Experiments with Ultracold Neutrons at PSI

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Ultracold Neutrons - UCN

Subatomic Particles at Human Velocities

$$E_{\mathrm{kin}} \lesssim 335\,\mathrm{neV}$$

$$\Leftrightarrow$$

$$v < 8\,\mathrm{m\,s^{-1}} \simeq 30\,\mathrm{km\,h^{-1}} \simeq 18.6\,\mathrm{mph}$$

18.6 mph

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UCN Interactions

- Strong Interaction
  - Neutron Optical Potential (Fermi Potential):
  - $V_F \propto \rho b_{\text{coh}}$
  - ^{58}Ni: ~335 neV, Stainless steel: ~190 neV, Al: ~54 neV

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- Gravity
  - $102.5\,\mathrm{neV\,m^{-1}}$
- Magnetism
  - Spin polarization with strong magnetic fields.
  - $\mu_n = -60.3\,\mathrm{neV\,T^{-1}}$

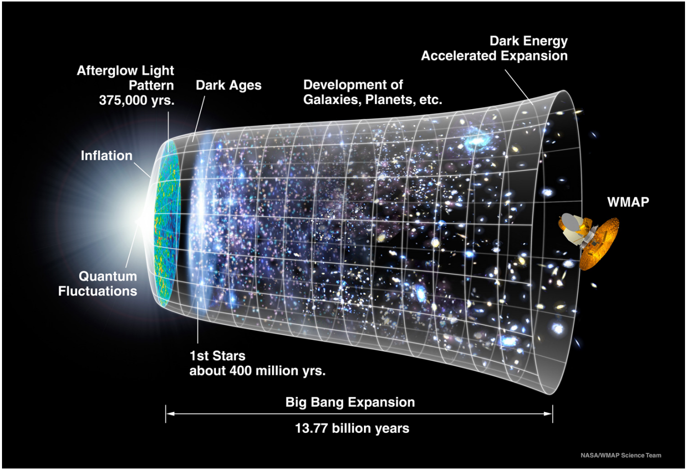
What for?

- **Free neutron lifetime**
- **Neutron electric dipole moment**
- Gravitationally bound quantum states
- Neutron to mirror-neutron oscillations

Why Neutron Lifetime?

a) Big Bang Nucleosynthesis (He abundance)
[Cyburt et al., doi:10.1103/RevModPhys.88, 2016]

Big Bang Nucleosynthesis



$@t = 2\,\text{min}:\ n/p \simeq 1/6$ $@t = 4\,\text{min}:\ n/p \simeq 1/7$

Neutron Lifetime

Why n-lifetime?

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b) CKM Unitarity (V_{ud})
[Czarnecki, Marciano, Sirlin, doi:10.1103/PhysRevD.100.073008, 2019]

Cabibbo–Kobayashi–Maskawa matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

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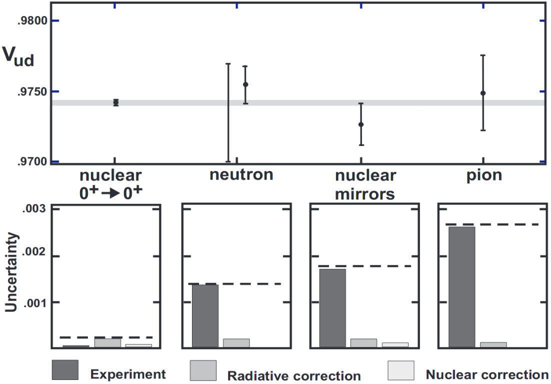
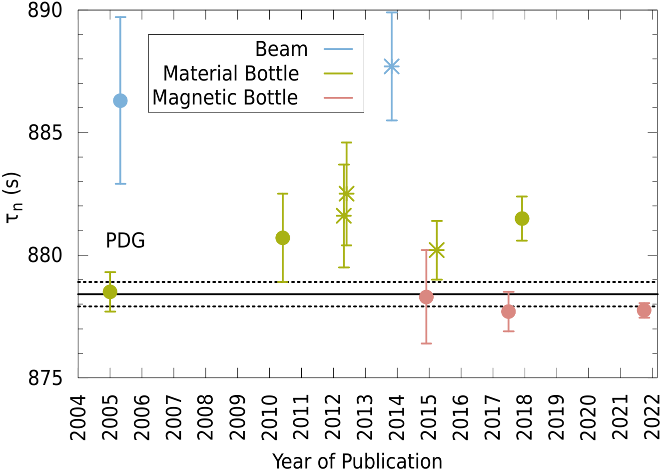


[Hardy and Towner, doi:10.48550/arXiv.1807.01146, 2018]

The Lifetime Puzzle



Neutron Lifetime

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[Marciano and Sirlin, doi:10.1103/PhysRevLett.96.032002, 2006]

c) "It's 2023. We cannot agree on τ_n to better than 10s?!"

$$\tau_{\text{n,beam}} = 887.7 \pm 1.2 \pm 1.9\text{s}$$
$$\neq$$
$$\tau_{\text{n,stored}} = 877.75 \pm 0.28 \pm 0.22\text{s}$$

τSPECT

Concept:

- 3-D magnetic storage
  - Two solenoids + Octupole

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- 3-D magnetic storage
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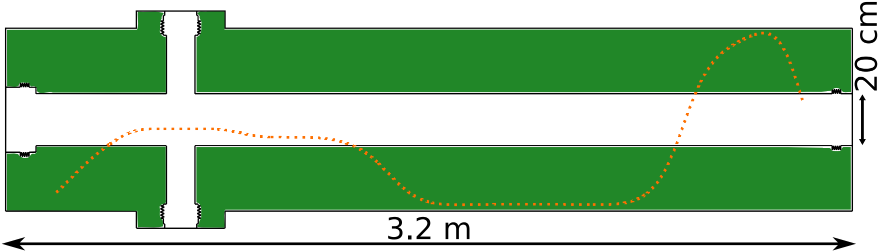
- Spinflip-loading
  - Holding field polarizes neutrons
  - Fast adiabatic spinflip as loading mechanism
- In-situ UCN detection
  - Minimizes extraction losses
  - High detector requirements wrt temp. & B-field

τSPECT fields



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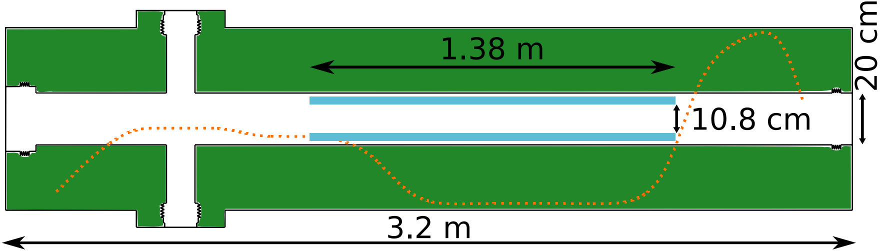

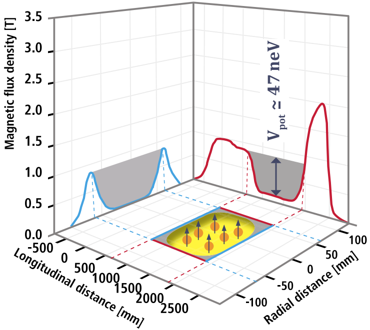

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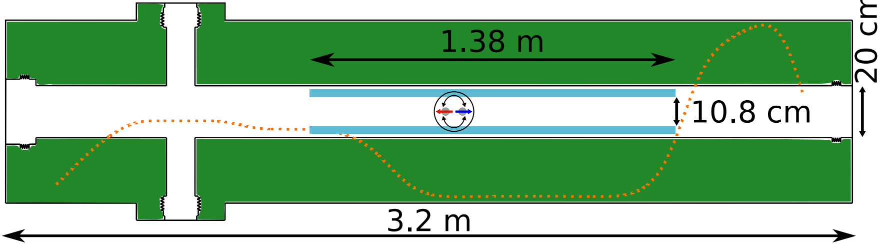
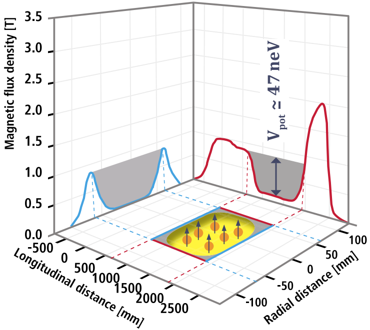
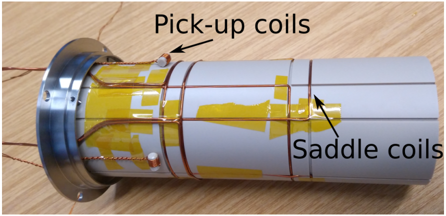
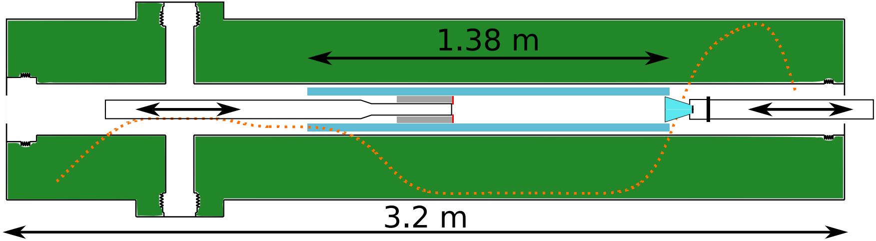






K. U. Ross

Measurement Procedure



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   - Simultaneously: Intensity Monitoring (non-trappable UCN)

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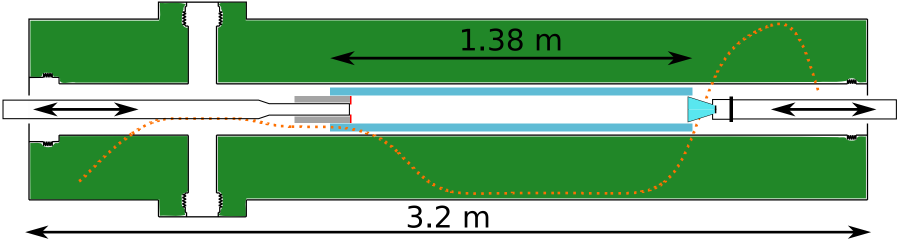

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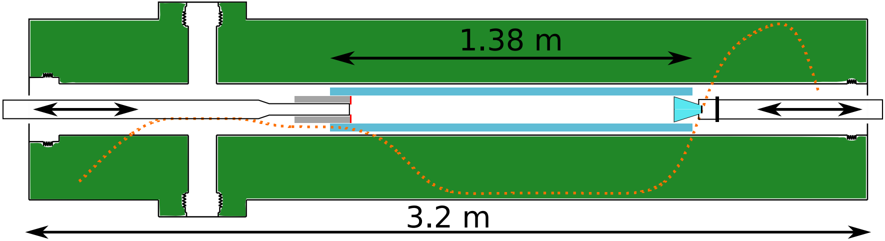

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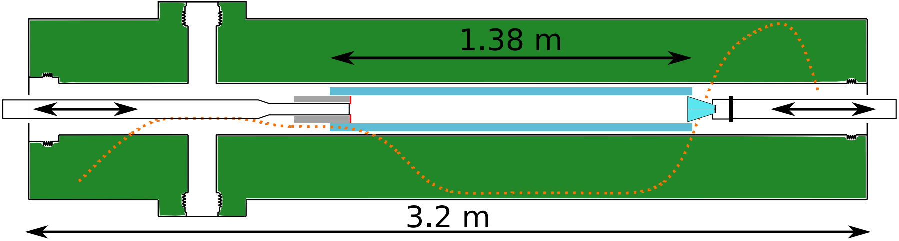

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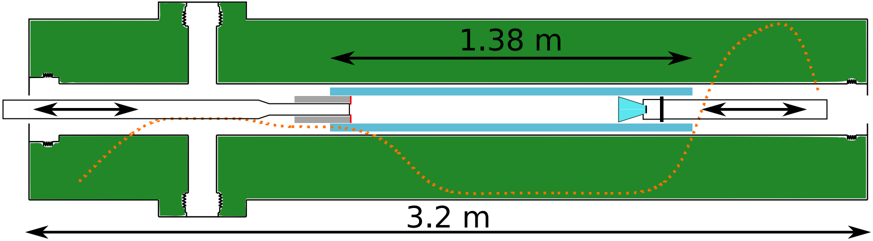

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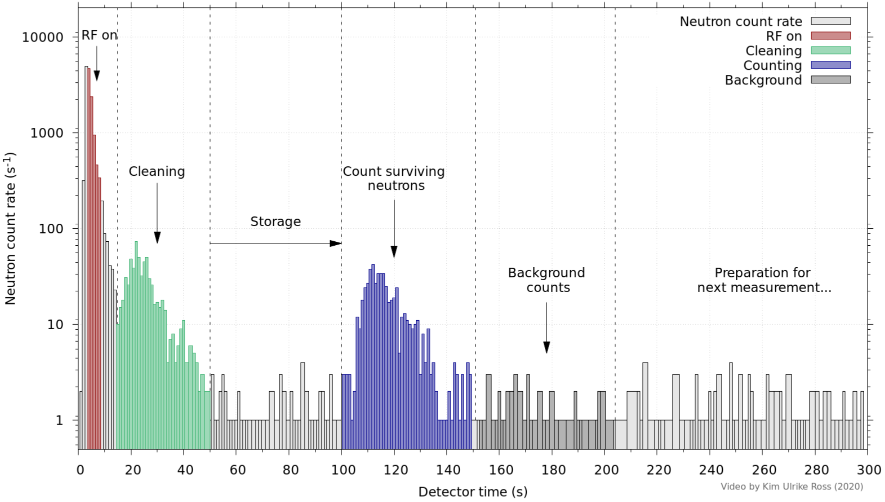
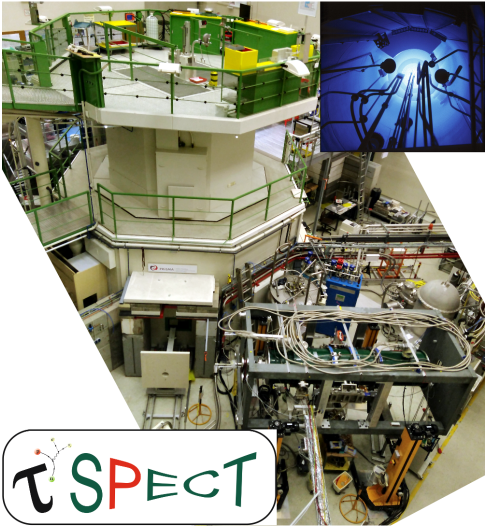
4. Wait ...
5. Count UCN

A look at the data



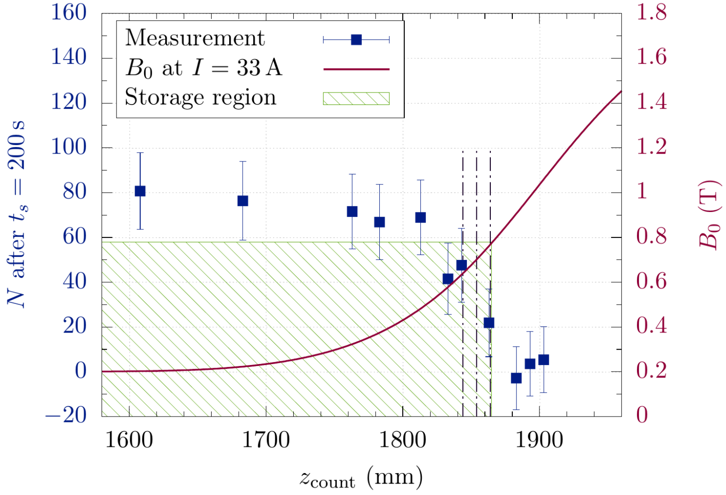
τSPECT@TRIGA Mainz



Systematics

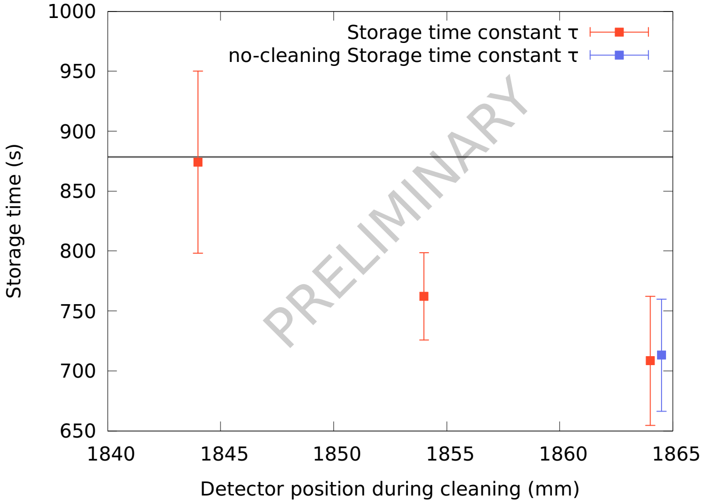
- Gaps: $\rightarrow 0$ ✓
- Wall losses: $\rightarrow 0$ ✓
- Depolarisation: $<< 0.1\,\mathrm{s}$ ✓
- Rest gas interactions: $\lesssim 0.1\,\mathrm{s}$ ✓
- Marginally trapped neutrons: Spectrum cleaning necessary! ✓

Countermeasures



K. Ross

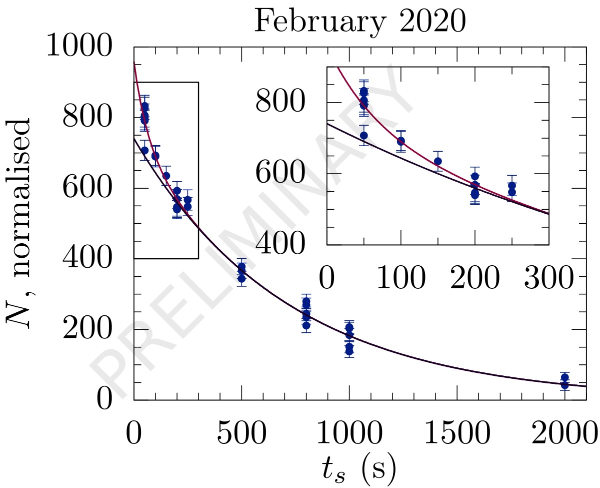
Countermeasures



Systematics Control

- Marginally trapped neutrons:
  - Clean spectrum with active detector before $t = 0$
  - Demonstrated to work
  - 2 parameters: position and duration
  - Too aggressive cleaning → lower statistics
  - Introduce asymmetry: τSPECT at a small tilt angle

Without Energy Spectrum Cleaning

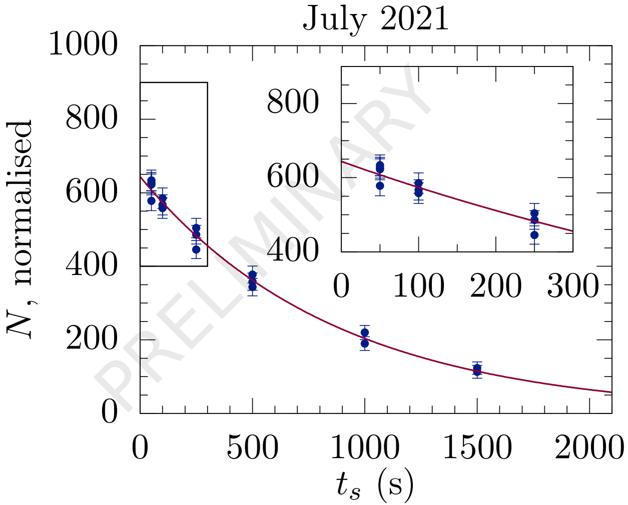


Decay times:
Fast:
$\tau = 64.5\,\mathrm{s}$
Slow:
$\tau = 740(47)\,\mathrm{s}$

$\chi^2 = 1.6$

K. U. Roß

With Energy Spectrum Cleaning



Decay times:

$\tau = 869(29)\,\text{s}$

$\chi^2 = 0.6$

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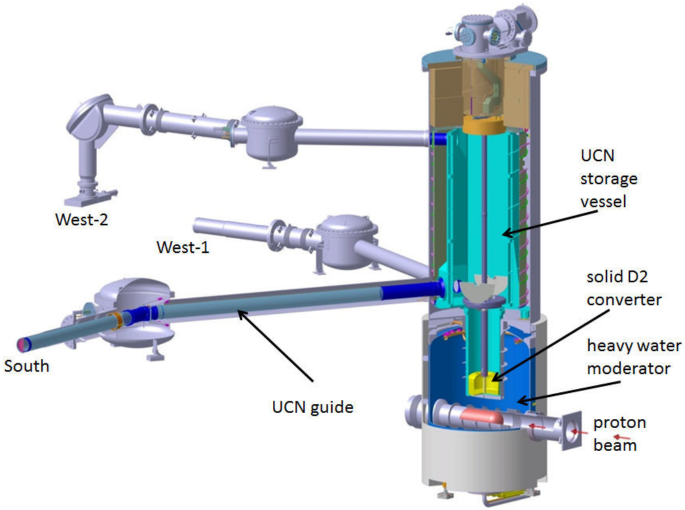
PSI UCN area


West-2
West-1
South
UCN guide
UCN
storage
vessel
solid D2
converter
heavy water
moderator
proton
beam

τSPECT at PSI

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Status

- τSPECT has been fully commissioned at TRIGA Mainz
- Move and setup to PSI are being concluded
- First pump-down / cool-down successfully done
- First neutrons in the trap expected every day now!

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Goal: Show statistical reach and systematics control for a physics run aiming for a precision of 0.1 s in the next years.

Team

+ W. Heil & P. Blümler

Team

J. Auler[1], P. Blümler[1], M. Engler[2], M. Fertl[1], K. Franz[2], W. Heil[1], S. Kaufmann[2], N. Pfeifer[1], D. Ries[3], N. Yazdandoost[2]

[1] Institute of Physics, Johannes Gutenberg University Mainz, Germany
[2] Institute of Nuclear Chemistry, Johannes Gutenberg University Mainz, Germany
[3] Paul Scherrer Institute, Villigen, Switzerland

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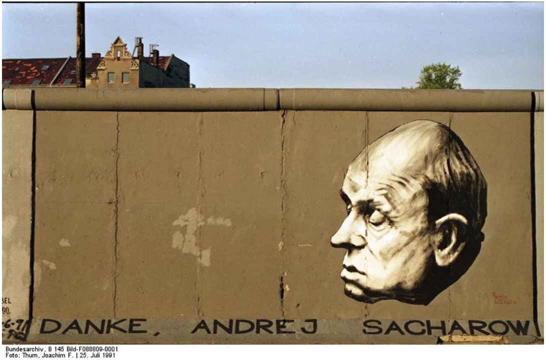
nEDM motivation

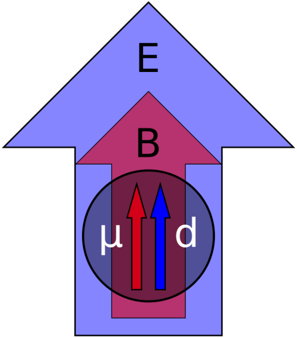
Sakharov Conditions

- Baryon number violation
- C and CP symmetry violation
- Thermal non-equilibrium



[Bundesarchiv, B 145 Bild-F088809-0001 / Thurn, Joachim F. / CC-BY-SA 3.0]

CP symmetry violating EDM



$$\mathscr{H} = -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{B} - d\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{E}$$

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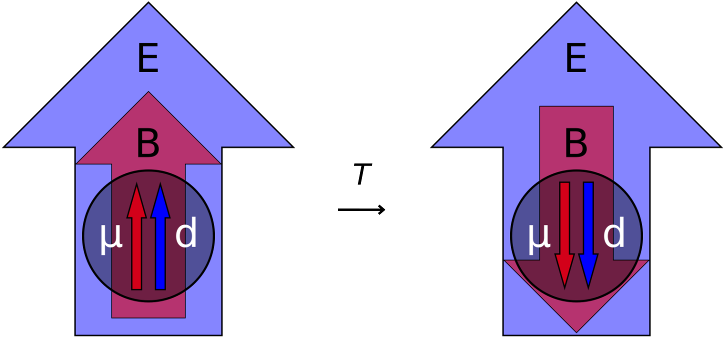
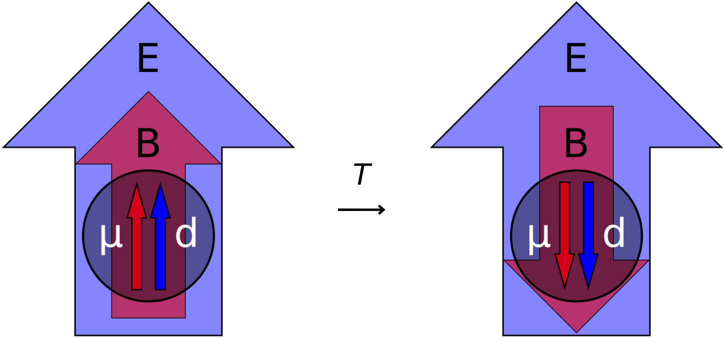


$$\mathscr{H} = -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{B} - d \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{E} \neq -\mu \frac{-\vec{\sigma}}{|\vec{\sigma}|} (-\vec{B}) - d \frac{-\vec{\sigma}}{|\vec{\sigma}|} \vec{E}$$

CP symmetry violating EDM



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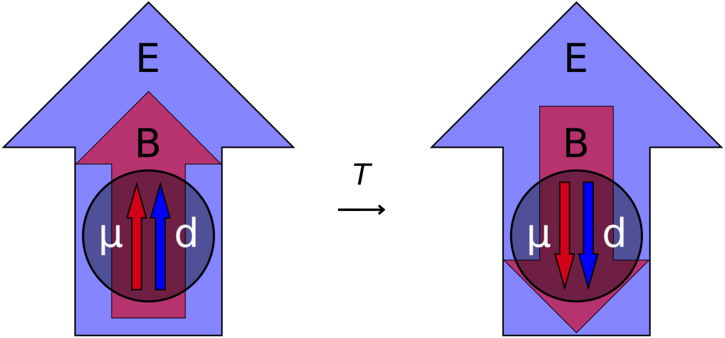

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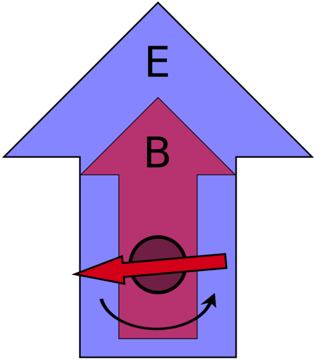
T symmetry violation $\xrightarrow{\text{CPT theorem}}$ CP symmetry violation

How do we measure an EDM?



$$2\pi f = \frac{2\mu}{\hbar} B$$

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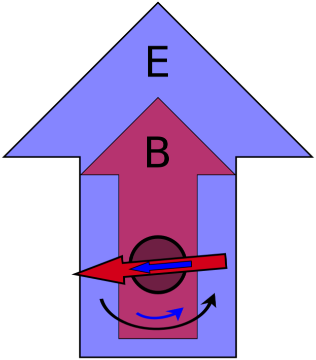

$$2\pi f = \frac{2\mu}{\hbar}B + \frac{2d}{\hbar}E$$

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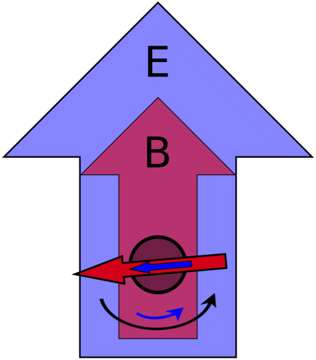

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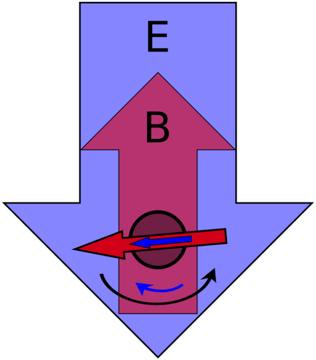

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How do we measure an EDM?

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{2}{\pi\hbar} dE$$

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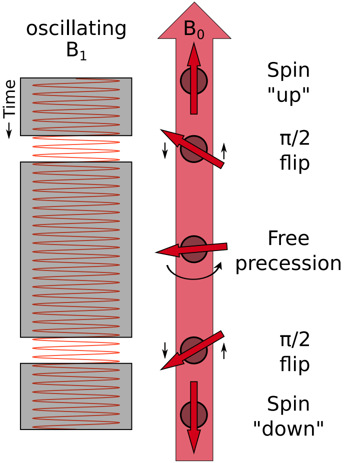
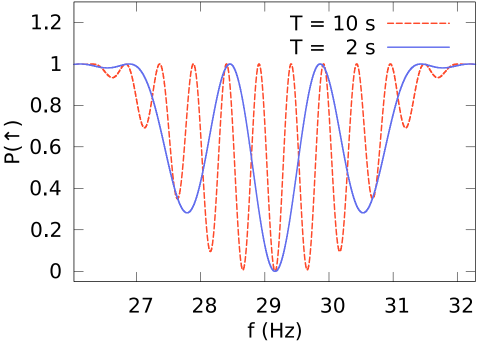
'Never measure anything but frequency!'

Arthur Schawlow

Ramsey's method of separated oscillatory fields





- Precision spectroscopy
- Atomic clocks
- EDM measurements

In which system do we measure an EDM?

The ideal system for EDM measurements:

- simple
- spin = 1/2
- neutral

High Precision

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

$$|d_n| < 1.8 \times 10^{-26}\,\text{e}\cdot\text{cm} \qquad (90\%\ \text{CL})$$

[Phys. Rev. Lett. **124**, 081803 (2020)]

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Image Credit: NASA

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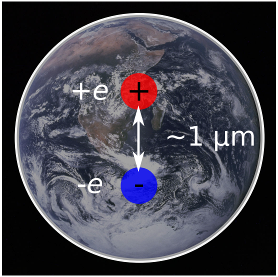

Image Credit: NASA

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[Phys. Rev. Lett. **124**, 081803 (2020)]

Statistical sensitivity:

$$\sigma = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

With:

- E: Electric field strength
- α: Visibility of pattern, $\alpha = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$
- T: Free precession time
- N: Number of neutrons

nEDM apparatus

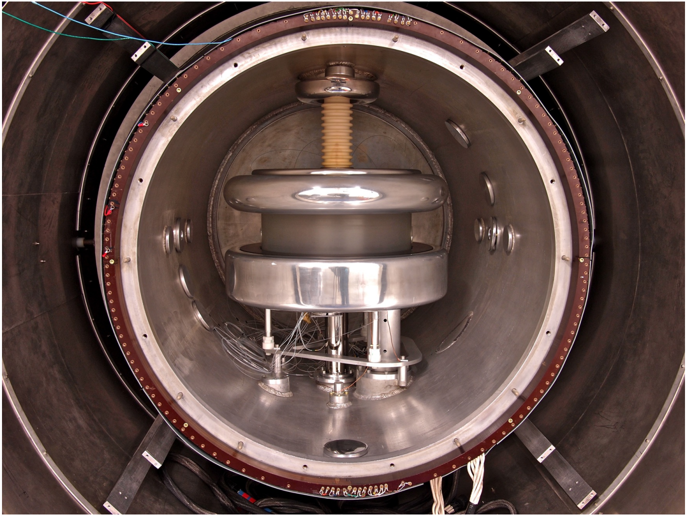

Photo: Zema Chowdhuri, PSI

Reminder

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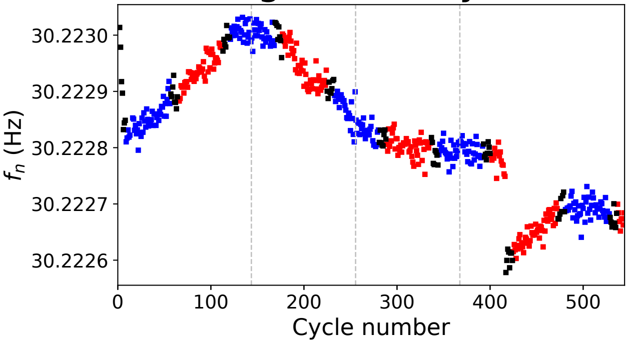
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{2}{\pi\hbar}dE$$

only if: $\frac{2\mu}{\hbar}(B(t \triangleq \uparrow\uparrow) - B(t \triangleq \uparrow\downarrow)) = 0$

Co-magnetometry



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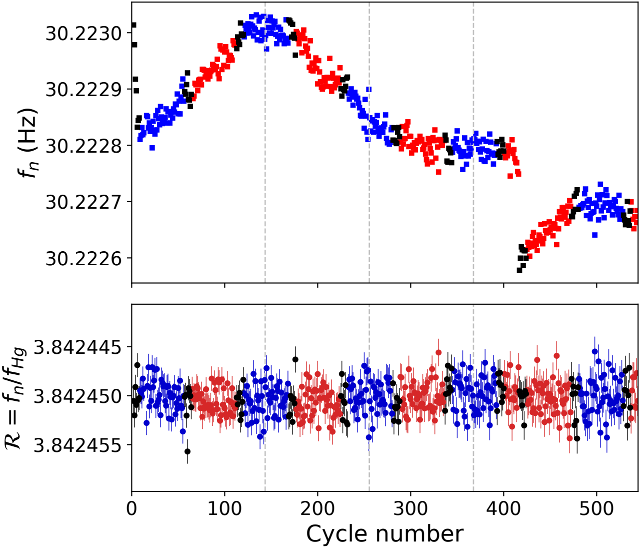

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Systematic effects

$$\mathcal{R} = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right| \Big(1 + \delta_{\mathrm{EDM}}$$

$$+\delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{quad}} + \delta_{\mathrm{grav}} + \delta_T + \delta_{\mathrm{Earth}} + \delta_{\mathrm{light}} + \delta_{\mathrm{inc}} + \delta_{\mathrm{other}}\Big)$$

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- δ_{Earth}: Earth rotation
  - $\gamma_n < 0 < \gamma_{\text{Hg}}$.
  - PSI not at Earth's equator.
  - $\mathcal{R}$ depends on direction of B_0.
  - luckily, ω_{Earth} well known.

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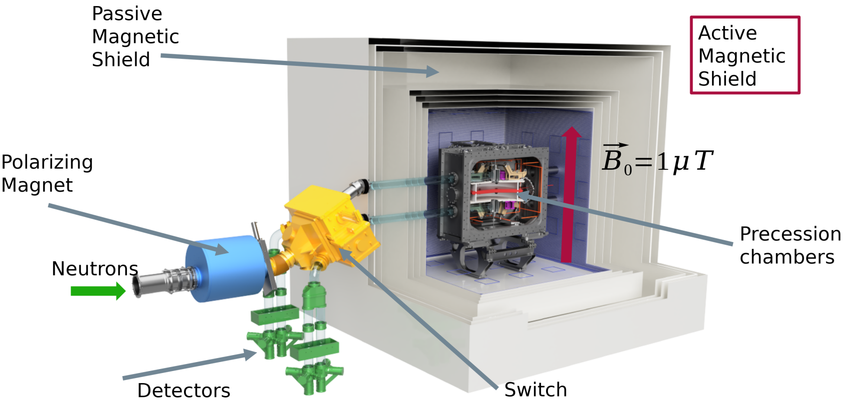
- ...

n2EDM Overview

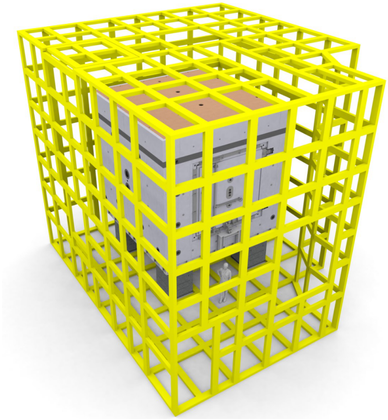


n2EDM Magnetically Shielded Room

$< 100\,\text{pT}$ in inner m^3 shielding factor 10^5 at $0.01\,\text{Hz}$

Active Magnetic Shielding

- 8 independent Coils
  - 3 currents each
- 490 wire paths
- 55 km wires
- 3.2 t of wire
- 780 m cable trays
- Several kW heat



2023: UCN Switch and Detetectors

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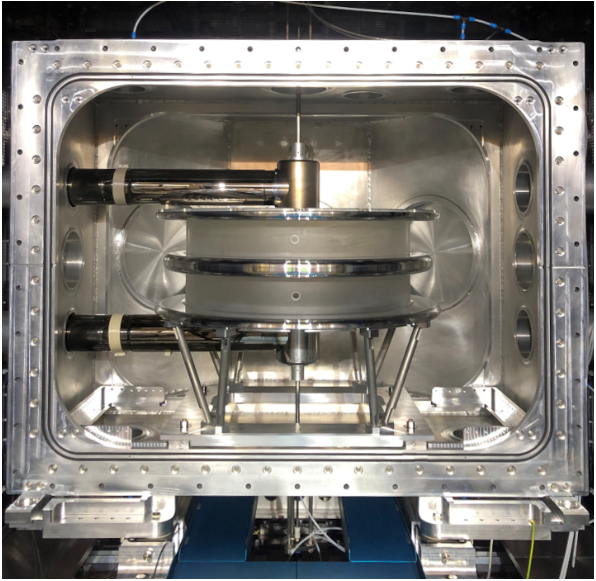
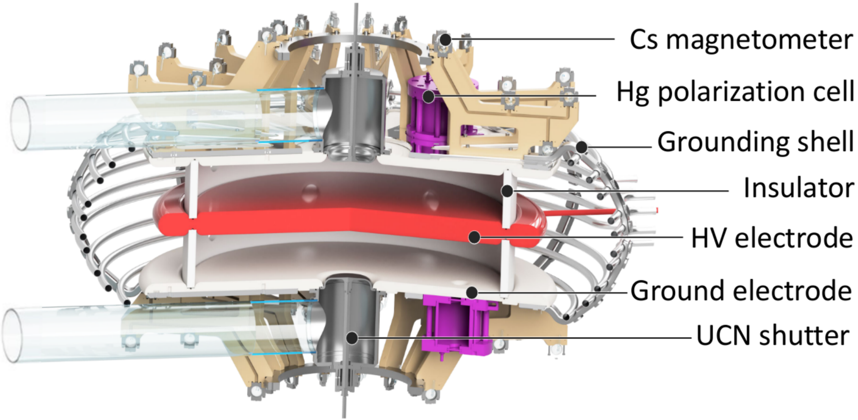
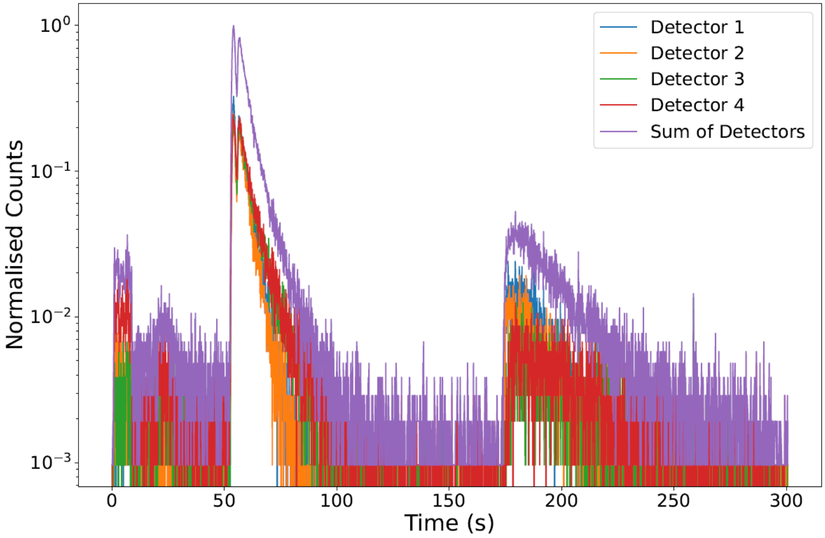
Precession Chamber



Precession Chamber



July 8 2023


Detector 1
Detector 2
Detector 3
Detector 4
Sum of Detectors
Normalised Counts
10^0
10^{-1}
10^{-2}
10^{-3}
0
50
100
150
200
250
300
Time (s)

Status

- n2EDM has entered its commissioning with neutrons phase
- Neutron optics / switch / shutters, DAQ / Control, spin analysing detectors, spin transport coils already working, being optimized.
- Up next: Spin flippers, Hg co-magnetometry, Cs vapor magnetometers, high voltage.
- Stay tuned for the first Ramsey measurements and EDM results!

Thank you for your attention!

Backup

UCN Detection

Slow neutrons are fundamentally hard to detect
(= to generate an electric signal)

UCN Detection

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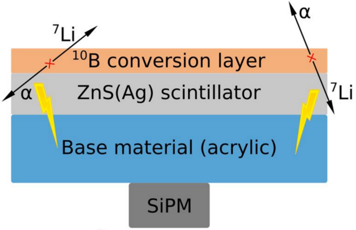

- Neutron capture on ^{10}B
- Subsequent decay into $\alpha + {}^7$Li back-to-back
- Charged particle generates light in scintillator
- Detect light in Silicon Photomultiplier (SiPM)

UCN Detection

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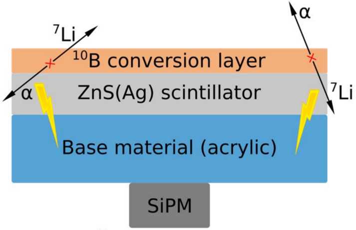
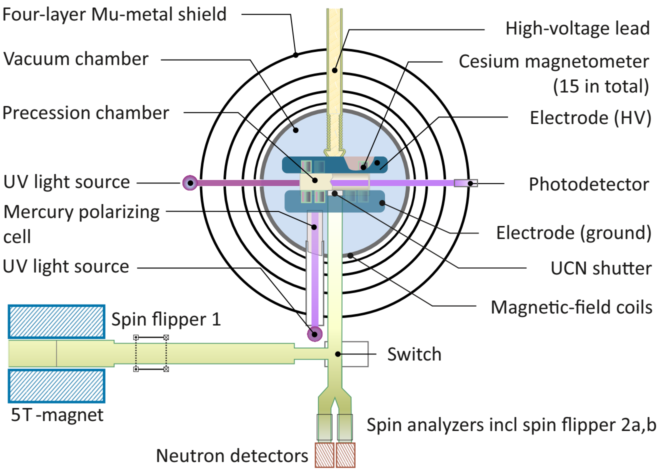


- Neutron capture on ^{10}B O(100 nm)
- Subsequent decay into $\alpha + {}^7$Li back-to-back
- Charged particle generates light in scintillator O(10 µm)
- Detect light in Silicon Photomultiplier (SiPM)

nEDM schematic



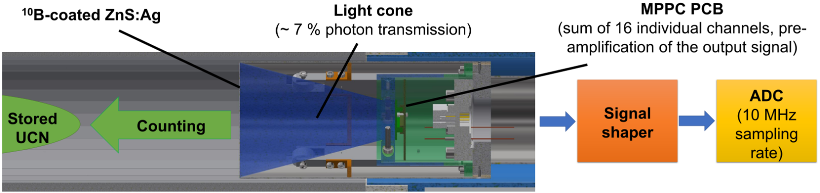
[Phys. Rev. Lett. **124**, 081803 (2020)]

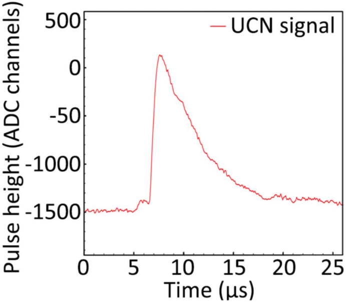
nEDM numbers

- Applied electric field: $11\,\mathrm{kV\,cm^{-1}}$
- Average visibility α: 0.76
- Time of free precession: $180\,\mathrm{s}$
- Average # of UCN in chamber: 11400
- Sensitivity per cycle: $\sigma = 2 \times 10^{-24}\,\mathrm{e \cdot cm/c}$

- Data taken: 2015 & 2016
- Total measurement cycles: 54068

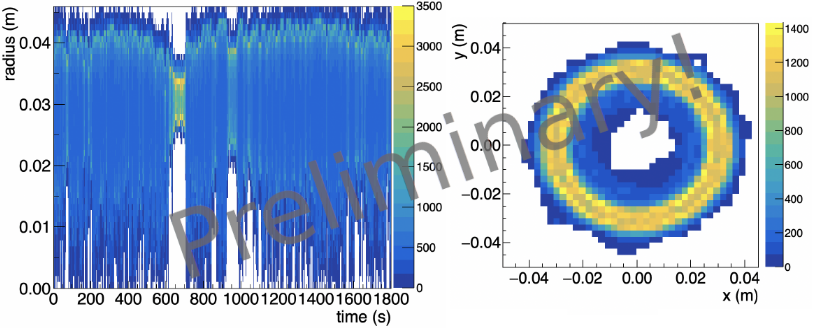
τSPECT Detector





PhD work of J. Kahlenberg

Systematics: Marginally Trapped Neutrons



C. Schmidt

Populated closed orbits:

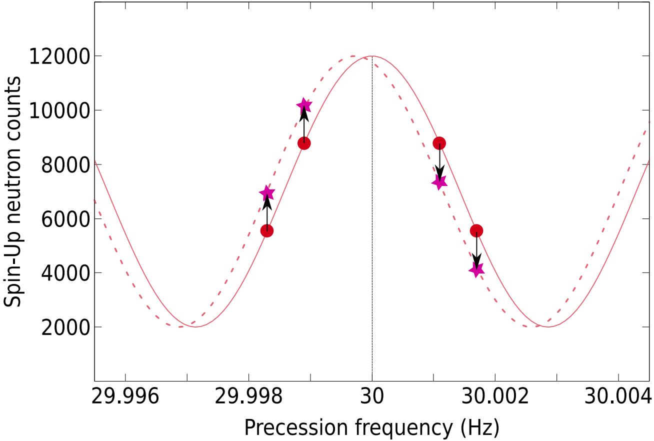
- Counted in short storage time runs
- Lost in long runs

⇒ Systematic shift towards small τ_n!

Data Blinding

Precision measurement with a long history
Expected zero result ⇒ Blind analysis necessary!

How to blind a clock comparison experiment?



More results: Dark matter

Another question for the Standard Model:

What is dark matter made of?

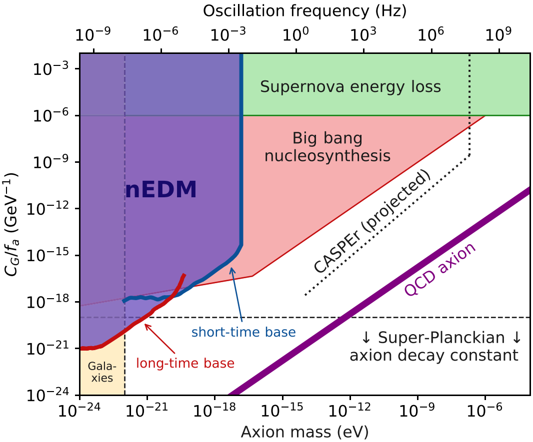
Axions, or Axion like particles (ALPs):

- Proposed in 1977 to solve the strong CP problem.

[R. Peccei and H. Quinn, Phys. Rev. Lett. **38**, 1440 (1977)]

- Very low mass ALPs: Good dark matter candidate.
- Could form coherently oscillating field permeating the universe.
- Coupling to gluons → nucleons → oscillating EDM.
- Analyses on EDM data looking for oscillations: Limits on axion couplings etc.

nEDM axion result



[Abel et al., Phys. Rev. X **7**, 041034 (2017)]