Status of neutron EDM measurements

DIS2024, Grenoble
April 11, 2024

Skyler Degenkolb

Physikalisches Institut, Universität Heidelberg

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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Caveat: Euro-centric perspective,
other efforts in the US and Canada
are also in commissioning phases
(details: see nEDM2023 workshop)

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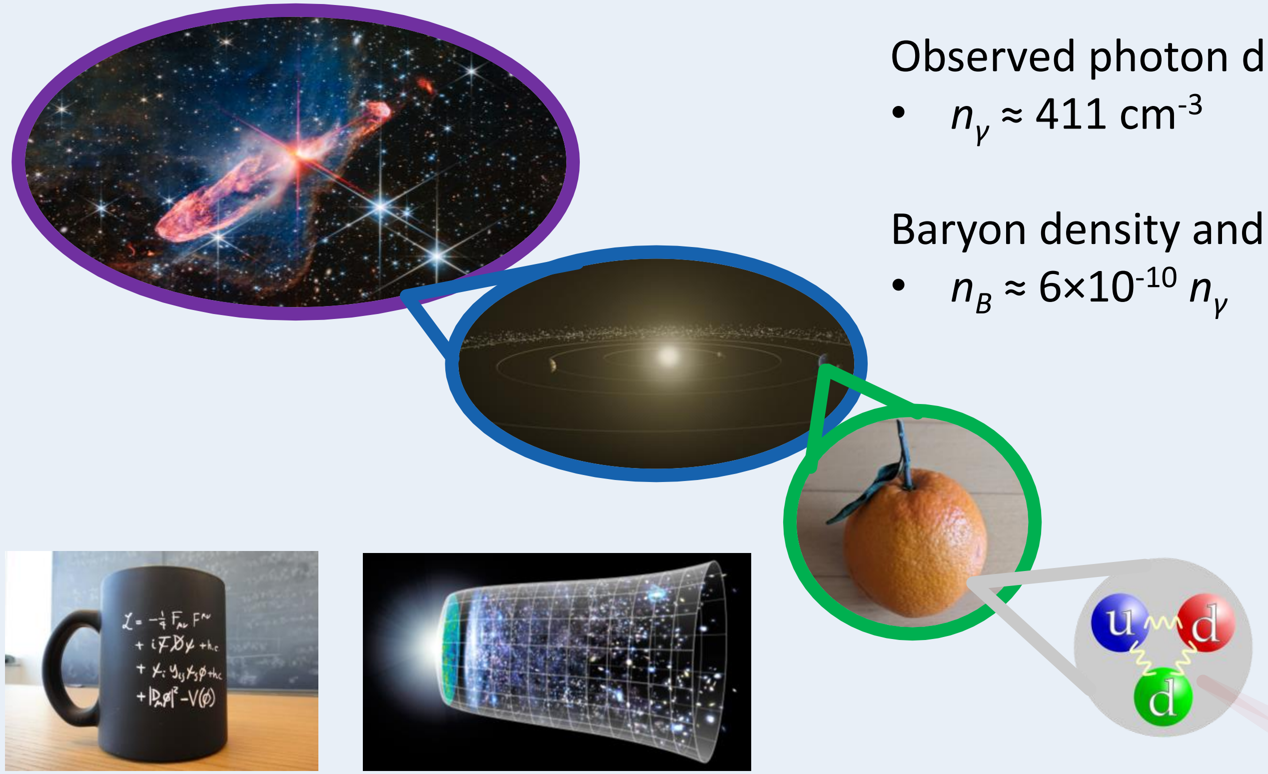
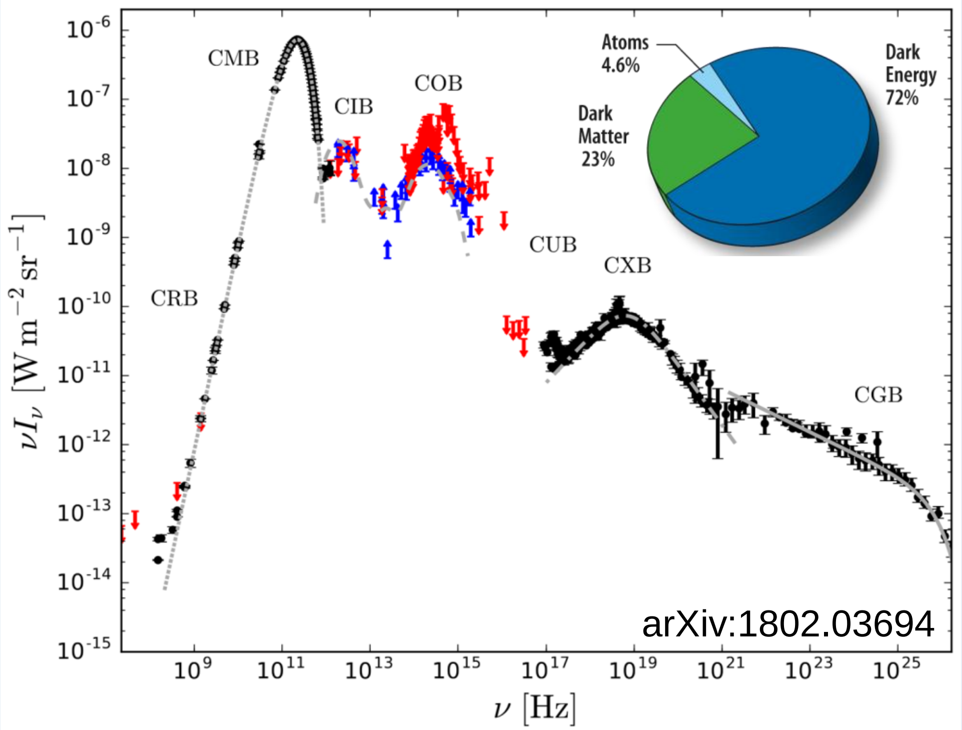


Observed photon density (CMB):

- $n_\gamma \approx 411\ \mathrm{cm}^{-3}$

Baryon density and asymmetry:

- $n_B \approx 6\times10^{-10}\ n_\gamma$



Sakharov criteria for Baryogenesis:

1. B non-conservation
2. **C and CP violation**
3. Far from thermal equilibrium

$$\mathscr{L}_{\text{fermion}} = -\frac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi - i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi$$

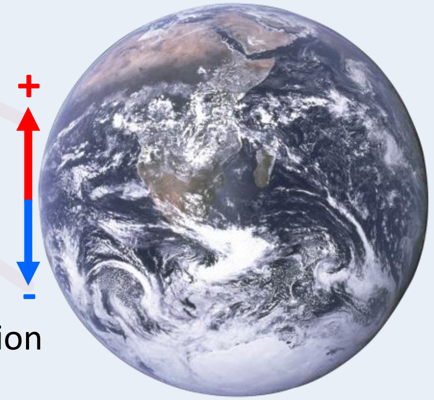
MDM **EDM**

Strong CP problem:

- $|d_n| < 10^{-26}\ e\cdot\mathrm{cm}$ (measured)
- implies $|\theta_{\mathrm{QCD}}| < 10^{-10}$ (too small)

$$H_{spin} = -\boldsymbol{\mu}\cdot\mathbf{B} - \mathbf{d}\cdot\mathbf{E}$$

neutron (enlarged)



EDM separation
< 1 μm

A Taxonomy of Form Factors

*not just for composite particles!

$$\mathscr{L}_{\text{fermion}} = -\tfrac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi - i\tfrac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi$$

MDM **EDM**

$$\begin{aligned}\langle p_f|\, j^\mu \,|p_i\rangle = \bar{u}(p_f)\Big[& F_1(q^2)\gamma^\mu \\ & + \frac{i\sigma^{\mu\nu}}{2m} q_\nu F_2(q^2) \\ & + i\epsilon^{\mu\nu\rho\sigma}\sigma_{\rho\sigma}q_\nu F_3(q^2) \\ & + \frac{1}{2m}\left(q^\mu - \frac{q^2}{2m}\gamma^\mu\right)\gamma_5 F_4(q^2)\Big] u(p_i)\end{aligned}$$

$$d = -\frac{F_3(0)}{2m} \qquad Q = F_1(0)$$

$$\mu = \frac{F_1(0)+F_2(0)}{2m} \qquad a = F_4(0)$$

A Taxonomy of Form Factors

$$\mathscr{L}_{\text{fermion}} = \boxed{-\frac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi}\boxed{-i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi}$$

MDM **EDM**

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$$Q = F_1(0)$$

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$$a = F_4(0)$$

2020 European Strategy Update

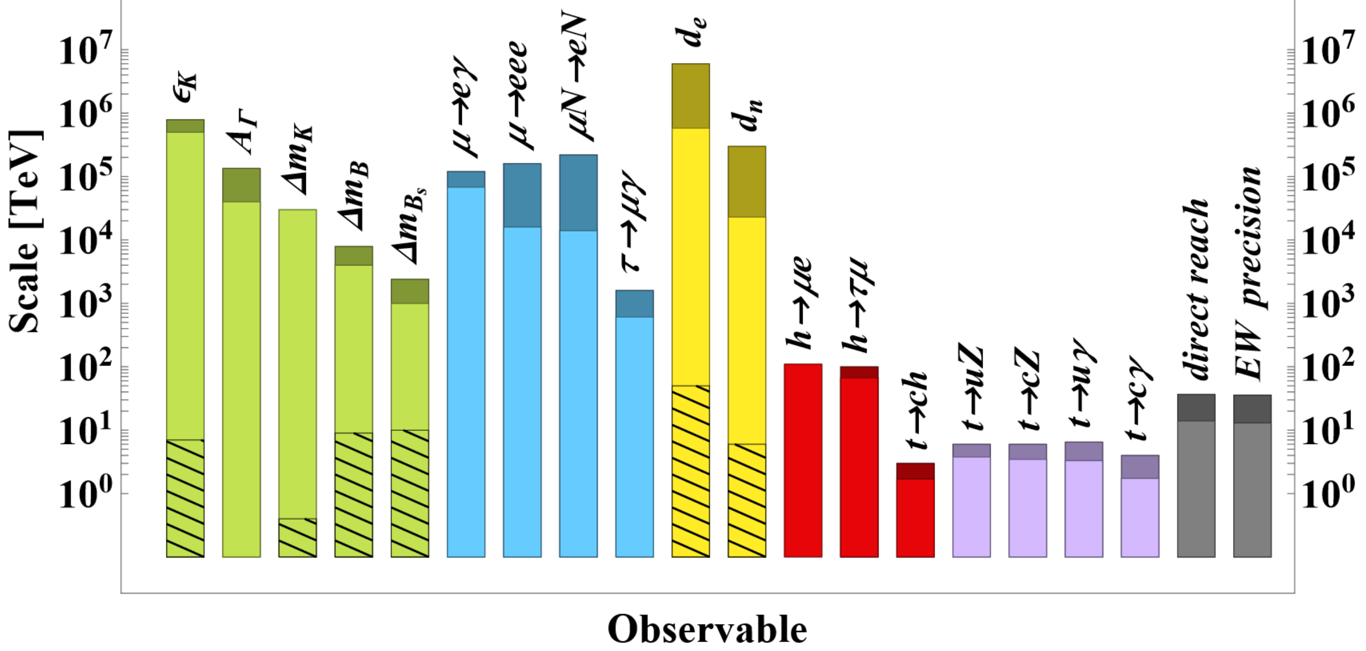
Other essential scientific activities for particle physics

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

2020 European Strategy Update

From the Physics Briefing Book input (arXiv:1910.11775):

(Do not over-interpret!)

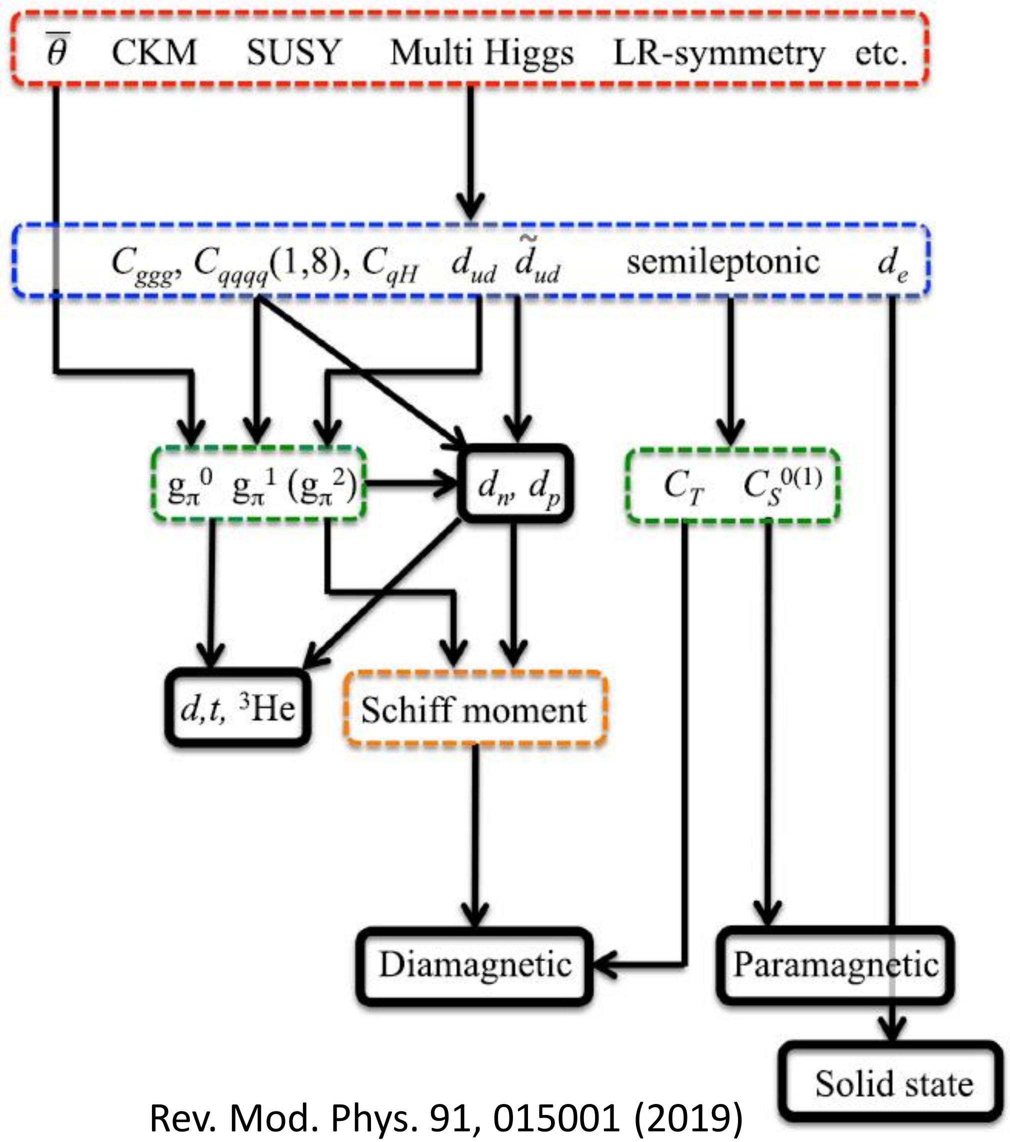


Reality: many parameters, many experiments

System i	Measured d_i [e cm]	Upper limit on $\lvert d_i \rvert$ [e cm]	Reference
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$	[47]
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	[48]
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	[49]
HfF$^+$	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$	[50]
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$	[51]
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$	[52]
^{199}Hg	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$	[53, 54]
^{129}Xe	$(-1.76 \pm 1.82) \cdot 10^{-28}$	$4.8 \cdot 10^{-28}$	[55, 56]
^{171}Yb	$(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$	$1.5 \cdot 10^{-26}$	[57]
^{225}Ra	$(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	[58]
TlF	$(-1.7 \pm 2.9) \cdot 10^{-23}$	$6.5 \cdot 10^{-23}$	[59]
	Measured ω_i [mrad/s]	Rescaling factor x_i for d_i	Reference
HfF$^+$	$(-0.0459 \pm 0.0716_{\text{stat}} \pm 0.0217_{\text{syst}})^*$	0.999	[50]
ThO	$(-0.510 \pm 0.373_{\text{stat}} \pm 0.310_{\text{syst}})$	0.982	[51]
YbF	$(5.30 \pm 12.60_{\text{stat}} \pm 3.30_{\text{syst}})$	1.12	[52]

Table 1: Measured EDM values and 95% C.L. ranges used in our global analysis. For ^{129}Xe we combine two independent results with similar precision, using inverse-variance weighting. For the paramagnetic molecules, we also provide the measured angular frequencies and the rescaling factor which allows us to use $x_i d_i$ for each experimentally reported d_i. *The frequency for HfF$^+$ is scaled by a factor of 2 relative to Ref. [50], to consistently use Eq.(27) for all systems.

arXiv:2403.02052



Rev. Mod. Phys. 91, 015001 (2019)

Joint analysis: 11 experiments / 7 parameters

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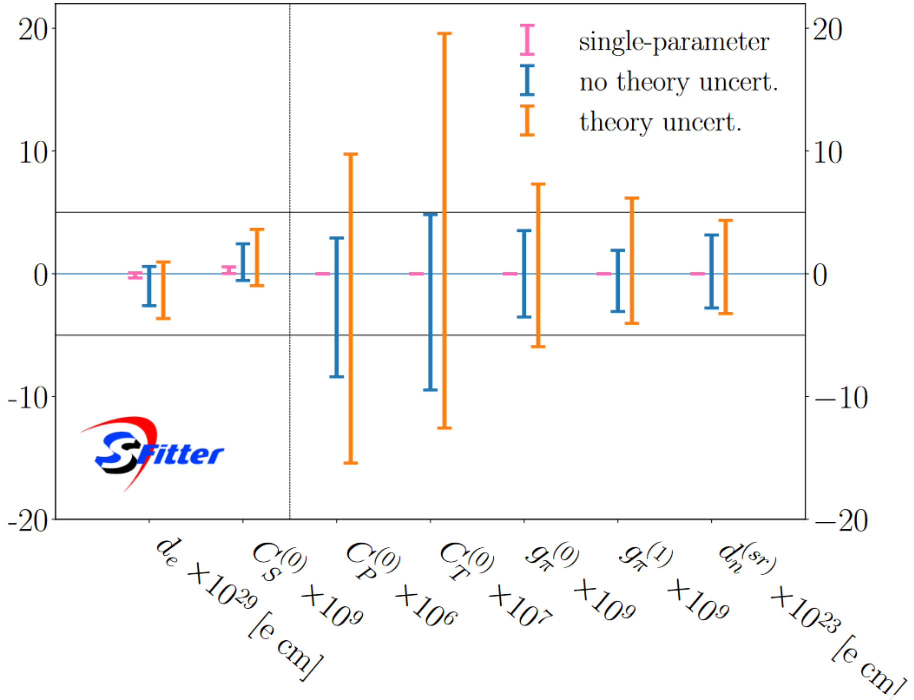
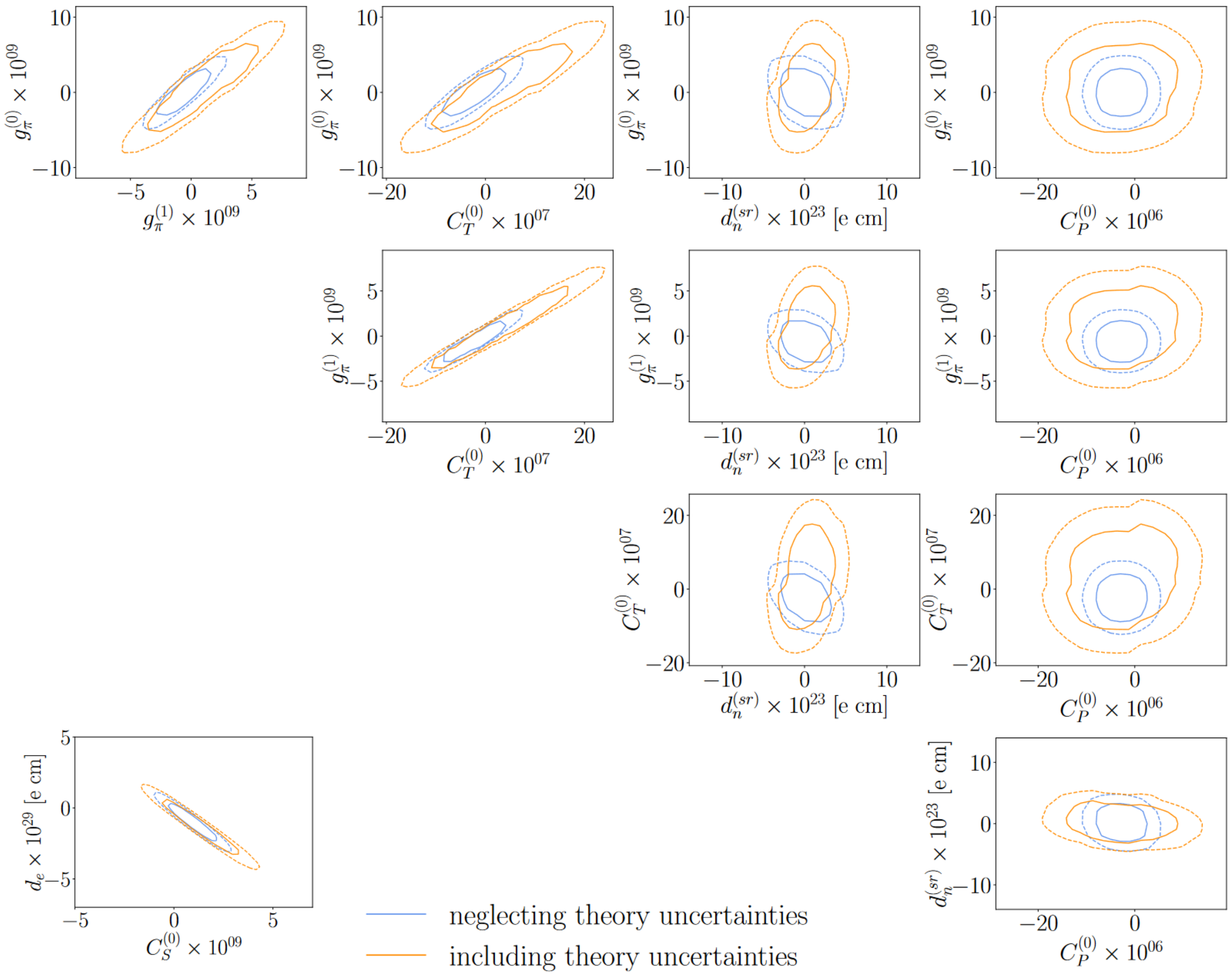
Hadronic scale global analysis: arXiv:2403.02052



"A Global View of the EDM Landscape"

SMD, Nina Elmer, Tanmoy Modak, Margarete Mühlleitner, Tilman Plehn

Impact of theory uncertainties



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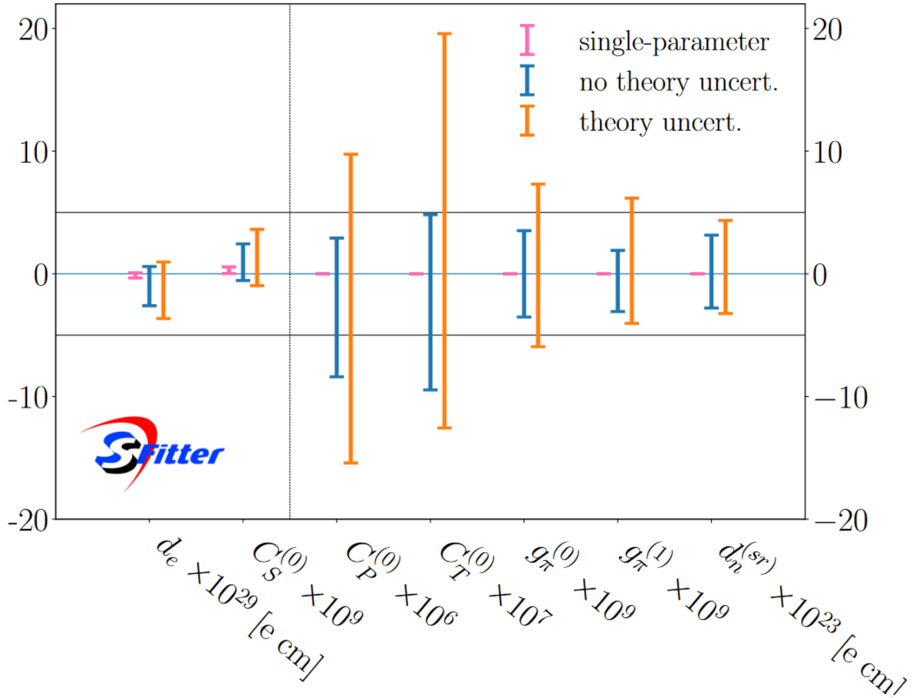

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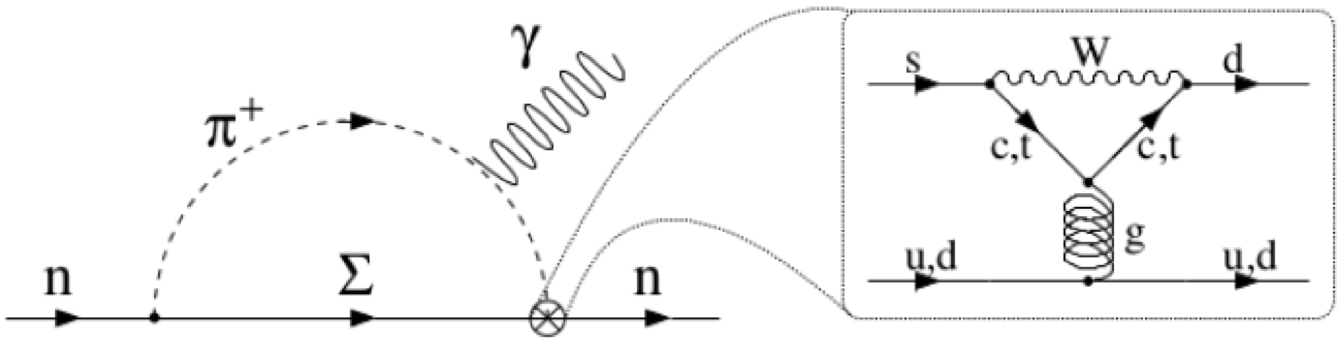
Neutrons: “Testing the SM” vs. “New Physics”

Neutron EDM within the Standard Model (CKM):



Pospelov & Ritz, *Annals of Physics* 318 (2005): 119-169

In more detail (work in progress / broad effort):

Not all coefficients are yet well known:

$$d_n = g_T^{(n,u)} d_u + g_T^{(n,d)} d_d + g_T^{(n,s)} d_s$$

Lattice QCD, 5-10% for *u*, *d*

$$-(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d$$

*QCD sum rules

$$+ \text{ Weinberg } + \text{ 4-fermion}$$

*Naïve dim. analysis

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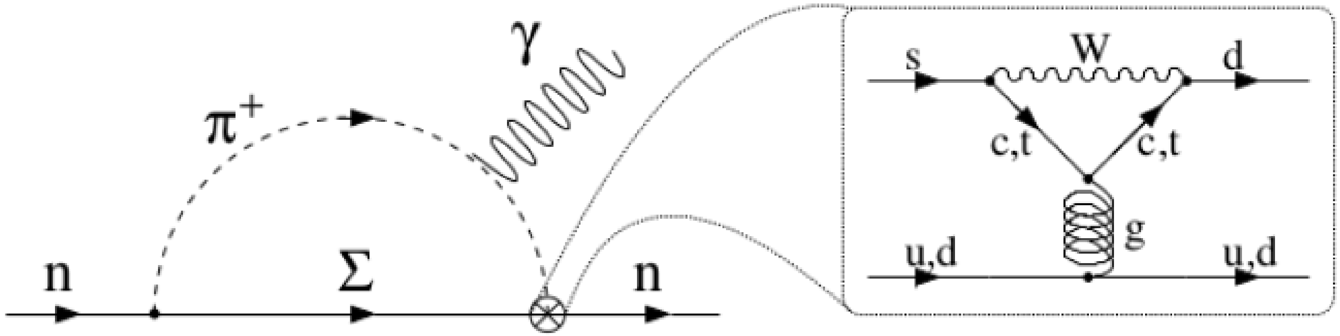

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Naïve estimate for generic new physics:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\mathrm{CPV}}$$

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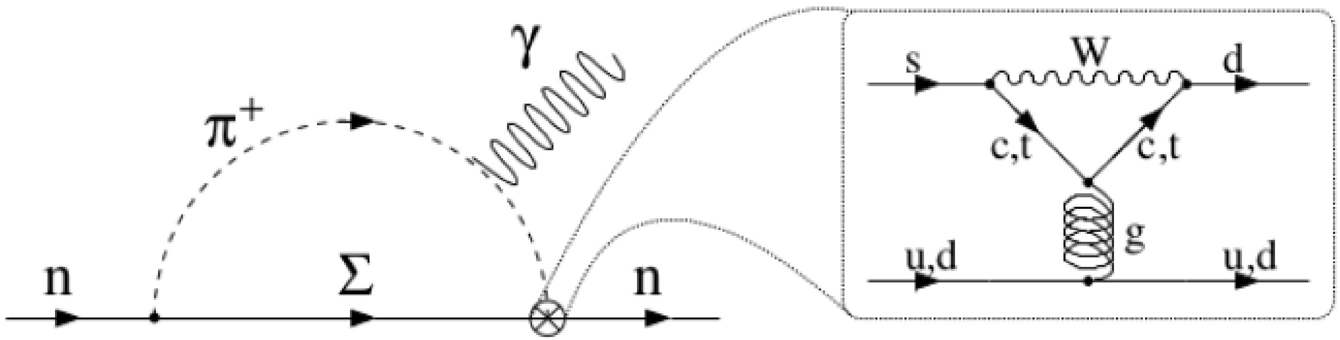

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$$+ \text{ Weinberg } + \text{ 4-fermion}$$

Naïve estimate for generic new physics:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\text{CPV}}$$

Λ ≈ 30 TeV

Statistical sensitivity, count-rate limited:

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

first saturate "classical" parameters
…then new approaches, quantum sensing

Current limit (PSI):
2.2×10^{-26} e cm, 95% C.L.

PRL **124**, 081803 (2020)

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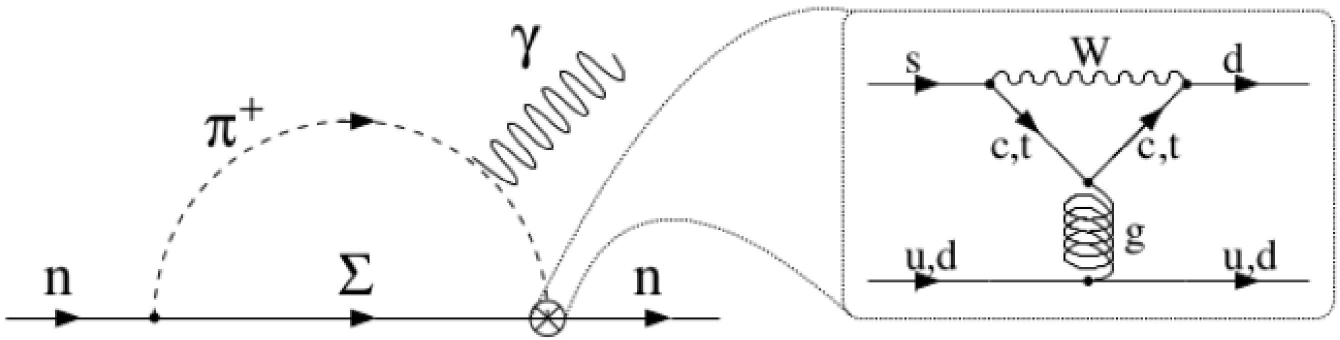

Pospelov & Ritz, *Annals of Physics* 318 (2005): 119-169

Current experimental limit: 10^{-26} *e* cm

Standard Model CKM: 10^{-32} *e* cm

Standard Model QCD: 10^{-16} *e* cm × θ [???]

Standard Model PMNS

→ Insufficient for baryogenesis

Naïve estimate for generic new physics:

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PRL **124**, 081803 (2020)

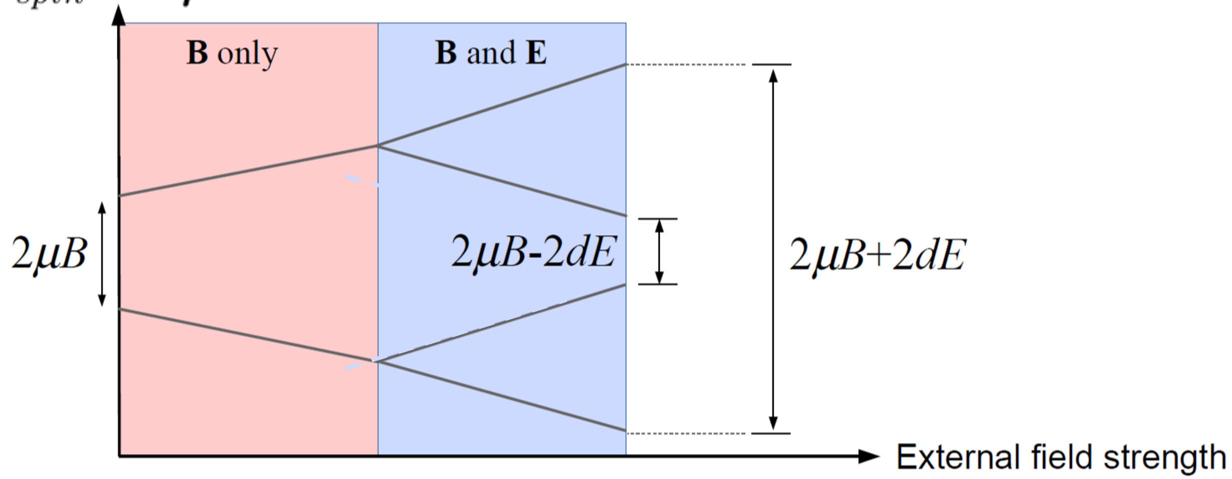
The Role of Ultracold Neutrons

"Never measure anything but frequency"

–Arthur Schawlow (1981 Physics Nobel Prize)

$$\delta\omega \sim \frac{1}{\delta t} \longleftrightarrow \sigma(d_n) \gtrsim \frac{\hbar}{2\alpha\,|\boldsymbol{E}|\,T\sqrt{N}}$$

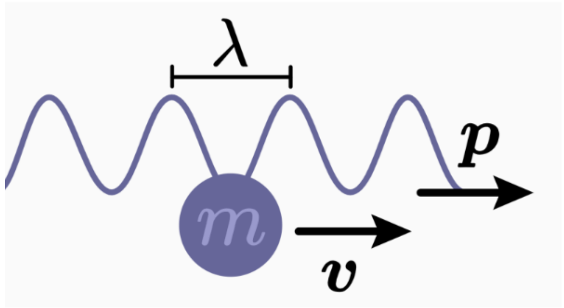
$$H_{spin} = -\boldsymbol{\mu}\cdot\mathbf{B} - \mathbf{d}\cdot\mathbf{E}$$



$$\hbar(\omega_+ - \omega_-) = 4dE$$

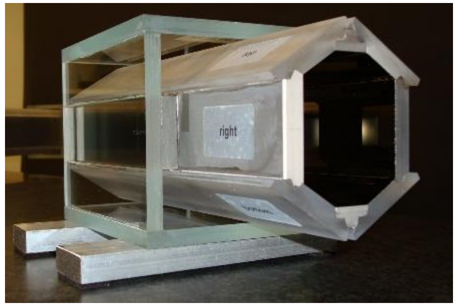
But… how to store or cool ensembles?

Wave optics, with massive particles!



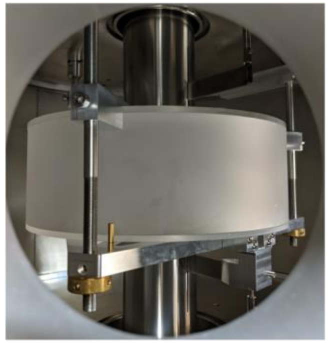
"Cold" beams: O(500 m/s)

particles fly through most experiments in milliseconds



S-DH

S-DH

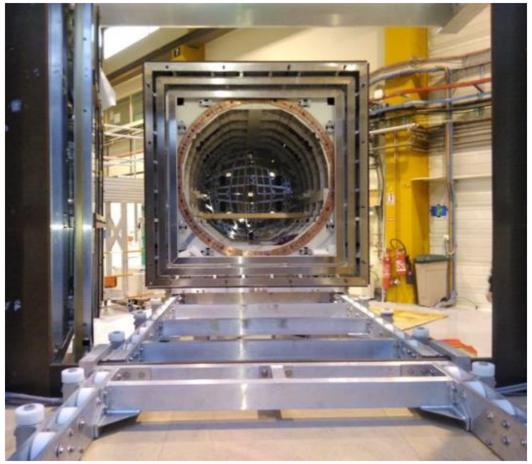


"Ultracold" traps: O(5 m/s)

particles stored for minutes (>10^5 ms)

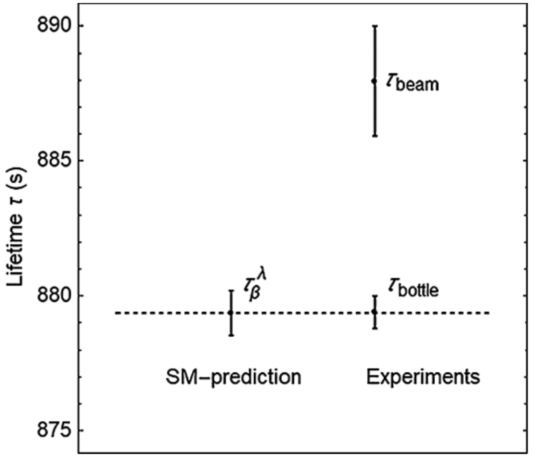
The (many) Roles of Ultracold Neutrons

Neutron EDM:



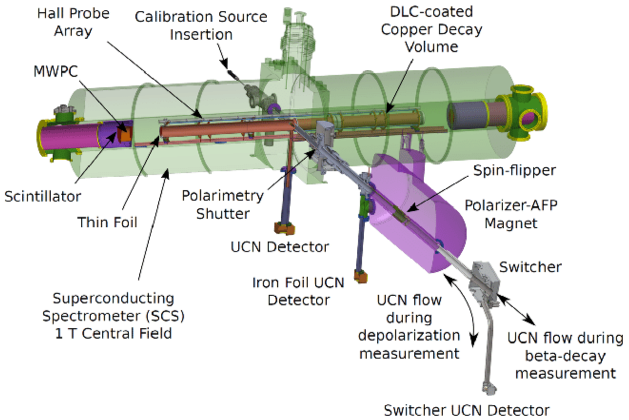
EPJ Conf: **219**, 02006 (2019)
Eur. Phys. J. C **81**:512 (2021)

Neutron lifetime:



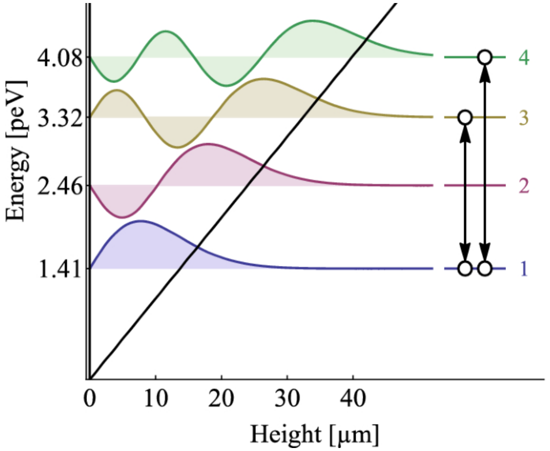
Phys. Lett. B **791**, 6-10 (2019)

β decay correlations:



Phys. Rev. C **97**, 035505 (2018)

Gravitational quantum states:



EPJ Conf. **219**, 05003 (2019)

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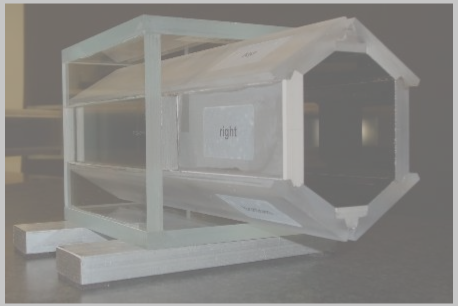

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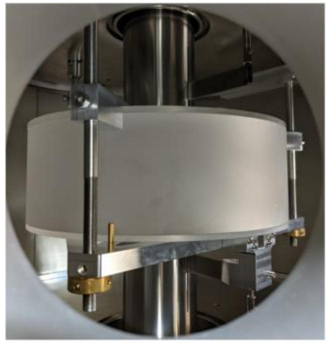

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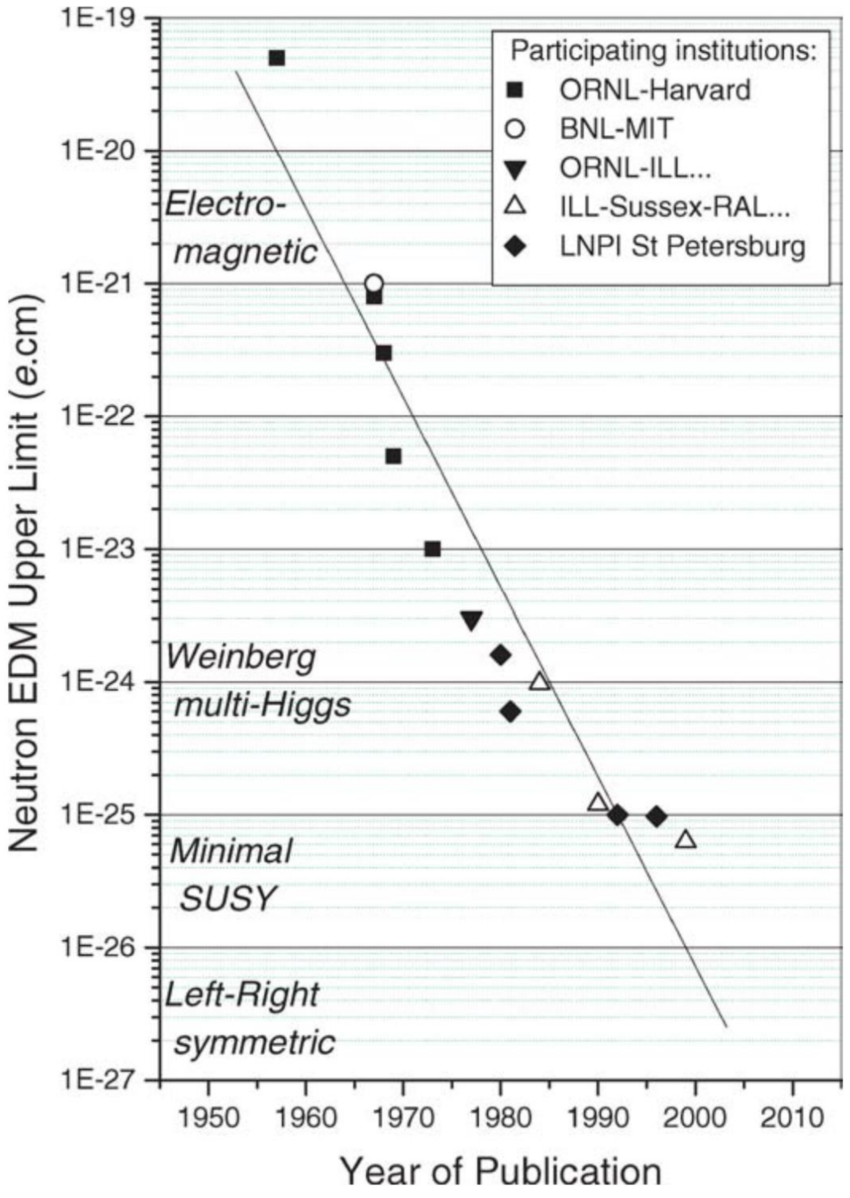
“Testing the Standard Model” vs. “New Physics”



2005 review: [Nico & Snow, Annu. Rev. Nucl. Part. Sci.]

Statistical sensitivity of the PSI experiment:

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

Current limit (PSI):
2.2×10^{-26} e cm, 95% C.L.

Polarization contrast ≈ 0.8

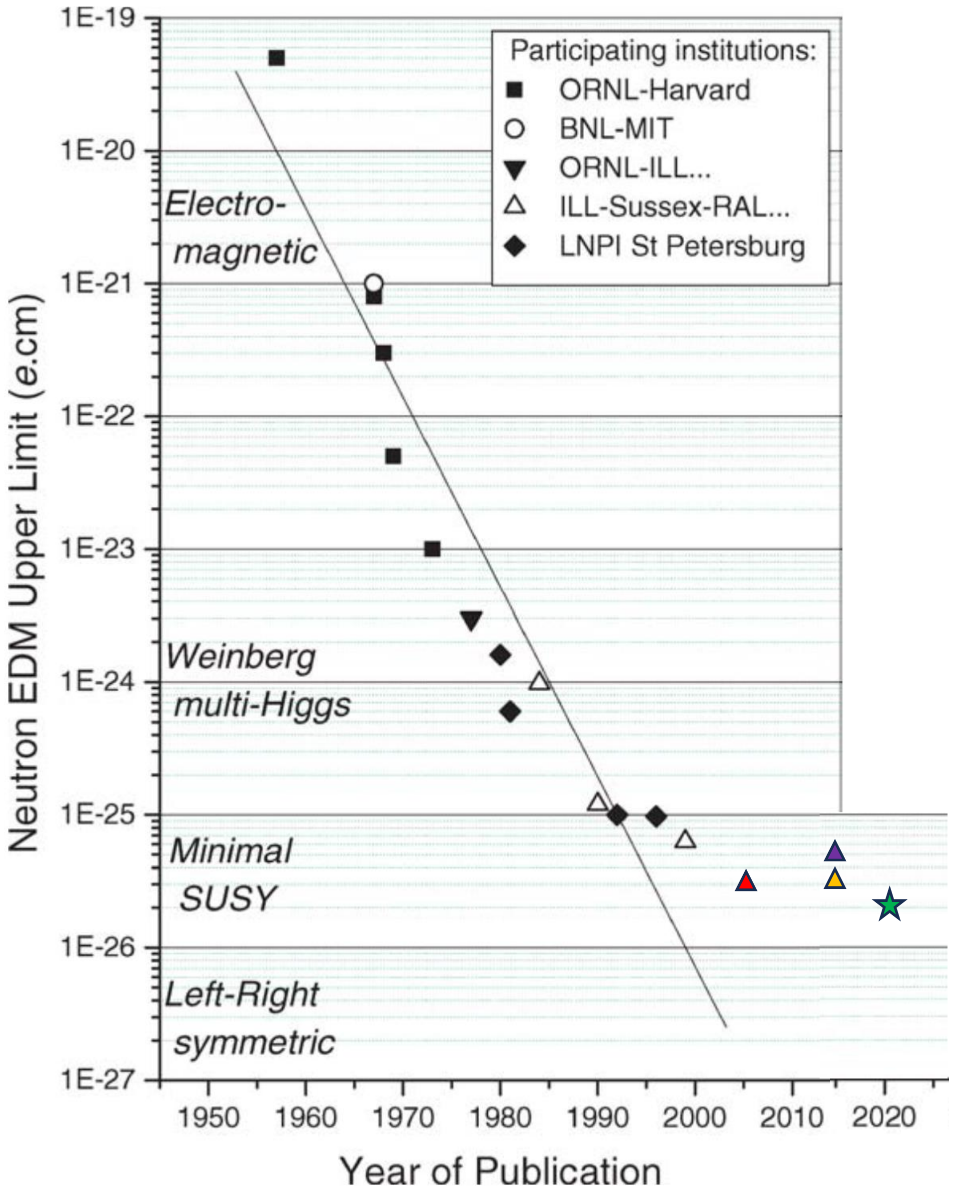
11 kV/cm

180 s

$(54\times10^{3})\times(10^{4}/\text{shot})$

Tour-de-force in systematics studies…
But statistics not much improved for 20 years!

The Real Problem



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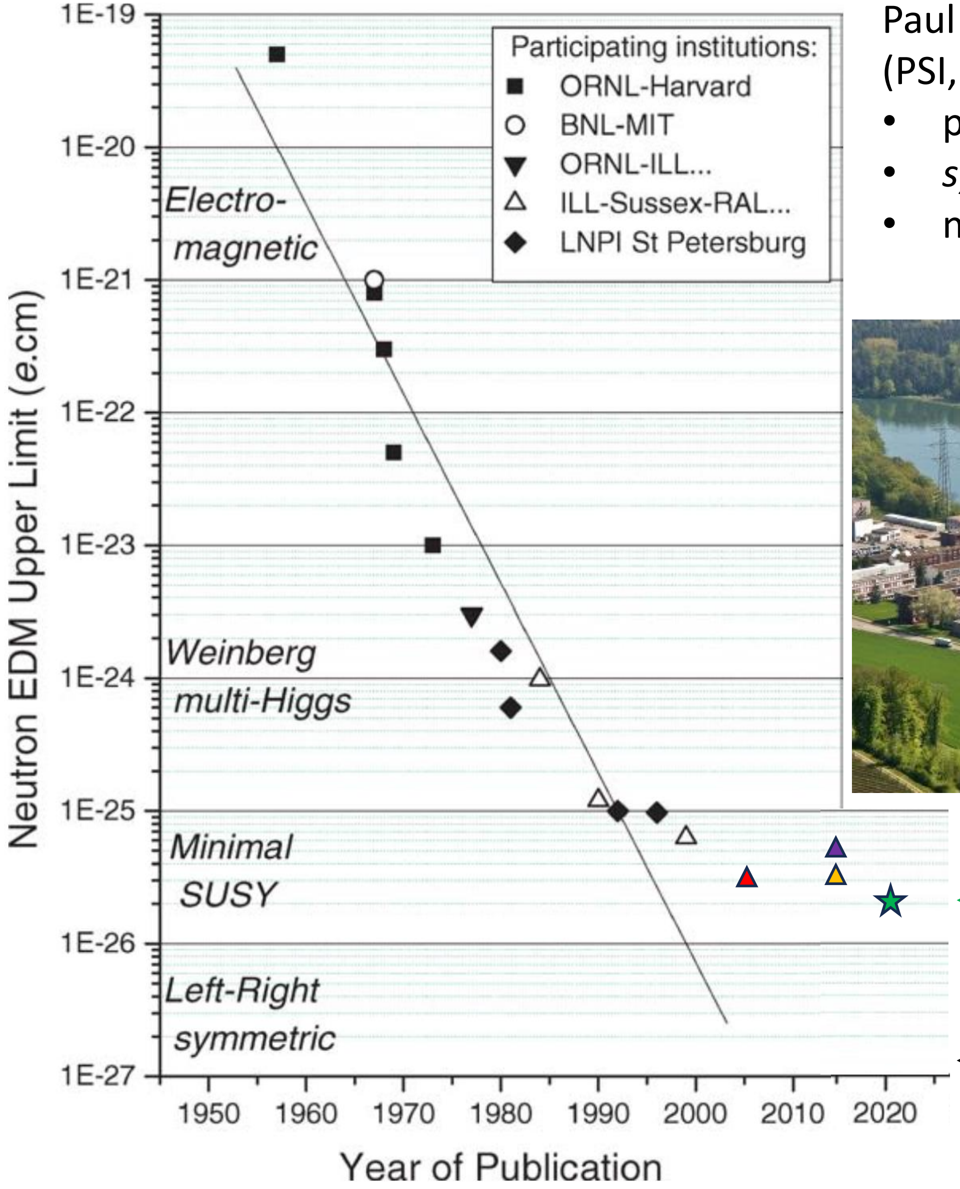
Now strongly limited by available neutrons

Working to get more neutrons

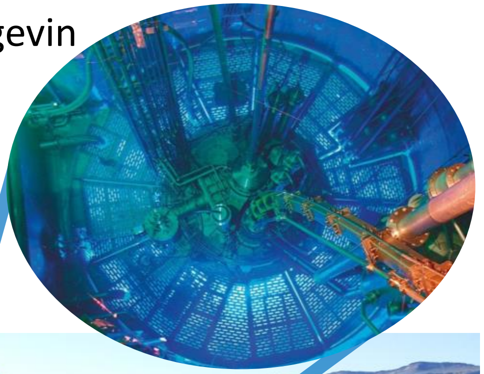


Paul Scherrer Institut
(PSI, Villigen)

- present limit
- *systematics*
- n2EDM

Institut Laue- Langevin
(ILL, Grenoble)

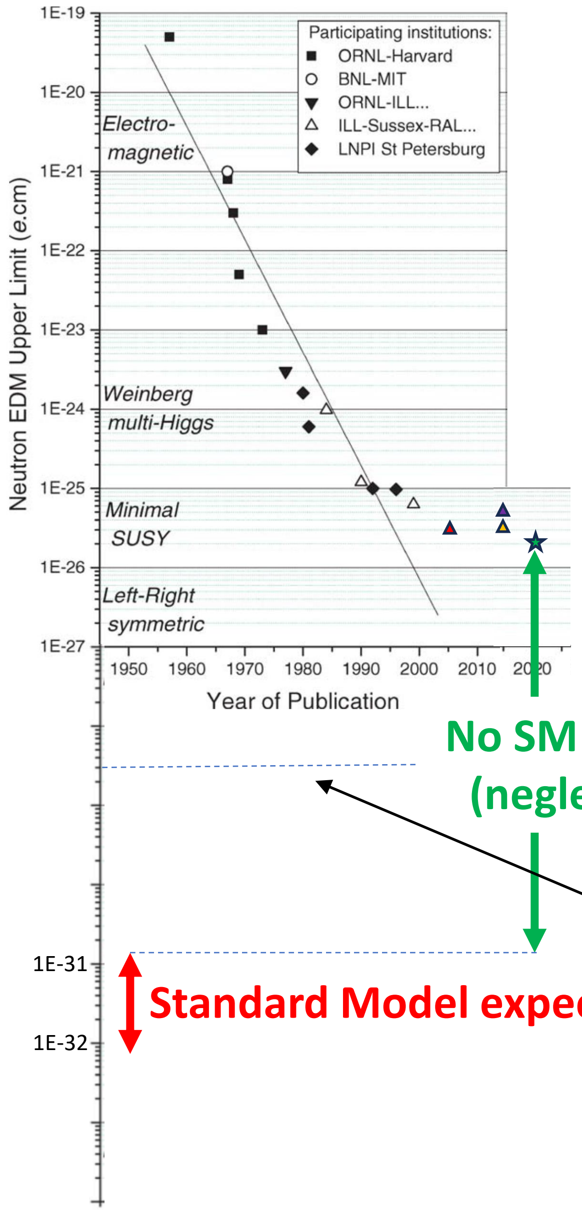
- previous limit
- *statistics*
- PanEDM



Now strongly limited by available neutrons

Sensitivity target for experiments now commissioning

Working to get more neutrons



No SM background (neglecting θ_{QCD})

Standard Model expectation

<u>JNR (2022) **24**(2), 123-143</u>
potential reach with today's technology
*(**statistics only**)*

Paul Scherrer Institut
(PSI, Villigen)

- present limit
- *systematics*
- n2EDM

Institut Laue- Langevin
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- previous limit
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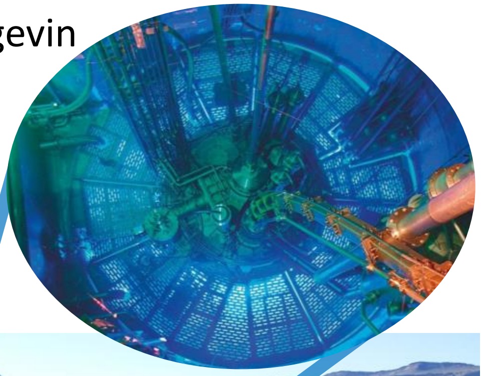


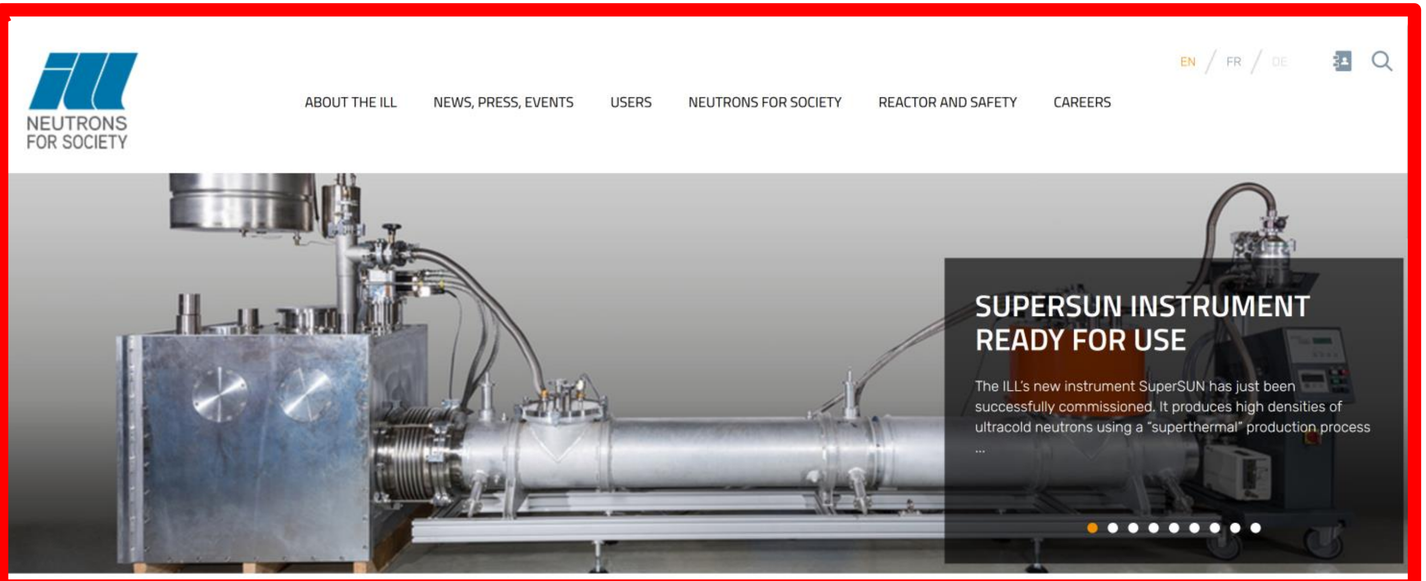
Very rough factors separating today's experiments and SM predictions:

10^8 *10^7* *10^5-10^6*

How do electron and atomic/molecular EDMs compare to neutron?

$$\{d_e, C_S, C_T, C_P, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}\}$$

New Source at the Institut Laue-Langevin



SuperSUN: High density UCN source

Phase I characterization

Measurement agrees with expectation (48 MW)

cf. EPJ Conf. 219, 02006 (2019)

Total UCN output: 3.8×10^{6} (integral of blue peak)
Source density: 270 UCN/cm^3
Long storage times: 126000 UCN remaining after 20min
Expected density in PanEDM: 3.9 UCN/cm^3 (58 MW)
Source characterization, PanEDM commissioning ongoing

Phase II expectation

Peak field:	2.1 T
Source density:	1670 UCN/cm^3 (**x5 gain**)
Density in PanEDM:	40 UCN/cm^3 (**x10 gain**)

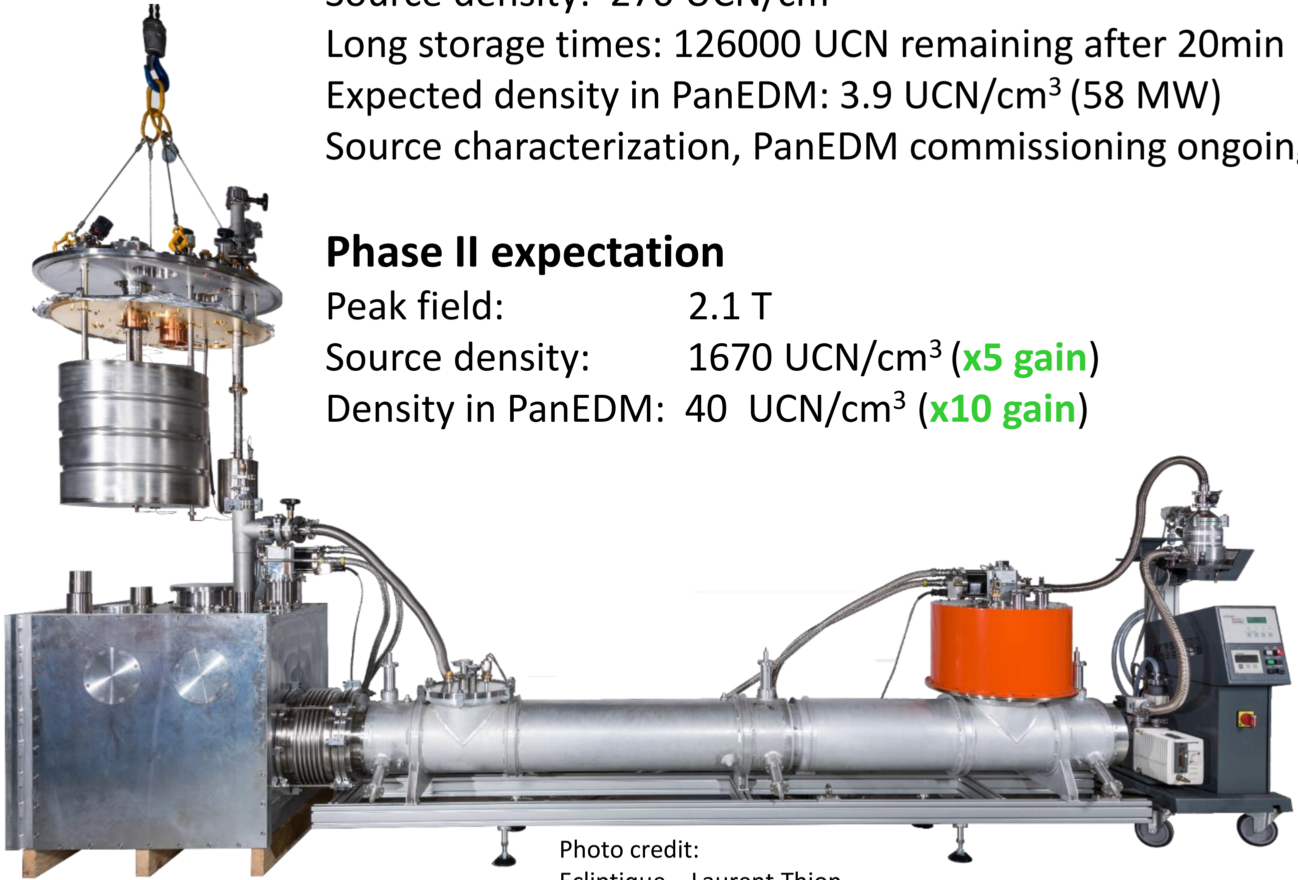
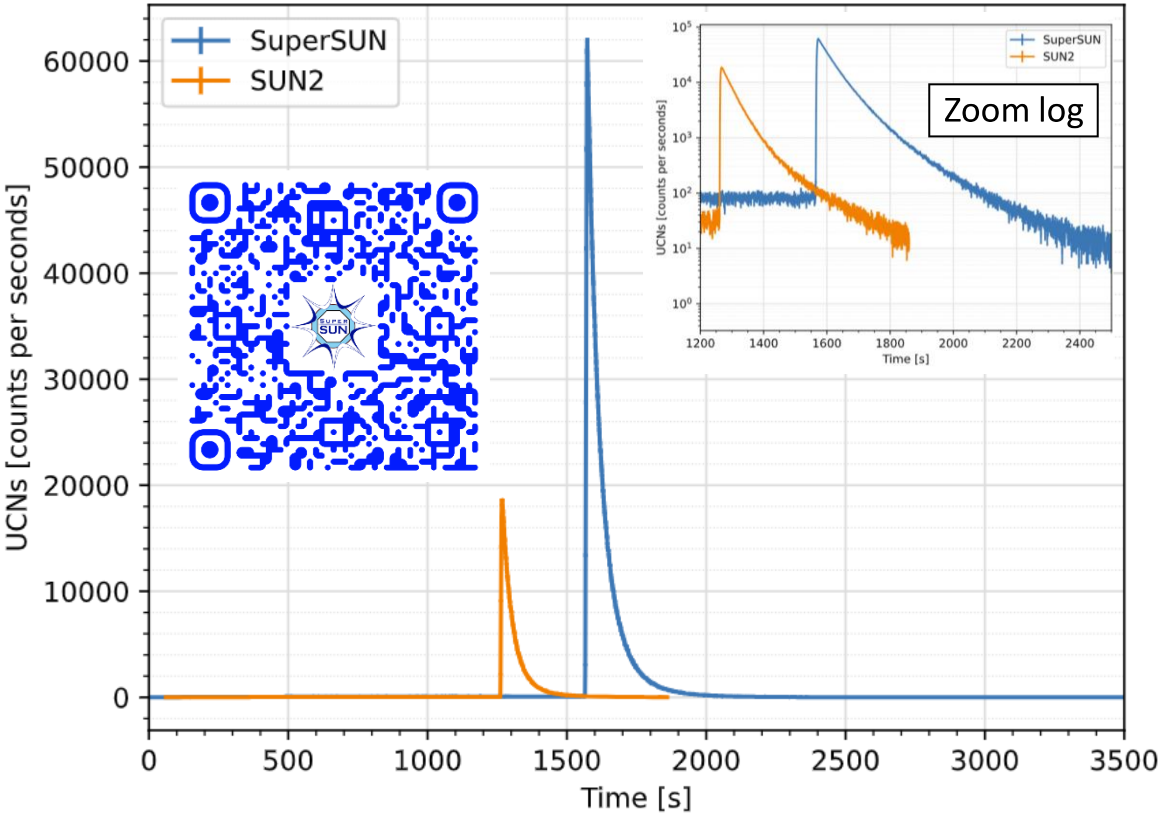


Photo credit:
Ecliptique – Laurent Thion.

Comparison to the prototype source SUN2



NEUTRONS FOR SCIENCE
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

SuperSUN: High density UCN source

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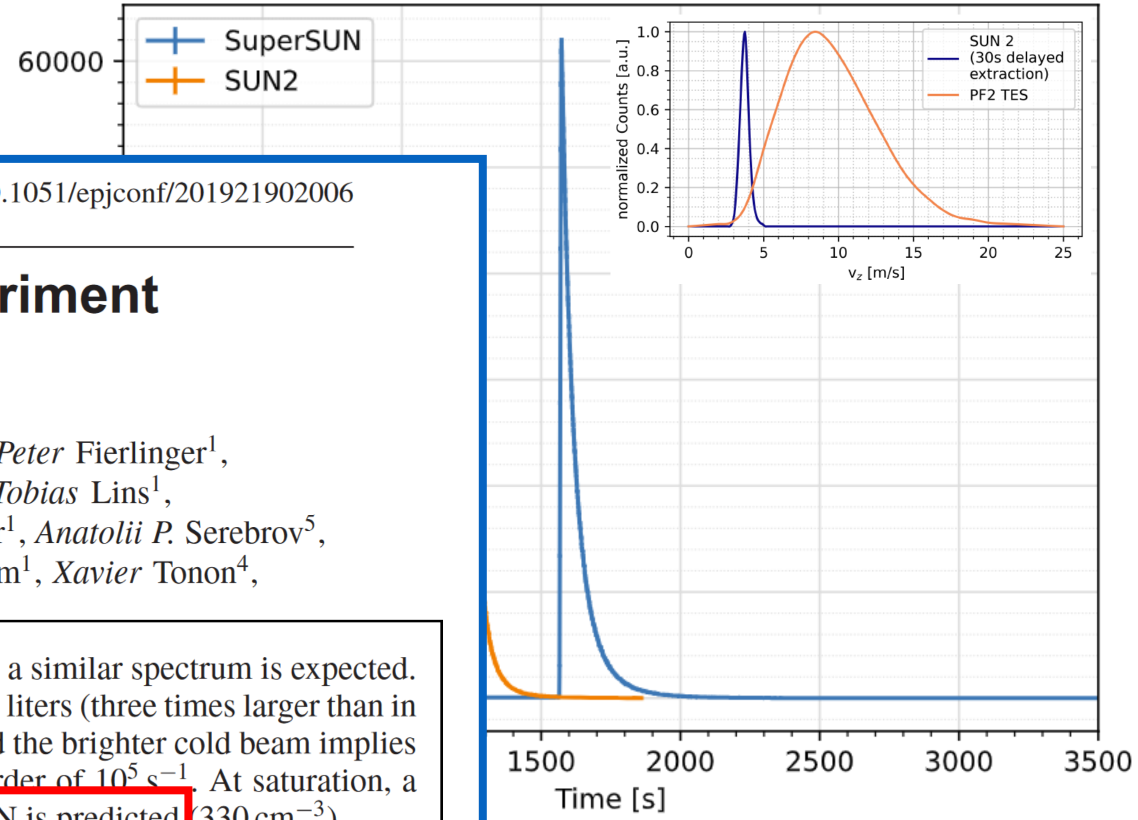


EPJ Web of Conferences **219**, 02006 (2019) https://doi.org/10.1051/epjconf/201921902006
PPNS 2018

The PanEDM neutron electric dipole moment experiment at the ILL

David Wurm[1], *Douglas H.* Beck[2], *Tim* Chupp[3], *Skyler* Degenkolb[4,a], *Katharina* Fierlinger[1], *Peter* Fierlinger[1], *Hanno* Filter[1], *Sergey* Ivanov[5], *Christopher* Klau[1], *Michael* Kreuz[4], *Eddy* Lelièvre-Berna[4], *Tobias* Lins[1], *Joachim* Meichelböck[1], *Thomas* Neulinger[2], *Robert* Paddock[6], *Florian* Röhrer[1], *Martin* Rosner[1], *Anatolii P.* Serebrov[5], *Jaideep Taggart* Singh[7], *Rainer* Stoepler[1], *Stefan* Stuiber[1], *Michael* Sturm[1], *Bernd* Taubenheim[1], *Xavier* Tonon[4], *Mark* Tucker[8], *Maurits* van der Grinten[8], and *Oliver* Zimmer[4]

Ongoing work: spectrum, transfer efficiency and storage in external volumes, etc…

by material walls only, and a similar spectrum is expected. The converter volume is 12 liters (three times larger than in SUN2); scaling for this and the brighter cold beam implies a production rate on the order of $10^5\ \mathrm{s}^{-1}$. At saturation, a total of 4×10^{6} stored UCN is predicted ($330\ \mathrm{cm}^{-3}$).

3.8×10^{6} UCN measured (fill-and-empty)

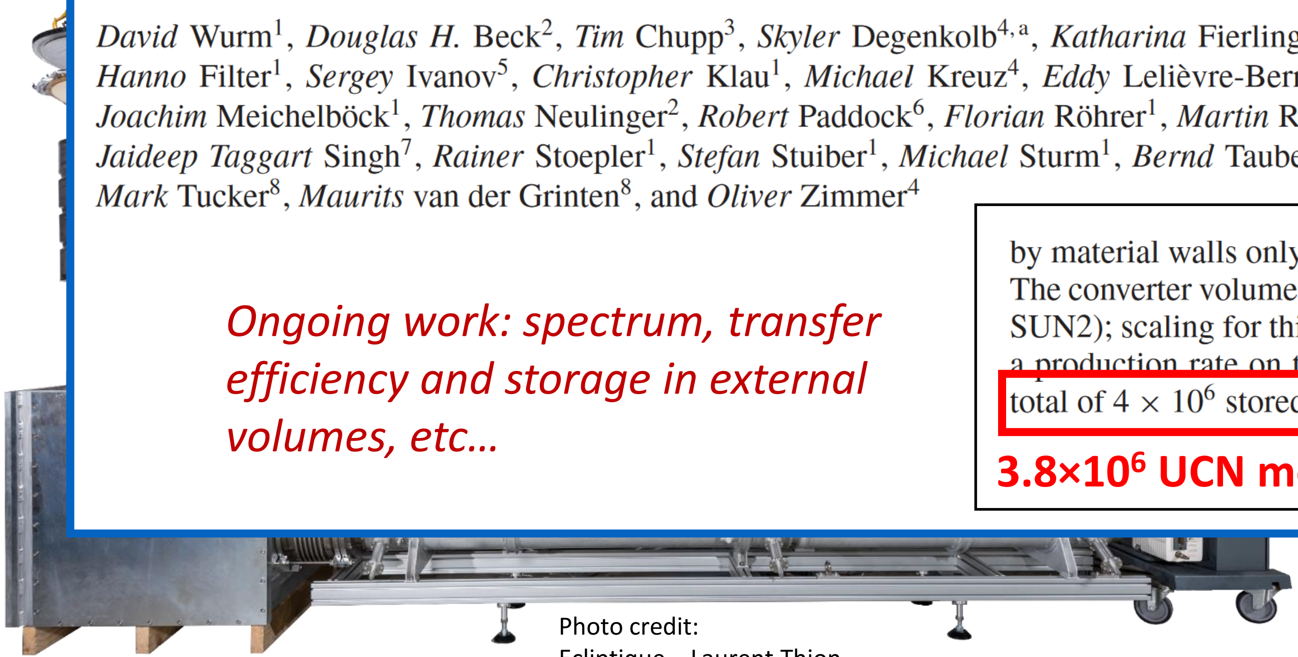
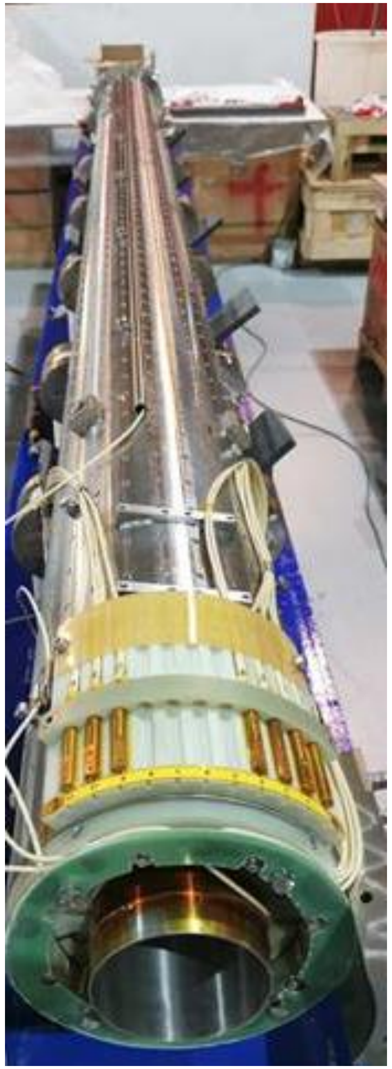


Photo credit:
Ecliptique – Laurent Thion.

SuperSUN phase II: polarized UCN and magnetic storage



Benefits in phase II

- Increase storage potential for one spin state
- Decrease loss rate for stored UCN

→ UCN already polarized within the source

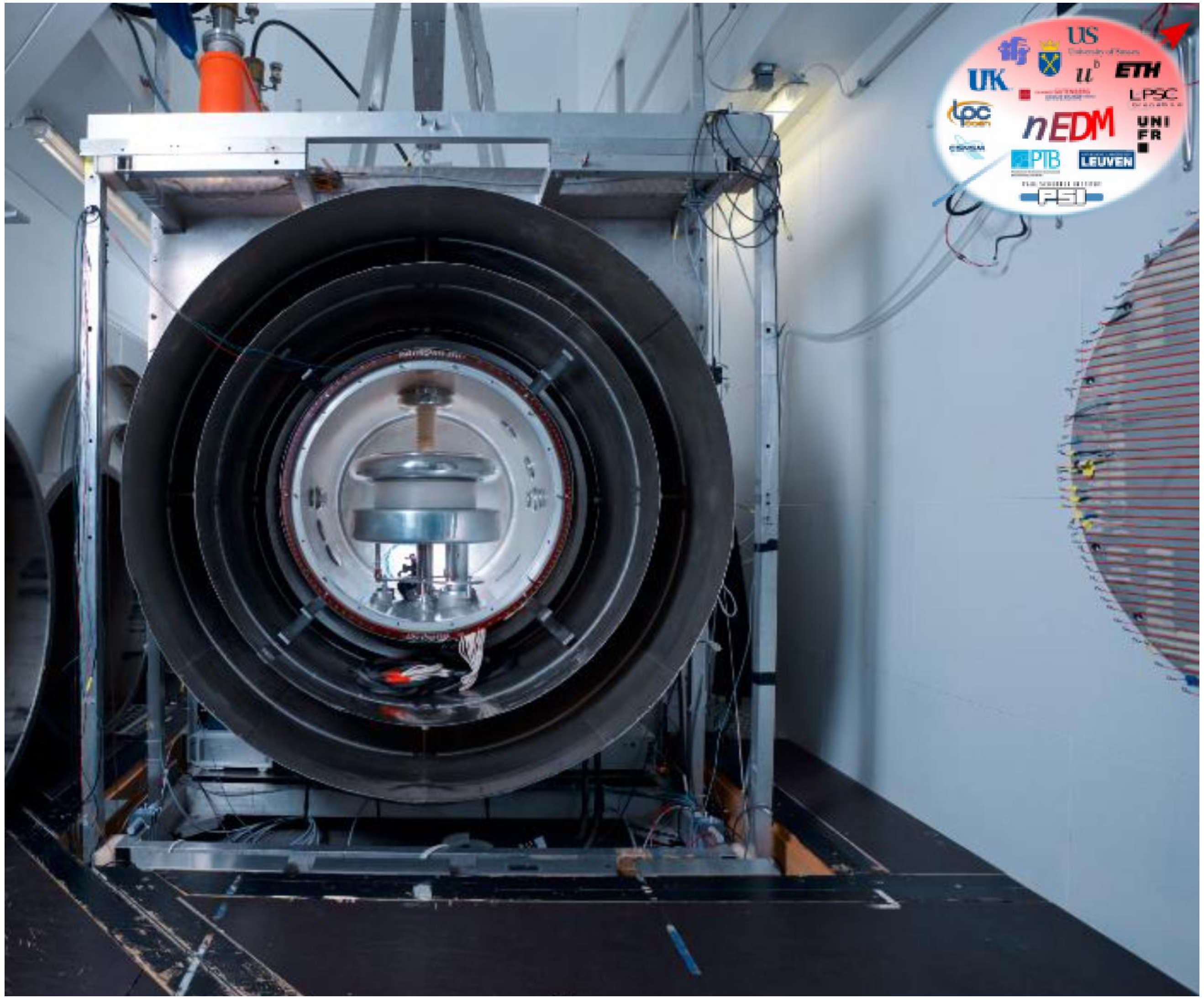
Phase II expectations (gain over phase I)

Peak field: 2.1 T
Source density: 1670 UCN/cm^3 (**x5 gain**)
Density in PanEDM: 40 UCN/cm^3 (**x10 gain**)

Status

Quench protection validated
Octupole trained up to 1 T
Preparing impregnation of the octupole, to reach nominal field

The Current Best Limit: PSI 2020



RAL/Sussex apparatus from ILL (from 2006 limit, and 2015 revised analysis)
…almost completely rebuilt and upgraded

Previous result (ILL): Phys. Rev. D. **92** 092003 (2015)

$$d_n = \left(-0.2 \pm 1.5_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}\right) \times 10^{-26}\ ecm$$

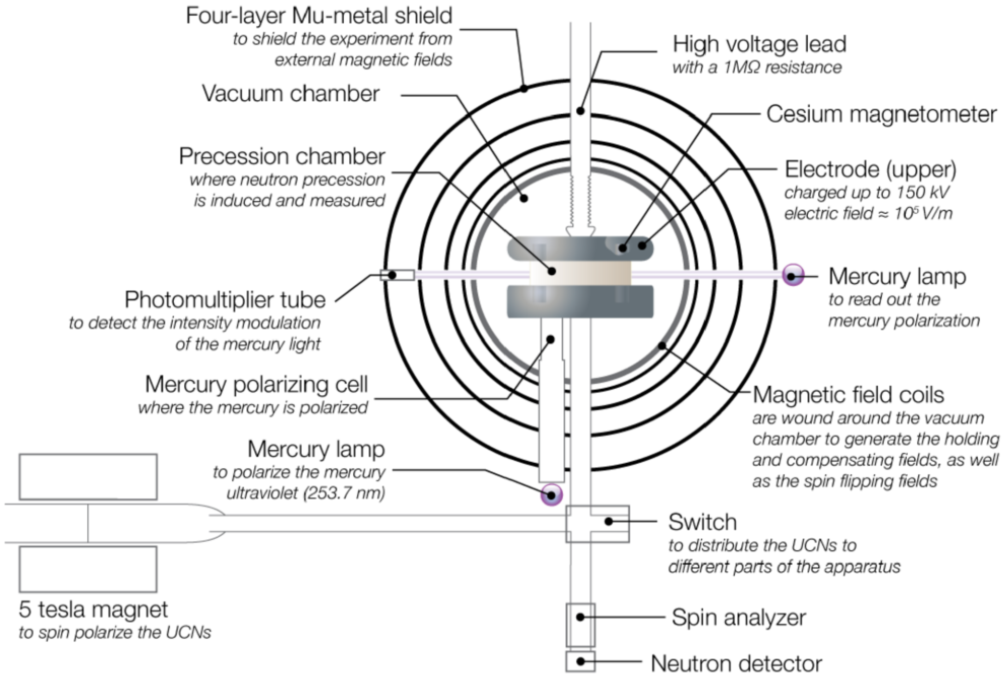
Most recent result (PSI): PRL **124** 081803 (2020)

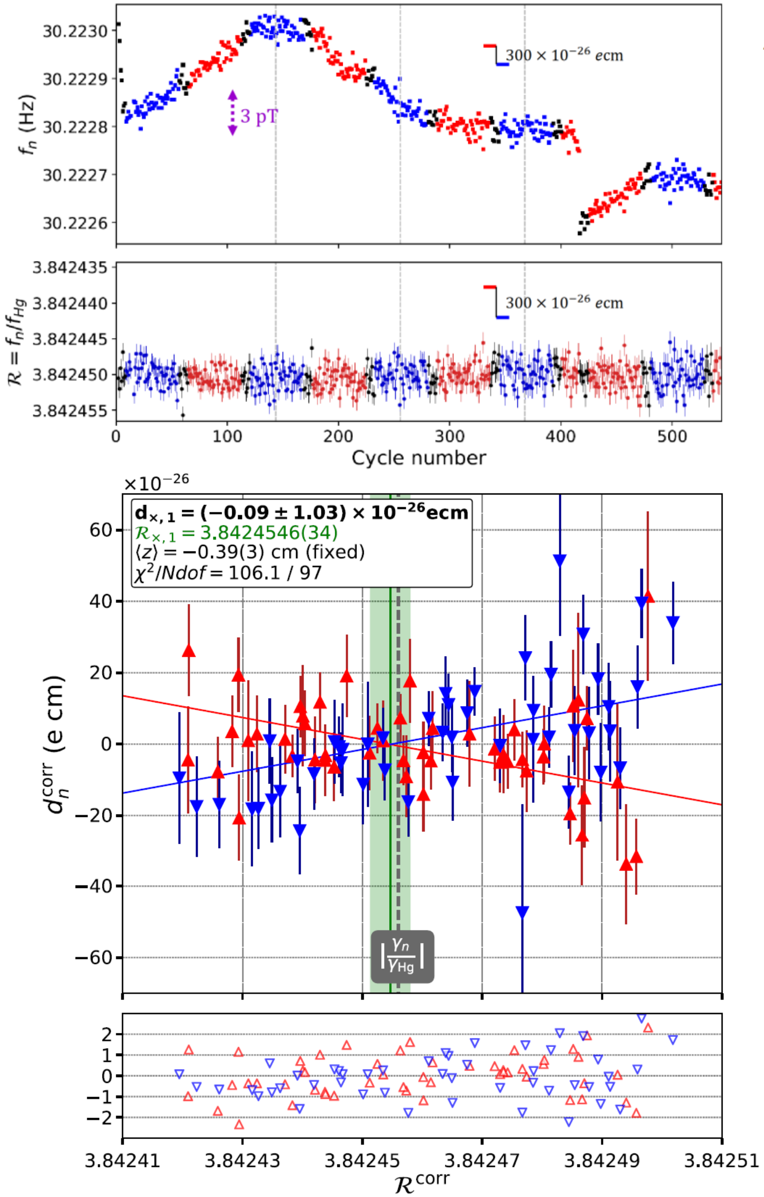
$$d_n = \left(\ 0.0\ \pm\ 1.1_{\mathrm{stat}}\ \pm\ 0.2_{\mathrm{syst}}\right) \times 10^{-26}\ ecm$$

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

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

The Current Best Limit: PSI 2020

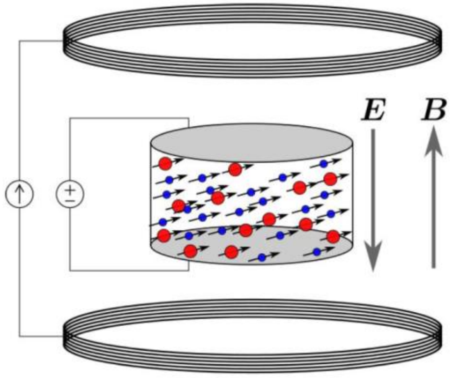




$$\mathcal{R} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right|(1 + \delta_{EDM} + \delta_{EDM}^{false} + \delta_{quad} + \delta_{grav} + \delta_T + \delta_{Earth} + \delta_{light} + \delta_{inc} + \delta_{other})$$

$\nu_{Earth} \approx 11.6$ μHz is a *very large* and well-understood correction

Key technique:
^{199}Hg comagnetometer



$$d^{false} = \frac{\hbar}{8c^2}|\gamma_n\gamma_{Hg}|R^2(G_{grav} + \hat{G})$$

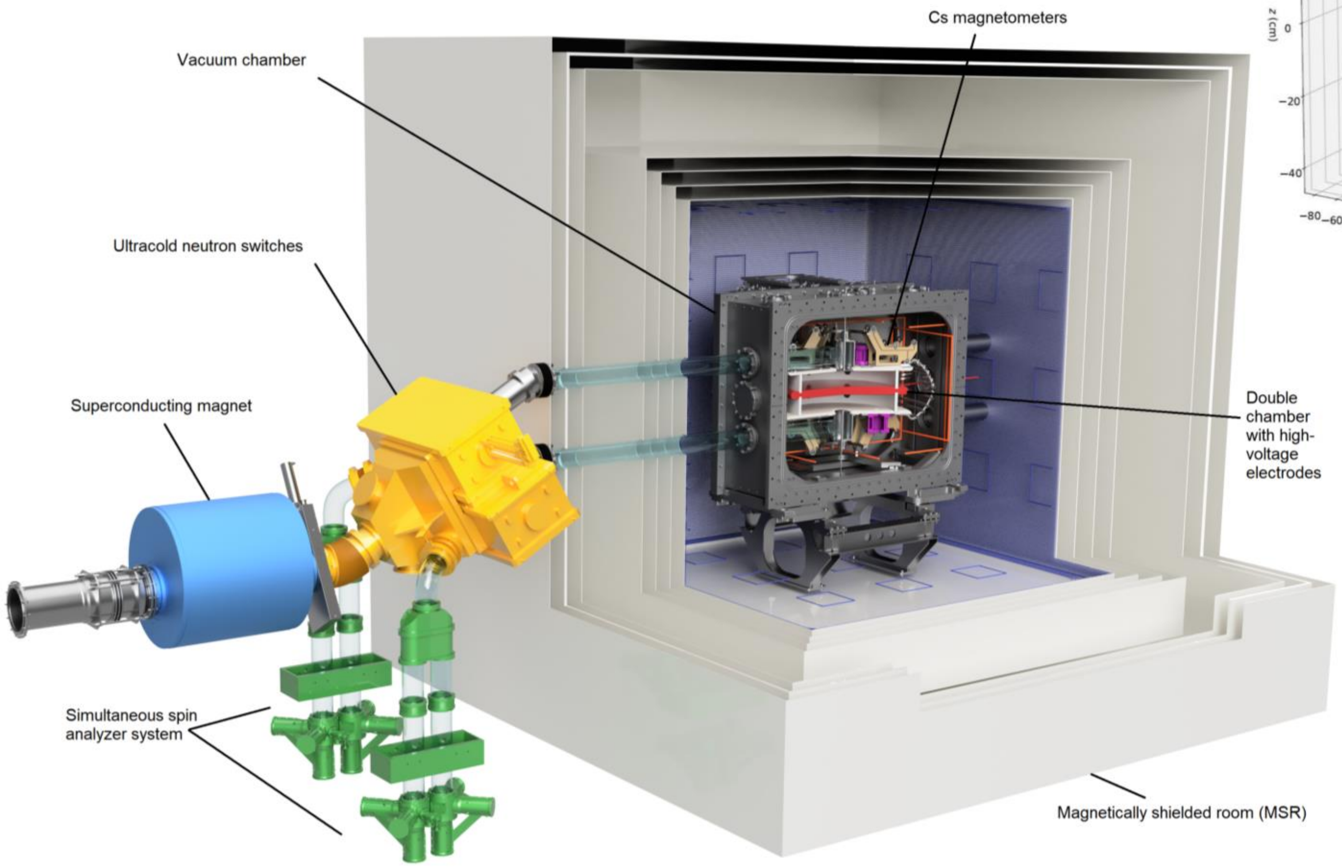
$$d_n^{corr} = d_n^{meas} - \hbar|\gamma_n\gamma_{Hg}|R^2\hat{G}/(8c^2)$$

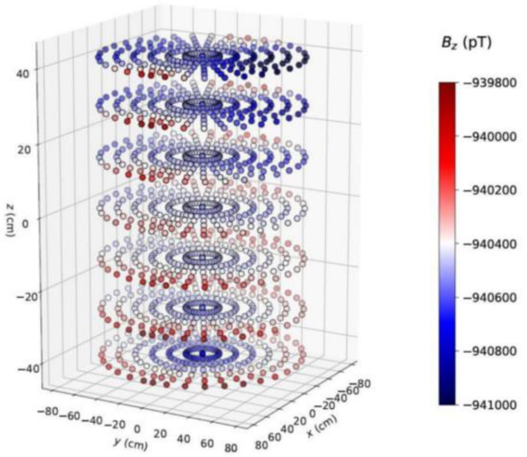
$$\mathcal{R}^{corr} = \mathcal{R}/(1 + \delta_T + \delta_{Earth})$$

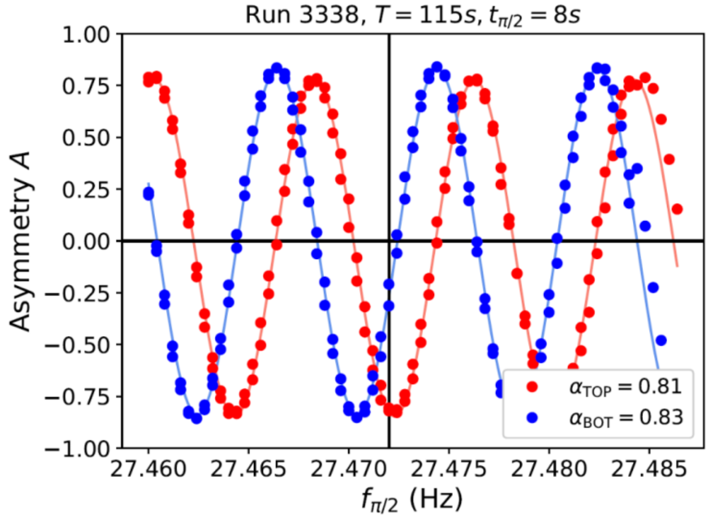
n2EDM commissioning

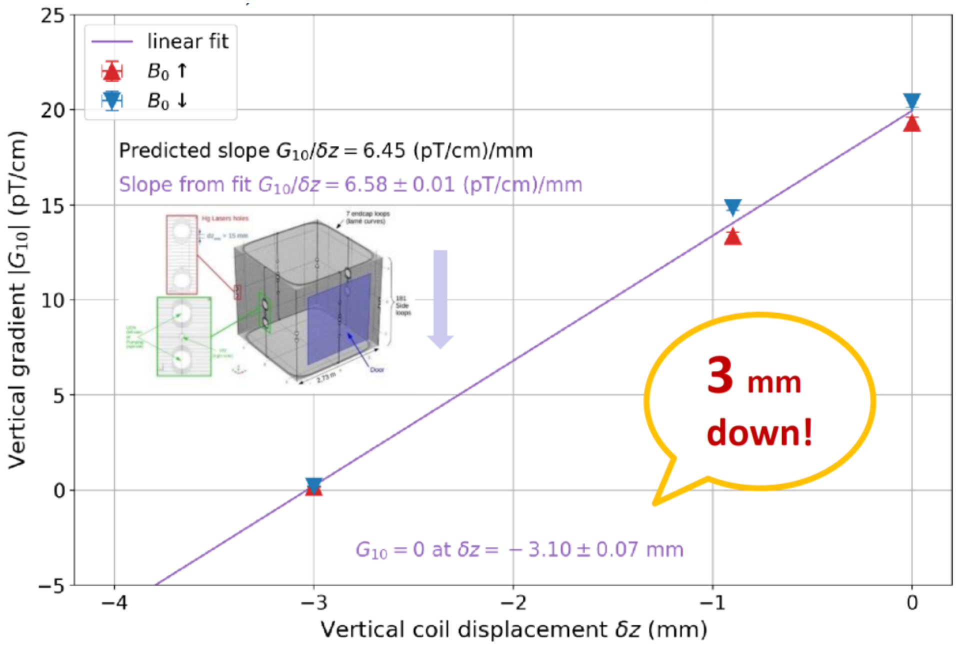
First Ramsey curves in 2023!

Magnetic environment with active compensation;
Residual gradient specifications achieved through field-mapping campaigns.







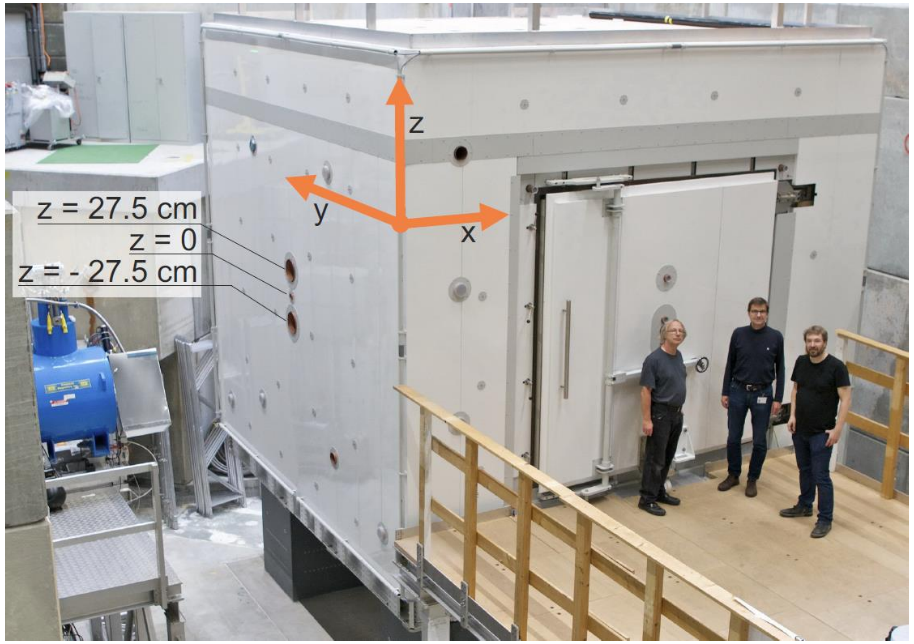


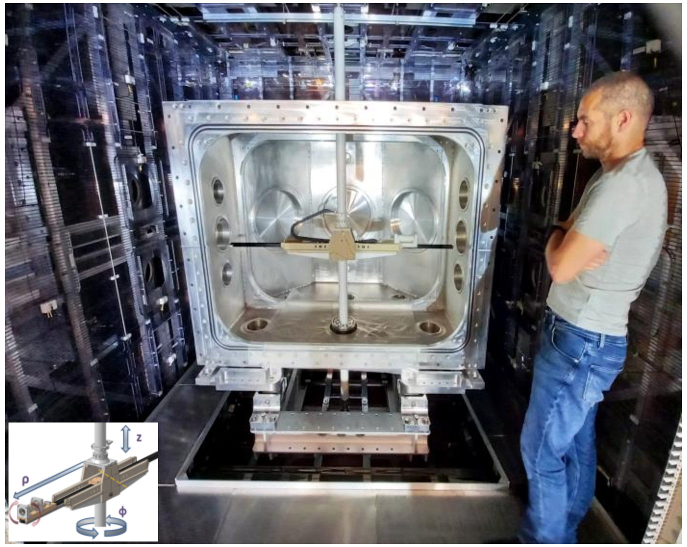
see Eur. Phys. J. C **81**, 512 (2021)

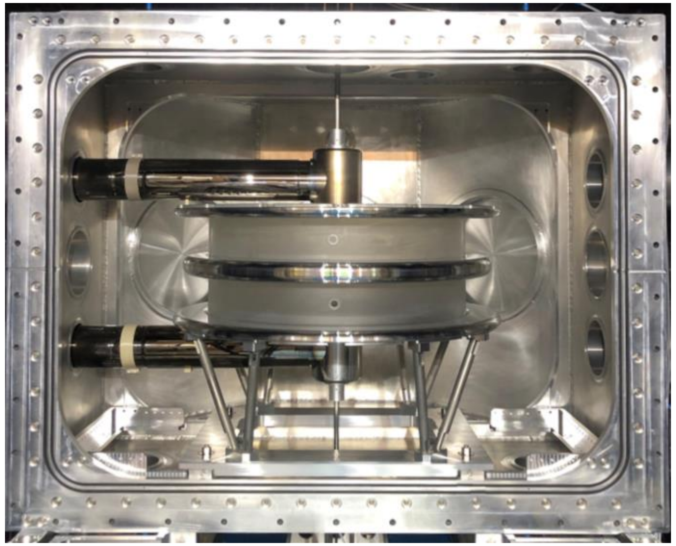
Thanks – S. Roccia, K. Svirina

n2EDM commissioning progress

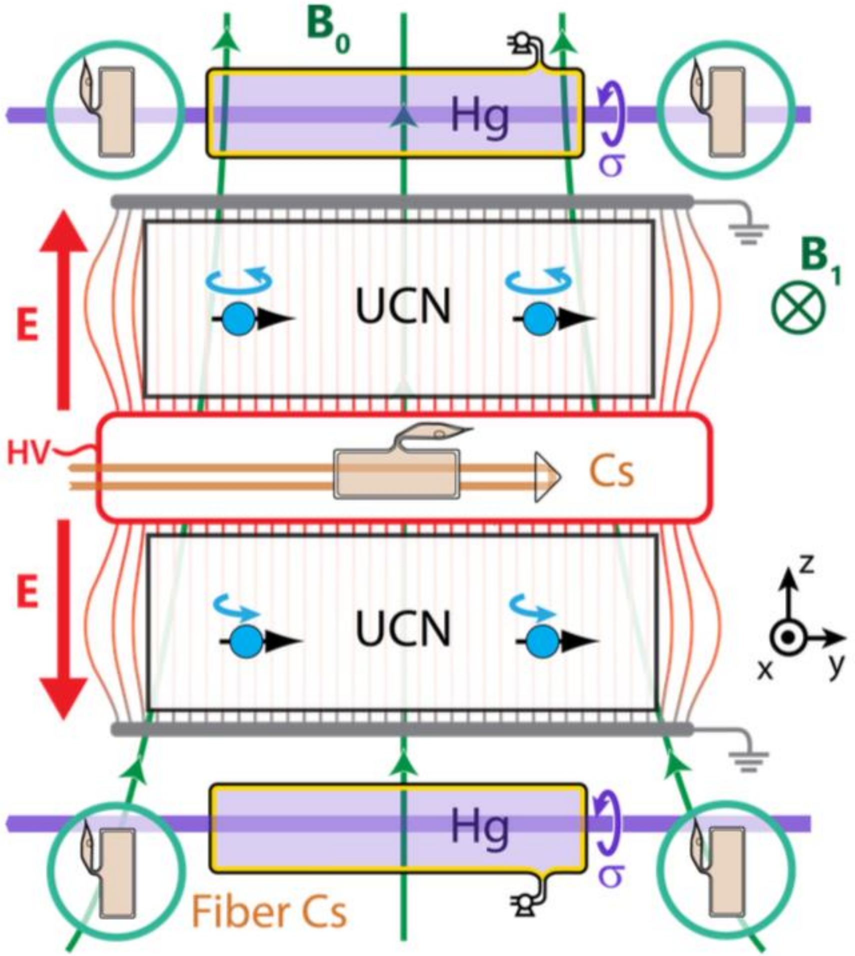
Thanks – G. Pignol, D. Ries







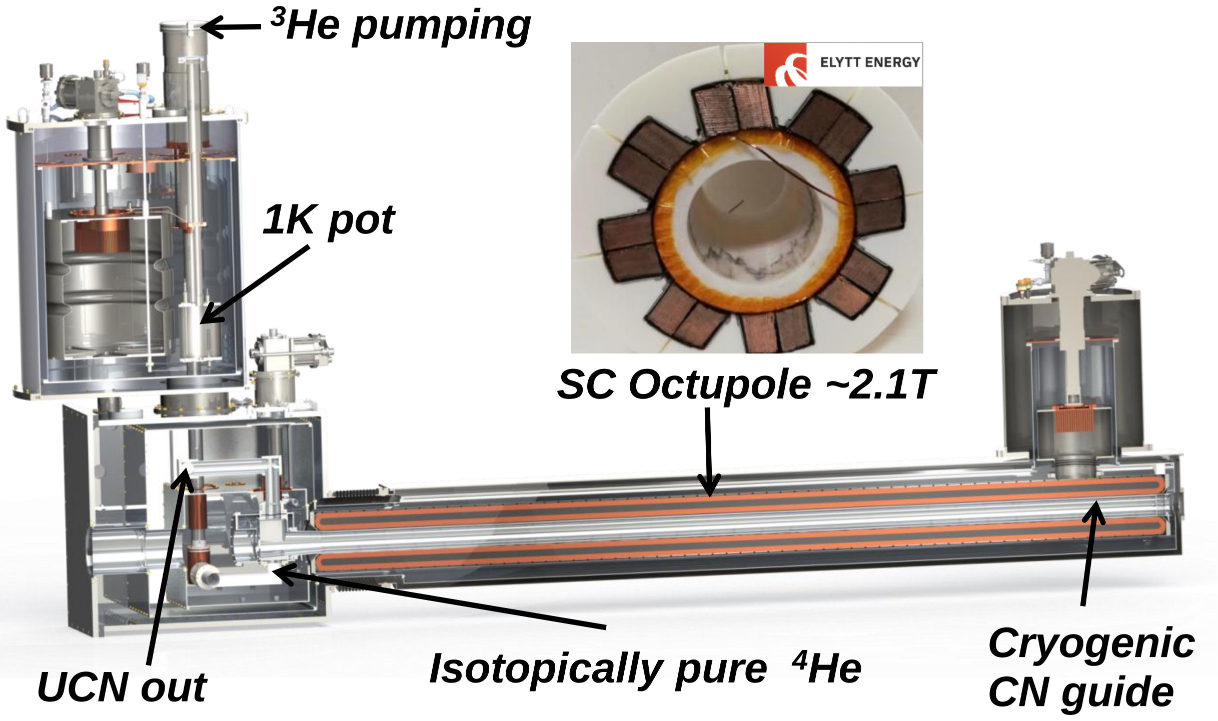
The PanEDM Experiment



- Double chamber Ramsey interferometer at room temperature (while E_{UCN}/k_{B} ~ 5mK)
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at high voltage)
- Magnetic shielding factor: $6{\times}10^6$ at 1 mHz
- Simultaneous spin detection for up/down
- SuperSUN UCN source at ILL in 2 phases:
  - Phase I: unpolarized UCN with 80 neV peak
  - Phase II: polarized UCN, magnetic storage
- Ongoing installation of interface parts, commissioning with UCN ongoing in 2024

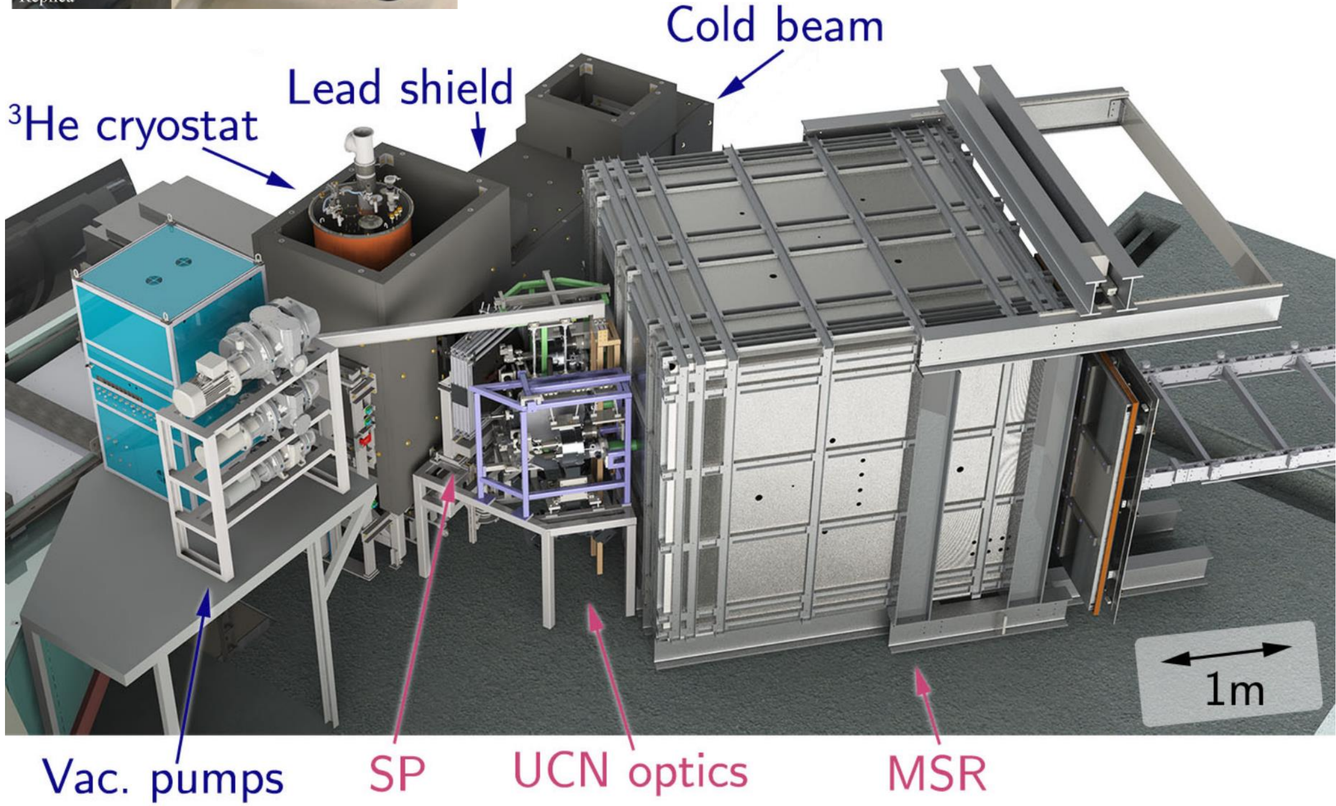
EPJ Conf. 219, 02006 (2019)

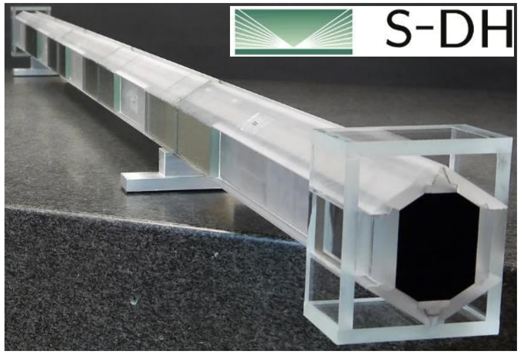
The SuperSUN-PanEDM Installation



Journal of Neutron Research, vol. 24, no. 2, pp. 111-121 (2022)

UCN density given by product of 0.89nm flux, and source storage time. High *in-situ* density, but extracting to external volumes is very penalizing. Cold neutrons guided under He-II by unique circular “replica” supermirror.

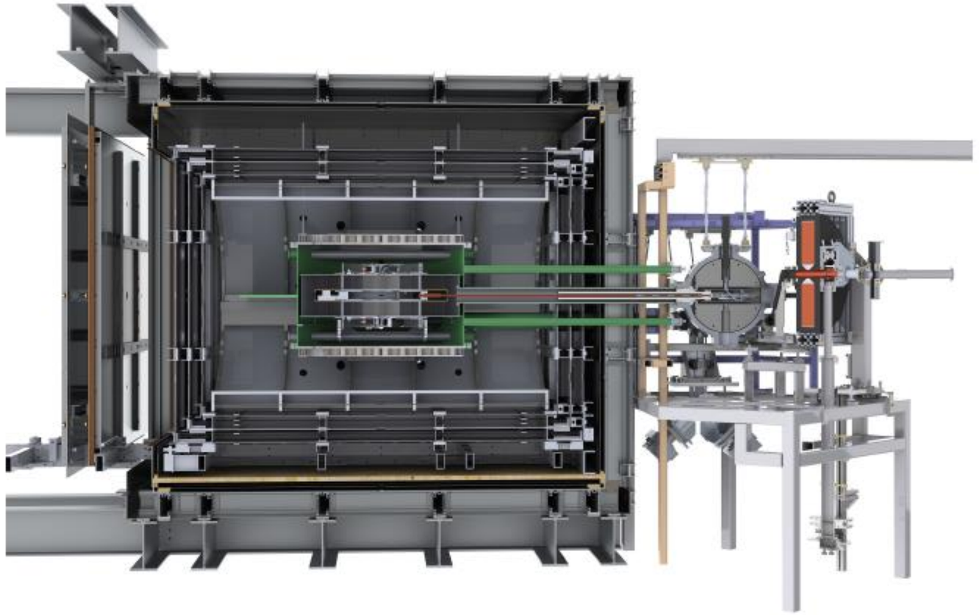




Cold neutron delivery via tapered octagonal guide:

J. Neutron Research ***20****(4), 117-122 (2018)*

PanEDM commissioning progress



The farther future

SuperSUN	Phase I
Saturated source density [cm^{-3}]	$\boxed{330}$
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	$\boxed{3.9}$
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

EPJ Conf. 219, 02006 (2019)

$|E| \approx 2$ MV/m
$T \approx 250$ s
$\alpha \approx 0.85$

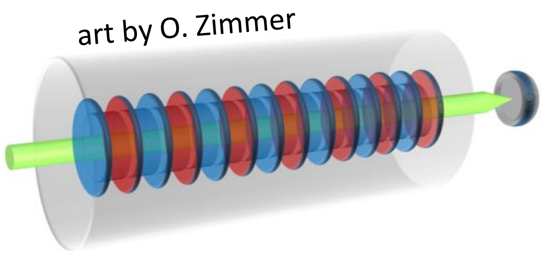
Transfer loss including dilution:
97-99% for filling phase only

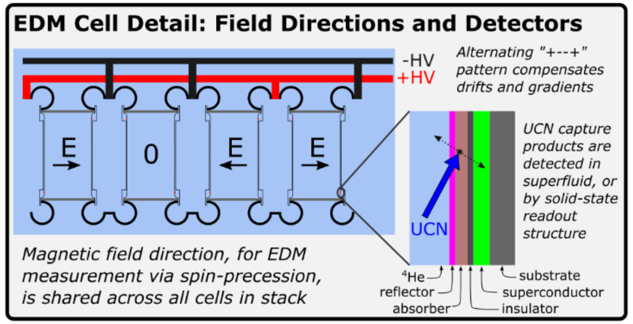
…this is a generic challenge when neutrons are extracted/transferred to experiments

Broad interest in the community to explore feasibility for ***in-situ* experiments,** performed within superthermal UCN sources based on superfluid ^{4}He, as a platform for future nEDM measurements.

…extraction and transfer losses can be eliminated.

One possible approach to investigate for high statistics:

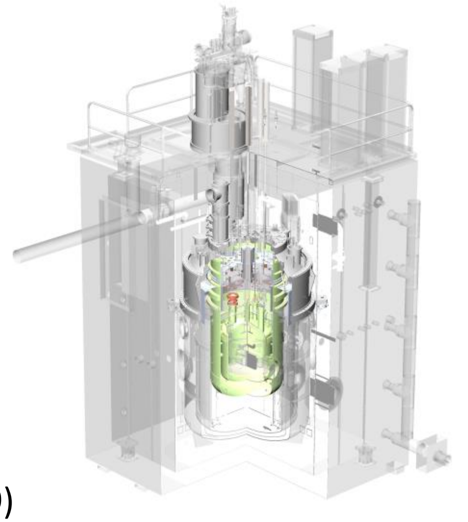




JNR (2022) **24**(2), 123-143

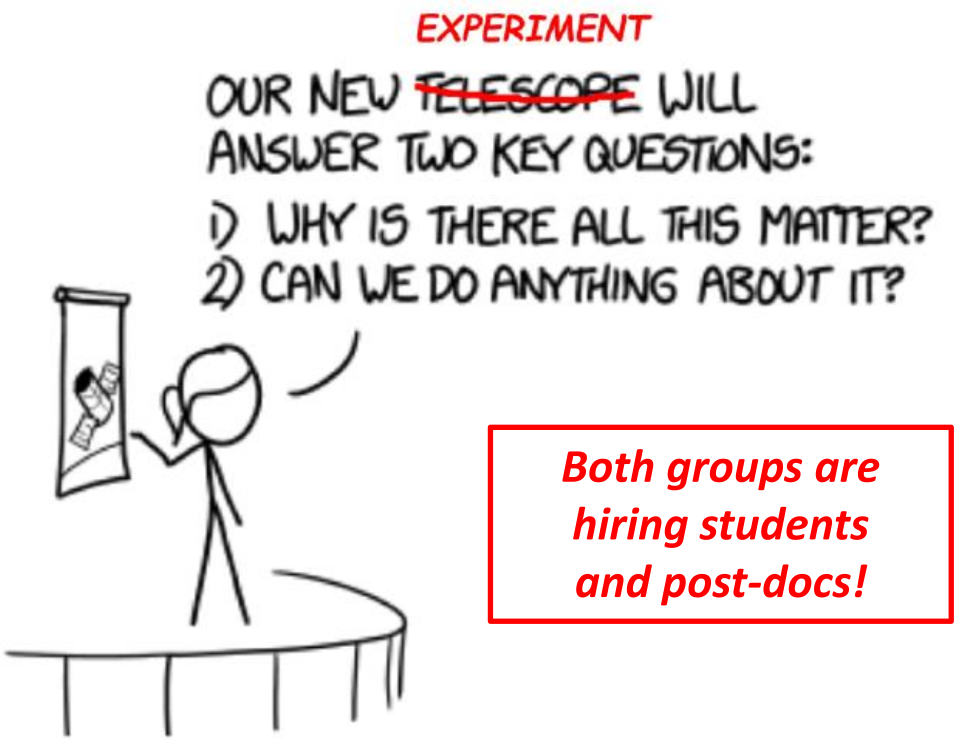
Intermediate sensitivity, with extensively studied *in-situ* concept: nEDM@SNS

…possible US-Europe collaboration



JINST **14** P11017 (2019)

Thanks! Questions?



what-if.xkcd.com

Both groups are hiring students and post-docs!

Special thanks to:

SuperSUN-PanEDM collaboration
Institut Laue-Langevin, NPP & SANE

PSI nEDM and n2EDM collaborations
LPSC and UGA groups (Grenoble)

Un-natural Units (orders of magnitude)

$$10^{-26} e \text{ cm} \times \frac{1 \text{ MV}}{m} \times \frac{1}{2\pi\hbar} = 24 \text{ nHz}$$

$$\frac{1}{24 \text{ hours}} = 11.6 \ \mu\text{Hz}$$

$$\frac{1}{15 \text{ min}} = 1 \text{ mHz}$$

$$\mu_{\text{N}} \times \frac{1\mu\text{T}}{2\pi\hbar} = 8 \text{ Hz}$$

$$\mu_{\text{B}} \times \frac{1\mu\text{T}}{2\pi\hbar} = 14 \text{ kHz}$$

$$1 \ e \text{ cm} = 10^{13} e \text{ fm}$$

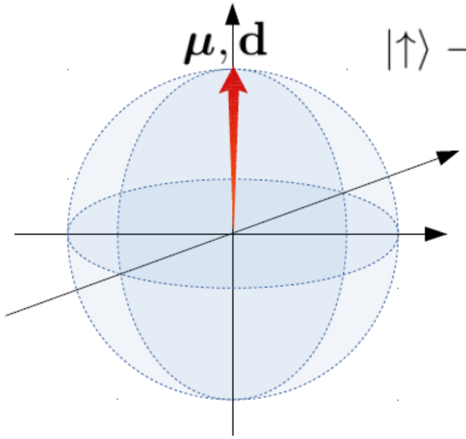
$$1 \text{ neV} = 1 \frac{\text{GeV}}{c^2} \times 1 \text{ cm} \times g$$

Terminology for Slow Neutron Spectra

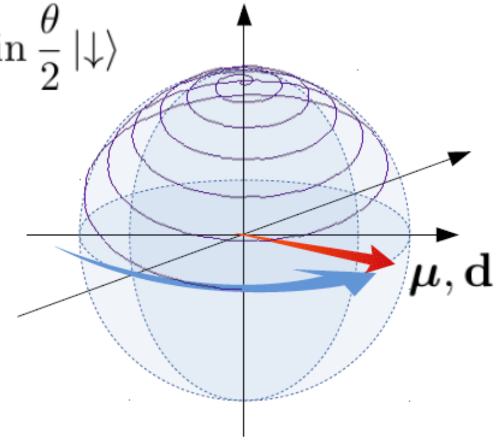
Velocity	"Temperature"	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 µeV – 50 µeV
$10^2 - 10^3$ m/s	Cold	50 µeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2\times10^3 - 2\times10^4$ m/s	Hot	20 meV – 2 eV

Seven decades of progress

Ramsey's method to measure frequencies*:

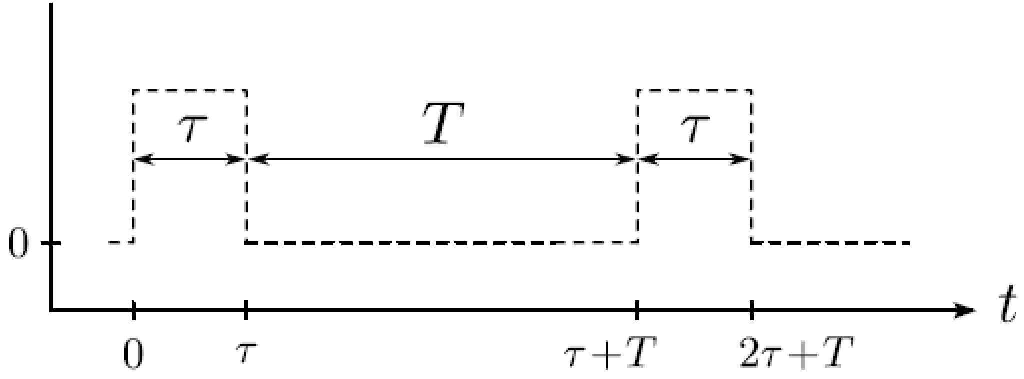


$$|\uparrow\rangle \longrightarrow \cos\frac{\theta}{2}\,|\uparrow\rangle + e^{i\omega t}\sin\frac{\theta}{2}\,|\downarrow\rangle$$

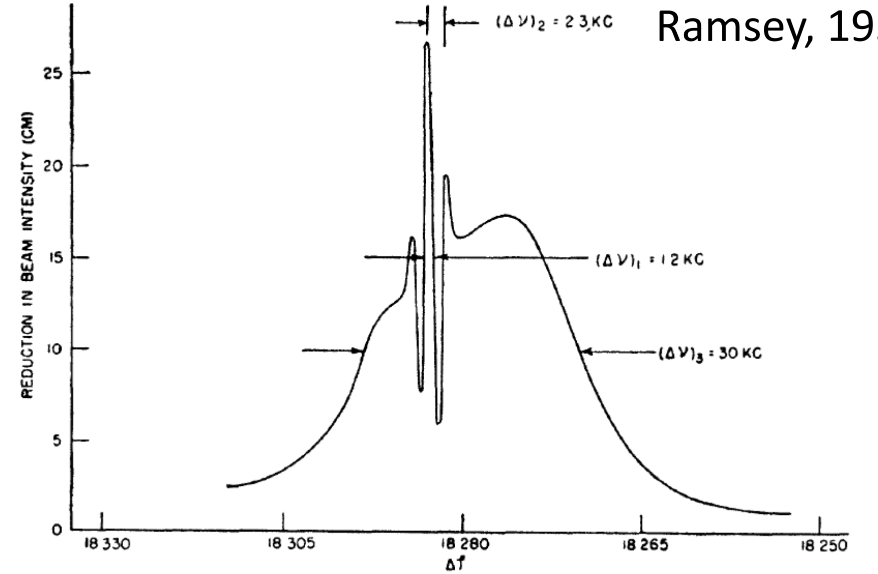


phase evolution:

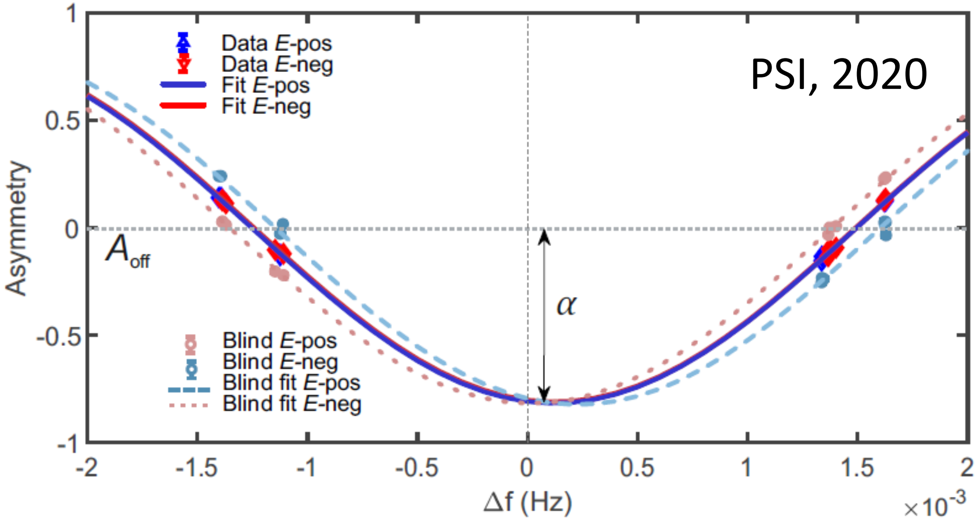
$$\phi(t) \sim \int dt\ \omega(t)$$



Ramsey, 1957

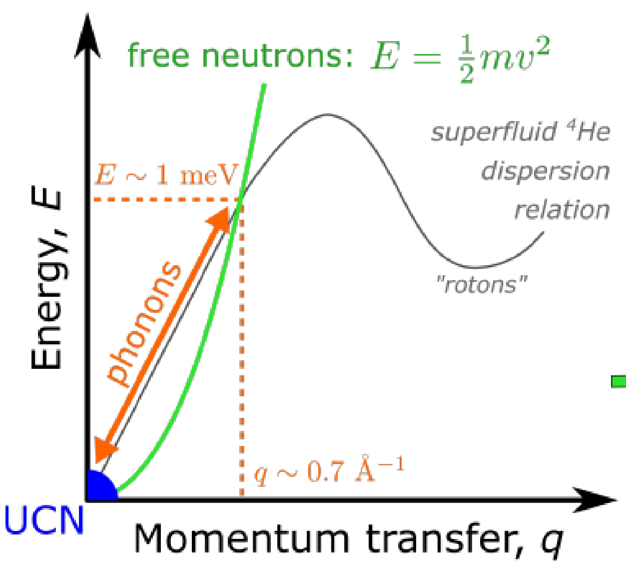


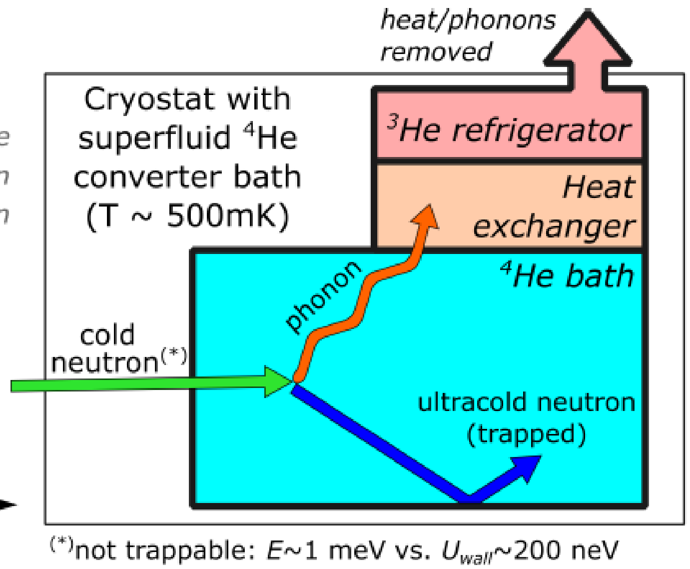
PSI, 2020

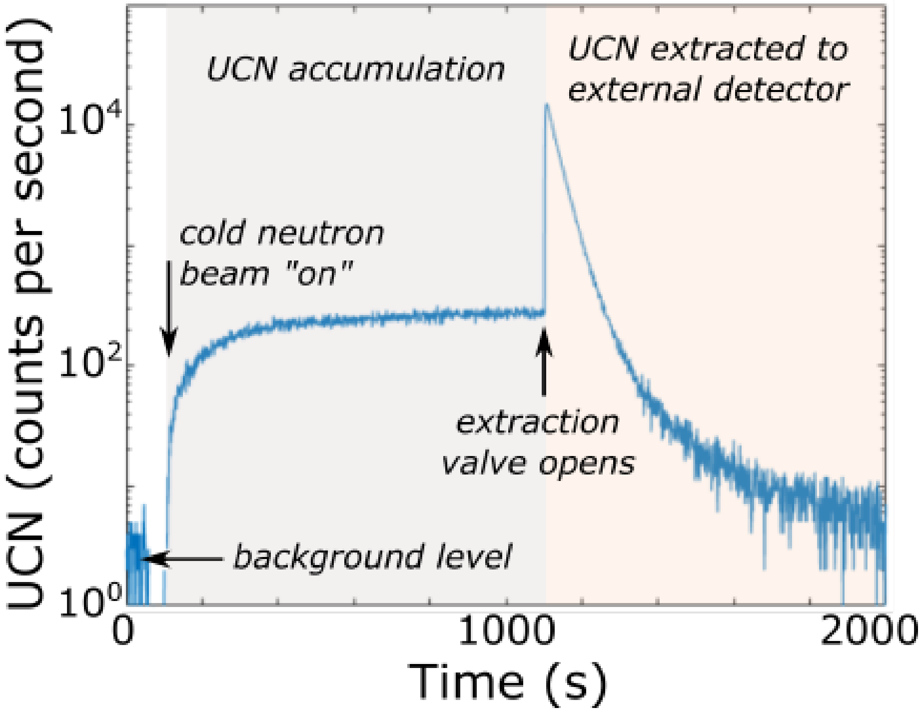


*we can come back to *frequency* vs. *phase*

UCN and Production in He-II







Velocity	"Temperature"	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 µeV – 50 µeV
$10^2 - 10^3$ m/s	Cold	50 µeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2\times10^3 - 2\times10^4$ m/s	Hot	20 meV – 2 eV

$$R \sim \left(\frac{5\times10^{-8}}{\mathrm{cm}^3\ \mathrm{s}}\right) \times \left.\frac{d\Phi}{d\lambda}\right|_{8.9\text{Å}} \times \left(\frac{V_{\mathrm{trap}}}{233\ \mathrm{neV}}\right)^{\frac{3}{2}}$$ **production**

$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{capture}}} + \frac{1}{\tau_{\mathrm{wall}}} + \cdots$$ **loss**

EDMs in the SM do not vanish

- CP violation from three sources (ignoring neutrinos):

$$\mathcal{L}_{\mathrm{CPV}} = \mathcal{L}_{\mathrm{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\mathrm{BSM}}$$

- CKM CP-violation (Standard Model):

$$\mathcal{L}_{\mathrm{CKM}} = -\frac{i g_2}{\sqrt{2}} \sum_{p,q} V^{pq} \bar{U}_L^p \not{W}^+ D_L^q + \mathrm{H.c.}$$

- Strong CP-violation (Standard Model):

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_S}{16\pi^2} \bar{\theta} \mathrm{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$$

details:
arXiv:2403.02052
*Rev. Mod. Phys. **91**, 015001 (2019)*
*Phys. Rev. C **91**, 035502 (2015)*
*Prog. Part. Nucl. Phys. **71**, 21 (2013)*

Effective Field Theory for EDMs

General Effective Lagrangian:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Global Analysis:
arXiv:2403.02052
arXiv:2312.08858
Rev. Mod. Phys. ***91****, 015001 (2019)*
Phys. Rev. C ***91****, 035502 (2015)*

Dimension-six terms for the neutron:

$$\mathscr{L}_{\text{eff}}^{(6)} = -\frac{i}{2} \sum_{l,q} d_q \bar{q} \sigma_{\mu\nu} \gamma^5 F^{\mu\nu} q - \frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma_{\mu\nu} \gamma^5 G^{\mu\nu} q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Prog. Part. Nucl. Phys. ***71****, 21 (2013)*

Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}$, $\mathrm{Im}\, C_{\ell eqd}$	Semi-leptonic (6)	3
δ_q	Quark EDM (6)	2
$\tilde{\delta}_q$	Quark chromo EDM (6)	2
$C_{\tilde{G}}$	Three-gluon (6)	1
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	Four-quark (6)	2
$\mathrm{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1
Total		13