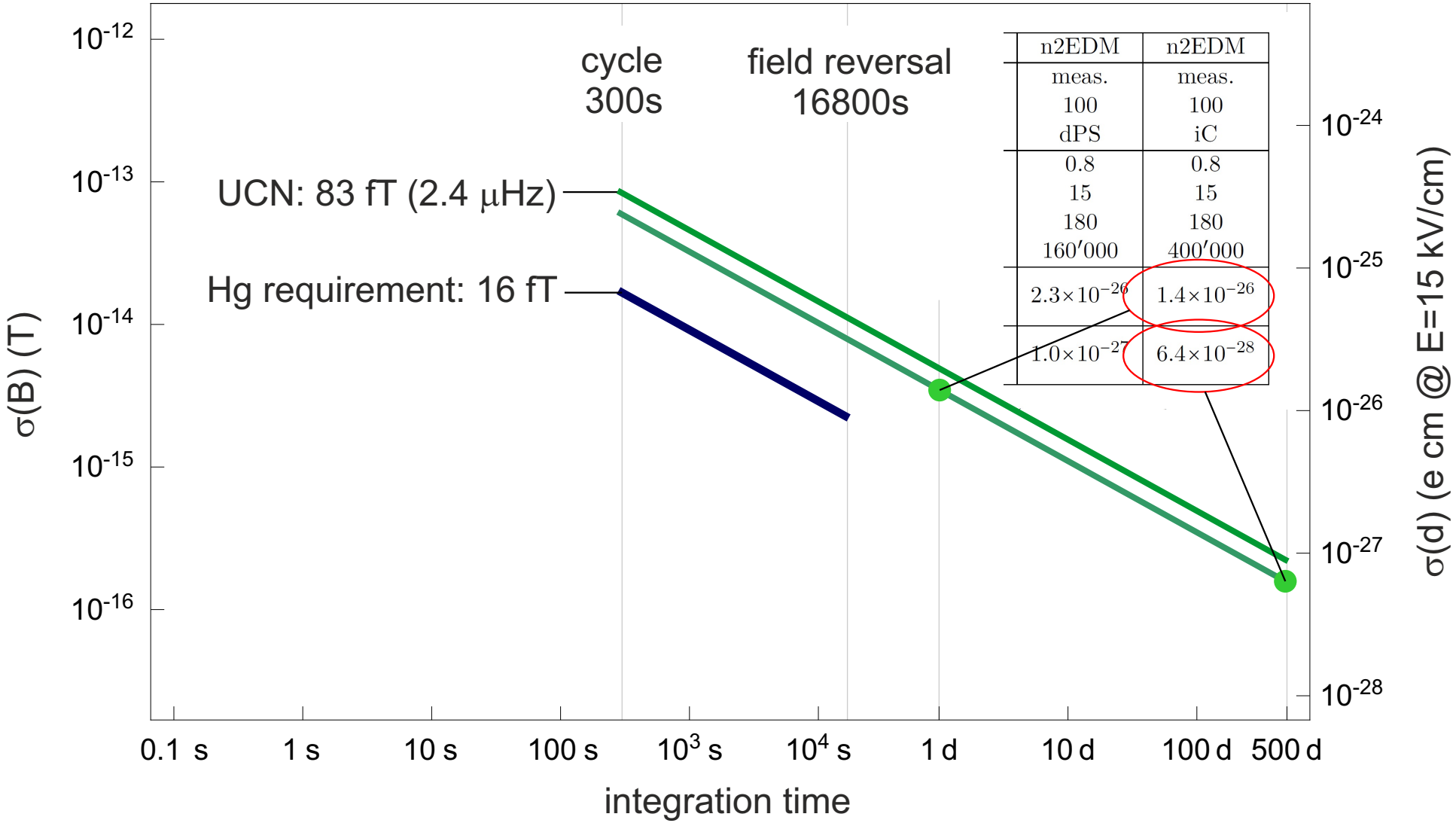
- primary magnetic correction
- online gradient monitoring

Experiment design



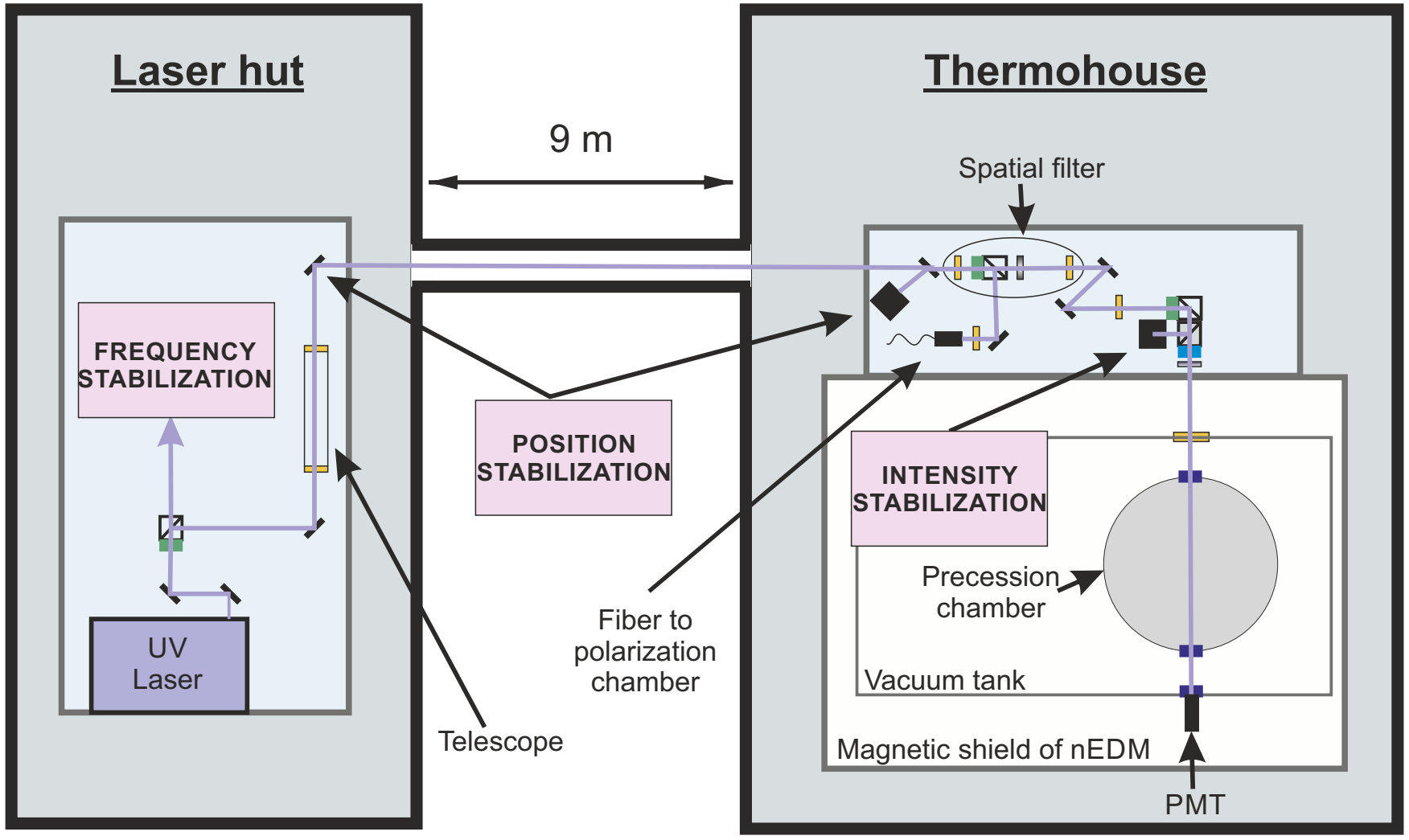
Magnetometer performance comparison

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

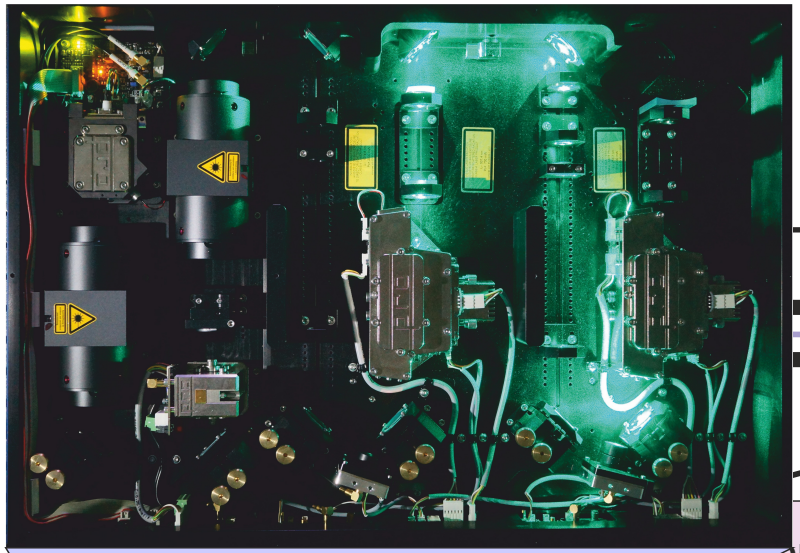


n2EDM	n2EDM
meas. 100 dPS	meas. 100 iC
0.8 15 180 160′000	0.8 15 180 400′000
2.3×10^{-26}	1.4×10^{-26}
1.0×10^{-27}	6.4×10^{-28}

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

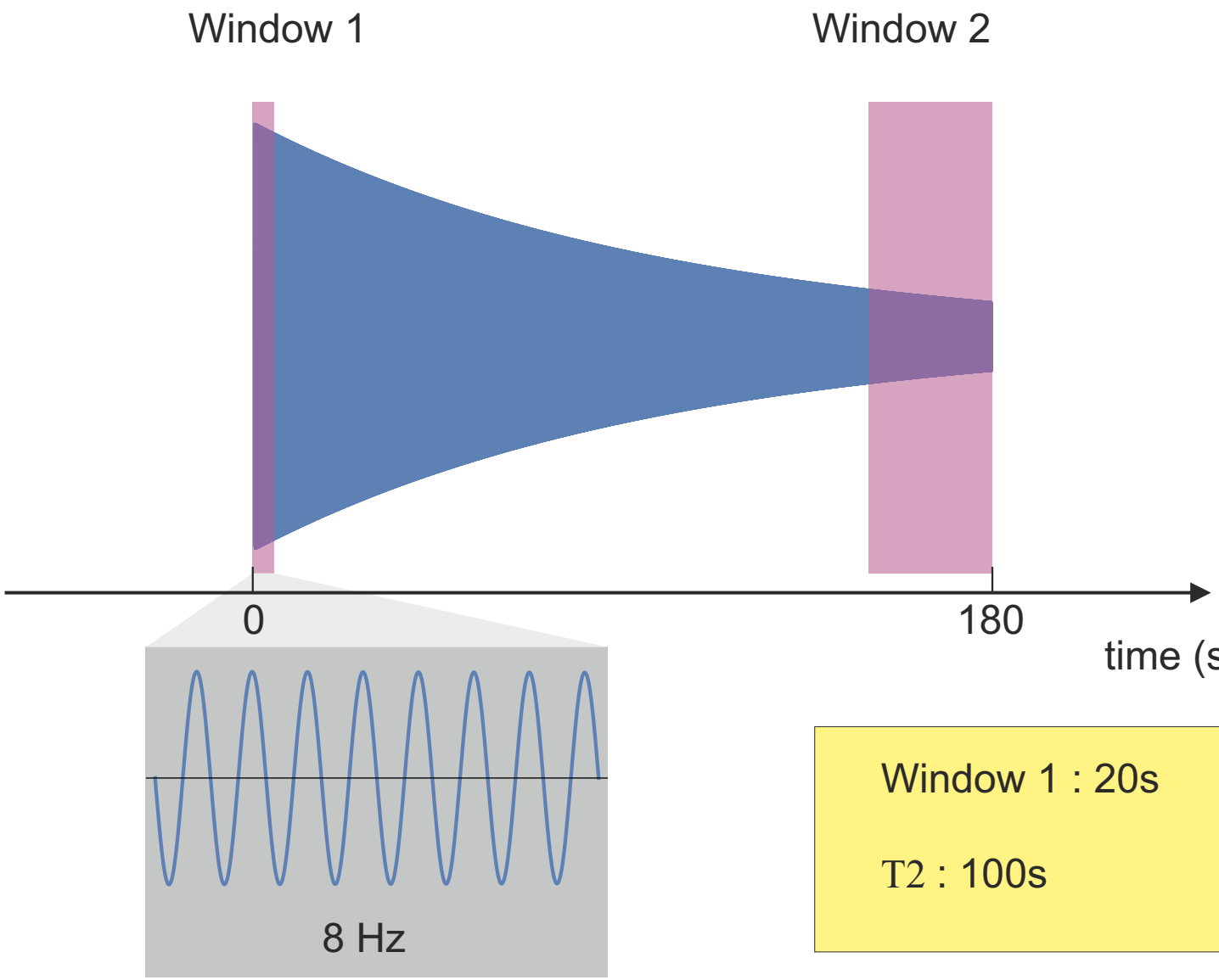
UV transmitting window

Photo detector

Mirror

almost shot-noise limited performance @ 8 Hz

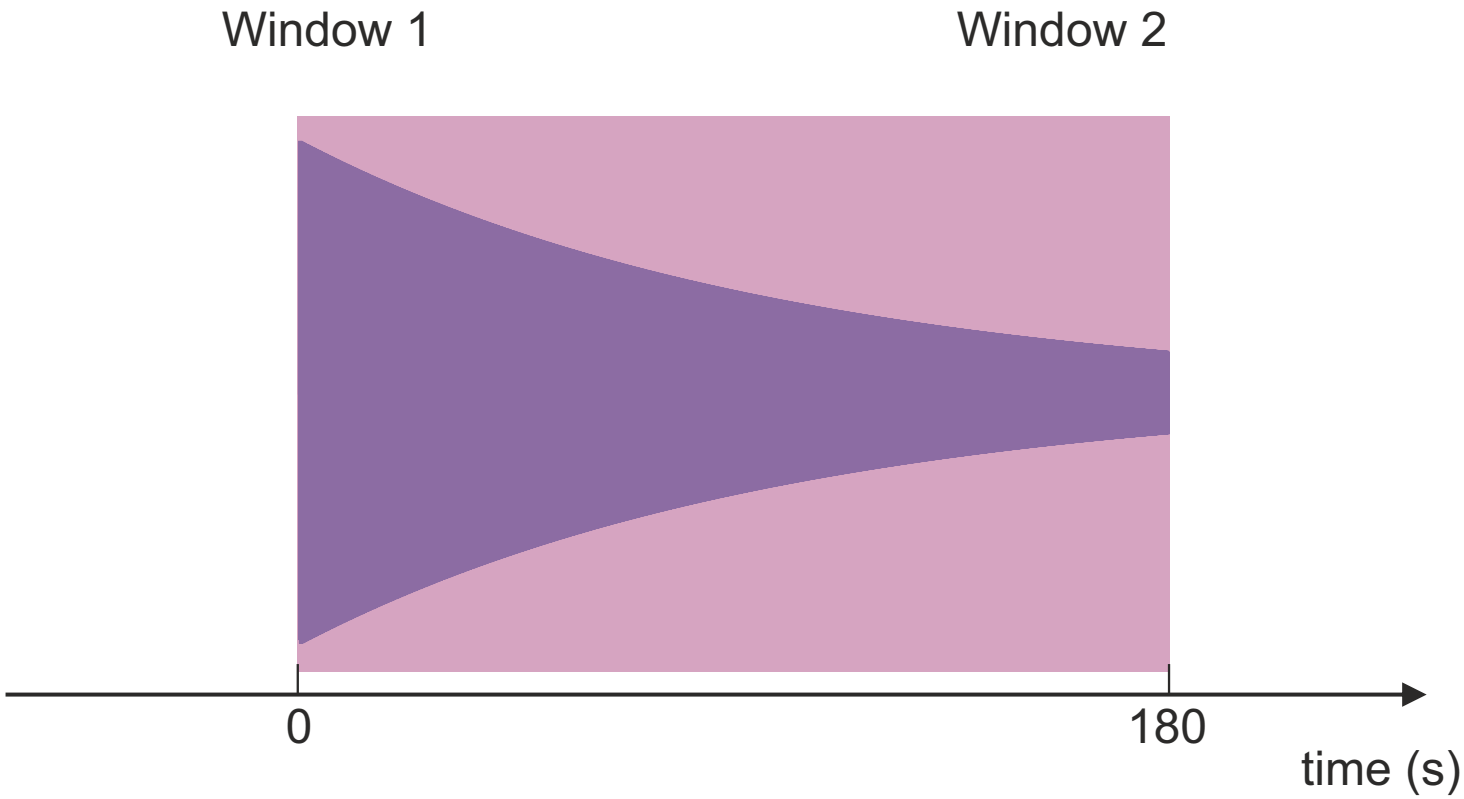
Hg Magnetometer Readout



Window 1 : 20s

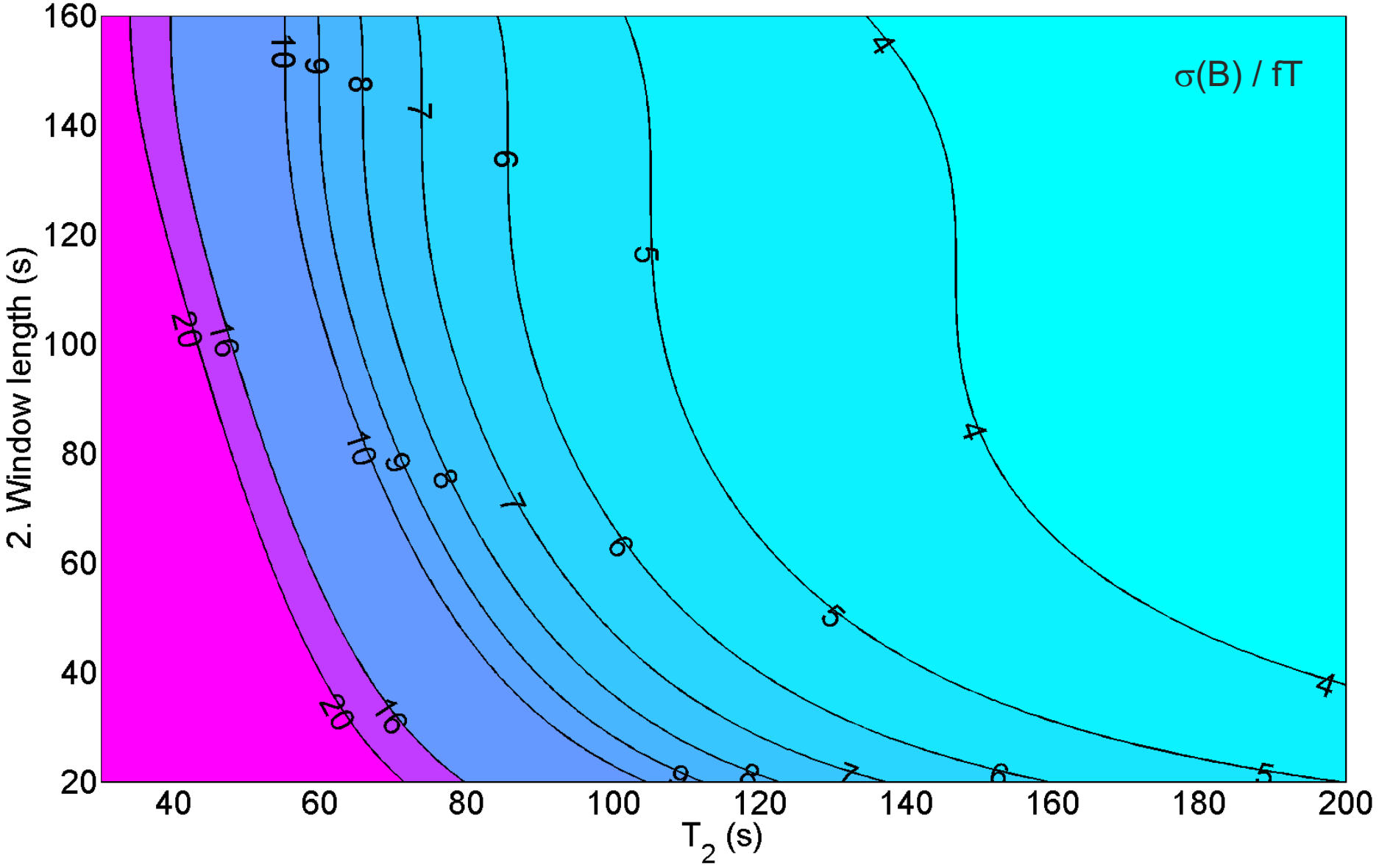
T2 : 100s

Hg Magnetometer Readout

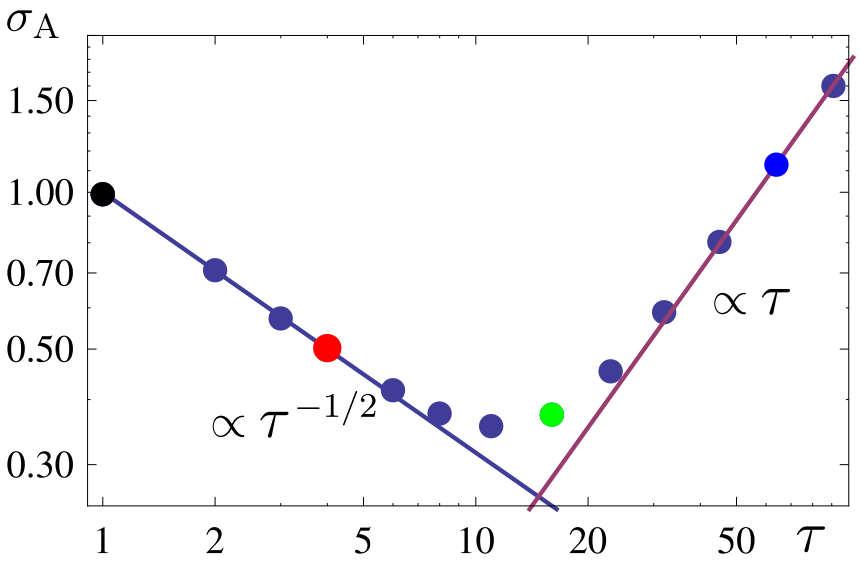


Window 1 : 20s
Window 2 : 160s
T2 : 100s

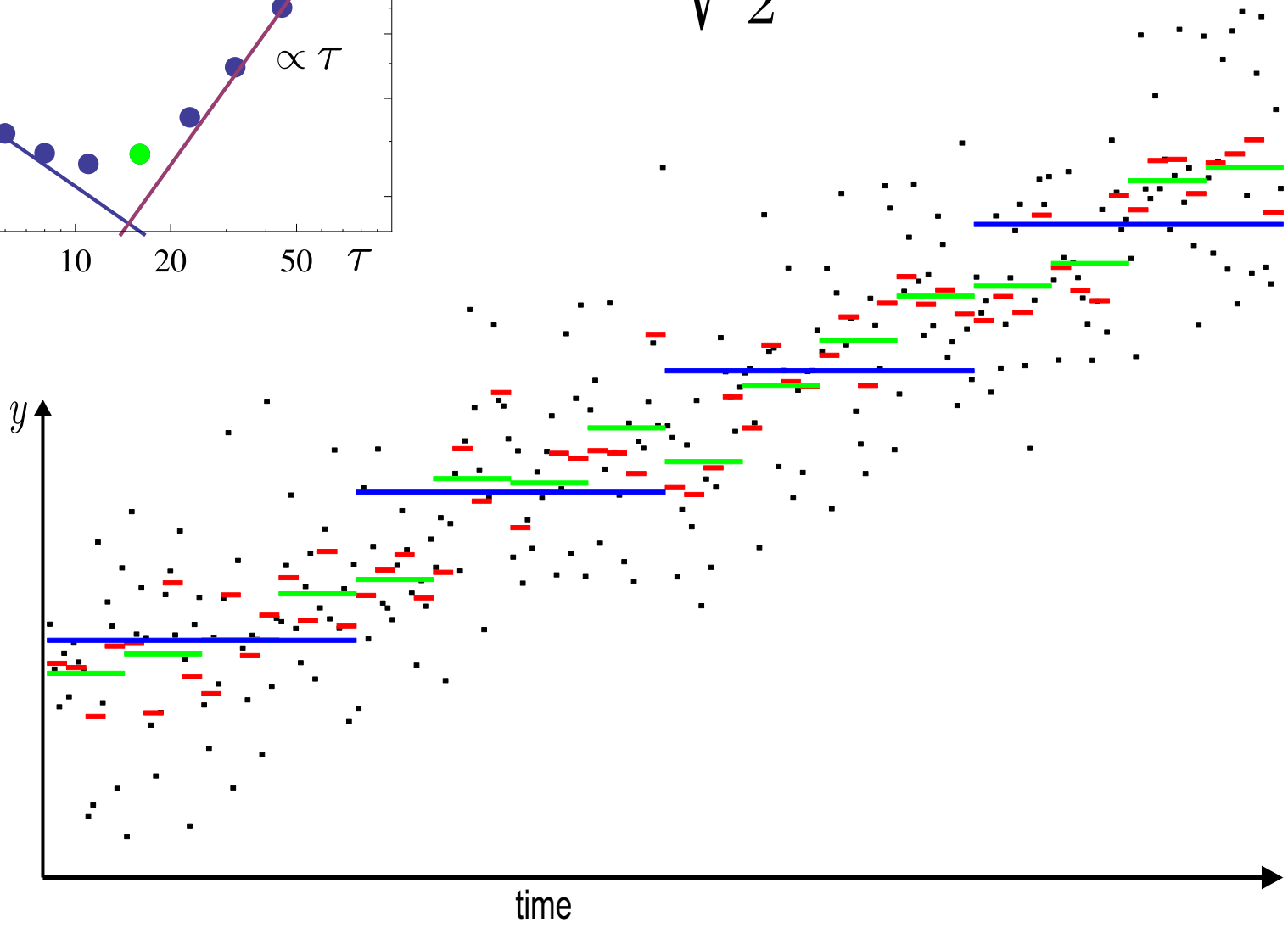
Statistical Magnetometer Performance



Allan Standard Deviation

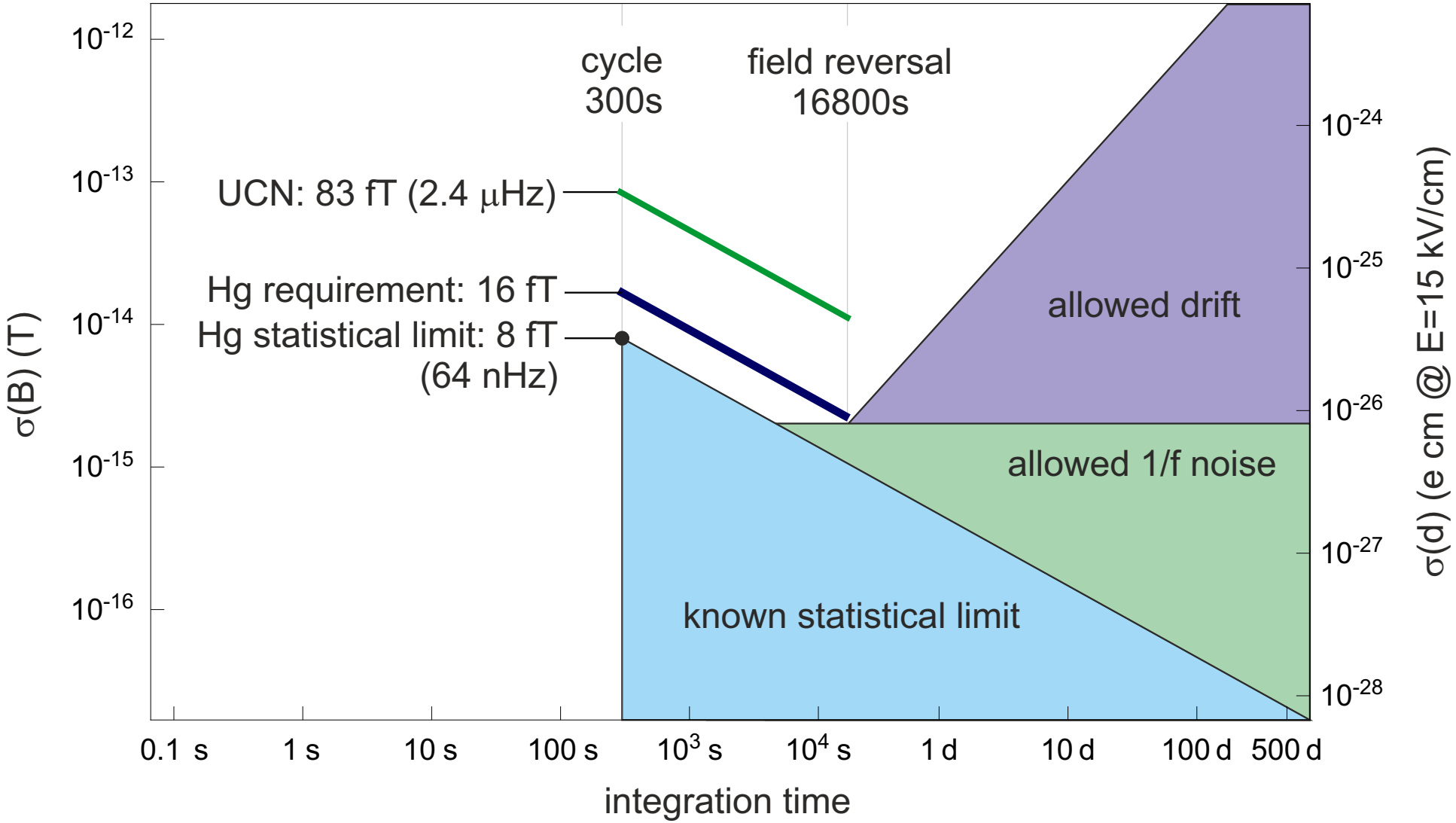


$$\sigma_A = \sqrt{\frac{1}{2}\left\langle (y_{n+1} - y_n)^2 \right\rangle}$$



Statistical magnetometer performance

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



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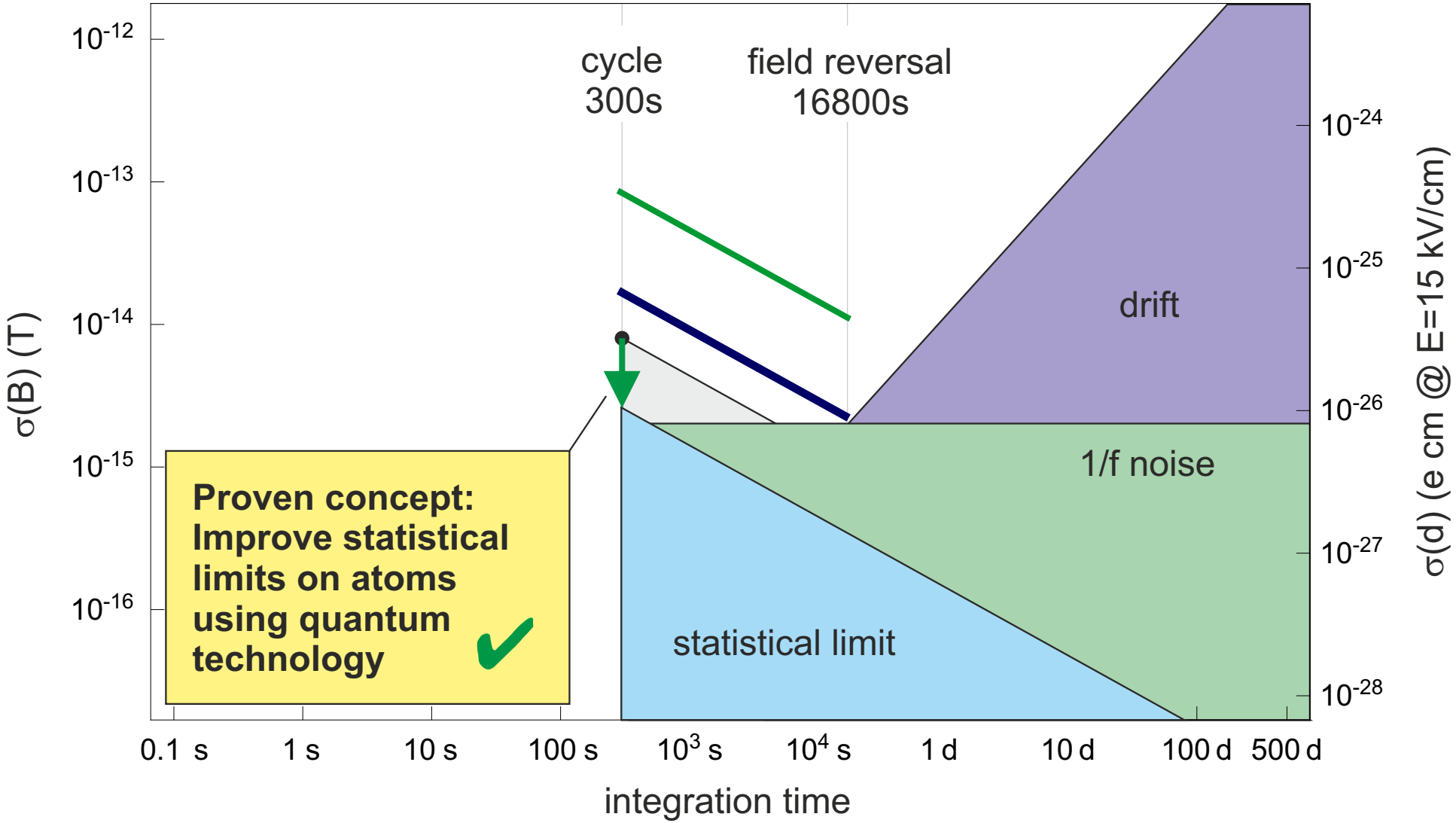

Statistical magnetometer performance

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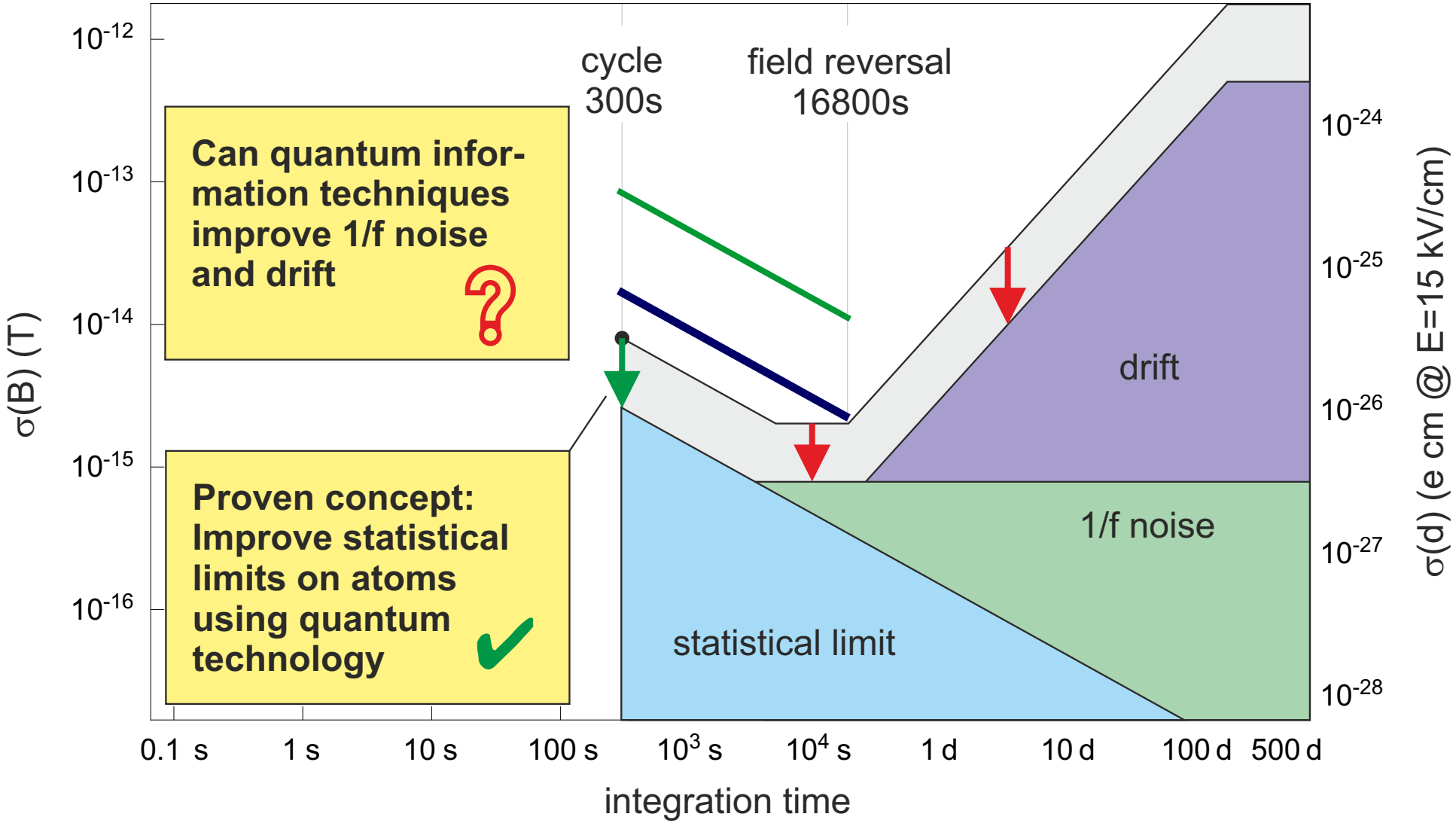
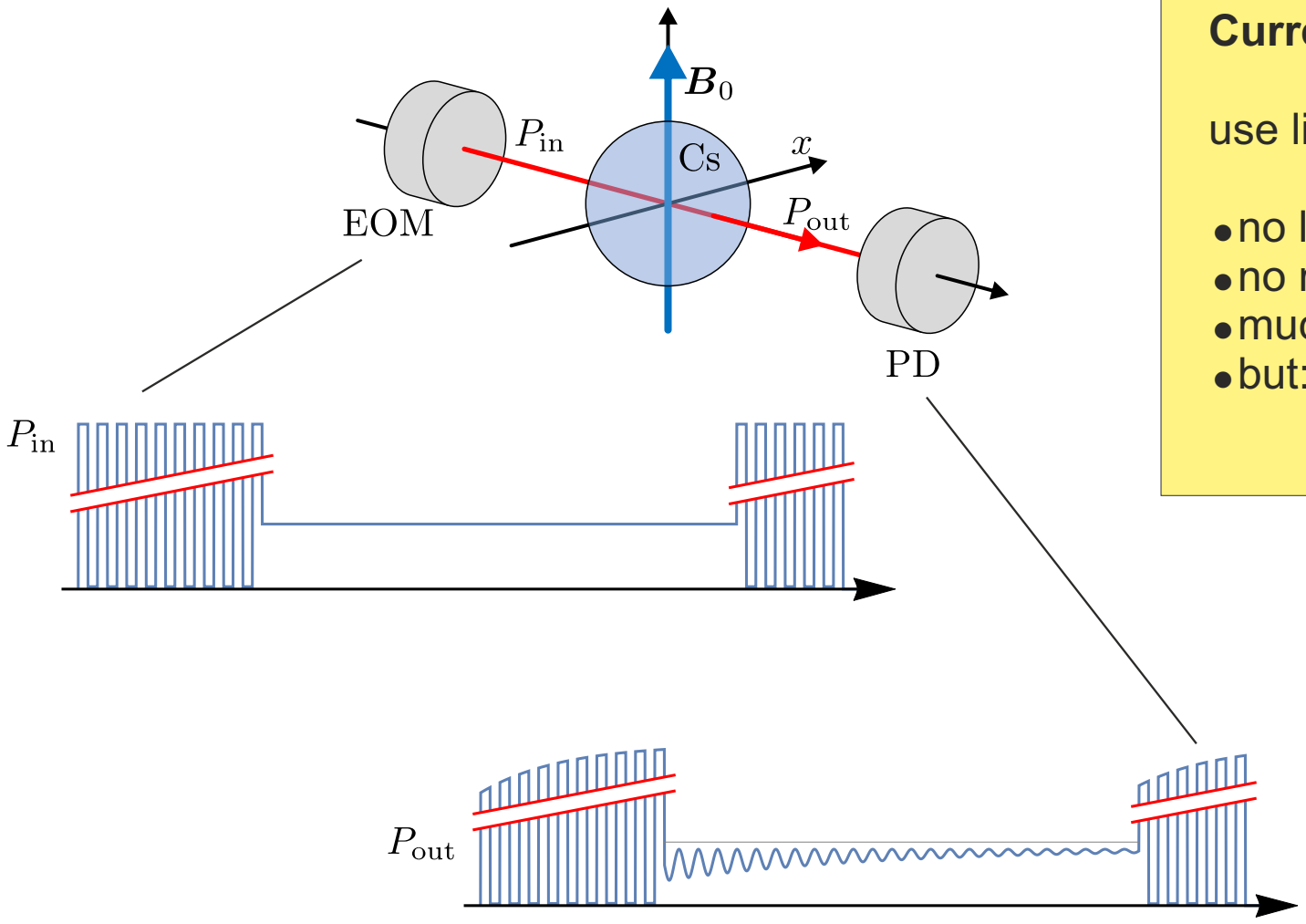


All optical Cs Magnetometer



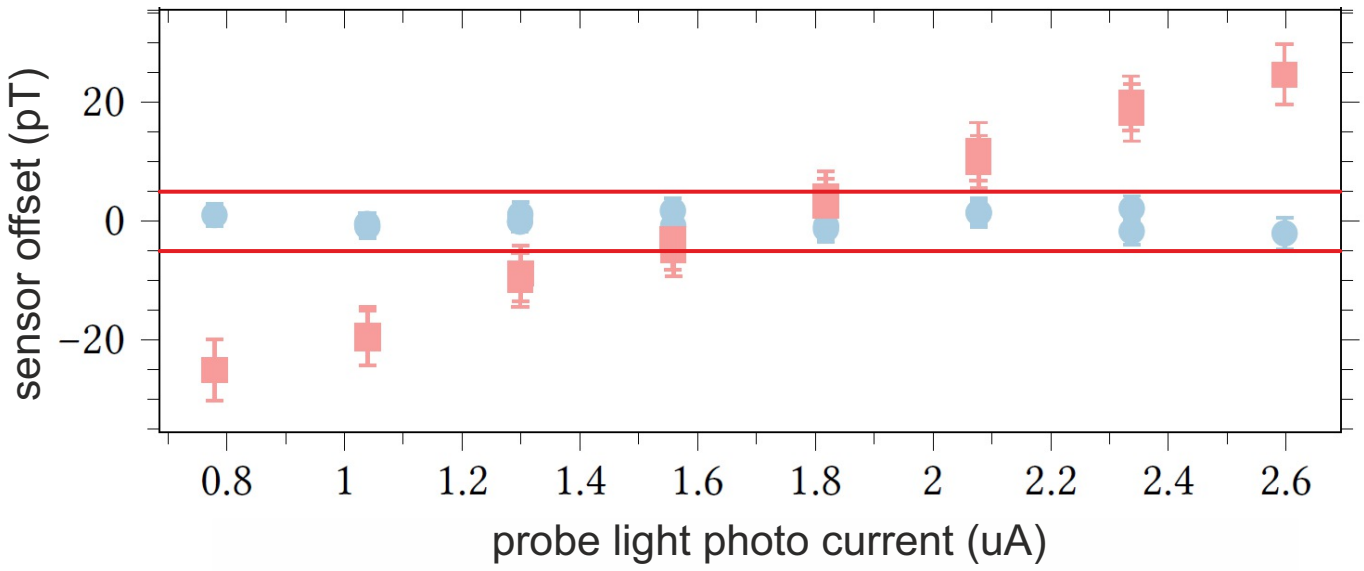
Current R & D:

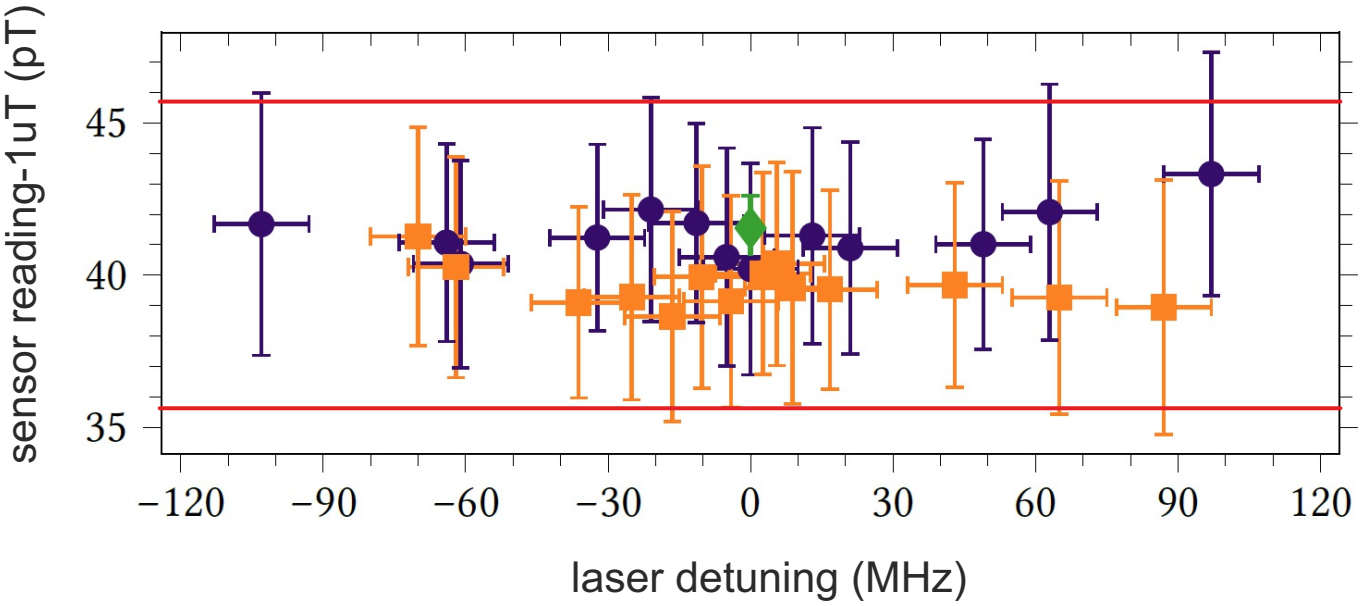
use linear polarized light

- no light shift
- no magnetic cross-talk
- much less offset effect
- but: less sensitive

A sensitive and accurate atomic magnetometer based on free spin precession.
Z. D. Grujic, P. A. Koss, G. B., and A. Weis. Eur. Phys. J. D, 69(5), 2015.

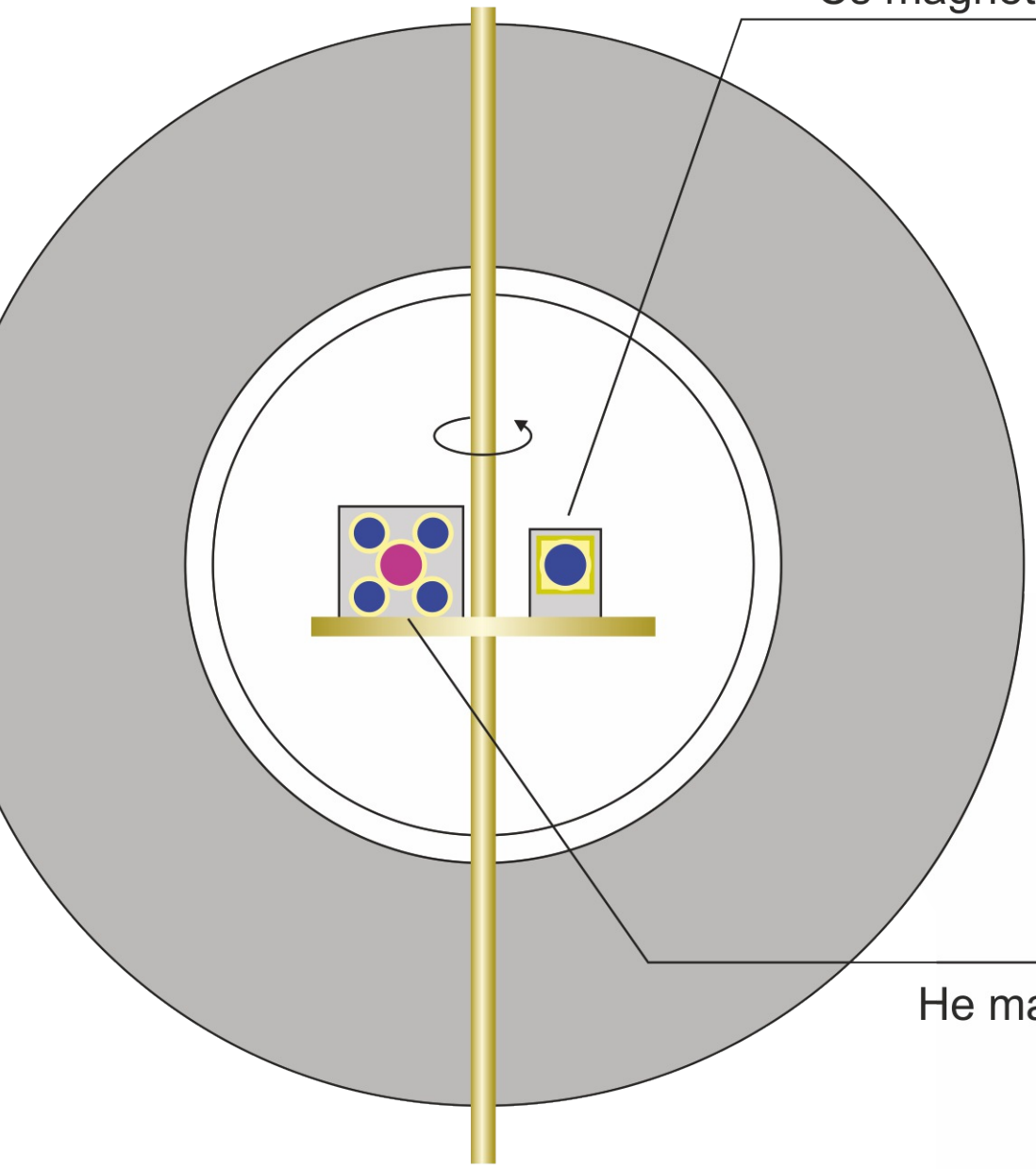
All optical Cs Magnetometer

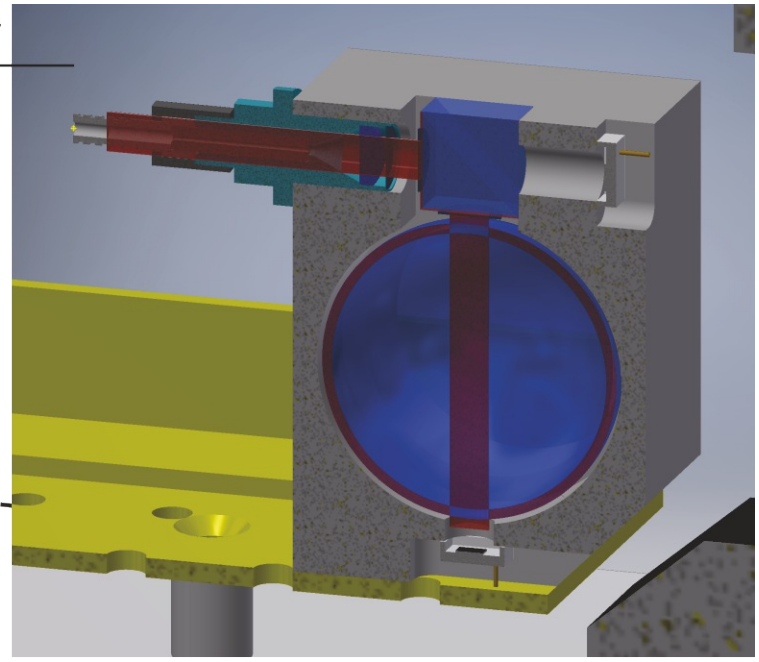


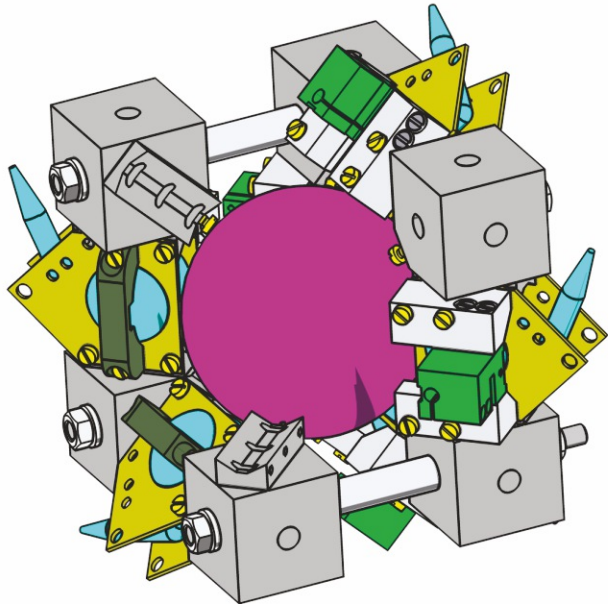


PhD thesis Duarte Pais, Development of the caesium magnetometer array for the n2EDM experiment, ETH Zürich 2021

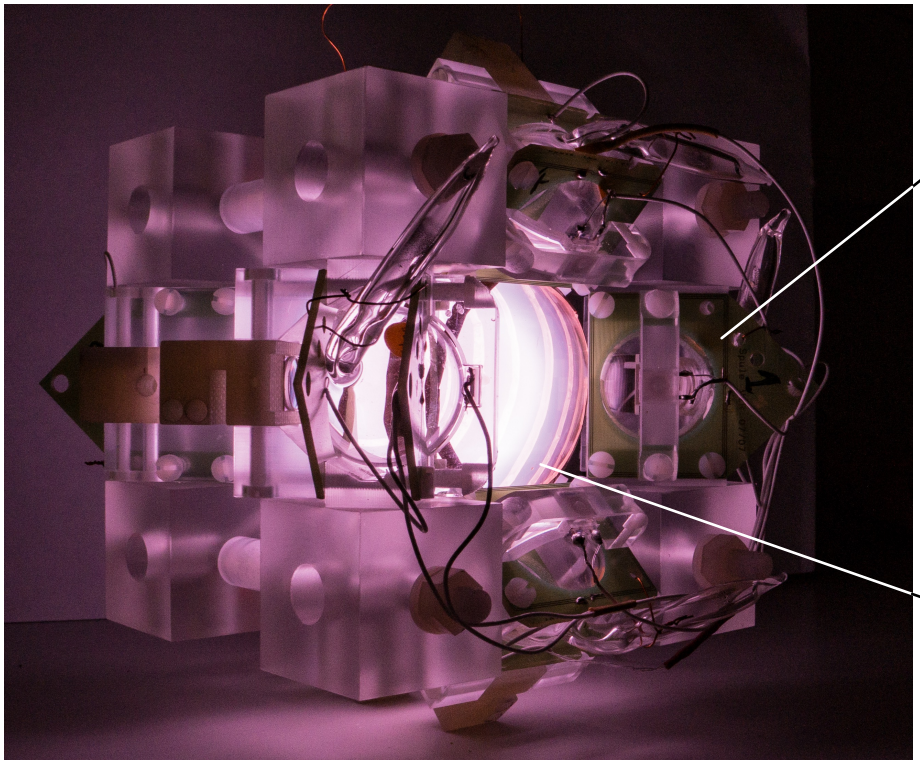
Cs magnetometer calibration

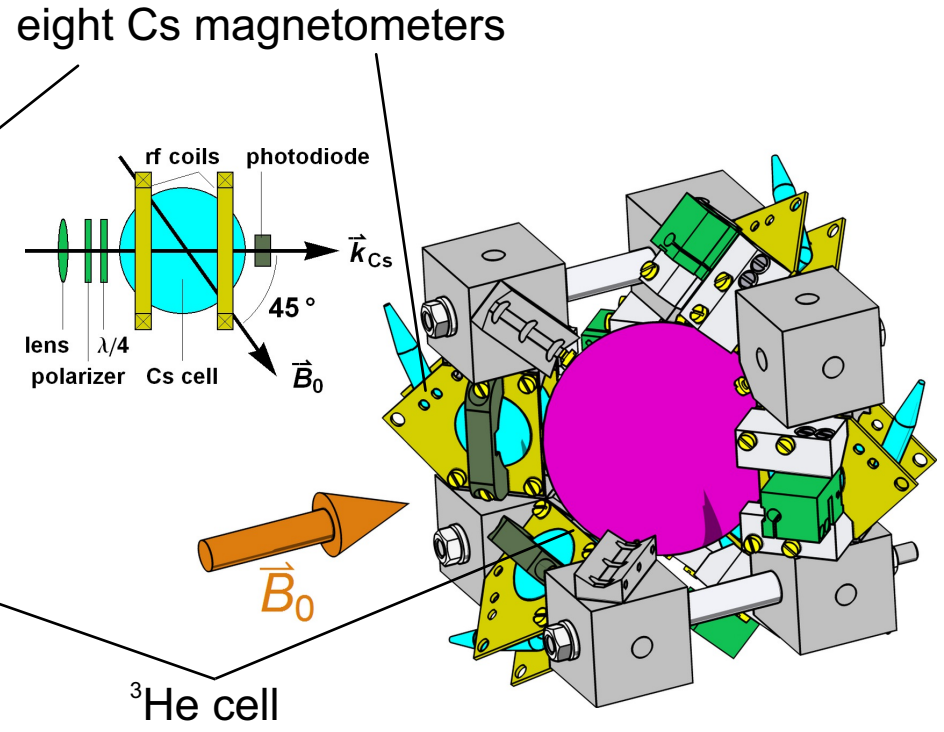






He Magnetometer



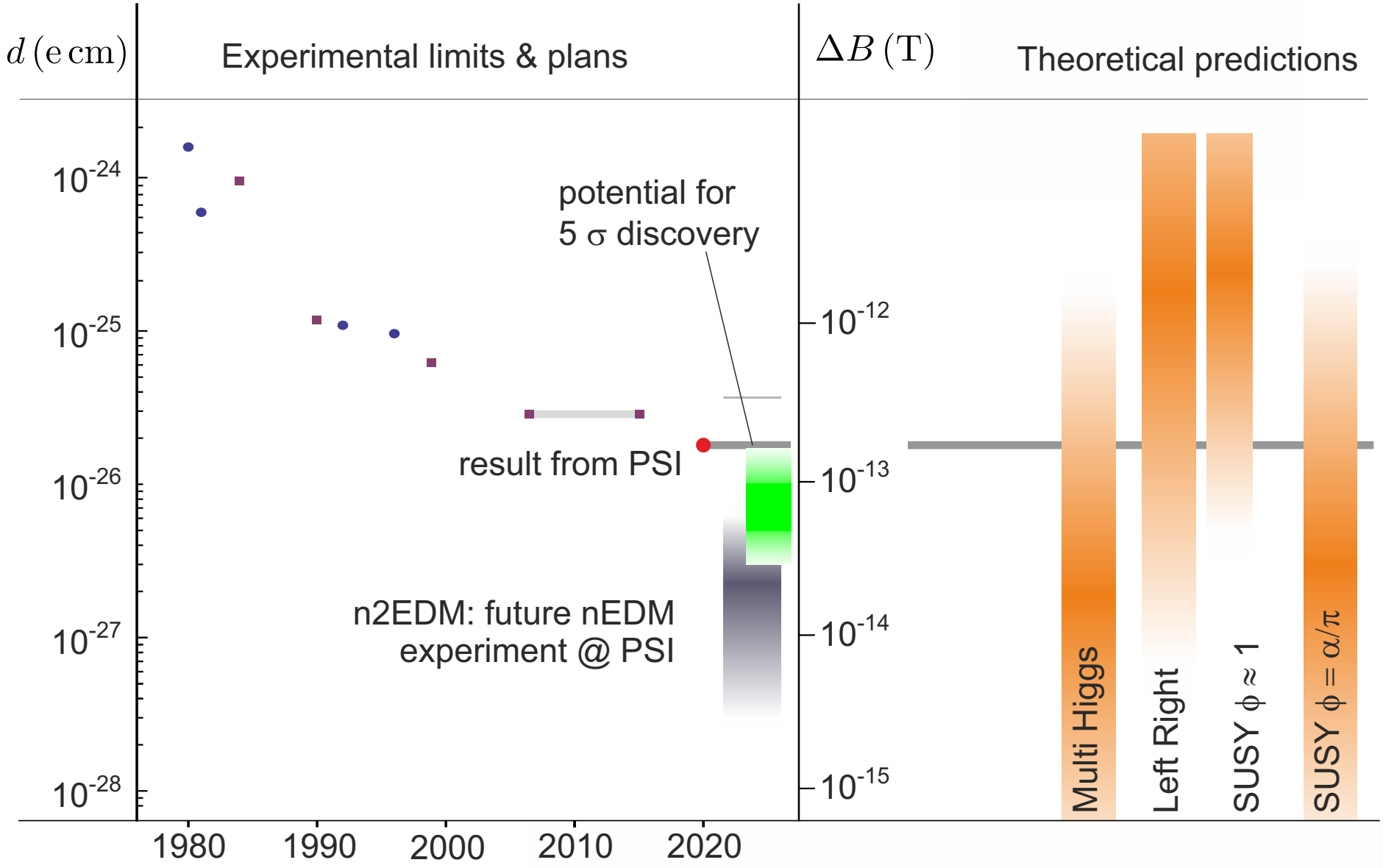


metastable exchange optical pumping

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)

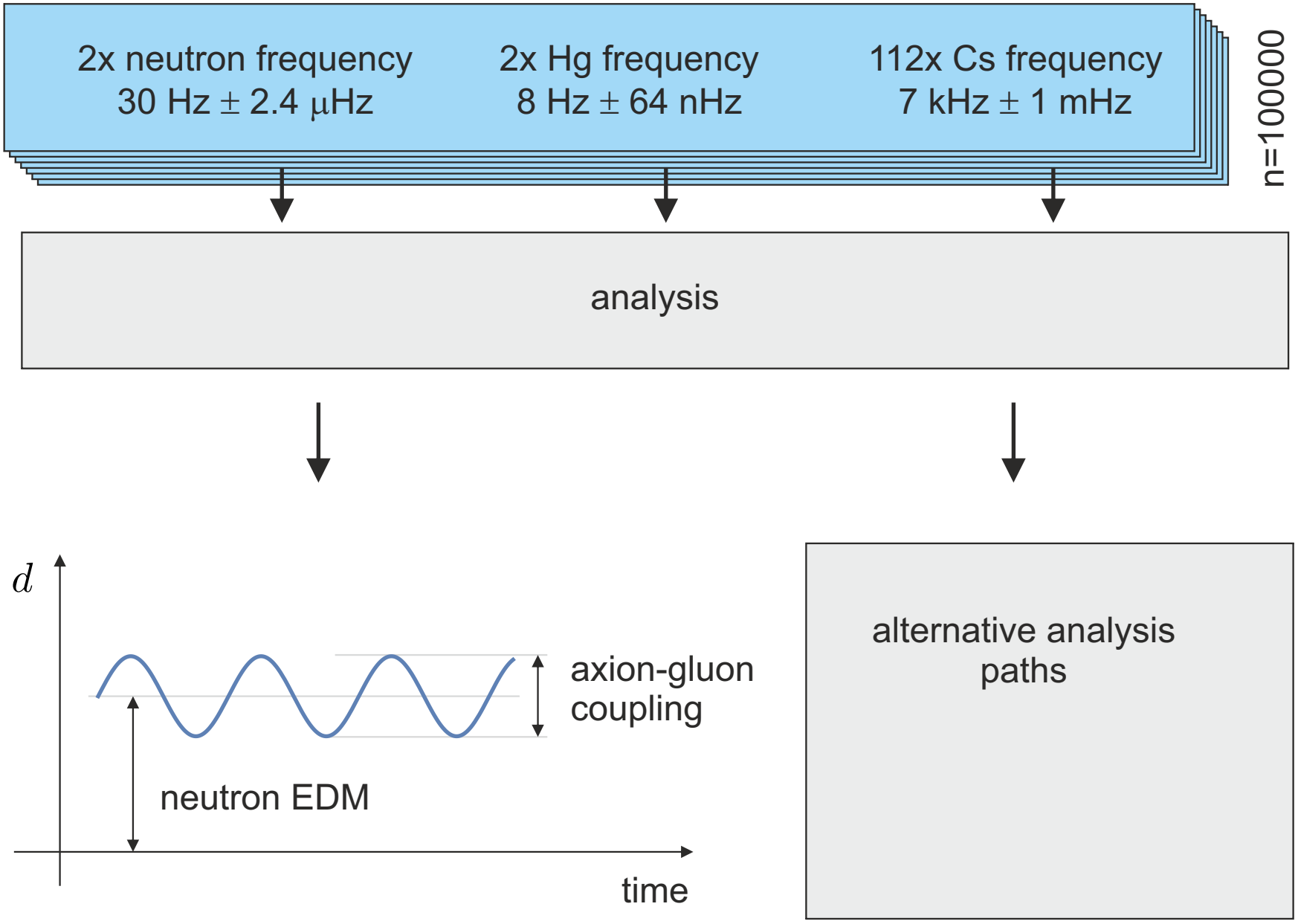
Investigation of the intrinsic sensitivity of a ^{3}He/Cs magnetometer. H.-C. Koch, G. Bison, Z. D. Grujić, W. Heil, M. Kasprzak, P. Knowles, A. Kraft, A. Pazgalev, A. Schnabel, J. Voigt, A. Weis Eur. Phys. J. D 69: 262 (2015).

Outlook for our n2EDM



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

He Magnetometer



The nEDM collaboration

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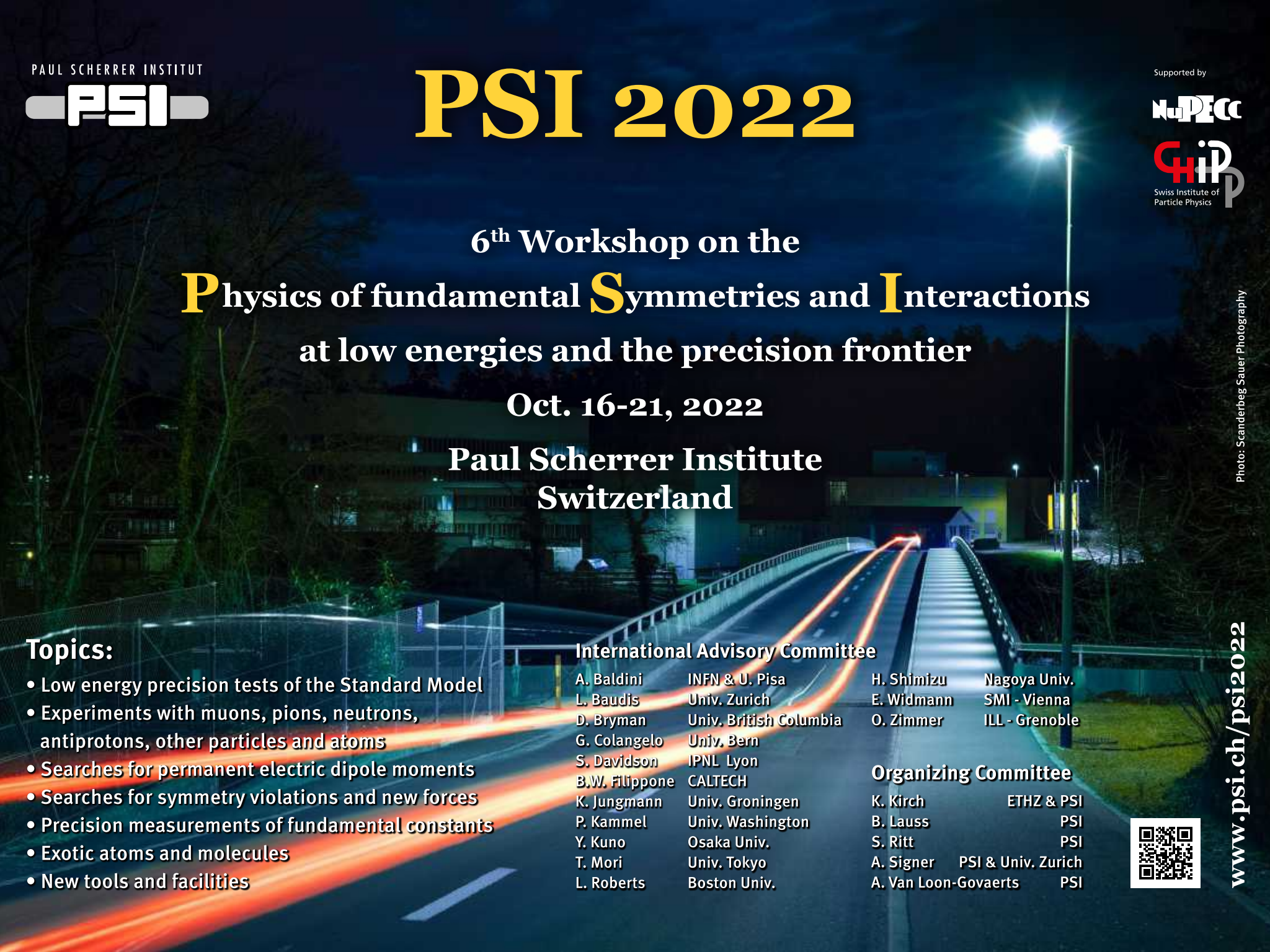

Photo: Scanderbeg Sauer Photography

Topics:

- Low energy precision tests of the Standard Model
- Experiments with muons, pions, neutrons, antiprotons, other particles and atoms
- Searches for permanent electric dipole moments
- Searches for symmetry violations and new forces
- Precision measurements of fundamental constants
- Exotic atoms and molecules
- New tools and facilities

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