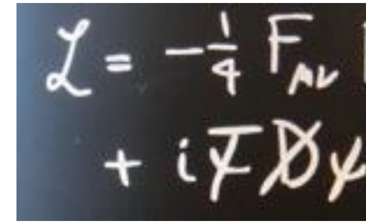
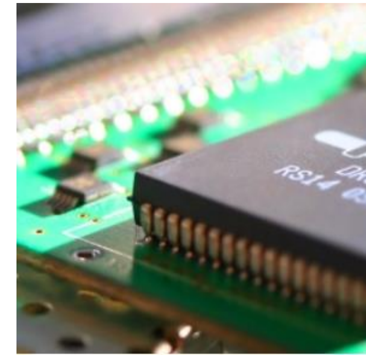
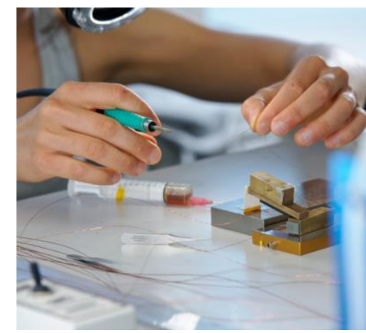
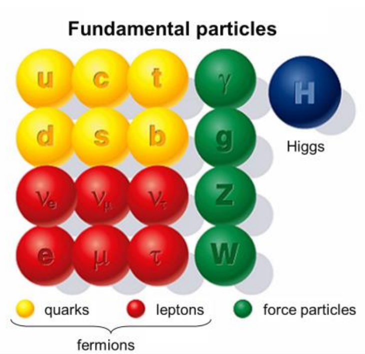
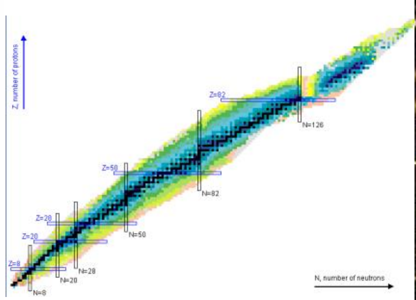
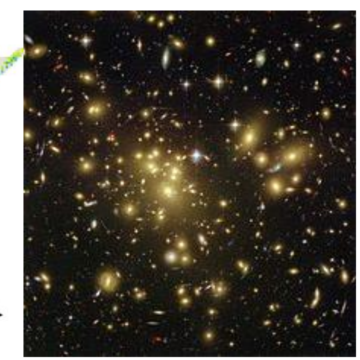
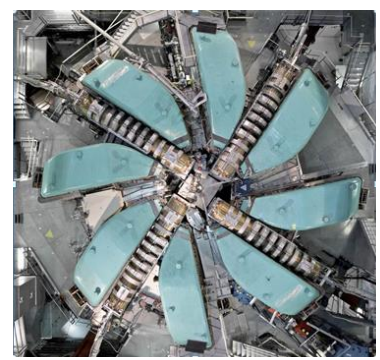
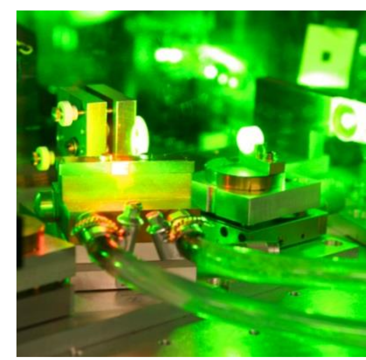
Analysis of the latest nn’ search at PSI

Nordita workshop
Particle Physics with neutrons at the ESS

K.Kirch, ETH Zurich – PSI Villigen, Switzerland
for the nEDM collaboration at PSI

nEDM@PSI

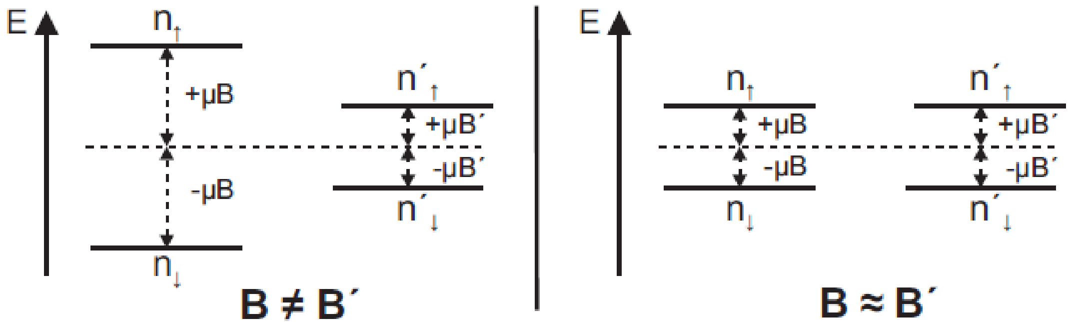
Our collaboration (50 people, 15 institutions, 7 countries) just finished nEDM and is assembling the n2EDM experiment aiming at an improvement in sensitivity by an order of magnitude.

nEDM collaboration in Berlin, Nov 2018

nEDM@PSI

Topic of this talk, nn’ is part of the PhD thesis of Prajwal Mohan Murthy (supervised by Geza Zsigmond, KK at PSI-ETHZ):

Search for nn' with possible B'



Disappearance Experiment: Look for B-field dependence of number of neutrons stored for time t_s

Ratio	Asymmetry

$$E_B(t_s) = \frac{n_0(t_s)}{n_B(t_s)} - 1 = \nu_s \Delta_B = \frac{t_s}{\langle t_f \rangle} \frac{\eta^2(3-\eta^2)}{2\omega'^2 \tau_{nn'}^2 (1-\eta^2)^2}$$

$$\nu_s = t_s / \langle t_f \rangle$$

$$\eta = B/B'$$

$$A_B(t_s) = \frac{n_B(t_s) - n_{-B}(t_s)}{n_B(t_s) + n_{-B}(t_s)} = -\nu_s D_B Cos(\beta) = -\frac{t_s}{\langle t_f \rangle} \frac{\eta^3 Cos\beta}{\omega^2 \tau_{nn'}^2 (1-\eta^2)^2}$$

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]
- Z. Berezhiani et al., EPJC78(2018)717: $\tau_{nn'}$>17s (95 % C.L.), 8<B′<17μT $\tau_{nn'}/\sqrt{\cos\beta}$>27s (95 % C.L.), 6<B′<25μT

- nEDM@PSI (2017/18) 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 et al., see also Berezhiani et al., PRD96(2017)035039 B′≠0 [ORNL(HFIR)]

Our previous B' result (PRD80, 2009)

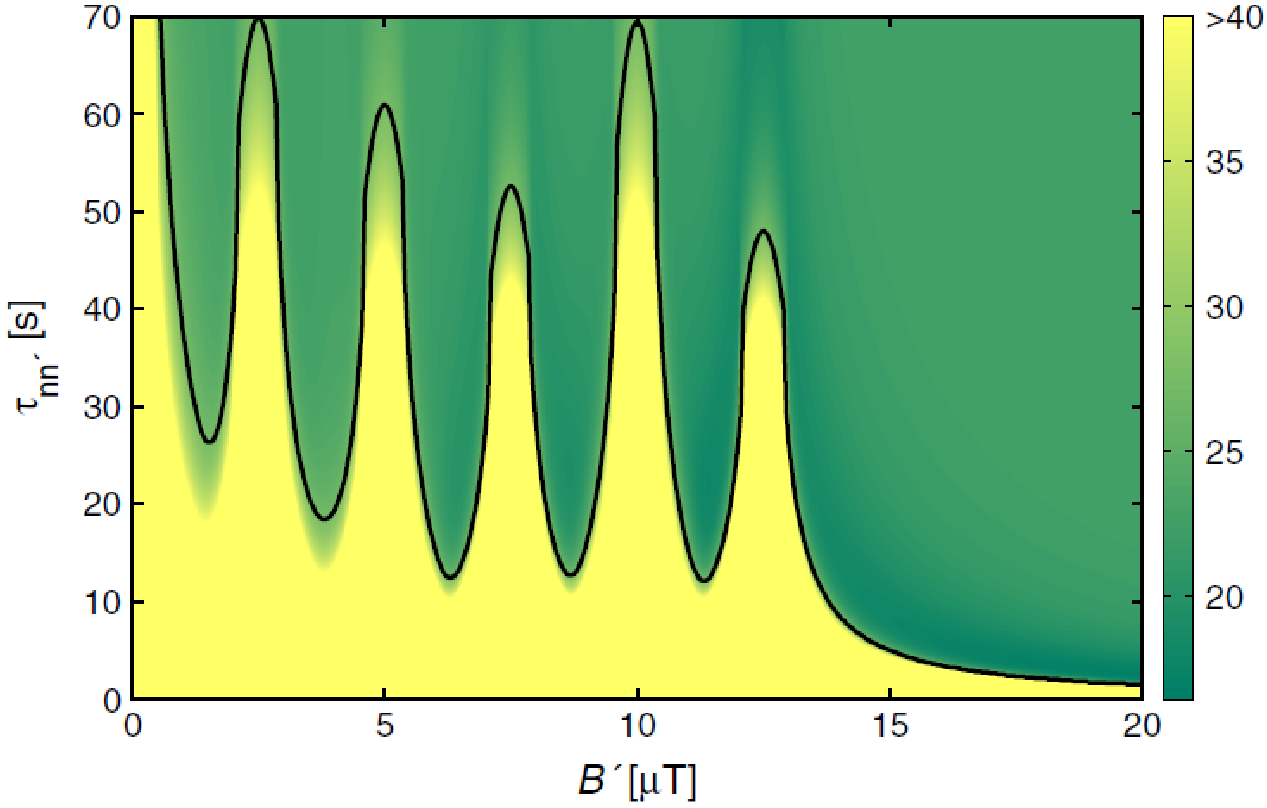


FIG. 2 (color online). Contour plot of the minimal χ^2 at the point $(B', \tau_{nn'})$. The solid line denotes the 95% C.L. contour line for an exclusion of $\tau_{nn'}$. We evaluated a lower limit on $\tau_{nn'}$ at the minimum of this contour for B' between 0 and 12.5 μT.

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]

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[2]INFN, Laboratori Nazionali Gran Sasso, 67010 Assergi, L'Aquila, Italy

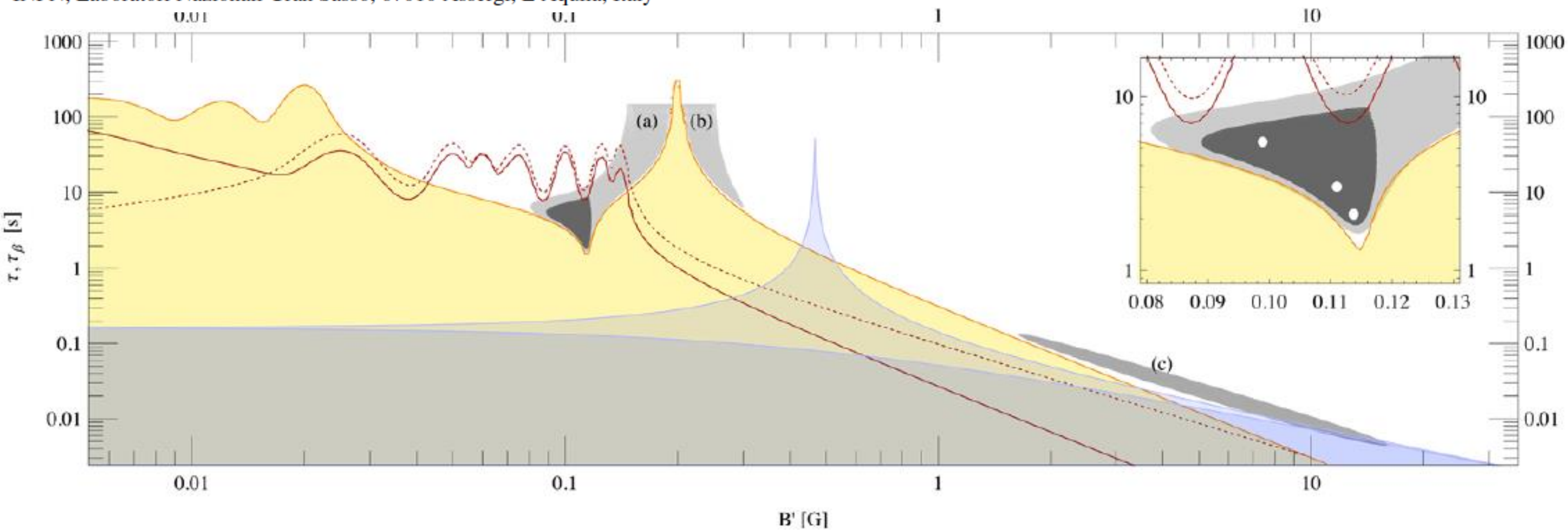


Fig. 2 Global fit in the B'-τ, τ_β plane. The positive result (anomaly) corresponds to the *gray-shaded areas*, which show the parameter space allowed at 90 % CL (*darker*) and 99 % CL (*lighter*) by the global fit of non-zero $\overline{D}_B$, (6), with magnetic field marginalized over the uncertain 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_{Earth} parallel (*lighter blue*) and antiparallel (*darker blue*) (Color figure online)

Our previous result (PRD80, 2009)

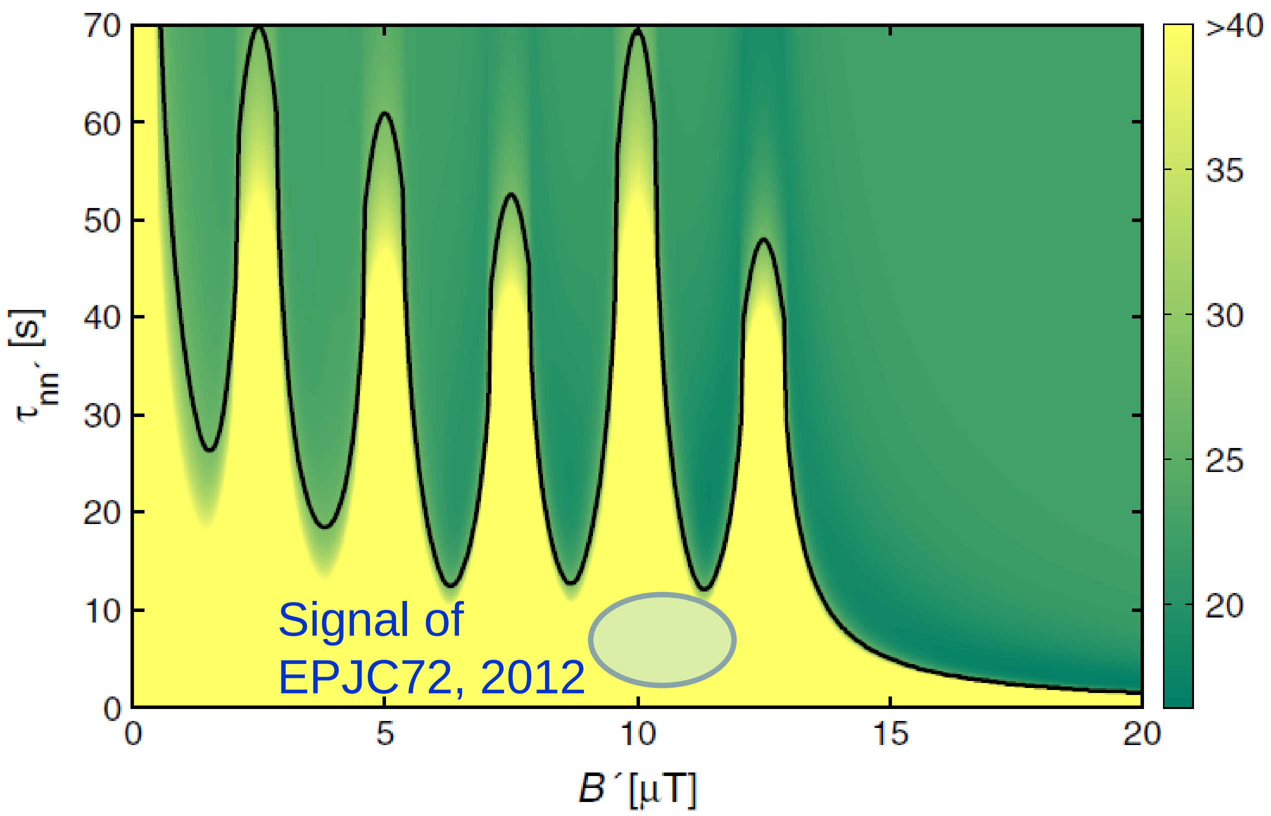
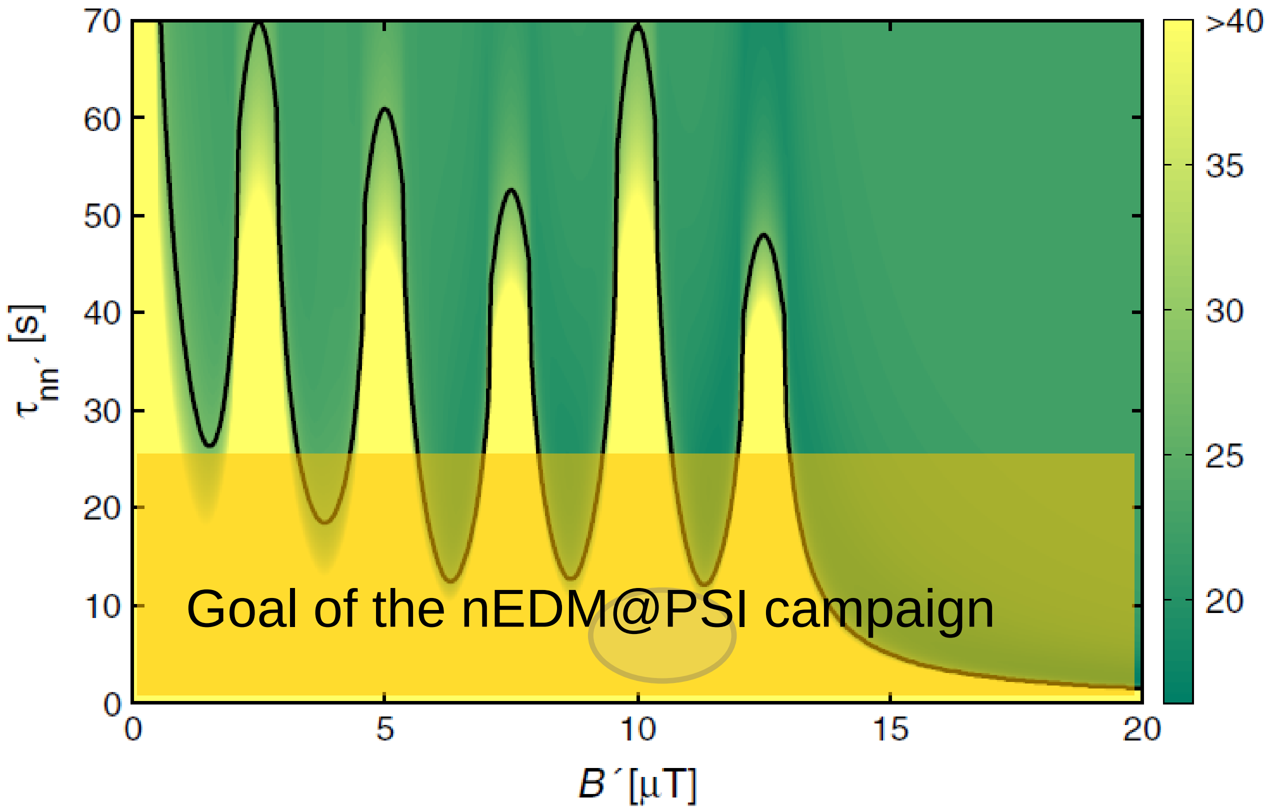


FIG. 2 (color online). Contour plot of the minimal χ^2 at the point $(B', \tau_{nn'})$. The solid line denotes the 95% C.L. contour line for an exclusion of $\tau_{nn'}$. We evaluated a lower limit on $\tau_{nn'}$ at the minimum of this contour for B' between 0 and 12.5 μT.

Our previous result (PRD80, 2009)



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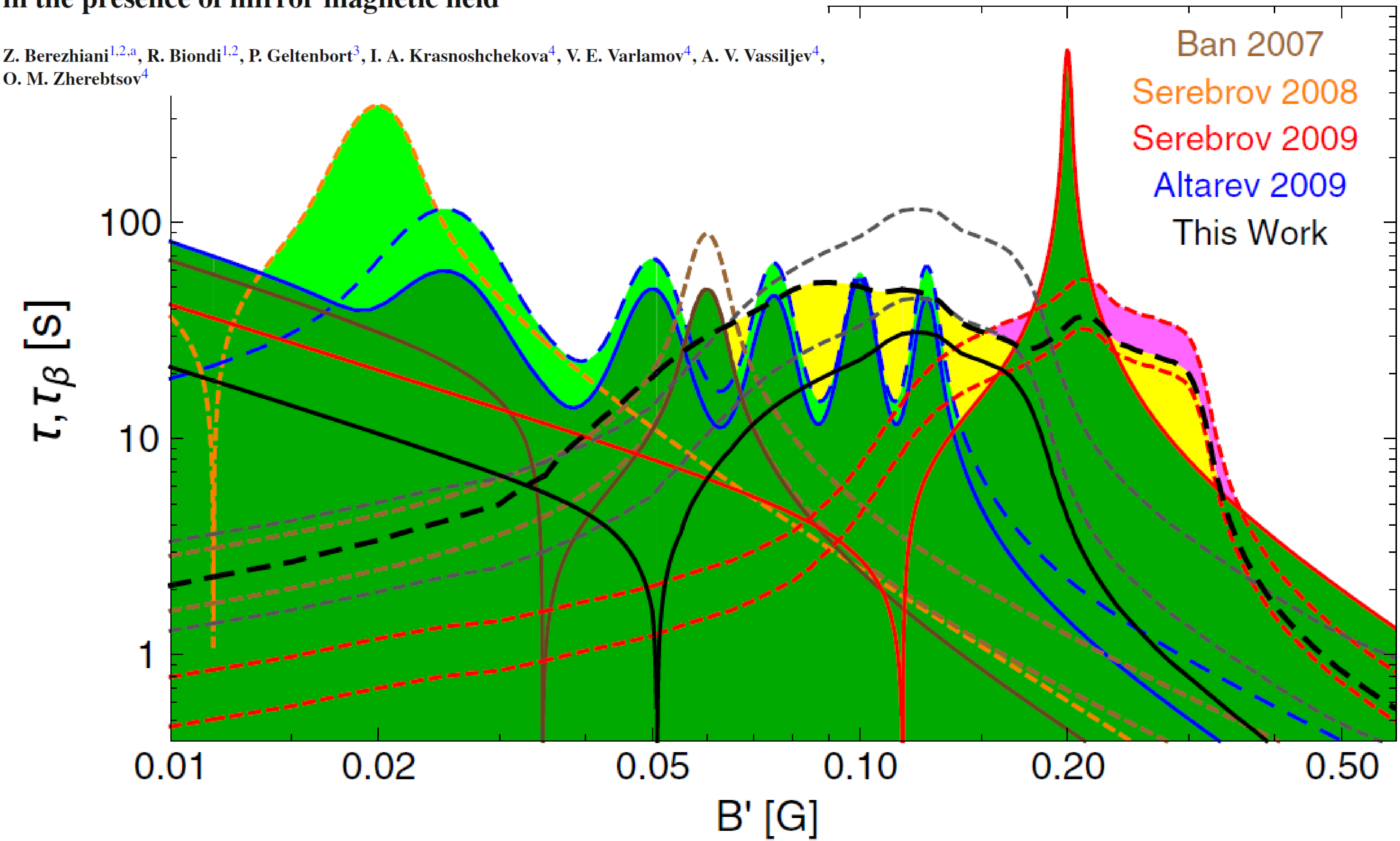
https://doi.org/10.1140/epjc/s10052-018-6189-y

THE EUROPEAN PHYSICAL JOURNAL C

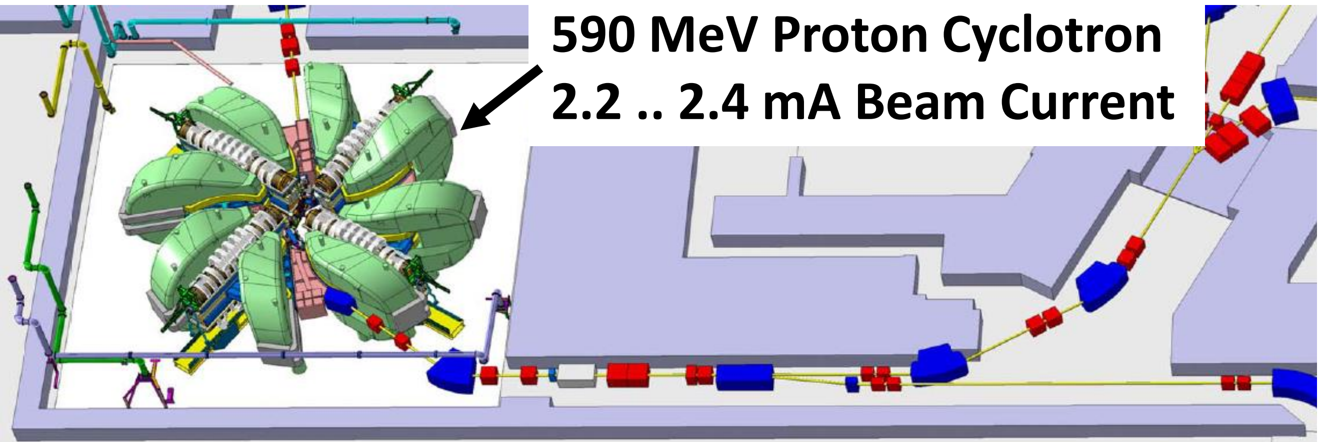
Regular Article - Experimental Physics

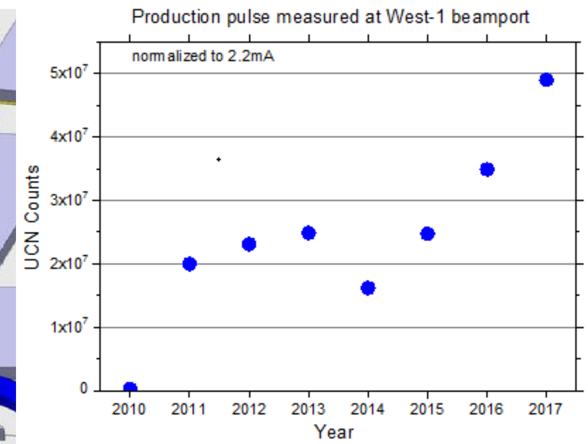
New experimental limits on neutron – mirror neutron oscillations in the presence of mirror magnetic field

Z. Berezhiani[1,2,a], R. Biondi[1,2], P. Geltenbort[3], I. A. Krasnoshchekova[4], V. E. Varlamov[4], A. V. Vassiljev[4], O. M. Zherebtsov[4]

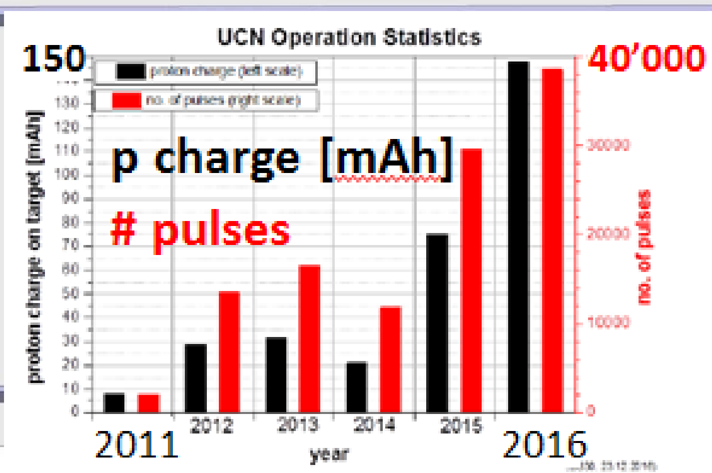


Ultracold Neutron Source & Facility





Excellent performance of HIPA
and regular beam delivery to UCN



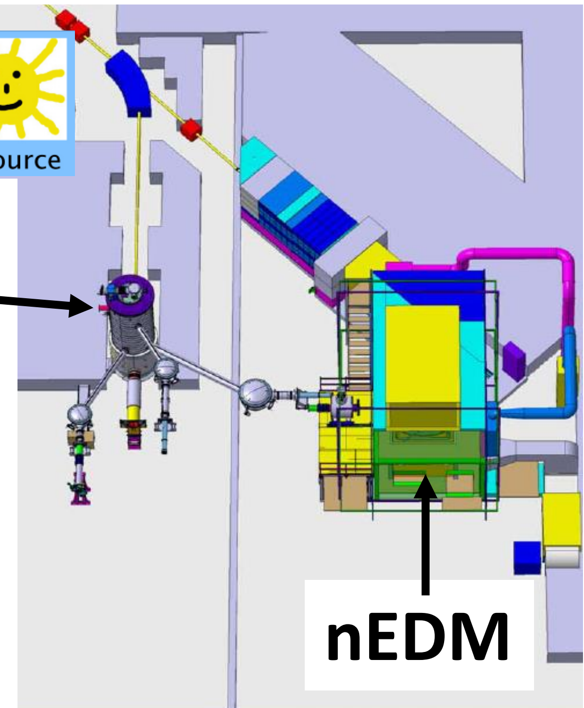
Ultra Cold Neutron Source

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)

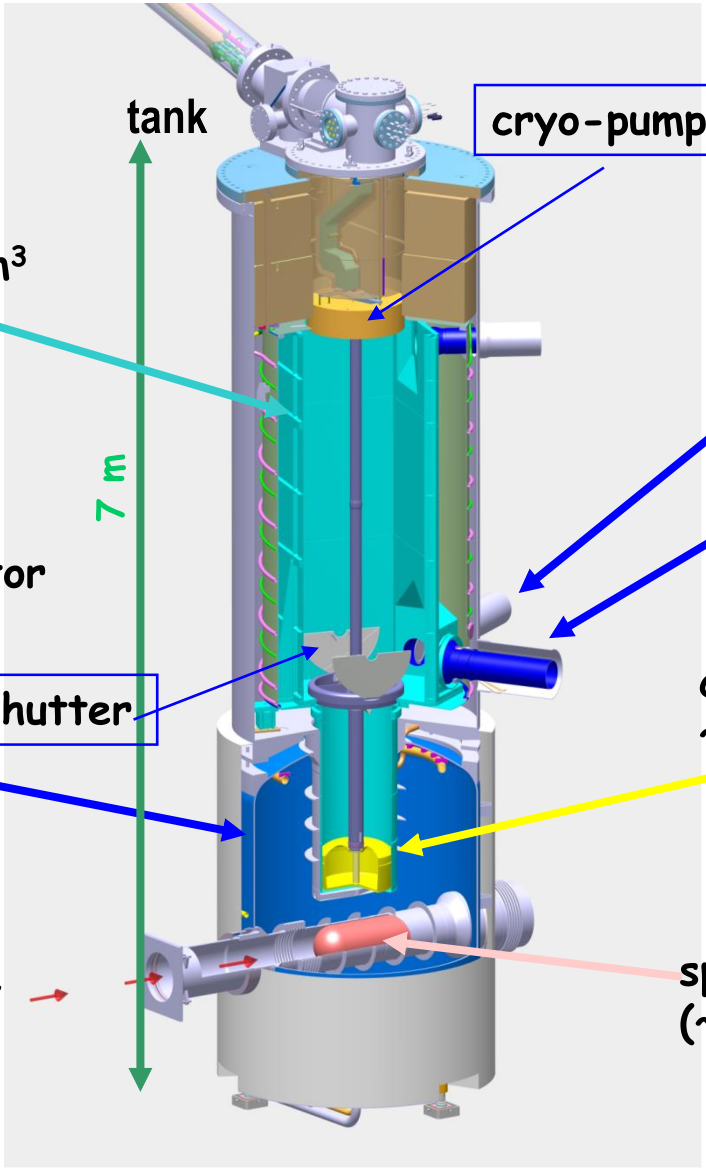


The PSI UCN source

Ultra Cold Neutron Source

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

cryo-pump



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

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

SV-shutter

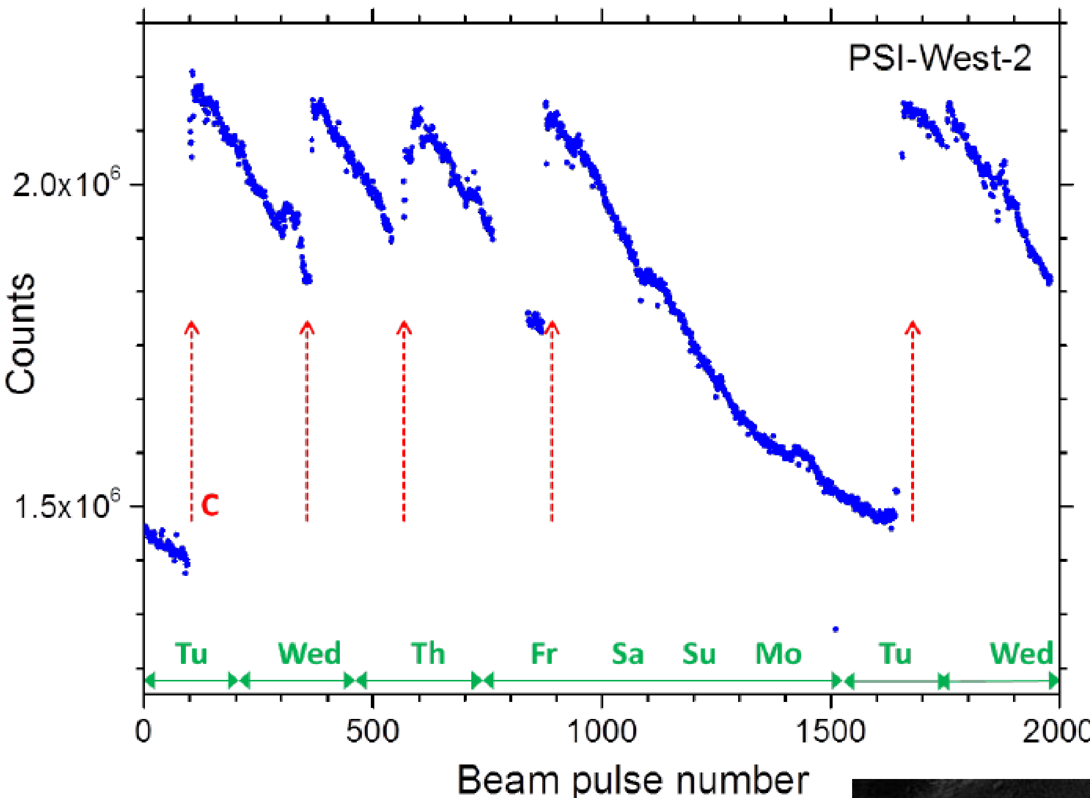
cold UCN-converter
~30 dm^3 solid D_2 at 5 K

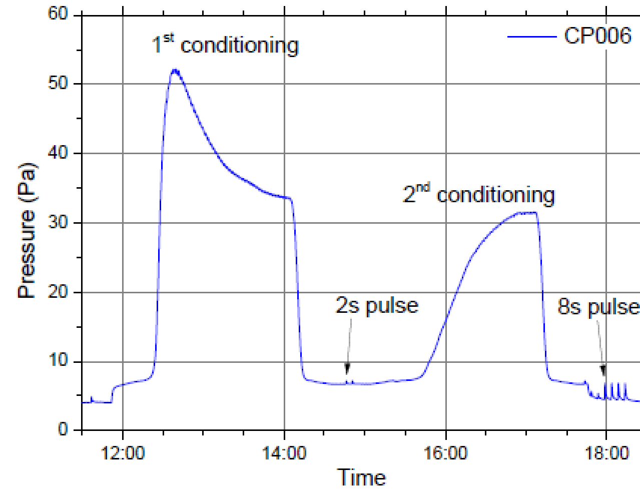
pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% duty cycle

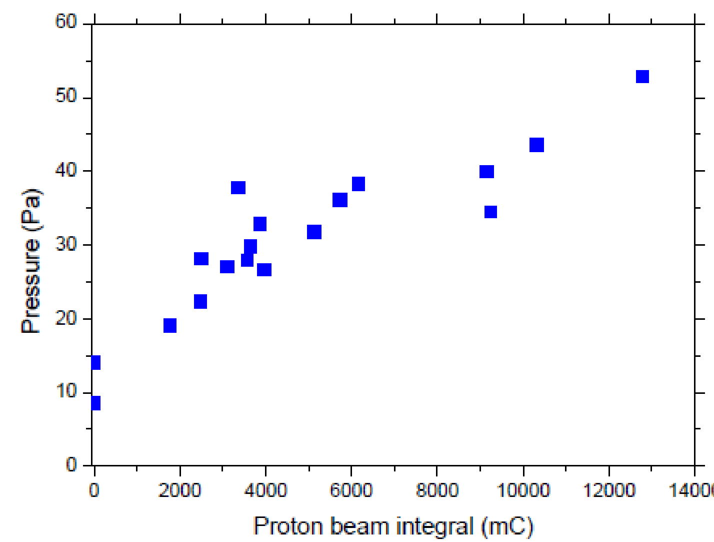
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

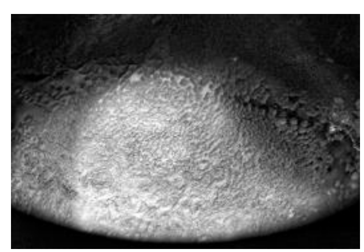
Solid D_2 issues

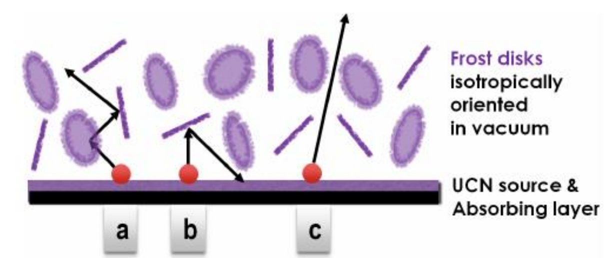
Growing frost on the surface during operation





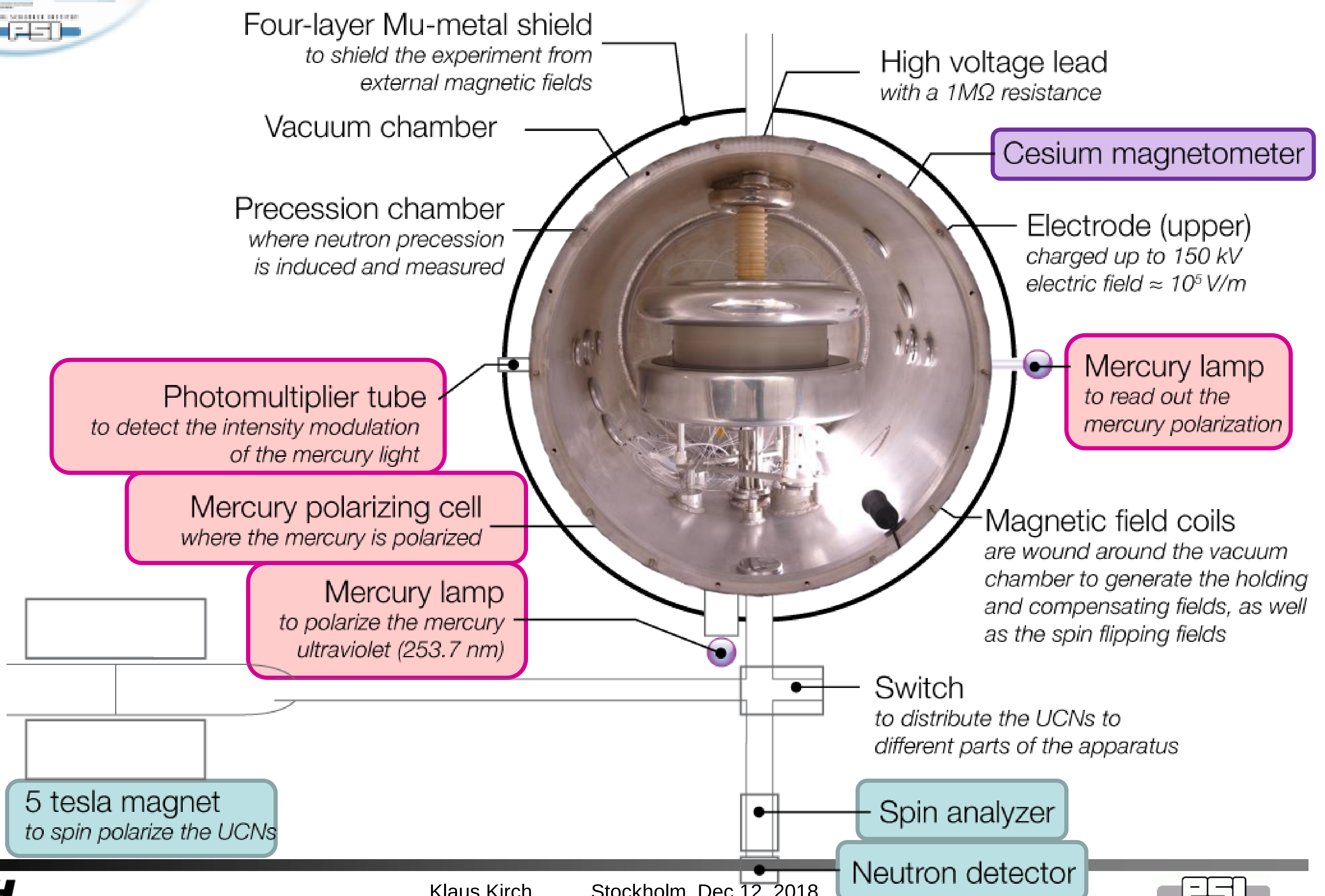




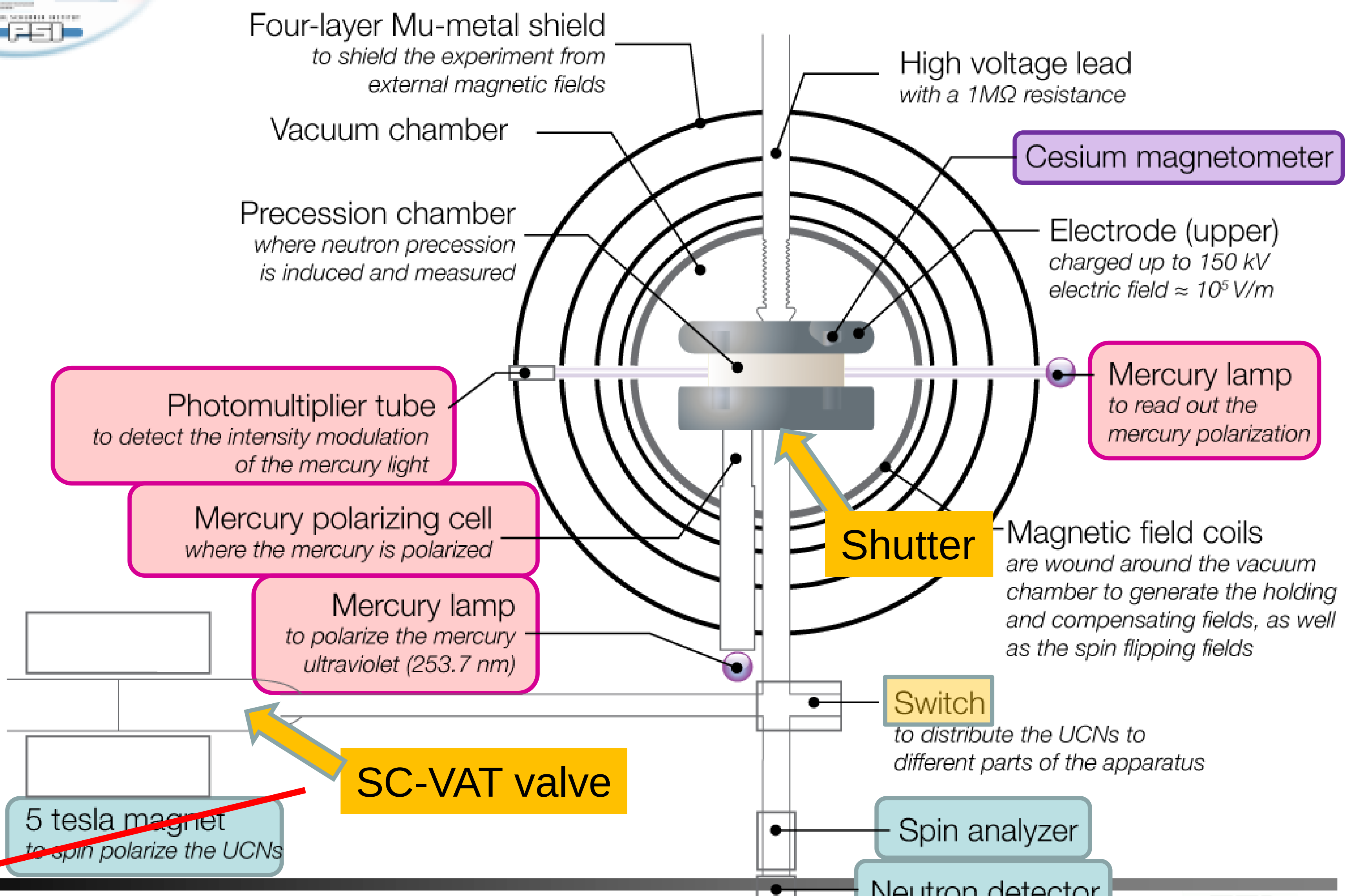


A. Anghel et al. EPJA54(2018)148

The nEDM spectrometer

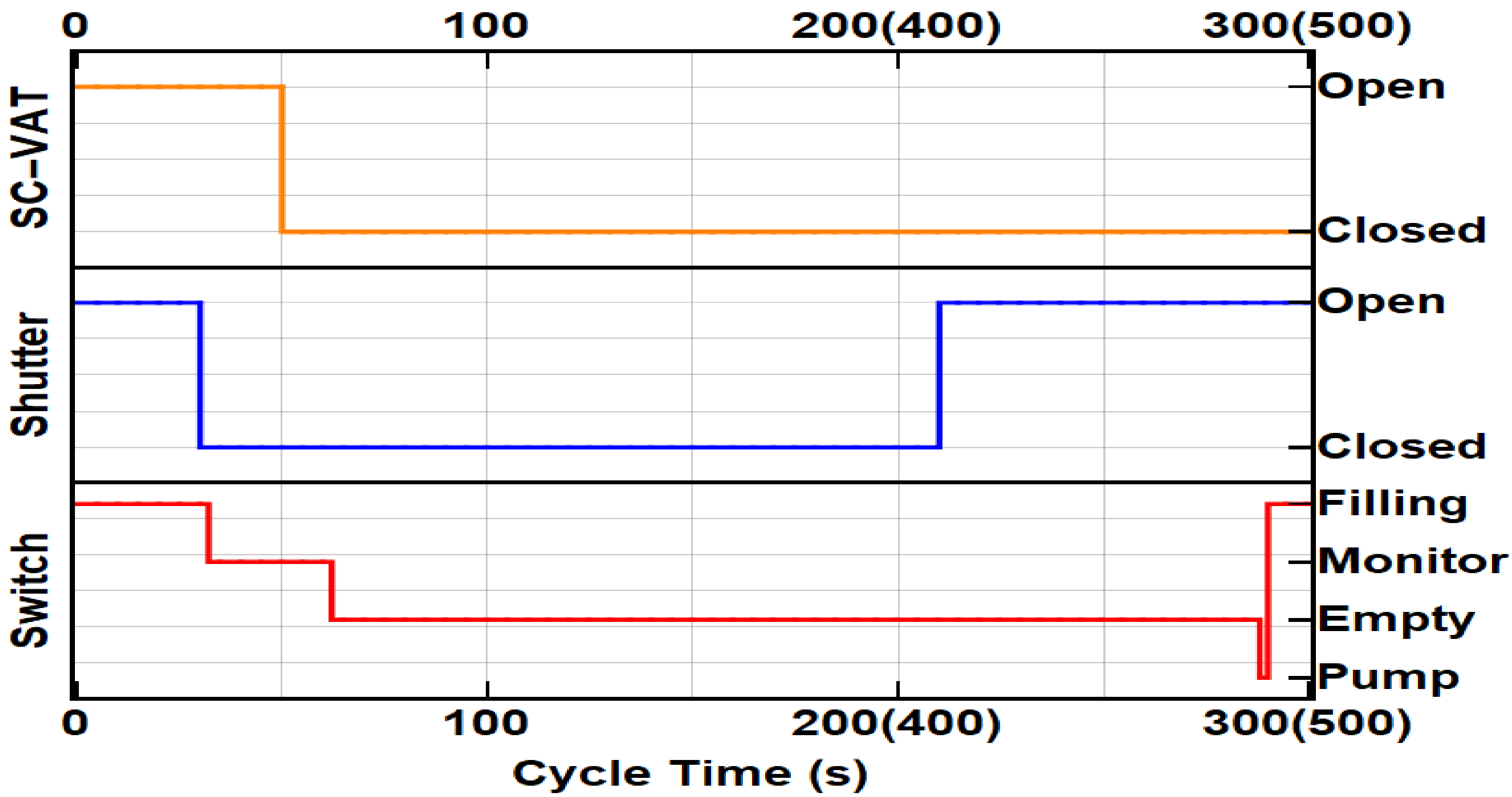


The nEDM spectrometer



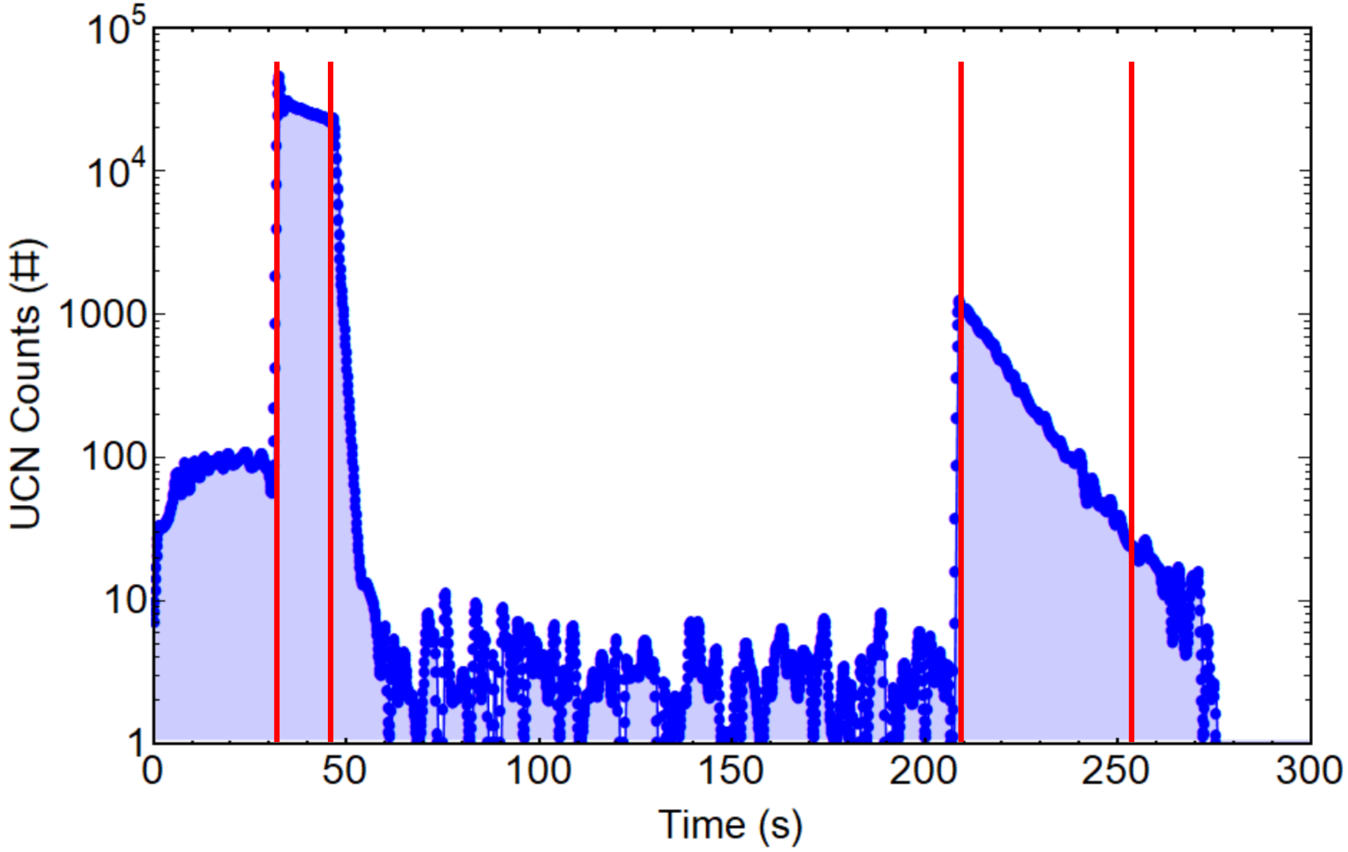
nn’ cycles

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

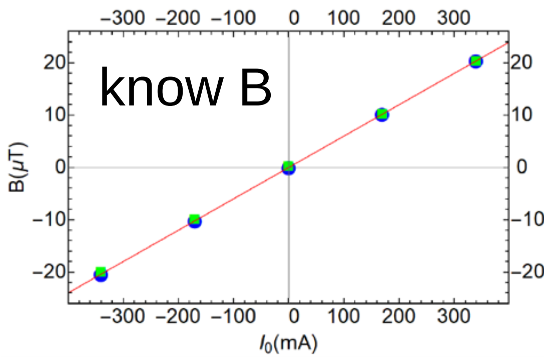


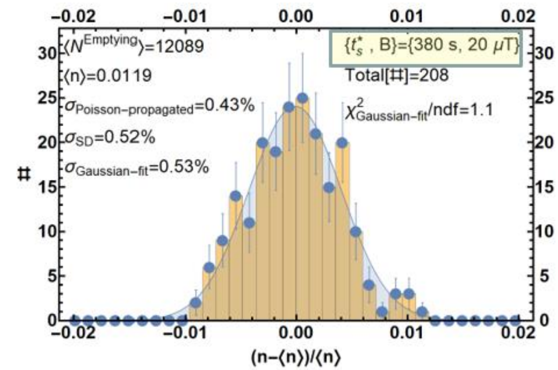
UCN counting

Cuts for monitoring and emptying



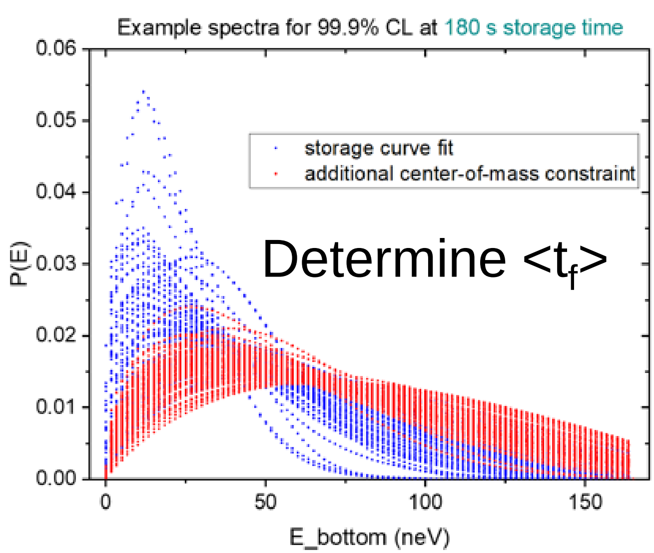
Determining nn’ from A

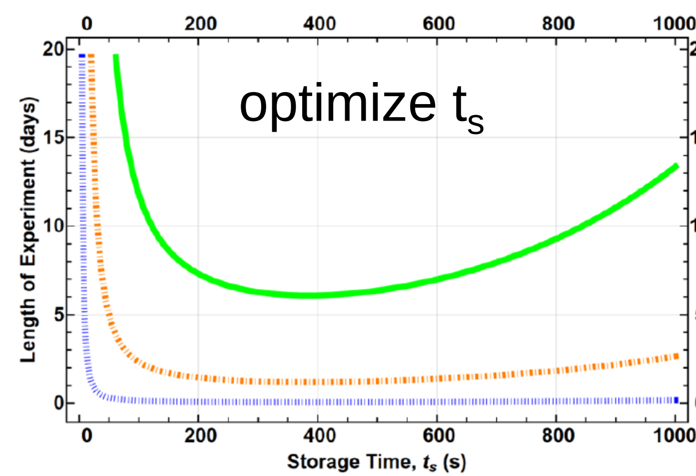




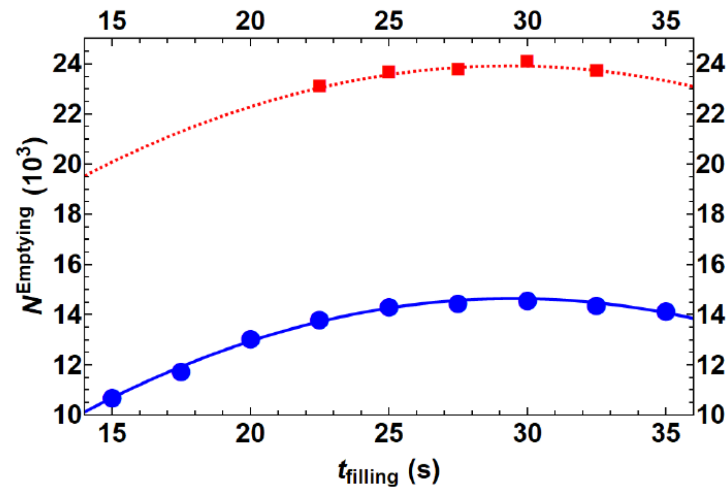
normalize counts

$$A_B\,(t_s) = \frac{n_B(t_s) - n_{-B}(t_s)}{n_B(t_s) + n_{-B}(t_s)}$$
$$= -\nu_s D_B Cos(\beta)$$
$$= -\frac{t_s}{\langle t_f \rangle} \frac{\eta^3 Cos\beta}{\omega^2 \tau_{nn'}^2 (1-\eta^2)^2}$$

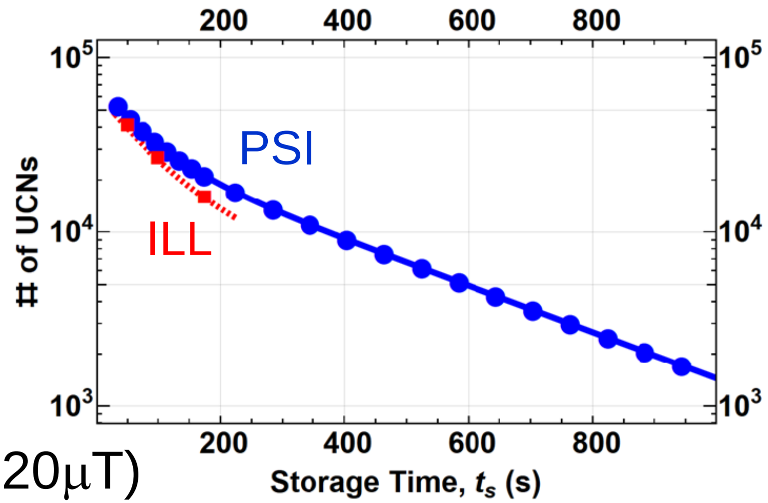




Support measurements



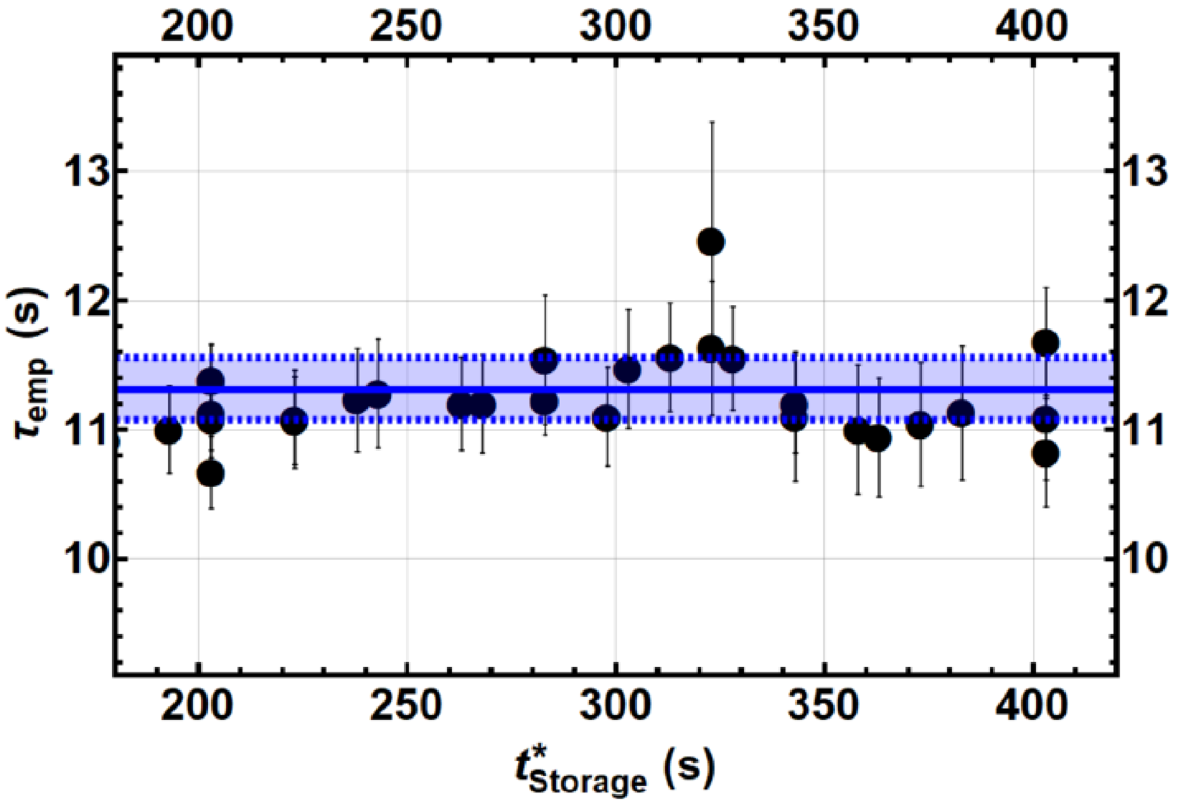
- Optimize filling and counting time
  - found 29s filling and used 75s counting
- Optimize storage time
  - Worked at 180s and 380s with cycle lengths between proton pulses to UCN source of 300s and 500s, respectively
  - Determine effective storage time (longer by roughly 2x11s due to possible nn' 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 (0, 10, 20μT)



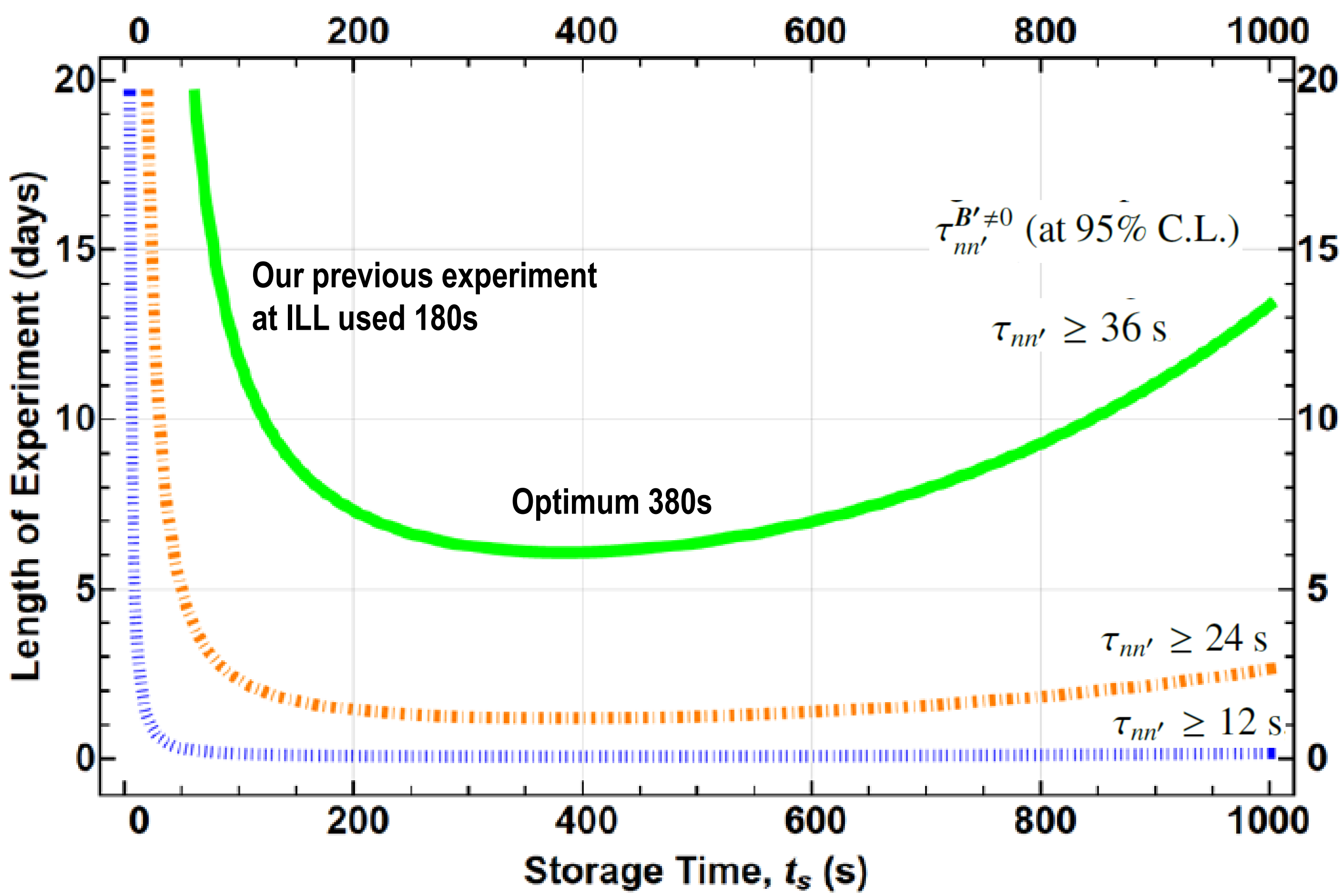
Emptying time constants

- no dependence on storage time found

$$t_s \quad = \quad t_s^* + 2\tau_{\text{emp}}$$



Optimize storage time



Magnetic field in nn' search

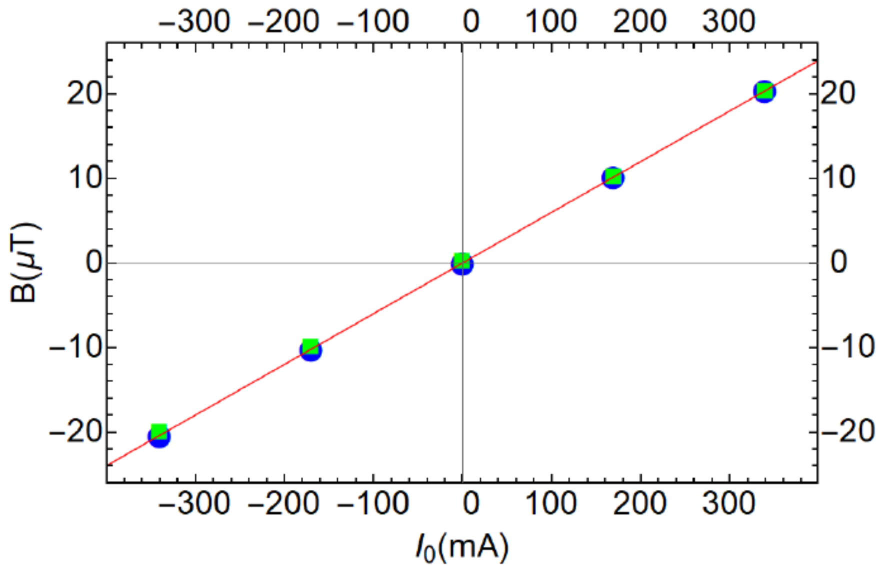


Figure 5. Plot showing the B_0 magnetic field measured by ^{199}Hg (indicated by blue dots) and ^{133}Cs (indicated by green squares) magnetometers as a function of B_0 coil current.

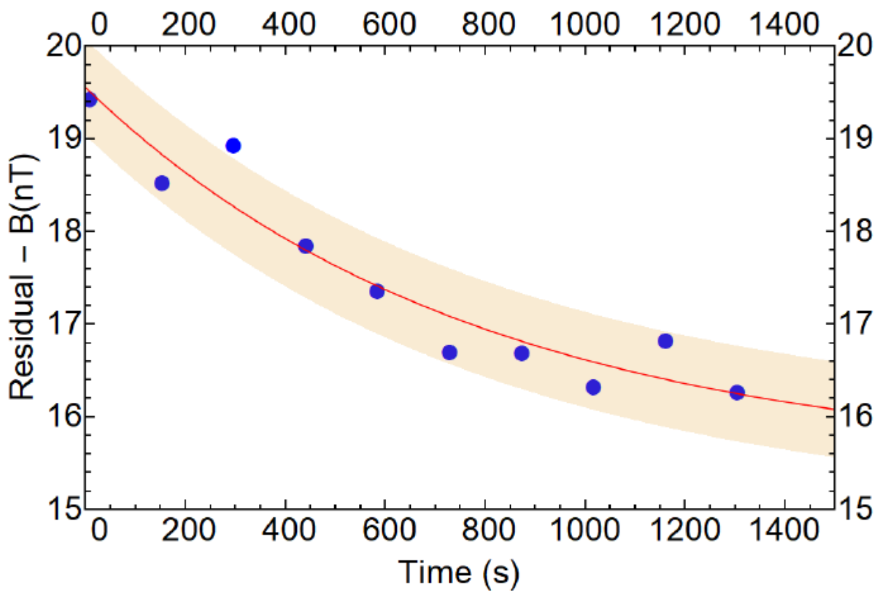


Figure 6. Decay in the magnitude of B_0 magnetic field when the current through the B_0 coil is turned off, as measured by the ^{199}Hg magnetometer. The line and the shaded region indicate an exponential decay fit and its 1σ uncertainty, respectively.

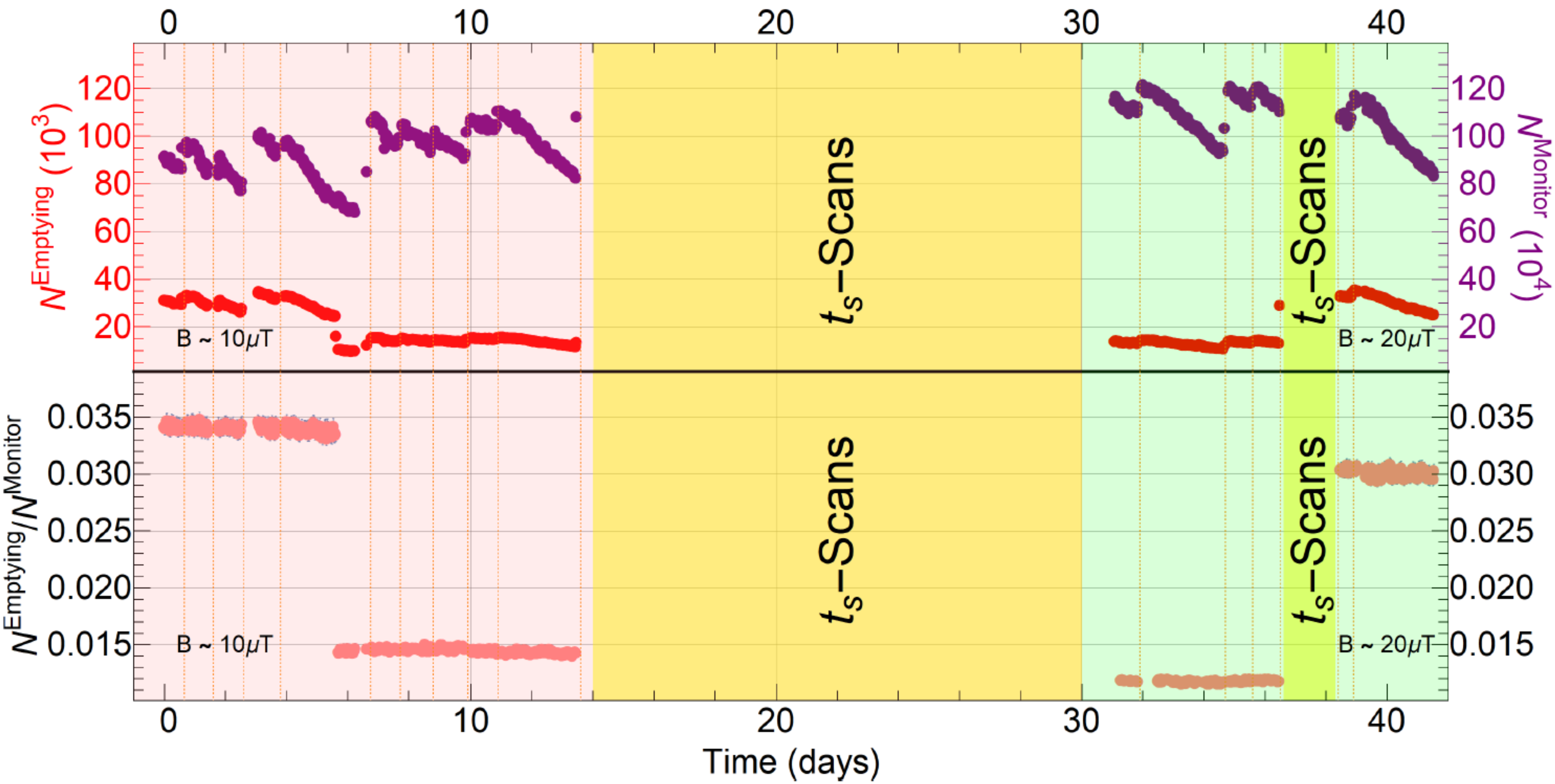
nn’ data collection

We took data Aug-Oct 2017.

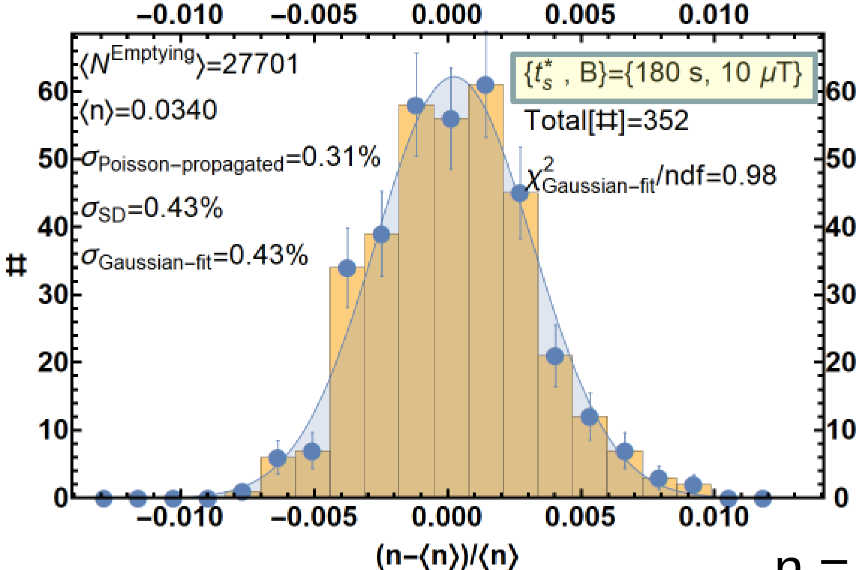
Cluster	Pattern	t^*_s (t_t) /s	B_0 /μT	# Cycles
1	**0↑0↓0↓0↑0↓0↑0↑0↓0**	**180 (300)**	**10**	**1243**
2	**0↑0↓0↓0↑0↓0↑0↑0↓0**	**380 (500)**	**10**	**1136**
3	**0↑0↓0↓0↑0↓0↑0↑0↓0**	**180 (300)**	**20**	**864**
4	**0↑0↓0↓0↑0↓0↑0↑0↓0**	**380 (500)**	**20**	**775**

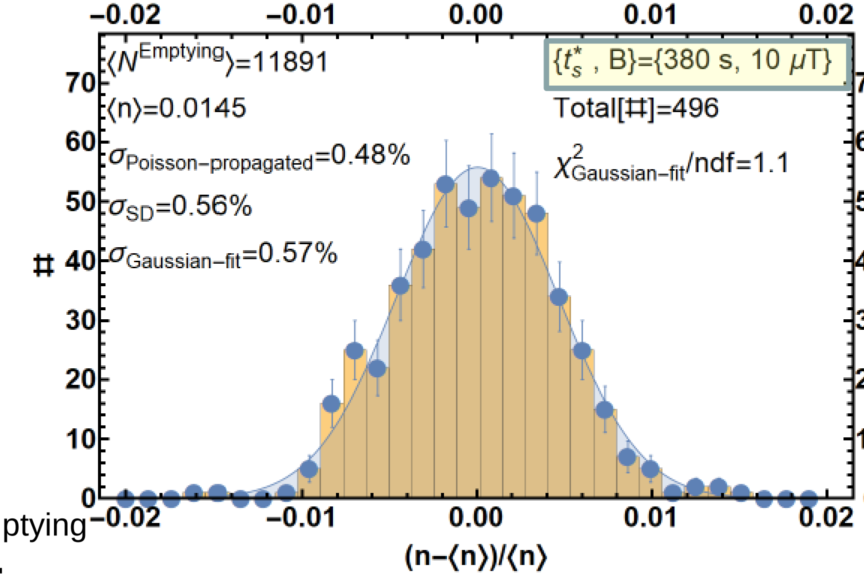
- There was a break in between 10 and 20μT cycles for a different physics measurement
- The data was collected such that the potential signal could be confirmed (or rejected) with just 10μT data and on addition of 20μT data also at 150μT … 1.5mT could exclude τ below 1.5 … 0.15s
- In addition to the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

nn’ data taking

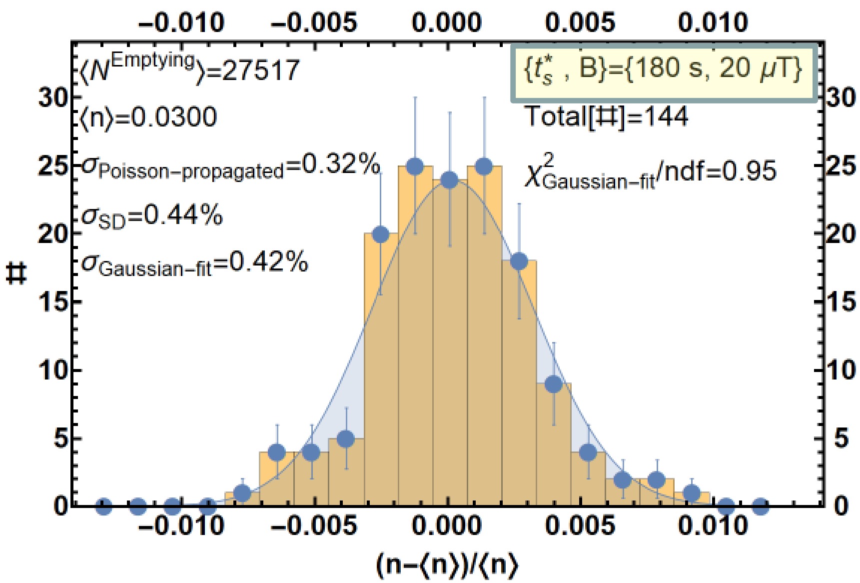


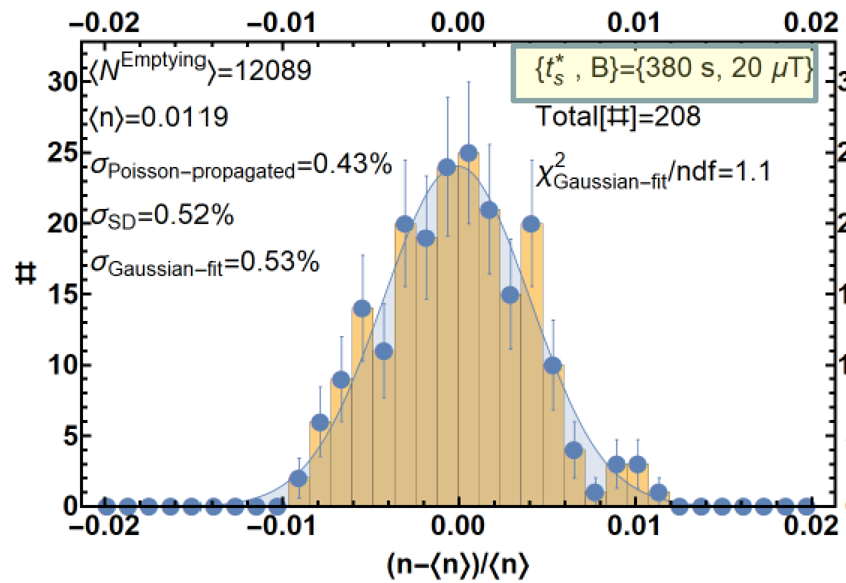
Normalization to UCN monitor



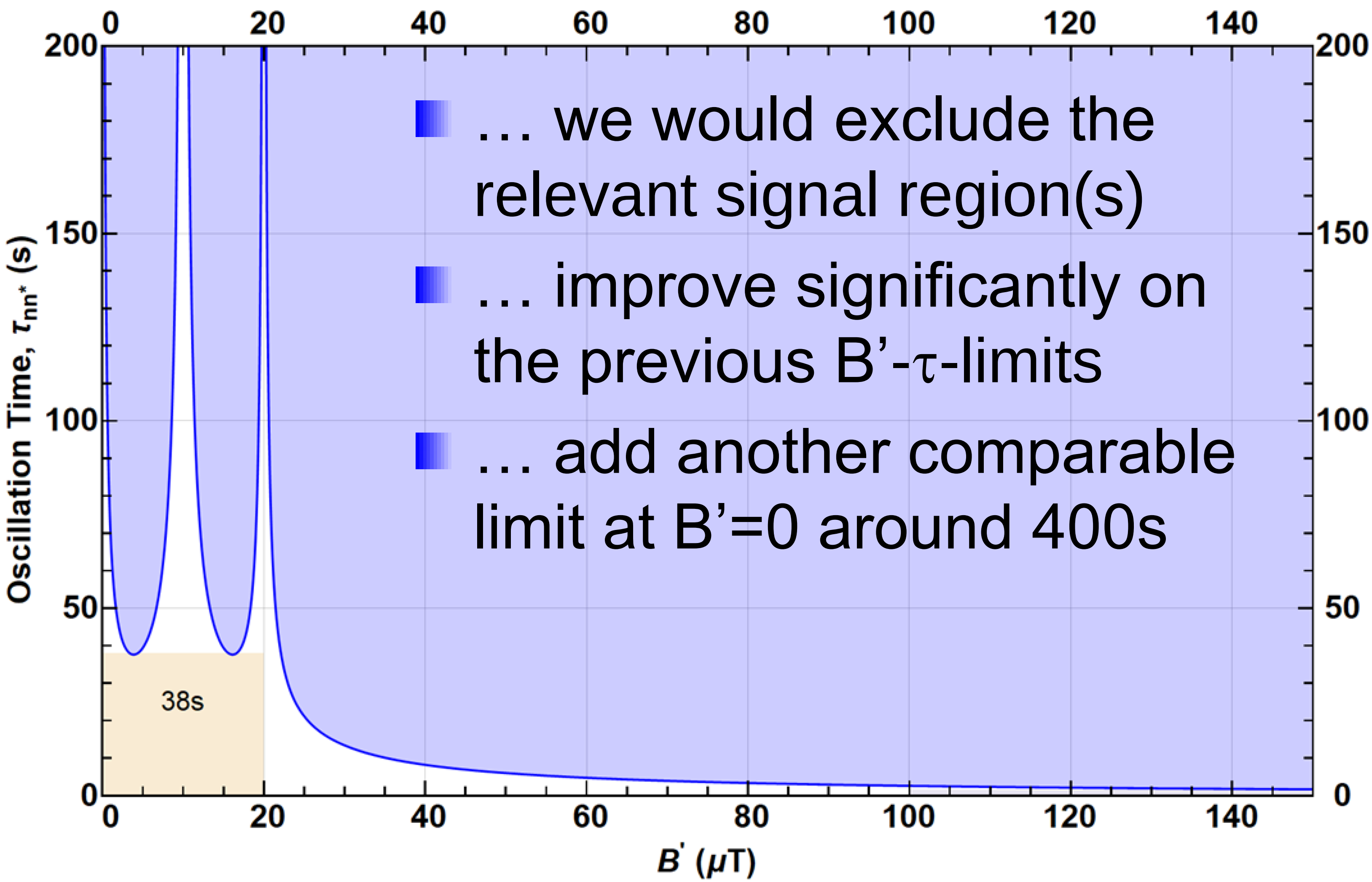


$$n = \frac{N^{\text{Emptying}}}{N^{\text{Monitor}}}$$

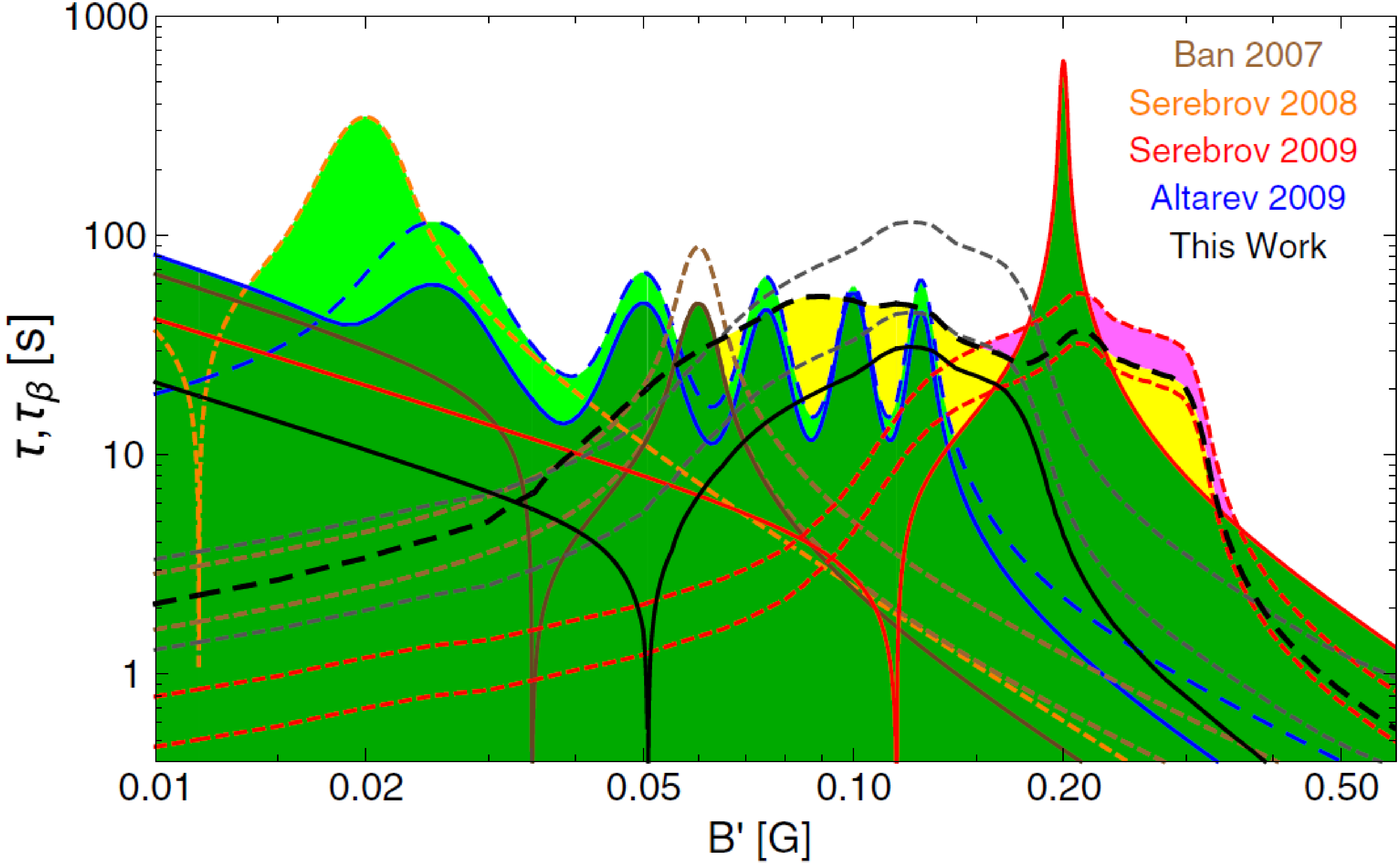




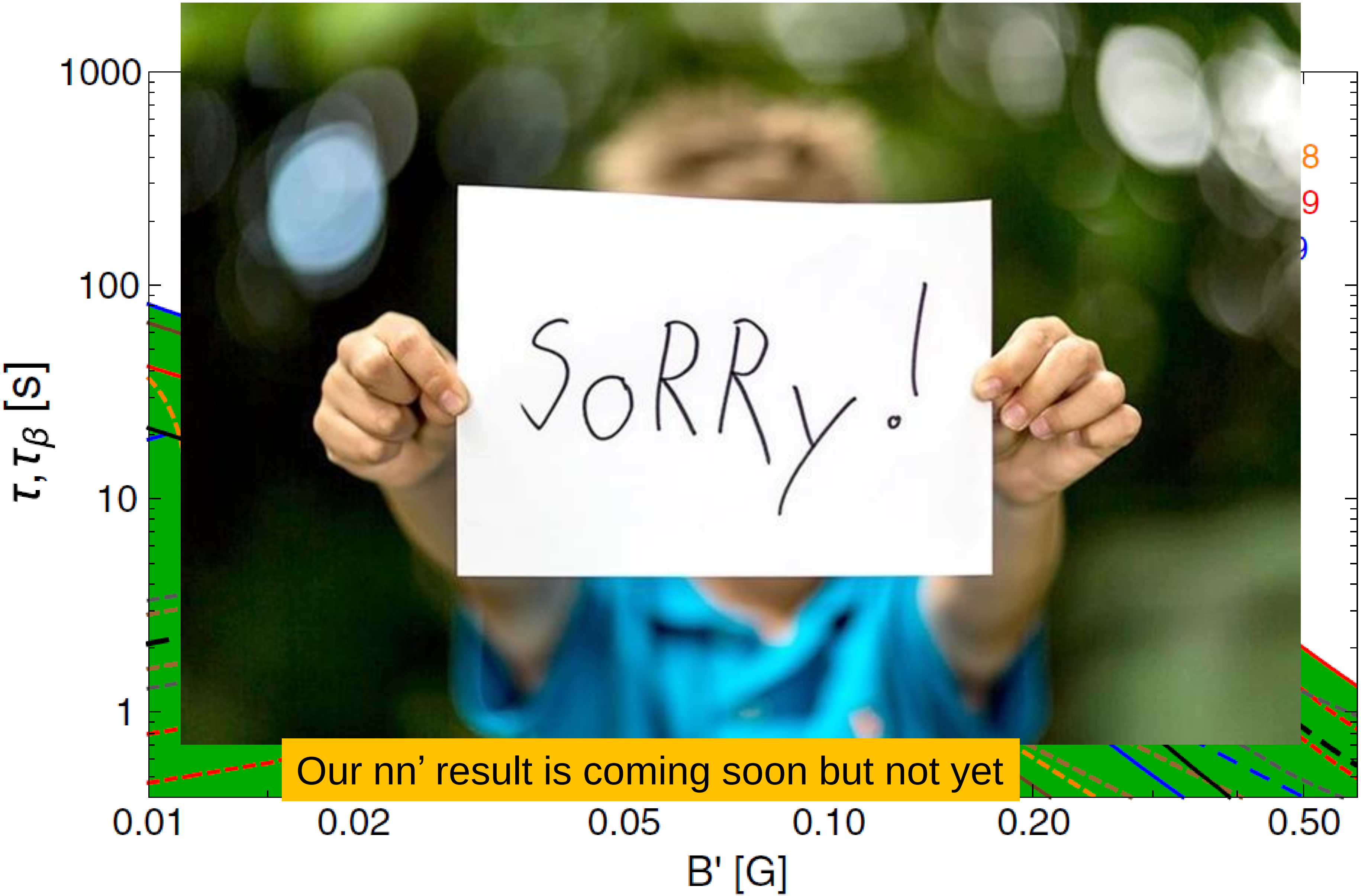
In case we wouldn't find a signal …



- … 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



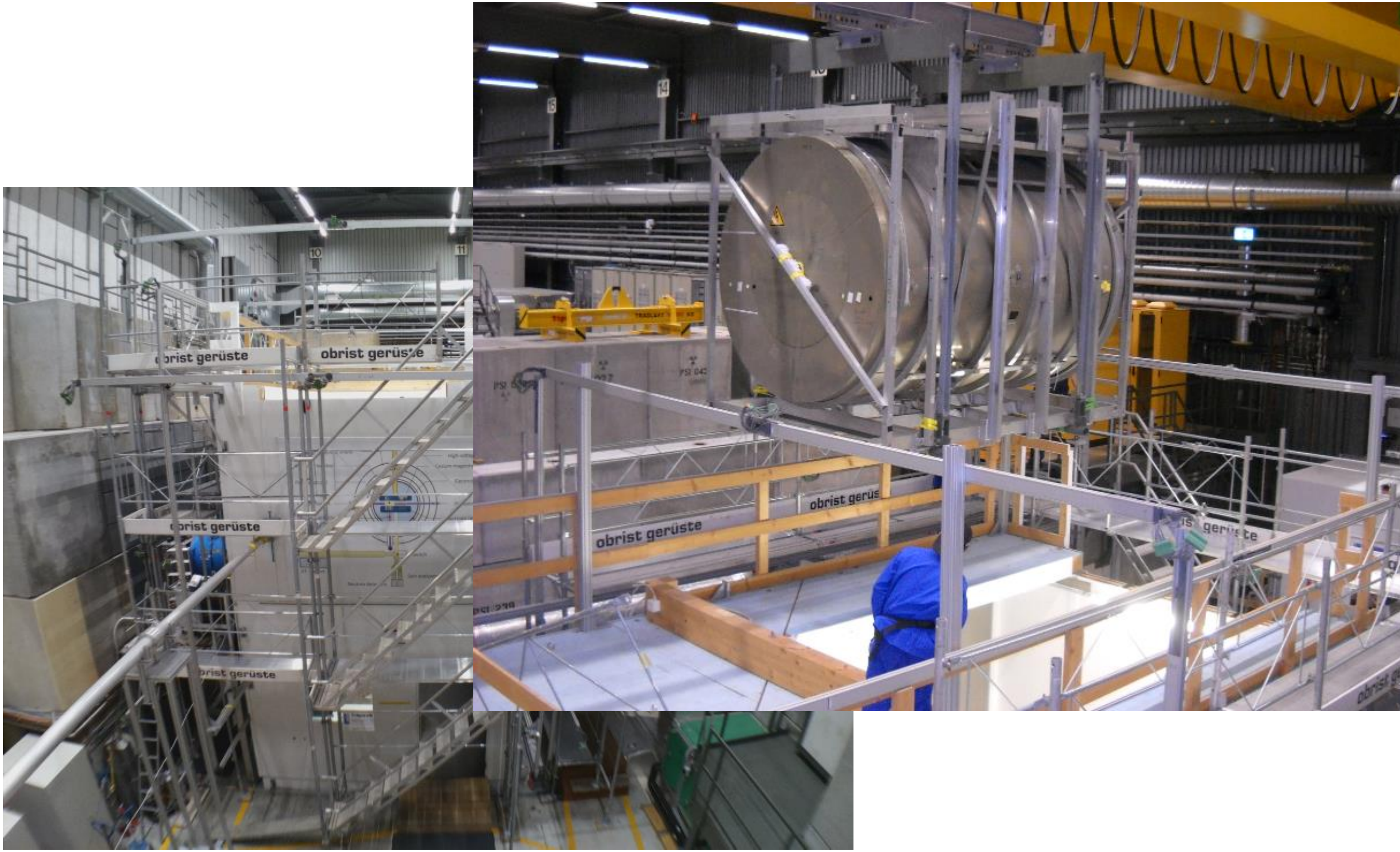
Ban 2007
Serebrov 2008
Serebrov 2009
Altarev 2009
This Work
1000
100
10
1
0.01
0.02
0.05
0.10
0.20
0.50
B' [G]
τ, τ_β [s]



Our nn’ result is coming soon but not yet

nEDM finished fall 2017

nEDM finished fall 2017

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Académie des sciences naturelles

PSI 2019

Swiss Institute of Particle Physics

5th Workshop on the

Physics of fundamental Symmetries and Interactions at low energies and the precision frontier

Oct. 21-25, 2019

Paul Scherrer Institute

Switzerland

Topics:

- Low energy precision tests of the Standard Model
- Experiments with muons, pions, neutrons, antiprotons, other particles and atoms
- Searches for permanent electric dipole moments
- Searches for symmetry violations and new forces
- Precision measurements of fundamental constants
- Exotic atoms and molecules
- New tools and facilities

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Backup

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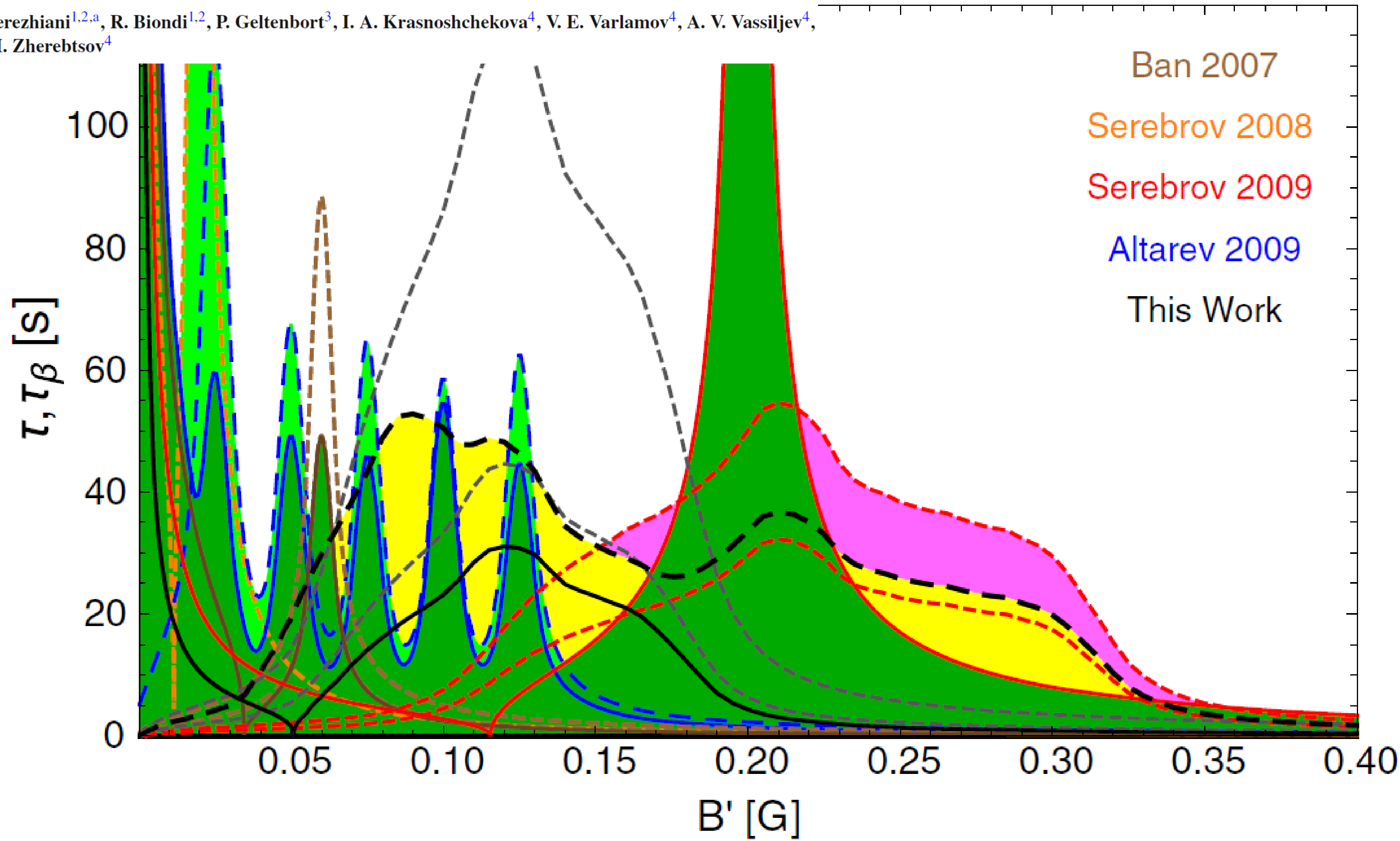
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

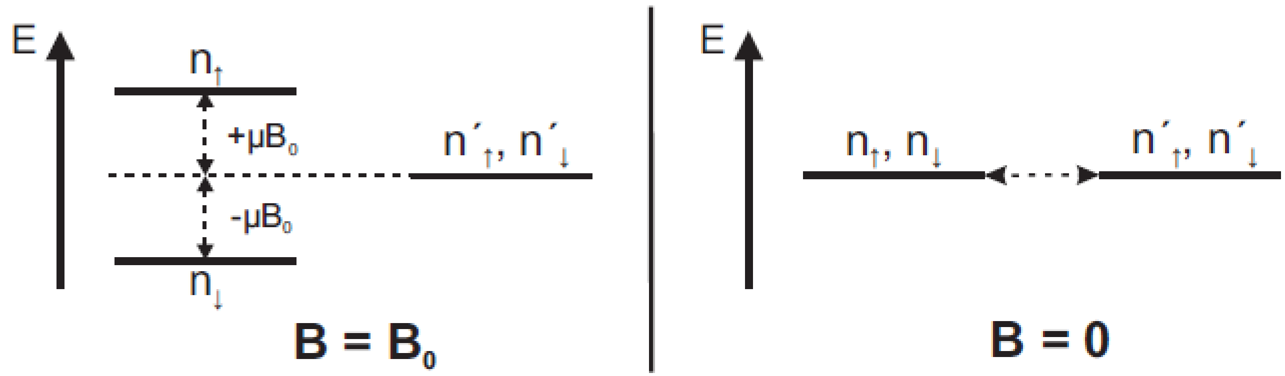
New experimental limits on neutron – mirror neutron oscillations in the presence of mirror magnetic field

Z. Berezhiani[1,2,a], R. Biondi[1,2], P. Geltenbort[3], I. A. Krasnoshchekova[4], V. E. Varlamov[4], A. V. Vassiljev[4], O. M. Zherebtsov[4]



Mirror neutron experiments

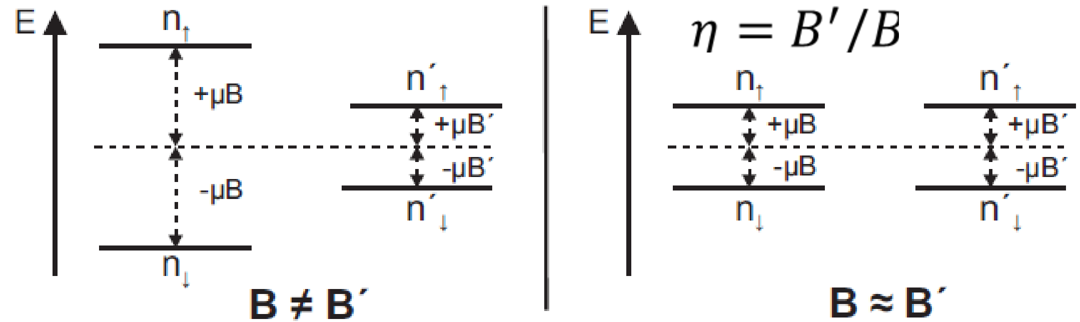
$$\frac{n_0}{n_{\uparrow\downarrow}} = 1 - \frac{t_f t_s}{\tau_{nn'}^2}$$



- 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

Mirror neutron experiments

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



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Beam vs. storage experiments

Beam:

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

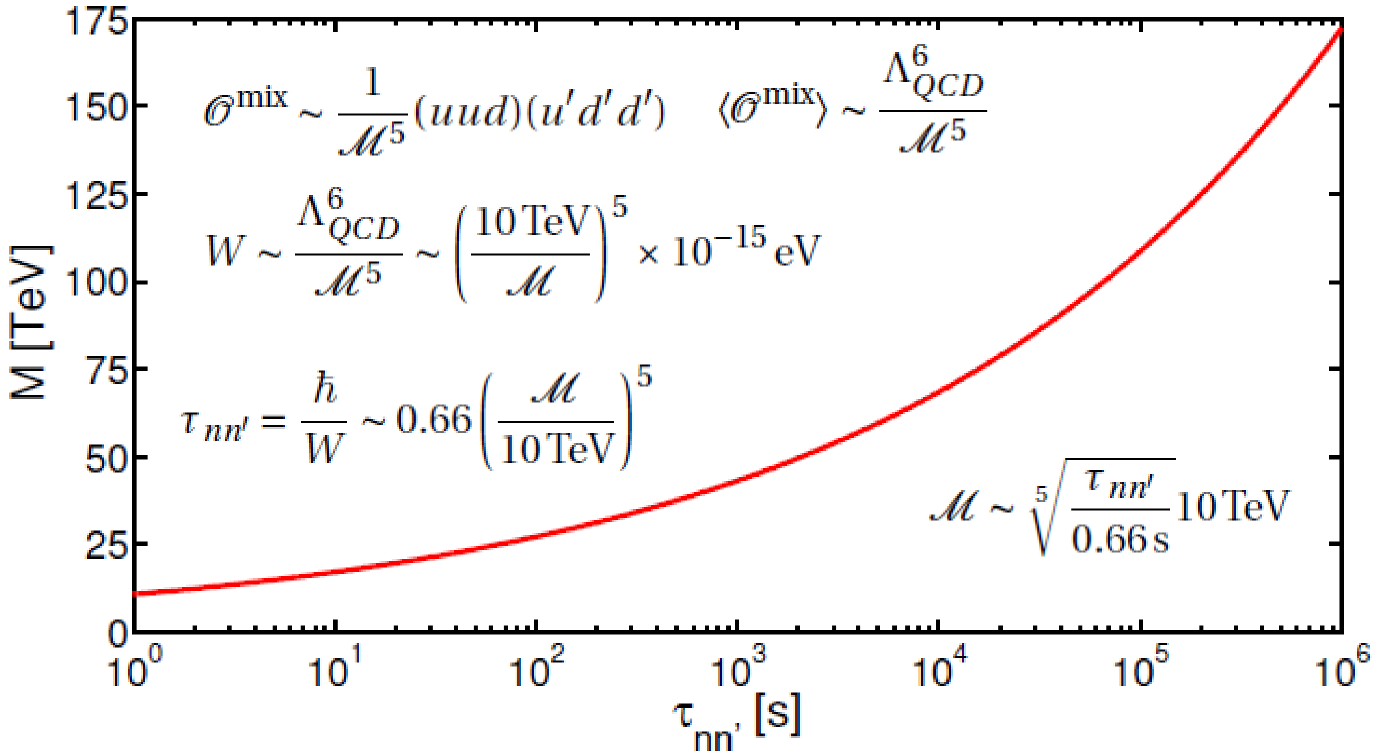
- N=1, $t_f^2 \sim 0.05^2\ s^2$ (VCN), $\Delta N \sim 10^{-7} \rightarrow$ **$\tau_{nn'} > 100$ s**
- # of counts needed ~ **10^{13}**

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**

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).

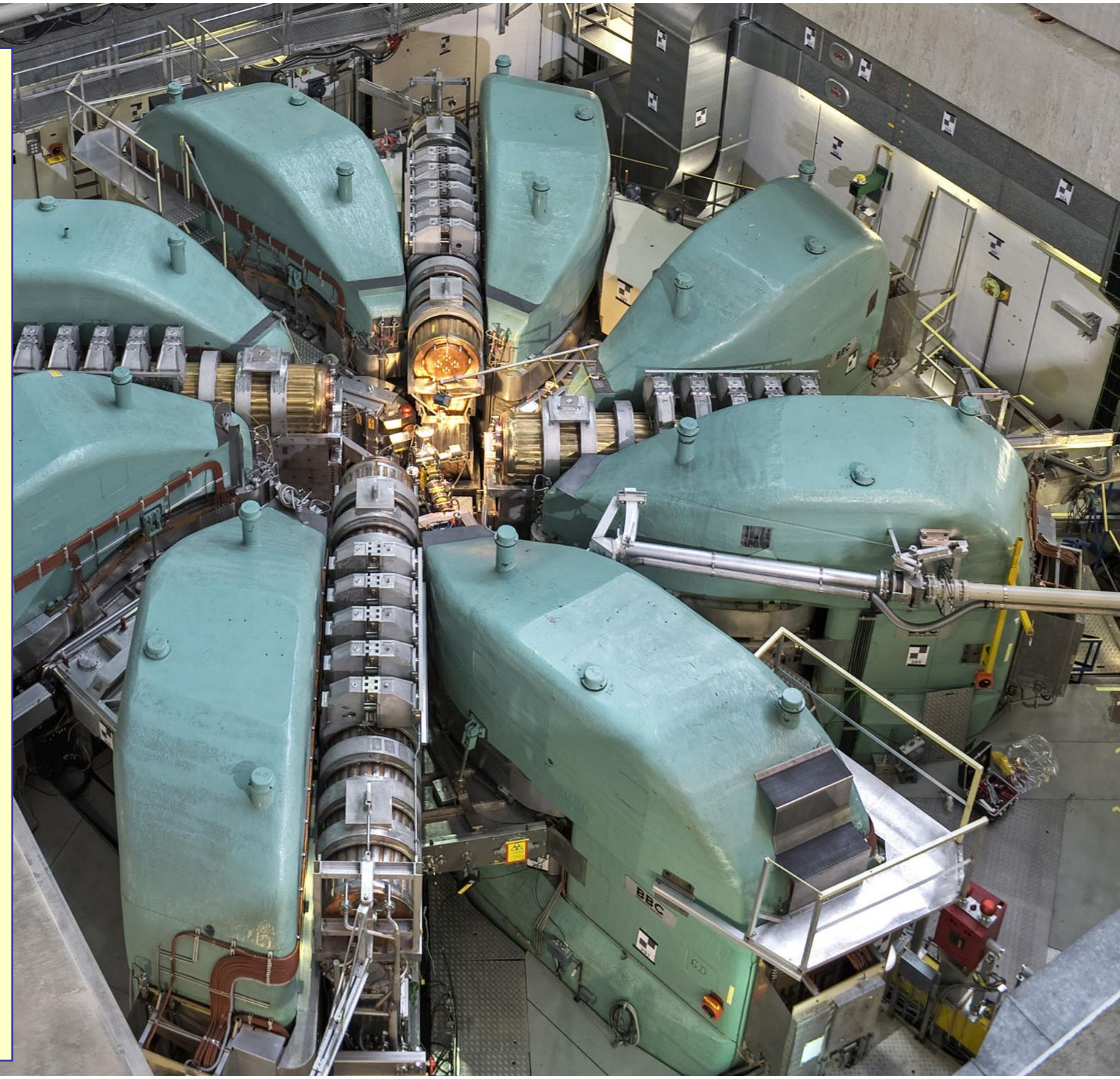
- nn' limits probe effective mass scale 10…100TeV
- Mass of exchange boson can be much lower

PSI ring cyclotron

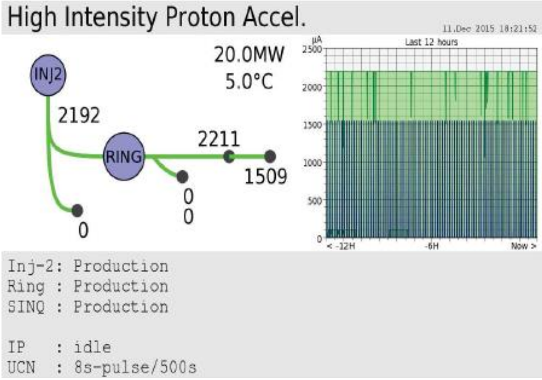
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

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

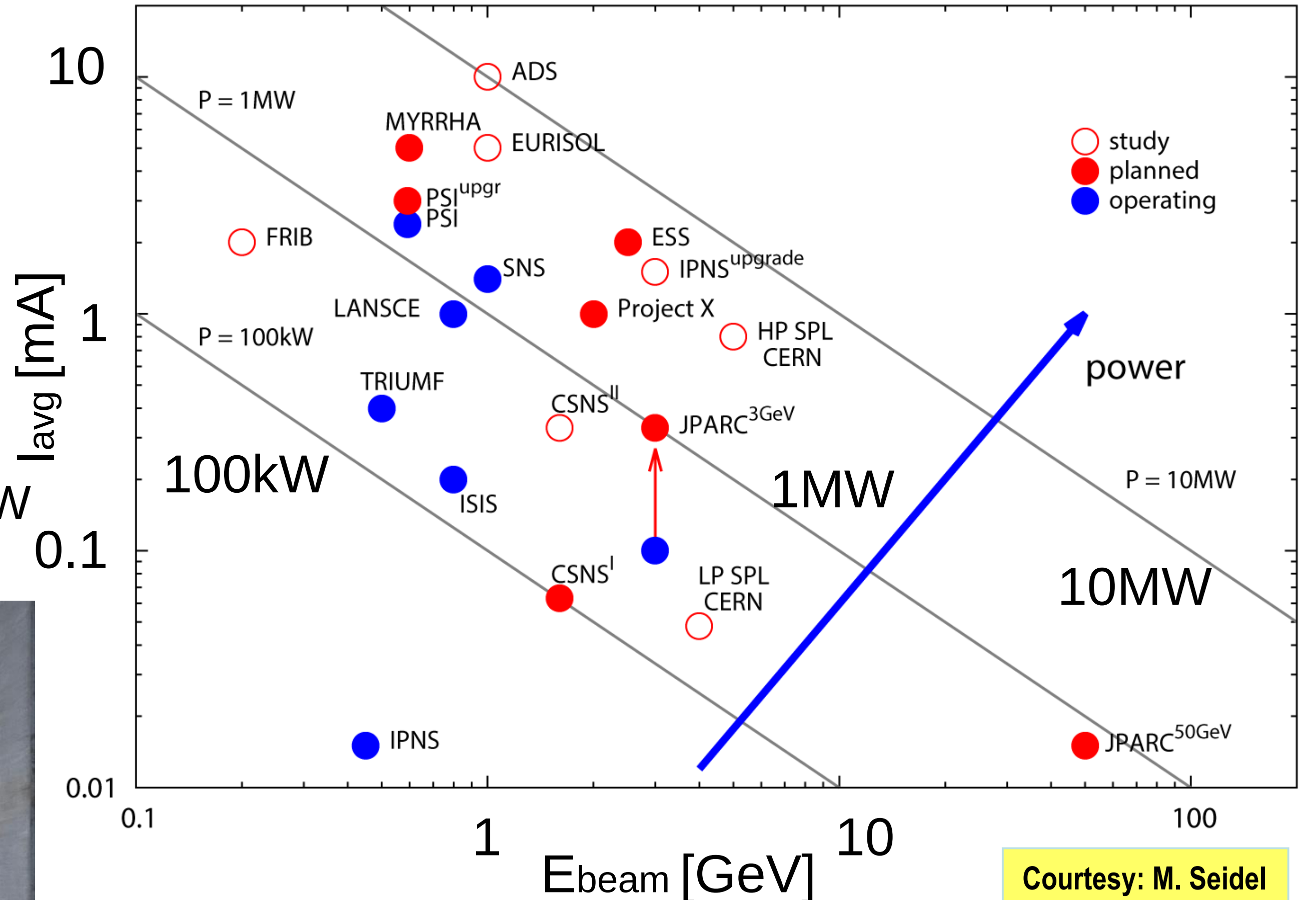
- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW

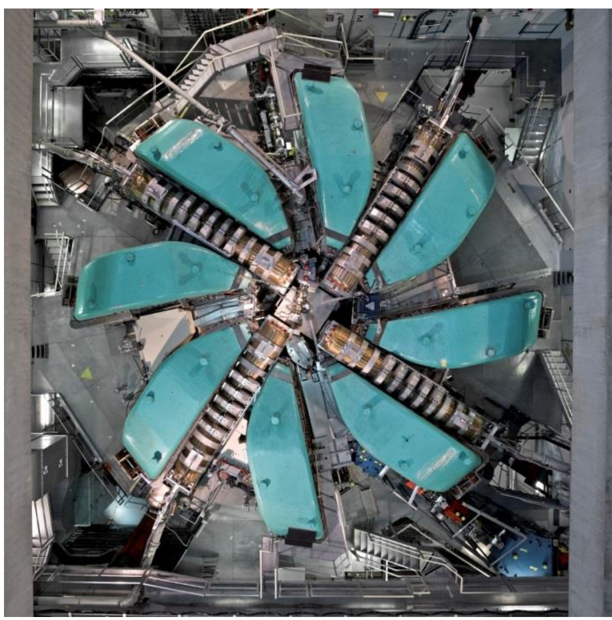


PSI ring cyclotron



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

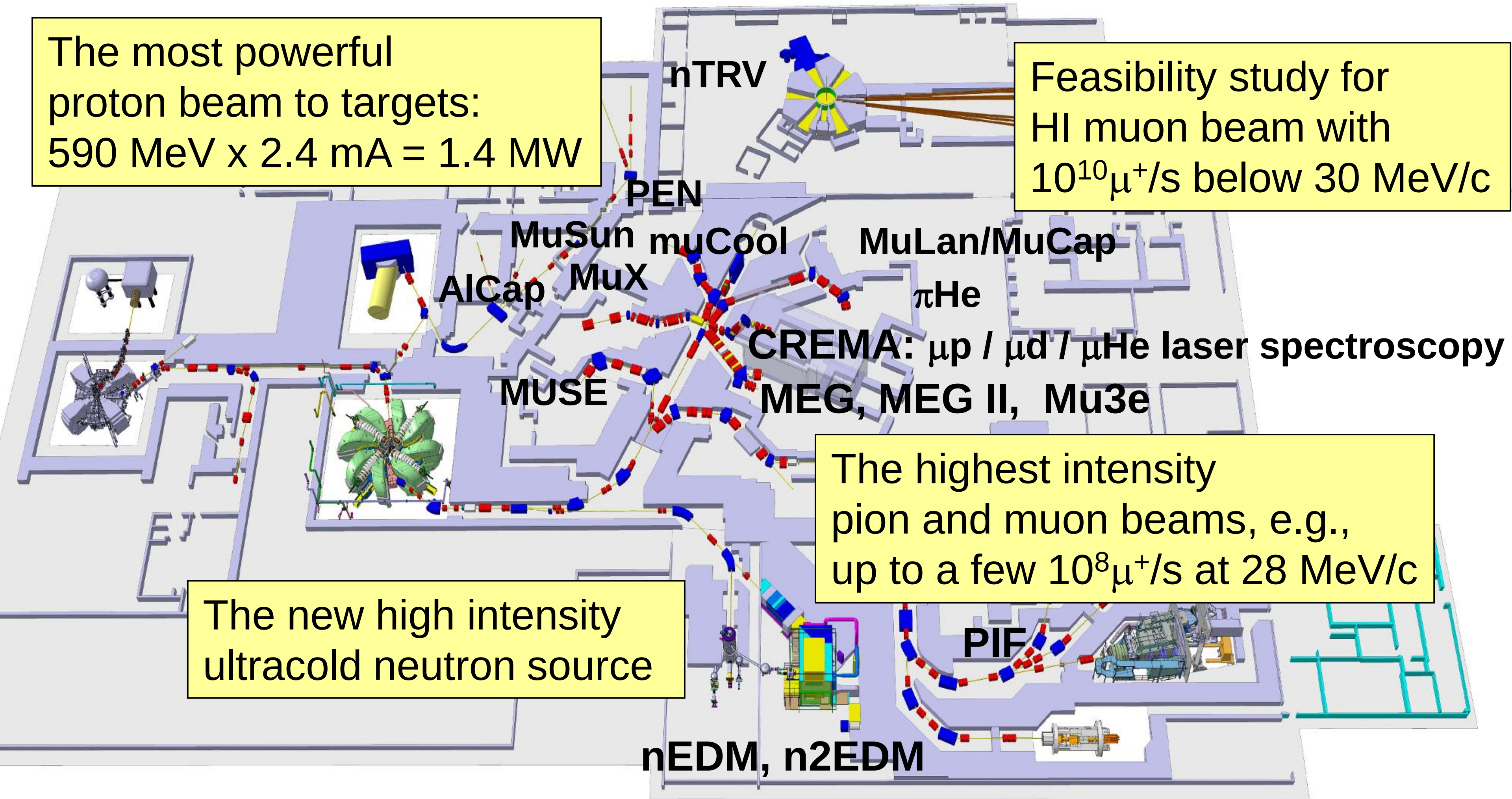




HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions at low momenta and of ultracold neutrons.

The intensity frontier at PSI: π, μ, UCN

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



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