




Neutron Electric Dipole Moment Search at Paul Scherrer Institute

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On behalf of the nEDM and n2EDM collaborations
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Outline

Why measuring EDMs

Measurement Principle

nEDM to n2EDM

Conclusion

Find new sources of CP violation

Electric Dipole Moment d

Charge separation along the spin

Similar as magnetic moment μ

S= Spin

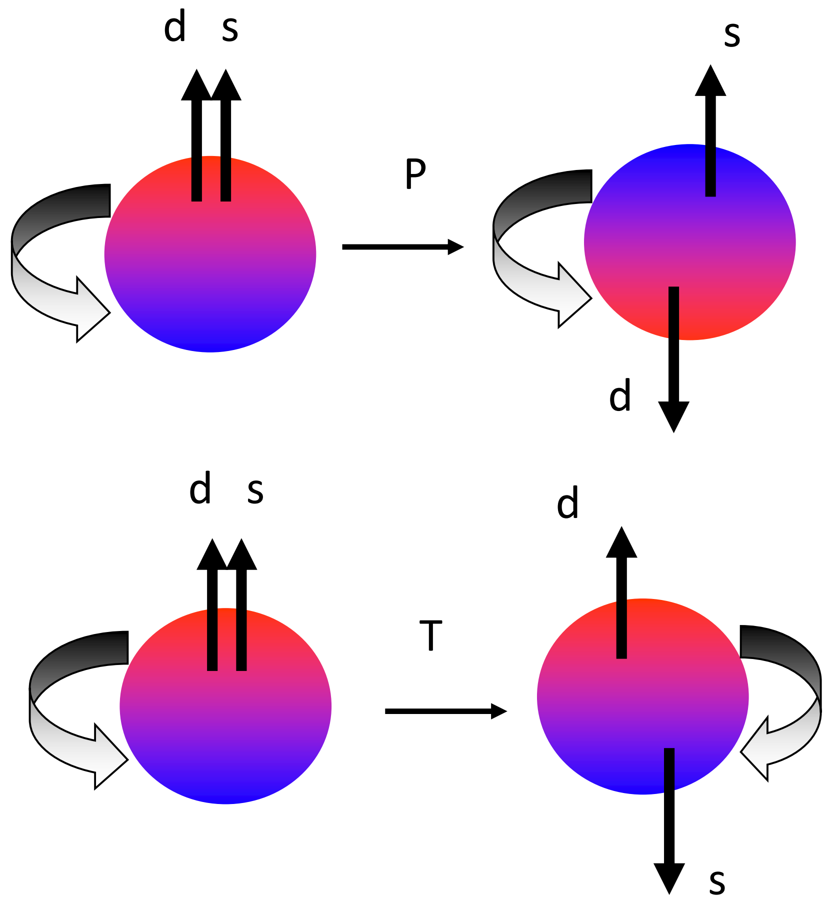
$\mu = \mu . S$ and $d = \delta . S$

$$H = -(\mu.B + d.E) = -(\mu B + \delta E)S$$

d is P odd and T odd

Assuming CPT

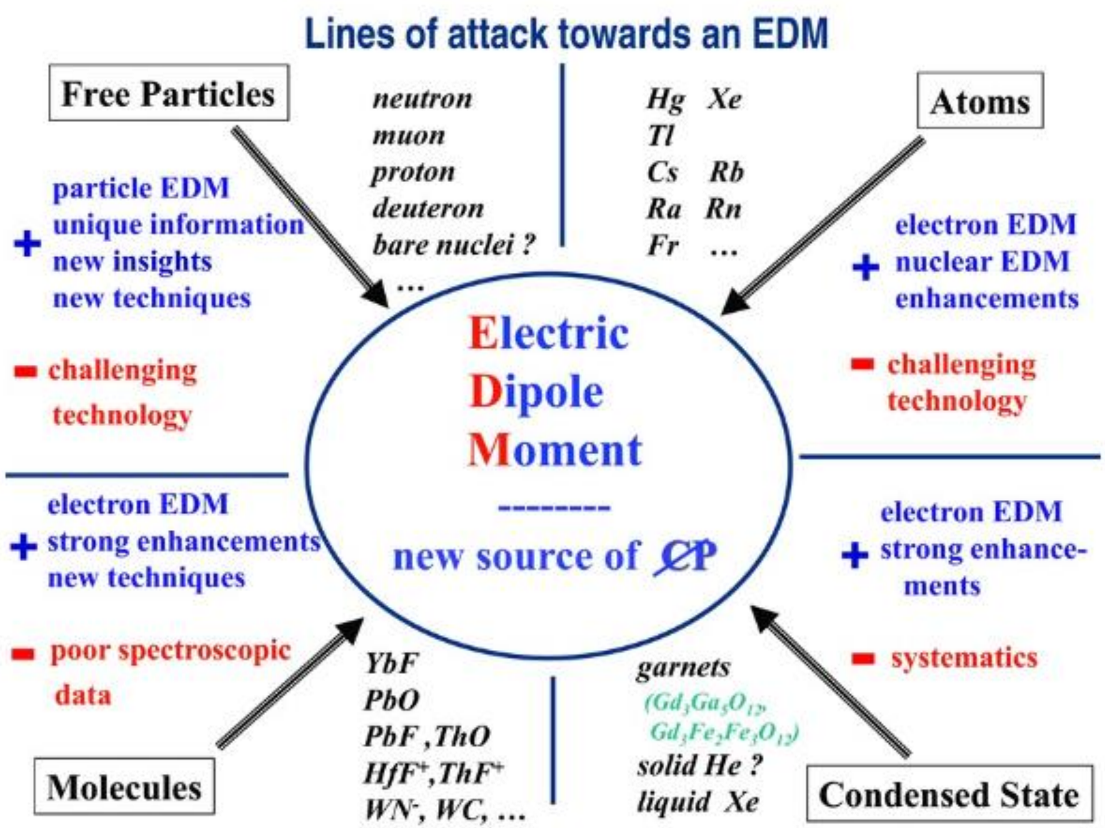
→d is CP odd



SEARCH for new source of CP violation

Purcell and Ramsey, PR78(1950)807

Can be measure with any particle



Neutron

Electrons, Protons, Particles

Molecules

Atoms…

All of them are part of the solution

Different techniques…

Laser, Storage rings, Bottles…

K Jungmann Annalen der Physik 2013, 525, 8-9

Why looking for EDMs and CPV ?

Baryon Asymmetry

A. Sakharov 1967:

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today….

Other requirements B violation, non equilibrium

Other motivations, strong CP, SUSY, axions,…BSM

ANY SM extension will be tested by EDMs

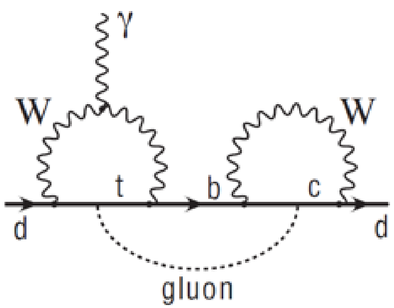
Observed:

$n_B - n_{\bar{B}} / n_\gamma = 6 \times 10^{-10}$

SM expectation:

$n_B - n_{\bar{B}} / n_\gamma \sim 10^{-18}$

Theories



CKM contribution to the quark EDM vanishes at two loops…

Prediction: $d_n \approx 10^{-33} e$ cm

Kobayashi-Maskawa background negligible

The QCD contribution $\frac{\alpha}{8\pi}\theta\, G^{\mu\nu}\widetilde{G_{\mu\nu}}$

Generates a potentially enormous EDM

$d_n \approx \theta \times 10^{-16}\, e$ cm

$\rightarrow \theta < 10^{-10}$

« Strong CP problem »

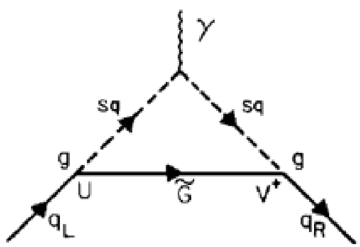


Fig. 2. One-loop diagram which may contribute to d_n in a softly broken susy model.

*Ellis, Ferrara, Nanopoulos, PLB **114** (1982). EDM induced by soft mass terms for squarks and gluinos*

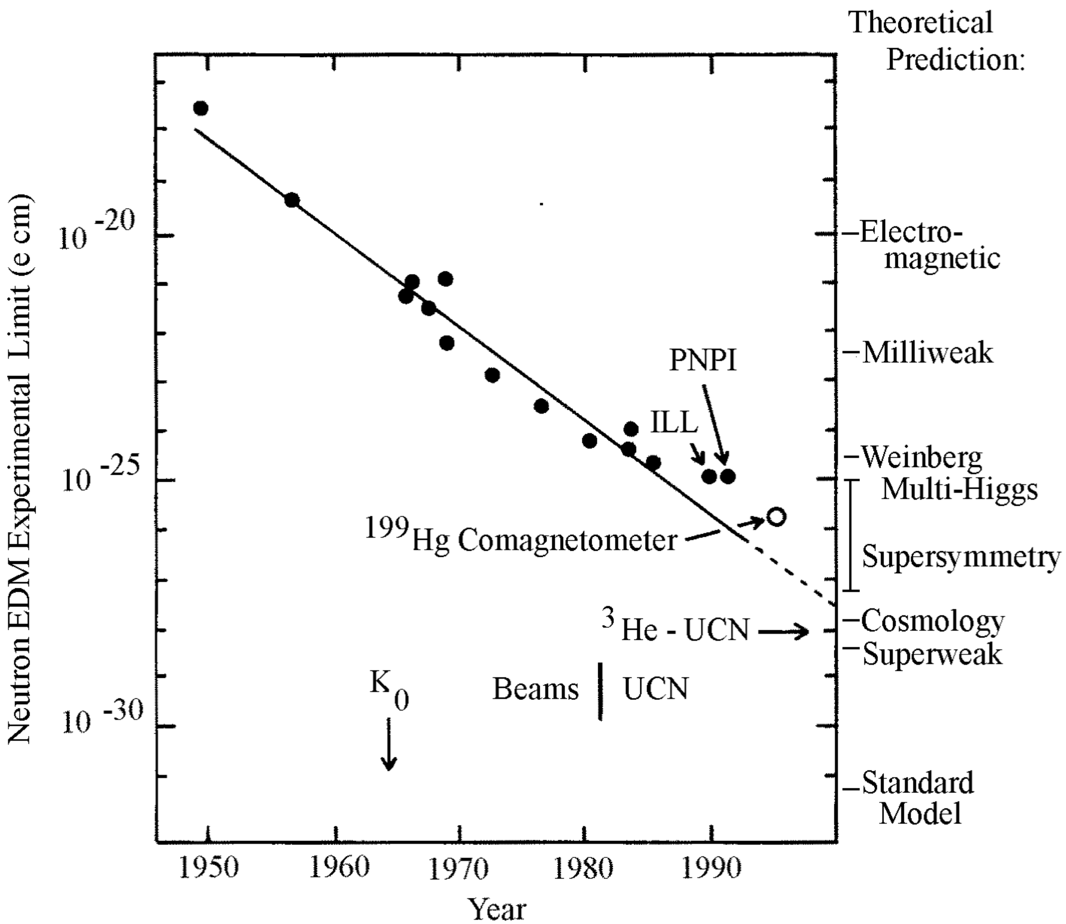
MSSM contains ~40 CP violating imaginary parameters…

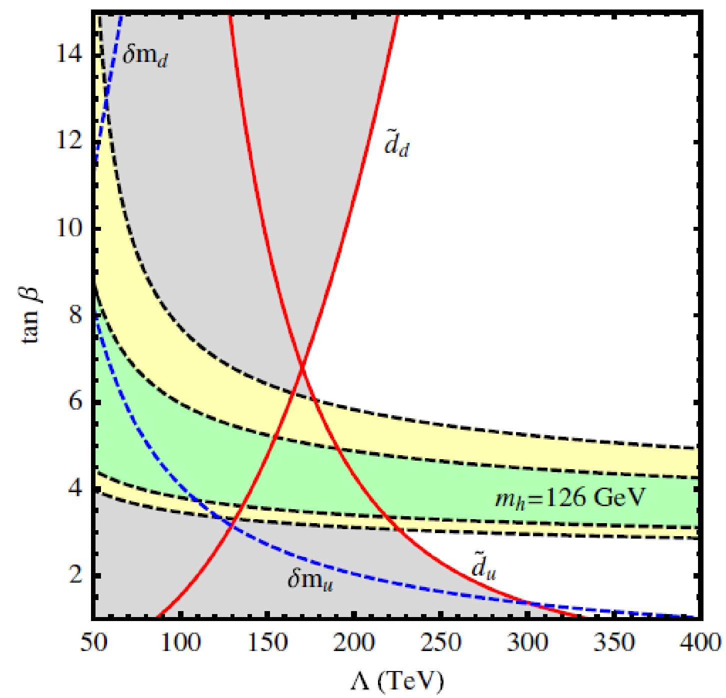
$$d_n \approx e\frac{\alpha}{4\pi}\frac{m_q}{M_{CPV}^2} \approx \left(\frac{1\ \text{TeV}}{M_{CPV}}\right)^2 \times 10^{-25}\, e\ \text{cm}$$

« SUSY CP problem »

Courtesy G Pignol

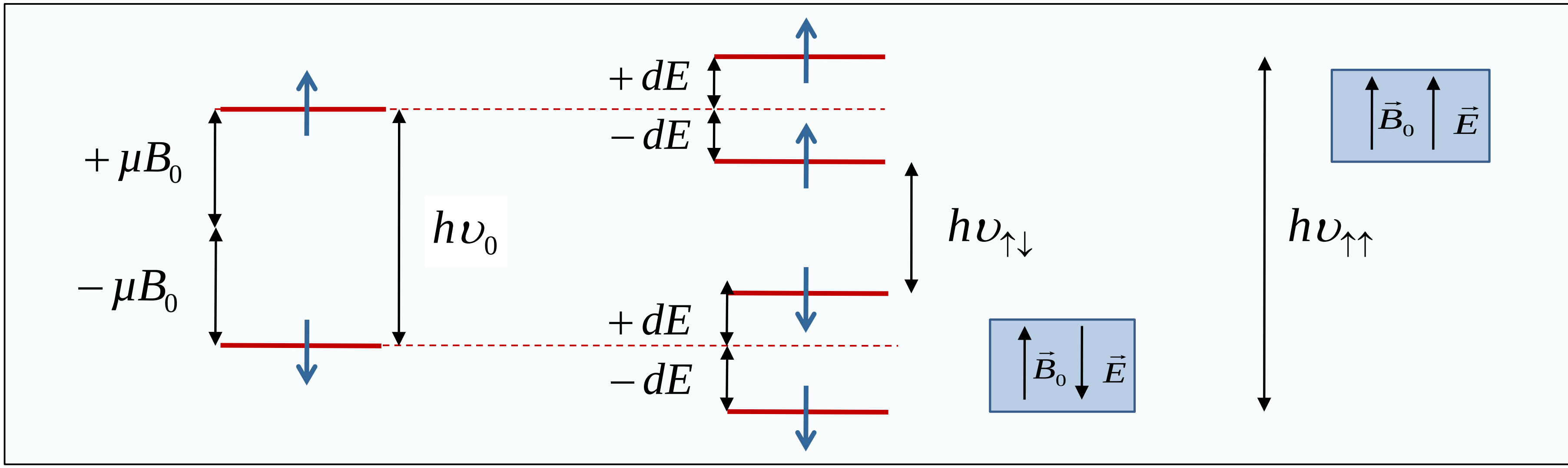
Theories exp tests





McKeen, Pospelov, Ritz
PRD 87 2013

Neutron Larmor frequency shift induced by electric field



$$h\upsilon_{\uparrow\uparrow} - h\upsilon_{\uparrow\downarrow} = 4d_n E$$

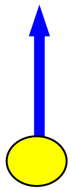
Frequency shift between parallel and anti parallel = EDM

At the present d_n limit 60 nHz difference at ~30 Hz

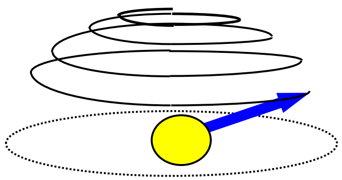
μ one turn in 3ms EDM one turn in ~1 year

→Control over B and E

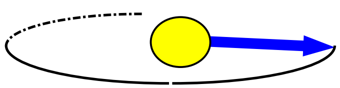
Ramsey Method of separated oscillatory Fields

1. 

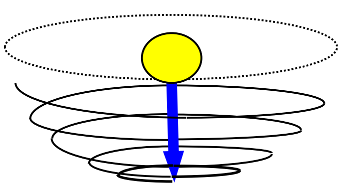
"Spin up" neutron...

2. 

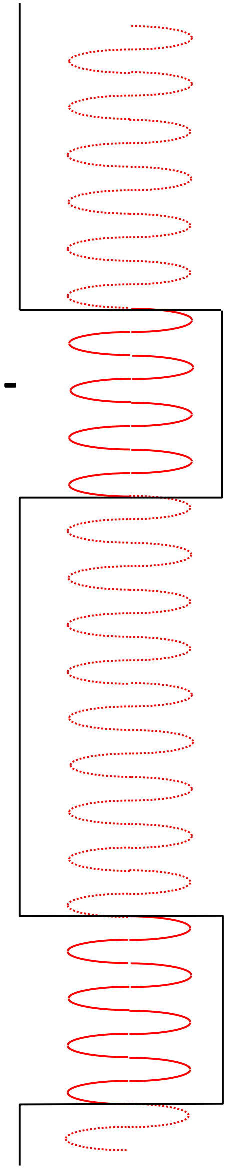
Apply π/2 spin-flip pulse
Start Clock

3. 

Free precession...

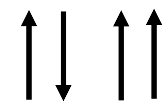
4. 

Second π/2 spin-flip pulse
Stop Clock



Measure frequency shift with

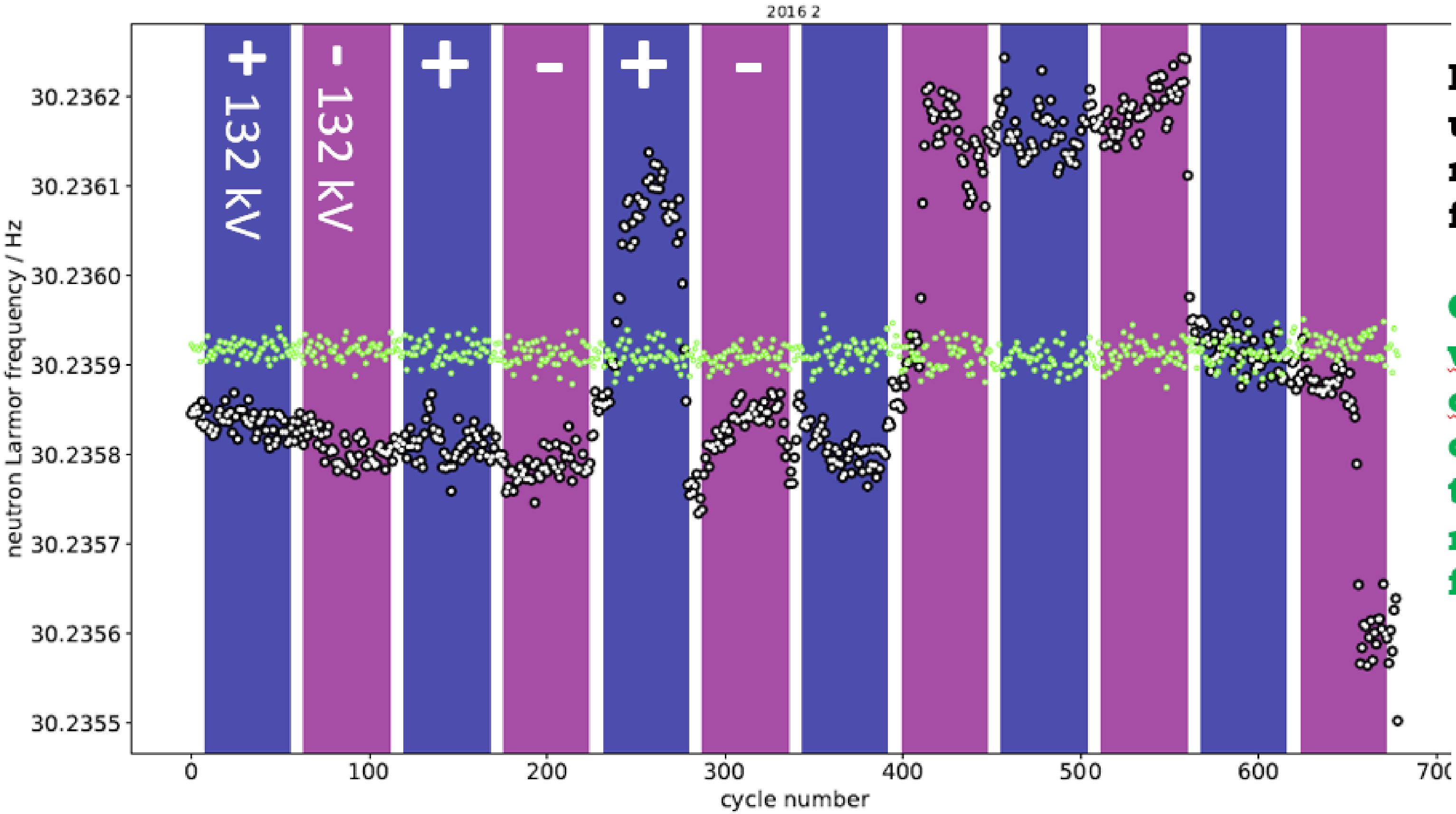
field inversion



The two precession frequency are
 obtained by scanning
the frequency

And measuring the neutron spins Counts
Ramsey pattern→ frequency

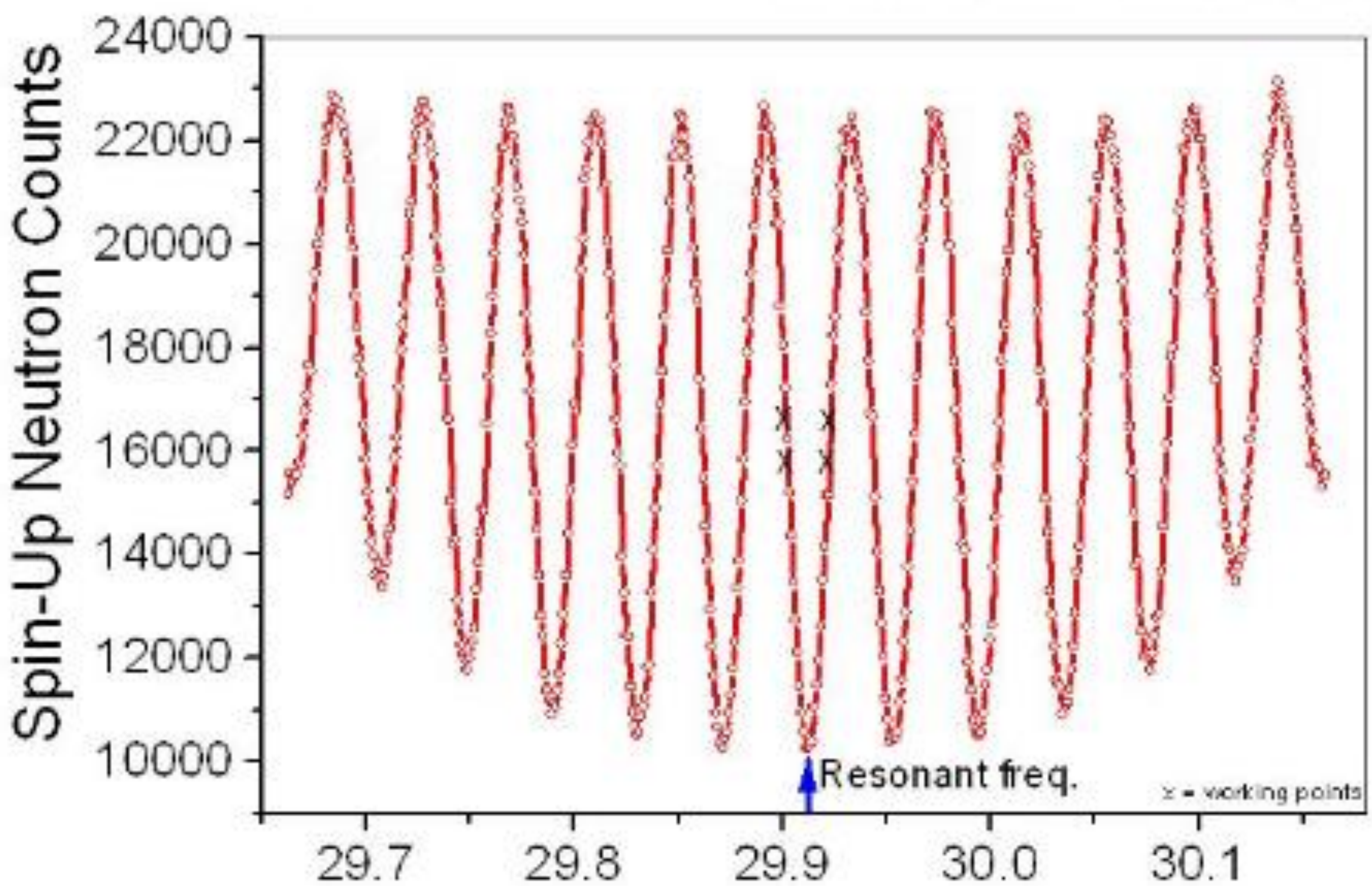
Measurement sequence and co magnetometer



Black: uncorrected neutron frequency

Green: corrected with the mercury co-magnetometer, compensates for the residual magnetic field fluctuations

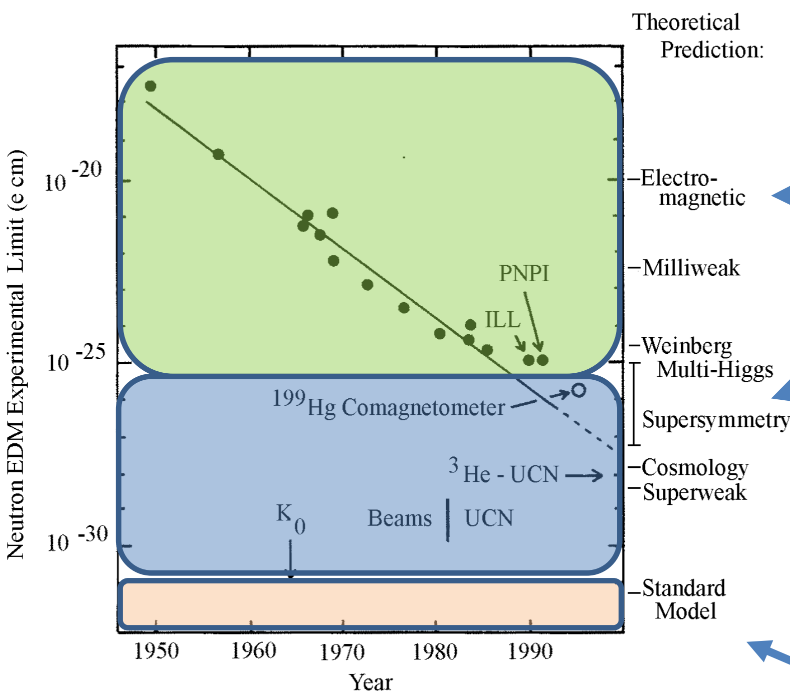
Ramsey Pattern



Sensitivity and limits

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

Highest E field (~12 kV/cm)
Longest precession time T (>100 s)
Large neutron number (few 10/cm³)
Large polarisation α (90%)



And Systematics…

Experiments

NP BSM ~10^{-27} e.cm Right there…

SM ~10^{-31} e.cm Unreachable

Ultra Cold neutrons or UCNs

To have the longest precession (observation) time we use ultra cold neutrons UCNs

Energy : En~ 10^{-7} eV~100neV, v=4-6 m/s

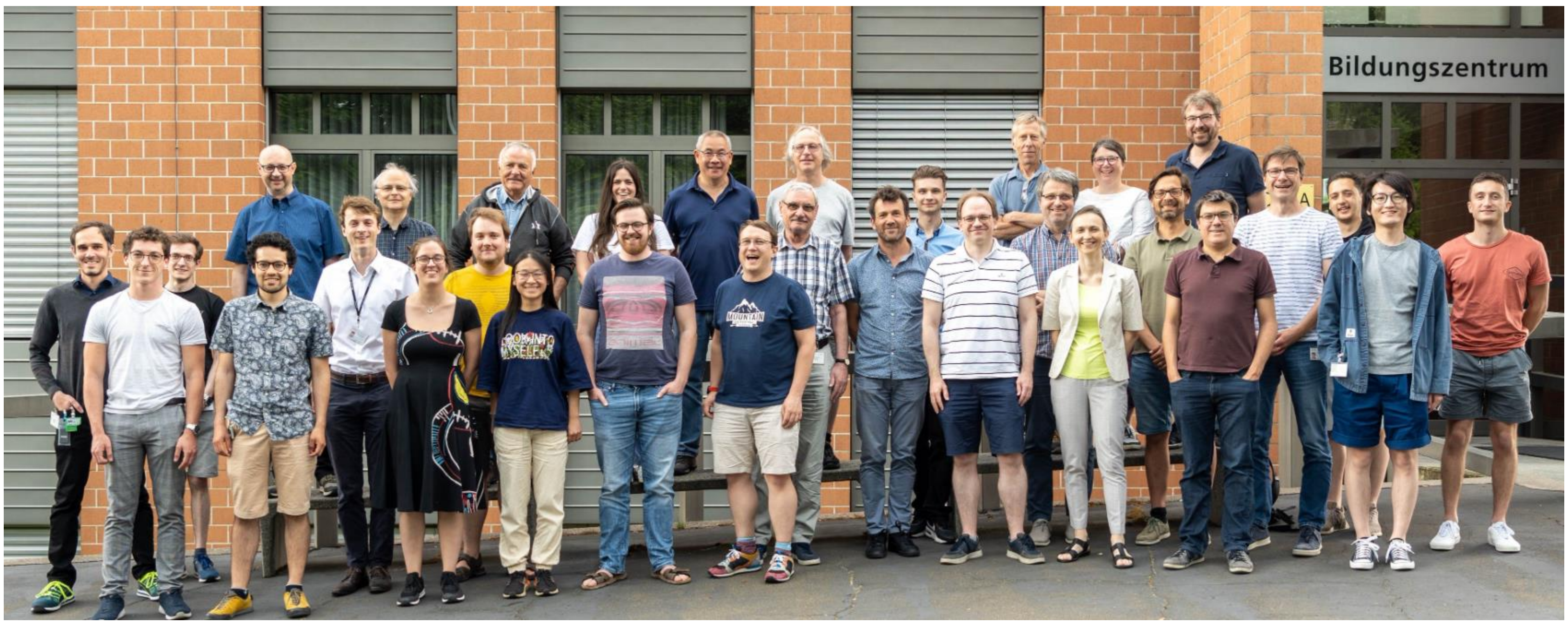
1 m jump in the earth gravity field
Can be stored in material bottles (Fermi potential 250 neV)
Or magnetic bottle (60 neV~1T)

Production from fast neutrons with fission (HFR@ILL) or spallation (PSI, LANL) through ultra cold moderators (5 K) e.g. Solid D_2
or conversion of VCN to UCN in Superfluid He (SNS, ILL)

Around the world

Place	Neutron source	Concept	Stage/Readiness
SNS	Spallation + UCN production in situ	Cryogenic double chamber with helium comagnetometers	« large scale integration » phase
PSI	Spallation + sD2 UCN source	n2EDM: double Ramsey chamber with mercury comagnetometers	Source running, experiment under construction
LANL	Spallation + sD2 UCN source	double Ramsey chamber with mercury comagnetometers	Source running, experiment in design phase
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber	Source under construction, experiment in conceptual phase
ILL	Reactor + superfluid He UCN source	panEDM: double Ramsey chamber, no comagnetometers	Source and experiment under construction
PNPI	WWR-M reactor + inpile superfluid He UCN source	Getting a really high density of UCNs	Source under construction
ESS	Spallation + Cold neutron beam	100m double beam + time of flight	Demonstration phase, small prototype operational @ ILL

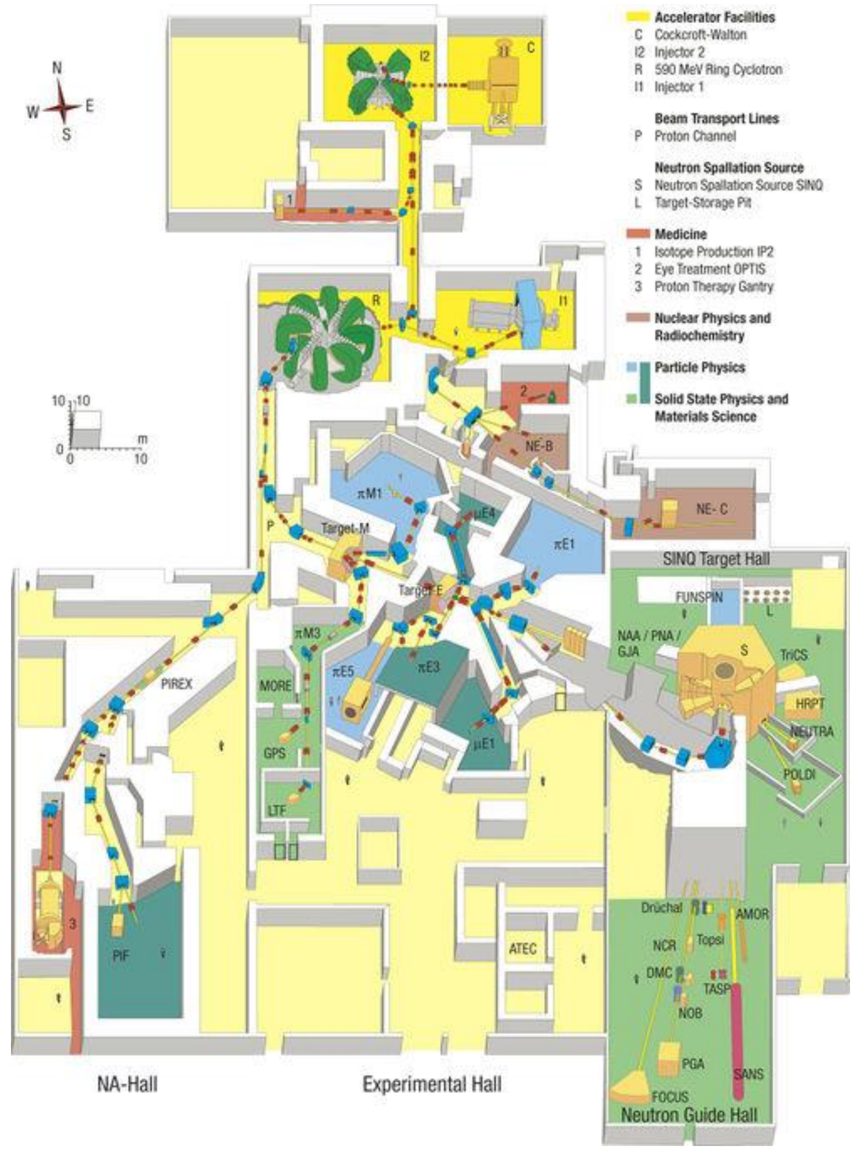
nEDM (n2EDM) collaboration 16 Institutions ~ 50 scientists



PAUL SCHERRER INSTITUT

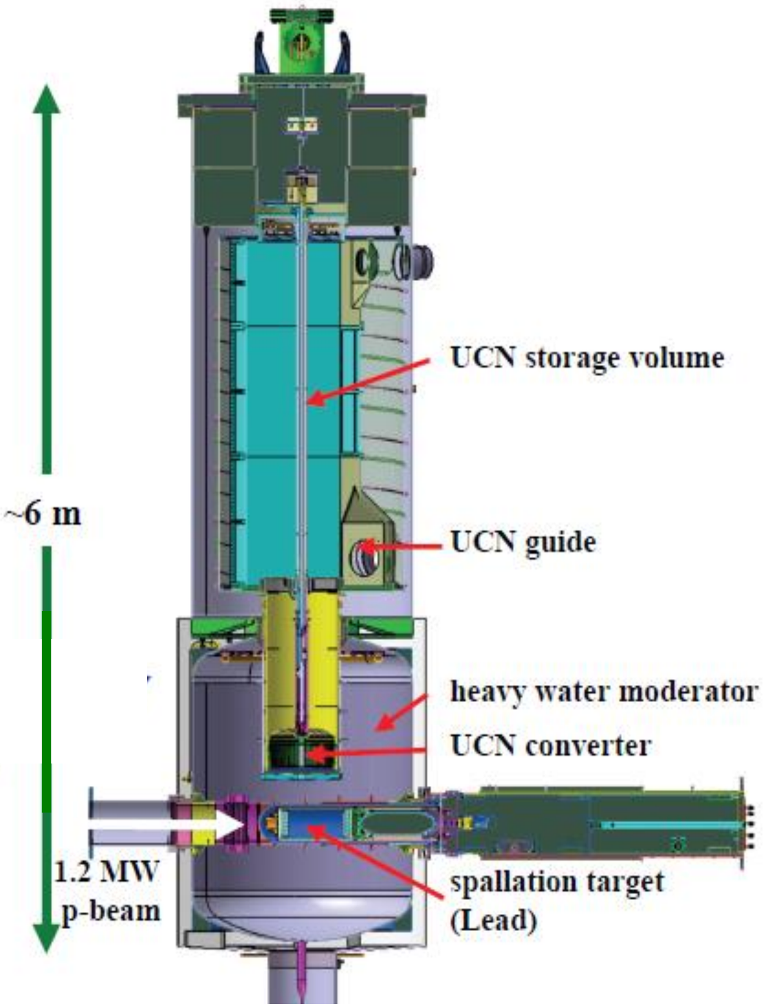
PSI

600 MeV P, 2.3 mA



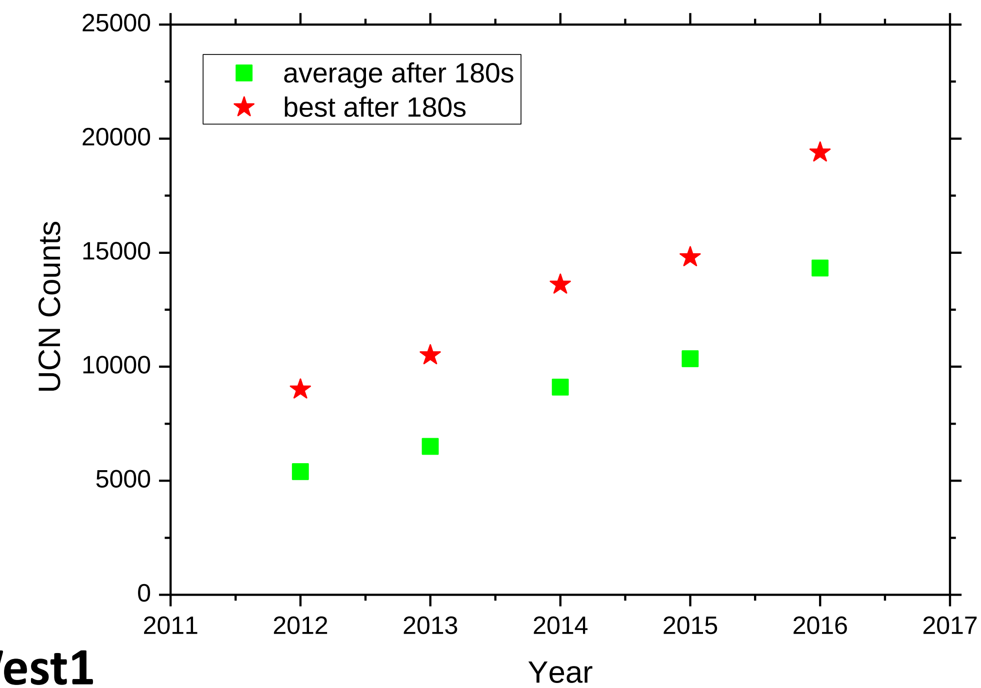
Protons & Muons & Neutrons

UCN source @ PSI (B. Lauss)



Spallation Source
~2.3 mA protons@600 MeV on lead target

Commissioning at end of 2010
Improving constantly since
a little off the prediction…

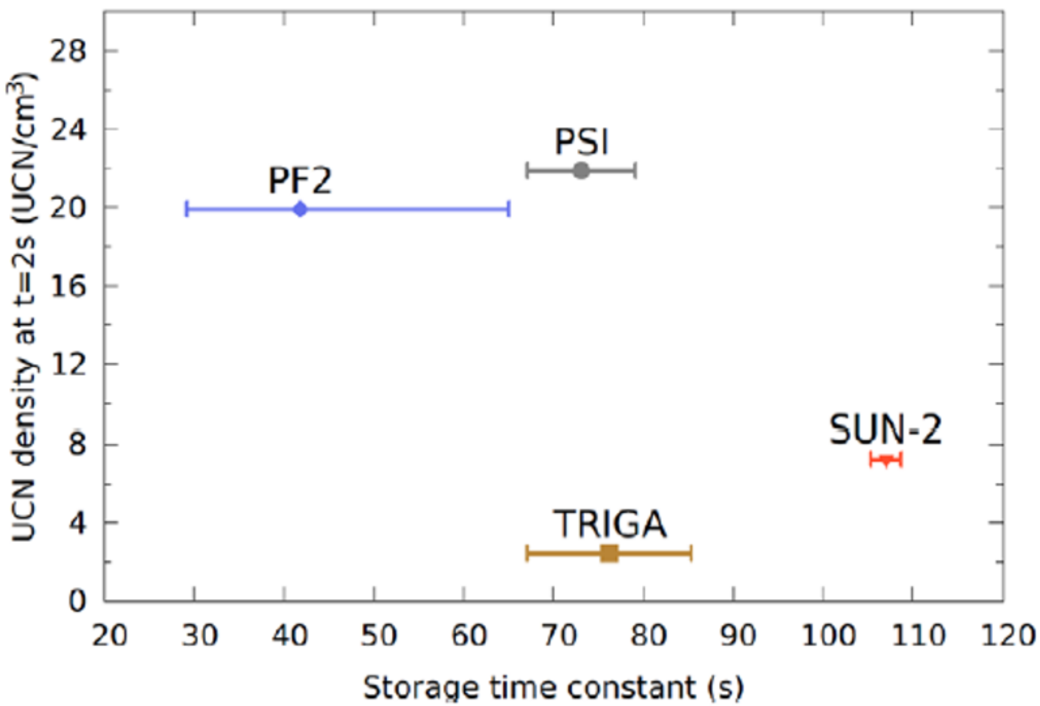


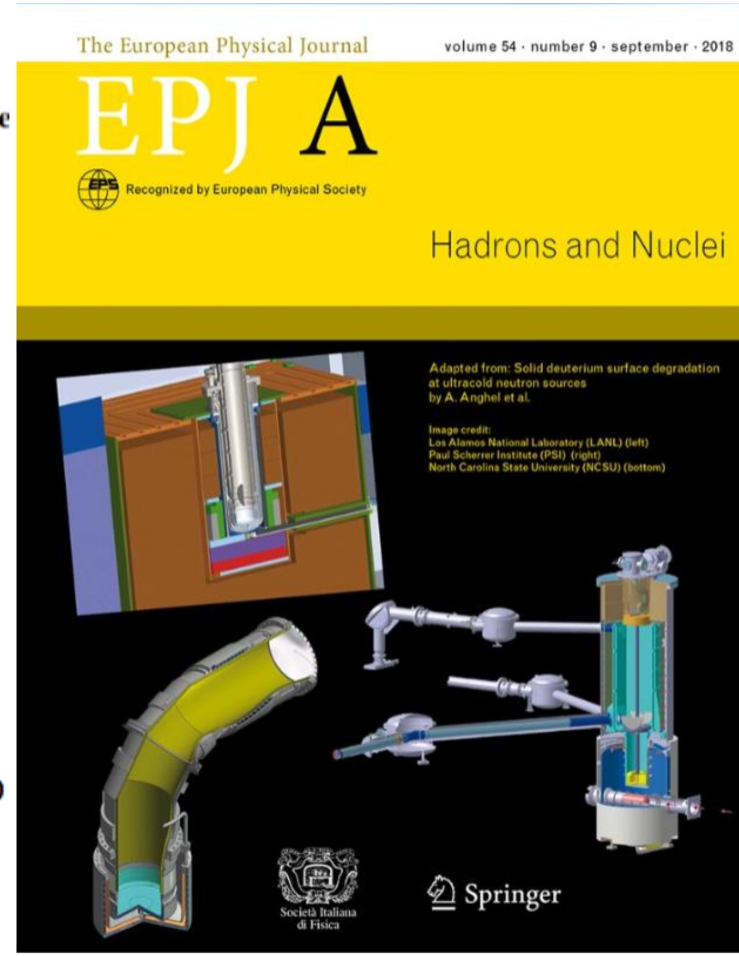
UCN density measured at West1
22 UCN/cm3

Steady improvements and understanding…

PHYSICAL REVIEW C 95, 045503 (2017)

Comparison of ultracold neutron sources for fundamental physics measureme

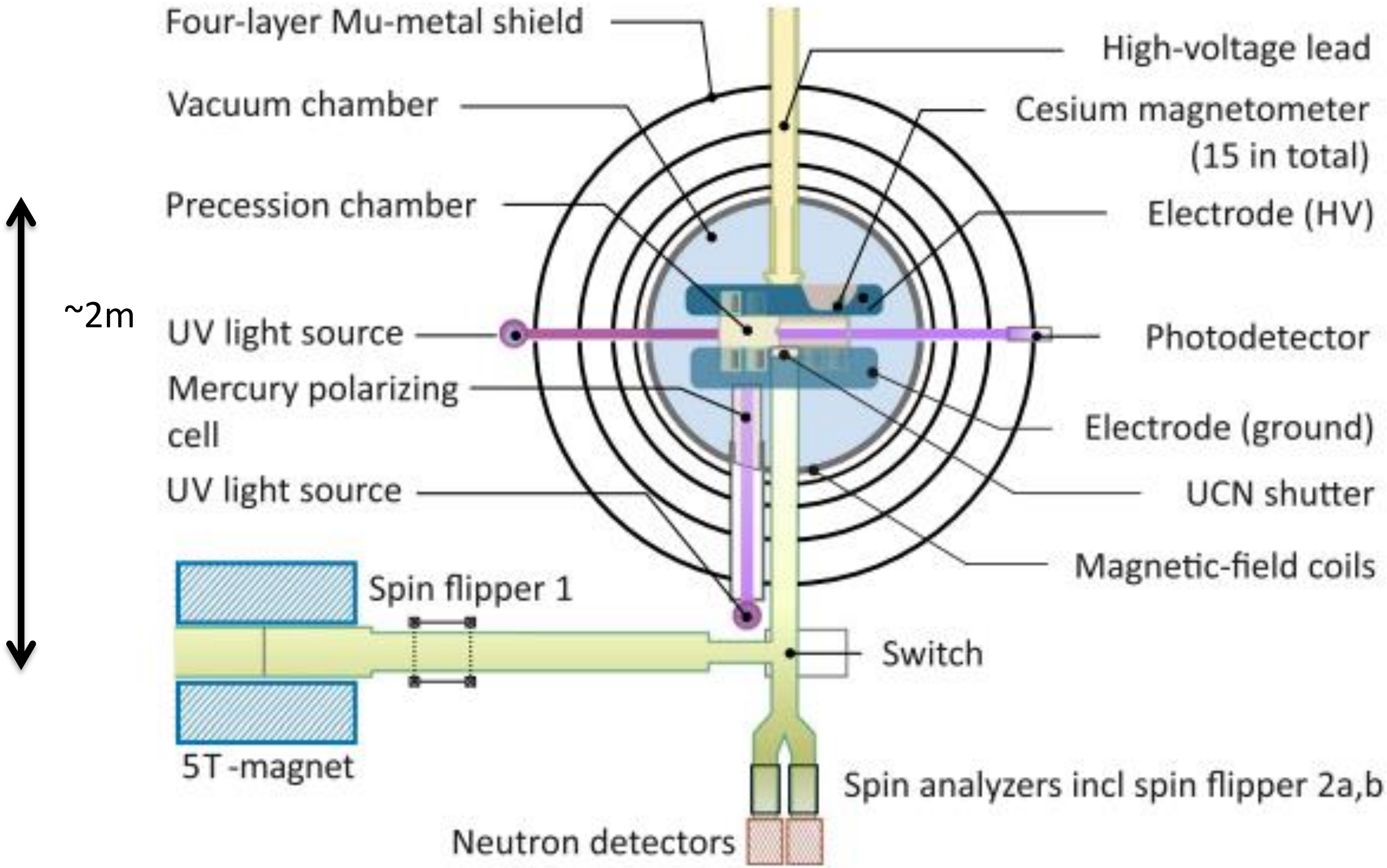




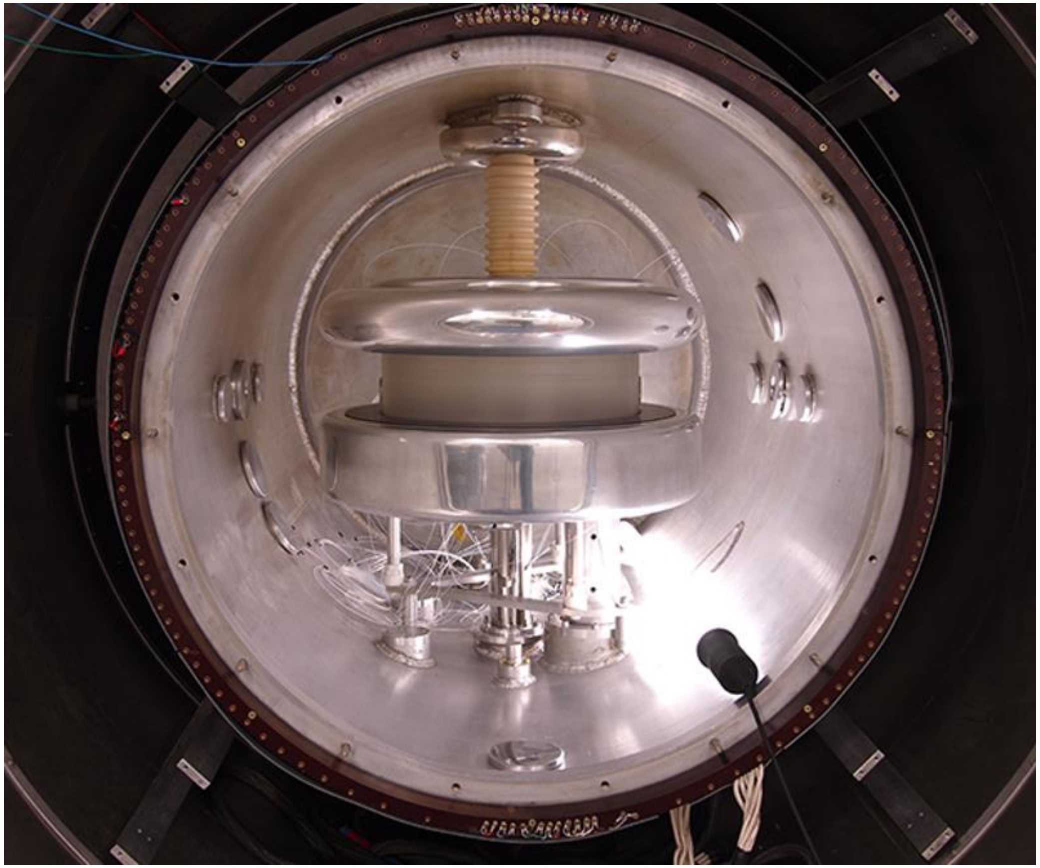
+ New source @LANL

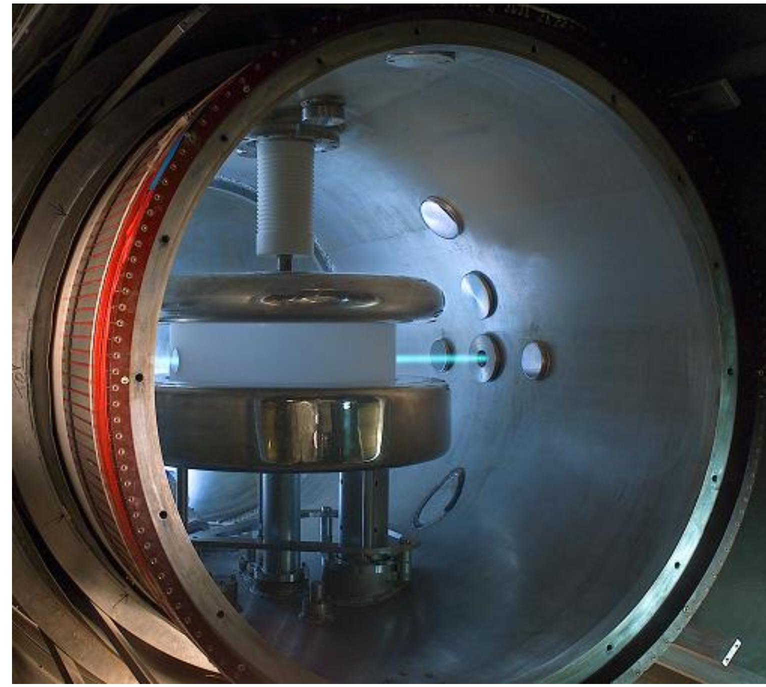
Global effort…

Spectrometer



B Field control and monitoring at the pT level





Limit and Systematics

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

$$|d_n| < 1.8 \times 10^{-26}\, e\cdot\text{cm} \;\; (90\% \text{ C.L.})$$

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

In 10^{-28} ecm

Stats..

Systematics improved x5

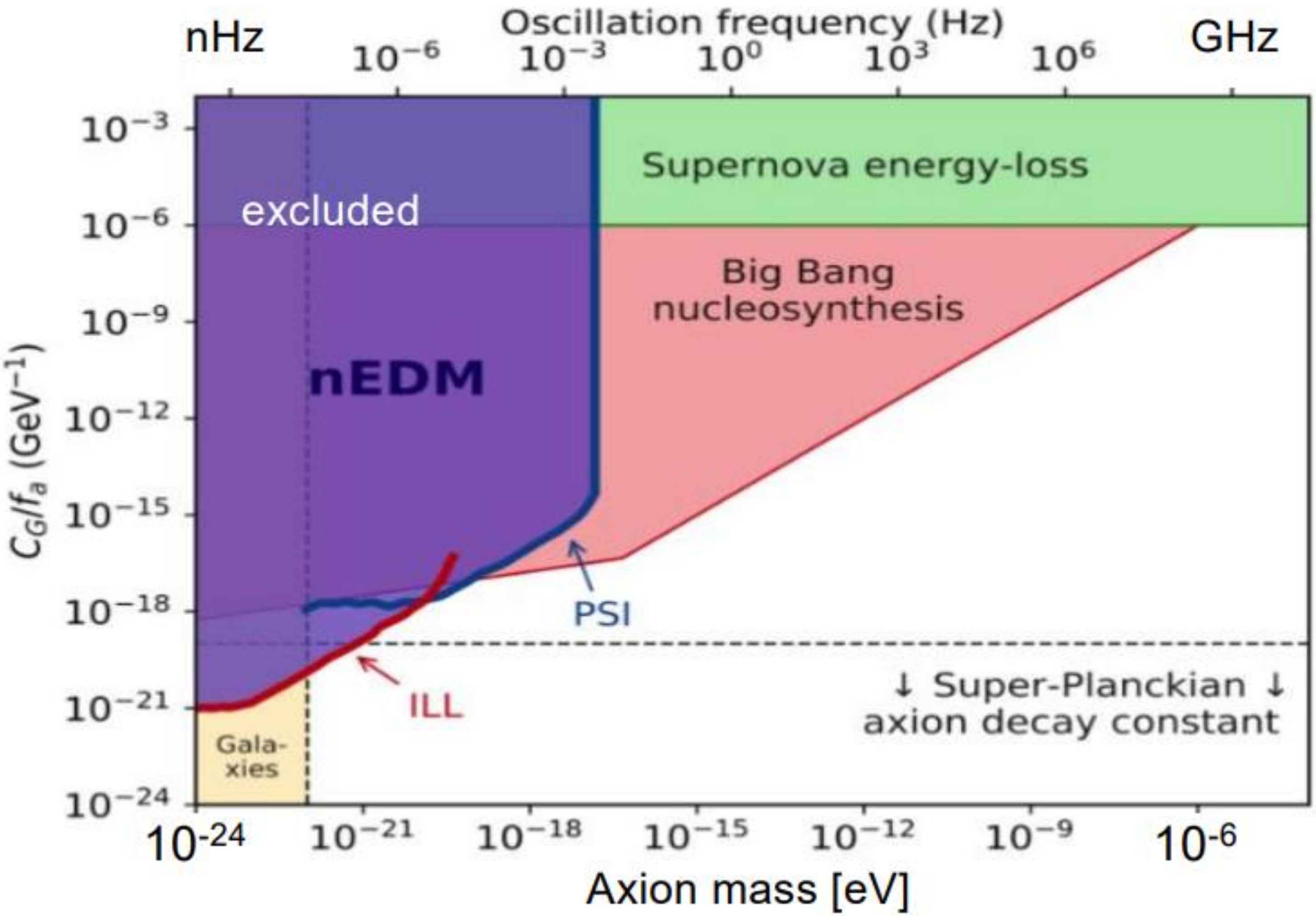
B field

Gradients

…

C. Abel et al. PRL 124081803 (2020)

Other result
Ultra light Axions in lab…



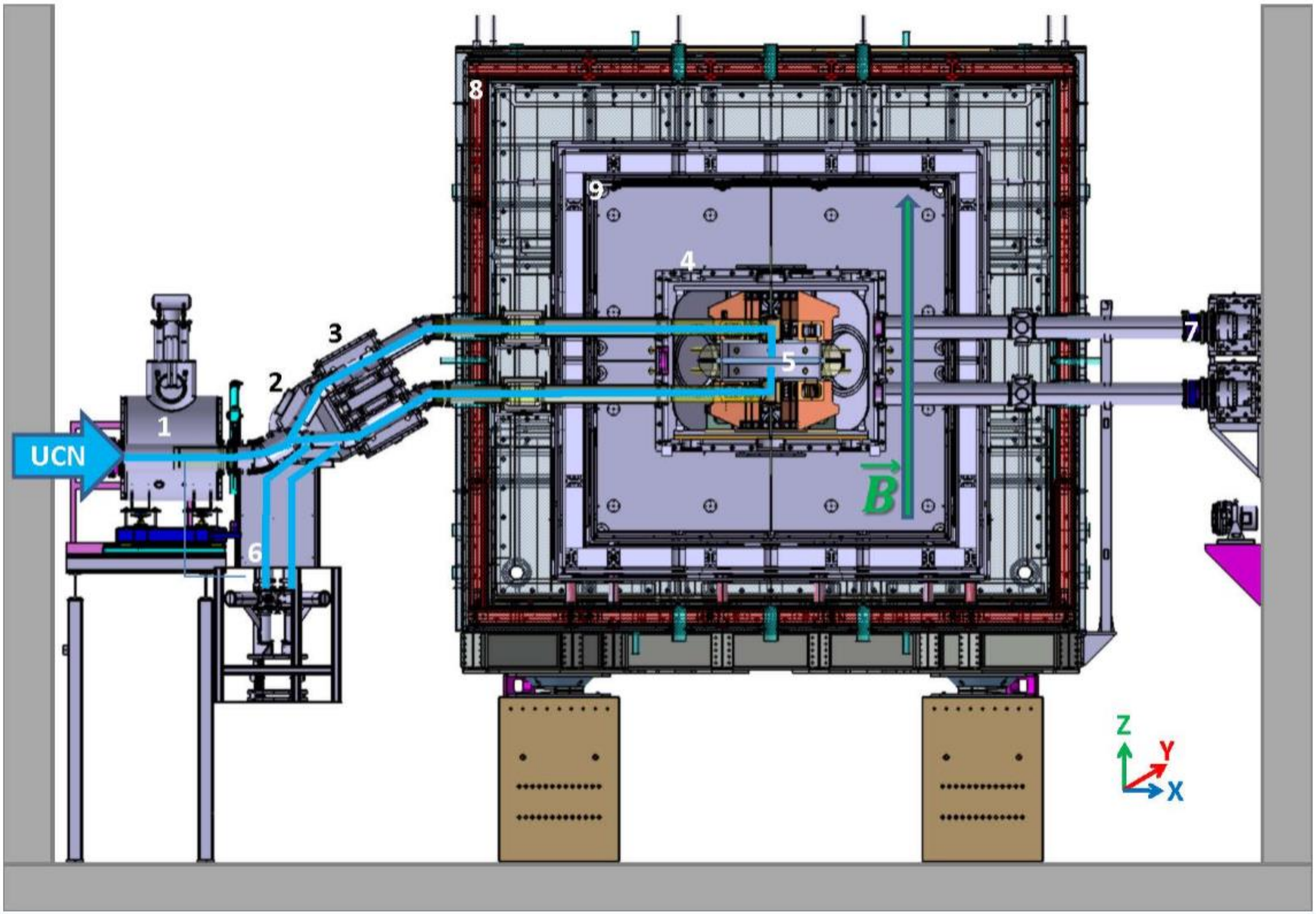
n2EDM

«Same techniques but every component is new and upgraded

New shielding
New guides
New vaccum vessel
Double chamber
....

N.Ayres et al. Eur. Phys. J. C 81: 512 (2021)

Multi layer µmetal shielding ~5x5x5 m 3x3x3 internal

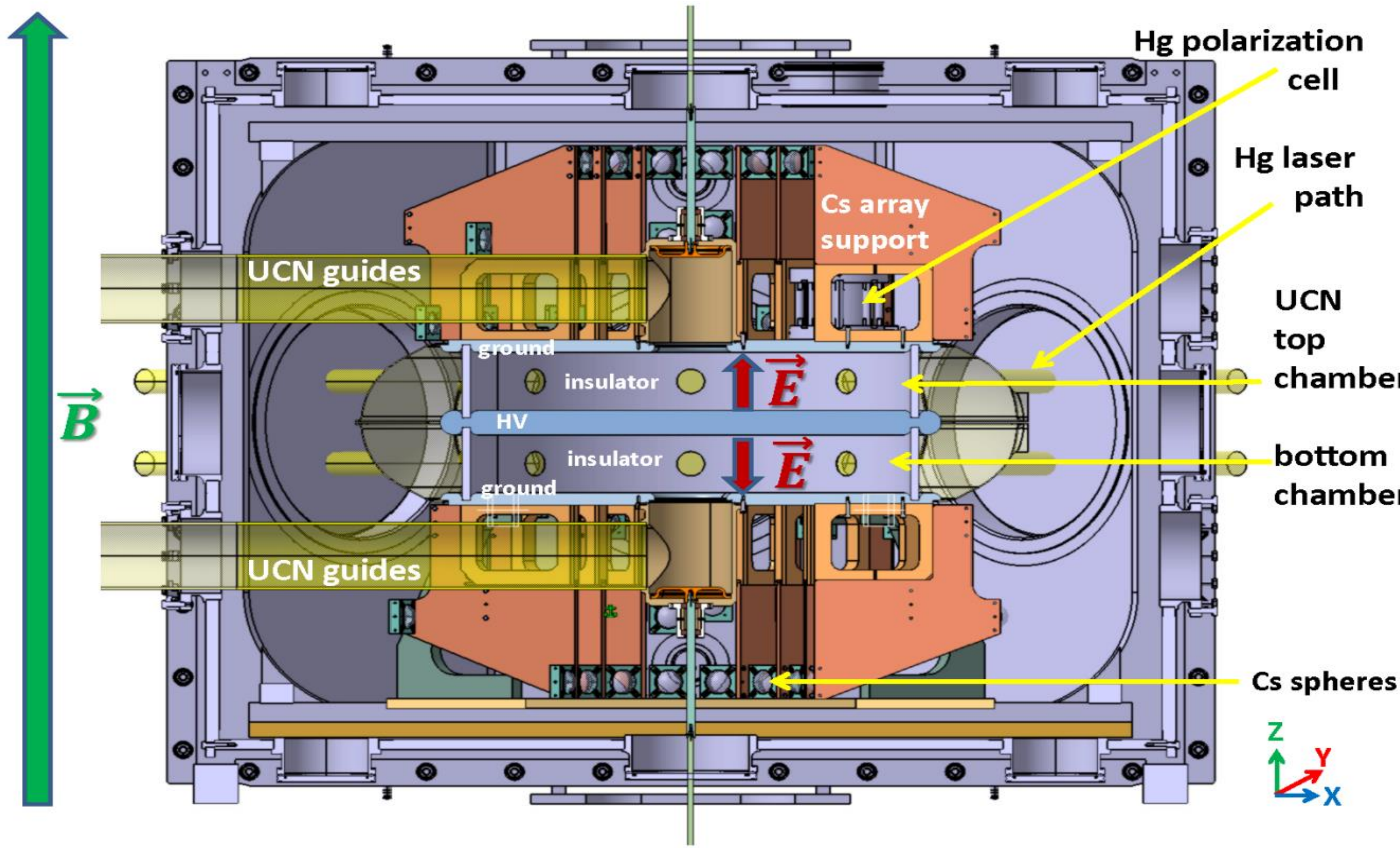


B field requirements

Stringent requirements to the magnetic field homogeneity and its measurement

Related to statistical errors	
(B-gen) Top-Bottom resonance matching condition	$-0.6\,\mathrm{pT/cm} < G_{1,0} < 0.6\,\mathrm{pT/cm}$
(B-gen) Field uniformity	$\sigma B_z = \sqrt{\langle (B_z^c)^2 \rangle} < 170\,\mathrm{pT}$
(B-gen) Field stability on minutes timescale	30 fT
(B-meas) Precision Hg co-magnetometer, per cycle, per chamber	30 fT
Related to systematical errors	
(B-gen) Gradient stability on the timescale of minutes	50 fT/cm
(B-meas) Accuracy mercury co-magnetometer per chamber	100 fT
(B-meas) Accuracy on cubic mode (Cs magnetometers)	$\delta G_{3,0} = 4 \times 10^{-5}\,\mathrm{pT/cm^3}$
(B-gen) Reproducibility of the order 5 mode	$\sigma G_{5,0} = 2 \times 10^{-8}\,\mathrm{pT/cm^5}$
(B-meas) Accuracy of the order 5 mode (field mapper)	$\delta G_{5,0} = 2 \times 10^{-8}\,\mathrm{pT/cm^5}$
(B-gen) Dipoles close to the electrode	20 pT at 5 cm

n2EDM Room temperature spectrometer
Double chamber, Larger volume



Expected Statistical sensitivity

	nEDM 2016	n2EDM
chamber diameter D	DLC & dPS 47 cm	DLC & dPS 80 cm
N (per cycle) T E α	15'000 180 s 11 kV/cm 0.75	121'000 180 s 15 kV/cm 0.8
$\sigma(f_n)$ per cycle	9.6 μHz	3.2 μHz
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm
$\sigma(d_n)$ (final)	9.5×10^{-27} e cm	1.1×10^{-27} e cm

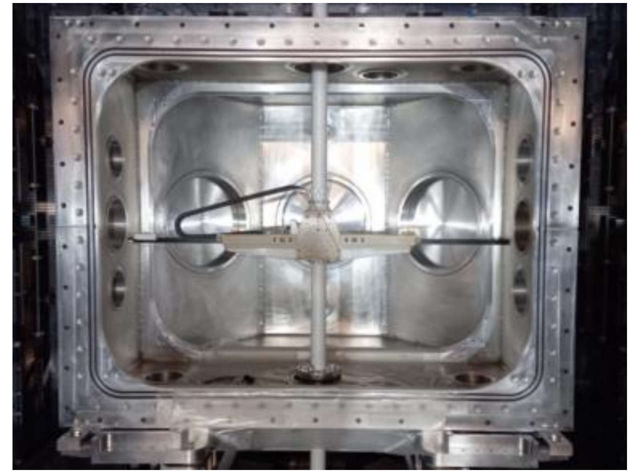
Obtained

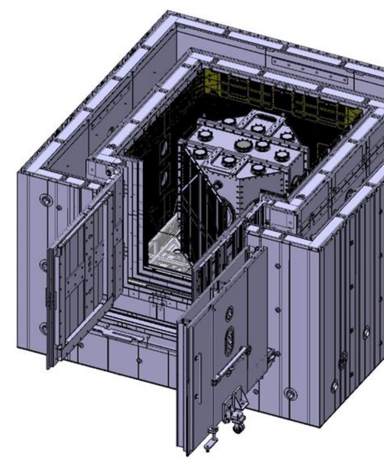
500 days data taking

nEDM to n2EDM

nEDM

Magnetic Shielding Room and vacuum chamber



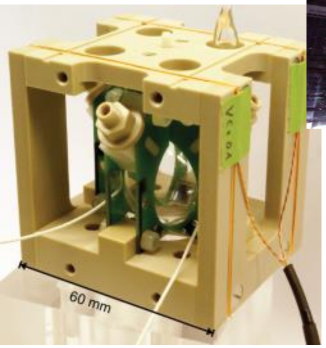


n2edm → commissioning 2021-22

Detector

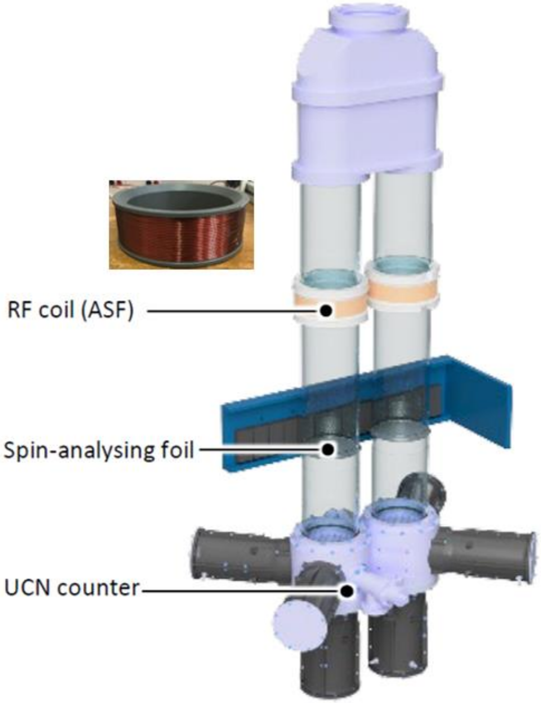
Room temperature spectrometer
Double chamber, Larger volume

- **Detection UCN Fast detectors (Gas Scintillation)**
- **CS HV magnetometers (pT)**
- **Laser Hg co magnetometry**
- **Double spin analysis**
- **Coil design…**



CS vector magnetometer

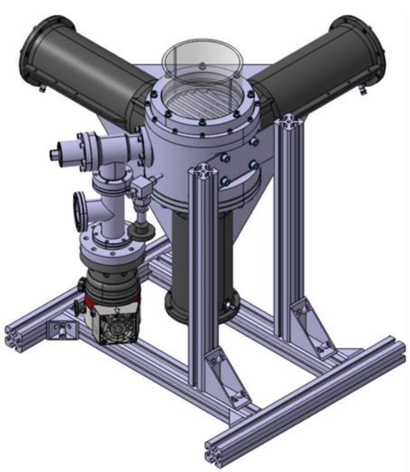
Coils

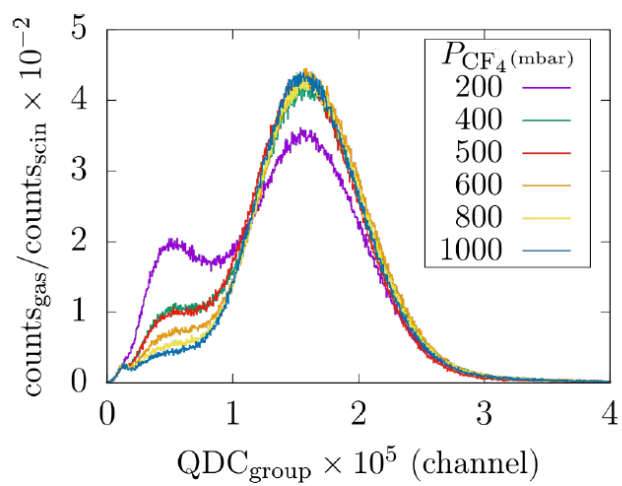


Spin analysis

UCN detectors

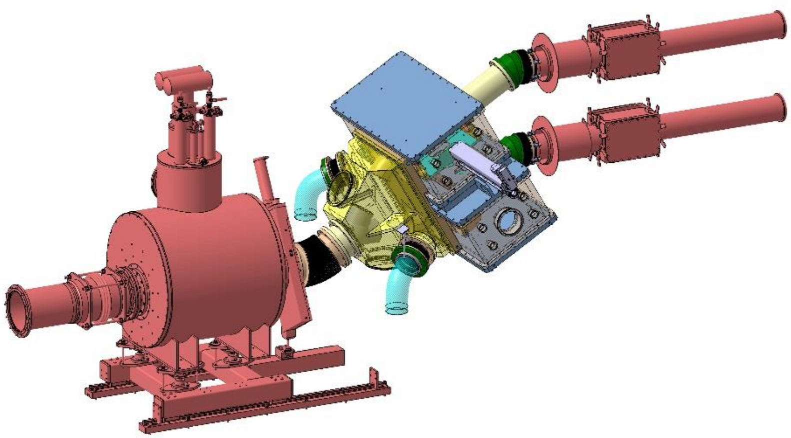
Fast UCN detectros (up to 10^{6} UCN/s)
Gas scintillation with CF4 and ^{3}He

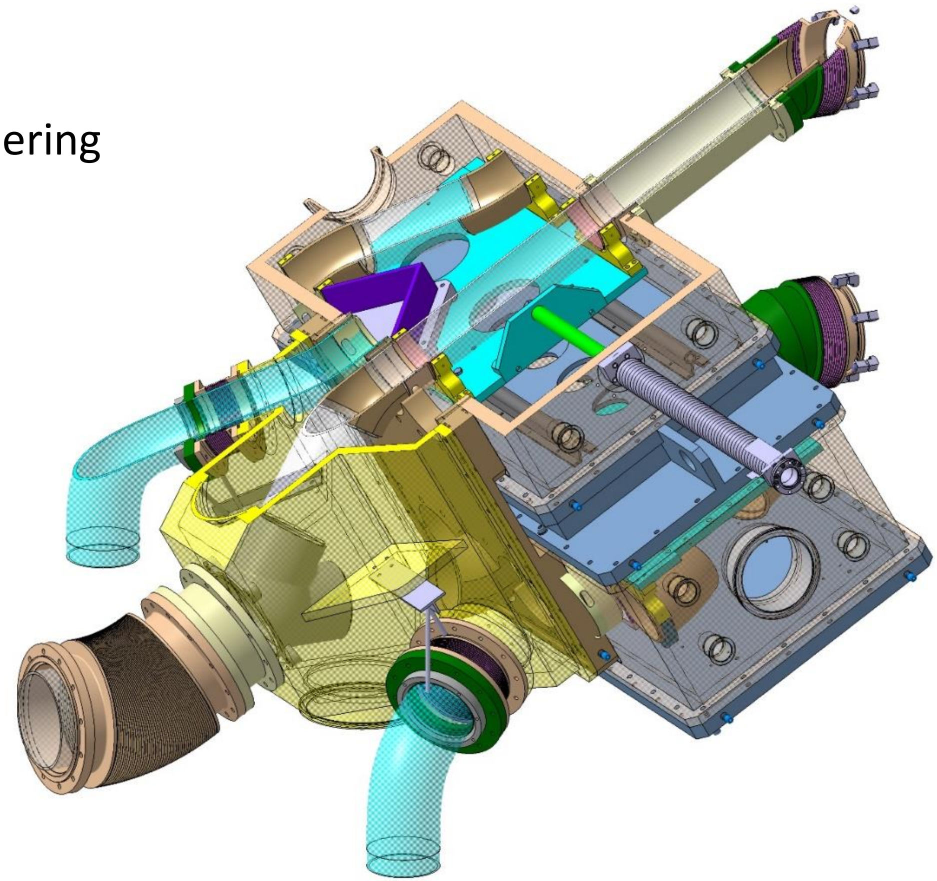




UCN Switch

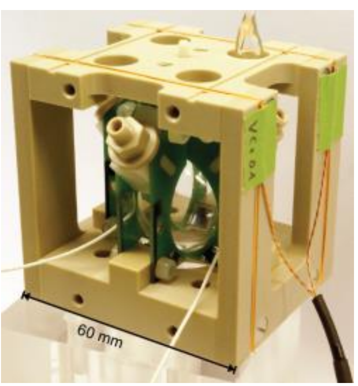
Fill up the neutron
Keep them in the precession chamber
Detect them
→
Very complicated piece of engineering

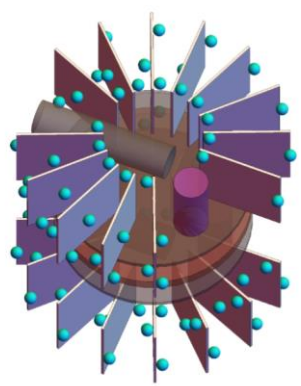




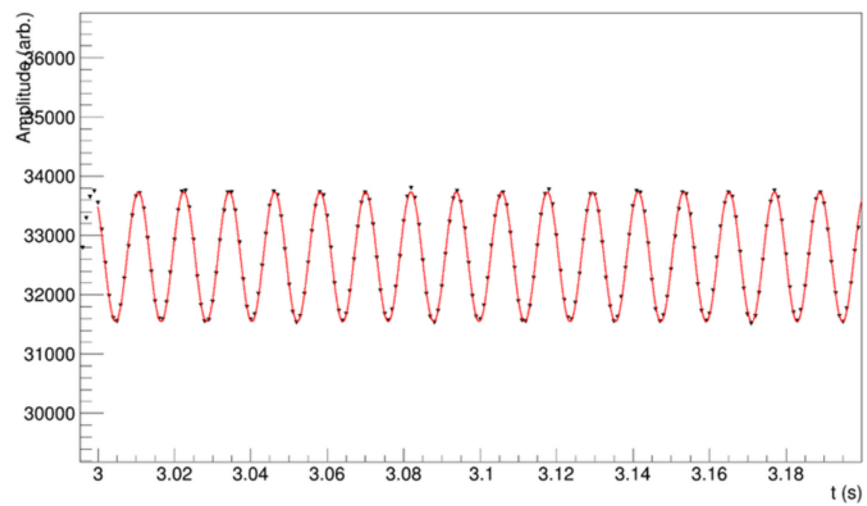
Magnetometry CS and Hg Magnetometer

	2017, 1 µT, standard Cs array	2018, 1 µT, optimized Cs array	2018, 10 µT optimized Cs array
Cs accuracy requirement	< 1.3 pT	< 5.2 pT	approx. 150 pT
Cs accuracy goal	0.5 pT	2 pT	approx. 60 pT
Cs position accuracy	0.1 mm	0.5 mm	approx. 1.5 mm
B0 stability goal	30 ppb	30 ppb	3 ppb
B0 homogeneity requirem.	170 ppm	170 ppm	17 ppm
MR pulse generation	30 Hz	30 Hz	300 Hz
		baseline	upgrade



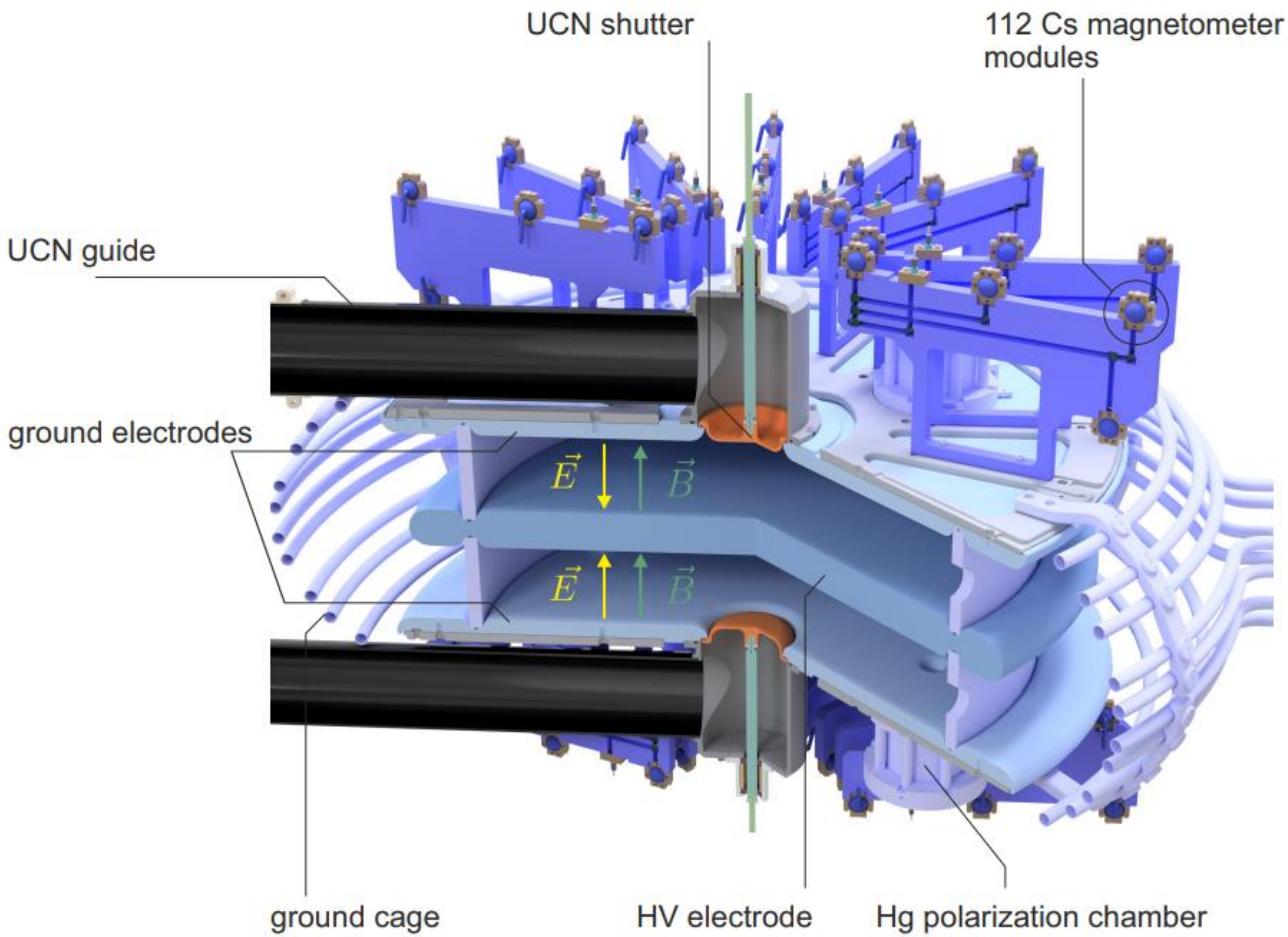


Cs magnetometer PSI



Hg precession with laser Grenoble

Double chamber + Cs Array



Conclusion

EDM are a powerful probe to search for BSM CPV source

It might explain Baryon asymmetry

Present limit <1.8 10^{-26} e.cm (2020)

All new spectrometer under completion
neutrons by the end of 2022

Goal a non zero EDM or a limit 10^{-27} e.cm in ~2027

THANK YOU
For Your ATTENTION !!