neutron EDM and Axions

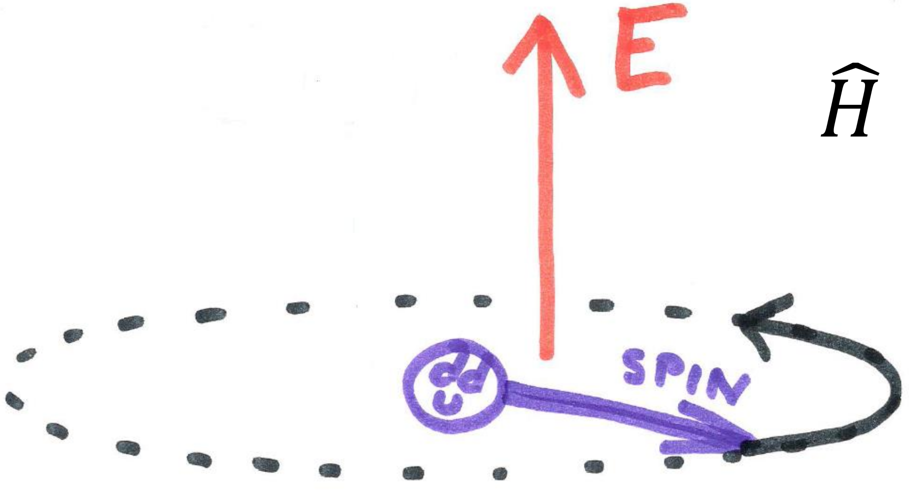
G. Ban and G. Pignol,
On behalf of the nEDM collaboration
AXION QUEST Quy Nhon 2024

Outline

1. Physics case for searching EDMs
2. How to measure nEDM: state of the art
3. n2EDM
4. Search for ALPs with the neutron EDM apparatus
5. Conclusion

EDM = coupling between spin and E-field

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



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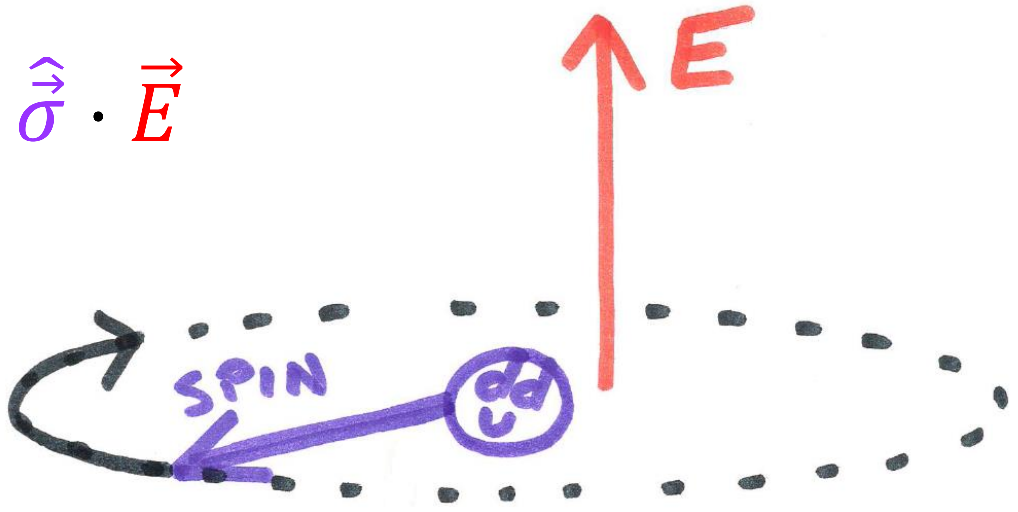


<< REWIND <<

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

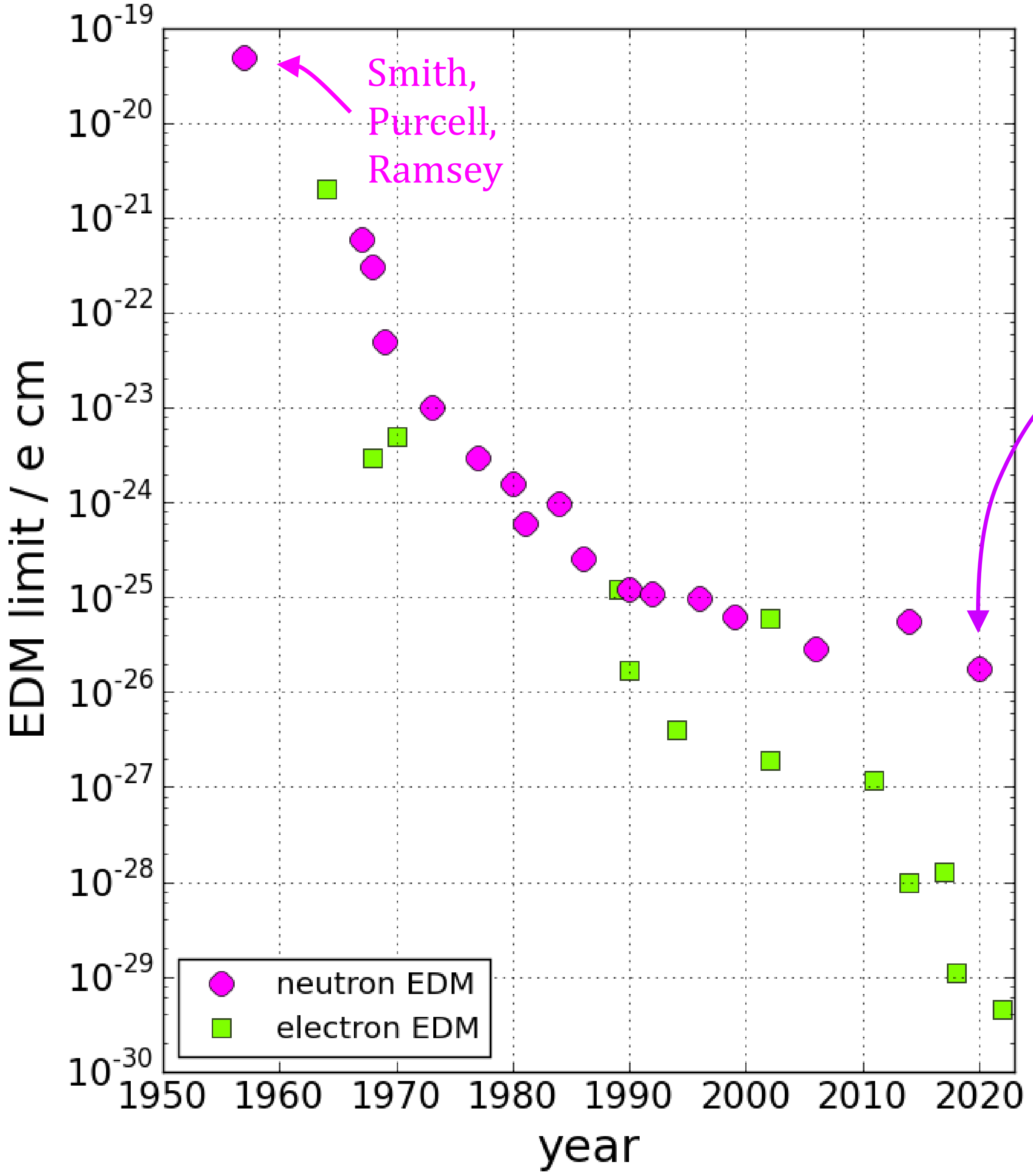
Violation of T CPT **Violation of CP**

Baryon asymmetry

Observed:
$n_B - \mathbf{n_B} / n_\gamma = 6 \times 10^{-10}$

SM expectation:
$n_B - \mathbf{n_B} / n_\gamma \sim 10^{-18}$

EDM limits



Best limit from the nEDM experiment @PSI

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

Abel et al, PRL (2020)

Nuclear magneton

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

In natural units $|d_n| < 2 \times 10^{-12} \times \mu_N/c$

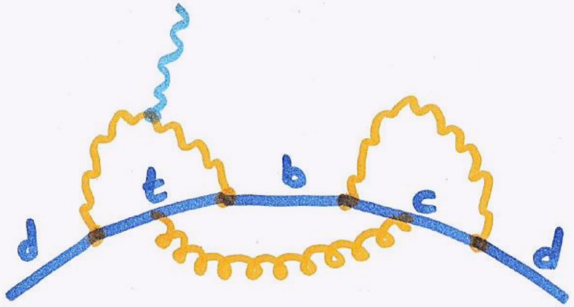
In comparison $\mu_n = -1.9130427(5)\ \mu_N$

The neutron EDM is quasi-forbidden

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

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 neutron EDM is quasi-forbidden
For known reason (CKM)
And unknown reason (strong CP)

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 : $d_n \sim -0.02 \times \bar{\theta}\,\mu_N/c$

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

Strong CP problem

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 »

Some theories could explain why the strong interaction conserves CP

Massless quarks..
Spontaneous CP breaking…
Axion

→Peccei Quinn … θ → axion Field → θ cancellation = no CPV
→axion DM → Oscillating EDM

Following part by Guillaume Pignol

CP violation and EDM in the SMEFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

$$\mathcal{L}_{\mathrm{D=6}} = \sum_{a=1}^{3045} \frac{c_a}{\Lambda^2} O_a^{(6)}$$

New physics at high scale would generate these new interactions, many of which are CP-violating and contribute to create EDMs.

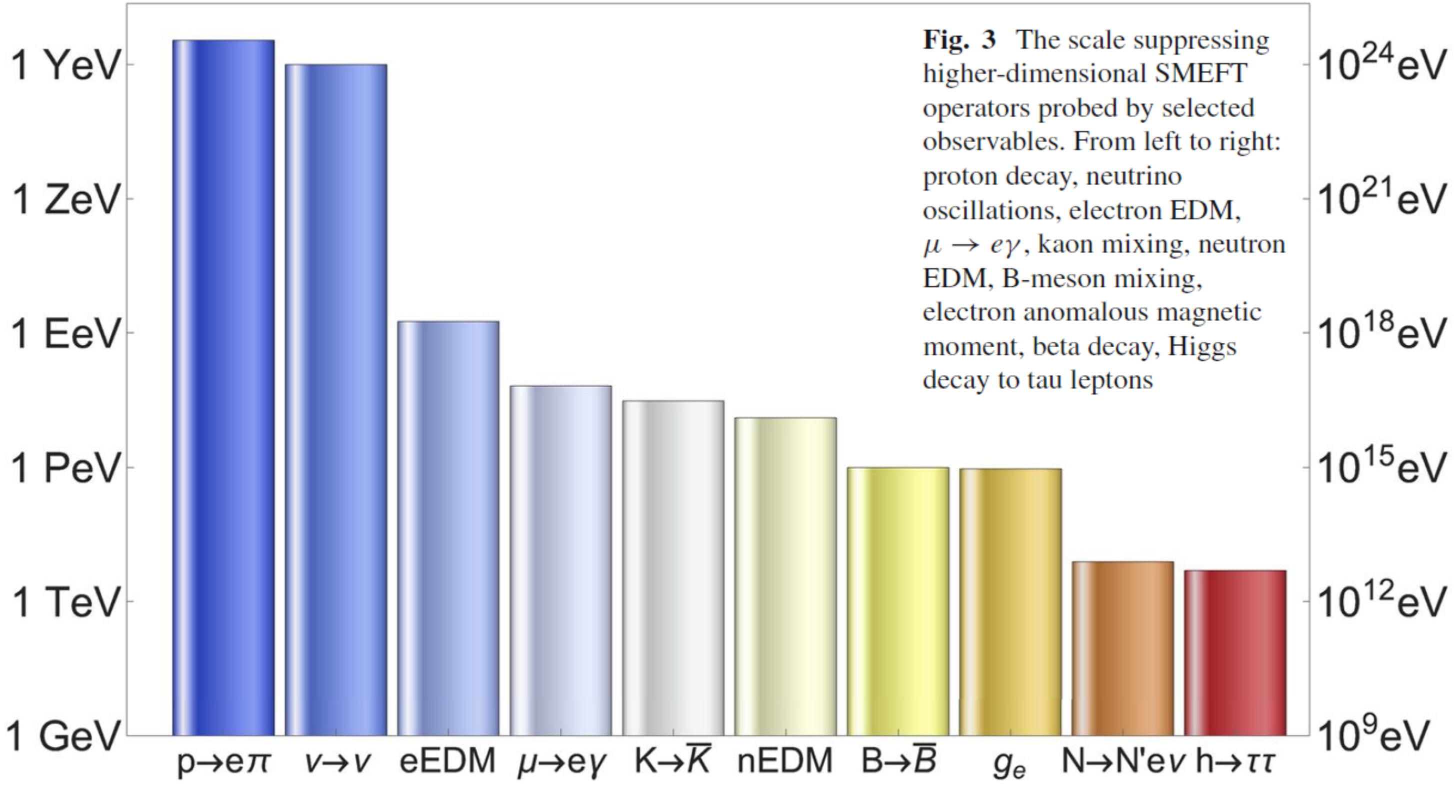


Fig. 3 The scale suppressing higher-dimensional SMEFT operators probed by selected observables. From left to right: proton decay, neutrino oscillations, electron EDM, $\mu \to e\gamma$, kaon mixing, neutron EDM, B-meson mixing, electron anomalous magnetic moment, beta decay, Higgs decay to tau leptons

Figure A. Falkowski, ***Lectures on SMEFT*** EPJC (2023)

nEDM probes $\Lambda = 10$ PeV

Physics case to search for nEDM

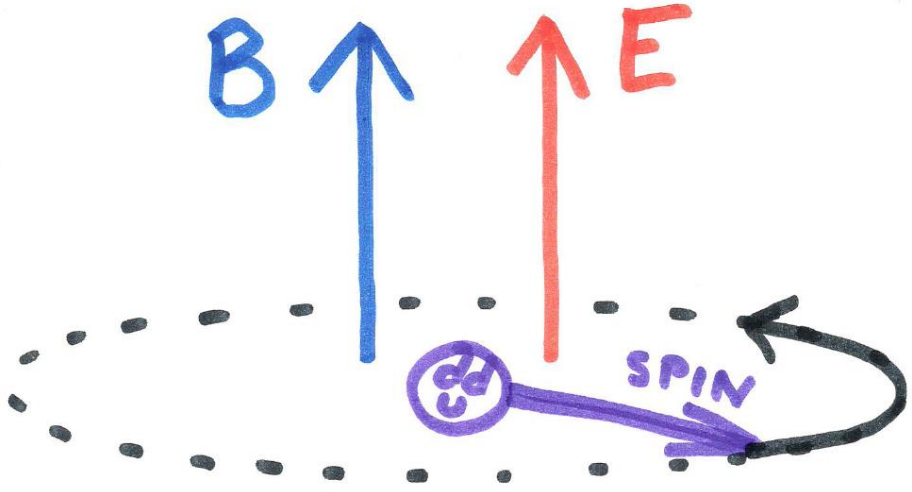
1. **Great puzzle with Great Sensitivity**.
   New sources of CPV required to explain baryogenesis (Sakarov).
   A broad class of models "BSM electroweak baryogenesis" predict
   new CPV physics at the ~TeV scale probes new CPV physics at the scale $\Lambda = 10$ PeV.
   Next generation experiments will increase the reach by $\sqrt{10}$.
   Note: some concrete models predict $\frac{1}{\Lambda^2} \sim \frac{g^2}{(4\pi)^2} \frac{y_q}{M^2}$ $M \sim 1$ TeV $\leftrightarrow$ $\Lambda \sim 10$ PeV

2. **Complementarity**.
   Importance of measuring the EDMs in different systems
   (neutron, atoms, muons…) to cover the many different possible fundamental sources of CP violation.

3. **So far EDMs ~ ZERO → Strong CP problem**

Axions will clean up the problem of such a small θ in $d_n \sim -0.02 \times \bar{\theta}\, \mu_N/c$

Basics of nEDM measurement



Larmor frequency

$\sim 30\ \mathrm{Hz}\ @\ B = 1\ \mu\mathrm{T}$

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

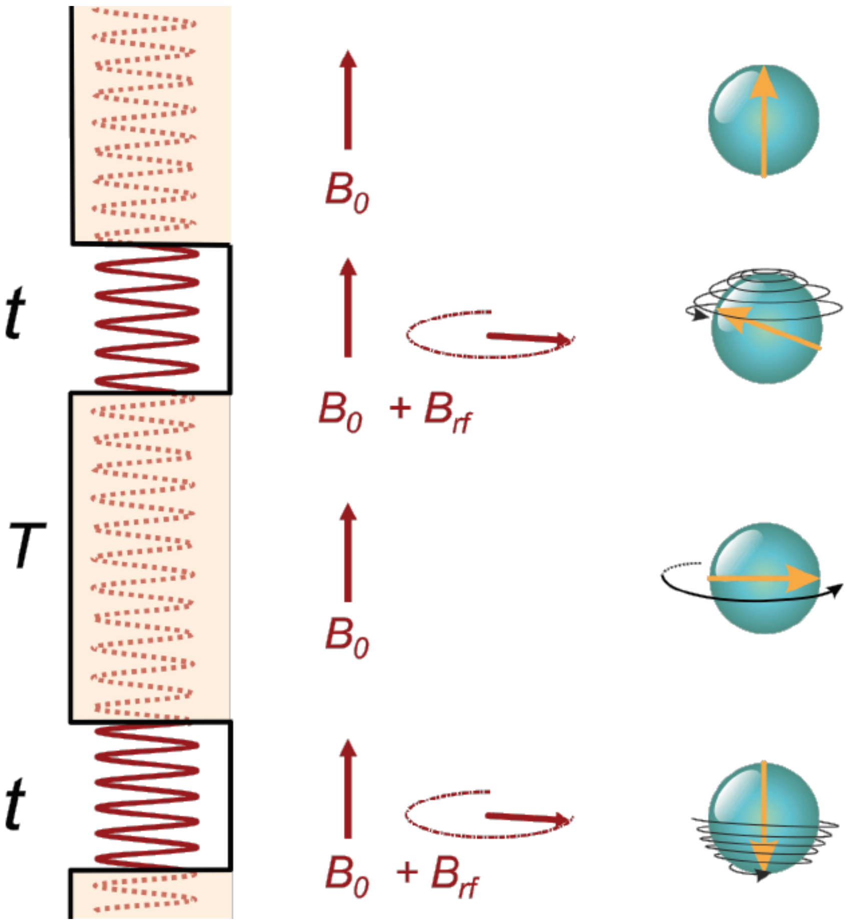
If $d_n \sim 10^{-26}\ e\ \mathrm{cm}$ and $E \sim 10\ \mathrm{kV/cm}$

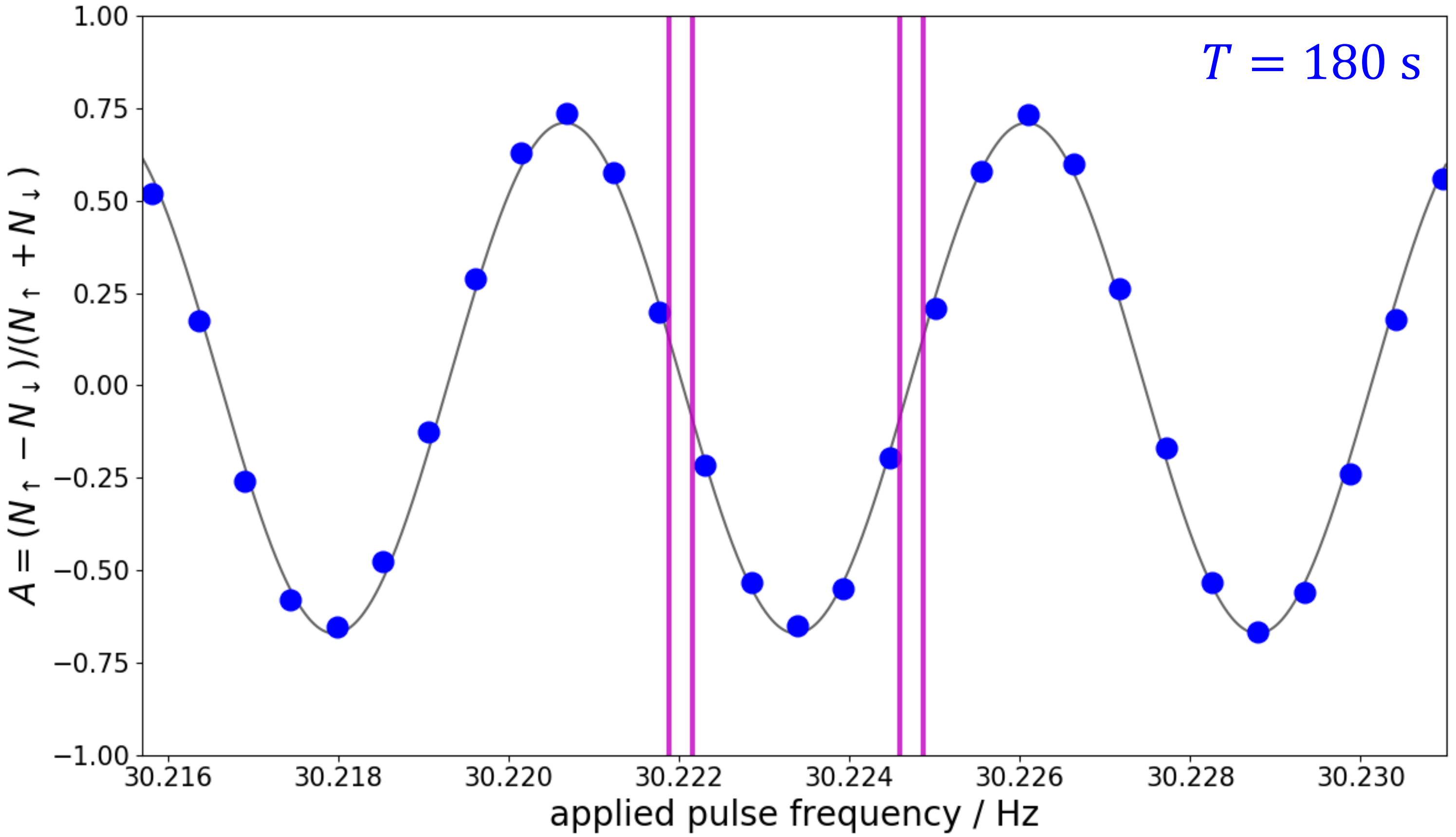
duration of one full turn $\sim$ 1 year

To detect such a minuscule coupling:

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

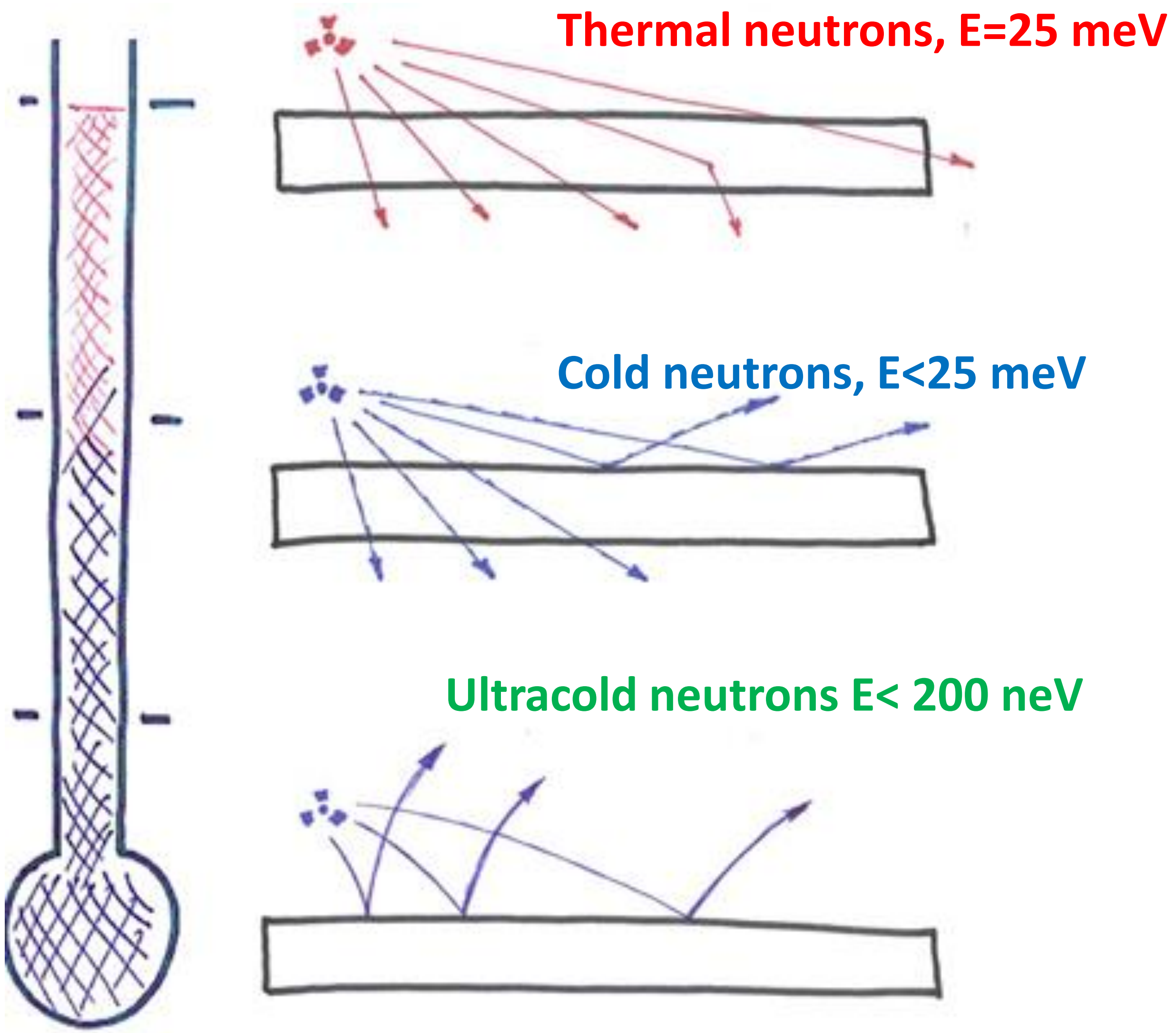
Ramsey's method to measure precession frequency





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

Ultracold neutrons



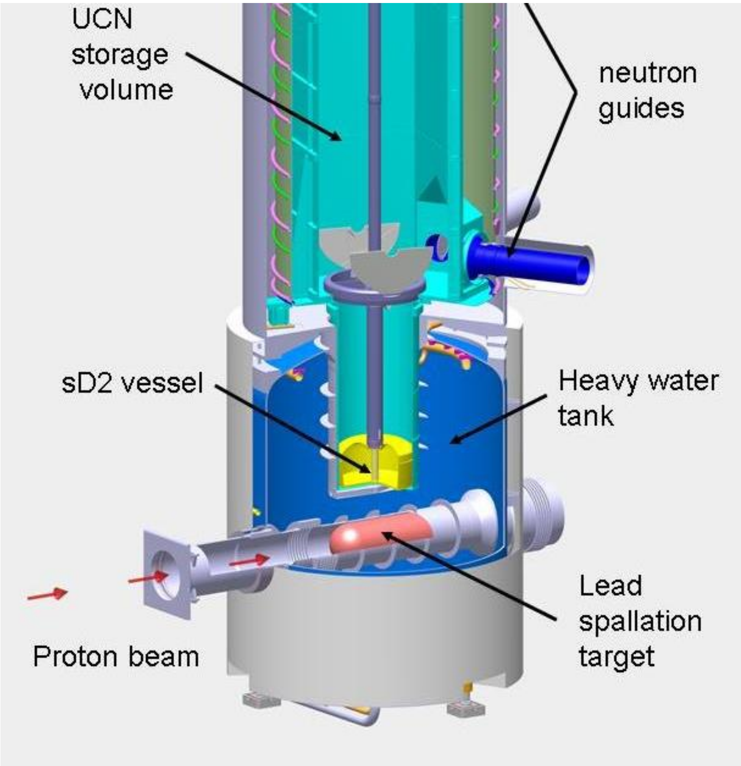
Thermal neutrons, E=25 meV

Cold neutrons, E<25 meV

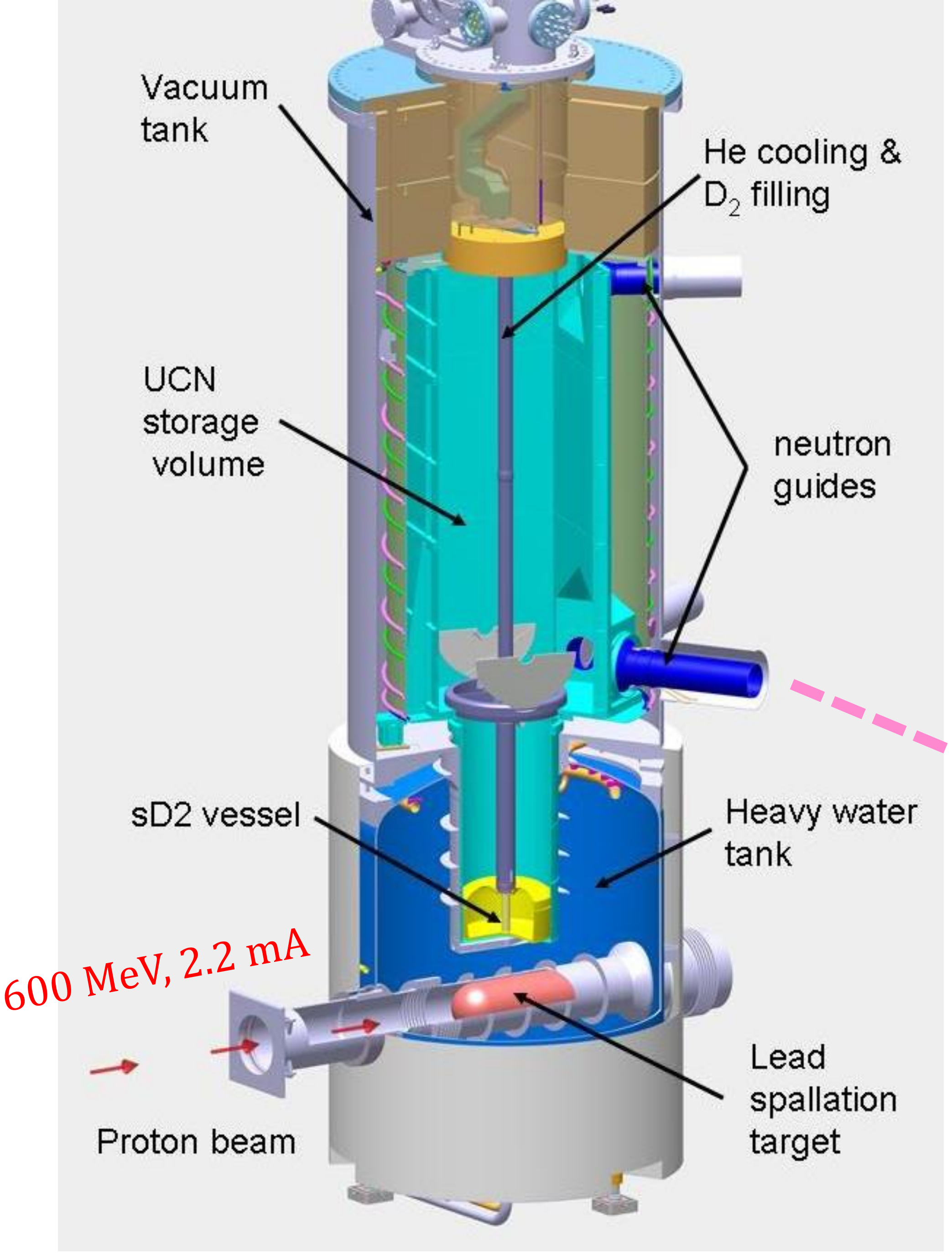
Ultracold neutrons E< 200 neV

To produce UCNs:
convert thermal/cold neutrons to UCNs

- in <u>solid deuterium (PSI</u>, Los Alamos)
- or superfluid helium (TRIUMF, ILL).

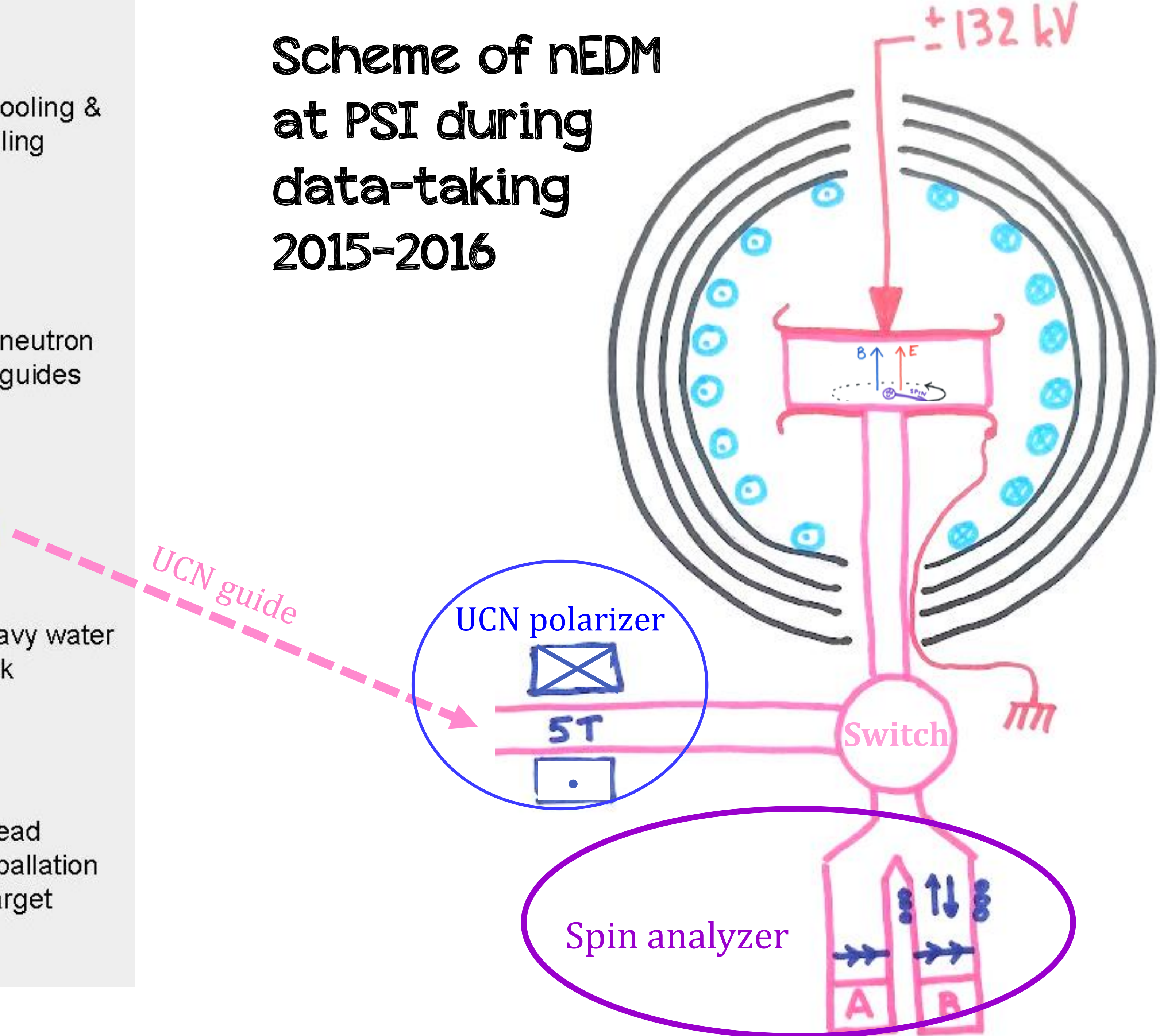


PSI UCN source, since 2011



PSI UCN source

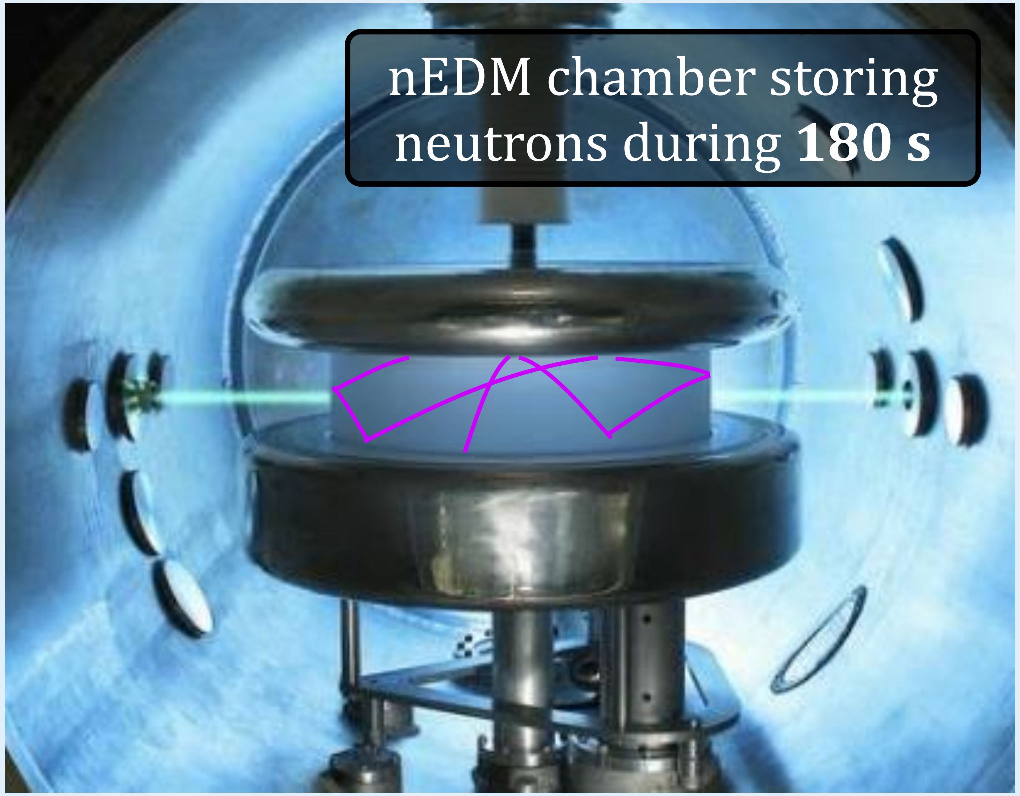
Scheme of nEDM at PSI during data-taking 2015-2016



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

Use Ultracold neutrons

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



nEDM chamber storing neutrons during **180 s**

Use big magnetic shielding

+ Use quantum magnetometry

With mercury and cesium atoms

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)

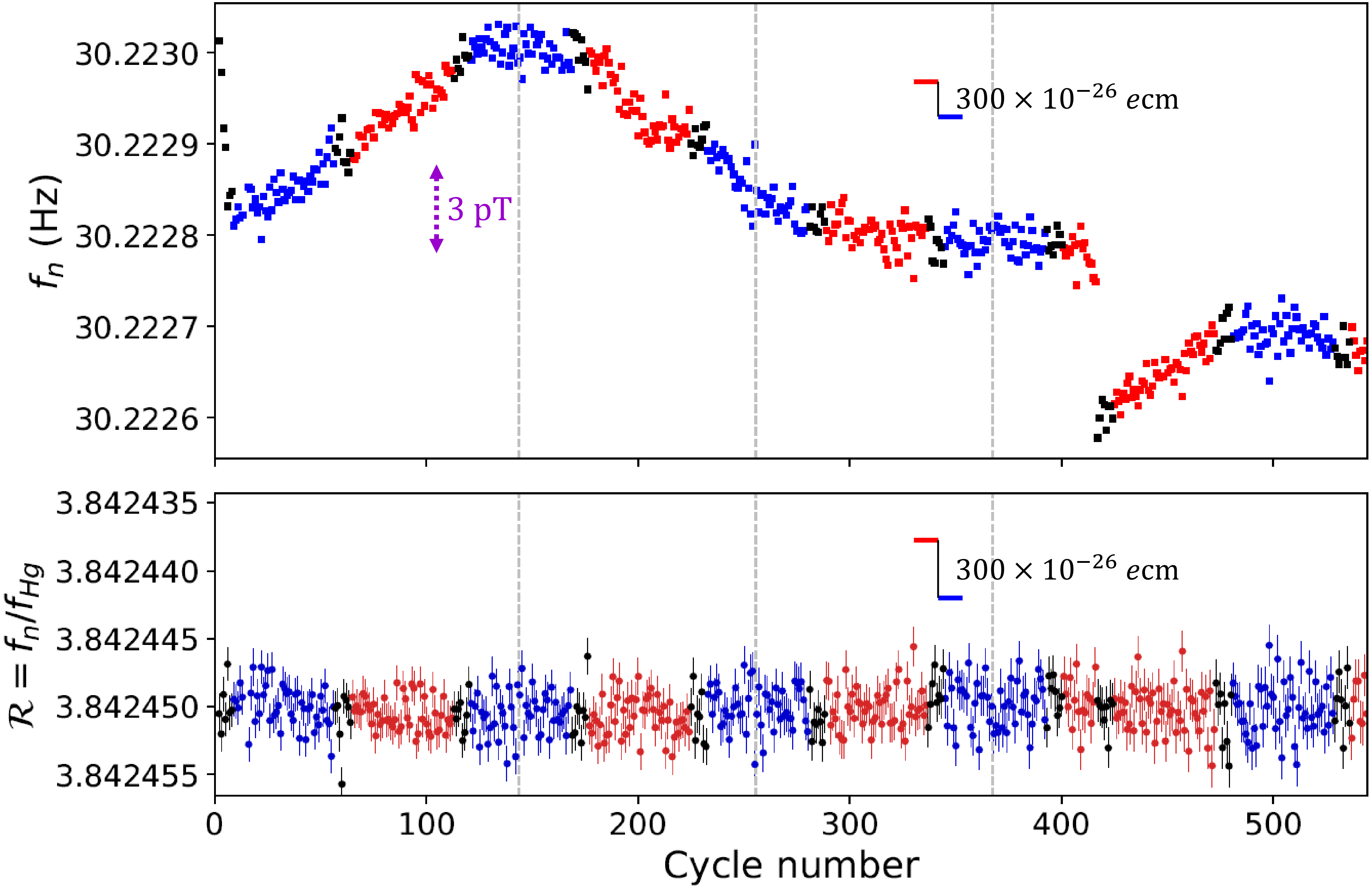
Uniformity of the B-field

nEDM data collected in 2015-2016 and Hg Co Mag

2015-2016
54,068 cycles recorded - one cycle every 5 min, grouped in 99 sequences, alternating E field polarity every 48 cycles
11,400 neutrons counted per cycle.

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

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

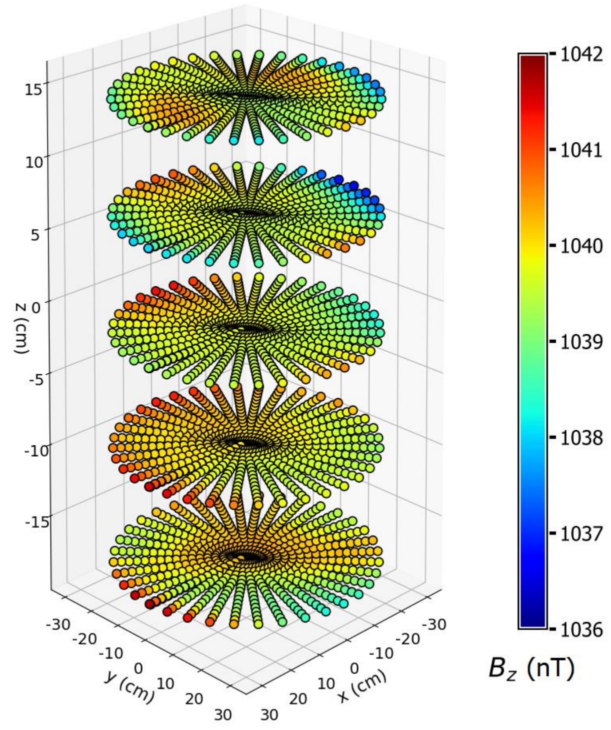


Budget of systematic errors

TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error
Error on $\langle z \rangle$	$\cdots$	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	$\cdots$	4
$v \times E$ UCN net motion	$\cdots$	2
Quadratic $v \times E$	$\cdots$	0.1
Uncompensated G drift	$\cdots$	7.5
Mercury light shift	$\cdots$	0.4
Inc. scattering ^{199}Hg	$\cdots$	7
TOTAL	69	18

Leading systematics associated with B-field uniformity



Field mapping, Quemener et al.

The result

PHYSICAL REVIEW LETTERS 124, 081803 (2020)

Editors' Suggestion   Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

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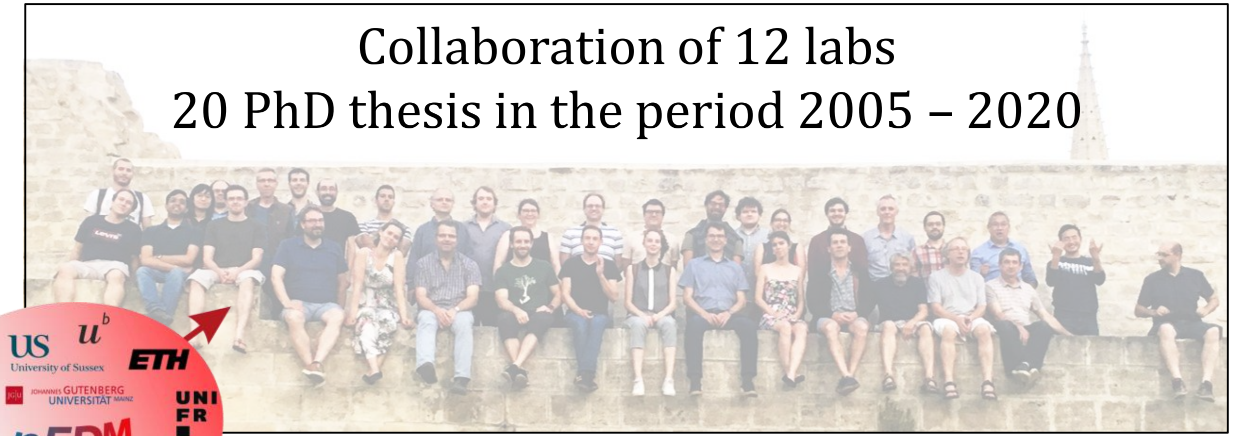
We present the result of an experiment to measure the electric dipole moment (EDM) of the neutron at the Paul Scherrer Institute using Ramsey's method of separated oscillating magnetic fields with ultracold neutrons. Our measurement stands in the long history of EDM experiments probing physics violating time-reversal invariance. The salient features of this experiment were the use of a ^{199}Hg comagnetometer and an array of optically pumped cesium vapor magnetometers to cancel and correct for magnetic-field changes. The statistical analysis was performed on blinded datasets by two separate groups, while the estimation of systematic effects profited from an unprecedented knowledge of the magnetic field. The measured value of the neutron EDM is $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}$ e.cm.



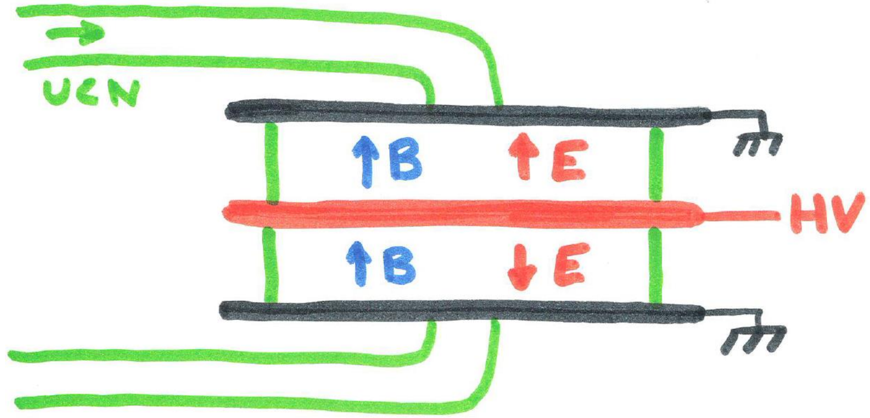
Collaboration of 12 labs
20 PhD thesis in the period 2005 – 2020

Best limit from the nEDM experiment @PSI

$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$$ Abel et al, PRL (2020)

Concept for the next generation nEDM

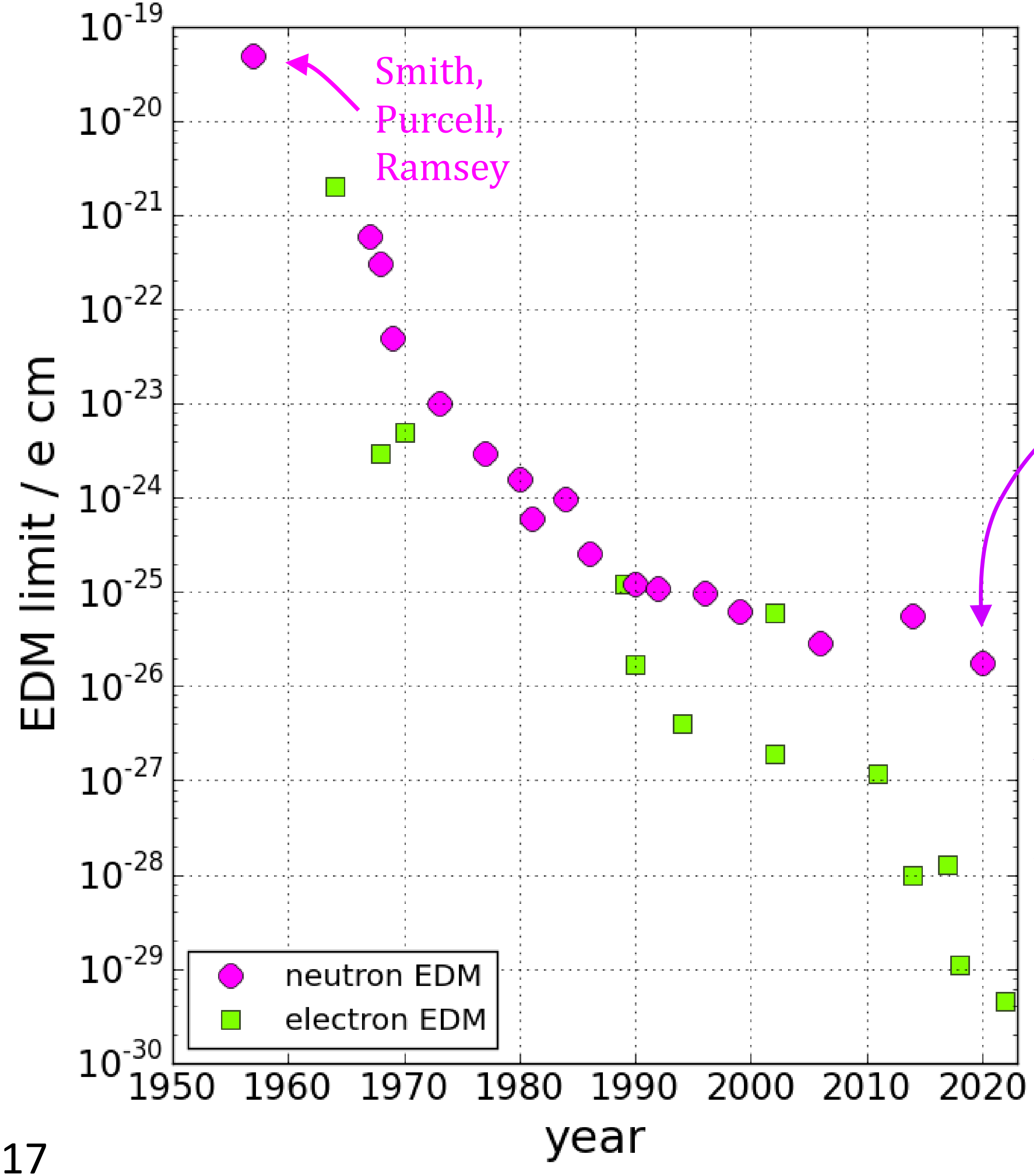
Double-chamber UCN @room temperature



+ 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 under construction
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) commissionning experiment under construction
PSI	Spallation + sD2 UCN source	n2EDM: large double Ramsey chamber with Hg comagnetometers + Cs mag	Source running, experiment almost running

Next generation nucleon EDM



Best limit from the nEDM experiment @PSI

$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$ Abel et al, PRL (2020)

Design sensitivity of 4 new experiments:

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

Design sensitivity cryogenic nEDM@SNS

Conceptual reach proton & neutron EDM

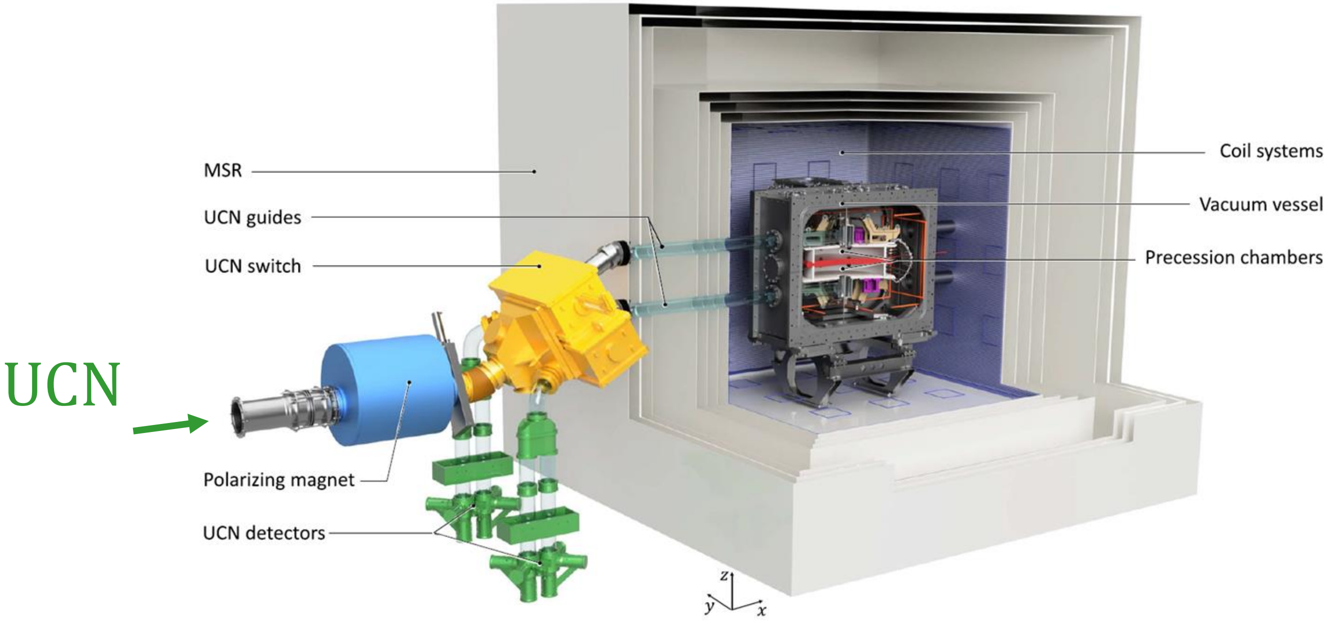
CKM background uncertain, possibly 10^{-31} e cm

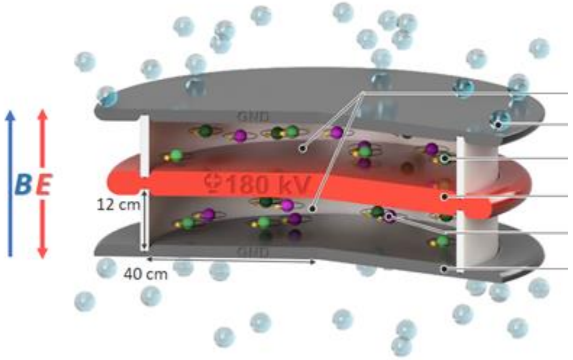
The Design of the n2EDM experiment

From the measurement of two frequencies (parallel and antiparallel fields configurations)

$$d_n = \frac{\pi\hbar}{2|E|}(f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow})$$

→ Ramsey's method: required polarized neutrons





Storage chambers where neutron frequency measurement is performed

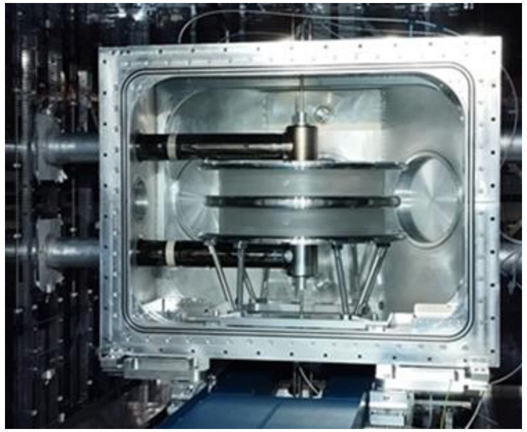
Two main challenges

neutron statistic & magnetic field uniformity and stability

Control of the magnetic field

Magnetically shielded Room (MSR): 6-layers mu-metal shield (suppression factor of 10^5 for quasistatic field)

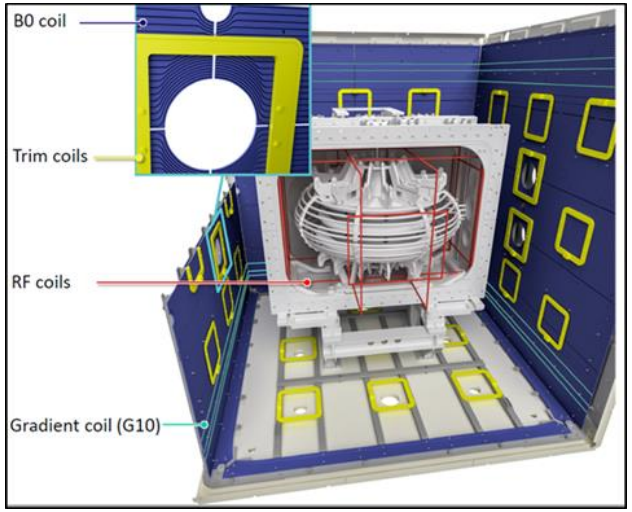
MSR in the thermo-house



Storage chambers in the VT

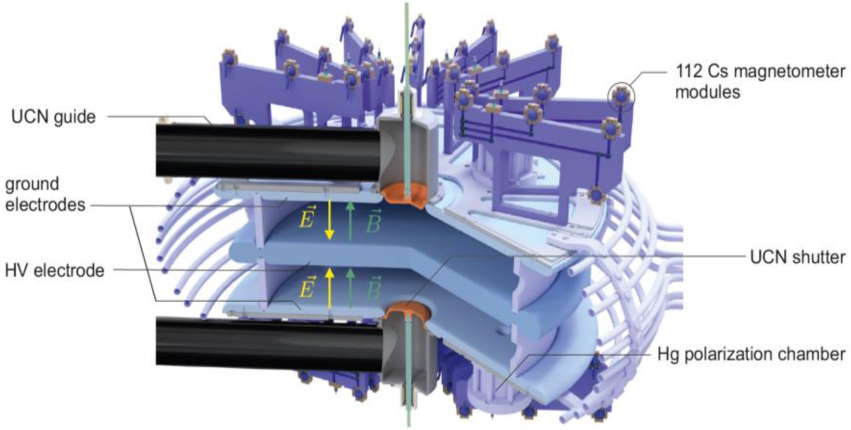
Magnetic field generation: internal coils system (64)

- 1 main B_0 coil + 63 correcting coils



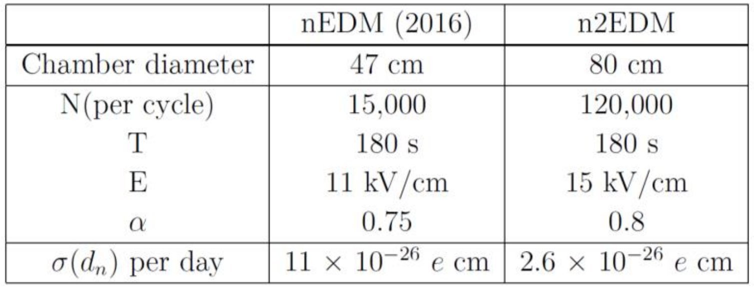
Online measurements of the magnetic field:

- Hg comagnetometer (in situ): mag. field drift
- 112 Cs magnetometers : field non



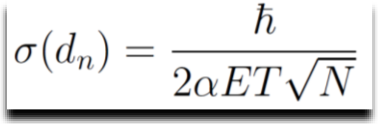
Expected Sensitivity

Gain with respect to the nEDM experiment:



	nEDM (2016)	n2EDM
Chamber diameter	47 cm	80 cm
N(per cycle)	15,000	120,000
T	180 s	180 s
E	11 kV/cm	15 kV/cm
α	0.75	0.8
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm

Based on 2016 UCN source performances



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

T: storage time
E: electric field intensity
⍰: UCN polarization
N: number of UCN

Sensitivity improvements:

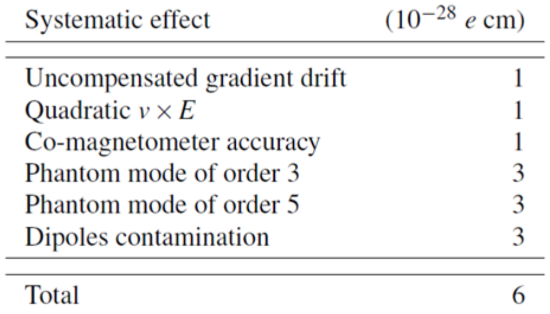
Number of UCN (x8): storage volume (x3) + optimized* connection source - apparatus
Electric field intensity (+35 %): HV electrode better insulated /nEDM

Final sensitivity of 10^{-27} e cm → 500 days of data taking (4 years)

Systematics: mostly induced by the magnetic field non uniformities

Highly uniform and stable magnetic field (1 µT) required

Field uniformity: $\sigma(B_z) < 170$ pT in the chambers
Field stability : *30* fT/min



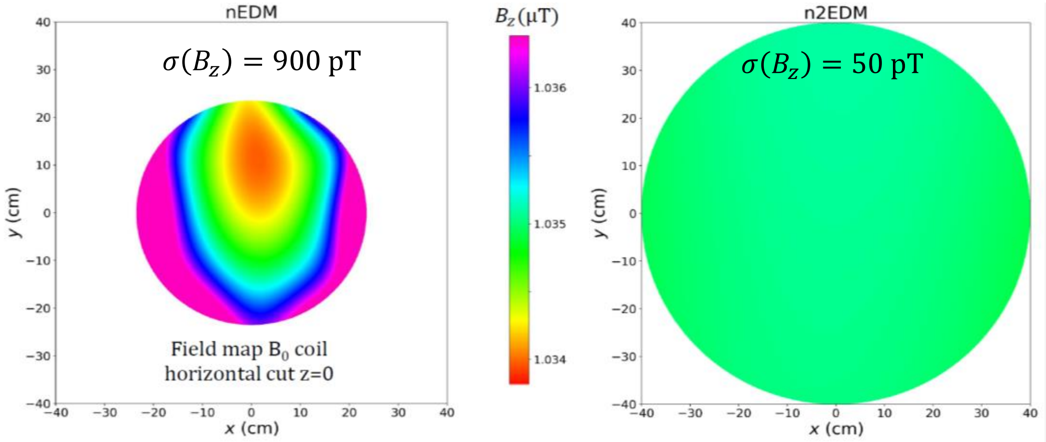
Systematic effect	$(10^{-28}$ e cm)
Uncompensated gradient drift	1
Quadratic $v \times E$	1
Co-magnetometer accuracy	1
Phantom mode of order 3	3
Phantom mode of order 5	3
Dipoles contamination	3
Total	6

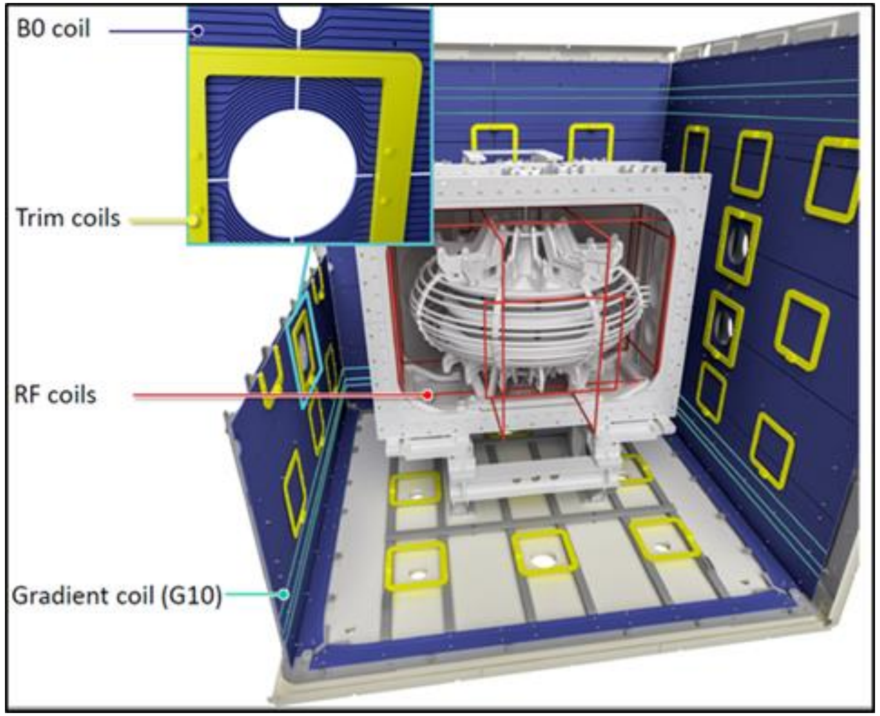
**G. Zsigmond et al, Eur. Phys. J.A 56, 33 (2020).*

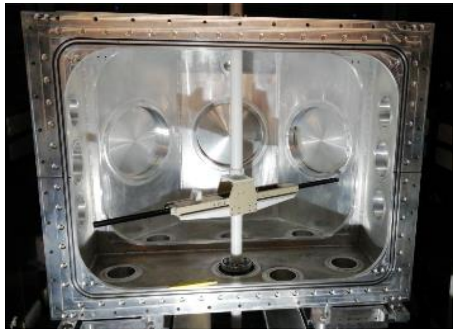
Magnetic Field Commisioning

Magnetic field characterization (2021-2022 :

- internal coils system simulated, built and installed
- field characterization







	Required	w/o optim.	w/ optim.
Statistical requirements			
Vertical uniformity $\sigma(B_z)$ (pT)	< 170	49.1 ± 1.5	34.7 ± 1.5
Systematical requirements			
$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}(\acute{G}_{30}\acute{\Pi}_{30})$ (10^{-28} e cm)	< 3	81.7 ± 2.9	2.3 ± 2.9
$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}(\acute{G}_{50}\acute{\Pi}_{50})$ (10^{-28} e cm)	< 3	9.2 ± 0.7	0.7 ± 0.7
$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}(\acute{G}_{70}\acute{\Pi}_{70})$ (10^{-28} e cm)	< 3	0.3 ± 0.1	0.2 ± 0.1

Performances are excellent

Part of the systematics already below requirements

T. Bouillaud, P. Flaux, "An exceptionally uniform magnetic field for the n2EDM experiment" (LPC-LPSC); internal review.

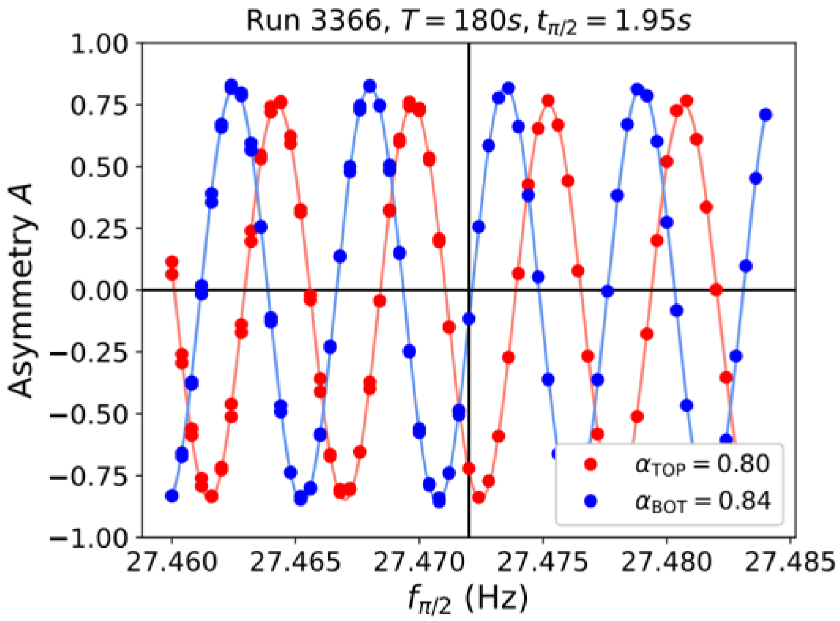
Apparatus Commisioning

Neutron frequency measurement:

Ramsey oscillating field method: operational !

neutron polarization, transport, storage and detection: OK !

Final polarization larger than in design goal (> 0.8) !!



Components	Operational	Performances
Neutrons statistic	√	24,000
Magnetic field	√	$\sigma(B_z) = 35$ pT ; systematics
High Voltage	√	+15 KV/cm
Ramsey meas.	√	$\alpha > 0.8$
Hg Comagnetometer	√	T_2 = 35 s ⟶ 100 s
Cs magnetometers		

2024 goal: first nEDM data

Current performances:

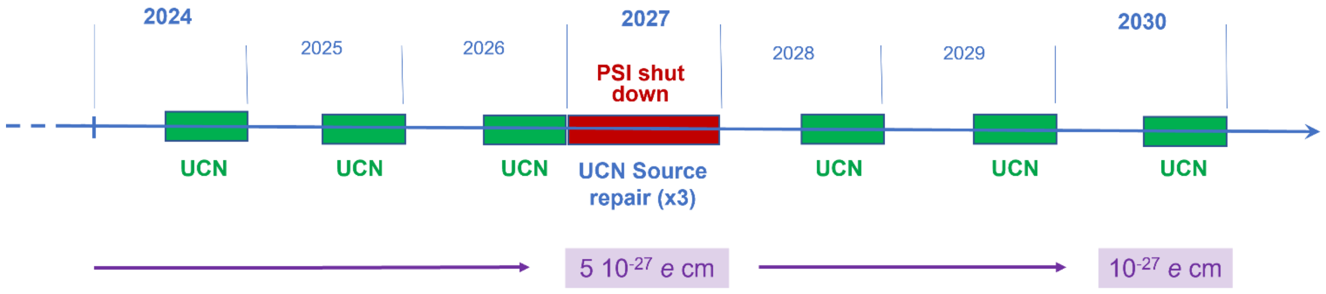
	N (per cycle)	T	E	α
06/2024	24,000	180 s	10 - 12.5 kV/cm	0.80 - 0.84

↑ 15 kV reached

Sensitivity already better than in nEDM (1.9)

Phasing n2EDM

Towards a final sensitivity of 10^{-27} *e* cm: two steps approach


2024 2025 2026 2027 2028 2029 2030

PSI shut down

UCN UCN UCN UCN Source repair (x3) UCN UCN UCN

5 10^{-27} *e* cm

10^{-27} *e* cm

First phase (2024-2026):

Sensitivity already improved / nEDM (x1.9): new result is guaranteed

final sensitivity will depend on new chambers storage properties

Systematics : part of the systematics already under control (magnetic commissioning)

Second phase (2028-2030):

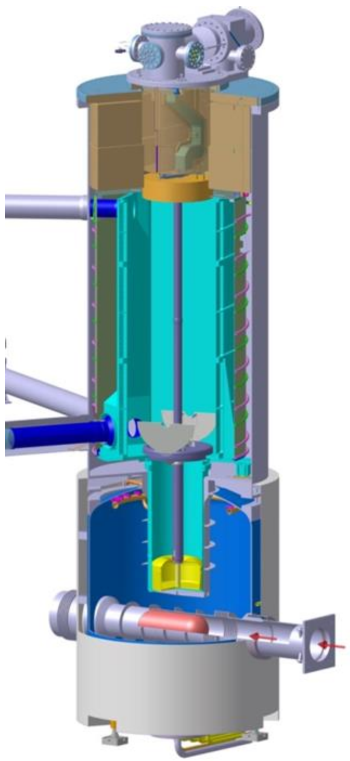
UCN source repair/upgrade (x3): D_2 container and UCN shutter exchanged, proton beam intensity, D_2 solid prod.

final sensitivity will depend on UCN source performances (missing 2.2)

New operation mode: suppress the main systematic effect (false motional EDM) with magic B0 field (10 μT)

Beyond 2030: nEDM measurement in superfluid Helium (SNS prototype move to Europe) ?

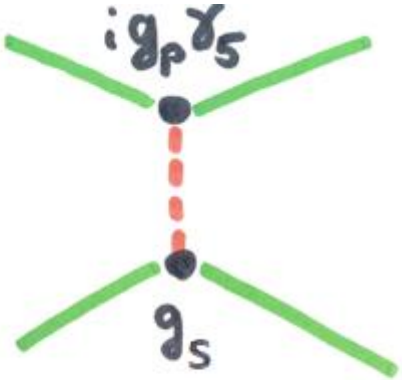
UCN source (PSI)



*G. Pignol, A magic magnetic field to measure the neutron electric dipole moment, Phys. Lett. B, **793**, 440 (2019)*

Search for ALPs with Neutron EDM apparatus

nEDM by-products: search for ALPs

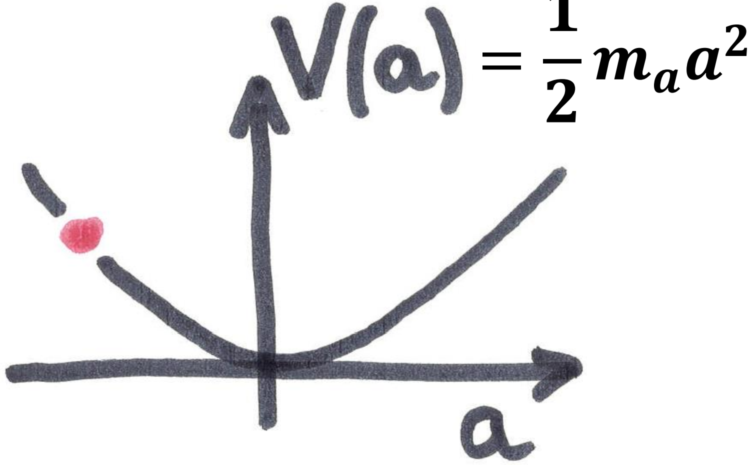


1) A new light particle of mass m_a mediates a fifth force

- The interaction is spin-dependent
- Range of the interaction = $\lambda = \hbar c/m_a$

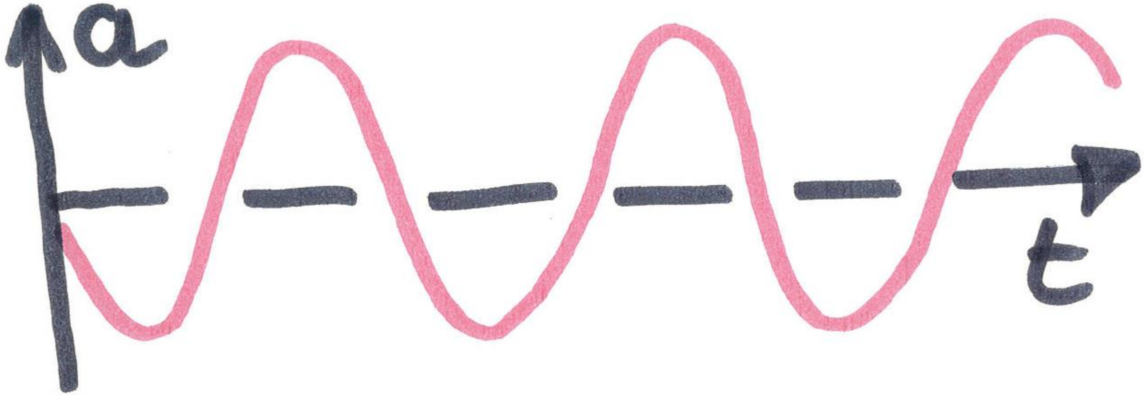
Dedicated talk
Pin-Jung Chiu

2) Formation of a classical oscillating field = DM candidate with $\rho_a = \frac{1}{2} m_a^2 a_0^2$



$$V(a) = \frac{1}{2} m_a a^2$$

$$a(t) = a_0 \cos m_a t$$



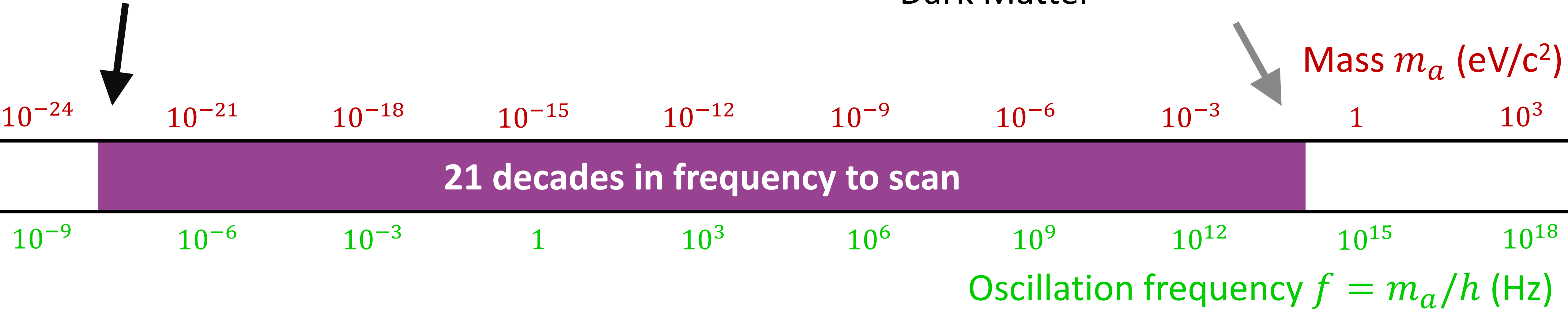
Possible frequencies of an ALPs DM field

The de Broglie wavelength $h/m_a v$ must be larger than the size of Dwarf Galaxies (1 kpc)

$\mathbf{10^{-22}\,eV < \boldsymbol{m_a}}$

Classical field limit of large number of particles inside the volume λ^3 : $\boldsymbol{m_a} < \mathbf{0.1\ eV}$

For $\boldsymbol{m_a} > \mathbf{0.1\ eV}$ it behaves as independent particles and hot Dark Matter



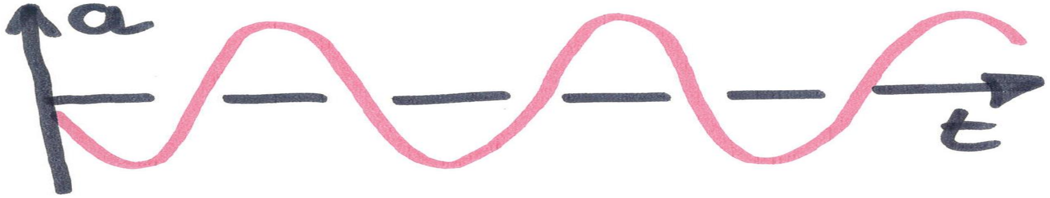
Mass m_a (eV/c^2)

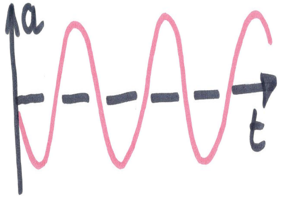
10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3}

21 decades in frequency to scan

10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

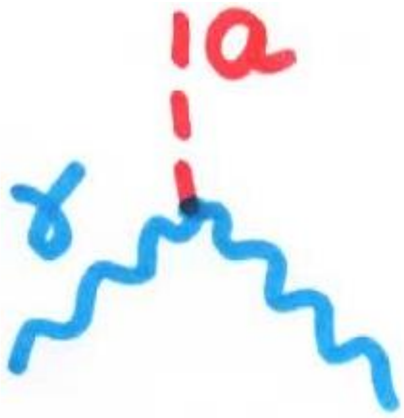
Oscillation frequency $f = m_a/h$ (Hz)





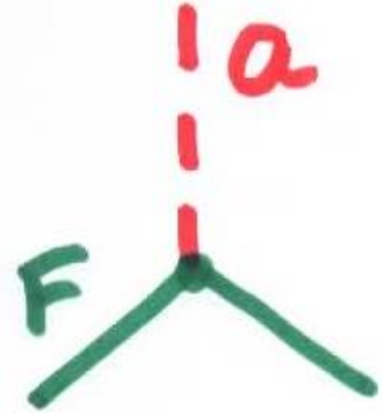
Non-gravitational interactions of ALPs

$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi}\, a\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \frac{C_G}{f_a}\frac{\alpha_s}{8\pi}\, a\, \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu} - \sum_F \frac{C_F}{2f_a}\partial_\mu a \bar{F}\gamma^\mu\gamma_5 F$$



Coupling to photons
axion-photon conversion

Coupling to gluons
Oscillating EDM



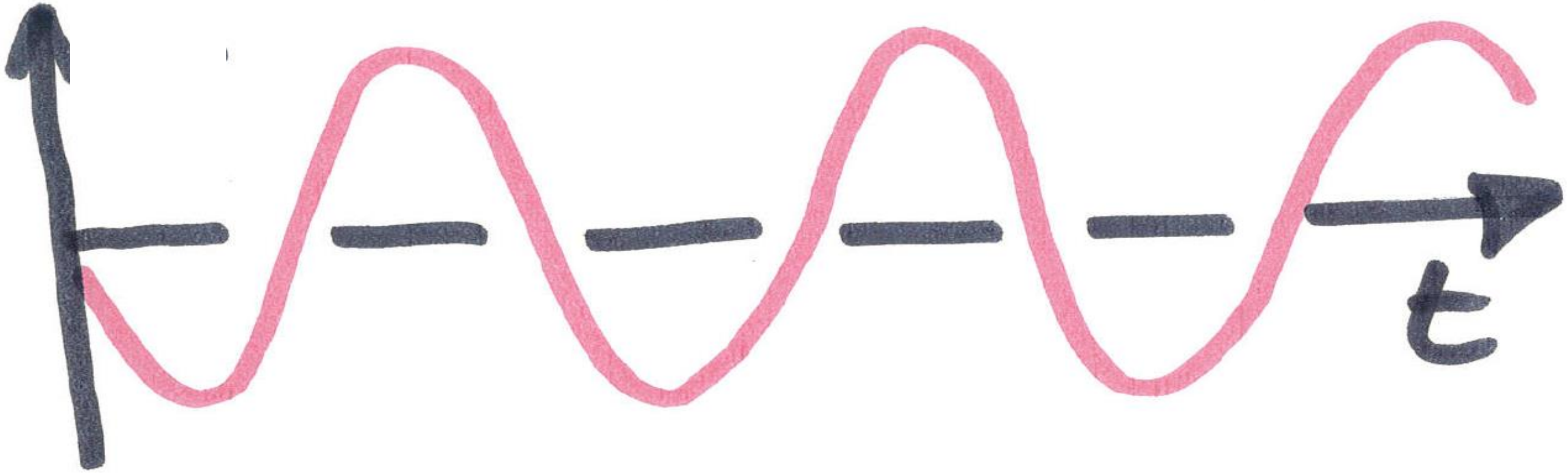
Coupling to fermions
"Axion wind"

Oscillating neutron EDM

$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi} a\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \boxed{\frac{C_G}{f_a}\frac{\alpha_s}{8\pi}\; a\, \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}} - \sum_F \frac{C_F}{2f_a}\partial_\mu a \bar{F}\gamma^\mu\gamma_5 F$$

Coupling to gluons
Oscillating EDM

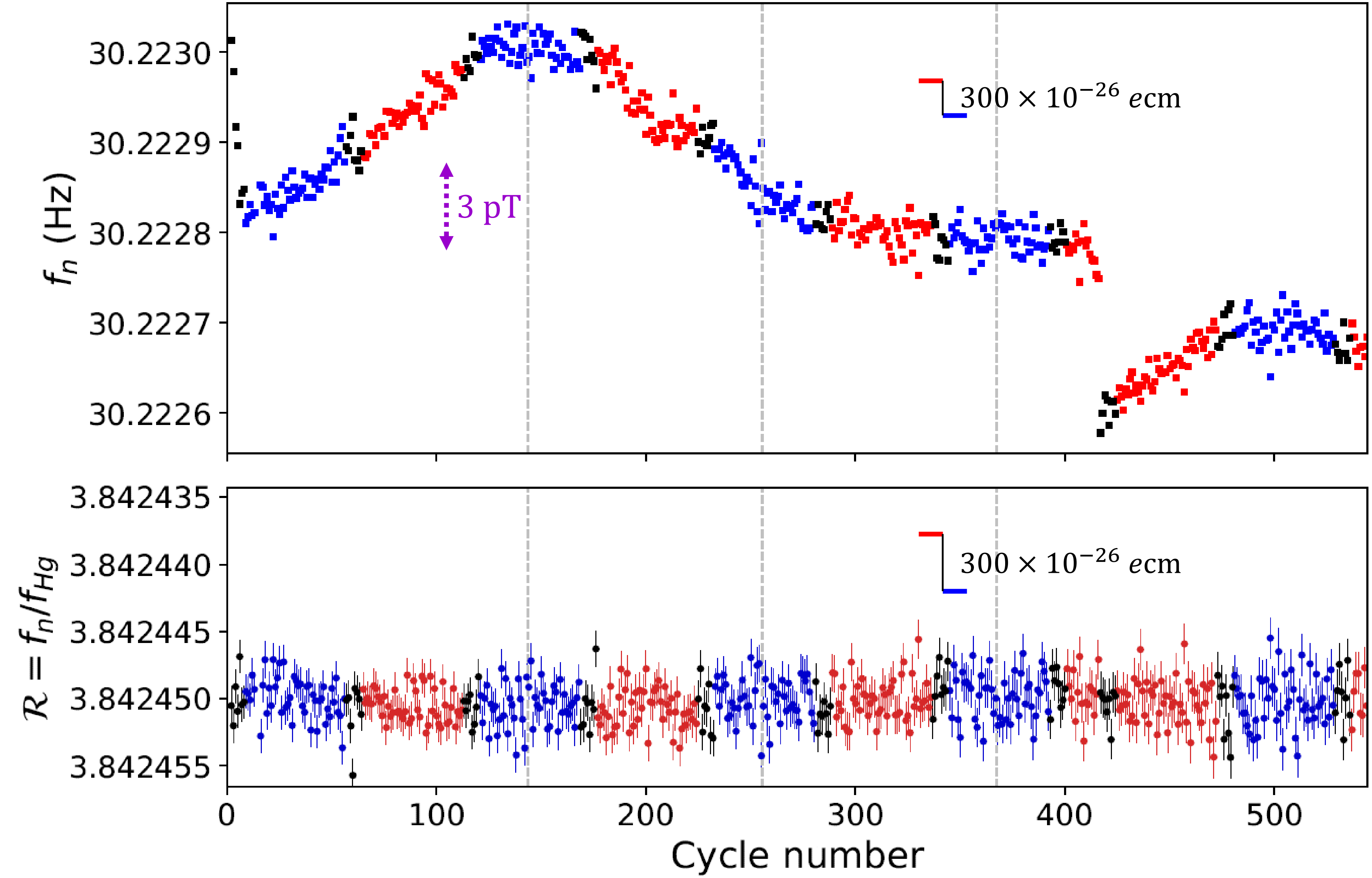
$$d_n(t) = 6 \times 10^{-22}\, e\ \mathrm{cm} \times \left(\frac{10^{-22}\mathrm{eV}}{m_a}\right) \times \left(\frac{10^{16}\mathrm{GeV}}{f_a}\right) \times \cos m_a t$$



nEDM data, with mercury correction

Magnetic fluctuations are corrected for at each cycle with the Hg magnetometer by measuring

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



Search for an oscillating signal

The 2015-2016 PSI dataset consists in 100 data sequence of $\mathcal{R} = f_n/f_{\mathrm{Hg}}$ measured with alternating E-field polarity

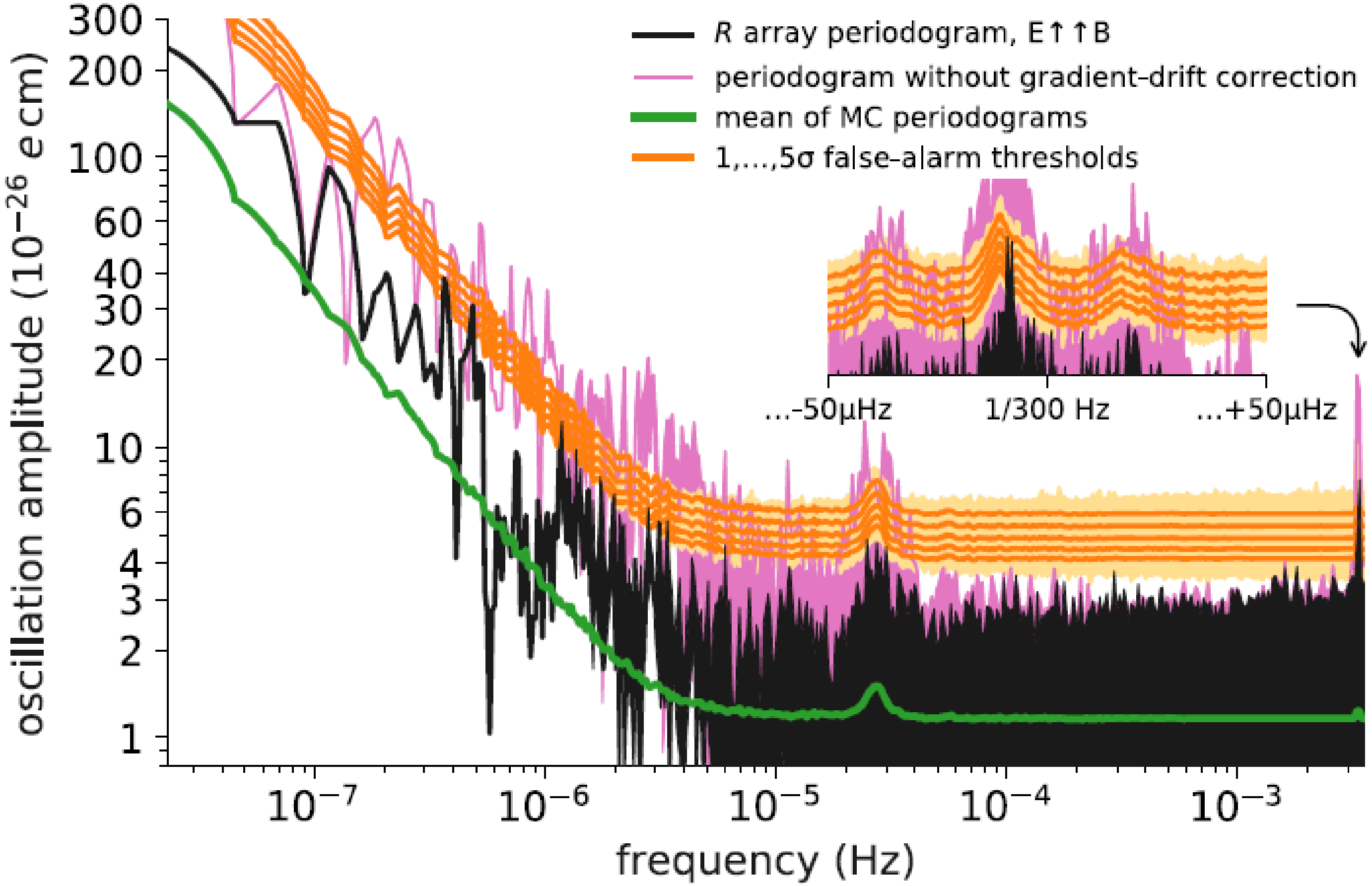
Least Square Spectral Analysis

- For each data sequence we fit

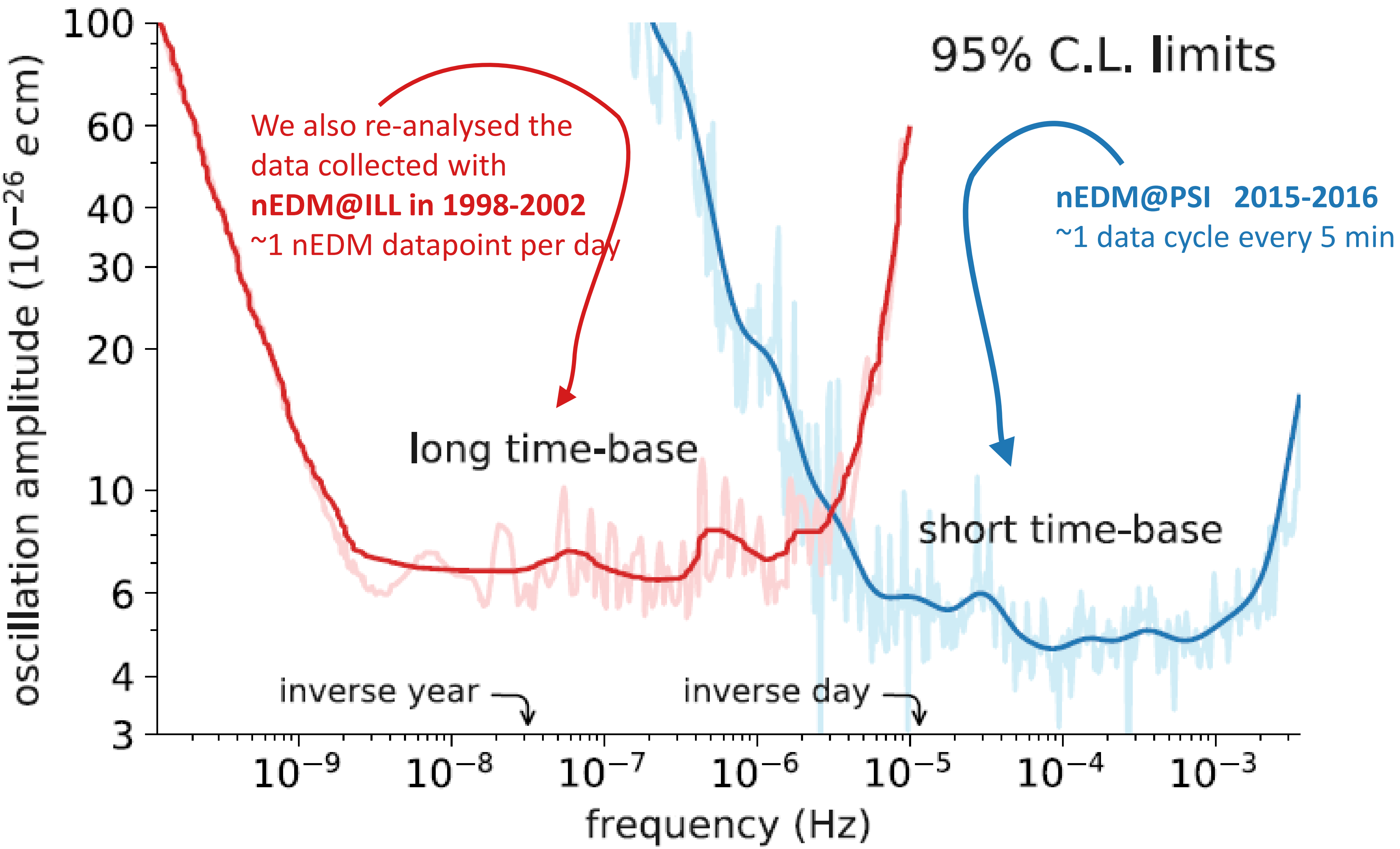
$$\mathcal{R}(t_i) = \mathcal{R}_{\pm} \pm A\cos 2\pi f t_i \pm B \sin 2\pi f t_i$$

with trial frequencies $10^{-7}\mathrm{Hz} < f < 10^{-2}\mathrm{Hz}$

- The set of fitted amplitudes $\sqrt{A^2+B^2}$ is an estimator of the **periodogram**
- False alarm thresholds are estimated by Monte-Carlo
- Found no signal (after correcting for magnetic gradient drifts)



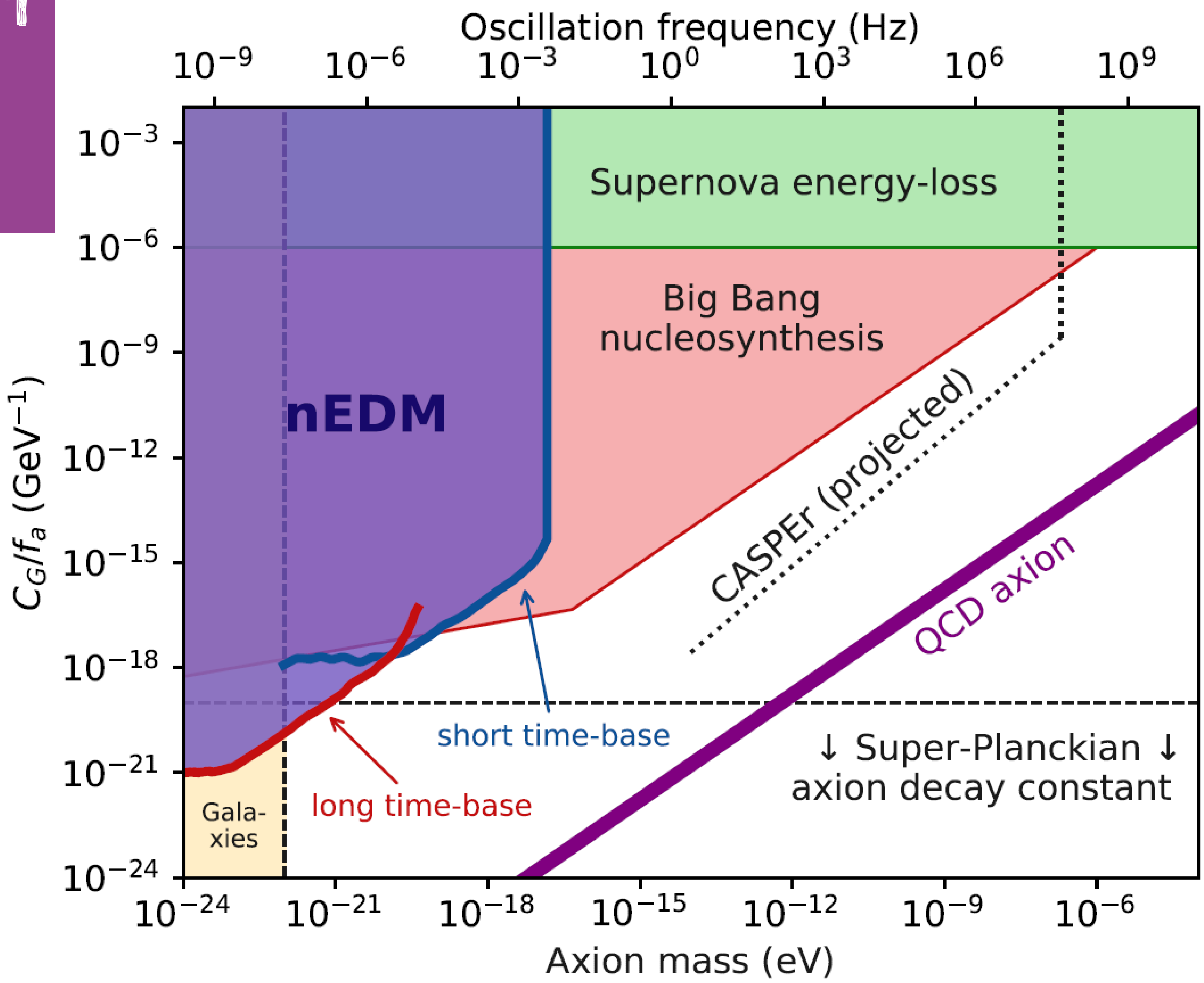
Limits on the nEDM oscillation amplitude



We also re-analysed the data collected with **nEDM@ILL in 1998-2002**
~1 nEDM datapoint per day

nEDM@PSI 2015-2016
~1 data cycle every 5 min

Limits on the nEDM oscillation amplitude



Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

Abel et al, PRX (2017)

Axion wind

$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi}\, a\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \frac{C_G}{f_a}\frac{\alpha_s}{8\pi}\, a\, \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu} - \sum_F \boxed{\frac{C_F}{2f_a}\partial_\mu a \bar{F}\gamma^\mu\gamma_5 F}$$

Coupling to fermions
⍰ "Axion wind"

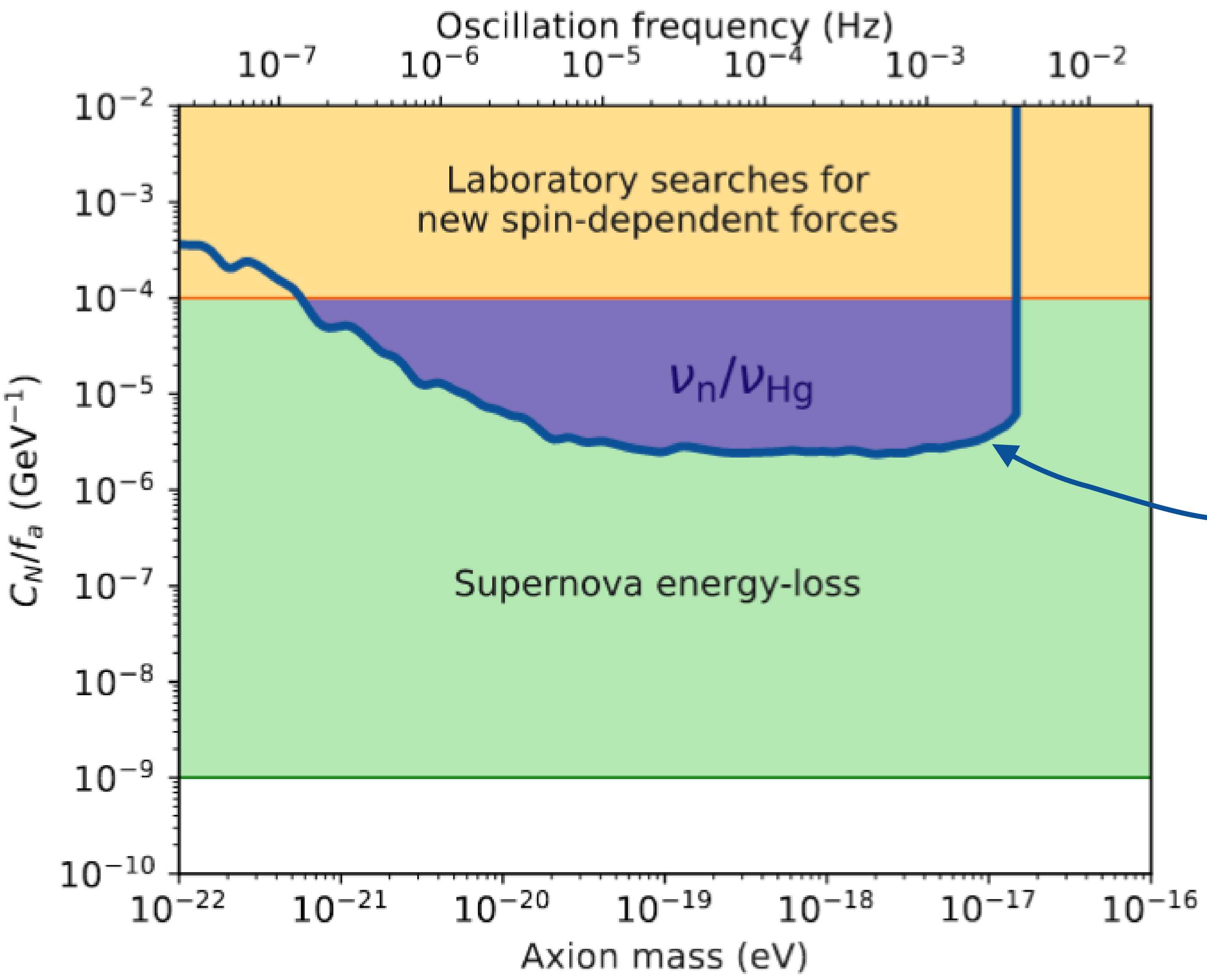
Nonrelativistic limit for F
Classical limit for a

$$\hat{H} = \frac{C_F}{2f_a}\vec{\sigma}\cdot\vec{\nabla}a(t) = \frac{\gamma}{2}\vec{\sigma}\cdot\left[\frac{C_F m_a}{f_a \gamma}\, a_0 \sin(m_a t)\, \overrightarrow{v_a}\right]$$

Oscillating pseudo-magnetic field

Axion wind associated to the velocity of Earth in the DM halo
$v_a \approx 10^{-3}c$

Axion wind limits, low frequency

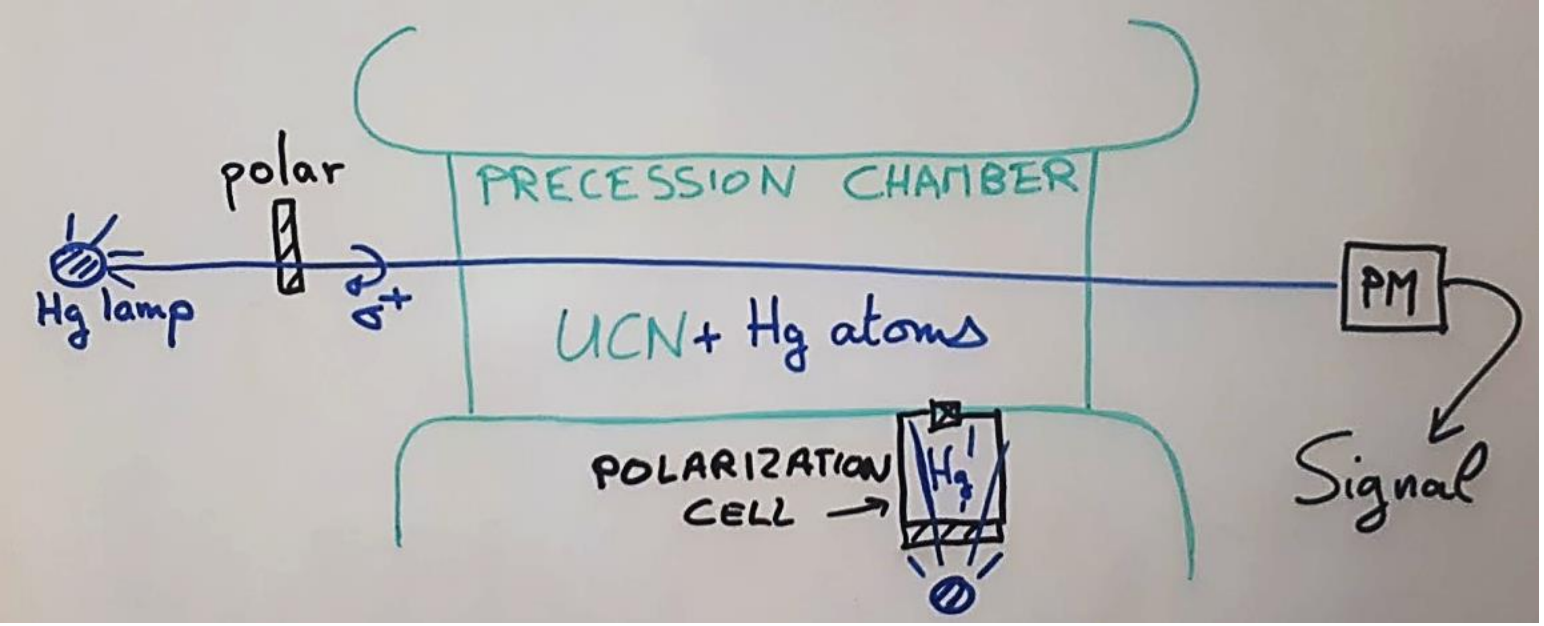


Limit from the 2015-16 nEDM data, based on the analysis of the $\mathcal{R} = f_n / f_{\mathrm{Hg}}$ timeseries.

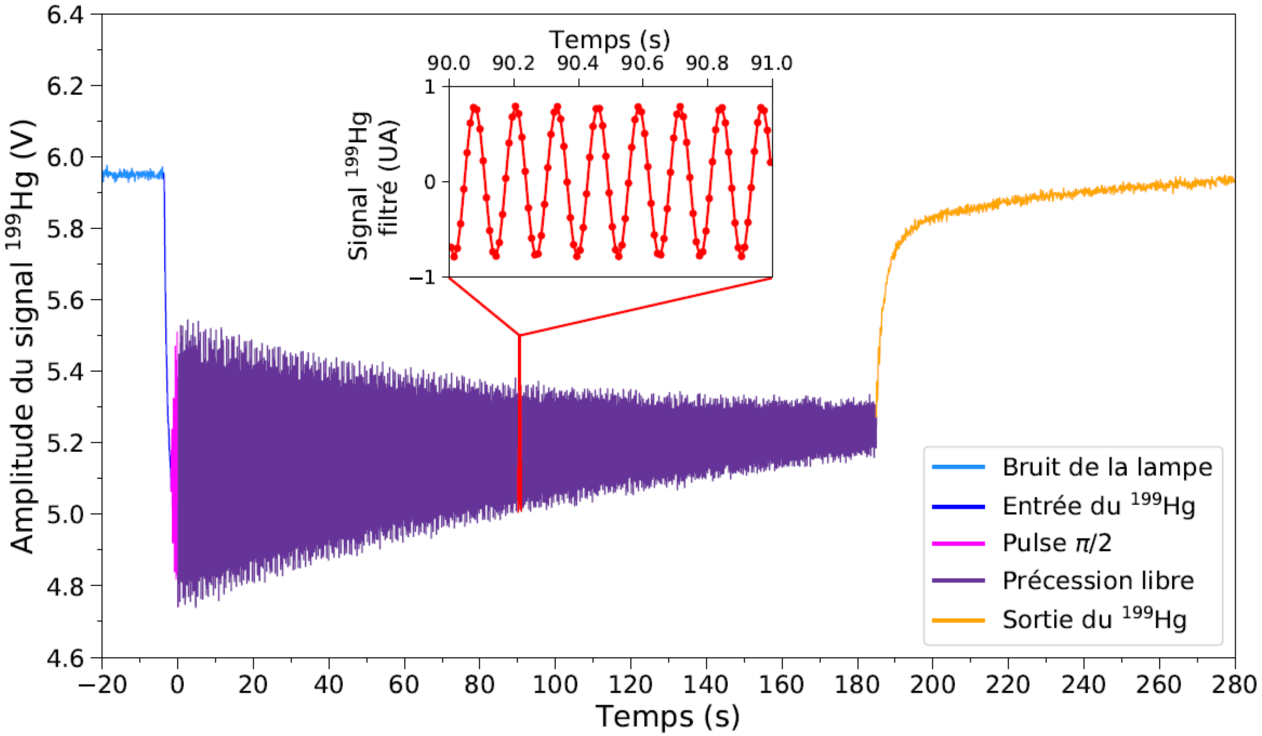
We get one $\mathcal{R}$ value every 5 min.
→ Insensitive to frequencies higher than 1/(5 min)

Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields
Abel et al, PRX (2017)

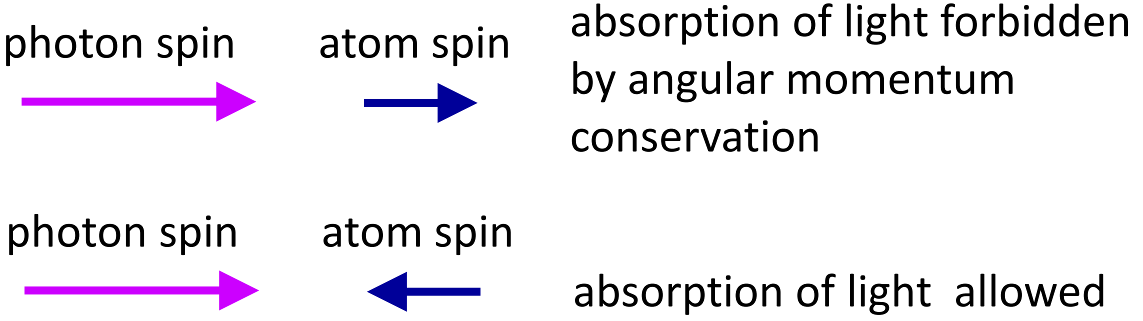
quantum magnetometry with ^{199}Hg



The magnetic field is extracted from the precession frequency of mercury-199 atoms: $f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$



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



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

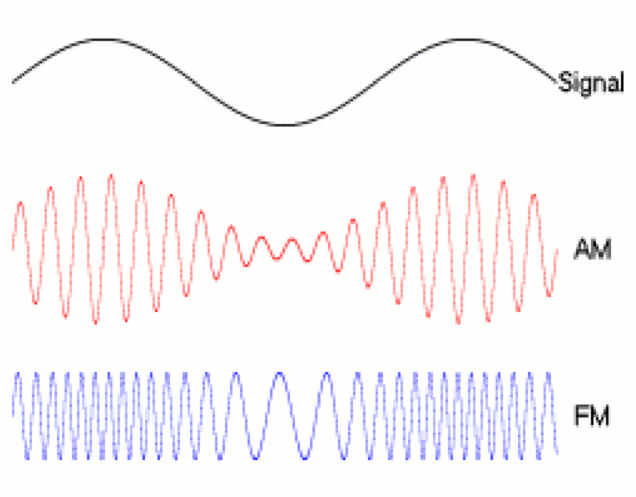
photon spin → atom spin ← absorption of light allowed

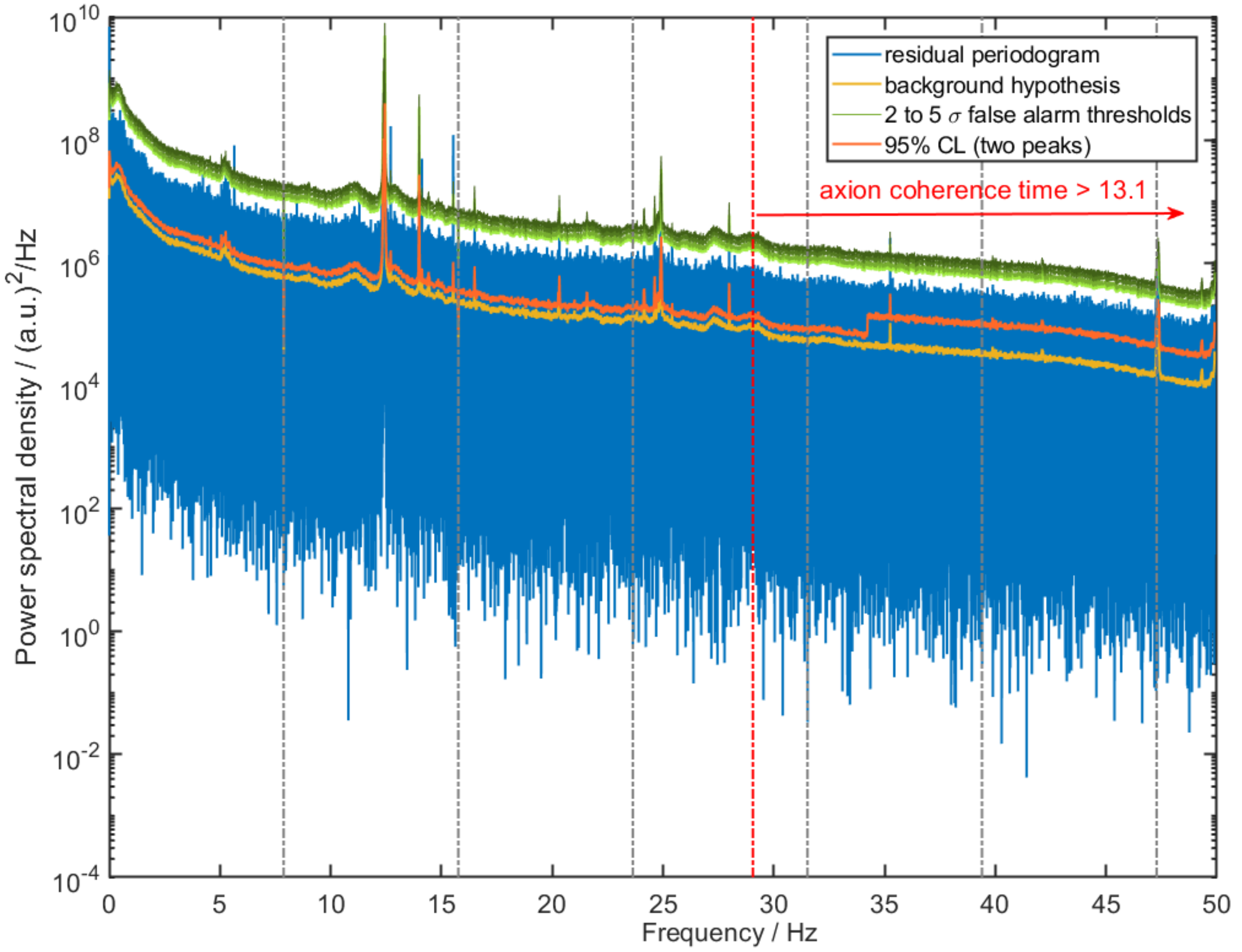
Use mercury signal to search for Axion Wind

Oscillation signal modifies to:

$$P_{FM}(t) = P\cos\left(\gamma B t + \boxed{\int_0^t a \sin\omega_{\mathrm{a}} t' \mathrm{d}t'}\right)$$

Modulation of the spin precession by Axion

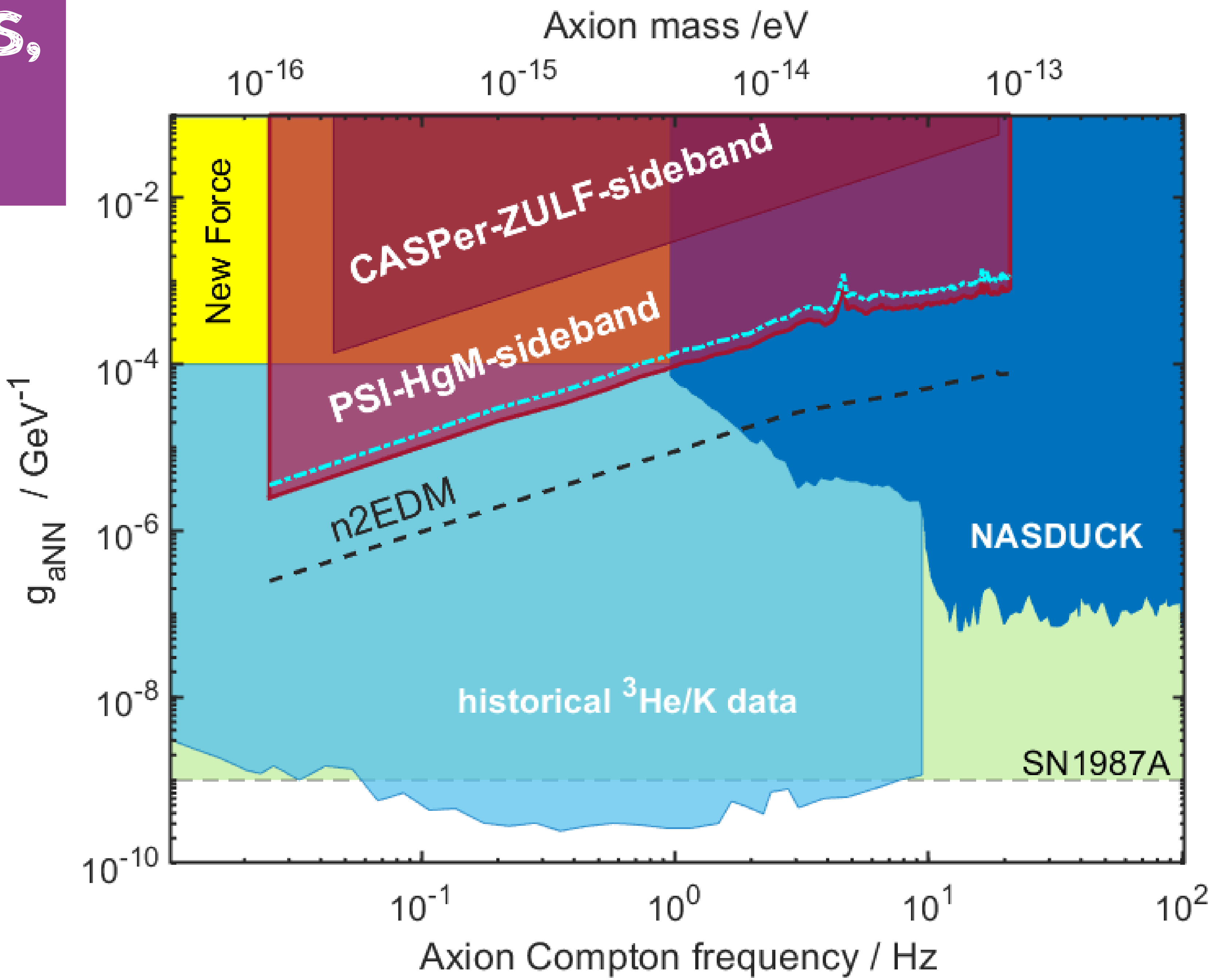




This is a FM modulation -> search for two side peaks at frequencies $\gamma B \pm \omega_a$.

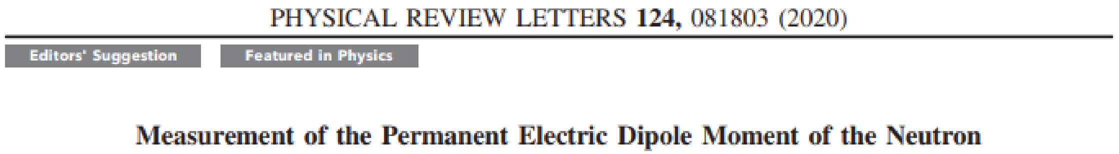
We analyzed a dedicated ~11h run taken in 2017 with nEDM@PSI

Axion wind limits, high frequency



Search for ultralight axion dark matter in a side-band analysis of a 199Hg free-spin precession signal
Abel et al, SciPost Phys (2023)

Summary of results and prospects



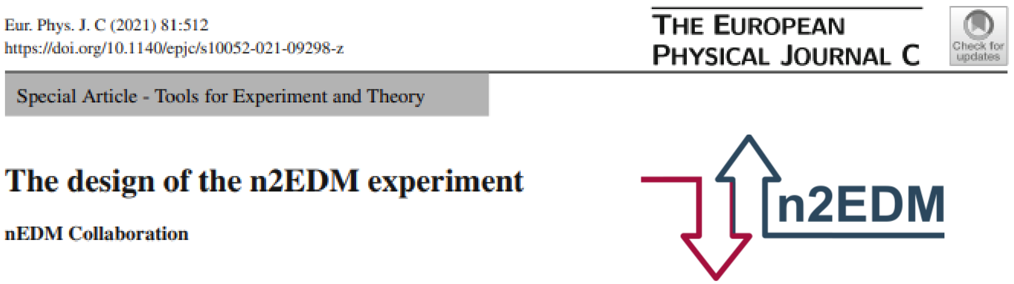
PHYSICAL REVIEW LETTERS **124,** 081803 (2020)

Editors' Suggestion **Featured in Physics**

Measurement of the Permanent Electric Dipole Moment of the Neutron

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

No CPV! → strong CP problem



Eur. Phys. J. C (2021) 81:512
https://doi.org/10.1140/epjc/s10052-021-09298-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Special Article - Tools for Experiment and Theory

The design of the n2EDM experiment

nEDM Collaboration

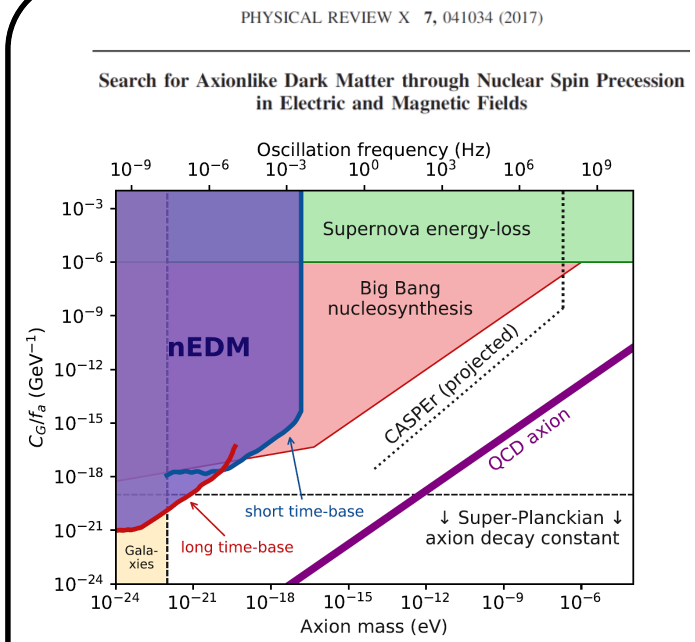
n2EDM

n2EDM in commissioning phase @PSI

Design sensitivity $1 \times 10^{-27}\ e$ cm

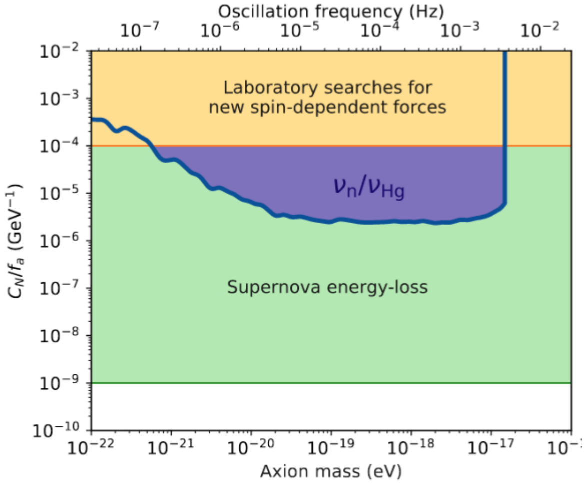
nEDM data to search for ALPs DM coherent field

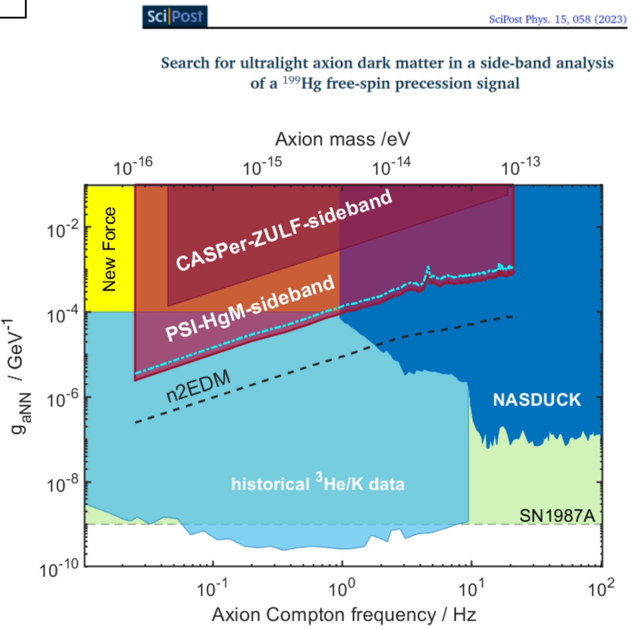
- Oscillating nEDM
- Oscillating pseudomagnetic field



PHYSICAL REVIEW X 7, 041034 (2017)

Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields





SciPost Phys. 15, 058 (2023)

Search for ultralight axion dark matter in a side-band analysis of a ^{199}Hg free-spin precession signal