Technische Universität München

SLOW NEUTRONS
DFG SPP 1491

Neutron EDM

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ANL Workshop Dec 14th 2017

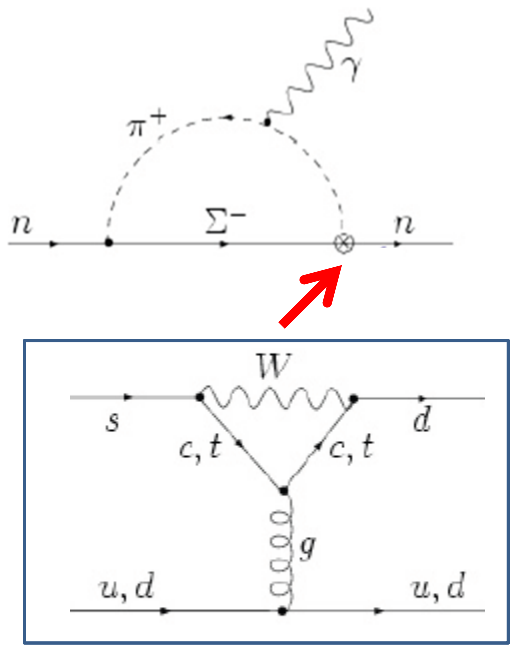
Content

- Neutron EDM - Status
- PanEDM experiment
- Future perspectives & spin-offs

Neutron EDM and the SM

Khriplovich Zhitnitsky (1986),
McKellar et al., (1987)

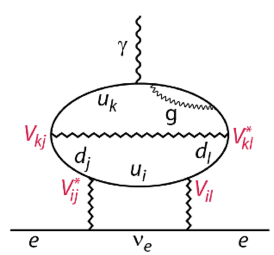
CP violation from CKM



Neutron EDM $d_n \approx 10^{-32}$ ecm

More complex calcuations may be required:
T. Mannel, N. Uraltsev, Phys.Rev. D85 (2012) 096002

Side note: $d_{electron} < 10^{-38}$ ecm…



M. Pospelov, et al., Sov. J. Nucl. Phys. 53, 638 (1991)

Strong Interaction

CP-odd term in Lagrangian:

$$L_\theta = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

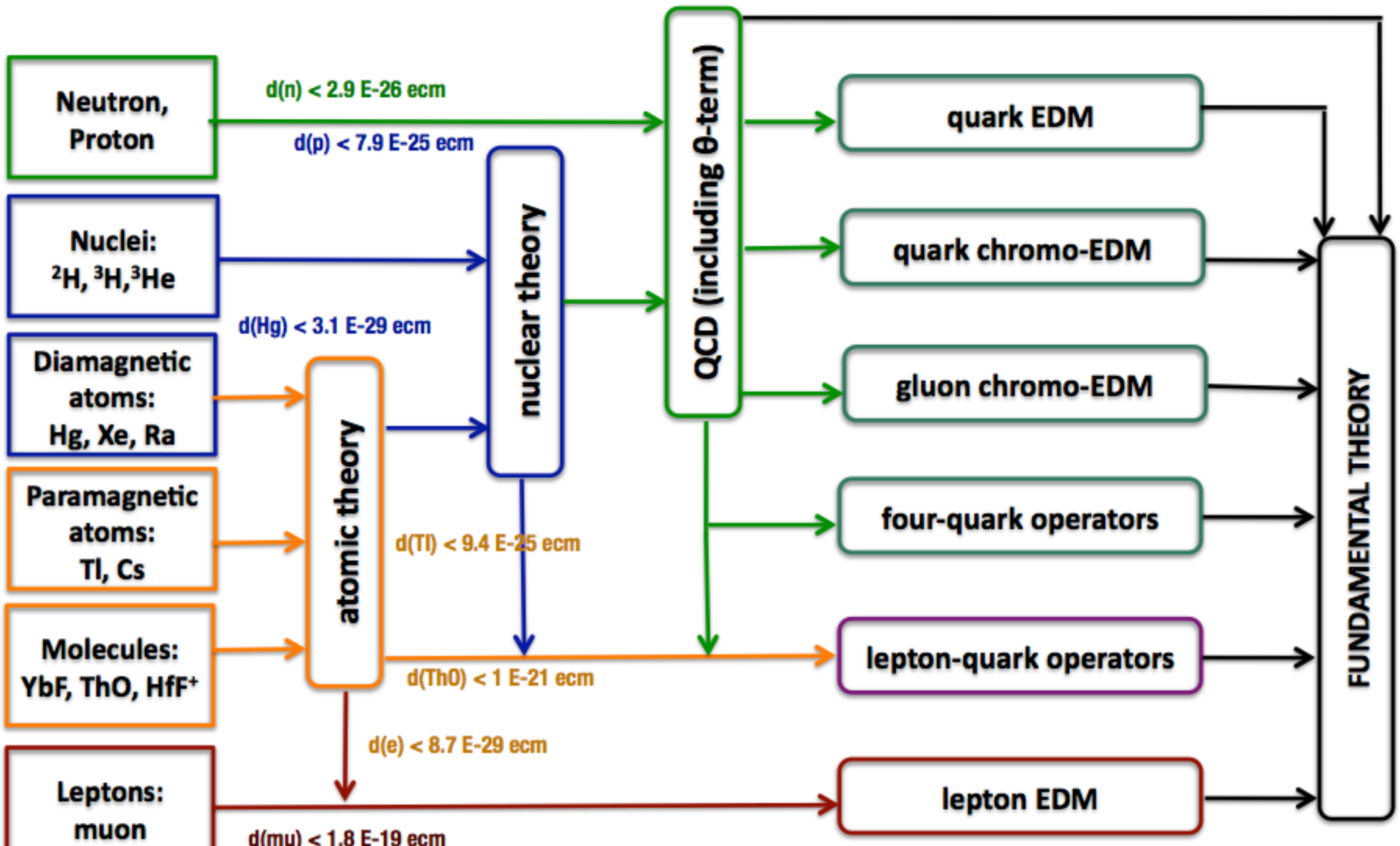
$$d_n(\bar{\theta}) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17}\,\bar{\theta} e \cdot cm$$

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

Strong CP problem

E.g. Pospelov, Ritz, Ann. Phys. 318(2005)119

EDM Landscape



(adapted from Jordy de Vries, Jülich, March 14, 2013)

Different systems and effective parameters

e and μ EDM

Nuclear-spin-dependent e-N coupling C_T,

Nuclear-spin independent couplings C_S^0

Intrinsic quark EDMs and chromo EDMs

Meson-nucleon couplings $g_\pi^{0,1,(2)}$

- Paramagnetic atoms

$$d_{para} = \eta_{d_e} d_e + k_{C_S} \bar{C}_S$$

- Polar molecules

$$\Delta\omega_{para}^{\not P \not T} = \frac{-d_e E_{eff}}{\hbar} + k^{\omega}_{C_S} \bar{C}_S$$

- Diamagnetic atoms

$$d_{dia} = \kappa_S S(\bar{g}_\pi^{0,1}) + k_{C_T} C_T + \ldots$$

- Nucleons

$$d_{n,p} = d^{lr}_{n,p}(\bar{g}_\pi^{0,1}) + d^{sr}_{n,p}(\tilde{d}_{u,d}, d_{u,d})$$

- Fundamental fermions

$$d_e, d_\mu, (d_\tau)$$

...Higher orders (199-Hg!) :

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{ h.o. (MQM)}$$

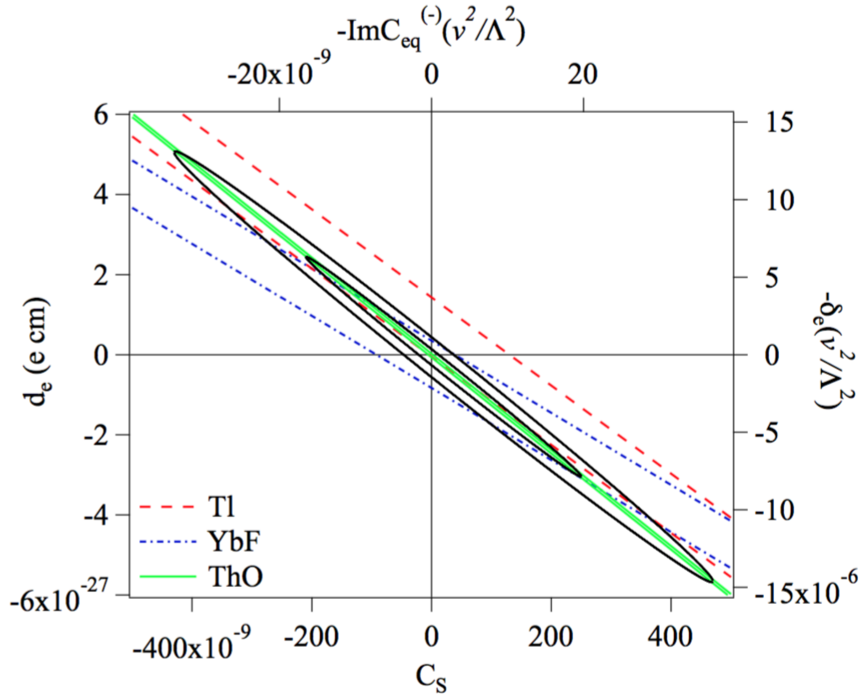
T. Chupp, PF, M.J. Ramsey-Musolf, J. Singh, arxiv (2017) & Rev. Mod. Phys.

Limits from different measurements

Measured limits (note: ‘sole-source‘ analysis)

System	Result	95% u.l.
	Paramagnetic systems	
Xe^m	...	
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ e-cm	1.4×10^{-23}
	$d_e = (-1.5 \pm 5.6) \times 10^{-26}$ e-cm	1.2×10^{-25}
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ e-cm	1.1×10^{-24}
	$d_e = (\ 6.9 \pm 7.4) \times 10^{-28}$ e-cm	1.9×10^{-27}
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$ e-cm	1.2×10^{-27}
ThO	$\omega^{NE} = 2.6 \pm 5.8$ mrad/s	
	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e-cm	9.7×10^{-29}
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}
	Diamagnetic systems	
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$ e-cm	7.4×10^{-30}
^{129}Xe	$d_A = (0.7 \pm 3) \times 10^{-27}$ e-cm	6.6×10^{-27}
^{225}Ra	$d_A = (-0.5 \pm 2.5) \times 10^{-22}$ e-cm	5.0×10^{-22}
TlF	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$ e-cm	6.5×10^{-23}
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$ e-cm	3.6×10^{-26}
	Particle systems	
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$ e-cm	1.8×10^{-19}
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$ e-cm	7.9×10^{-17}

Parameters are not independent: e.g. d_e as function of C_S

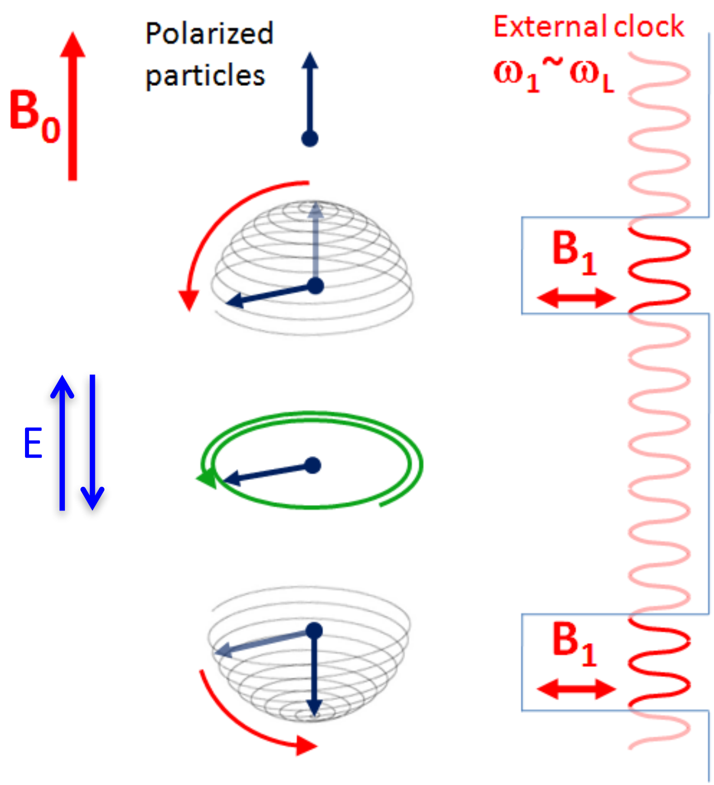


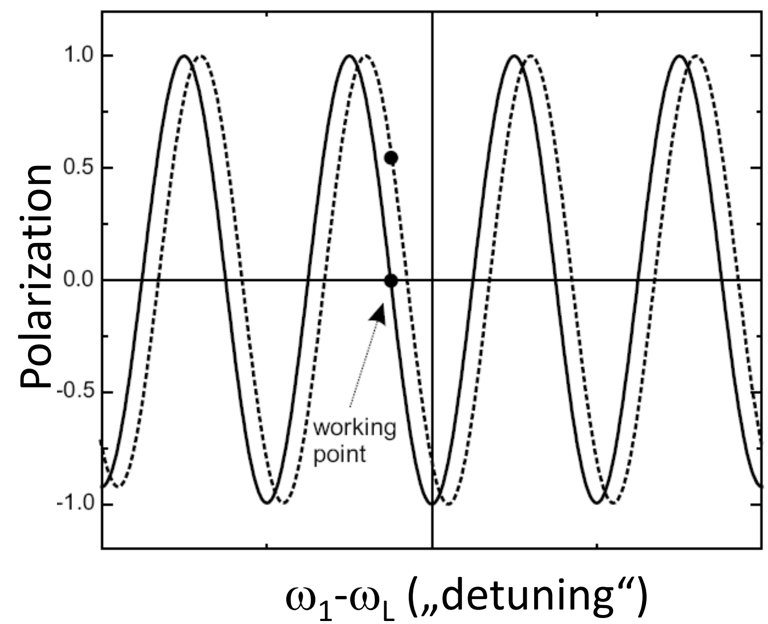
$$d_{\rm para}^{\rm exp} = d_e + \frac{\alpha_{C_S}}{\alpha_{d_e}} C_S$$

More measurements needed with different systems...

Ramsey‘s method

(Particle beam or trapped particles)





$$\hbar\omega_L \sim \mu B + dE$$

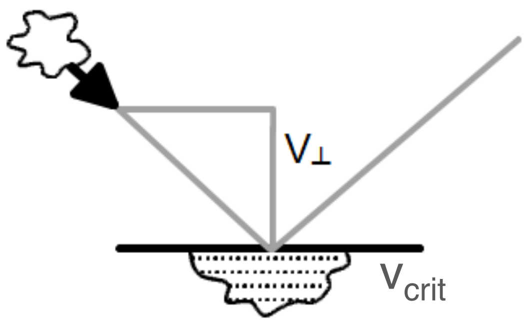
$$\sigma_{d_n} = \frac{h}{2\alpha ET\sqrt{N}}$$

Ultra-cold neutrons (UCN)

T ~ mK, E_{kin} < 200 **NANO**-eV, v < 7 m/s, λ > 50 nm

Strong Interaction: ‚Fermi potential‘

$$U_F \propto N \cdot b_c \sim 100 \text{ neV}$$



Optical properties:
- Neutron traps (UCN: $v_{tot} < v_{crit}$)
- Neutron guides (CN: $v_\perp < v_{crit}$)

Electromagnetism

Magnetic moment:
$|\mu|$ = 60 neV/T
… magnetic traps

Weak Interaction

$$n \rightarrow p + e^- + \bar{\nu}_e$$

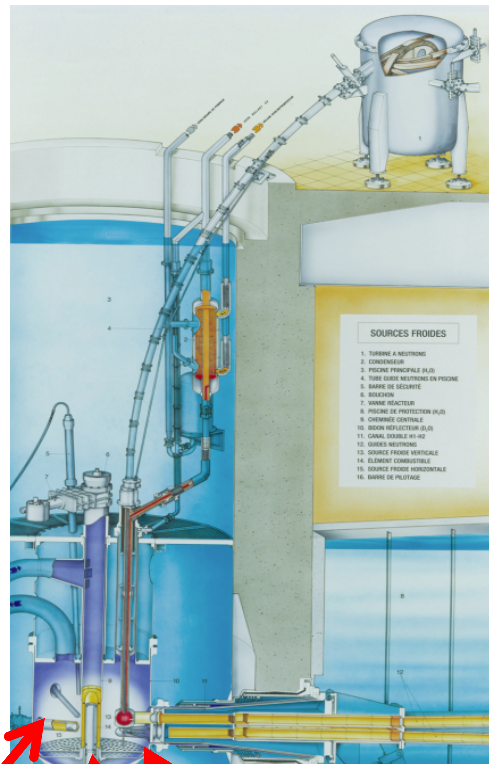
τ_n ~ 881 s

Gravity

$V = m_n g h$ 100 neV/m

Neutron production

Neutron source at Institute Laue-Langevin (Grenoble):



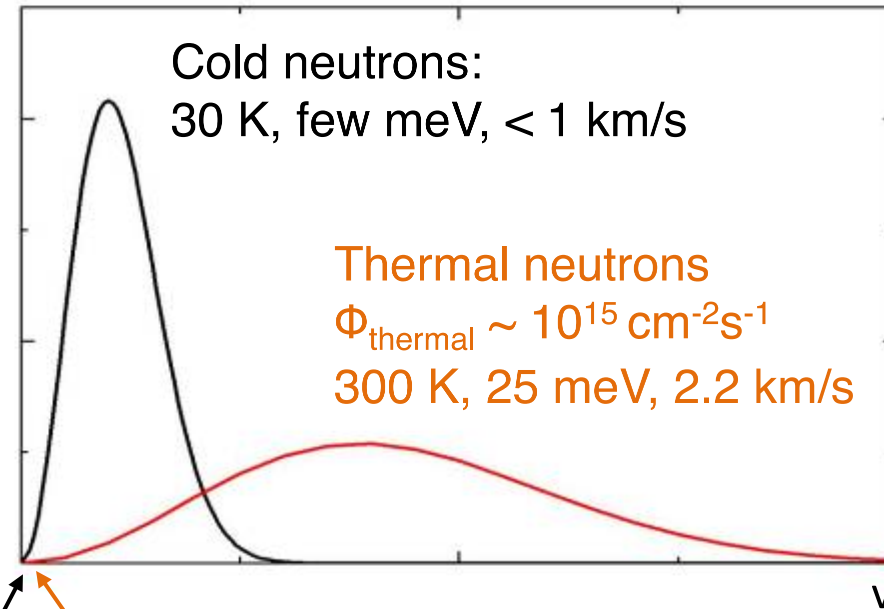
10 UCN/cm³

5 m

D_2O moderator (300K)

Fuel

Cold moderators (30K)

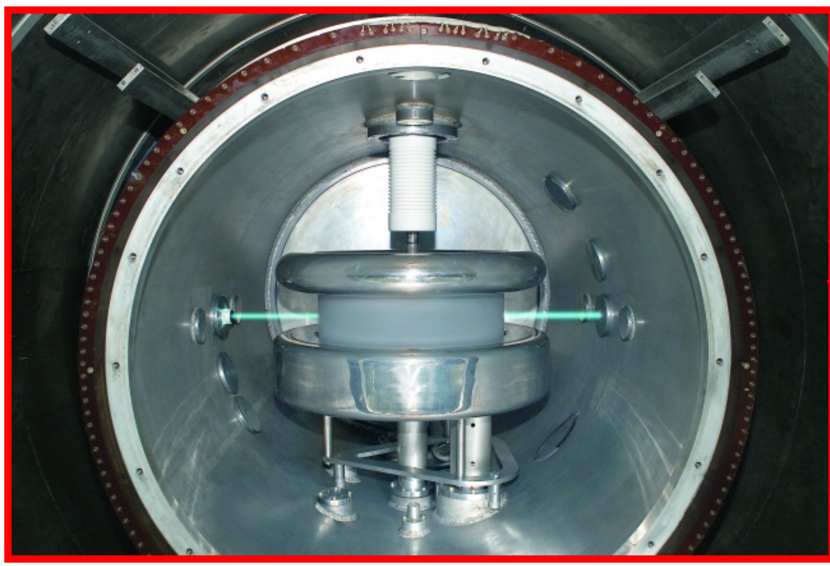


ρ(ultra-cold) ~ $10^{-13}\ \Phi_{thermal}[cm^{-2}s^{-1}]\ cm^{-3}$

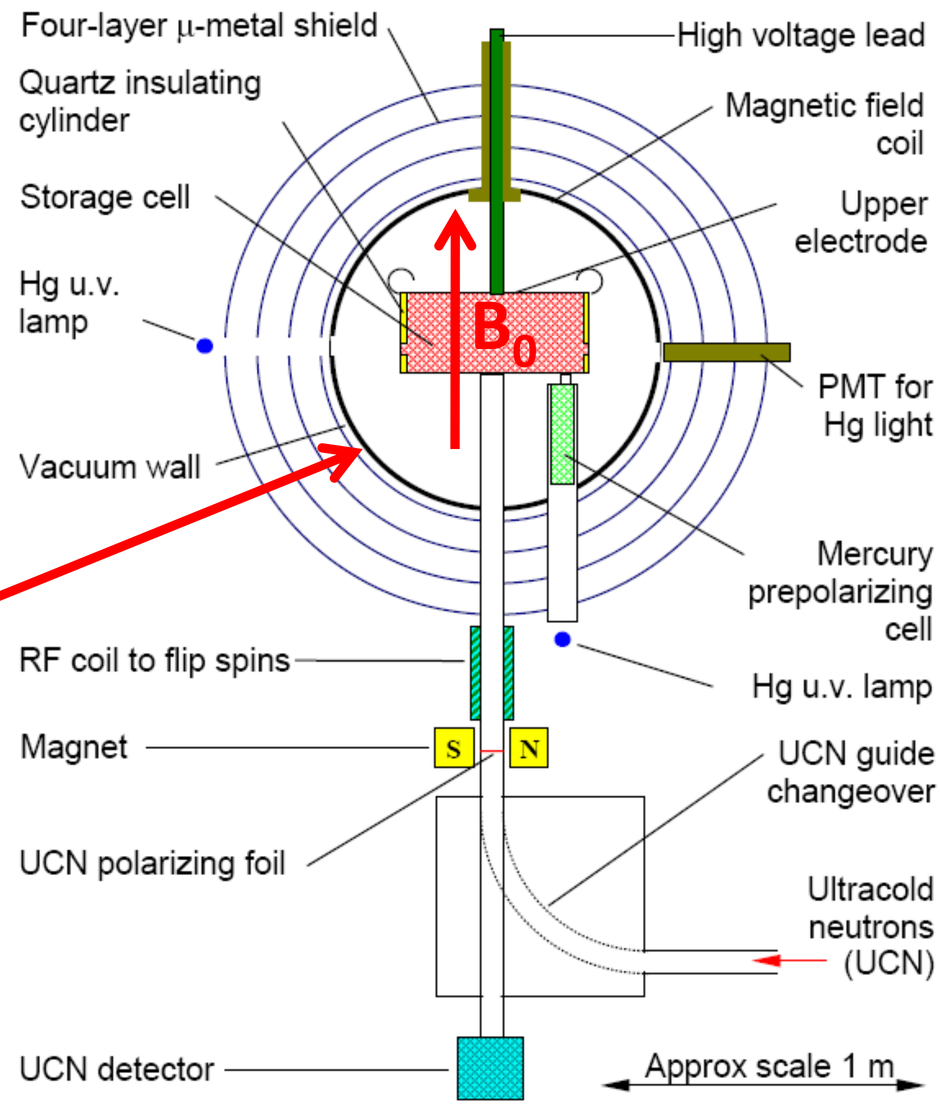
ρ(ultra-cold) ~ $70\times10^{-13}\ \Phi_{cold}\ [cm^{-2}s^{-1}]\ cm^{-3}$

Neutron EDM:
RAL-Sussex-ILL Experiment

(Still) the state of the art:
~ 1 trapped
ultra-cold neutron/ cm^3



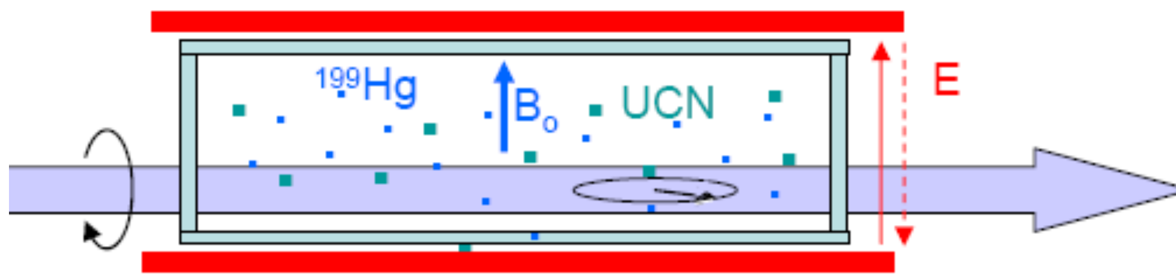
~ 0.5 m



Spin-clock with two species

- Neutrons + ^{199}Hg vapor measured simultaneously
- UCN center of mass is affected by gravity (CMS 2 mm below center of chamber)
- Obvious: $R = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right|\left(1 + \frac{(\partial B/\partial z)h}{B}\right)$
- Non-trivial: $T_2(z)$, $\Delta\omega(z)$....

Cohabitating spin magnetometer



Best limit: $d_n < 3 \times 10^{-26}$ e cm ($\Delta E \sim 10^{-22}$ eV)

Baker et al., Phys. Rev. Lett. 97 (2006) 131801. + re-analysis (2015)

Systematics: Understood problems

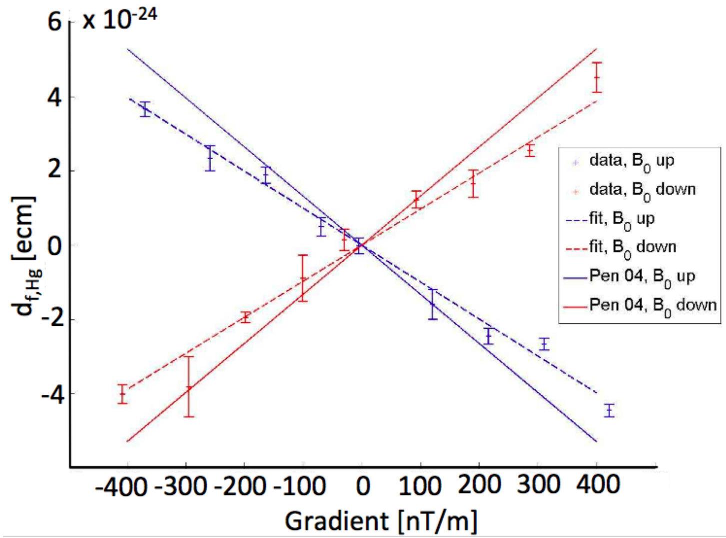
Most critical: Ramsey-Bloch-Siegert shift or ‚geometric phase‘ (GP):

$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)}$$

$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E \times v}{c^2}\right)^2 + \boxed{2\frac{\partial B_{0z}}{\partial z}\alpha \cdot \frac{E \times v}{c^2}}$$

Magnetic field requirements for 10^{-28} ecm – level accuracy:

- ~ < 0.3 nT/m gradient
  $d_f \sim 4 \cdot 10^{-27}$ ecm (^{199}**Hg** GP)
  $d_f \sim 1\text{-}2 \cdot 10^{-28}$ ecm (UCN GP)
- Max. 1 dipole with 5 pT in 2 cm distance
- < 10 fT drift stability
- Spin-echo for various systematics

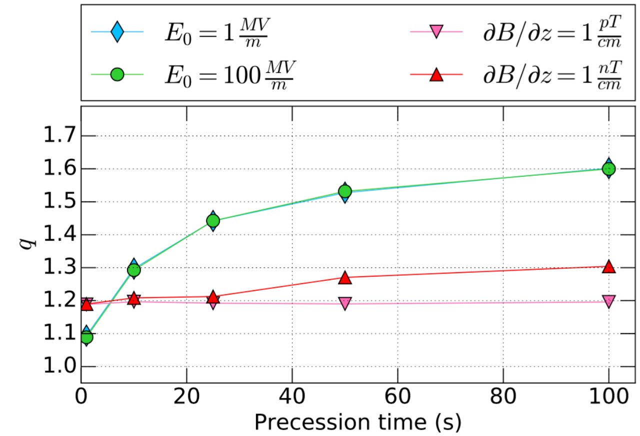


Pendlebury et al., Phys. Rev. A **70**, 032102 (2004)
Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006), also: G. Pignol, arXiv:1201.0699 (2012), A. Steyerl et al. Phys. Rev. A 89, 052129 (2014) etc…

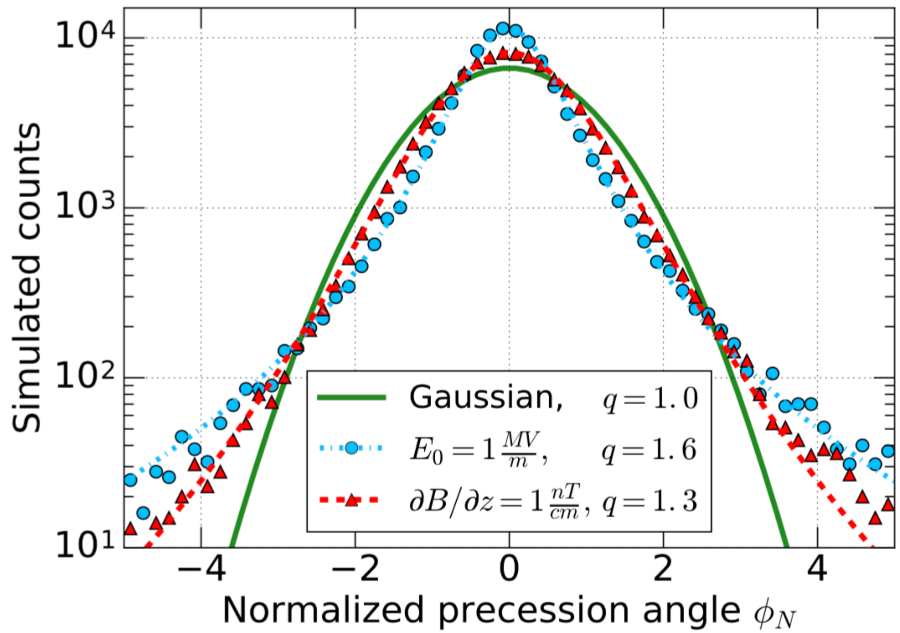
Systematics: The next generation...

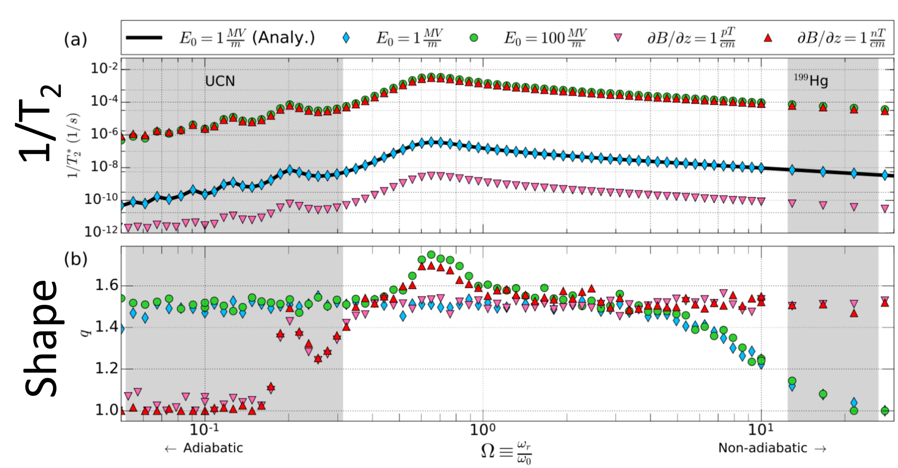
- **Non-Gaussian spin distributions: non-ergodic**
- Affects all previously known systematics: Error bars, skewness
- Largest for non-thermalizing ensembles
- Impact on other measurements ?!

Non-gaussianity build-up with time:



M. Bales et al., arxvi:1602.01082, EPL 2017





Adiabatic regime Non-adiabatic

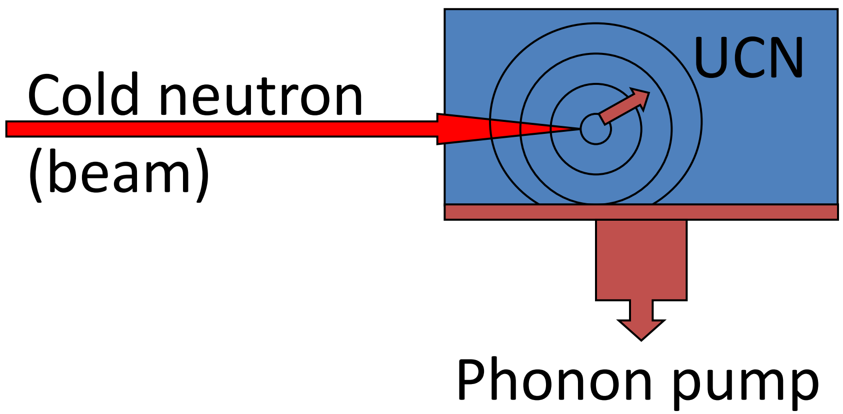
Neutron EDM projects

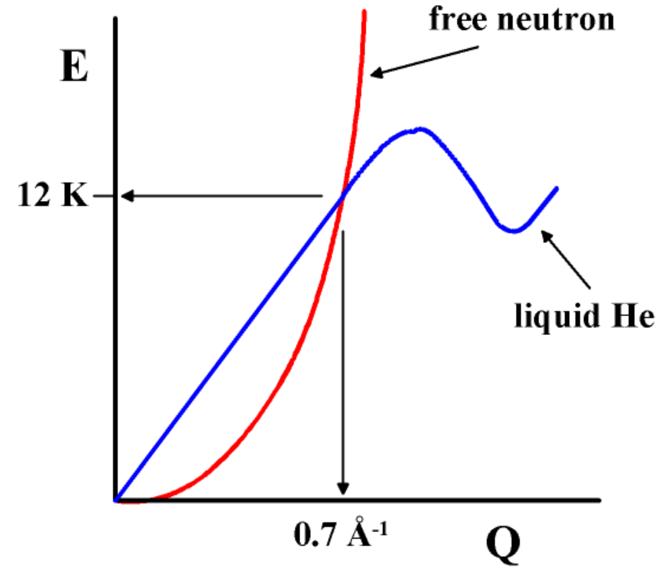
	RAL SUSSEX ILL (Grenoble, FR)	PSI (Villigen, CH)		TUM ILL (Grenoble, Munich)		LANCSE EDM (Los Alamos, US)	SNS EDM (Oakridge, US)	PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)		TRIUMF (Vancouver, CA)	
temperature	**RT**	RT		RT	0.7 K	RT	0.7 K	**RT**		RT	
comag	**Hg**	**Hg**		none		Hg	^{3}He	**none**		Xe+Hg	
source	**reactor, turbine**	**spall., sD_2**		reactor, cold neutrons, ^{4}He		D2	spall, internal ^{4}He	reactor, turbine, ^{4}He		spall., ^{4}He	
nr of cells	**1**	**1**	2	2		1	2	2	>2	1	2
[UCN/cc]	**2**	**3**	5	10	1000	~ 50	125	**4**	10^4	700	
goal [e·cm]	**$3 \cdot 10^{-26}$**	$1 \cdot 10^{-26}$	$1 \cdot 10^{-27}$	$2 \cdot 10^{-27}$	$< 10^{-27}$	few 10^{-27}	$2 \cdot 10^{-28}$	$5 \cdot 10^{-26}$	$5 \cdot 10^{-28}$		$1 \cdot 10^{-27}$
date	**2006**	**2017**	2019	2019	2021+	2018	2021	2015	2022	2017	2019
status	**done!**	RAL exp. **NEW LIMIT SOON** ~1.10^{-26}	new	**SETUP AT ILL STARTED: ‚PanEDM'**		**Sucessful source upgrade**	Critical Component Demonstration			**FIRST UCN OBSERVED from Prototype source (2017)**	
comment	**Best limit so far!**	Source delivery behind expectations		Modifications for Munich ⇒ ILL, D_2 ⇒ He		Will be faster than expected	great concept, higher risk				

Taken from R. Picker (2016), adapted

New UCN sources

‚Conversion' instead of moderation





Golub and Pendlebury, PL62A(1977)337: superfluid He
Golub and Böning, ZPB51(1983)95 : solid D_2

- Increases phase space density
- Main materials: **solid D_2, superfluid He**

Detailed balance: upscattering = exp(-ΔE/kT) x downscattering

Planned ~ 1000 UCN / cm^3

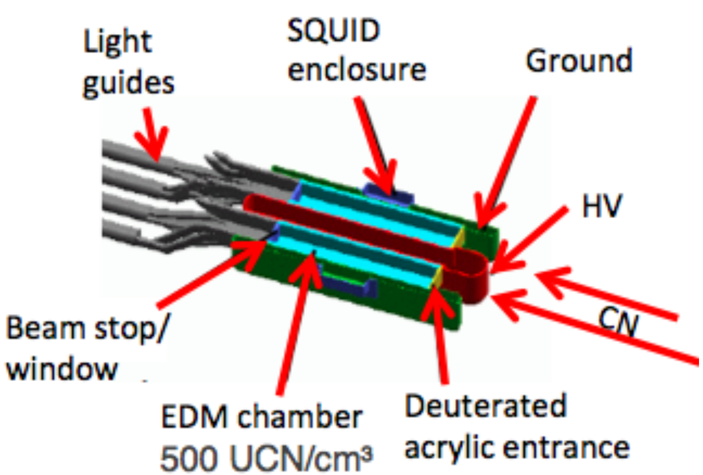
- Sites: (sD2) LANL, PSI, FRM2, NCSU; (lHe-II) ILL, PNPI, TRIUMF, KEK; SNS

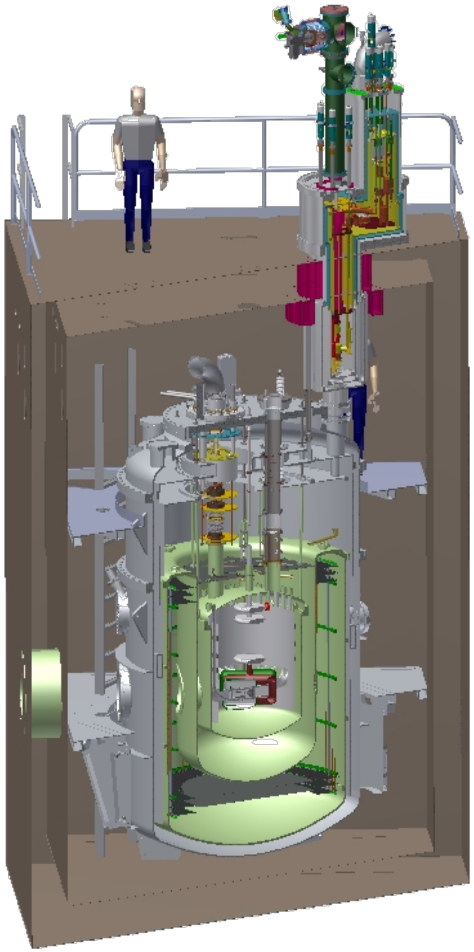
SNS EDM

- Cryogenic, 100 UCN/cm^3 site: SNS, placed at cold beam
- UCN source = EDM chamber, double chamber
- E = 75 kV/cm
- Co-magnetometer: spin dependent ^{3}He absorption and scintillation

Unique possibility: spin dressing

- Modulation of spin-dressing frequency to extract EDM

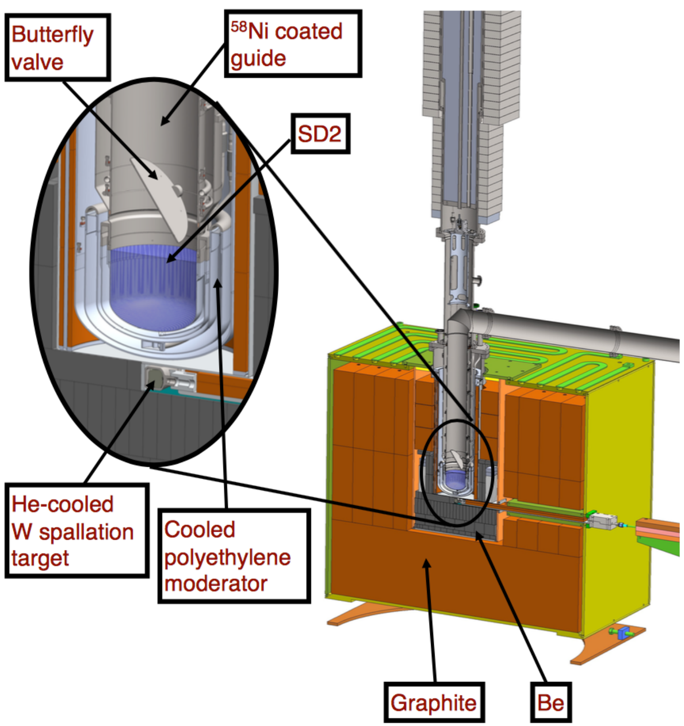


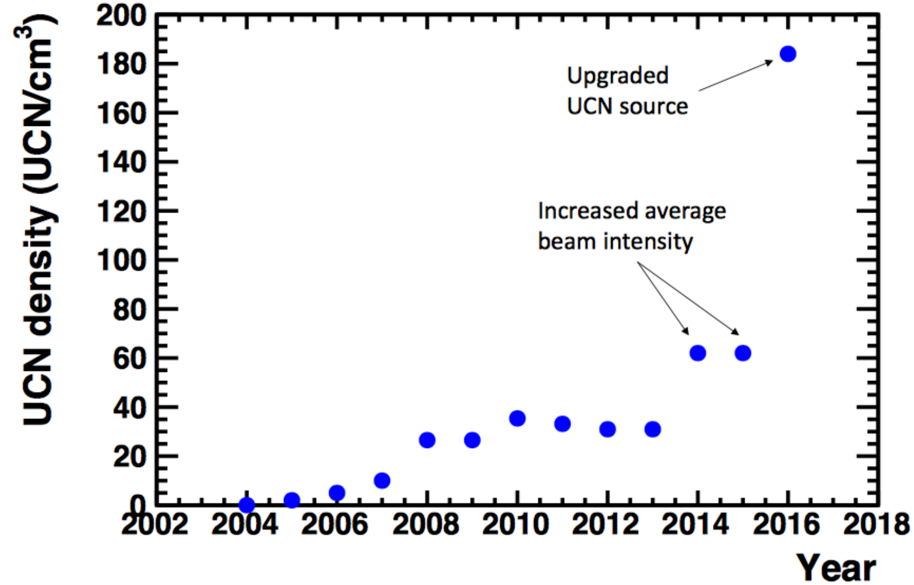


- Year 4/4 of critical component demostration phase

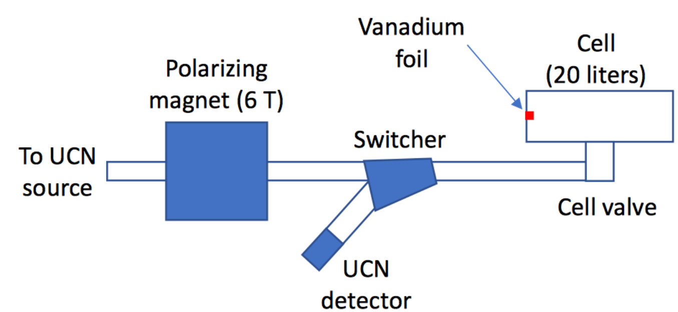
LANL EDM

Recent progress: UCN source upgrade





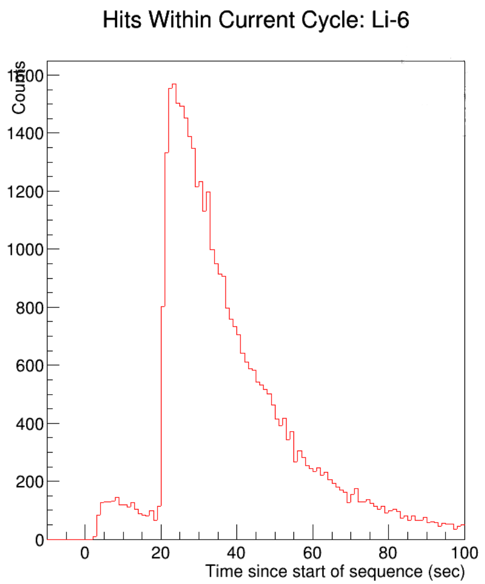
T.M.Ito et al., arXiv:1710.05182

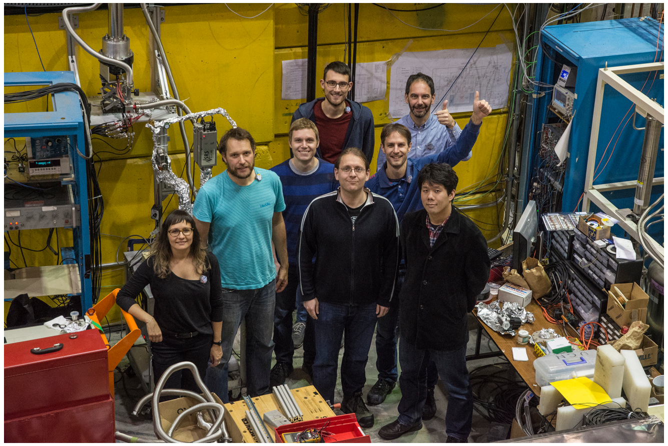


Planned nEDM: $\sigma_d < 3.10^{-27}$ ecm within next few years (room-temp. Ramsey)

First UCN at TRIUMF

- **Very recent progress: First operation of source, 500000 UCN**
- Behaviour within expectations
- p-Accelerator
- Neutron-production target with a 1 microamp, 480 MeV proton beam for 60 seconds
- Goal: $\sigma_d \sim 10^{-27}$ ecm, room-temp. Ramsey

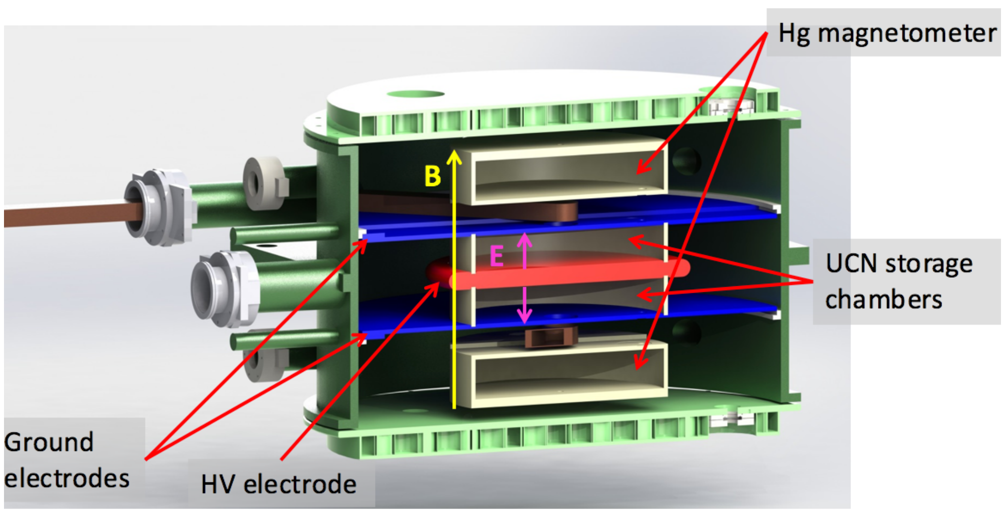


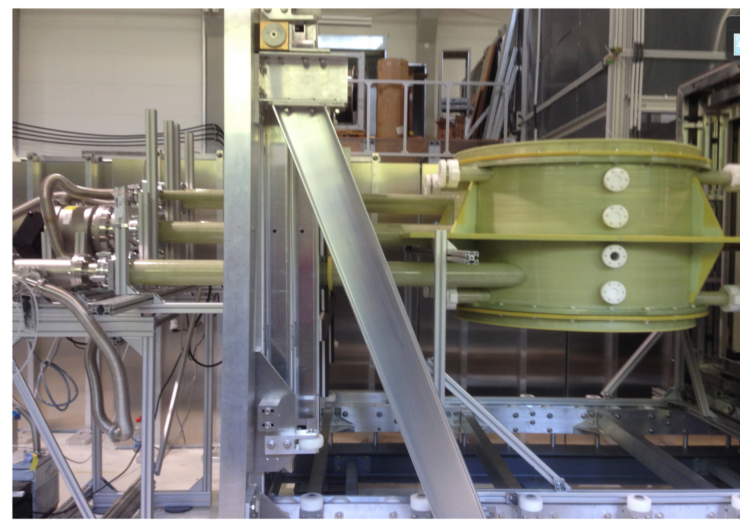


TRIUMF, CFI, BCKDF, MRF and NSERC in Canada, and KEK and RCNP

PanEDM

- Contributions from Berkeley, ILL, Jülich, LANL, U.Michigan, MSU, NCSU, PNPI, PTB, RAL, TUM, UIUC, Yale
- Spin-precession with coherent pulsing
- UCN at room temperature, later cryogenic
- Double chamber
- Minimized number of mechanical parts close to chambers
- Initially ^{199}Hg and Cs, if needed also ^{129}Xe, ^{3}He, SQUID magnetometers





Nonmagnetic vacuum chamber (2013!)

I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

Small magnetic fields

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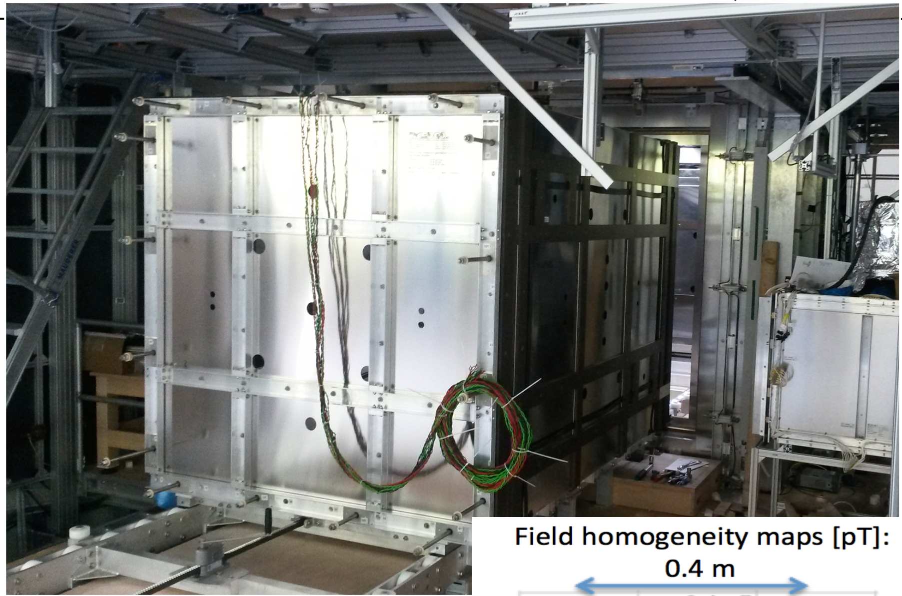
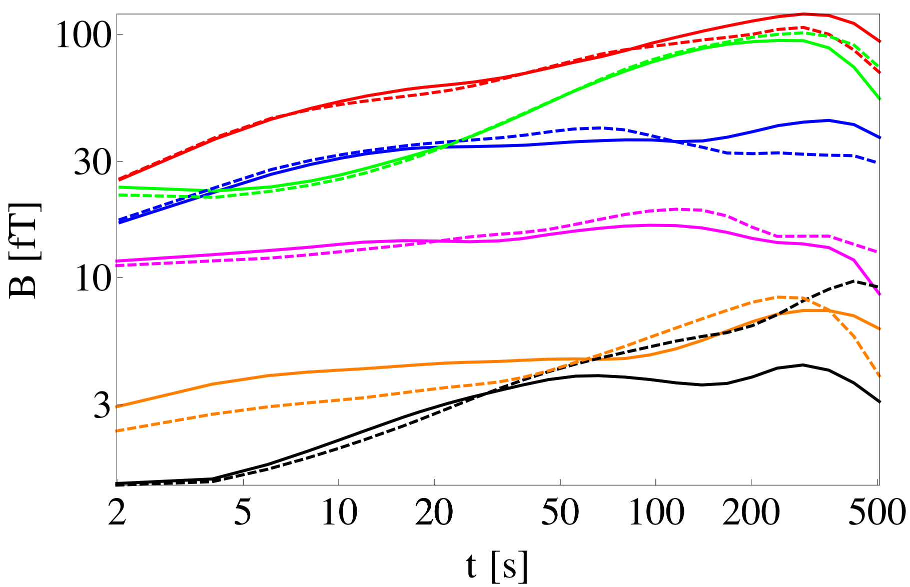
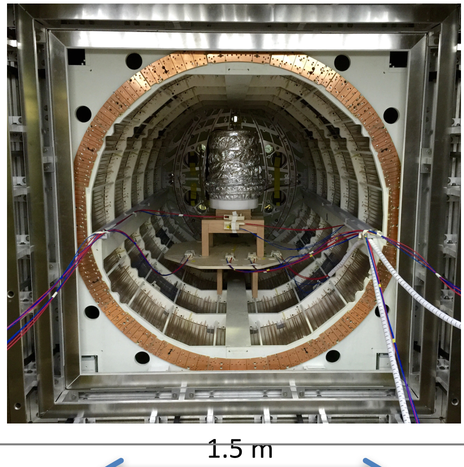
- Highest damping ever obtained: ~ 6.10^6 (mHz)
- Highest stability ever obtained: few 5 fT in 10^2 s (AIP Highlight 5/2015)
- Static gradient ~ 10^{-10} T/m over 1 m^3



SQUID Allan deviation (compare to typical 1/f noise!)



µT Ramsey field coils



Field homogeneity maps [pT]:

0.4 m

1 m

	Bx in pT	
Xend-18	Xmitte0	Xend+18
8	50	88
11	59	80
29	80	85
18	48	91
19	51	91
12	43	97
-2	30	91
	By in pT	
Xend-18	Xmitte0	Xend+18
-23	-22	-26
-35	-39	-32
-28	-26	-22
-18	-28	-22
-28	-31	-23
-56	-26	4
-79	-33	15
	Bz in pT	
Xend-18	Xmitte0	Xend+18
-106	-66	-67
-116	-82	-63
-87	-53	-54
-81	-31	-27
-77	-34	-42
-87	-47	-66
-93	-55	-75

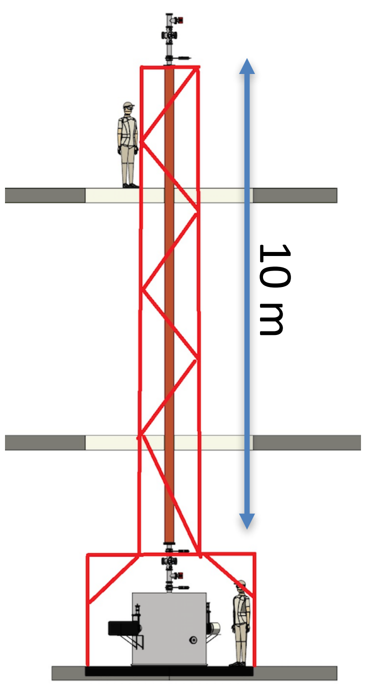
(Measurement dominated by sensor cables!)

I.Altarev et al., arXiv:1501.07408 / Rev. Sci. Instr (2915)
I. Altarev et al., , arXiv:1501.07861, J. Appl. Phys. (2015), Appl. Phys. Lett. (2015)

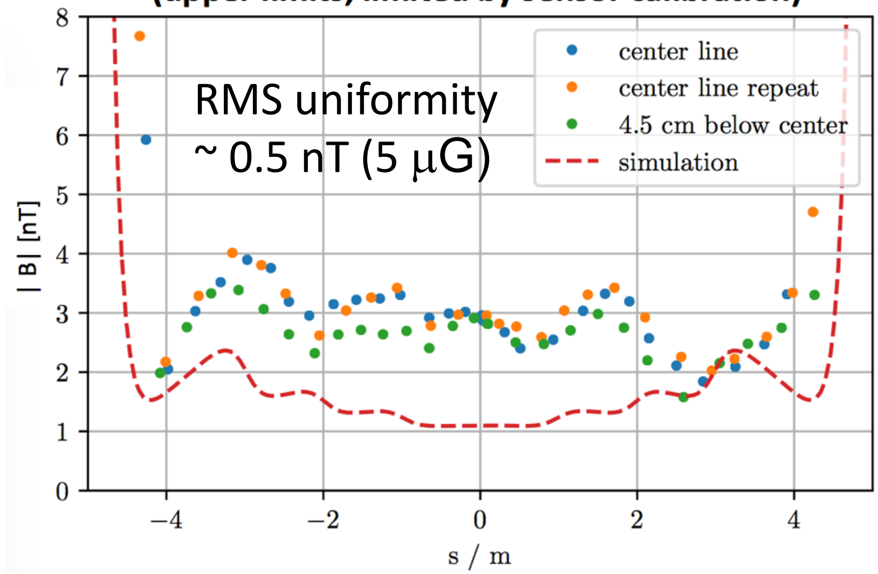
Spin-off: Designing small fields

- Time-dependent numerical modeling of hysteresis and magnetic equilibration (TUM, HIT) demonstrated: quantitative agreement of simulation + experiment
- |B| < 25 pT over large volume demonstrated
- **New: demonstrated now in 10 m long shield for atomic fountain!**

Z. Sun et al., J. Appl. Phys. 119, 193902 (2016)



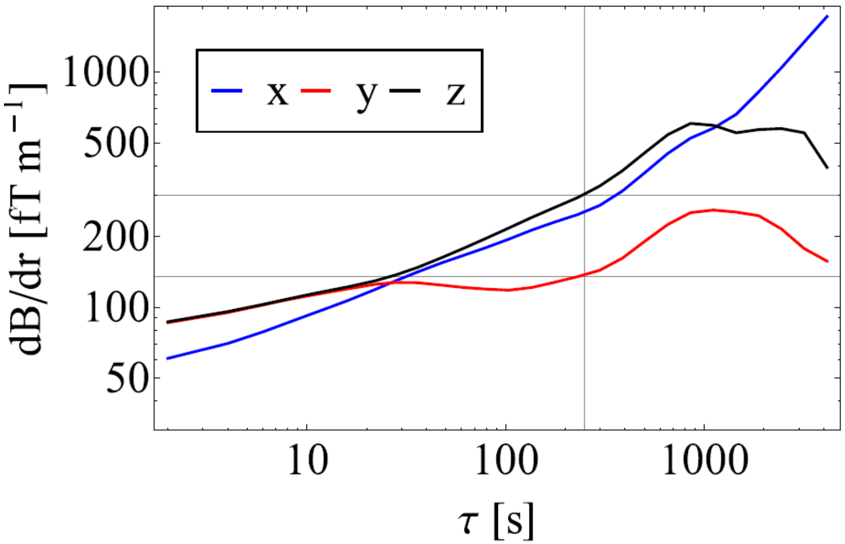
Very preliminary fields
(upper limits, limited by sensor calibration)



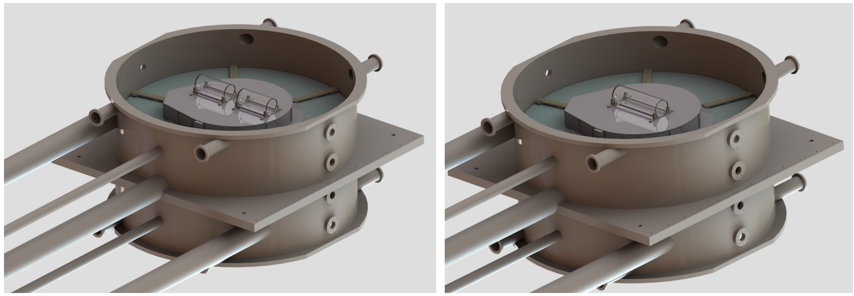
Gradient drifts

- Double chamber: first order field drifts canceled (limited by B_0 correction coils)
- Background gradient drift is small enough: SF ~ 6×10^6 at 1 mHz …

Allan std. dev. of gradient drift,
(inner shield removed for measurement)



100 fT/m / 10 (properties of additional shielding); 0.1 m cell distance... < 1 fT drift between cells

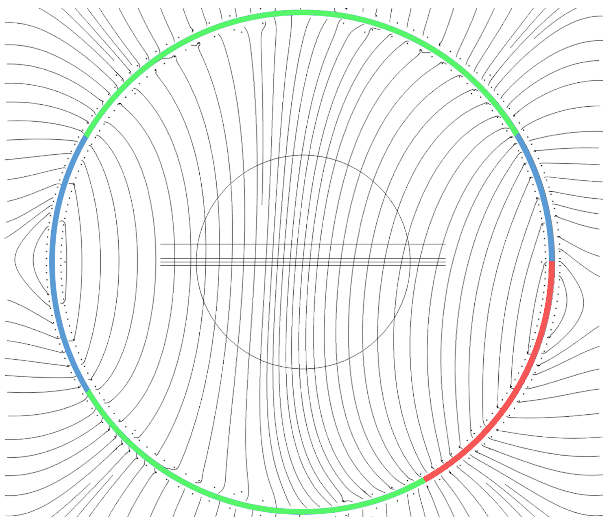


... Better use no comagnetometer and only very few components

B_0 field – a key for systematics

Main issue: shielding properties are never uniform!

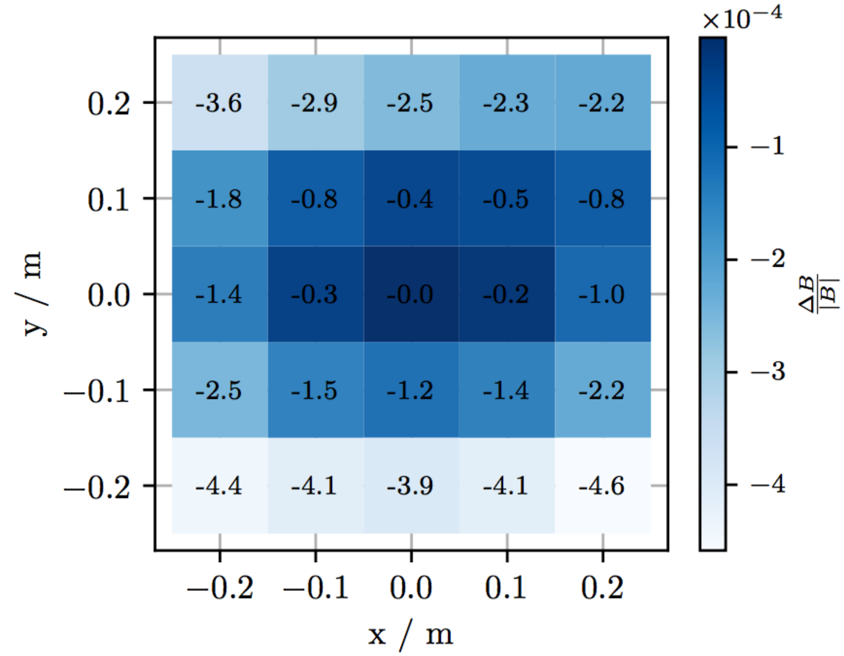
Simulation: permeability varied (strongly) along cylinder used for NMR B0 field coil:



(View into cylinder from front)

Any field inside will talk to the shield, almost impossible to avoid.

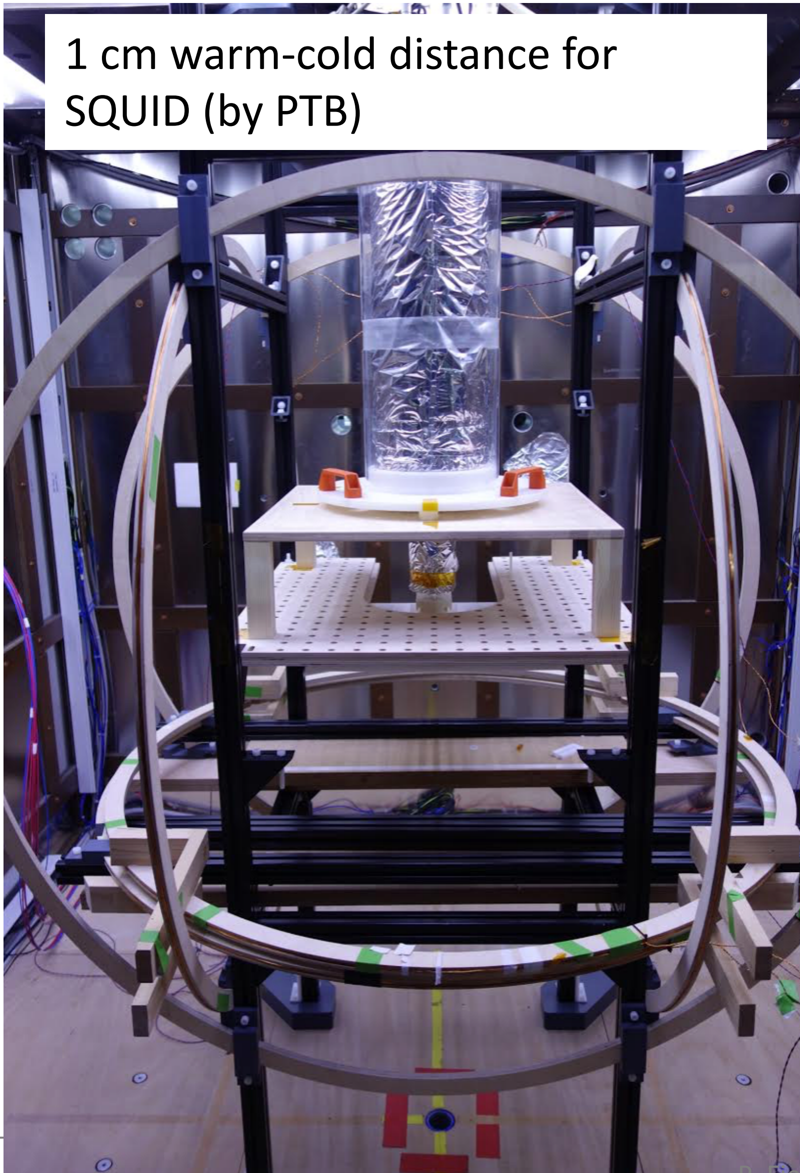
Measured: rel. field homogeneity in horiz. plane



- Only 4 correction coils
- Limited by sensor alignment

Cs, SQUID, ^{129}Xe, ^{3}He, ^{199}Hg...

1 cm warm-cold distance for SQUID (by PTB)



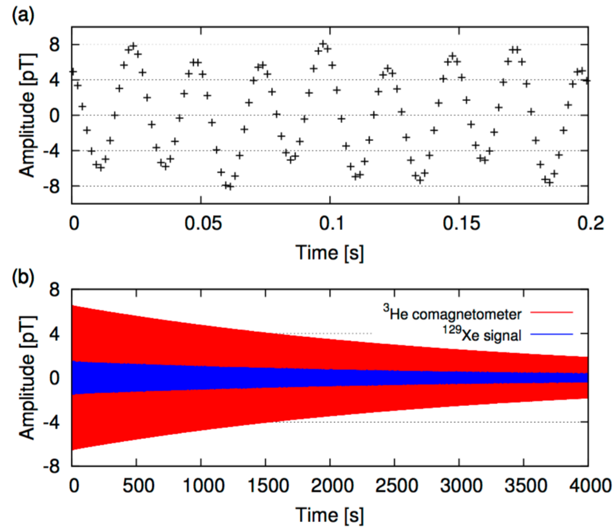
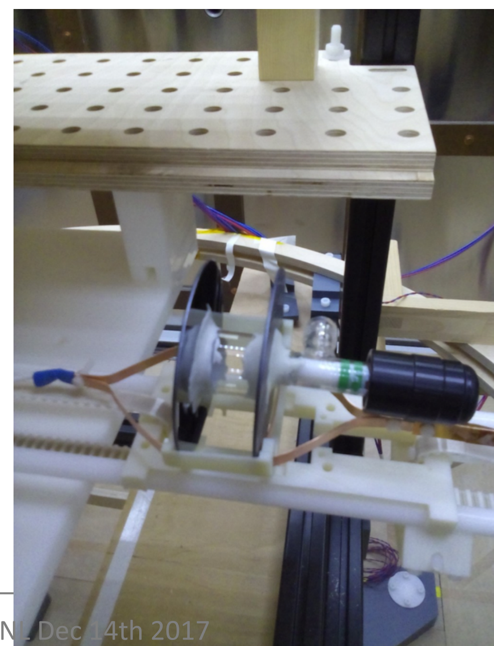


Illustration: simultaneous precession of ^{129}Xe and ^{3}He amplitude in cylindrical cell with 5 kV/cm applied



Issues:
Precision
Accuracy
Directionality
Stability
Bandwidth
Crosstalk

Progress without a stronger UCN source?

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}\sqrt{M}}$$

T ... Spin coherence & UCN storage time
E ... Electric field strength
α ... Visibility
N ... Number of UCN at end of measurement
M ... Number of repetitions

Some new achievements:

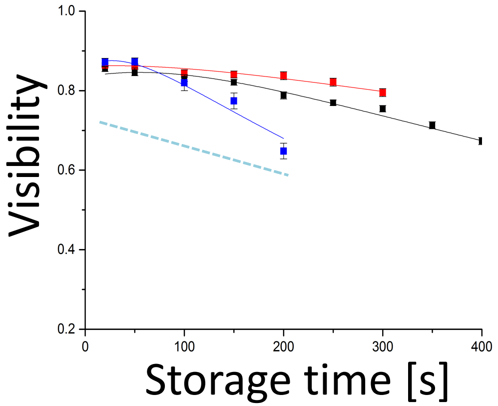
- **Fast magnetic equilibration: M x 2 (almost)**

  I. Altarev et al., arXiv:1501.07408, Appl. Phys. Lett. (2015)

- **Deuterated polyethylene, softer spectrum: T x 2, N x 2**

  I.Altarev et al., arXiv:1502.06252, Appl. Phys. Lett (2015)

- **Visibility: α x 1.25** T. Zechlau, PD thesis



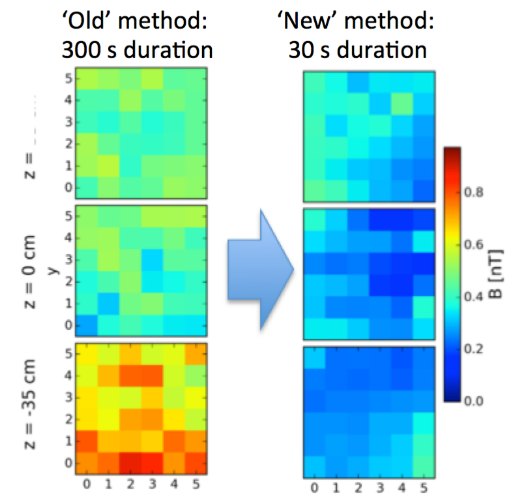


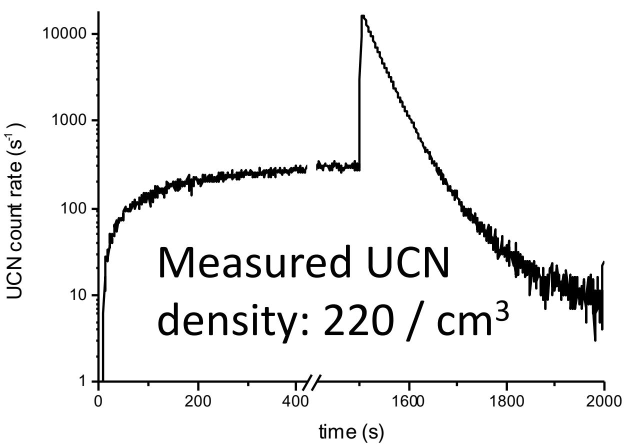
Illustration: Residual field maps in test-setup

… in total a factor 5 might be possible without better source!

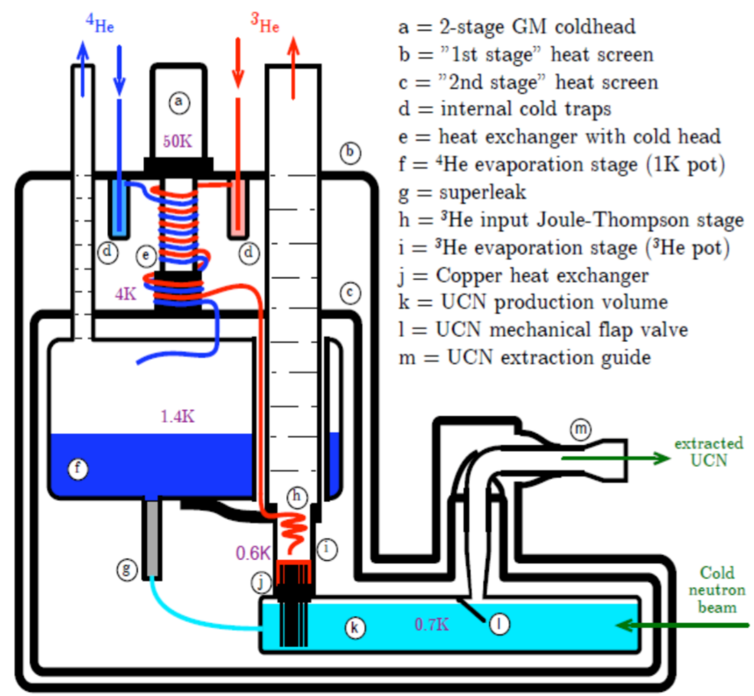
PanEDM at ILL

- **No UCN at the EDM beam position at FRM2 for several more years**
- **PanEDM won competition for UCN beamline at ILL ('SuperSUN')**

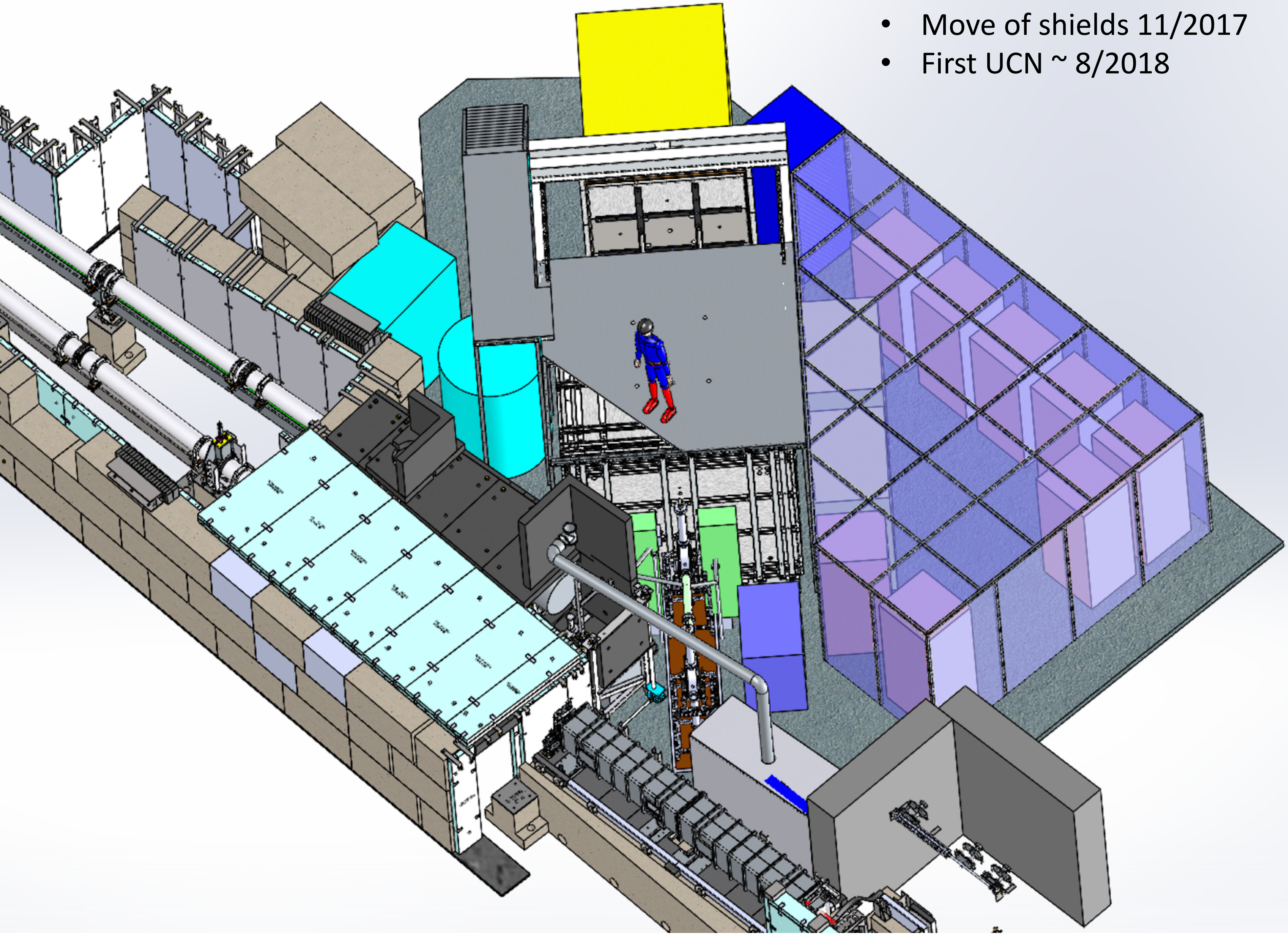
- Superfluid helium source
- Placed at a cold beam
- Very 'soft' spectrum: < 74 neV
- => T = 250 s demonstrated!
- Very small systematics (no geom. Phase!)



Precursor source: SUN2



- Move of shields 11/2017
- First UCN ~ 8/2018



Reassembly ongoing at ILL (Dec 2017)

Physics reach with super-SUN

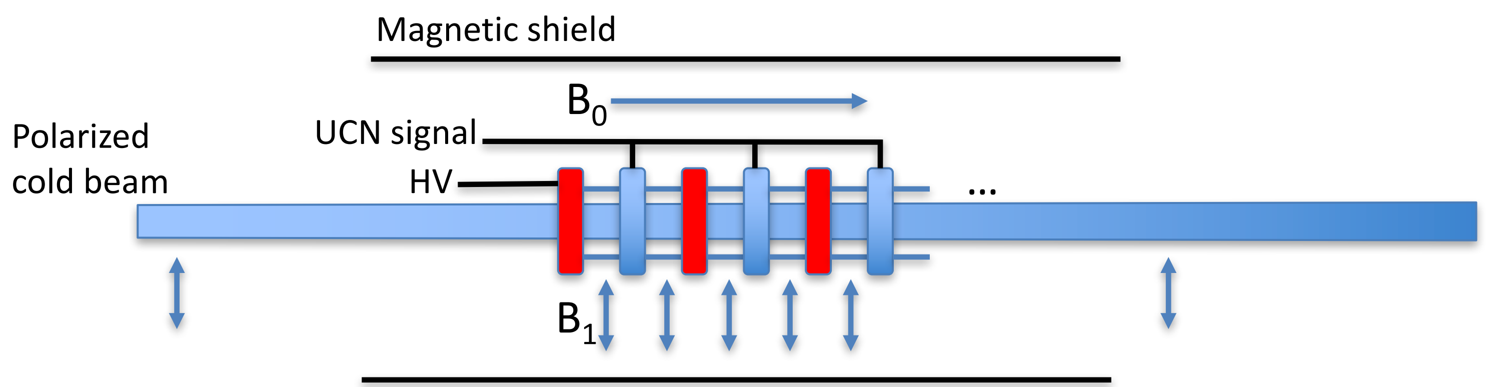
	2018-2020		2019-2022	
	SuperSun stage I		SuperSun stage II	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3	*	1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		2217760	
EDM sensitivity				
E	2,00E+04	V/cm	2,00E+04	V/cm
alpha	0,85		0,85	
T	250	s	250	s
N after time T (1/e)	39800		794000	
Number of EDM cells	2		2	
Sensitivity (1 Sigma, 1 cell)	3,9E-25	ecm	8,7E-26	ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25	ecm	6,1E-26	ecm
Preparation time	150	s	150	s
Measurements per day	216		216	
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26	ecm	4,2E-27	ecm
Sensitivity 100 days	**1,9E-27**	**ecm**	**4,2E-28**	**ecm**
Limit 90% 100 days	**3,00E-27**	**ecm**	**7,00E-28**	**ecm**

Recently reduced to “1“ (Transfer loss factor)

$$\sigma_{d_n} = \frac{h}{2\alpha E T \sqrt{N}}$$

Compared to current limit: 3.10^{-26} ecm

Future of nEDM?



The currently most promising option (in my opinion…):

- Cold beam produces UCN inside EDM cells in superfluid helium
- Cryogenic = low losses, large HV
- In situ = high density
- Control of systematic: many cells simultaneously
- Magnetic field quality demonstrated
- UCN source design with 3 m length demonstrated

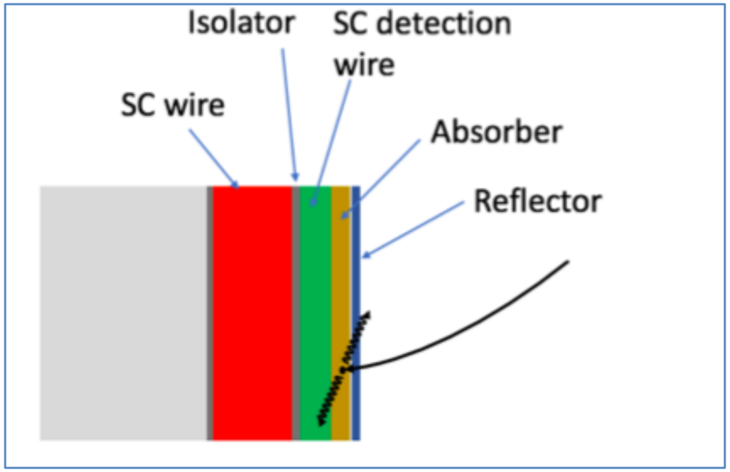
Towards a fully cryogenic measurement

- Only one component to be developed & multiplied:
  - SQUIDs/TES?
  - NV diamonds?
- $1 \cdot 10^{-29}$ ecm feasible without progress at neutron sources!
- No moving parts, cheap!

Reach:

hbar	6,57E-16	eVs	
HV	500000	V	
Cell "height"	7	cm	
E Field	71428,57143	V/cm	
alpha	0,95		
T	350	s	
Initial UCN density (in situ!)	1000	1/cm3	
Volume	2198	cm3	
N(t= 0)	2,20E+06		
N after T	8,14E+05		
sigma_d =	1,53E-026	ecm / measurement	
Cells	100		
Factor	10		
sigma_d =	1,53E-027	ecm / measurement	
Repetitions	10000		
Factor	100		
sigma_d =	**1,53E-029**	**ecm / measurement**	

Possible detection scheme: SC wire + SQUID for polarized UCN detection



Alternative: NV diamonds?

Summary

- Factor 10 - ongoing improvements:
  - ILL/TUM – PanEDM being reassembled & adapted for ILL source, operational in 2018
  - LANL – upgraded source in 2017
  - PSI – new shields in 2018
  - TRIUMF – first UCN in 2017

- Factor 100
  - SNS EDM

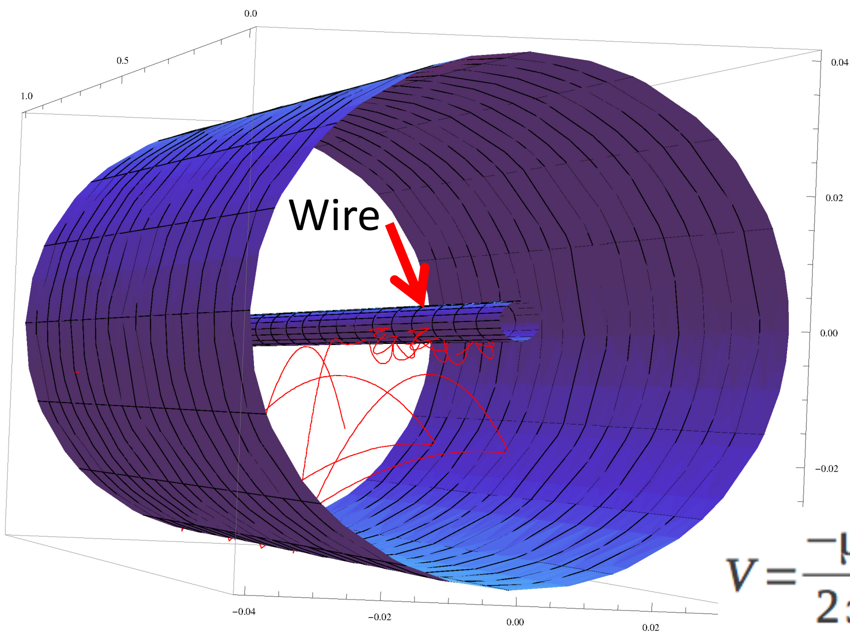
- TUM neutron EDM apparatus moved to ILL: ‚PanEDM'
  - Systematic effects reasonably well under control for 1.10^{-27} level
  - Magnetic field work has applications in different fields

- Factor 1000 in principle possible

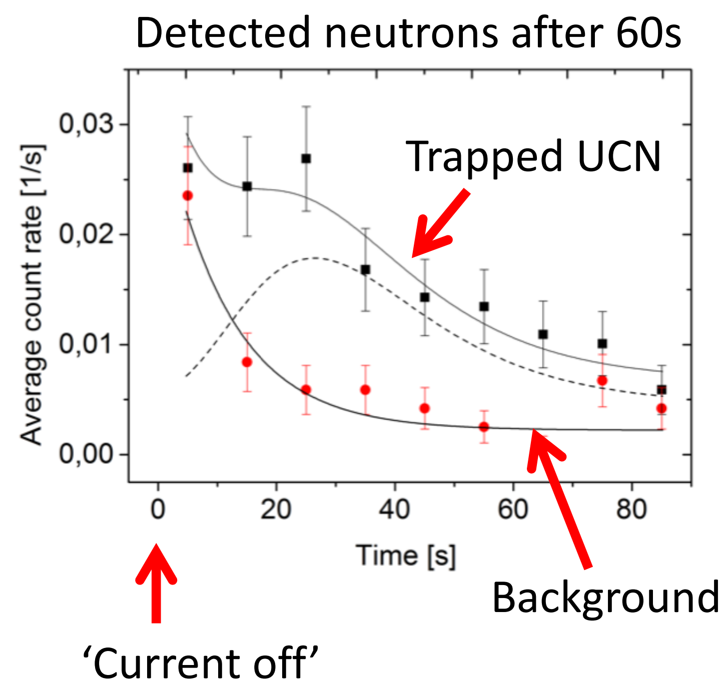
High-field seekers

Neutrons trapped on a wire with large current

- First trap for high-field seeking spin-states
- Closed trajectories with (sub)-millimeter distance to a mass without wall collisions
- Easy to detect decay products
- Next step: quantized states around wire



$$V = \frac{-\mu_0 I}{2\pi r}$$



T. Brenner et al., PLB (2015)