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Ingo Rienäcker :: Paul Scherrer Institute :: ETH Zurich
on behalf of the PSI UCN group and collaborators

Nicholas J. Ayres [1,*], Zurab Berezhiani [2,3], Riccardo Biondi [2,4], Georg Bison [4], Kazimierz Bodek [5], Vira Bondar [1], Pin-Jung Chiu [4], Manfred Daum [4], Reza Tavakoli Dinani [6], Cornelis B. Doorenbos [4], Solange Emmenegger [1], Klaus Kirch [1,4], Victoria Kletzl [1,4], Jochen Krempel [1], Bernhard Lauss [4,*], Duarte Pais [1,4], Ingo Rienäcker [1,4,*], Dieter Ries [7], Nicola Rossi [2], Dagmara Rozpedzik [5], Philipp Schmidt-Wellenburg [4], Kazuo S. Tanaka [4], Jacek Zejma [5], Nathalie Ziehl [1] and Geza Zsigmond [4]

Search for **neutron disappearance** into sterile states

PSI 2022 :: 20.10.2022

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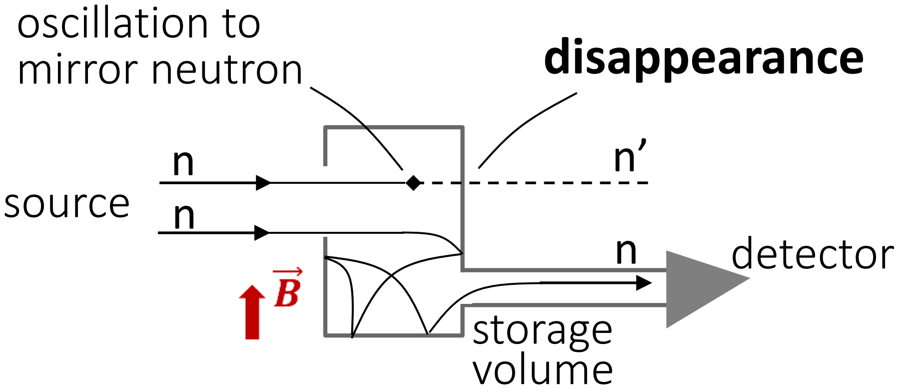
Motivation: mirror neutrons



oscillation of neutron into mirror neutron

$$|\psi\rangle = c_n\,|n\rangle + c_{n'}\,|n'\rangle$$

$$H_I = \begin{pmatrix} -V & \varepsilon \\ \varepsilon & -V' \end{pmatrix} \qquad \tau = \hbar/\varepsilon$$

- cosmology with mirror matter
- possible dark matter candidates in the mirror sector
- neutral SM particles **oscillation into mirror partner sterile state** (Baryon number violation $|\Delta B{=}1|$, neutron lifetime)
- …

Okun, Kobzarev, Pomeranchuk, Sov. J. Nucl. Phys. 3 837 (1966)
Foot, Lew, Volkas, Phys Lett B 272 67 (1991)
Berezhiani, Comelli, Villante, Phys Lett B 503 362 (2001)
Ignatiev, Volkas, Phys Rev D68 (2003)
Berezhiani, Bento, Phys Rev Lett 96 (2006)

$P_{n\to n'}$ is **resonant** if $(V - V') \ll \varepsilon$

vacuum → $V' = 0 \qquad V = \boldsymbol{\mu}\cdot\boldsymbol{B} \overset{!}{\approx} 0$

limit $\tau > 448$ s (magnetic shield |B| < 20 nT)

Serebrov et. al. NIMA 611 137 (2009)

mirror magn. field → $V' = \boldsymbol{\mu}\cdot\boldsymbol{B}' \qquad \boldsymbol{B} \overset{!}{\approx} \boldsymbol{B}'$

Berezhiani, EPJ C 64 421 (2009)

⋮

mass splitting …

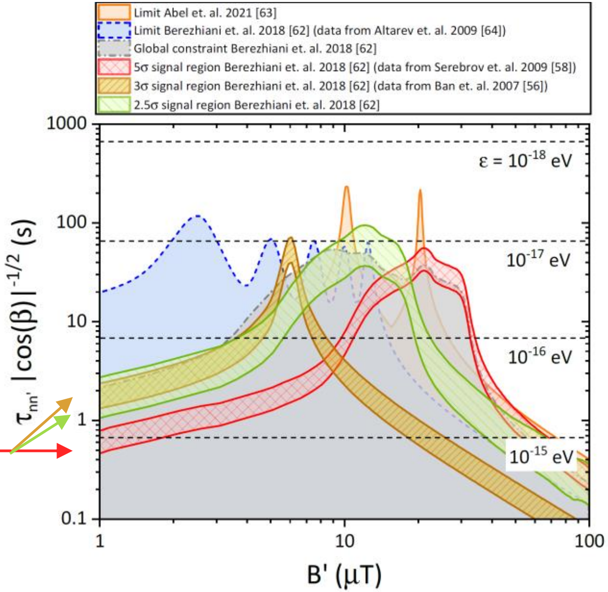
Motivation: mirror matter and magnetic fields

several experiments have excluded regions in $(\tau, \boldsymbol{B}')$ - parameter space

Ban et. al., Phys. Rev. Lett. 99 16 (2007)
Serebrov et. al., Phys. Lett. B 663 3 (2008)
Altarev et. al., Phys. Rev. D. 80 032003 (2009)
Abel et. al., Phys. Lett. B 812 (2021)

anomalies in the asymmetry observable and corresponding signal regions have been reported

Berezhiani, EPJ. C 78 9 (2018)



test signal regions and explore $(\tau, \boldsymbol{B}')$ - parameter space for large magnetic fields where previous limits are weak

scan magnetic field from 5 μT to 360 μT

Improved Search for Neutron to Mirror-Neutron Oscillations in the Presence of Mirror Magnetic Fields with a Dedicated Apparatus at the PSI UCN Source

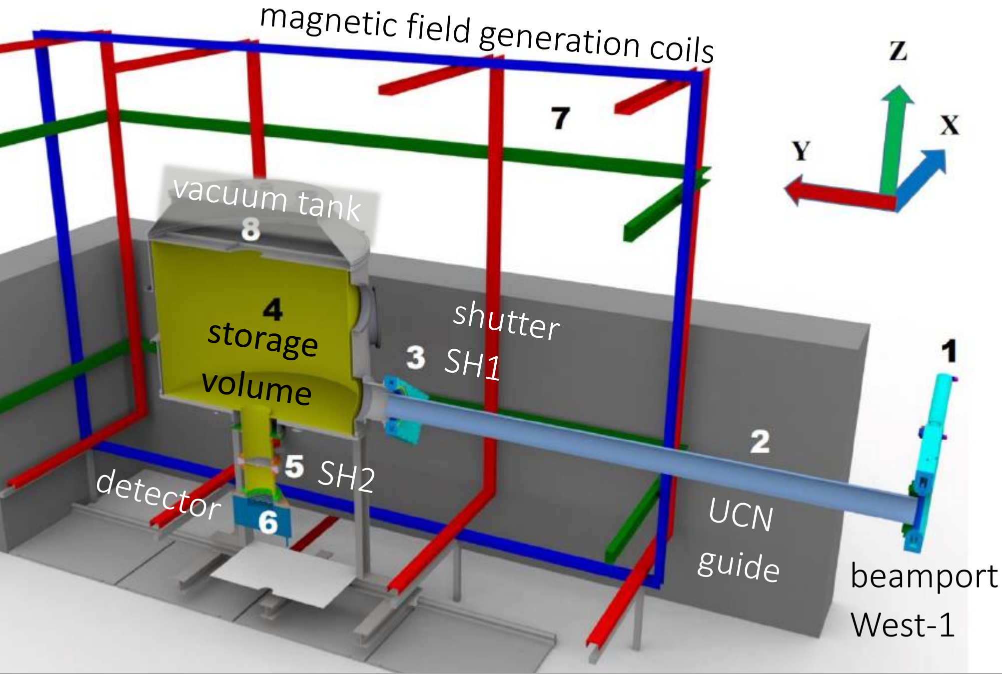
symmetry

Nicholas J. Ayres [1,*], Zurab Berezhiani [2,3], Riccardo Biondi [2,4], Georg Bison [4], Kazimierz Bodek [5], Vira Bondar [1], Pin-Jung Chiu [4], Manfred Daum [4], Reza Tavakoli Dinani [6], Cornelis B. Doorenbos [4], Solange Emmenegger [1], Klaus Kirch [1,4], Victoria Kletzl [1,4], Jochen Krempel [1], Bernhard Lauss [4,*], Duarte Pais [1,4], Ingo Rienäcker [1,4,*], Dieter Ries [7], Nicola Rossi [2], Dagmara Rozpedzik [5], Philipp Schmidt-Wellenburg [4], Kazuo S. Tanaka [4], Jacek Zejma [5], Nathalie Ziehl [1] and Geza Zsigmond [4]

Symmetry **2022**, *14*, 503

Setup to search for anomalous neutron losses

Experimental setup at beamport West-1



Measurement principle:

1. fill storage volume with **ultracold neutrons (UCN)**
2. count number of surviving UCN after storage
3. alternate magnetic field configuration (B_1 , B_2) and calculate asymmetry A_{12} between normalized counts

relative measurement

Signature: anomalous disappearance of stored UCN in resonance with applied magnetic field

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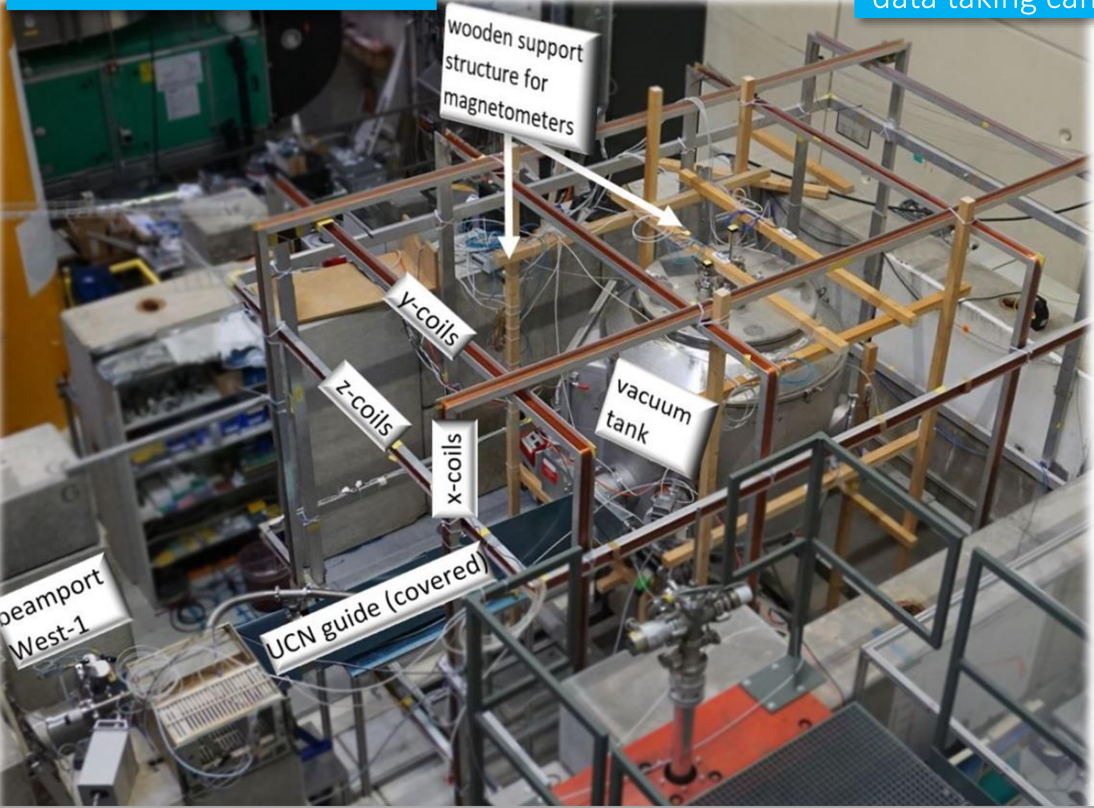
Apparatus at West-1 beamport

Commissioning and first test measurements in 2020

data taking campaign in 2021

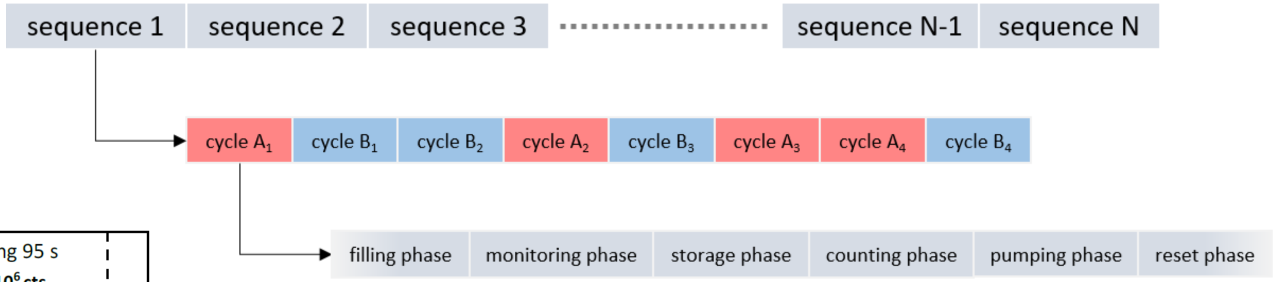


- 1.47 m^3 electro-polished, stainless steel UCN storage volume
- 8 magnetic field coils arranged in Helmholtz-like configurations in three spatial directions
- 16 three-axis fluxgate magnetometers for online measurement of magnetic field

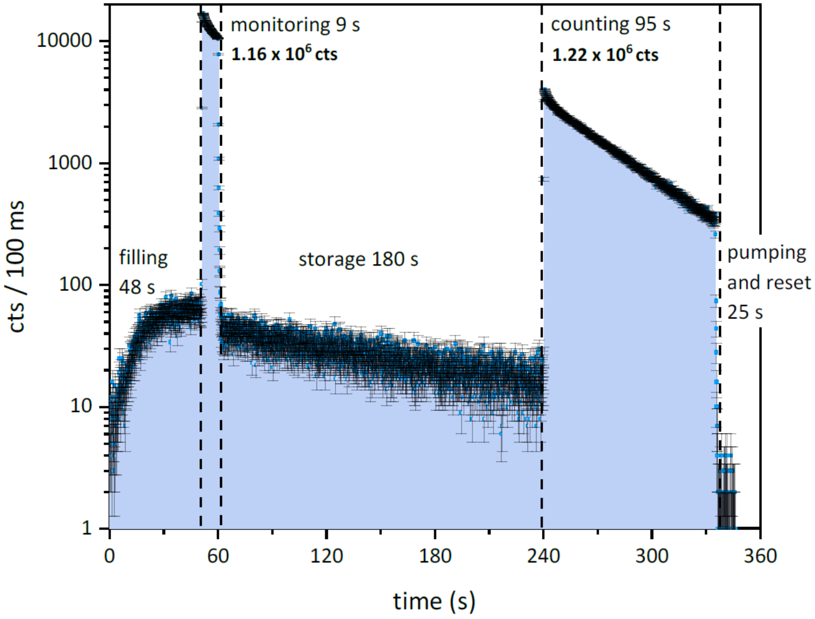
Ayres et. al., Symmetry 14 503 (2022)

Measurement cycles

360 s long cycles
(synchronized to proton beam pulses)
with monitoring phase for
normalization



	filling phase	monitoring phase	storage phase	counting phase	pumping phase	reset phase
SH1:	open	closed	closed	closed	open	open
SH2:	closed	open	closed	open	closed	closed
SH3:	closed	closed	closed	closed	open	closed
B-field:	**B ≈ 0**	**B ≈ 0**	**B ≈ ±Be$_z$**	**B ≈ ±Be$_z$**	**B ≈ ±Be$_z$**	**B ≈ 0**



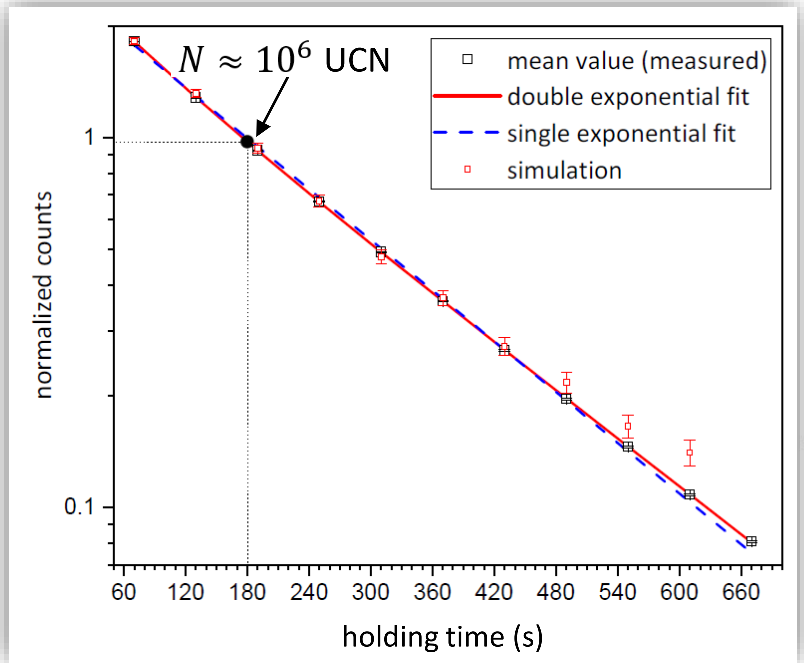
calculate asymmetry for a drift compensated sequence

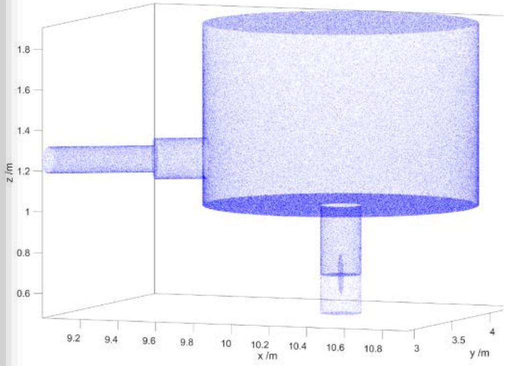
$$(A)_j = \frac{n_A - n_B}{n_A + n_B} \equiv \frac{\sum_i n_{A,i} - \sum_i n_{B,i}}{\sum_i n_{A,i} + \sum_i n_{B,i}}$$

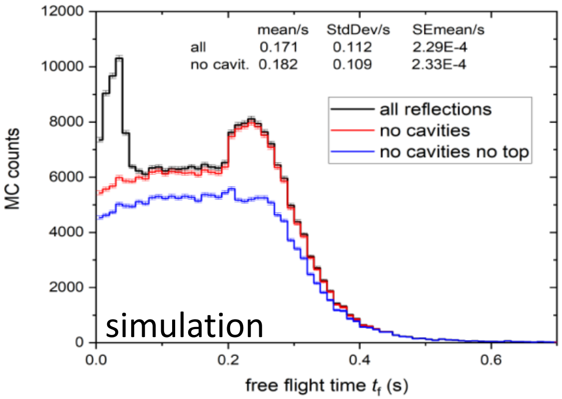
UCN characterization measurements

characterization of the UCN storage and comparison to Monte Carlo MCUCN simulation model

Performance nn′ experiment	data taking 2021
Average UCN counts during monitoring	1×10^6
Average UCN counts after storage	1×10^6
Filling time	48 s
Monitoring time	9 s
Storage time	180 s
Counting time	95 s
Simulated UCN mean free flight time	0.17 s
Storage time constants	$\tau_1 = 82$ s $\quad A_1 = 0.60$
$A_1\, e^{-t/\tau_1} + A_2\, e^{-t/\tau_2}$	$\tau_2 = 202$ s $\quad A_2 = 2.21$
UCN pulse duration and period	$t = 8$ s
	$T = 360$ s
Avarage proton beam current	2.0 mA

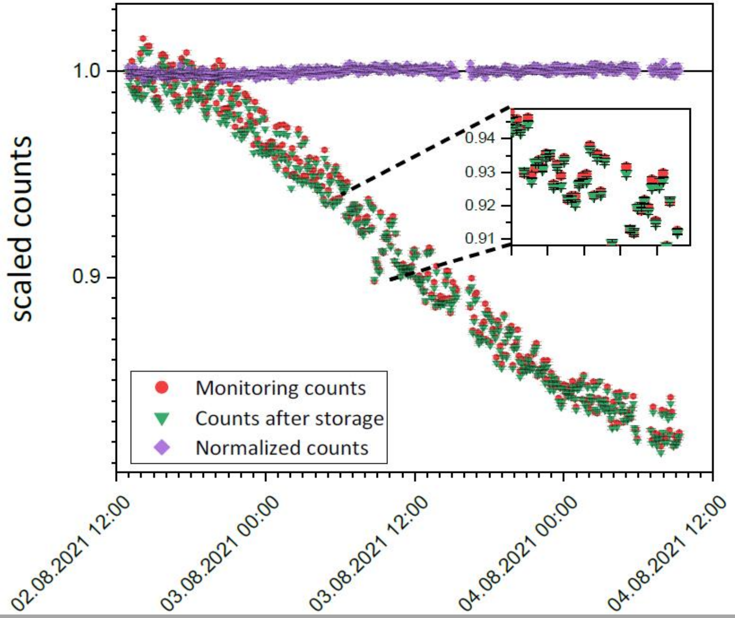






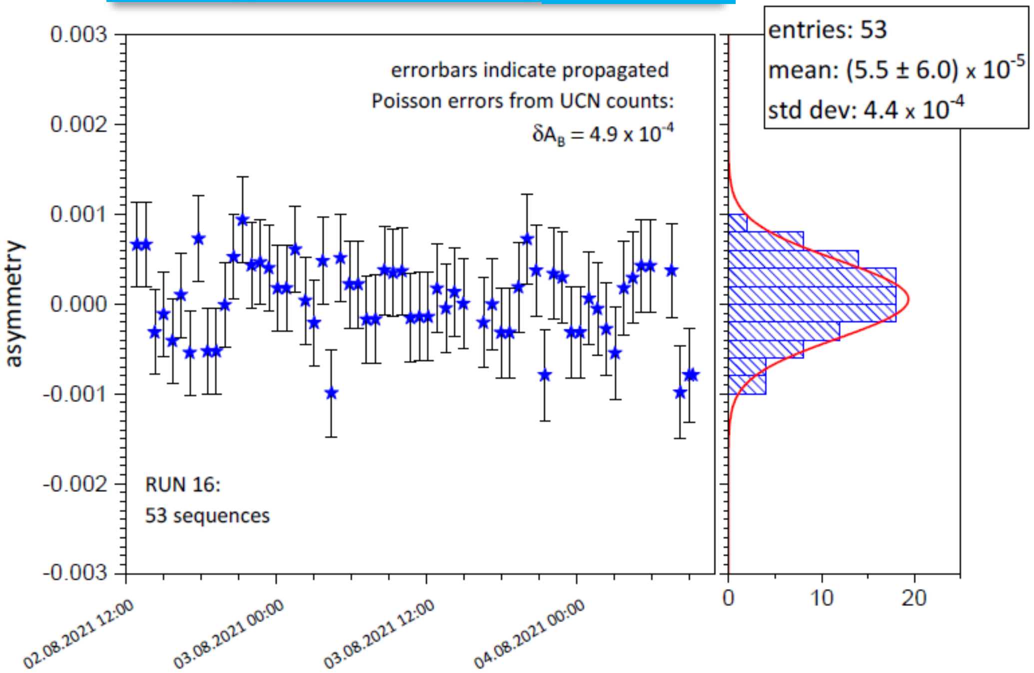
UCN data

neutron counts per cycle during a run with the normalization compensating for fluctuations in the UCN source output, proton beam power, …



asymmetry value per sequence during a run

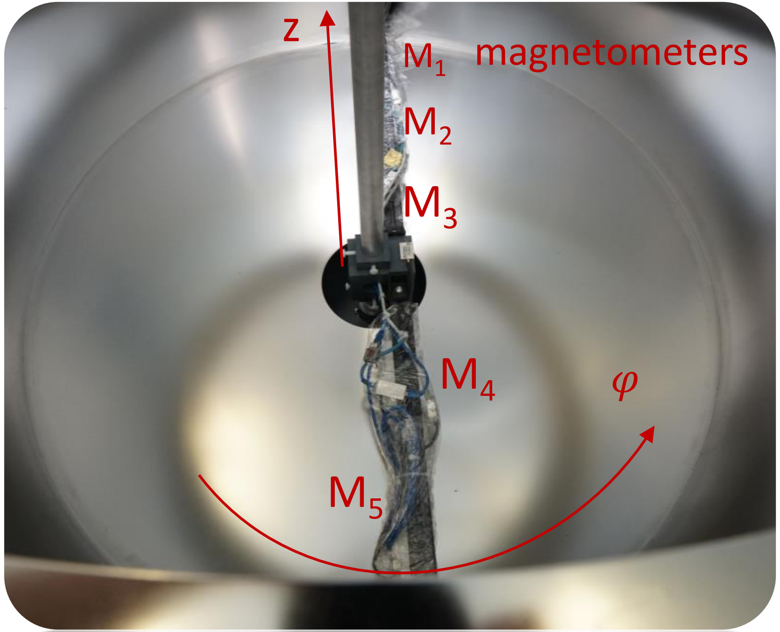
sensitivity per measurement day $\sigma(A) \sim 10^{-4}$



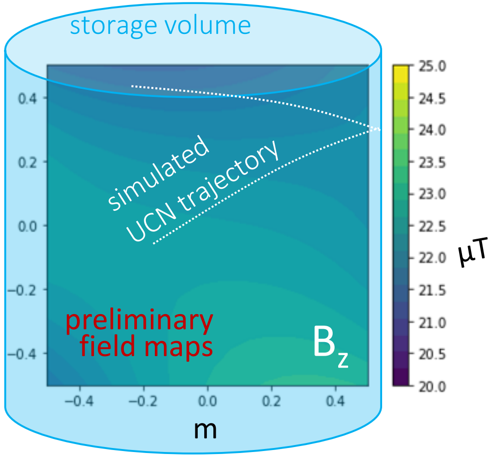
Magnetic field mapping

- mapping campaigns of the magnetic field inside the storage volume (before and after data taking)
- determine coil current to compensate external fields (by the Earth or local installations)
- tune feedback algorithm to achieve target magnetic field using external magnetometers during data taking

view of storage volume (opened at the top) with magnetic field mapper inserted



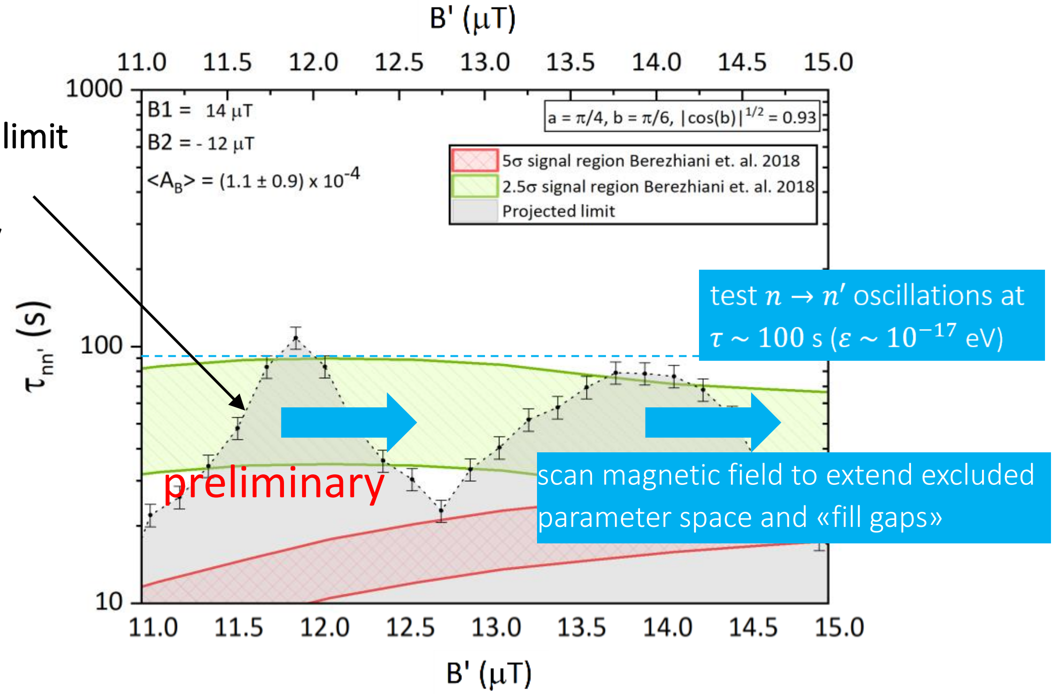
Projected $n \to n'$ oscillation limits



work in progress

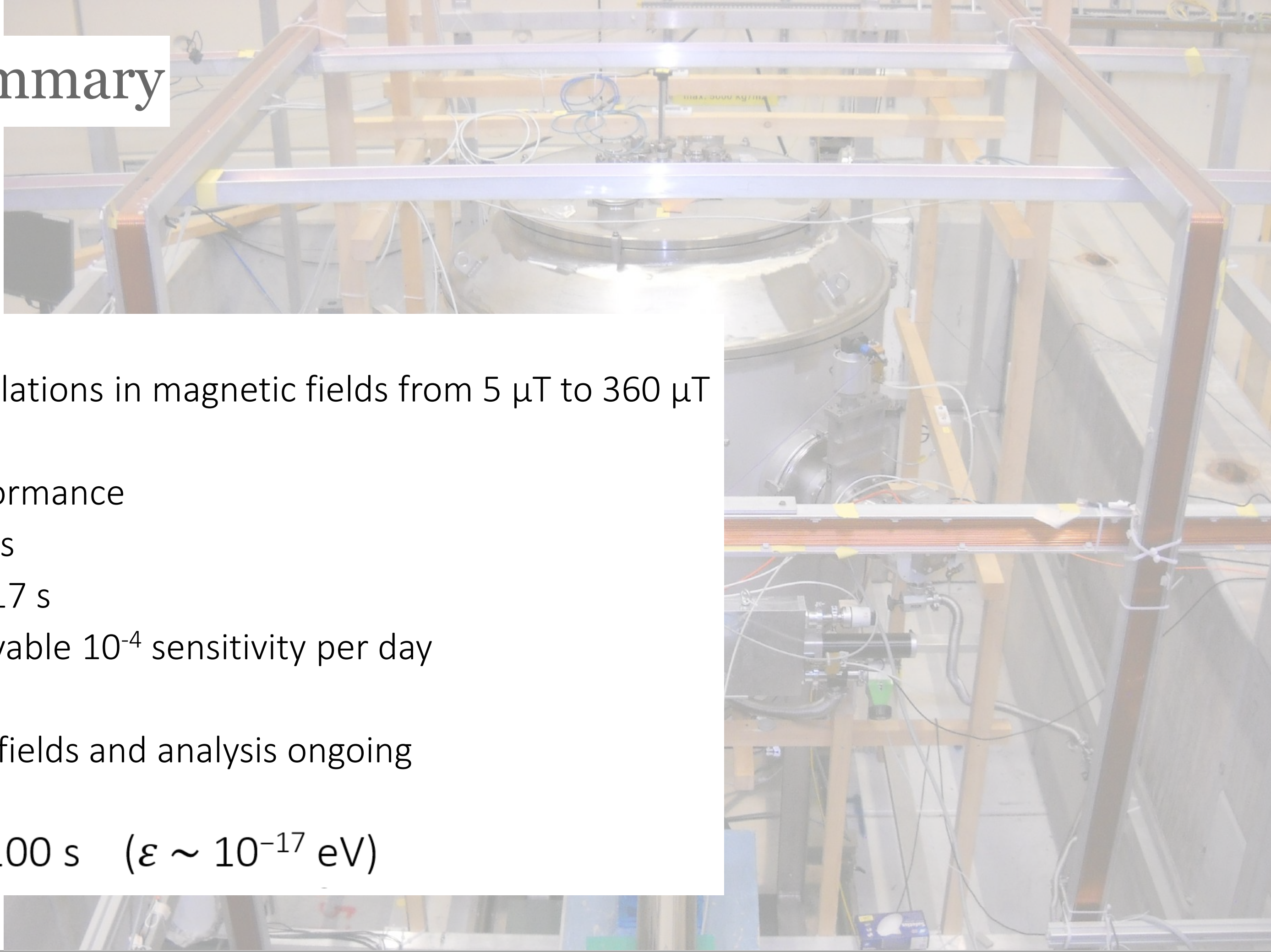
- evaluate magnetic field obtained from field mapping and online magnetometry
- integrate transition probabilities based on the local field along free flight segments
- parametrize transition probability $P_{BB'}(t_s^*)$ in units of ${}^1/_{\tau_{nn'}^2}$ during effective storage time $t_s^* = t_s + \tau_{\text{empty}}$

projected limit from one meas. day



$$\langle A \rangle = \frac{e^{-P_{B_1B'}(t_s^*)} - e^{-P_{B_2B'}(t_s^*)}}{e^{-P_{B_1B'}(t_s^*)} + e^{-P_{B_2B'}(t_s^*)}} \propto {}^1/_{\tau_{nn'}^2}$$

Summary



- searched for $n \rightarrow n'$ oscillations in magnetic fields from 5 µT to 360 µT
- good UCN storage performance
  - storage time 202 s
  - free flight time 0.17 s
  - asymmetry observable 10^{-4} sensitivity per day
- evaluation of magnetic fields and analysis ongoing
- projected limits $\tau \sim 100$ s $(\varepsilon \sim 10^{-17}$ eV$)$

Thanks for your attention

Backup

UCN characterization measurements

characterization of the stability and reproducibility of UCN shutters and other systematic effects