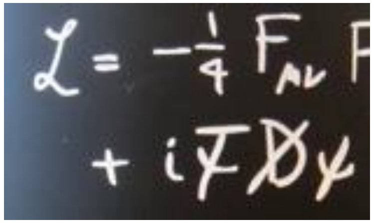
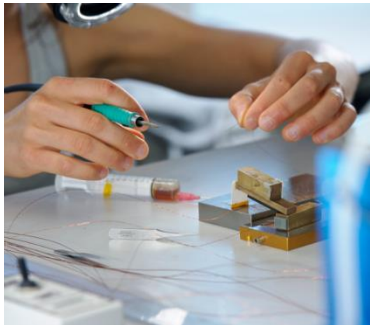
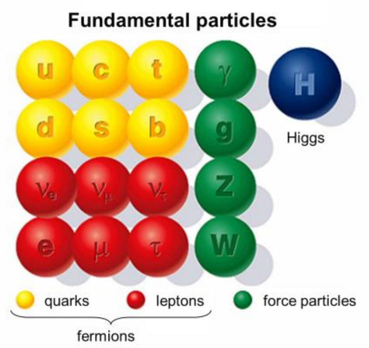
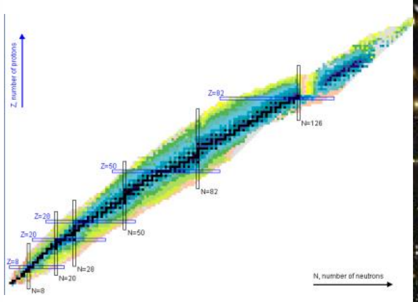
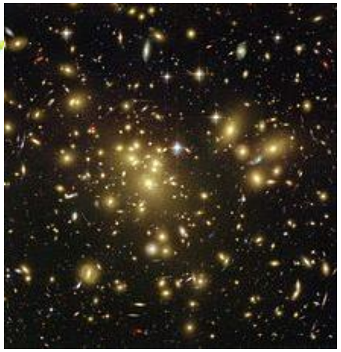
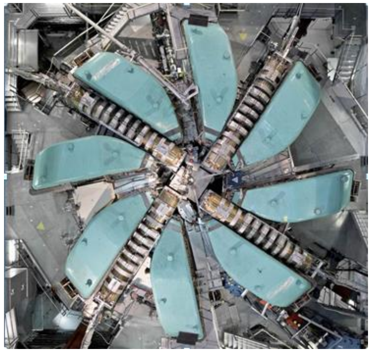
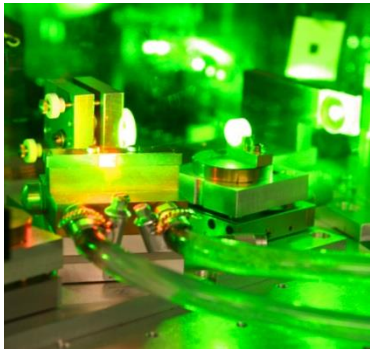
Previous and future nn' searches at ILL and PSI

INT workshop on nnbar oscillations

K.Kirch, ETH Zurich – PSI Villigen, Switzerland



nEDM@PSI

Our collaboration (50 people, 15 institutions, 7 countries) just finished nEDM and starts assembling the n2EDM experiment aiming at an improvement in sensitivity by an order of magnitude.

nEDM@PSI

Later this afternoon: talk by Guillaume Pignol about the nEDM experiment.

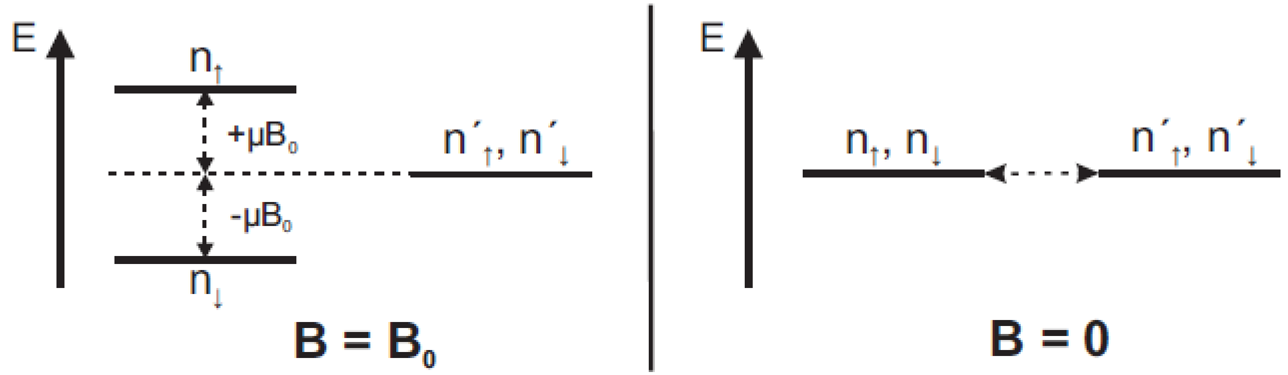
Topic of this talk, nn' is part of the PhD thesis of Prajwal Mohan Murthy (doctoral student at PSI-ETHZ):

This talk

- Previous nn' measurements
- The Berezhiani-Nesti signal
- PSI UCN source and nEDM experiment
- nn' search experiment Aug-Oct 2017
- Sensitivity and preliminary sanity checks
- Outlook

Mirror neutron experiments

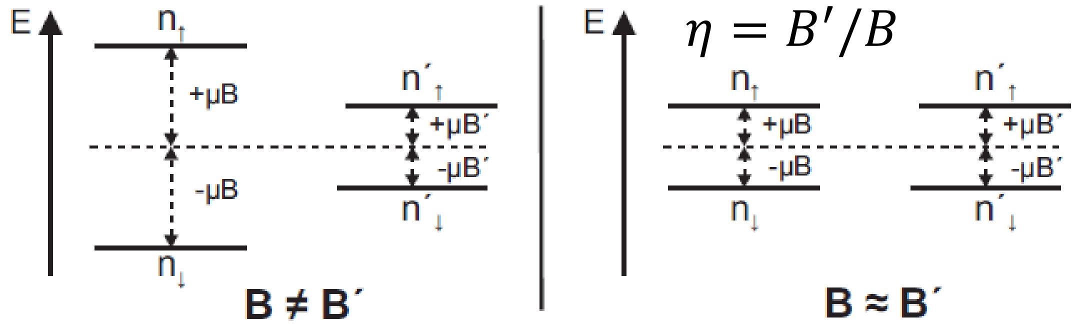
$$\frac{n_0}{n_{\uparrow\downarrow}} = 1 - \frac{t_f t_s}{\tau_{nn'}^2}$$



- Conceptually very simple:
  - Search for neutron disappearance n→n' as a function of B-field (in order to tune over degenerate states allowing resonant transitions, maximal losses at B~B')
  - If disappearance found,
    - n→n' signal frequency could point to the origin of B'
      (not bound to Earth → sidereal modulation,
      bound to Earth → static → experiments at various locations)
    - Regeneration experiments would prove n - 'dark state' oscillations → next talk

Mirror neutron experiments

$$\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = -\frac{t_s}{t_f}\frac{\eta^3 Cos\beta}{\omega^2 \tau_{nn'}^2 (1-\eta^2)^2}$$



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      (not bound to Earth → sidereal modulation,
      bound to Earth → static → experiments at various locations)
    - Regeneration experiments would prove n - 'dark state' oscillations → next talk

Beam vs. storage experiments

Beam:

- Ratio: $N = 1 - \frac{t_f^2}{\tau_{nn'}^2}$ Limit: $\tau_{nn'} > \sqrt{\frac{t_f^2}{1 - N + 1.65\Delta N}}$

- N=1, $t_f^2 \sim 0.05^2\ s^2$ (VCN), $\Delta N \sim 10^{-7} \rightarrow$ **$\tau_{nn'}$ > 100 s**
- # of counts needed ~ **10^{13}**

Storage:

- Ratio: $N = 1 - \frac{t_f t_s}{\tau_{nn'}^2} = 1 - \frac{t_f^2}{\tau_{nn'}^2}\frac{t_s}{t_f}$ Limit: $\tau_{nn'} > \sqrt{\frac{t_s t_f}{1 - N + 1.65\Delta N}}$

- N=1, $t_f\, t_s \sim 0.1 * 150\ s^2$, $\Delta N \sim 10^{-3} \rightarrow$ **$\tau_{nn'}$ > 100 s**
- # of counts needed ~ **10^6**

Mirror neutron experiments

B'=0 | **B'≠0**

UCN disappearance experiments

- G. Ban et al., PRL **99**, 161603 (2007): $\tau_{nn'}$>103s (95 % C.L.), B'=0 [PSI-ILL]
- A. P. Serebrov et al., PLB **663**, 181 (2008): $\tau_{nn'}$>414s (90 % C.L.), B'=0 [PNPI-ILL]
- A. P. Serebrov et al., NIMA **611** ,137(2009): $\tau_{nn'}$>403s (90 % C.L.), B'=0 [PNPI-ILL]
  comb.: $\tau_{nn'}$>448s (90 % C.L.), B'=0 [PNPI-ILL]

- I. Altarev et al., PRD **80**, 032003 (2009): $\tau_{nn'}$>12s (95% C.L.)@B'<13μT [PSI-ILL]
- A. P. Serebrov et al., NIMA **611** ,137(2009): $\tau_{nn'}$>200s (90 % C.L.), B'<1.2μT [PNPI-ILL]

- nEDM@PSI (2017) this talk

CN beam regeneration experiments

- U. Schmidt, Proceedings of 2007 BLNV Workshop: $\tau_{nn'}$>2.7s (90 % C.L.), B'=0 [FRM-II]

- L. Broussard next talk, see also Berezhiani et al., PRD96(2017)035039 B'≠0 [ORNL(HFIR)]

Eur. Phys. J. C (2012) 72:1974
DOI 10.1140/epjc/s10052-012-1974-5

Letter

Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

Zurab Berezhiani[1,2,a], **Fabrizio Nesti**[1]

[1]Dipartimento di Fisica, Università dell'Aquila, Via Vetoio, 67100 Coppito, L'Aquila, Italy
[2]INFN, Laboratori Nazionali Gran Sasso, 67010 Assergi, L'Aquila, Italy

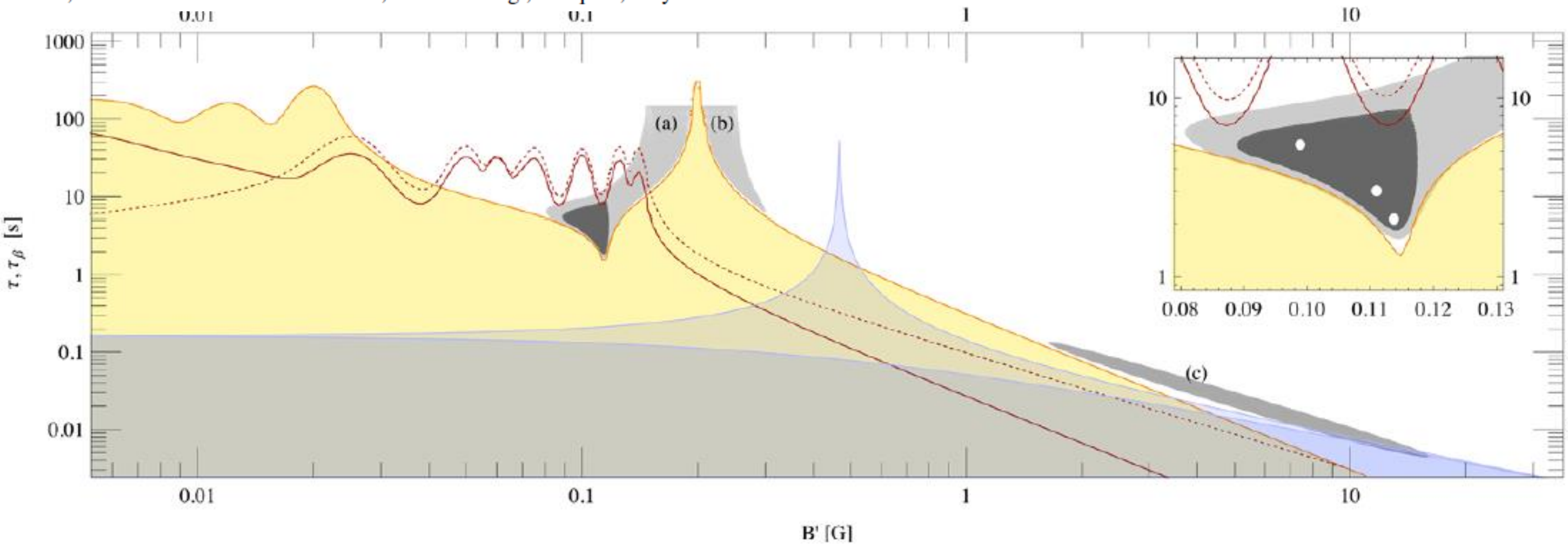


Fig. 2 Global fit in the B'-τ, τ_β plane. The positive result (anomaly) corresponds to the *gray-shaded areas*, which show the parameter space allowed at 90 % CL (*darker*) and 99 % CL (*lighter*) by the global fit of non-zero $\overline{D}_B$, (6), with magnetic field marginalized over the uncertain range $B = 0.15$–0.25 G (the zoomed inset displays the best fit points assuming a constant field $B = 0.15, 0.20, 0.25$, left to right). For comparison, available constraints from earlier measurements are also shown: the *yellow-shaded area* in the background is excluded at 99 % CL by the measurements of E_B from Refs. [48, 51]; the region of τ (τ_β) below the *wavy solid* (*dotted*) *curves* are disfavored by the measurements of Refs. [47, 49, 50] (not included in the fit). Interestingly, the data of Ref. [49] for E_B and A_B also imply a best fit value $B' = 0.11$ G, with $\tau = 14$ s and $\tau_\beta = 20$ s, respectively. The *blue-shaded* area peaked at $B' = 0.5$ G is excluded by measurements in the Earth magnetic field, illustrated for B' and $B_{\rm Earth}$ parallel (*lighter blue*) and antiparallel (*darker blue*) (Color figure online)

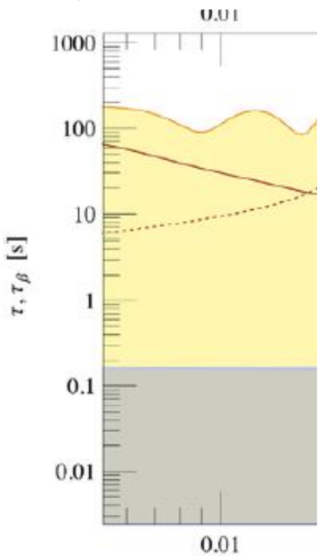
Eur. Phys. J. C (2012) 72:1974
DOI 10.1140/epjc/s10052-012-1974-5

Letter

Magnetic anom
signal for neutr

Zurab Berezhiani[1,2,a], **F**

[1]Dipartimento di Fisica, Unive
[2]INFN, Laboratori Nazionali (



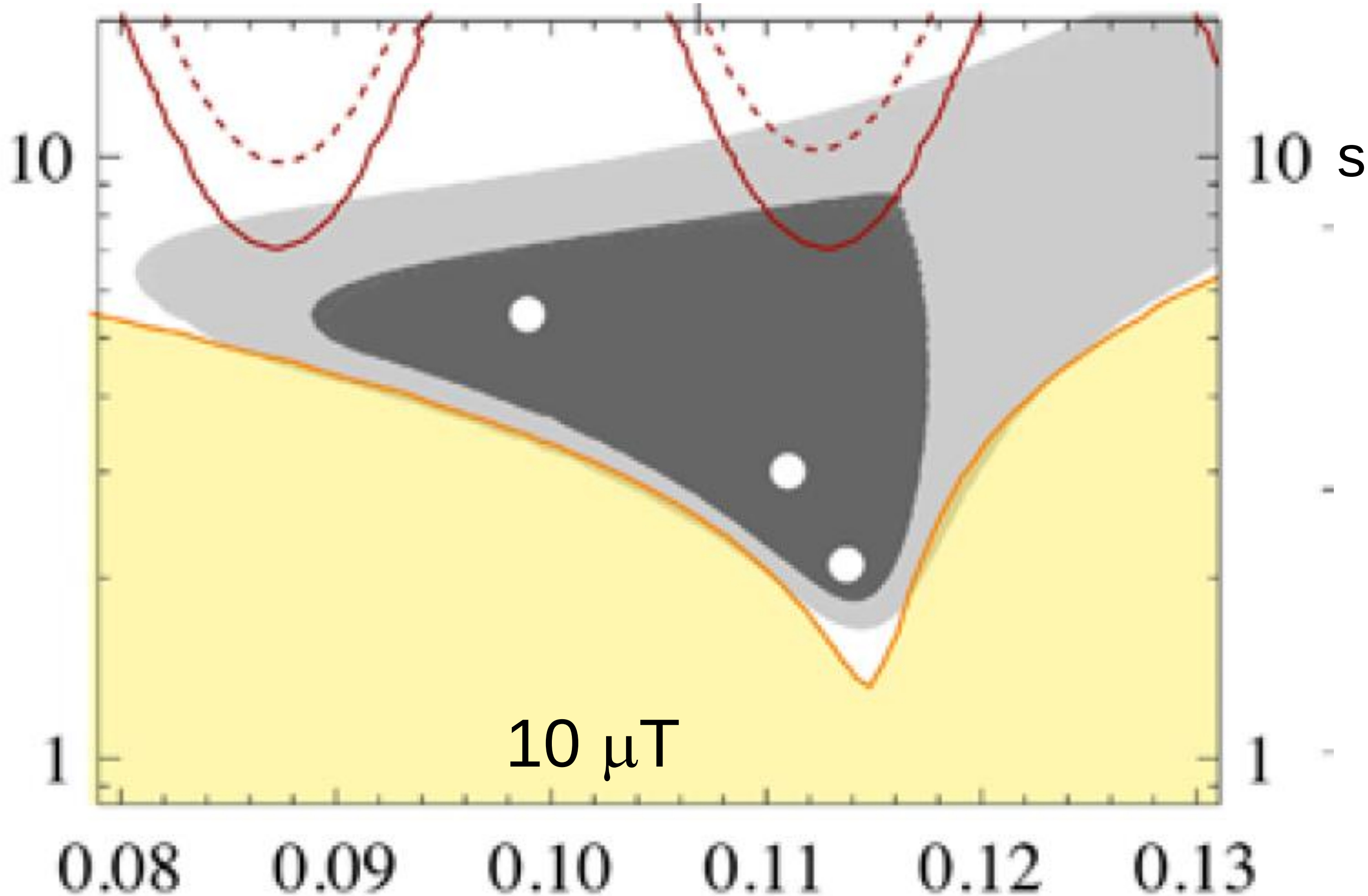


Fig. 2 Global fit in the *B*
corresponds to the *gray-sh*
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Our previous result (PRD80, 2009)

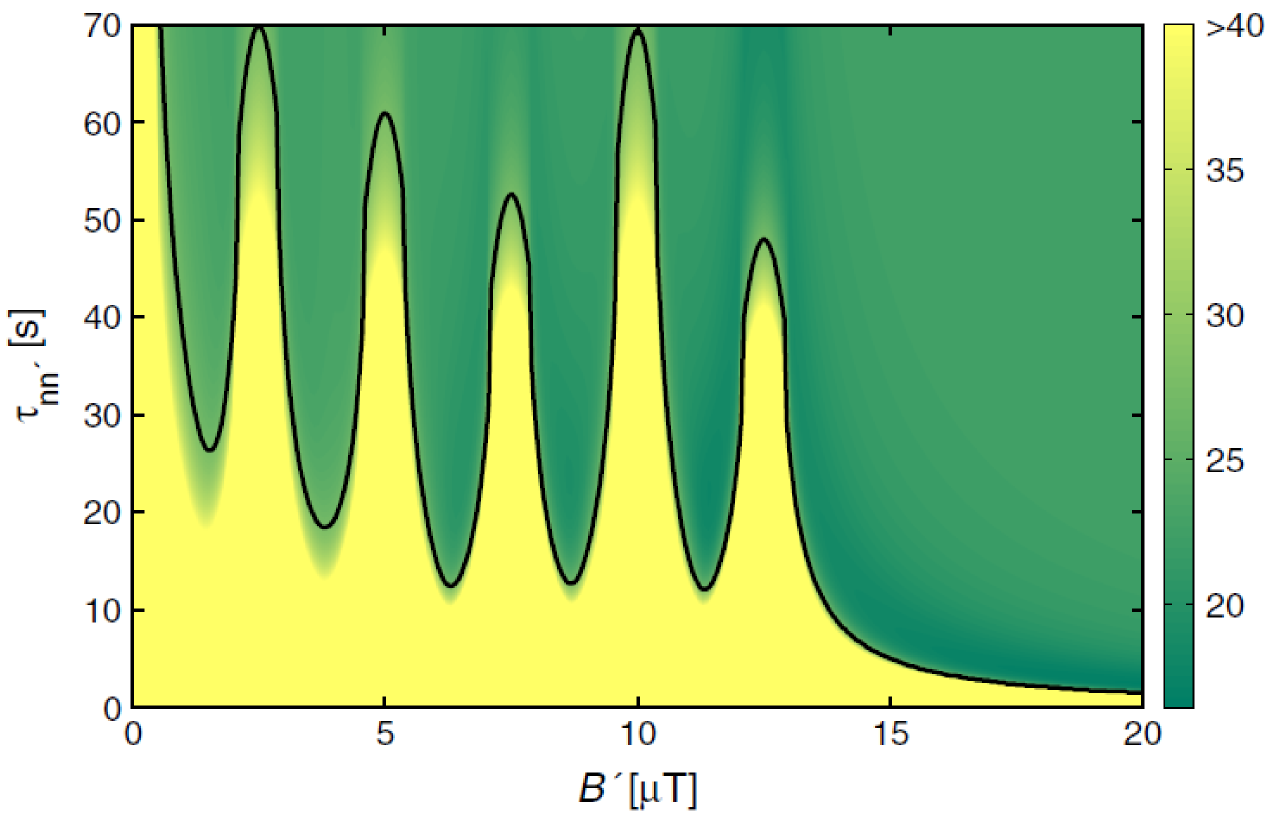

FIG. 2 (color online). Contour plot of the minimal χ^2 at the point $(B', \tau_{nn'})$. The solid line denotes the 95% C.L. contour line for an exclusion of $\tau_{nn'}$. We evaluated a lower limit on $\tau_{nn'}$ at the minimum of this contour for B' between 0 and 12.5 μT.

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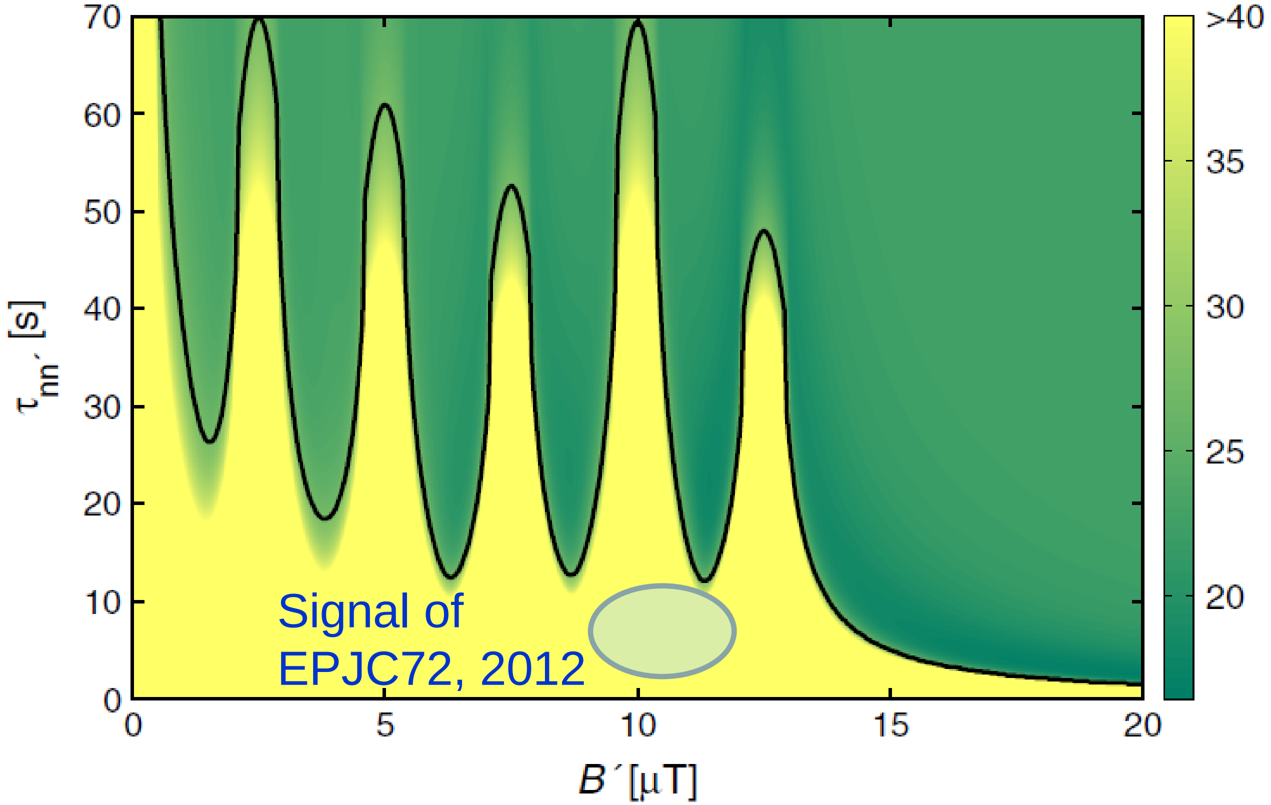

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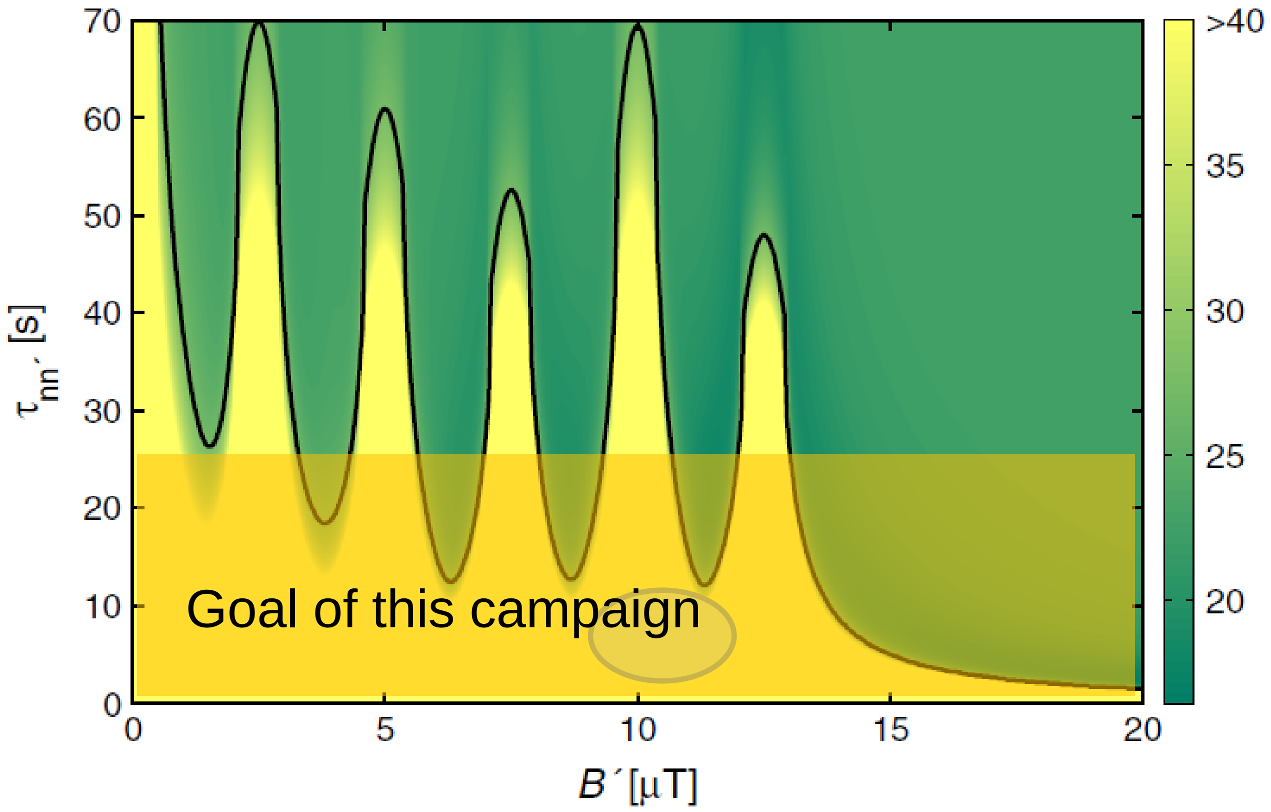

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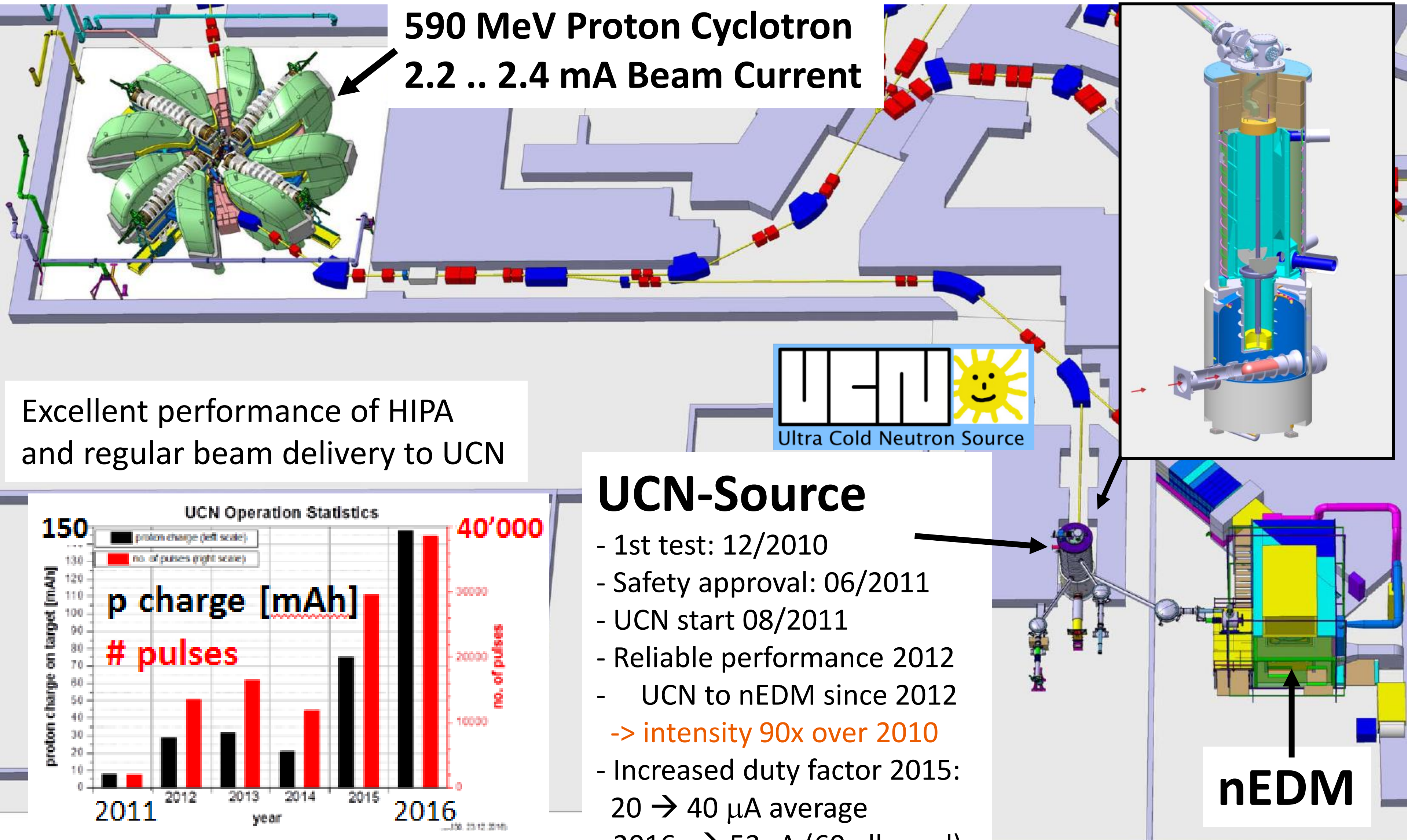
Ultracold Neutron Source & Facility



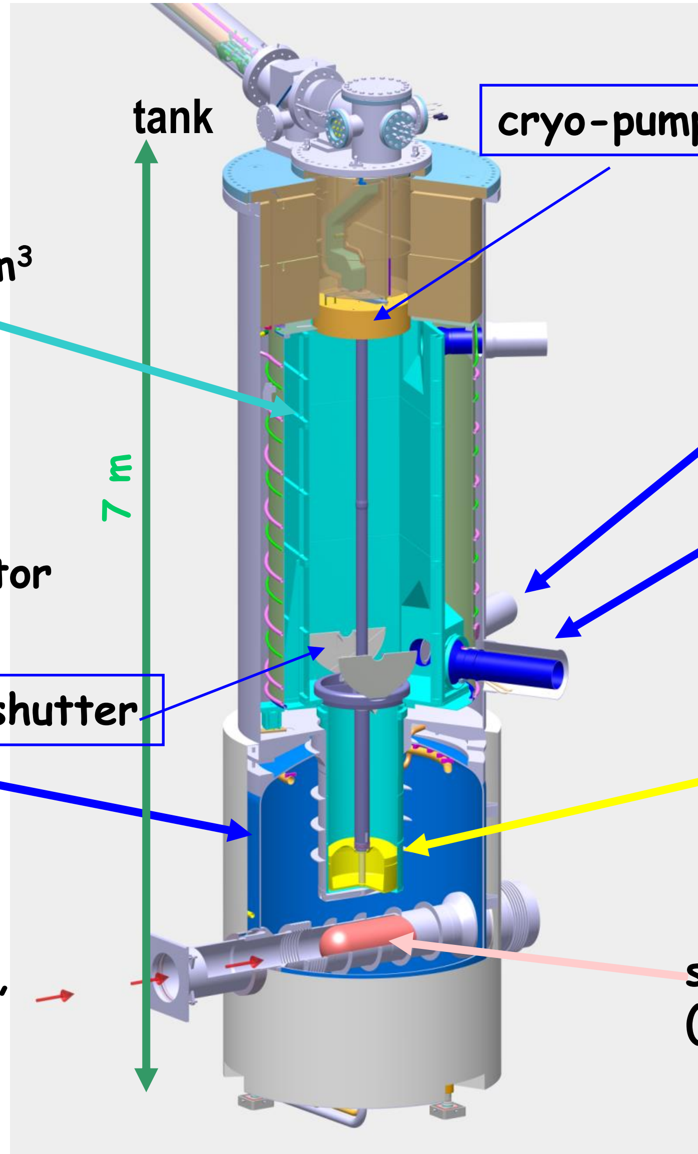
Excellent performance of HIPA and regular beam delivery to UCN

UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
- UCN to nEDM since 2012
  -> intensity 90x over 2010
- Increased duty factor 2015: 20 → 40 μA average
- 2016: → 53μA (60 allowed)

The PSI UCN source

Ultra Cold Neutron Source



DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

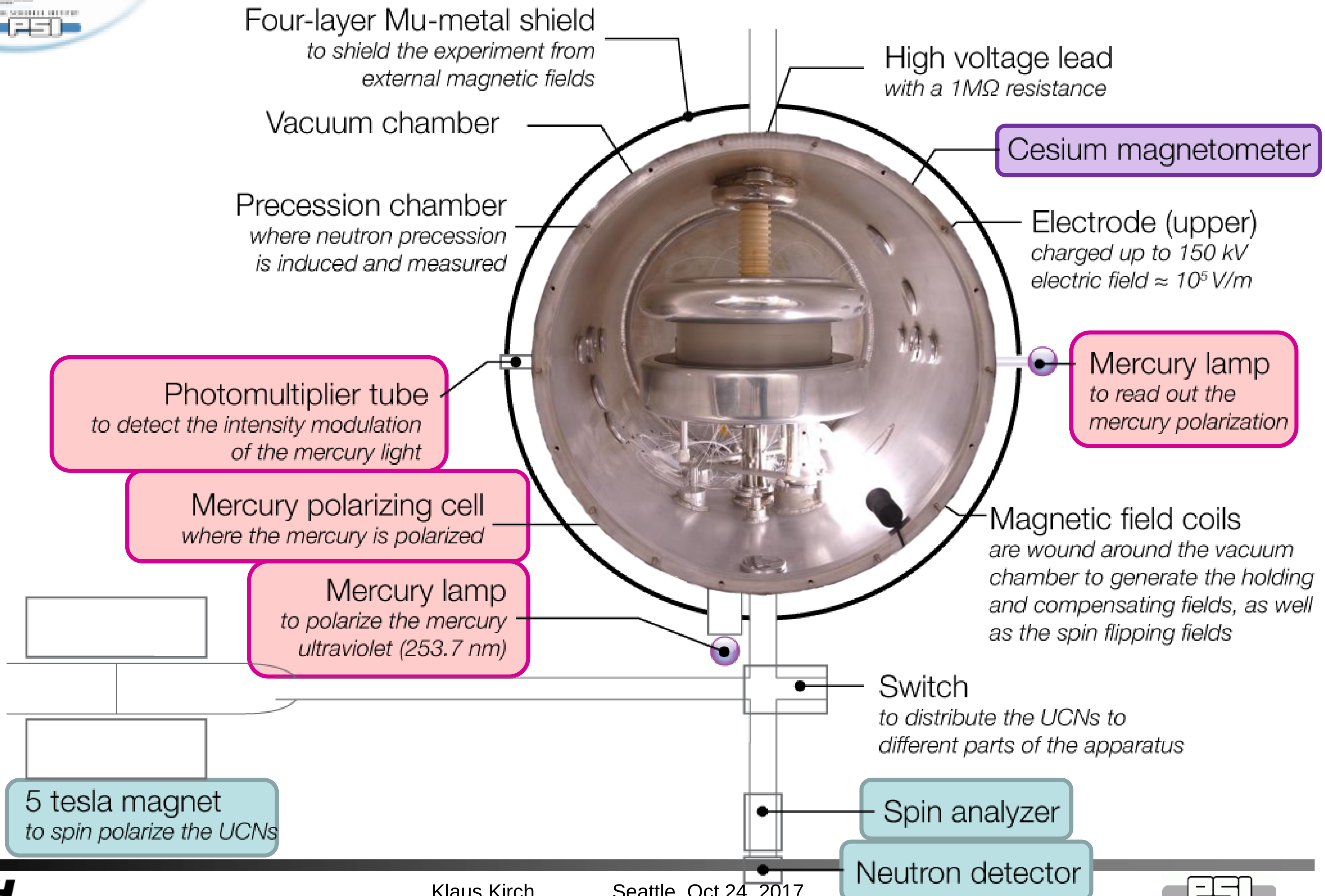
heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

cold UCN-converter
~30 dm^3 solid D_2 at 5 K

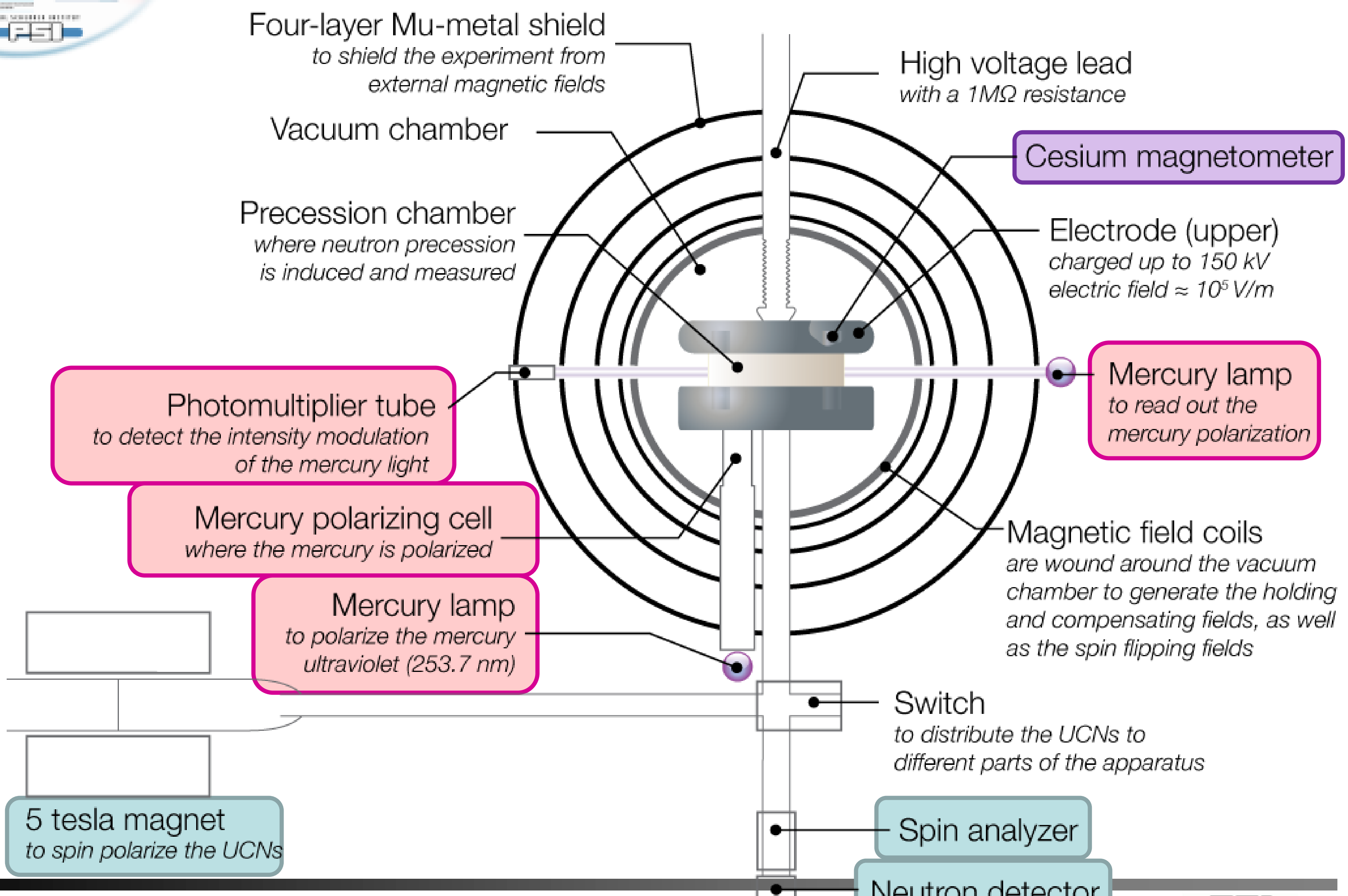
pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% duty cycle

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

The nEDM spectrometer



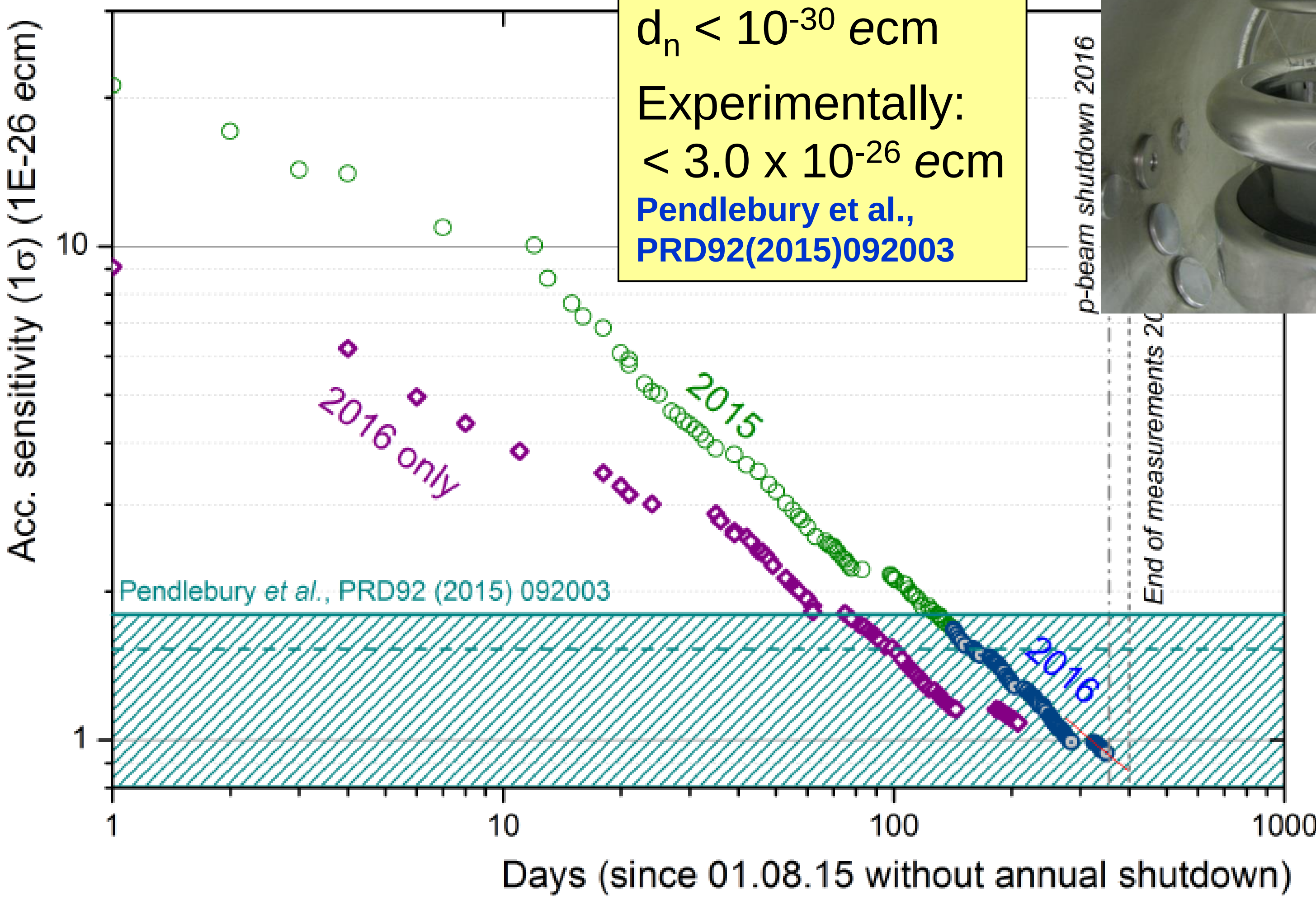
The nEDM spectrometer

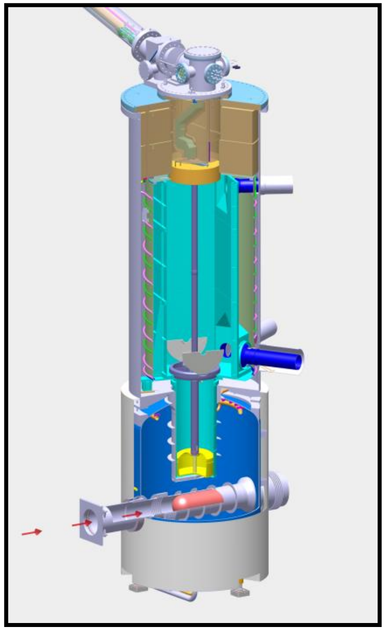


Searching for the neutron EDM

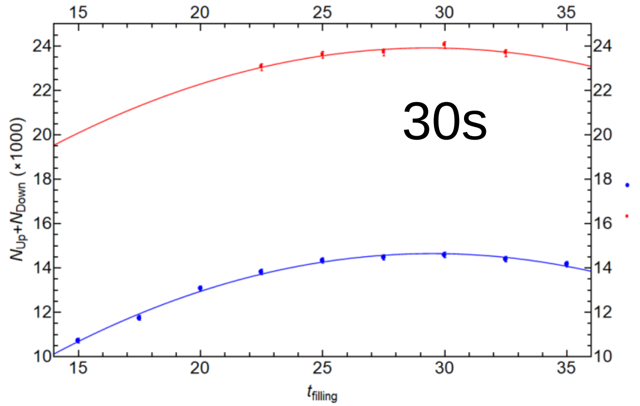
Expect from SM:
$d_n < 10^{-30}$ ecm

Experimentally:
$< 3.0 \times 10^{-26}$ ecm
Pendlebury et al., PRD92(2015)092003

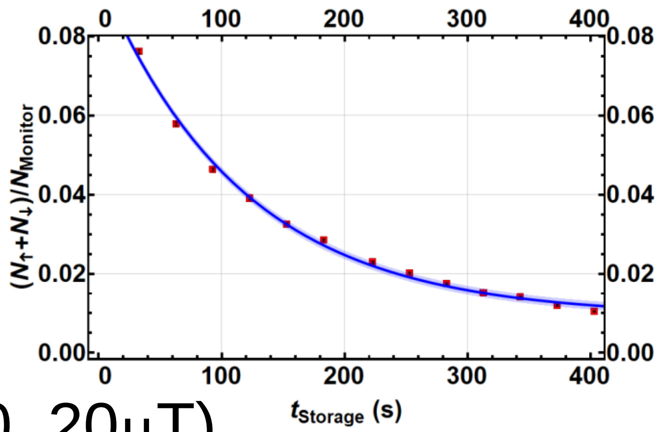




nn' support measurements

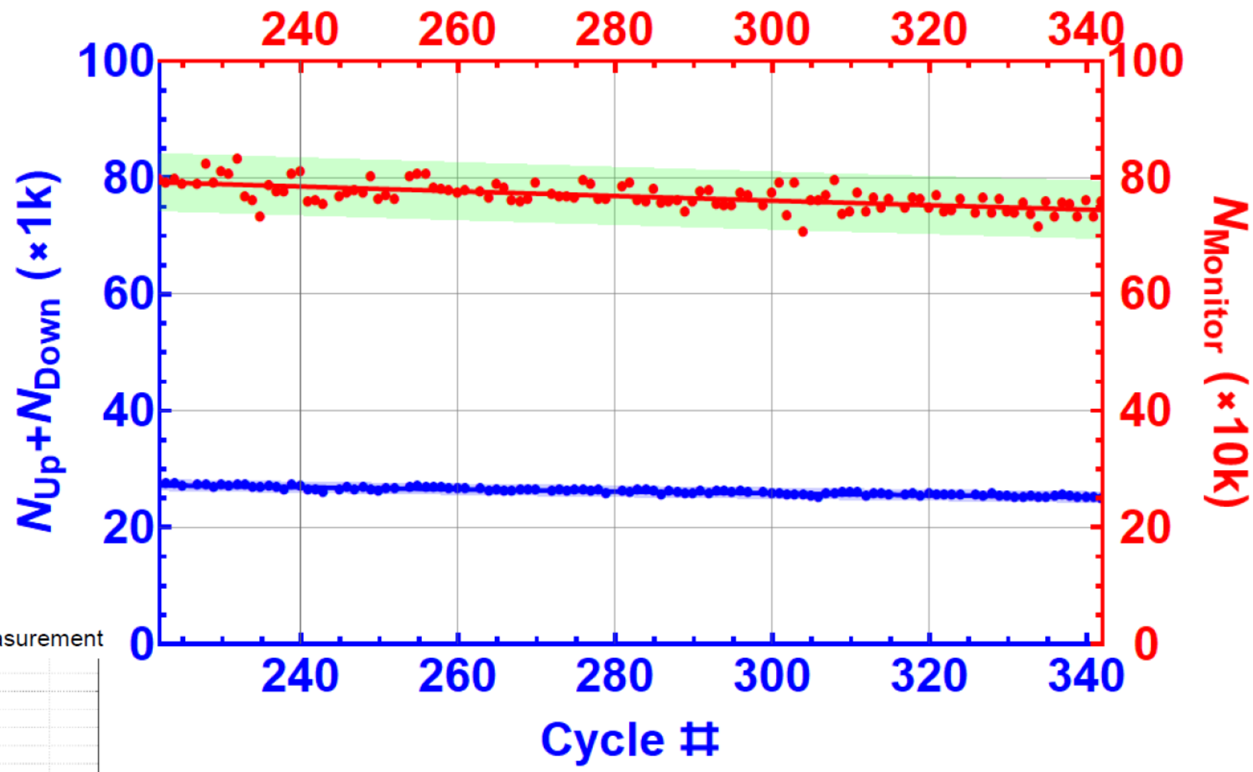


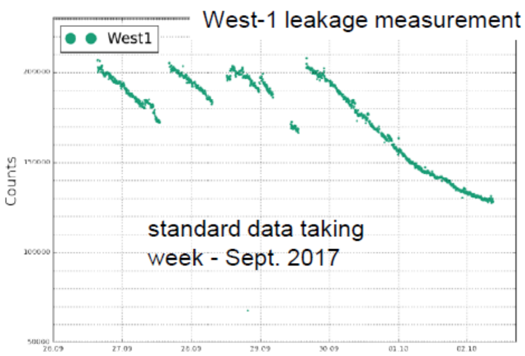
- Use unpolarized UCN
- Optimize filling and counting time
  - found 30s filling and used 75s counting
- Optimize storage time
  - Worked at 180s and 380s with cycle lengths between proton pulses to UCN source of 300s and 500s, respectively
  - Determine effective storage time (longer by roughly 2x11s due to possible nn' oscillations during filling and emptying)
- Measure storage time curve to fix MC parameters for extraction of $\langle t_f \rangle_{t_s}$ and $\sqrt{\langle t_f^2 \rangle_{t_s}}$
- Verify the performance of the UCN monitoring
- Verify magnetic field values (here 0, 10, 20μT)



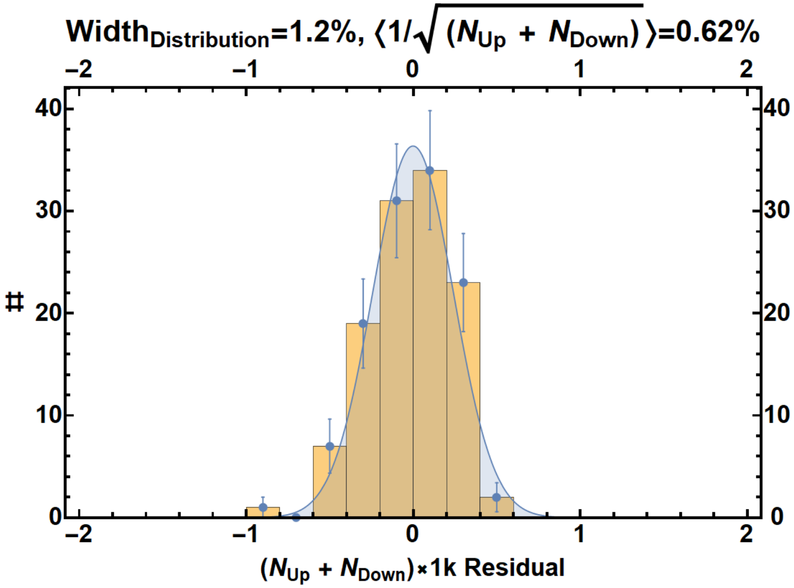
UCN counting

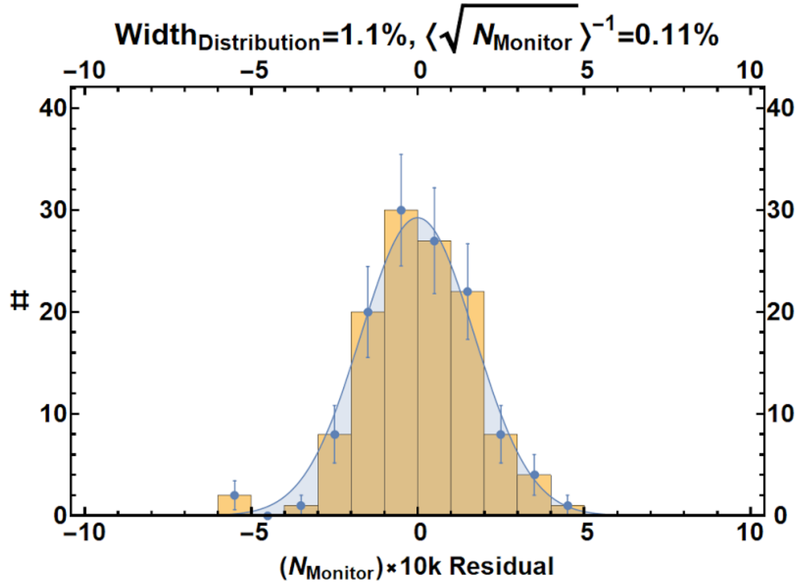
Raw counts without proper time cuts Monitor-counts

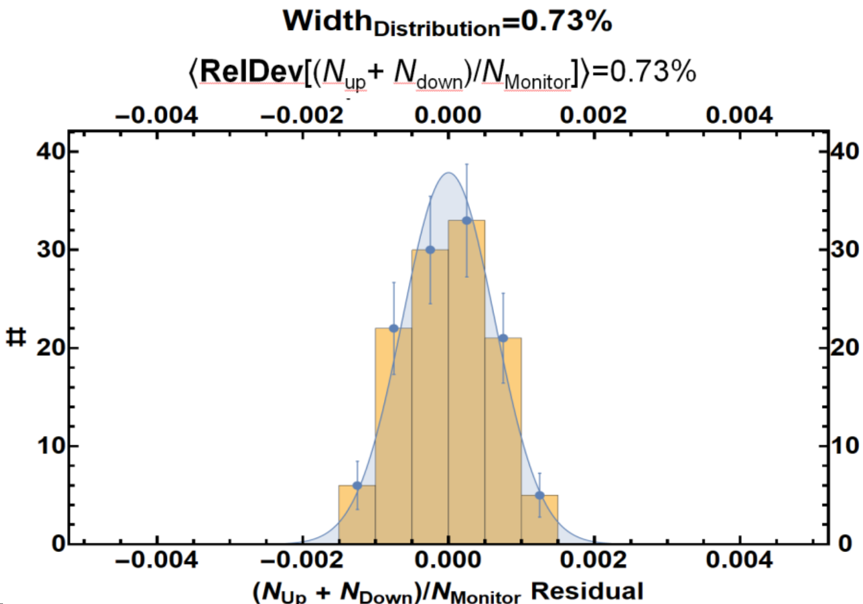




Statistics and normalization







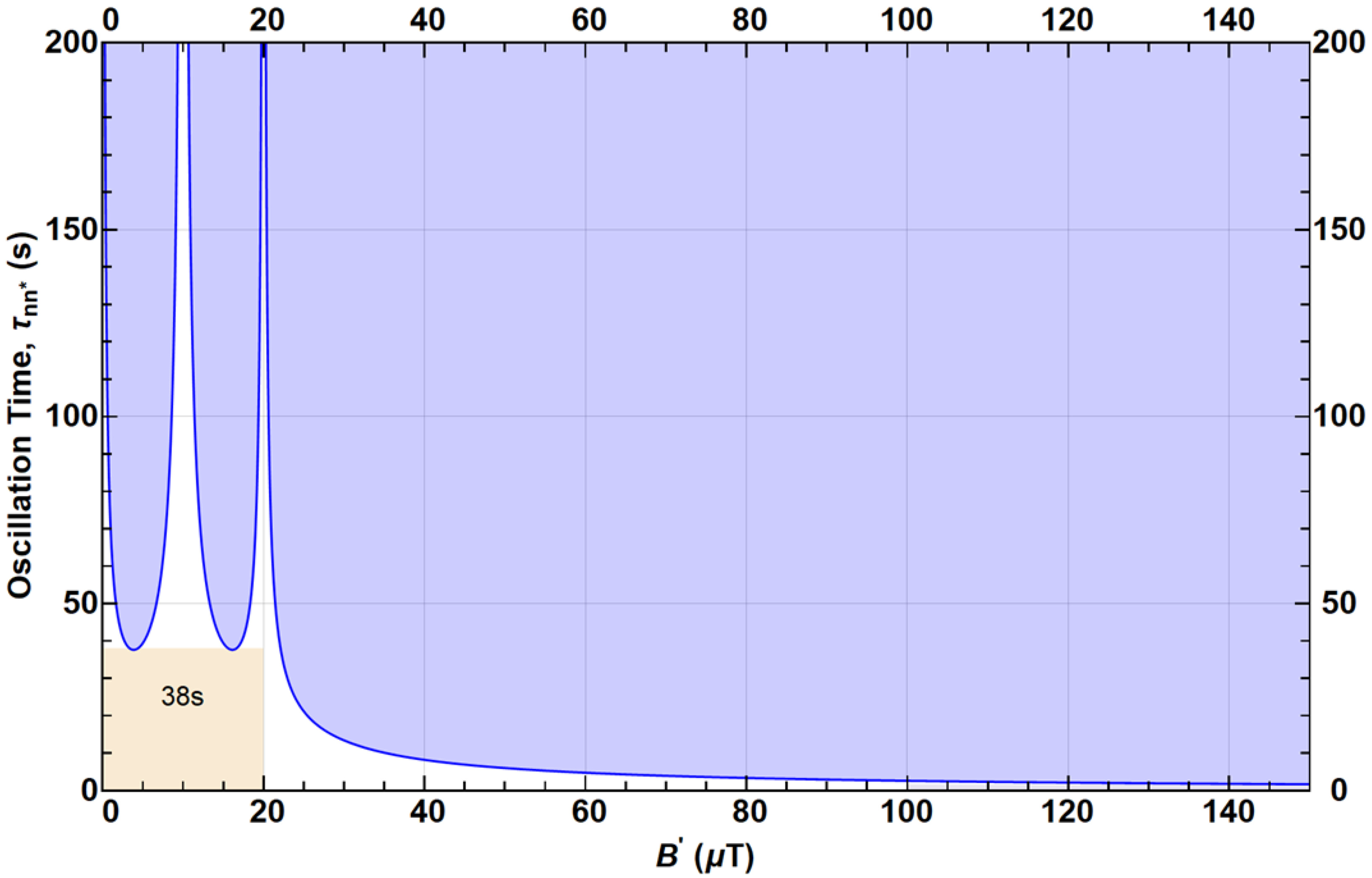
nn' data collection

We took data Aug-Oct 2017.

Cluster	Pattern	t^*_s (t_t) /s	B_0 /μT	# Cycles
1	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	10	1243
2	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	10	1136
3	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	20	864
4	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	20	775

- There was a break in between 10 and 20μT cycles for a different physics measurement
- The data was collected such that the potential signal could be confirmed (or rejected) with just 10μT data and on addition of 20μT data also at 150μT … 1.5mT could exclude τ below 1.5 … 0.15s
- In addition to the main cluster of nn' runs, there were data taken for also t_s scans, mainly to extract $t_f(t_s)$

In case we wouldn't find a signal …



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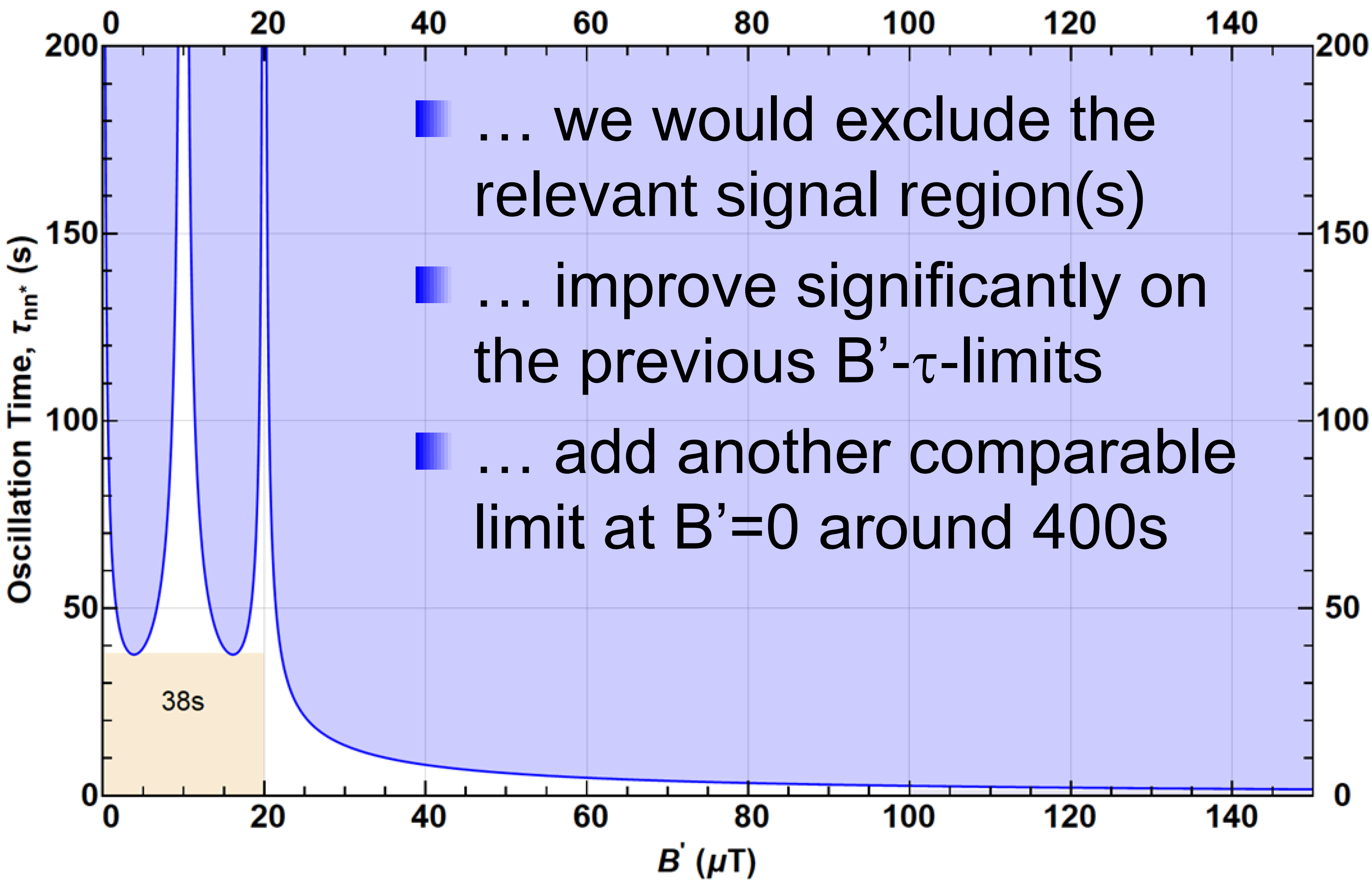
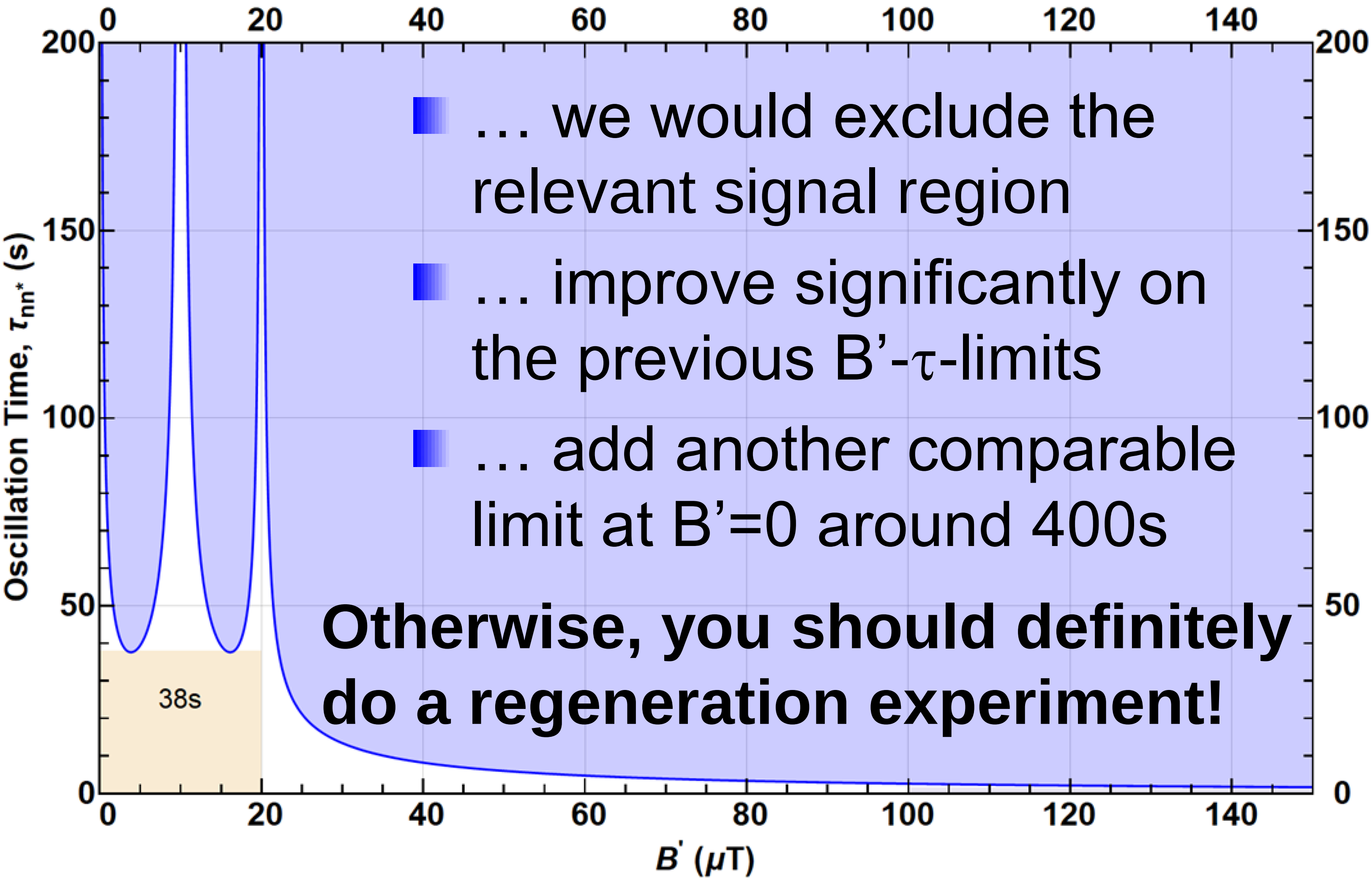


- … we would exclude the relevant signal region(s)
- … improve significantly on the previous B'-τ-limits
- … add another comparable limit at B'=0 around 400s

In case we wouldn't find a signal …



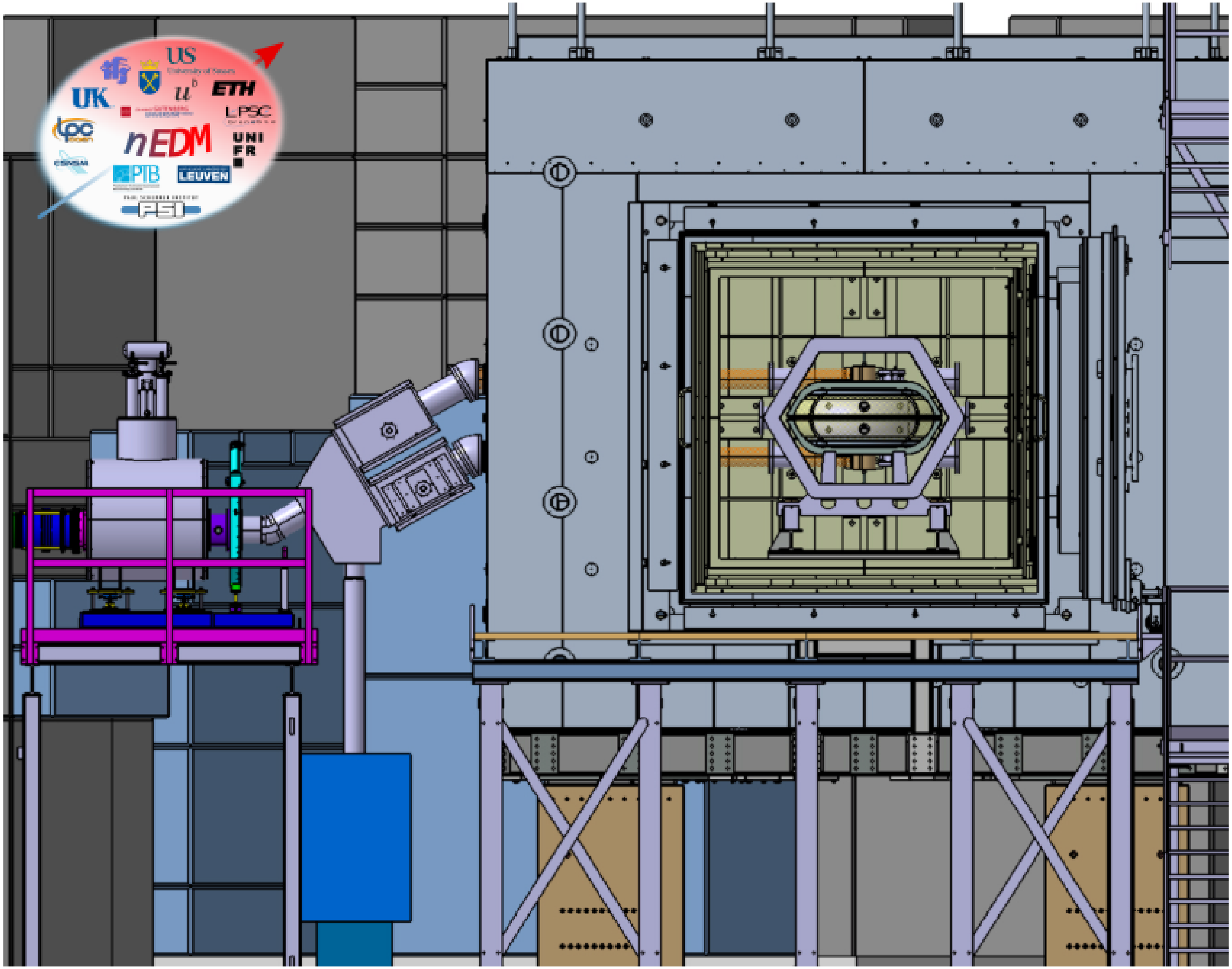
- … we would exclude the relevant signal region
- … improve significantly on the previous B'-τ-limits
- … add another comparable limit at B'=0 around 400s

Otherwise, you should definitely do a regeneration experiment!

nEDM is presently being taken apart

nEDM is presently being taken apart

We'll be back with n2EDM shortly



PAUL SCHERRER INSTITUT

PSI

Zuoz Summer School 12-18 August 2018

Dmitry Budker (Mainz)

Exotics searches in atoms and molecules

Augusto Ceccucci (CERN)

Exotics searches at low energy

Sacha Davidson (Lyon)

Exotics and flavour

Tobias Golling (Geneva)

Exotics searches in ATLAS and CMS

Francis Halzen (Wisconsin)

IceCube: building a new window on the Universe from Antarctica

Matthias Neubert (Mainz)

Flavour physics in the SM and beyond

Barbara Storaci (Zurich)

Status of B anomalies

David Straub (TU Munich)

Interpreting B anomalies

Frederic Teubert (CERN)

Future opportunities in flavour physics

Particle Flavour Fever

https://www.psi.ch/particle-zuoz-school

Adrian Signer, Michael Spira, Anita van Loon-Govaerts, **zuoz2018@psi.ch**

CHIPP Swiss Institute of Particle Physics

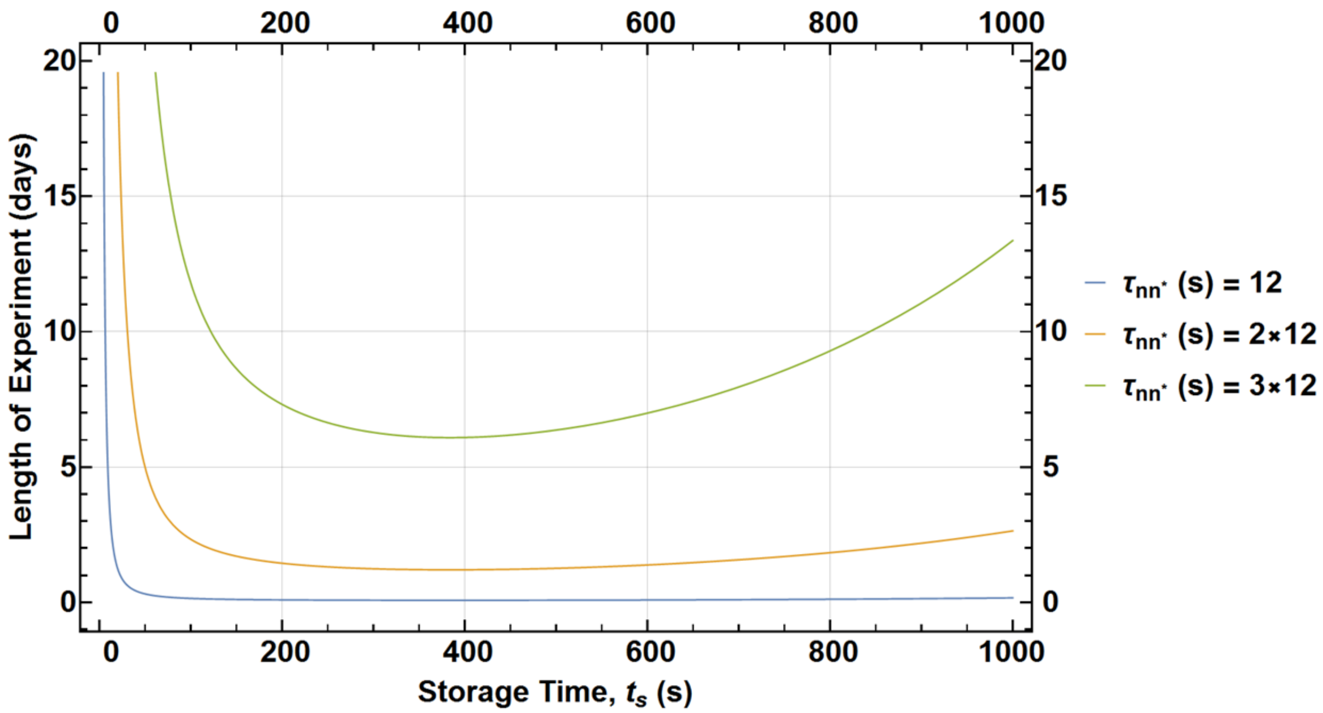
sc|nat

Swiss Academy of Sciences
Akademie der Naturwissenschaften
Accademia di scienze naturali
Académie des sciences naturelles

Backup

Optimizing t^*_s

Sensitivity per cycle ~ $\sqrt{t_s\sqrt{N}}$, but also N decreases exponentially and for longer cycle times less cycles can be performed.



$$\tau_{nn^*} \propto \sqrt[4]{N}$$

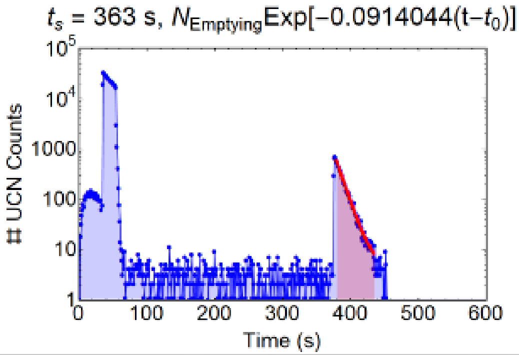
$$\tau_{nn^*} \propto \sqrt{t_s t_f}$$

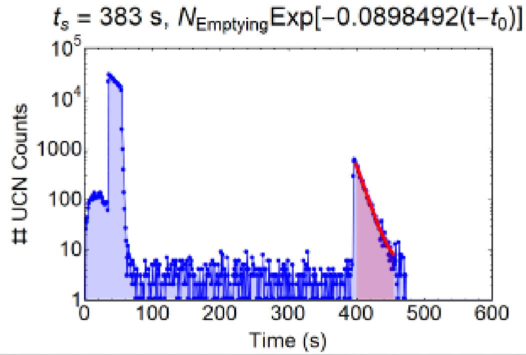
$$\tau_{nn^*}(t_t \propto t_s) \propto \sqrt{t_s\sqrt{N}},$$

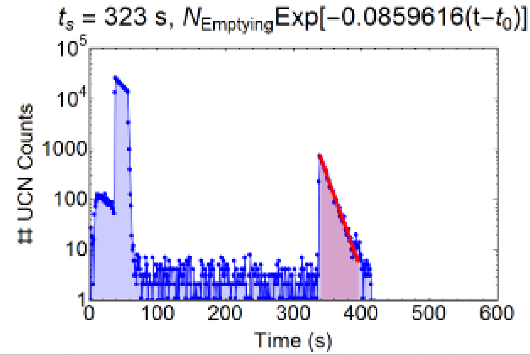
$$t_s^* = 380s$$

Optimizing $t_{emptying}$

We'd want $t_{emptying}$ to be the longest time possible to amply measure all the neutrons remaining.



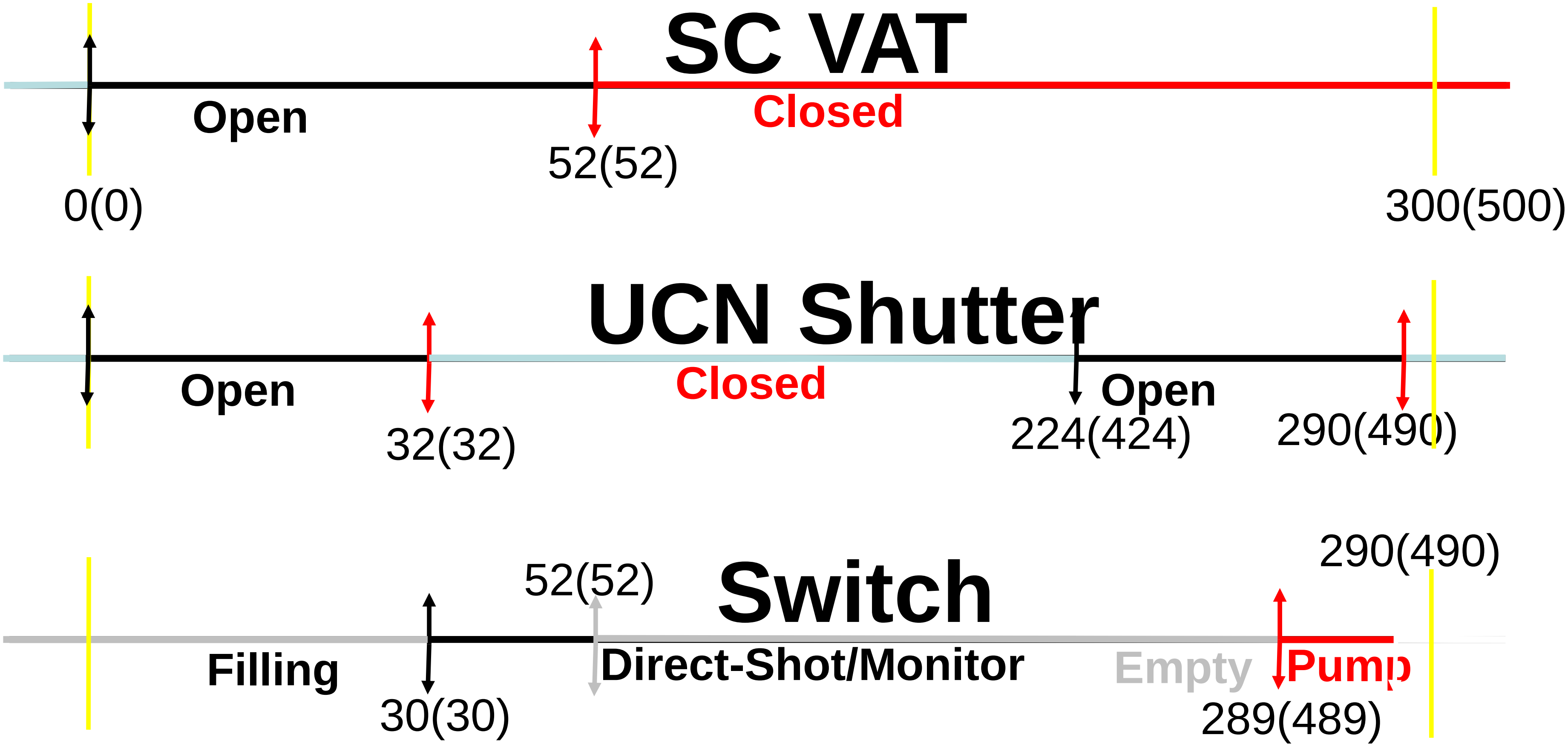




$t_{emptying}$=75s. They can be accommodated with t_s={180, 380}s, into cycles t_t={300,500}s long.

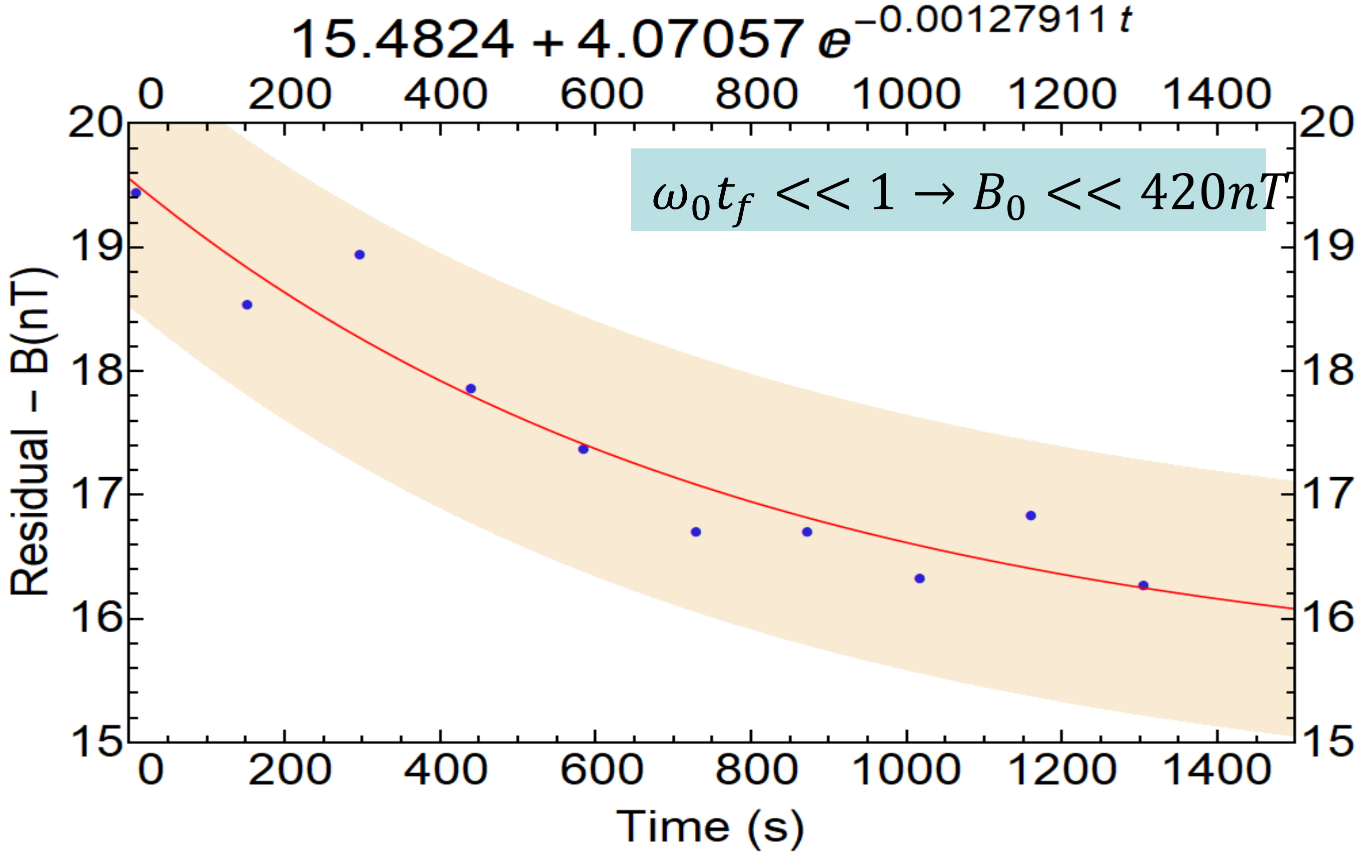
Cycle Plan

t_s=180s to replicate old experiment, t_s=380s for maximum sensitivity



What is the Magnetic Field Inside?

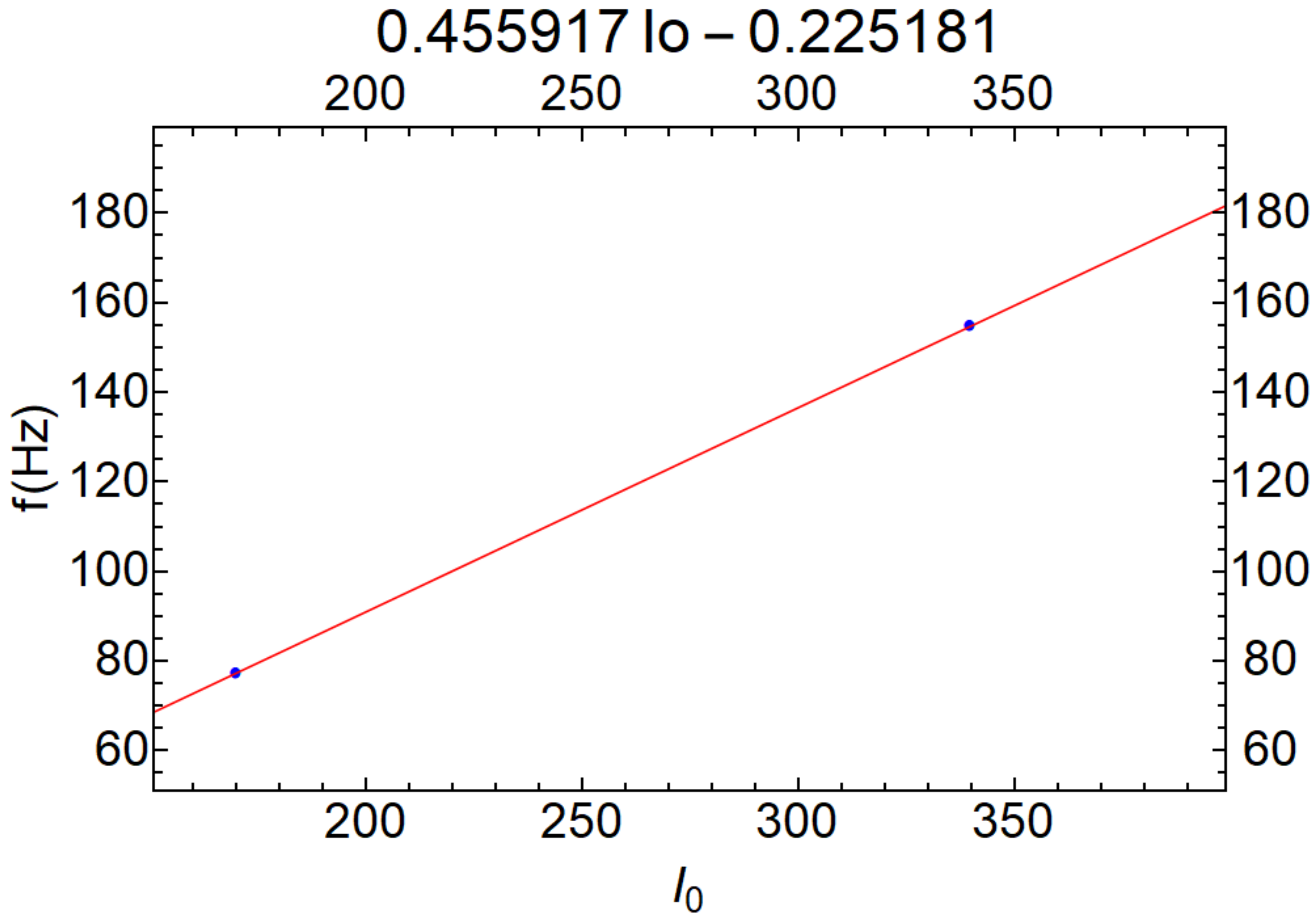
Once we ramp to ±20µT (max) and down to 0µT, do we any residual field?
This residual field must be <420nT. Using Hg co-magnetometer…:



We are interested in the average <B(I_0)> during storage.

What is the Magnetic Field Inside?

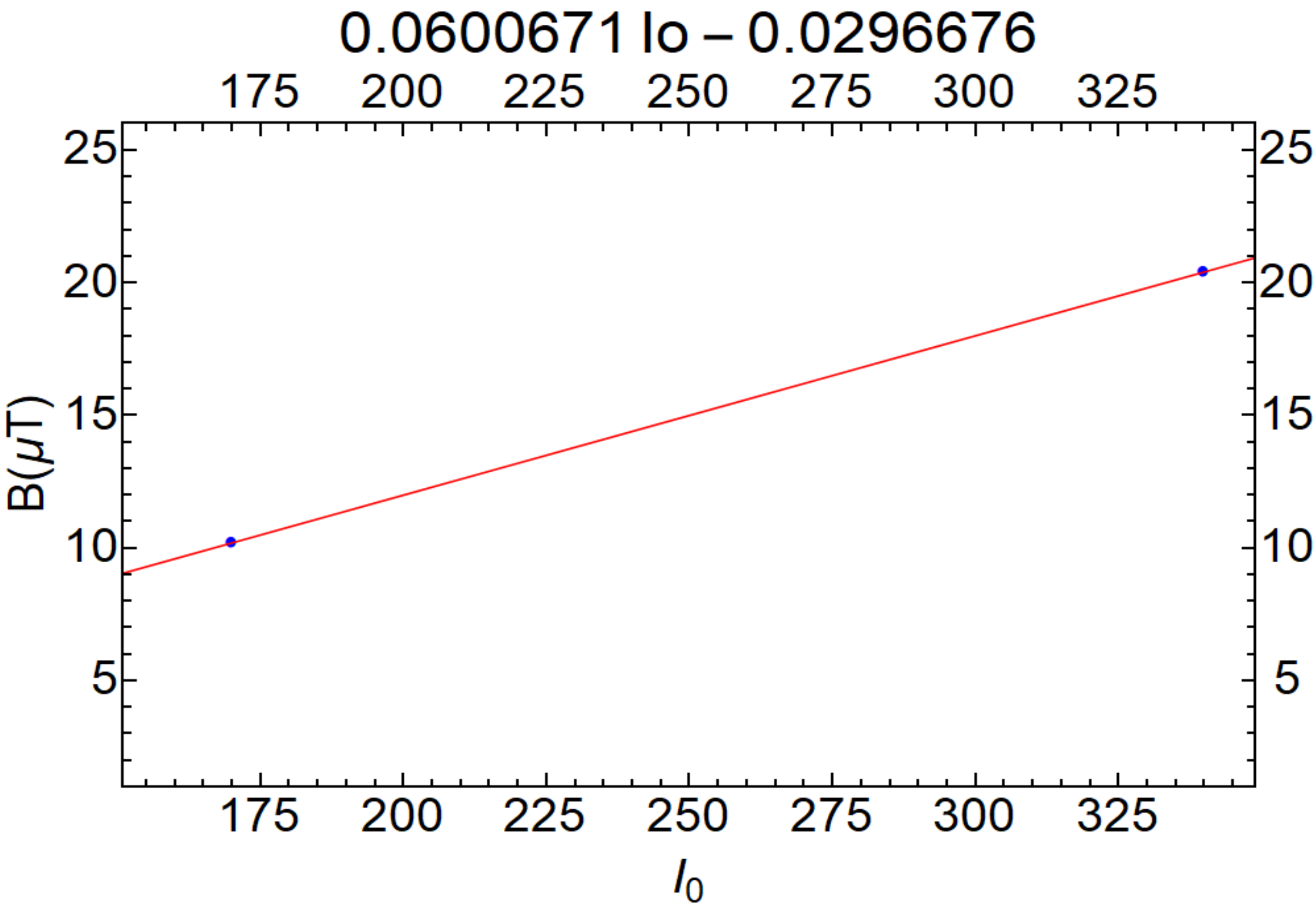
We used Hg-199 to measure the magnetic field in-situ.



$f(|I_0|)$ is obtained from Hg-fit, where I_0 is the input current read by the ammeter

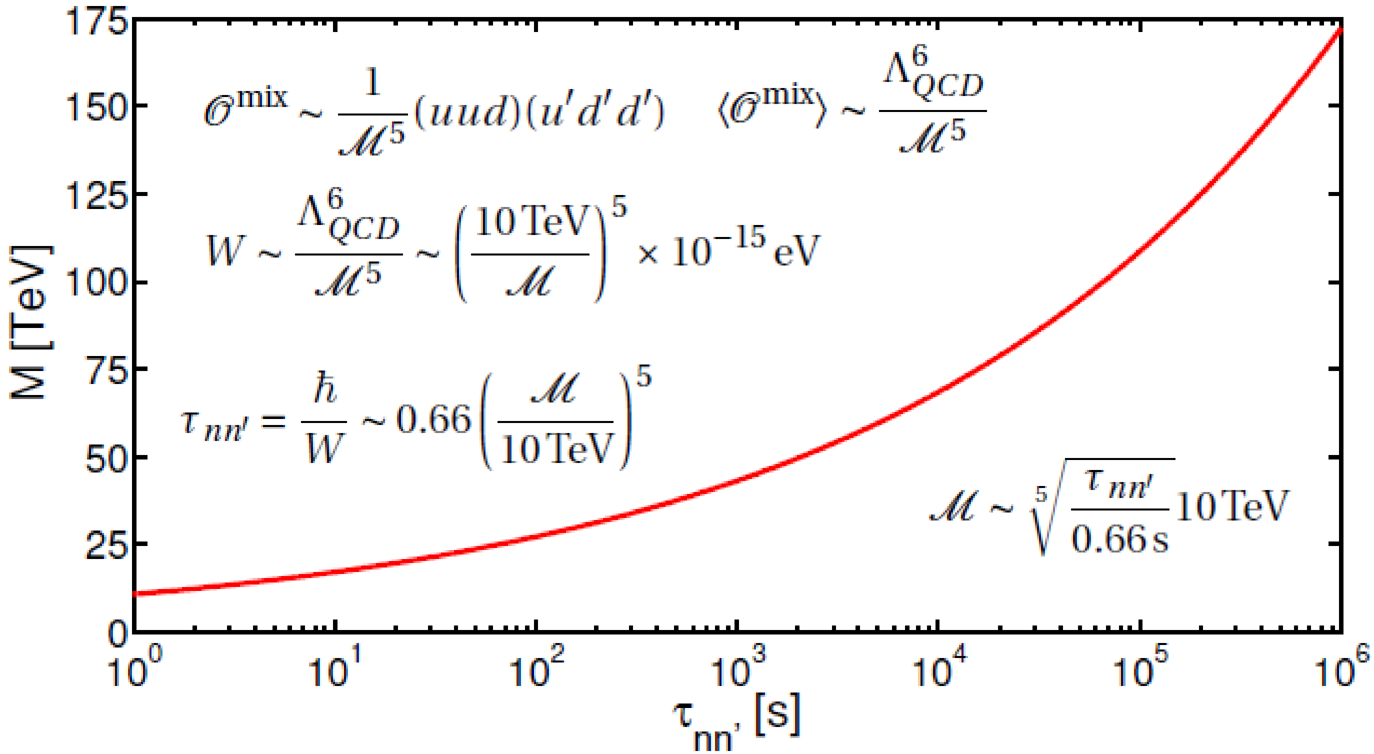
What is the Magnetic Field Inside?

We used Hg-199 to measure the magnetic field in-situ.



$B(I_0)=f(|I_0|)/\gamma_{Hg}$, where I_0 is the input current read by the ammeter

Effective mass scale from nn'



A. Knecht, PhD thesis, 2009, UZH

Figure A.5.: The figure shows the effective mass scale $\mathcal{M}$ corresponding to a given limit on the oscillation time $\tau_{nn'}$ as given in Eq. (A.48).

R. N. Mohapatra, S. Nasri and S. Nussinova, *Some implications of neutron mirror neutron oscillation*, Phys. Lett. B **627**, 124 (2005).

Z. Berezhiani and L. Bento, *Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?*, Phys. Rev. Lett. **96**, 081801 (2006).

Z. Berezhiani and L. Bento, *Fast neutron-mirror neutron oscillation and ultra high energy cosmic rays*, Phys. Lett. B **635**, 253 (2006).

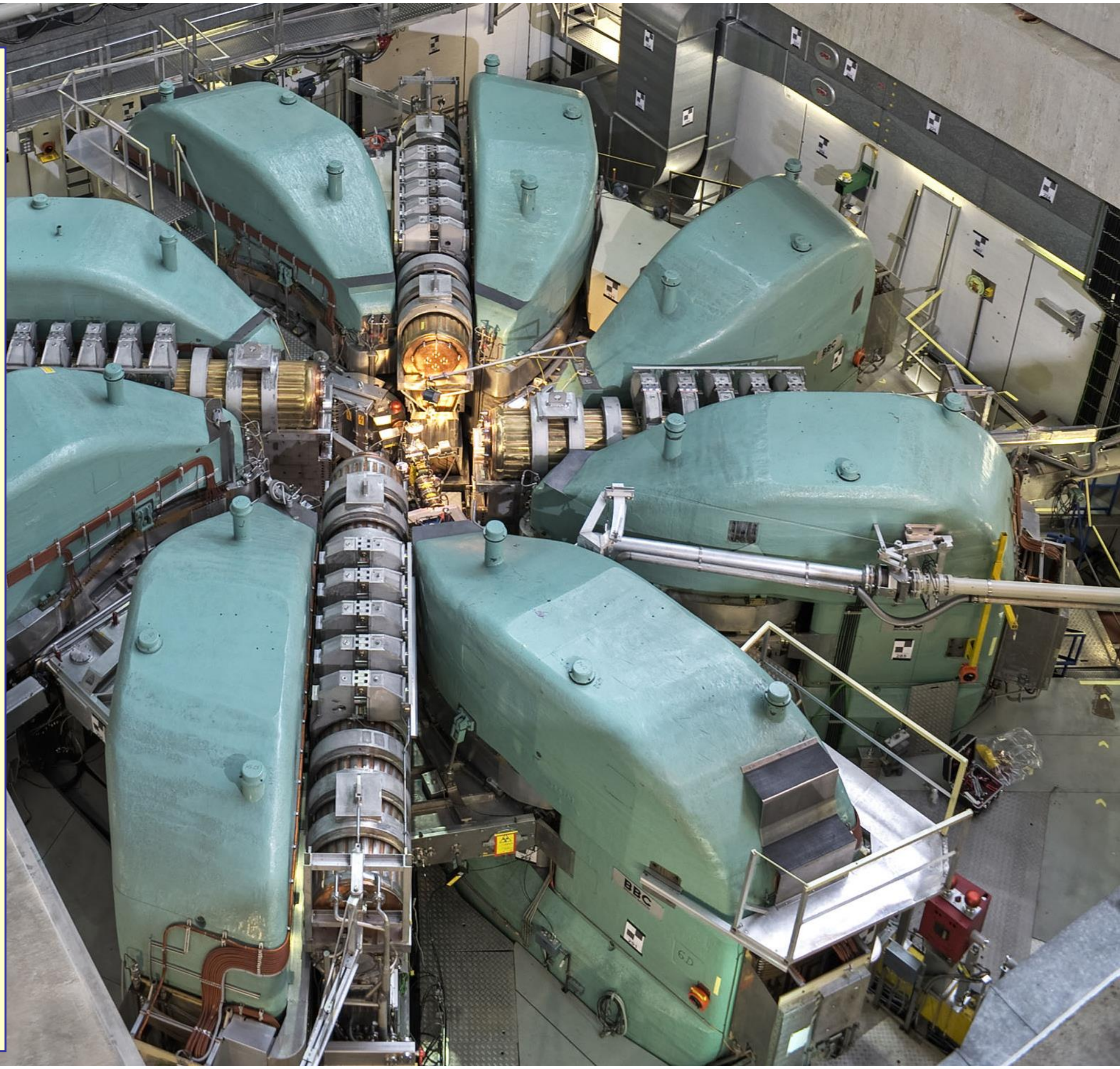
- nn' limits probe effective mass scale 10…100TeV
- Mass of exchange boson can be much lower

PSI ring cyclotron

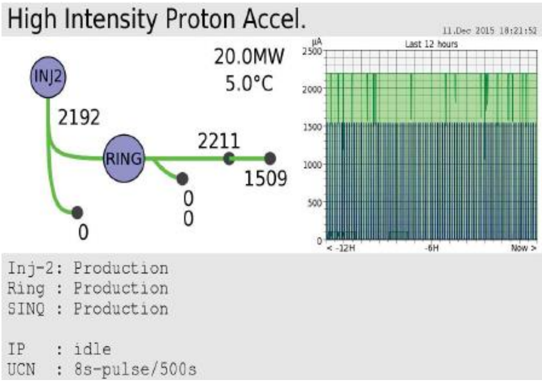
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

[losses $\propto$ (turn number)^3, W.Joho]

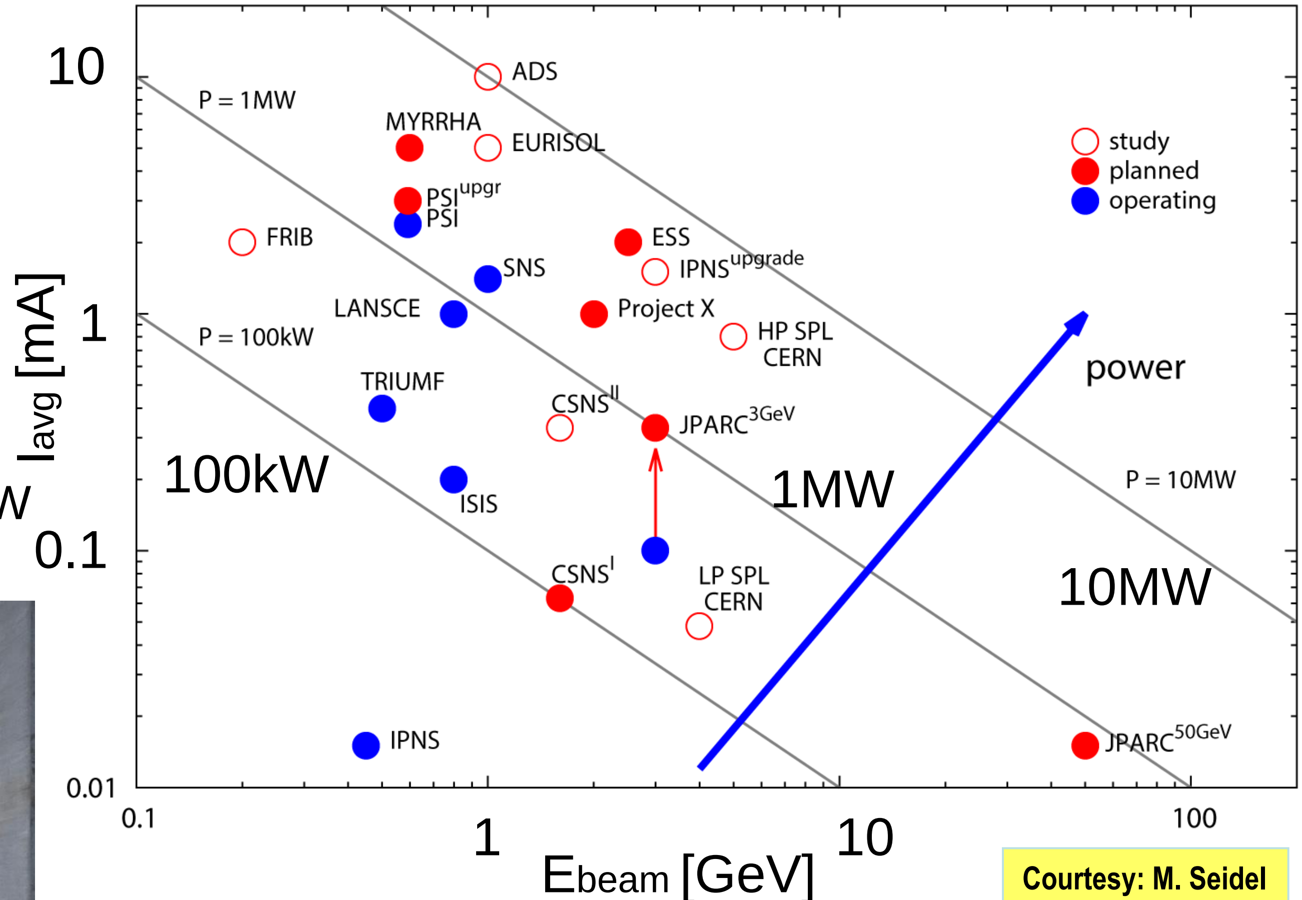
- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW

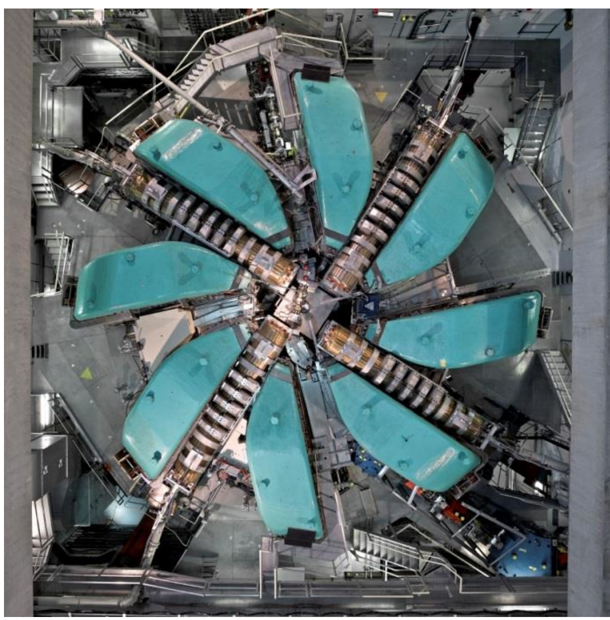


PSI ring cyclotron



The most powerful
proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW





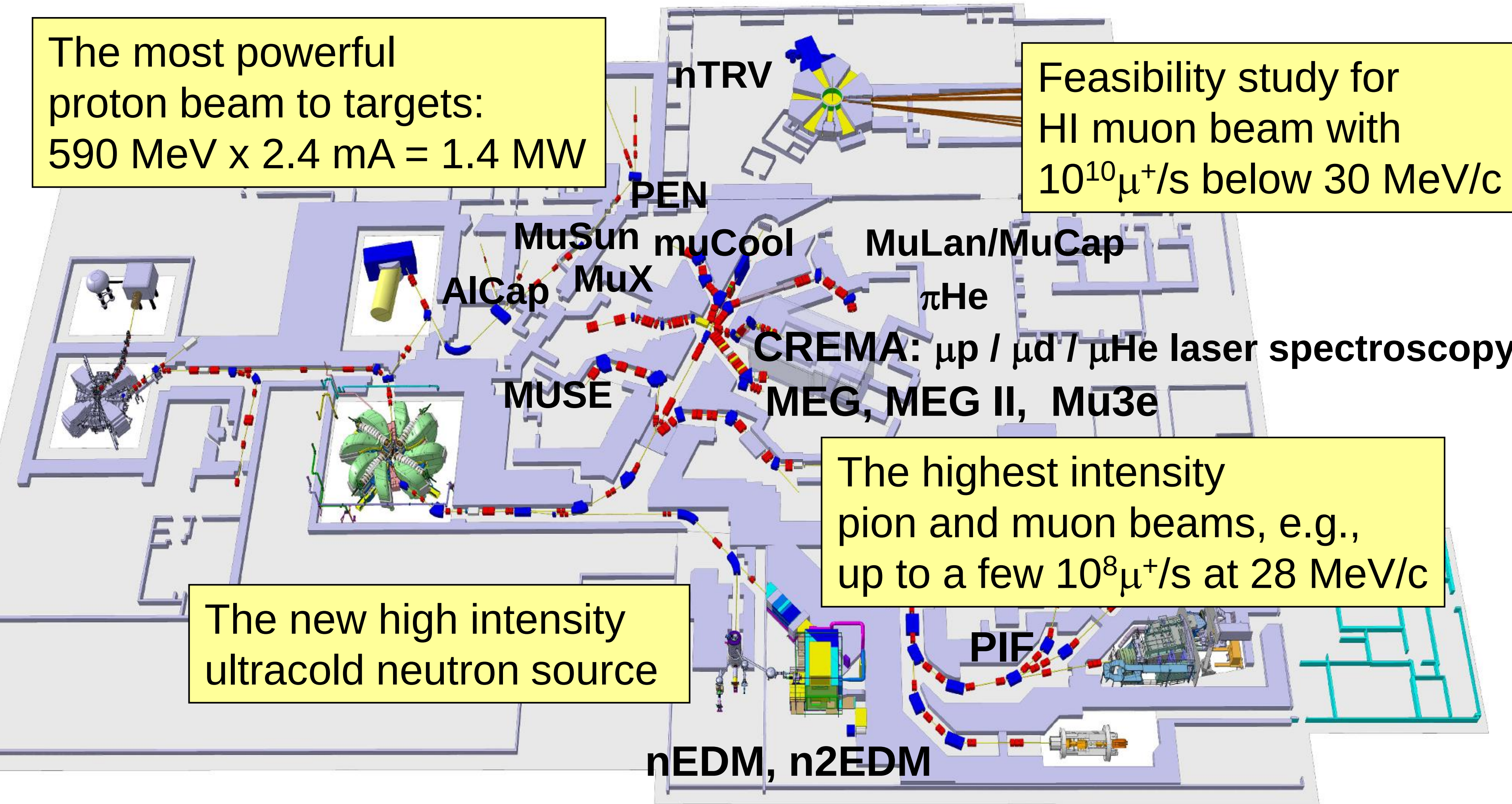
HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions at low momenta and of ultracold neutrons.

The intensity frontier at PSI: π, μ, UCN

Precision experiments with **the lightest unstable particles** of their kind

The most powerful
proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW

Feasibility study for
HI muon beam with
$10^{10}\mu^{+}$/s below 30 MeV/c



The highest intensity
pion and muon beams, e.g.,
up to a few $10^{8}\mu^{+}$/s at 28 MeV/c

The new high intensity
ultracold neutron source

Swiss national laboratory with <u>strong international collaborations</u>