Humboldt Kolleg on Particle Physics
Kitzbühel Austria (June 26 – July 01 2022)
"Clues to a mysterious Universe - exploring the interface of particle, gravity and quantum physics"

Experimental searches for *n-n*' oscillations - recent results from PSI

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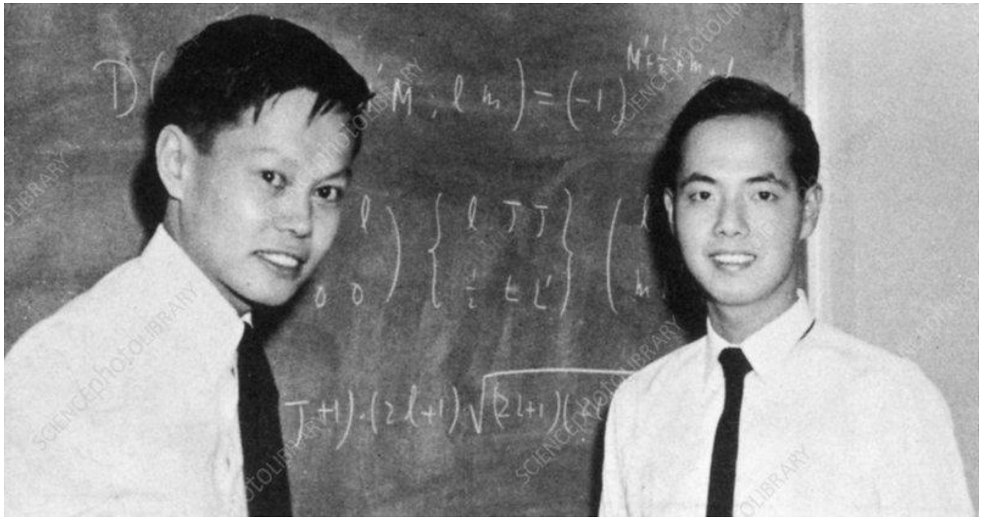
Outline

- Concept of Mirror Matter
- *n-n*' oscillations
- Neutrons – Cold Neutrons vs. Ultra-Cold Neutrons
- Experimental searches for *n-n*' oscillations
- Limits for n-n' oscillations at non-zero mirror-magnetic field
- Search for *n-n*' oscillations in nEDM apparatus at PSI
- Dedicated *n-n*' oscillation experiment at PSI
- Summary and outlook

Concept of a mirror world – attempt to restore global parity symmetry

- Discovery of Parity Violation in weak interaction (τ-θ puzzle)
  T.D. Lee, C.-N. Yang, Phys. Rev. 104 (1956)



C.N. Yang and Tsung-Dao Lee

Chien-Shiung Wu

- Restoration of parity: **parity conjugated copies of weakly interacting particles** ?

Concept of a mirror world – attempt to restore global parity symmetry

- "Mirror" particles would not interact with counterparts via strong, electromagnetic and weak interactions

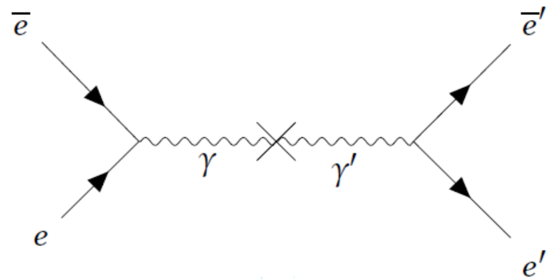
I.Yu. Kobzarev, L.B. Okun, I.Ya. Pomeranchuk, Sov. J. Nucl. Phys. 3 (1966),
R. Foot, H. Lew, R.R. Volkas, Phys. Lett. B 272 (1991),
R. Foot, H. Lew, R.R. Volkas, Mod. Phys. Lett. A 07 (1992).

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SM}} + \mathcal{L}'_{\text{SM}'} + \mathcal{L}^{\text{mixing}}_{\text{SM - SM}'}$$

- Parity and Time Reversal symmetries would be restored for electroweak interactions in a global sense

Mirror Matter

- **Mixing of SM with SM' would potentially solve several persisting physics problems:**
  - γ-γ' mixing – portal to interaction of SM with SM' – heavily constrained



A. de Angelis and R. Pain, Mod. Phys. Lett. A 17 (2002) 2491

  - Candidate for Dark Matter – mirror baryons would be the main components of DM

Z. Berezhiani, Int. J. Mod. Phys. A 19.23 (2004). 3775
HM Hodges, Phys. Rev. D 47 (1993) 456–459
Z Berezhiani, Eur. Phys. J. Spec. Top.163 (2008) 271

- Mixing ν-ν’ makes ν’ candidate for sterile neutrino – neutrino mixing with sterile neutrinos would include mirror neutrinos
  EK. Akhmedov, at al., Phys. Rev. Lett. 69 (1992) 3013
  V. Berezinsky, at al., Nucl. Phys. B658 (2003) 254
- Interaction of SM and SM’ particles with CP violation opens co-baryogenesis channels (ΔL=1, ΔB=1)
  L. Bento, Z. Berezhiani, Phys. Rev. Lett. 87 (2001) 231304
  L. Bento, Z. Berezhiani, Fortschr. Phys. 50 (2002) 489,
- Mirror Mater feels gravity generated by both SM and SM’ particles – formations of cosmological structures, gravitational lensing, …
  R. Foot, Phys. Lett. B 452 (1999) 83
  R. Foot, Phys. Lett. B 471 (1999) 191
- *n*-*n*’ oscillations would relax GZK energy limit of cosmic rays
  BR. Dawson et al., EPJ Web of Conf. 53 (2013) 01005
  M. Fukushima, EPJ Web of Conf. 53 (2013) 02002

n-*n*' oscillations

- *n* and *n*' can be considered as eigenstates |*n*⟩ and |*n*'⟩ of two-state system with the Hamiltonian

$$H = H_0 + H_I = \begin{pmatrix} m - i\Gamma/2 & 0 \\ 0 & m - i\Gamma/2 \end{pmatrix} + \begin{pmatrix} -V & \epsilon \\ \epsilon & -V' \end{pmatrix}$$

$$H_I = \begin{pmatrix} \mu_n \mathbf{B} \cdot \sigma & \epsilon\,\mathbf{1} \\ \epsilon\,\mathbf{1} & \mu_n \mathbf{B}' \cdot \sigma \end{pmatrix}$$

- Evolution is governed by Schrödinger equation

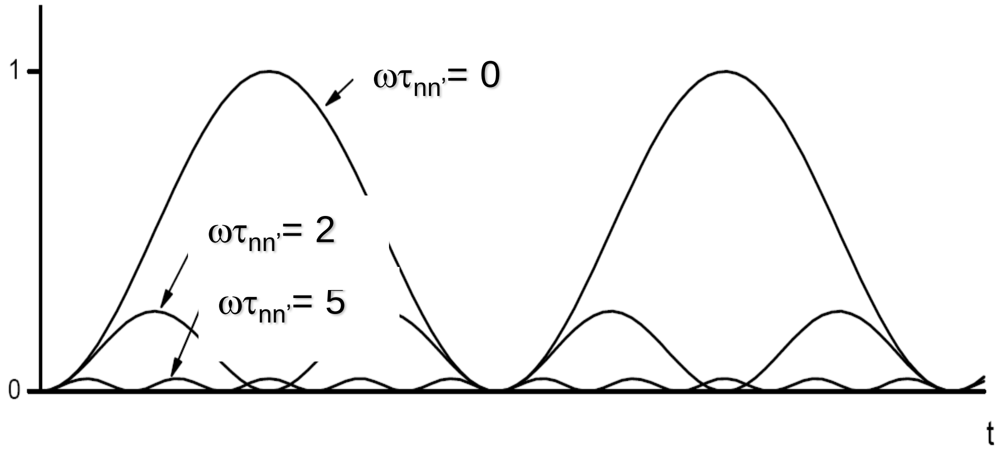
$$H|\psi(t)\rangle = i\frac{\partial}{\partial t}|\psi(t)\rangle$$

n-*n*’ oscillations

- Transition probability *n*→*n*’:

$$P_{n\to n'}(t) = \frac{1}{1+\left(\frac{V-V'}{2\,\epsilon}\right)^2}\sin^2\left(\sqrt{1+\left(\frac{V-V'}{2\,\epsilon}\right)^2}\,t\,\epsilon\right)$$

$$= \frac{1}{1+\left(\omega\tau_{nn'}\right)^2}\cdot\sin^2\left(\sqrt{1+\left(\omega\tau_{nn'}\right)^2}\cdot\frac{t}{\tau_{nn'}}\right)$$



$$\epsilon_{nn'} = \hbar\tau_{nn'}^{-1}$$

Neutrons: cold (CN) and ultra-cold (UCN)

- **Cold** Neutrons: $E_{\mathrm{kin}}^{\mathrm{CN}} \sim 5\ \mathrm{meV}, \qquad \upsilon^{\mathrm{CN}} \sim 1\ \mathrm{km/s}$
- **Ultra-Cold** Neutrons – can be stored if: $E_{\mathrm{kin}} < V_{\mathrm{F}} - \boldsymbol{\mu}_{\mathrm{n}} \cdot \mathbf{B} + mgh$

$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m} bN$$

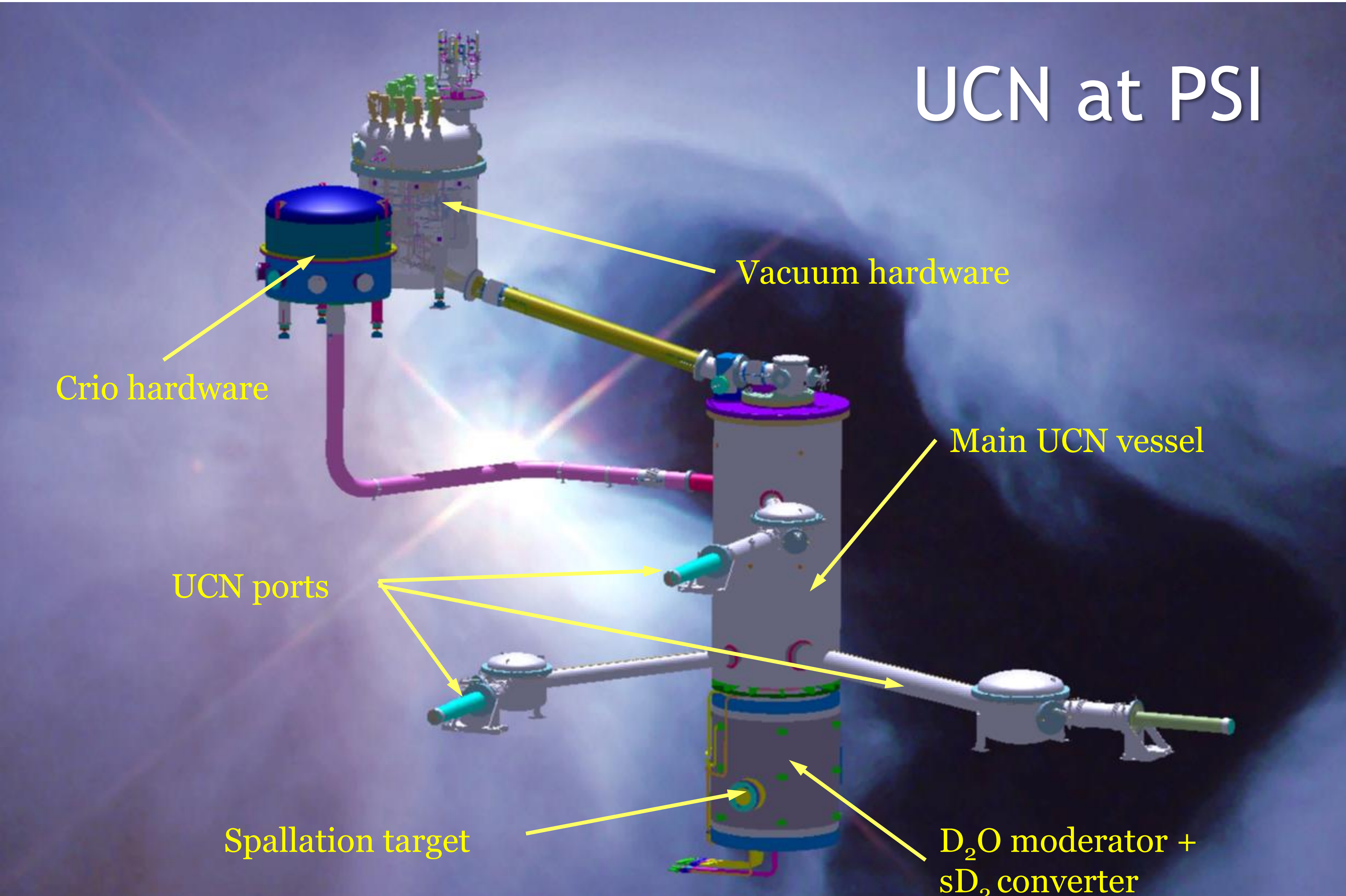
V_{F} – Fermi pseudo-potential,
b – scattering length,
N – density of wall material

- $V_{\mathrm{F}}(\mathrm{Be}) \leftrightarrow E_{\mathrm{kin}} = 252\ \mathrm{neV}$,
- $\mu_{\mathrm{n}} B(1\ \mathrm{T}) \leftrightarrow E_{\mathrm{kin}} = 60\ \mathrm{neV}$,
- $mgh(1\ \mathrm{m}) \leftrightarrow E_{\mathrm{kin}} = 100\ \mathrm{neV}$

- $\upsilon^{UCN} < 8\ \mathrm{m/s}$,
- $T^{UCN} < 4\ \mathrm{mK}$,
- $\lambda^{UCN} > 50\ \mathrm{nm}$

- UCN production through moderation of CN:
  - Gravitational field and turbine (e.g. ILL Grenoble)
  - Super-thermal process in solid deuterium (PSI, LANL, TRIGA), and super-fluid He (ILL, …)

UCN at PSI

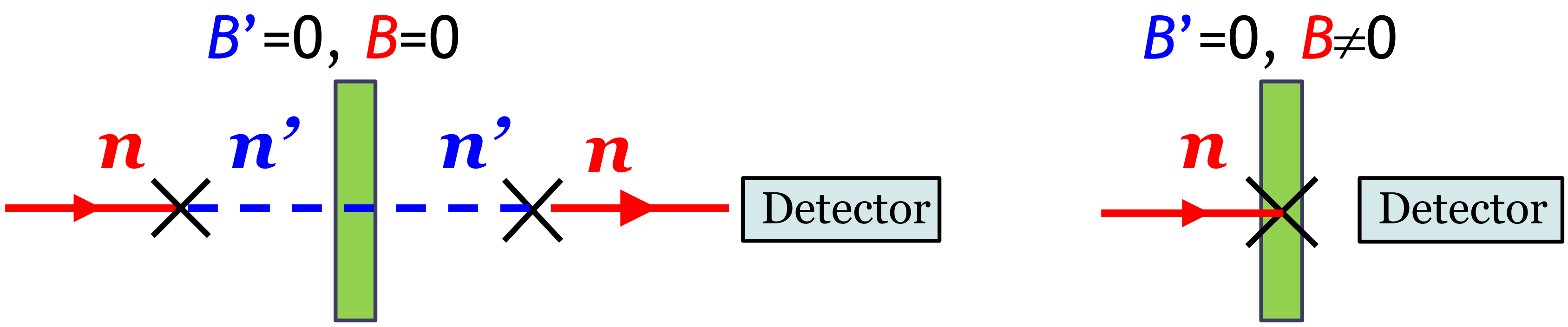


Vacuum hardware
Crio hardware
Main UCN vessel
UCN ports
Spallation target
D_2O moderator +
sD_2 converter

Experimental search for *n*-*n*’ oscillation using cold neutron beam

Regeneration experiment:

- Look for cold neutrons regenerating across a barrier through which neutrons could not have passed through. But, via mirror-neutrons as an intermediate state, which do not interact with the particles that make up the wall, they could pass through a barrier

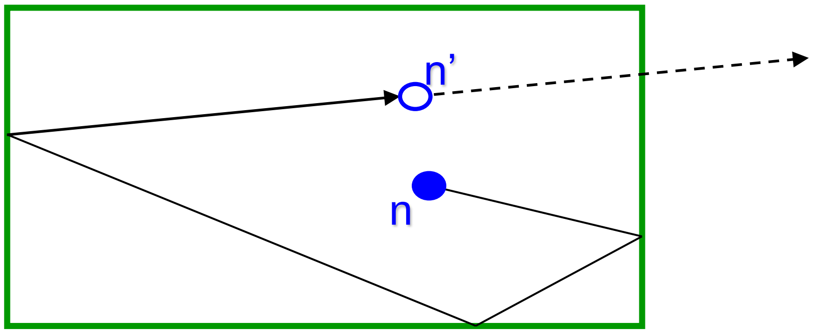


- Lifting off degeneracy ($B \neq 0$) will suppress the regeneration effect

Experimental search for *n-n'* oscillation using stored UCN

Disappearance experiment:

- $n \rightarrow n'$ conversion is viewed as additional loss channel in the storage time of ordinary neutrons – mirror neutrons are not stored
- Observation time, t_f - time between two consecutive wall collisions



- Transition rate must be properly averaged over the distribution of t_f during storage time t_s
- Compare rates when magnetic field is on (degeneracy lifted off), and magnetic field is off (degeneracy exists)

n-n' oscillations (cont.)

- **First indirect limits** from search dedicated to n-$\bar{n}$ oscillations: Z. Berezhiani, Int. J. Mod. Phys. A **19**, 3775 (2004); Z. Berezhiani, L. Bento, Phys. Rev. Lett. 96, 081801 (2006).
  - No mirror-magnetic field assumed,
  - $\epsilon_{nn'} \sim (10\,\mathrm{TeV}/M)^5 \cdot 10^{-15}\,\mathrm{eV}$ (effective 6-fermion int.)
  - $\Rightarrow \quad \tau_{nn'} \approx 1$ s
  - $\Rightarrow$ *n-n'* oscillations could be observable in magnetically shielded UCN storage experiments

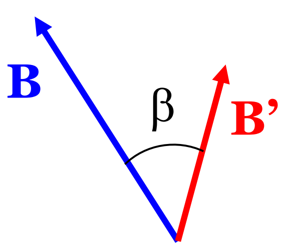
- **First direct searches (using stored UCN, B'=0):**
  - $\tau_{nn'} >$ 103 s (95% C.L.) G. Ban, et al., Phys. Rev. Lett. 99 (2007)
  - $\tau_{nn'} >$ 448 s (95% C.L.) A.P. Serebrov, et al., Phys. Lett. B 663, 181 (2008); A.P. Serebrov, et al., NIMA 611, 137 (2008)

Mirror-magnetic fields

- Trapping of mirror matter by the Earth gravitation; dynamo effect ⇒ *B*' up to ≈100 μT
  Z. Berezhiani, Eur. Phys. J. C 64 (2009) 421
- Interaction Hamiltonian in the presence of mirror magnetic fields

$$H_I = \begin{pmatrix} \mu_n \mathbf{B}\cdot\boldsymbol{\sigma} & \epsilon\,\mathbf{1} \\ \epsilon\,\mathbf{1} & \mu_n \mathbf{B}'\cdot\boldsymbol{\sigma} \end{pmatrix}$$

- $n \rightarrow n'$ transition probability in the presence of mirror magnetic fields

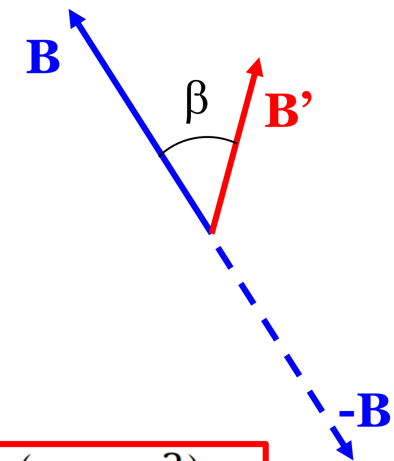


B, **B**' homogenous; cos(β) = const during free flight

$$P_{BB'}(t) = \left(\frac{\sin^2((\omega-\omega')t)}{2\tau^2(\omega-\omega')^2} + \frac{\sin^2((\omega+\omega')t)}{2\tau^2(\omega+\omega')^2}\right) + \left(\frac{\sin^2((\omega-\omega')t)}{2\tau^2(\omega-\omega')^2} - \frac{\sin^2((\omega+\omega')t)}{2\tau^2(\omega+\omega')^2}\right)\cos(\beta).$$

$$\omega = |\mu_u B|/2\hbar,\ \omega' = |\mu_u B'|/2\hbar$$

Observables



- Ratio channel

$$E_B^{(t_s)} + 1 = \frac{2n_0^{(t_s)}}{n_B^{(t_s)} + n_{-B}^{(t_s)}} = \frac{2e^{-\left(m_s P^{nn'}_{0B'}\right)}}{e^{-\left(m_s P^{nn'}_{BB'}\right)} + e^{-\left(m_s P^{nn'}_{-BB'}\right)}}$$

$$\tau_{nn'}^2 \overset{B'\neq 0}{\simeq} \underbrace{\frac{t_s}{\langle t_f\rangle}\frac{1}{E_B}}_{1/\Delta_B} \cdot \underbrace{\frac{\eta^2\left(3-\eta^2\right)}{2\omega'^2\left(1-\eta^2\right)^2}}_{f_{E_B}(\eta)}$$

- Asymmetry channel

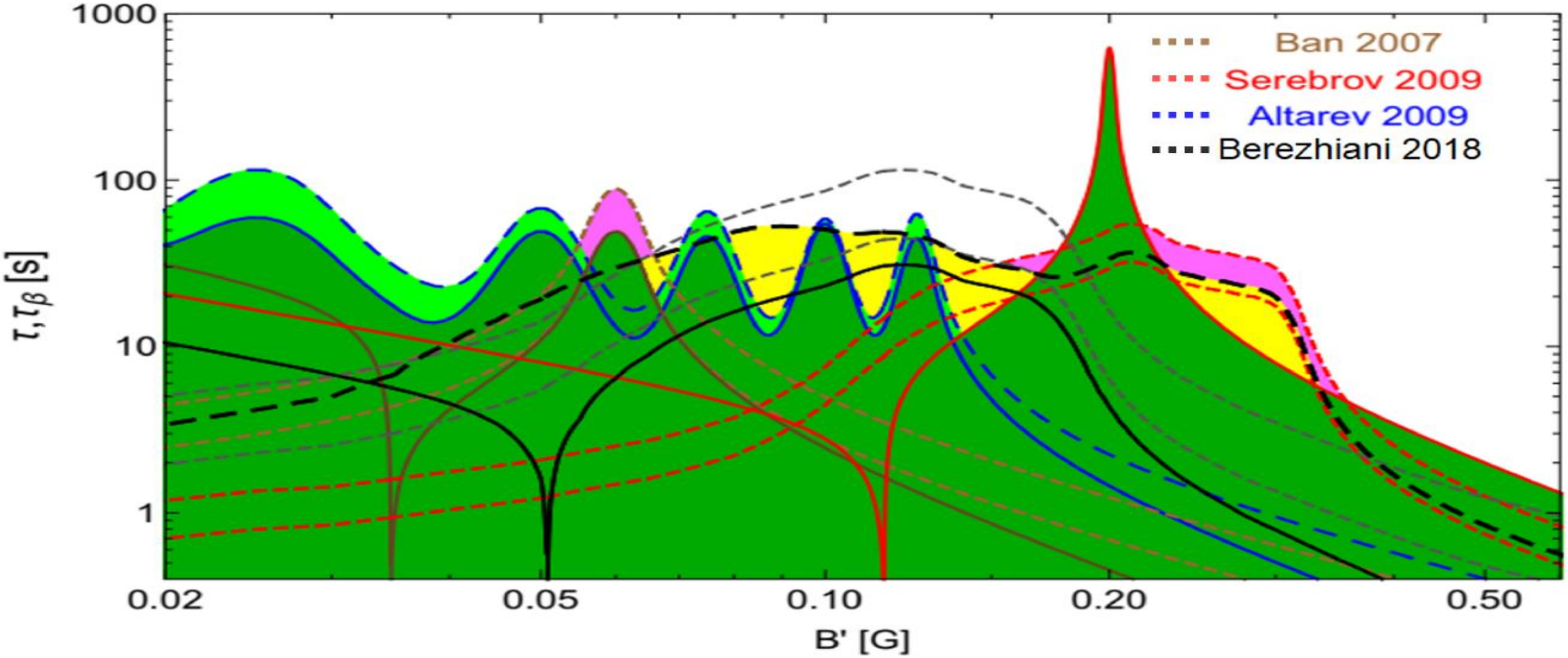
$$A_B^{(t_s)} = \frac{n_B^{(t_s)} - n_{-B}^{(t_s)}}{n_B^{(t_s)} + n_{-B}^{(t_s)}} = \frac{e^{-\left(m_s P^{nn'}_{BB'}\right)} - e^{-\left(m_s P^{nn'}_{-BB'}\right)}}{e^{-\left(m_s P^{nn'}_{BB'}\right)} + e^{-\left(m_s P^{nn'}_{-BB'}\right)}}$$

$$\eta = \omega/\omega'$$

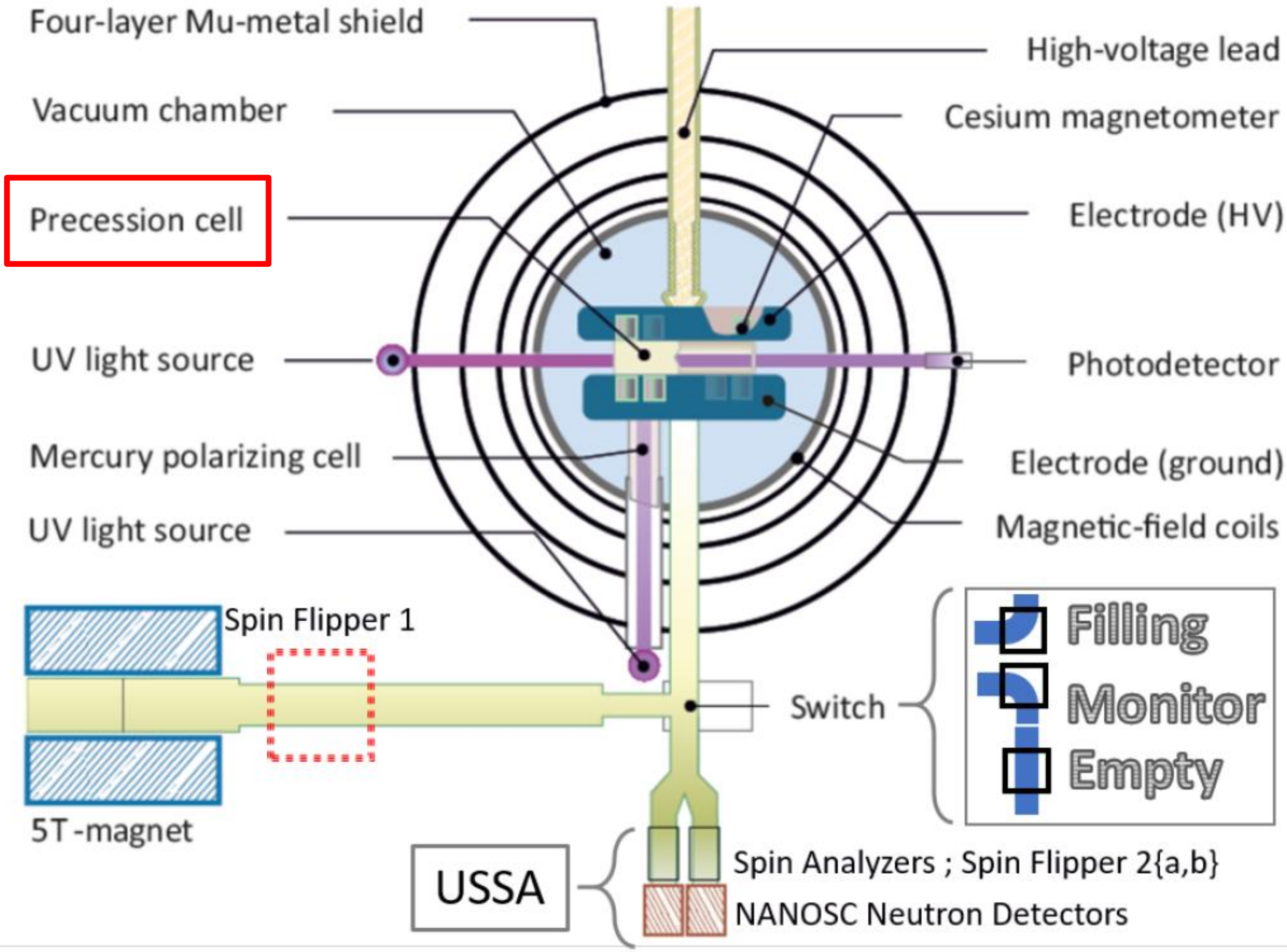
$$\frac{\tau_{nn'}^2}{\cos\beta} \overset{B'\neq 0}{\simeq} \underbrace{-\frac{t_s}{\langle t_f\rangle}\frac{1}{A_B}}_{-1/D_B} \cdot \underbrace{\frac{\eta^3}{\omega^2\left(1-\eta^2\right)^2}}_{f_{A_B}(\eta)}$$

n-*n*' oscillations before PSI measurement

- Reanalysis of former measurements led to:
  I. Altarev, et al., Phys. Rev. D 80 (2009) 032003
  Z. Berezhiani, et al., Eur. Phys. J. C 78 (2018) 717
  - $\tau_{nn'}$ >12 s (0.4<B'<12.5 μT
  - Several signal like anomalies



Experimental search for *n*-*n*' oscillation using stored UCN at PSI



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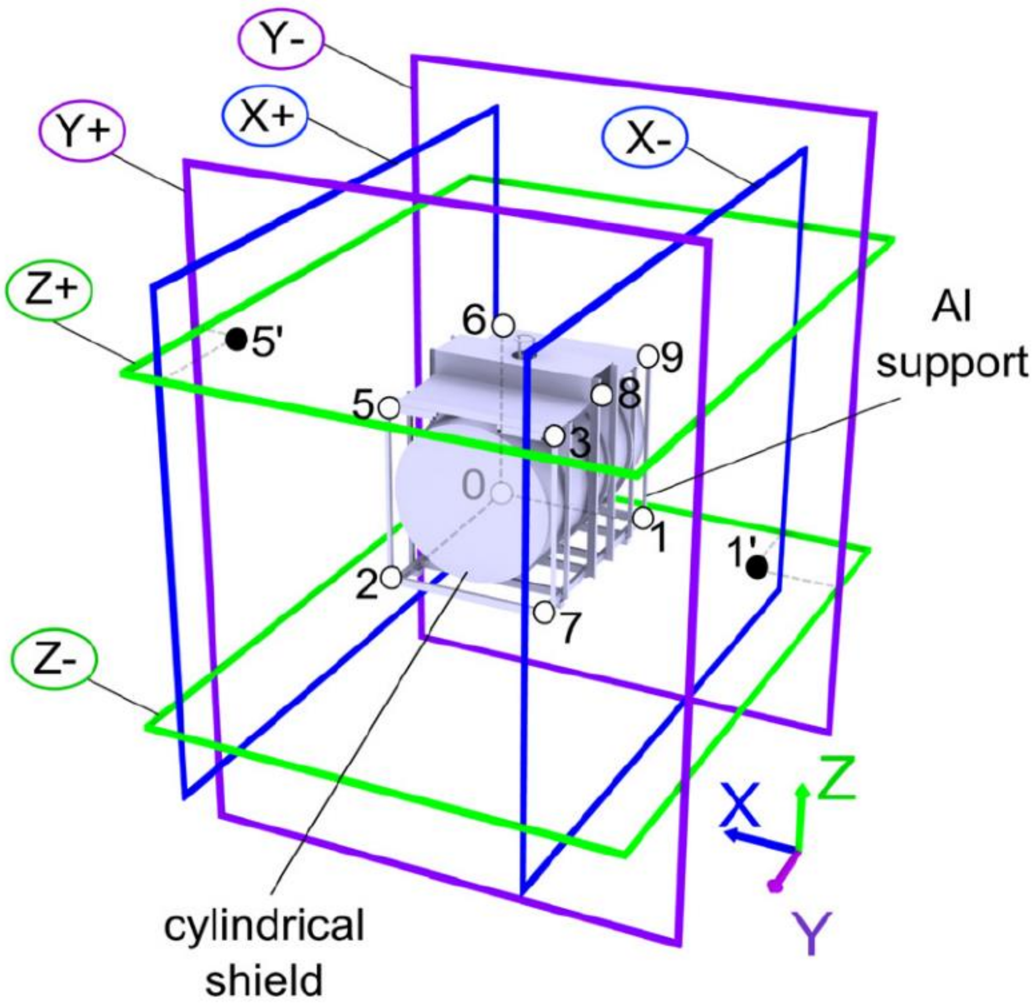
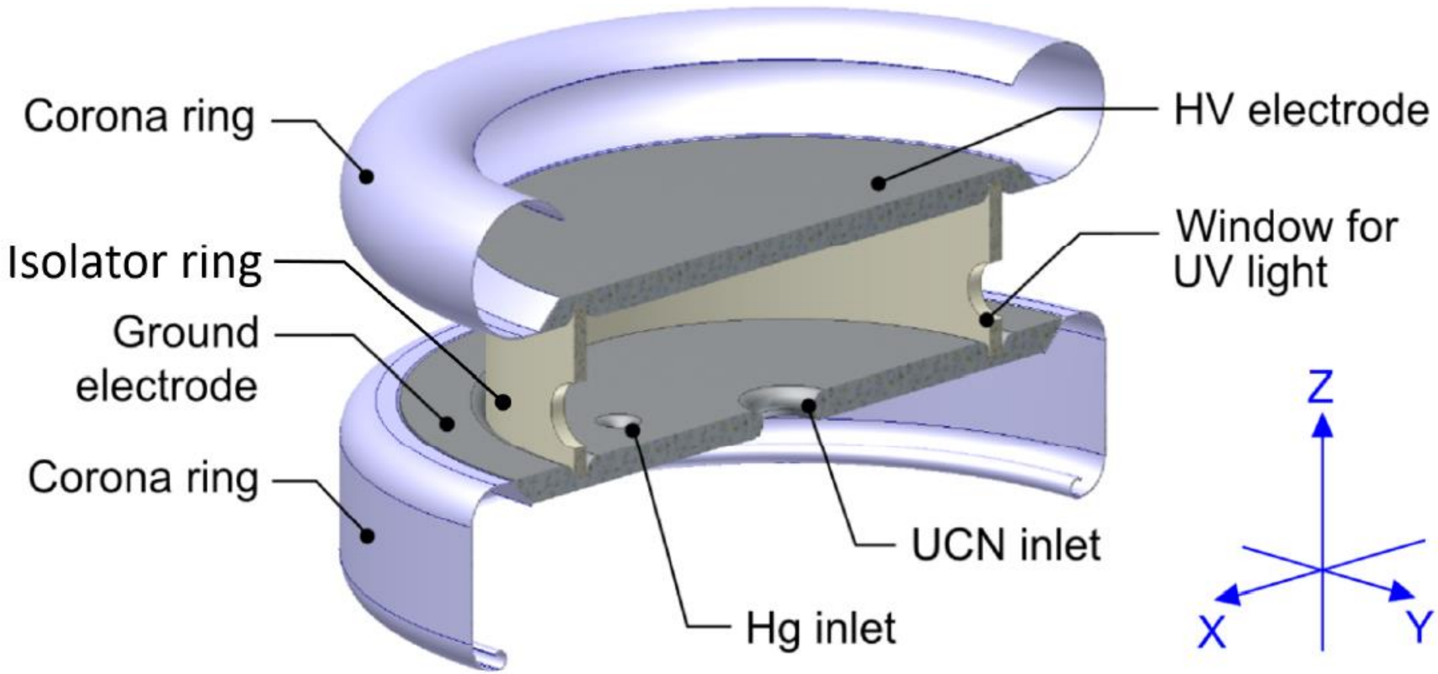
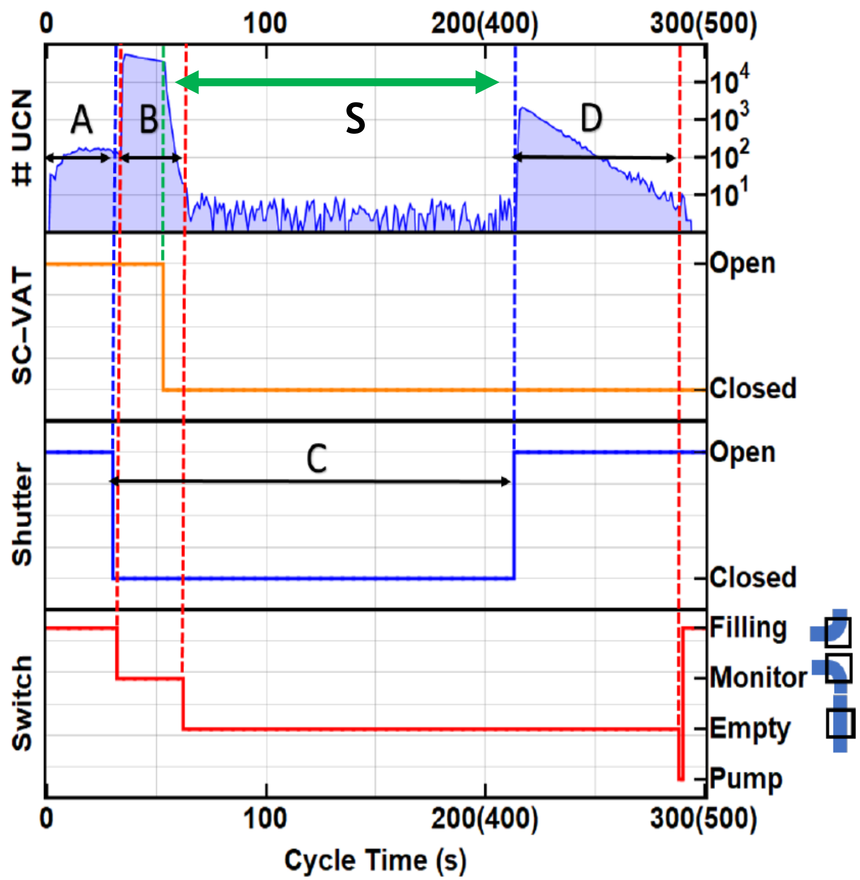


Experimental search for *n*-*n*' oscillation using stored UCN at PSI



Experimental search for *n-n'* oscillation using stored UCN at PSI

UCN detector counts

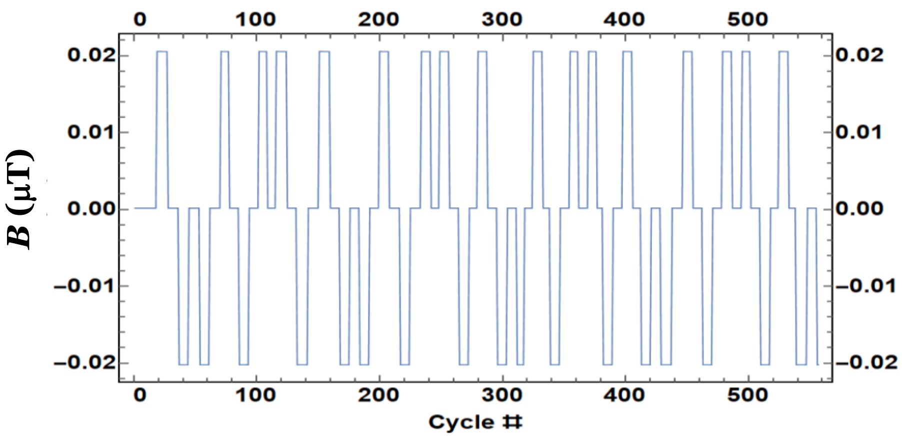


B - monitoring ($N_{monitor} \sim 10^6$)

D - empting ($N_{empting} \sim 5\times10^4$)

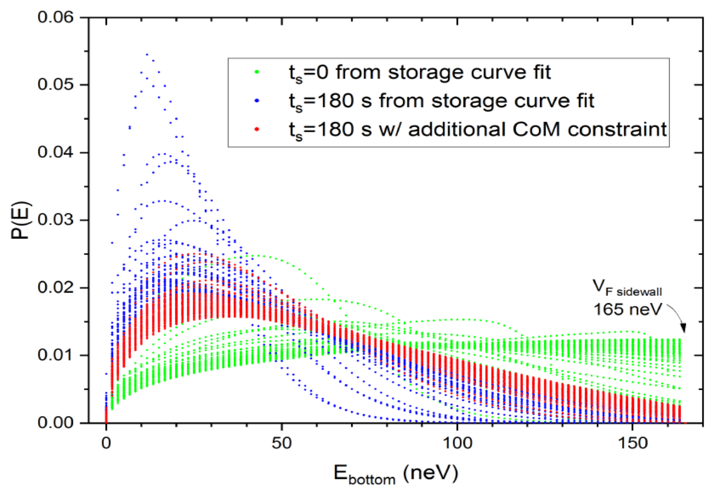
S - storage

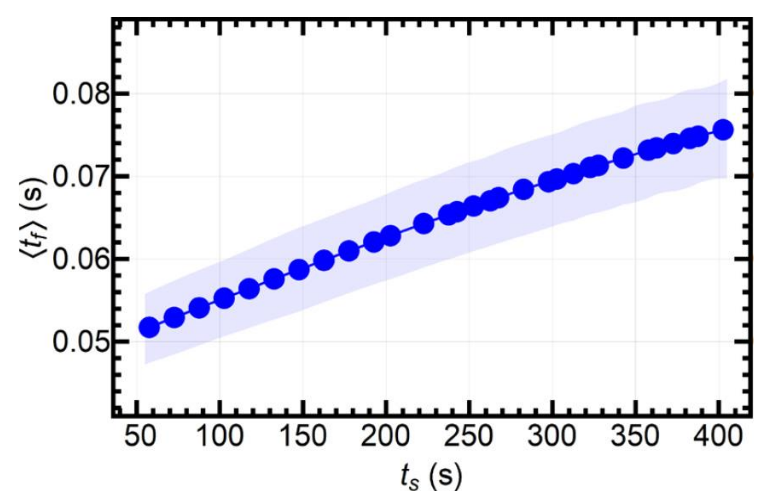
B-field pattern



Experimental search for *n*-*n*' oscillation using stored UCN at PSI – data analysis

- The attenuation in UCN counts due to losses at wall collisions and β-decay, and the detection efficiency are independent from the applied field *B* and thus will cancel out from the count ratios
- Mean free flight time $\langle t_f \rangle$ between two consecutive wall collisions: calibrated Monte Carlo simulation)





Experimental search for *n*-*n*' oscillation using stored UCN at PSI – results

$$\Big\langle \underbrace{\langle E_{B\sim 10\ \mu\mathrm{T}}\rangle \frac{\langle t_f\rangle^{(t_s)}}{t_s}}_{\Delta_{B\sim 10\ \mu\mathrm{T}}} \Big\rangle = \boxed{(2.5 \pm 5.9) \times 10^{-8}},$$

$$\Big\langle \underbrace{\langle E_{B\sim 20\ \mu\mathrm{T}}\rangle \frac{\langle t_f\rangle^{(t_s)}}{t_s}}_{\Delta_{B\sim 20\ \mu\mathrm{T}}} \Big\rangle = \boxed{(0.5 \pm 6.0) \times 10^{-8}},$$

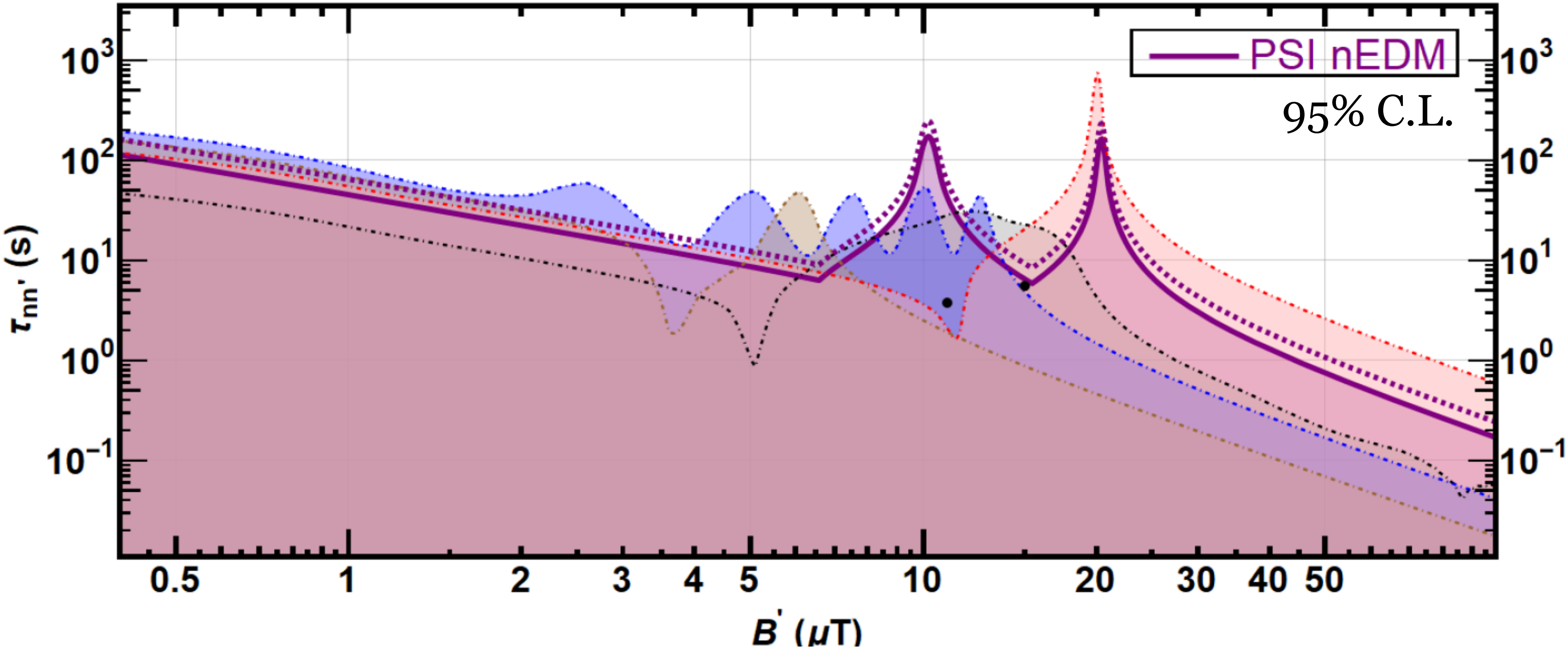
$$\Big\langle \underbrace{\langle A_{B\sim 10\ \mu\mathrm{T}}\rangle \frac{\langle t_f\rangle^{(t_s)}}{t_s}}_{D_{B\sim 10\ \mu\mathrm{T}}} \Big\rangle = \boxed{(1.4 \pm 3.1) \times 10^{-8}},$$

$$\Big\langle \underbrace{\langle A_{B\sim 20\ \mu\mathrm{T}}\rangle \frac{\langle t_f\rangle^{(t_s)}}{t_s}}_{D_{B\sim 20\ \mu\mathrm{T}}} \Big\rangle = \boxed{(1.9 \pm 3.9) \times 10^{-8}}.$$

Experimental search for *n-n'* oscillation using stored UCN at PSI – constraints

- The null-hypothesis is that there are no *n*–*n'* oscillations → **E_B consistent with zero**.

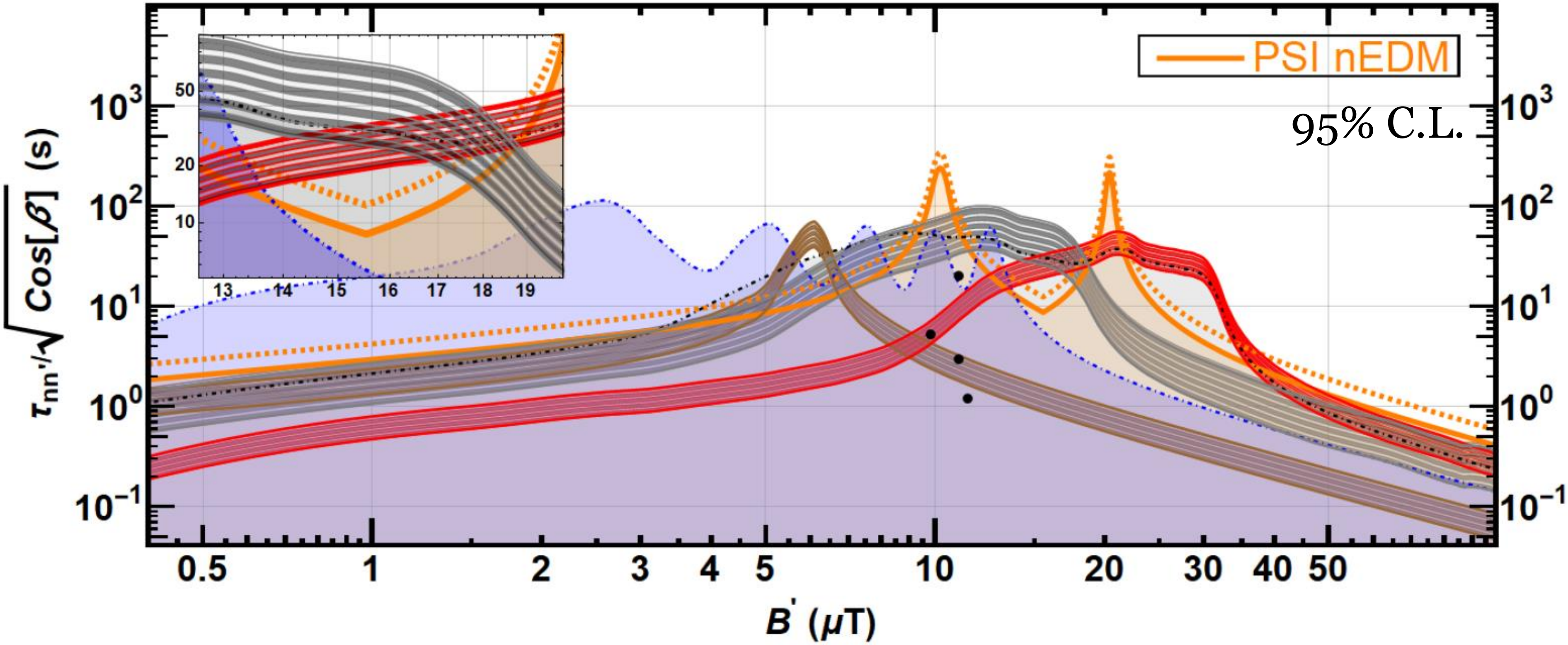
C. Abel et al., Physics Letters B 812 (2021) 135993



Experimental search for *n*-*n*’ oscillation using stored UCN at PSI – constraints

- The null-hypothesis is that there are no *n*–*n*’ oscillations → **A_B consistent with zero**

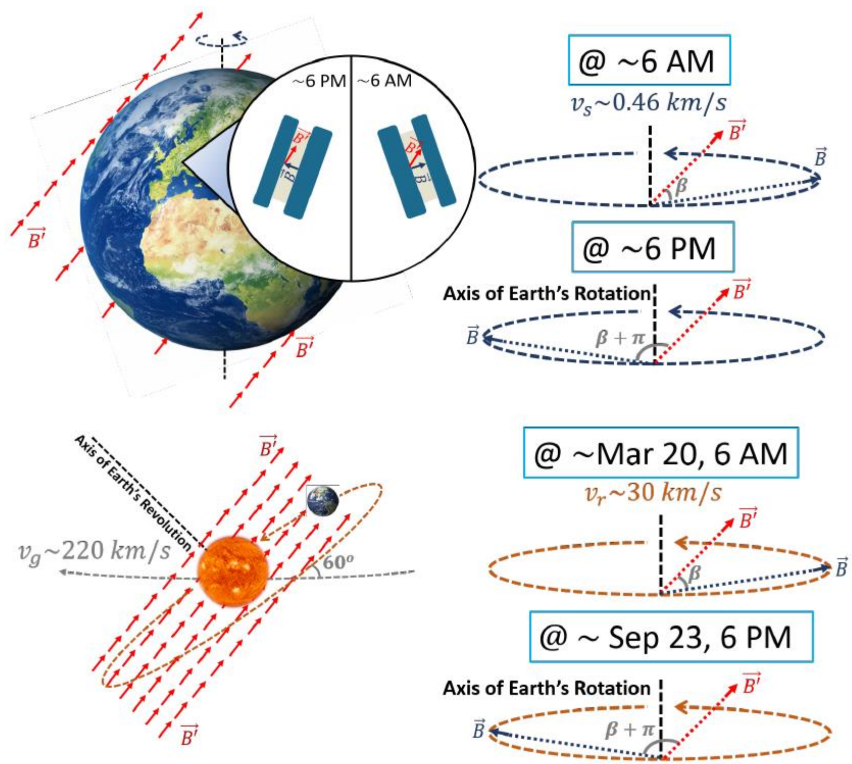
C. Abel et al., Physics Letters B 812 (2021) 135993

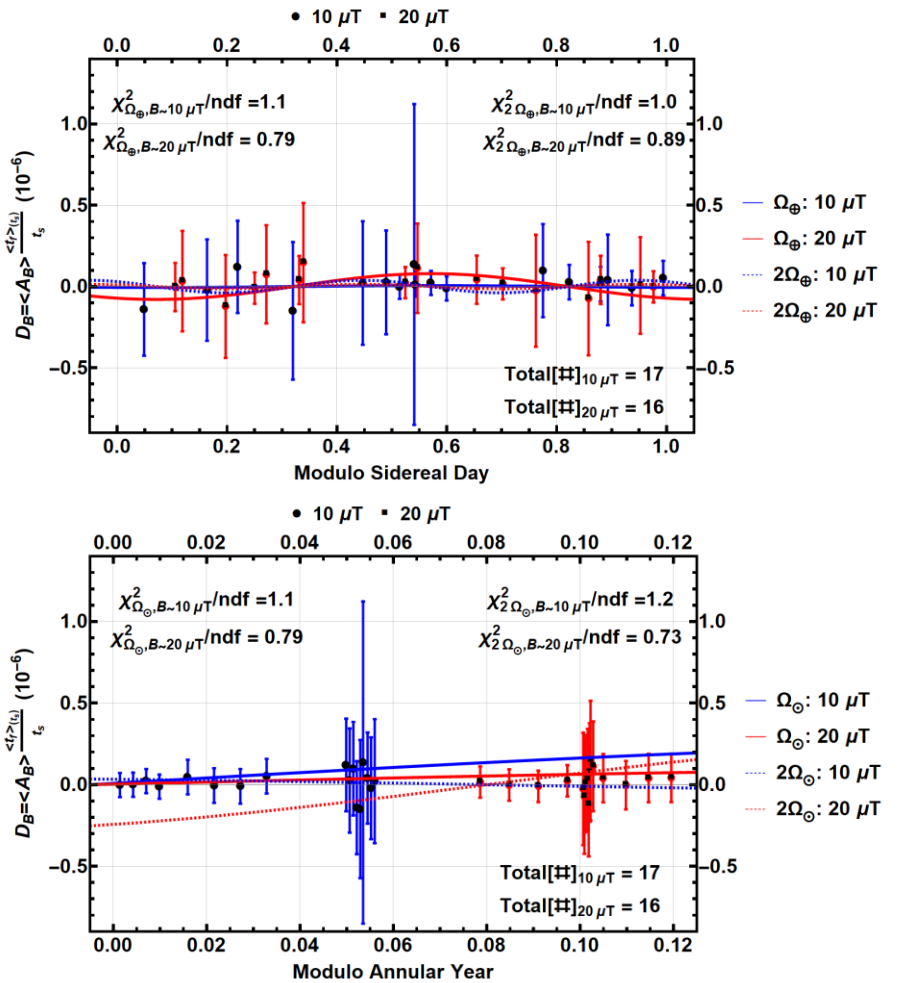


Alternative analysis – extraterrestrial origin of *B'*

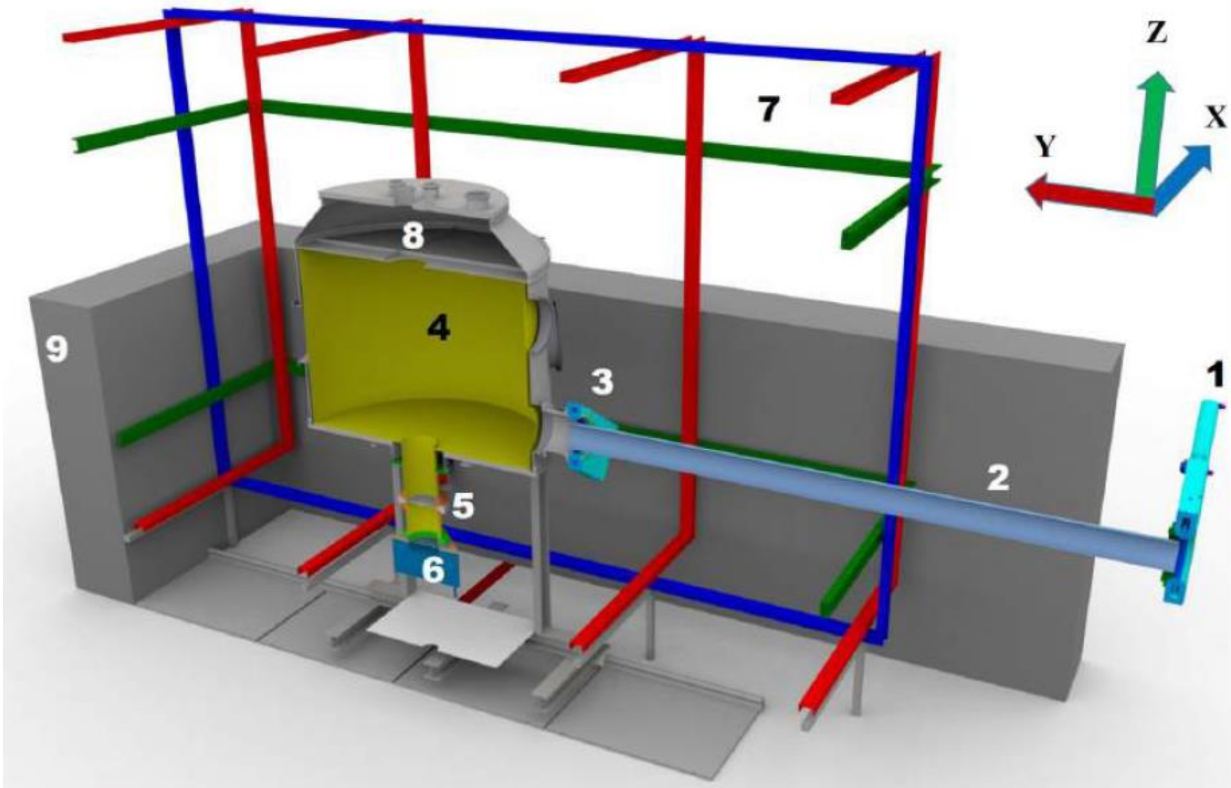
- If *B'* originates in the Sun or in Milky Way, the *n-n'* signal should reveal daily and sidereal modulation, respectively

P. Mohanmurthy,
PhD Thesis (ETH Zurich 2019)
/doi .org /10 .3929 /ethz -b -000417951.



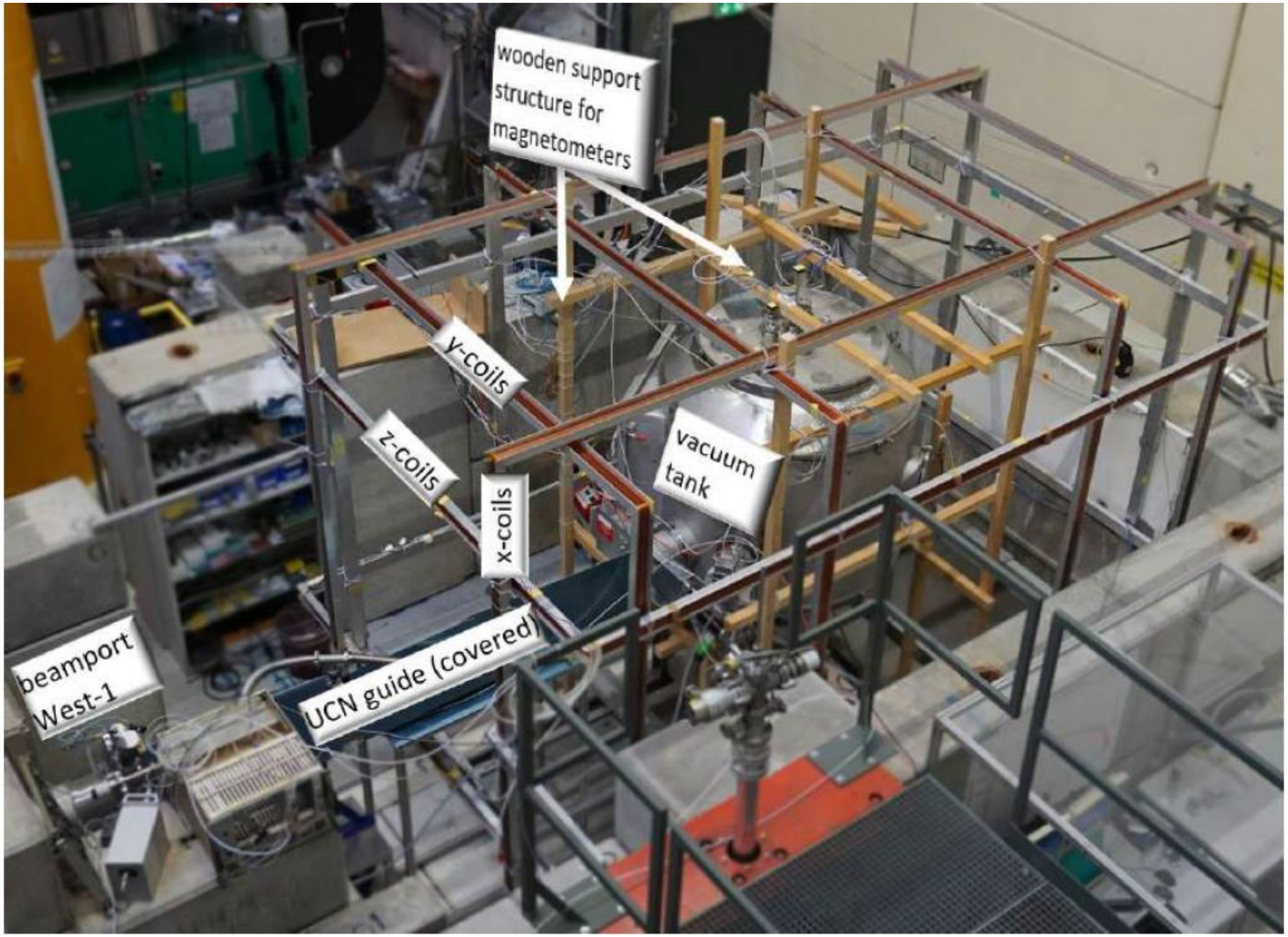


Dedicated experiment at PSI - setup

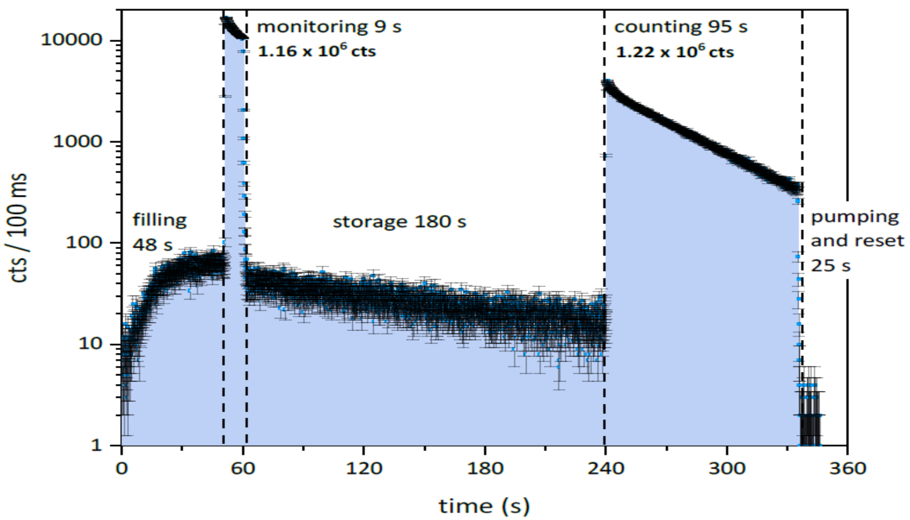


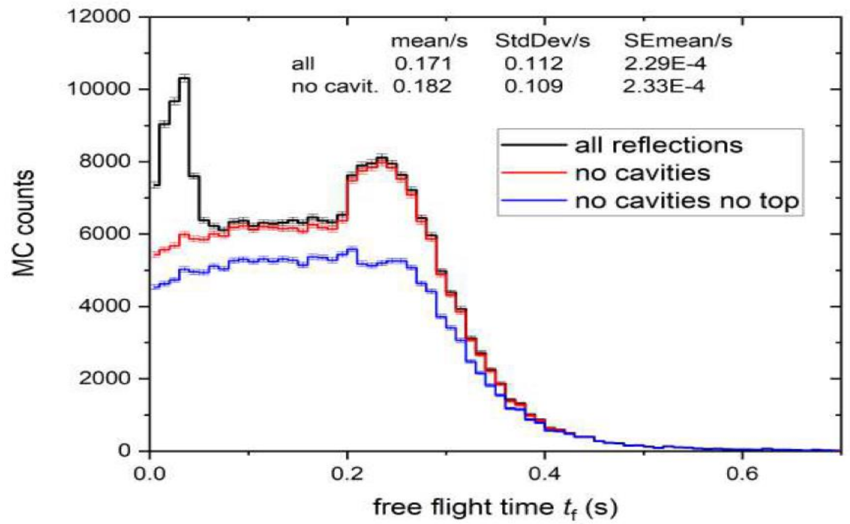
1. West-1 beamport shutter,
2. 275 cm long coated glass guide
3. Vacuum tight shutter
4. Electropolished stainless steel storage volume (≈1.5 m^3)
5. Fast butterfly shutter,
6. Cascade UCN detector,
7. 3D Helmholtz coil system
8. Vacuum system including the large vacuum tank.

Dedicated experiment at PSI – setup



Dedicated experiment - analysis

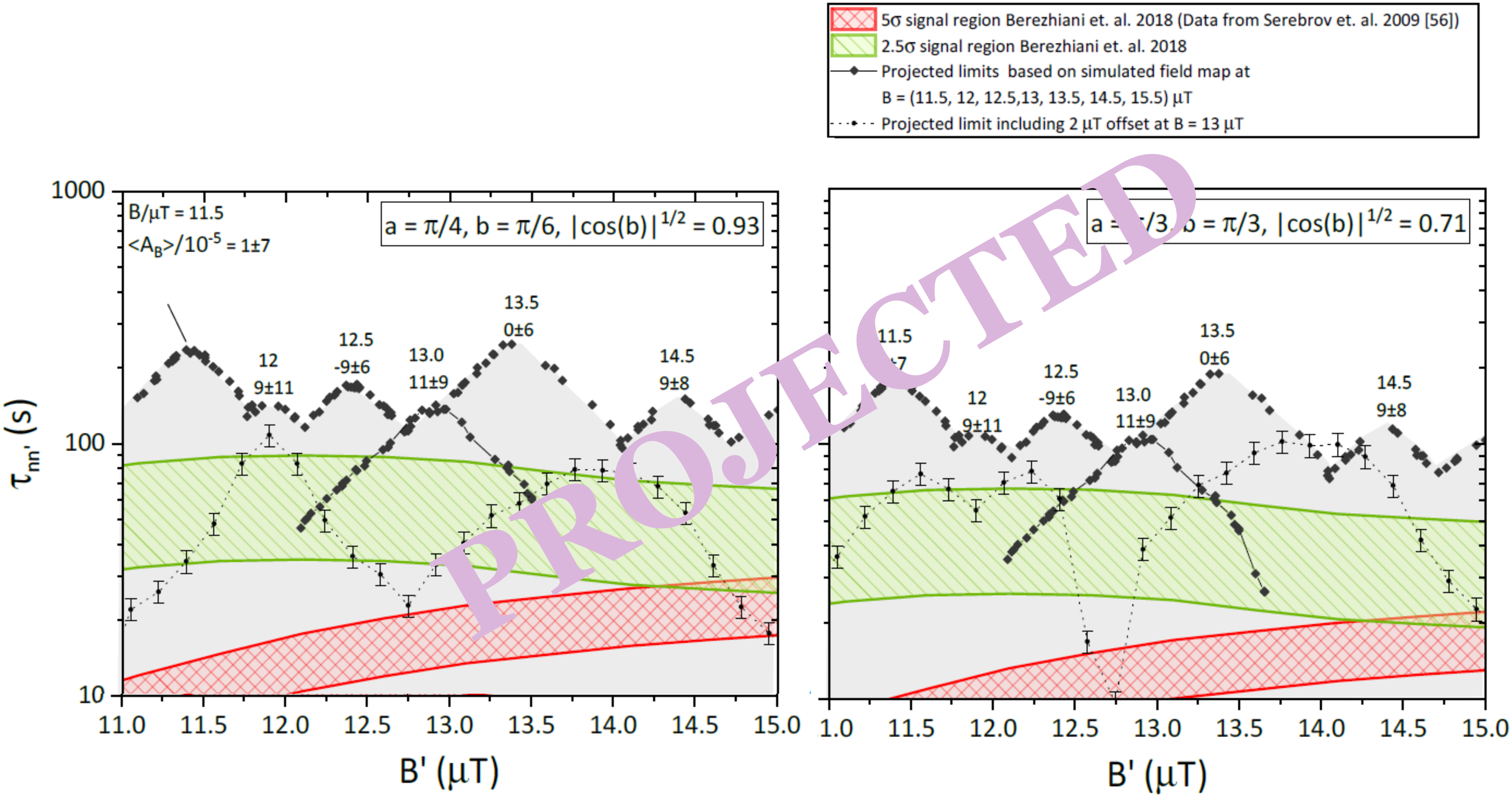




- Data taken in the range *B* = 5 – 360 μT (high statistics in critical range of potential *n*-*n*' signal)
- More reliable information on the UCN velocity spectrum ⇒ smaller systematic uncertainty of $\langle t_f \rangle$
- Analysis more demanding due to *B*-field non-uniformity in the storage ⇒ detailed field map must be implemented

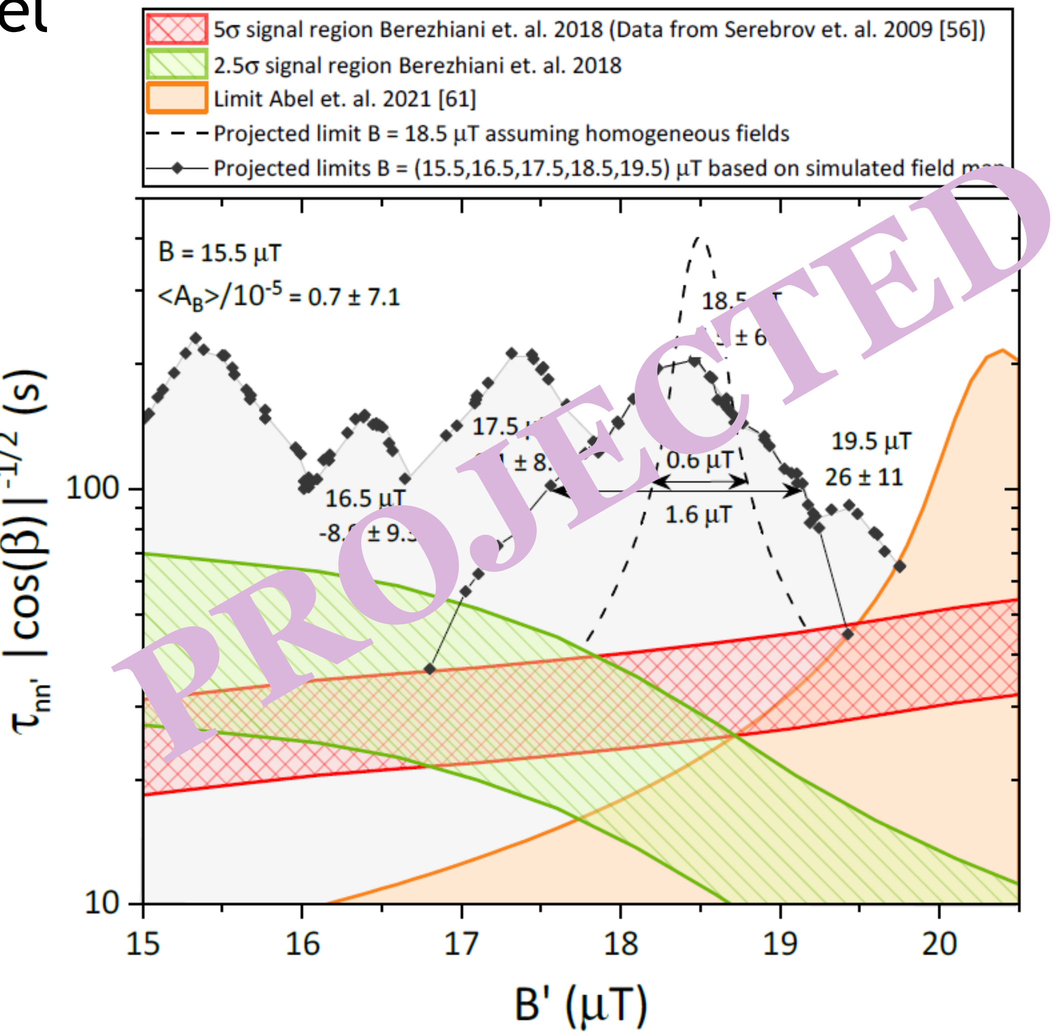
Dedicated experiment at PSI - results

- Ratio channel



Dedicated experiment at PSI - results

- Asymmetry channel



Summary and outlook

- Concept of Mirror Mater still not ruled out
- If discovered, could help solving several physics problems
- Search for *n*-*n*’ oscillation is ongoing
- Analyses are model dependent (e.g. origin and strength of mirror-magnetic field)
- Observed tension in the exclusion plots in the range of few μT partially excluded by measurement in the nEDM apparatus at PSI
- Dedicated experiment covering 5<*B*’<360 μT completed data taking; data analysis is advanced

nEDM Collaboration at PSI

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Department of Chemistry, Johannes Gutenberg University Mainz, Mainz, Germany

Institut Laue-Langevin, Grenoble, France

Backup slides

Fundamental neutron physics

- **Main goal of Particle Physics:**

  Establish consistent picture of Nature's fundamental interactions

  - **High Energy PP:**
    - Operates at TeV scale (10^{12} eV)

      $\Rightarrow$ study of 2nd (s, c, μ, ν_μ) and 3rd (b, t, τ, ν_τ) particle families

  "ENERGY frontier"

  - **Low Energy PP (e.g. with neutrons):**
    - Operates at neV scale (10^{-9} eV)

      $\Rightarrow$ study of 1st (u, d, e, ν_e) particle family
    - Reveals respectable sensitivity:
      - Energy: $\Delta E/E \sim 10^{-11} \div 10^{-13}$ ($\Delta E \sim 10^{-23}$ eV)
      - Momentum: $\Delta p/p \sim 10^{-10} \div 10^{-11}$
      - Spin polarization: $\Delta s/s \sim 10^{-7}$

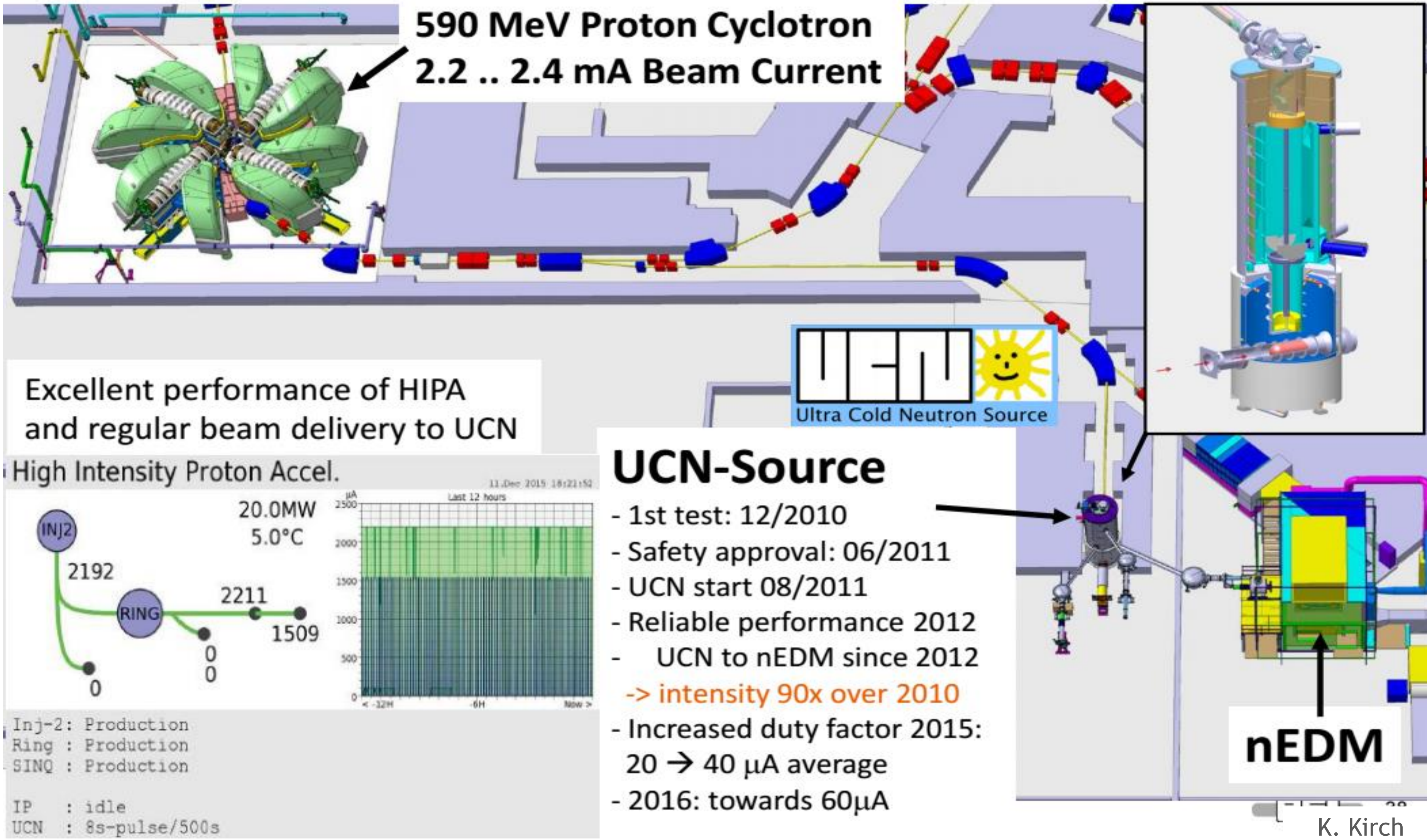
  "PRECISION (intensity) frontier"

  - *Fundamental neutron physics provides more than **20** observables reach in information which is difficult to achieve (or not achievable at all) in other fields of Particle Physics*

Ultra Cold Neutrons (UCN)

- **Discovery:**
  - **Y. Zeldovich, 1959: UCN can be stored in material vessels**
  - **Shapiro group (Dubna), 1969:** first experiment with UCN
- **Storage time:**
  - Wall collision losses can be as small as 10^{-6} (per collision) for certain materials and proper surface morphology
  - Storage time depends on wall collision frequency in the storage vessels and may be comparable with the neutron lifetime (880 s)
  - In nEDM experiment at PSI storage time is about 200 s
- **UCN production via moderation of CN:**
  - Earth gravitational field and/or scattering from turbine blades (ILL)
  - Super-thermal process e.g. in solid D_2 (PSI, LANL, GUM) or super-fluid He (ILL; in development)

Ultra-cold Neutron Source and Facility at PSI



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: towards 60μA

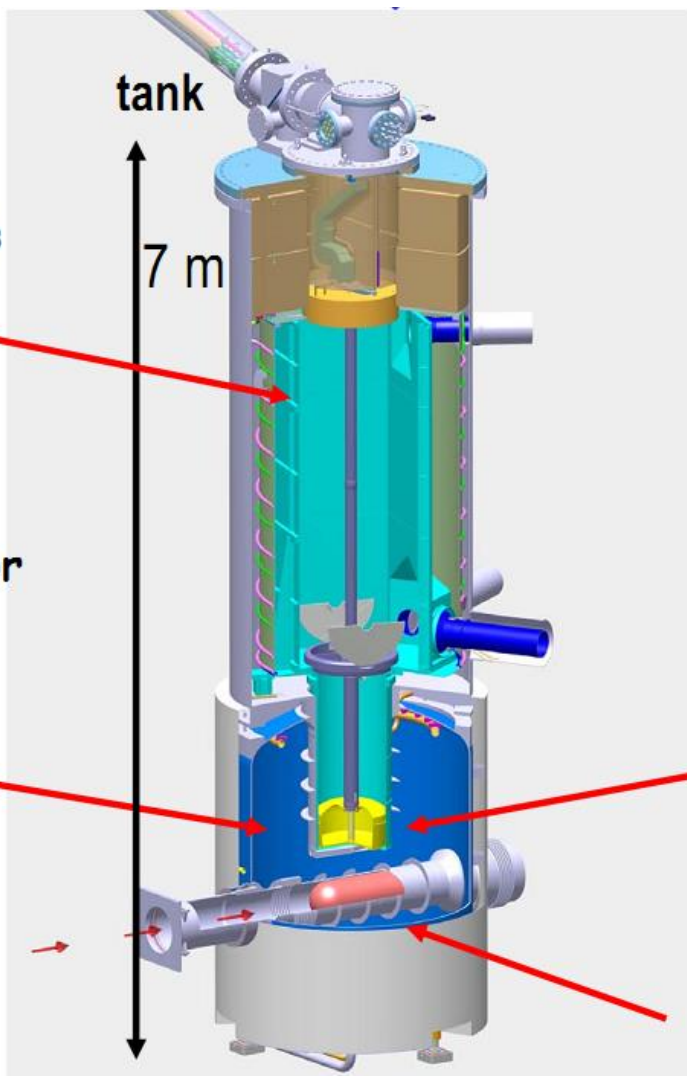
K. Kirch

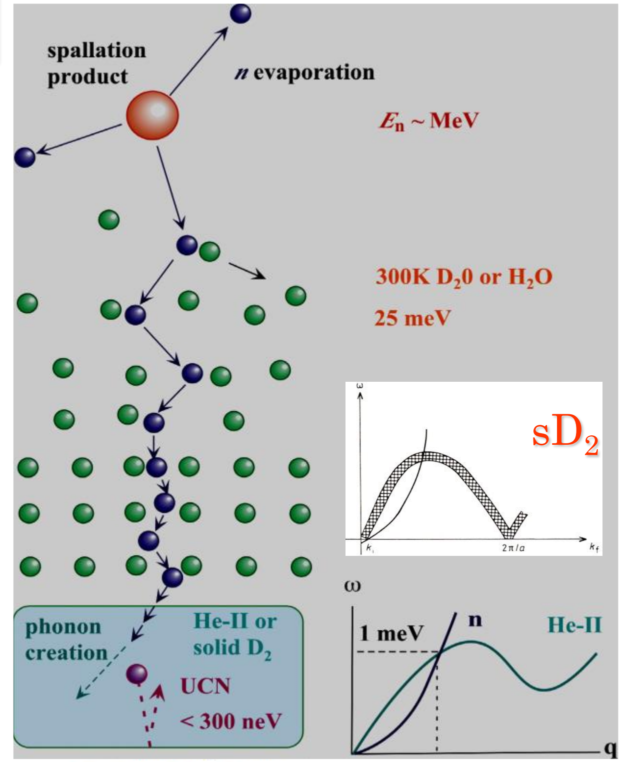
UCN spallation source at PSI

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

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
2% duty cycle





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

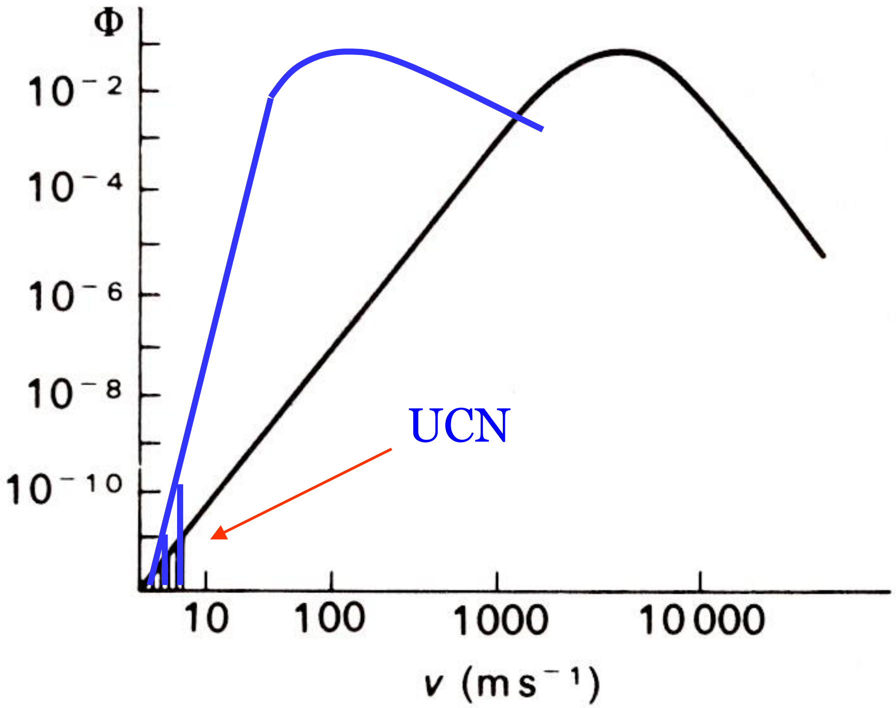
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

UCN production methods

- UCN are present in the moderator of fission reactor but they are rare there and impossible to extract (Fermi potential barrier)

$$\frac{\Phi_{\mathrm{UCN}}}{\Phi_0} \approx 5\times10^{-12}$$

$$\rho_{\mathrm{UCN}} \approx 10^{-13}\,\Phi_0\,\mathrm{cm}^{-3}$$

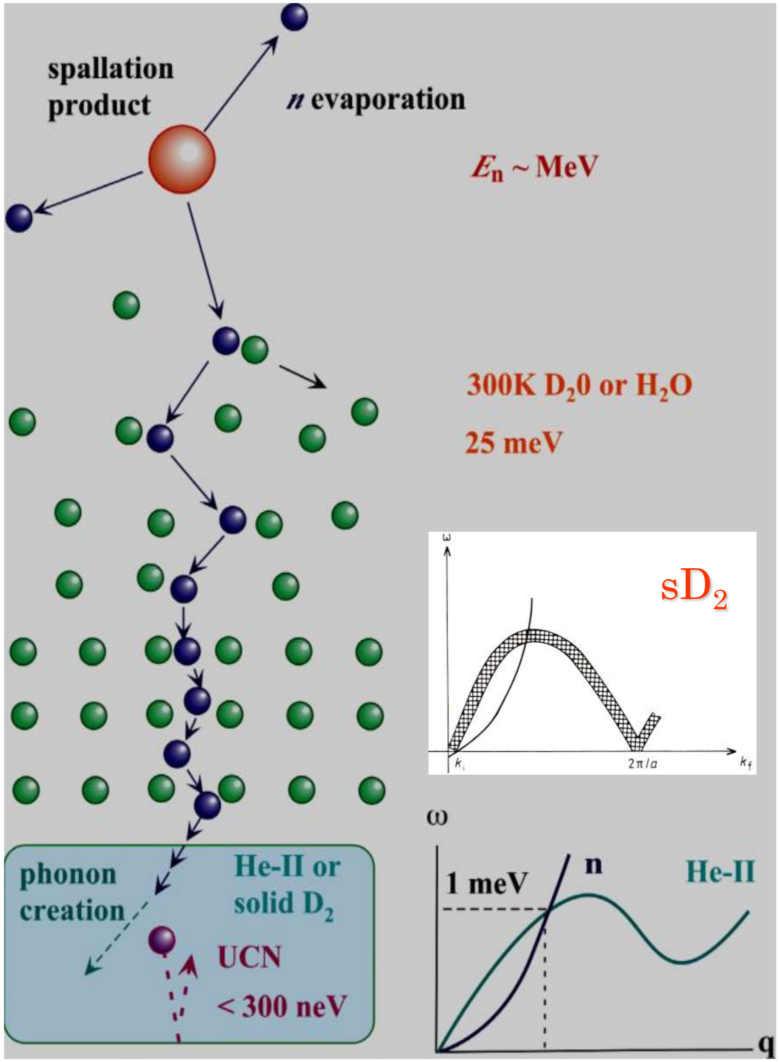


- Cooling moderator (~20 K) improves situation insignificantly

Super-thermal sources

- „Fool" Liouville's theorem:
  - Energy dissipation in super-thermal converter
  - Size of phase space occupied by neutron states decreases on cost of increasing phase space of converter space ⇒ increases UCN density
  - Liouville's theorem is fulfilled in the total system (UCN + converter)

- Super-thermal process:
  - Inelastic scattering of cold neutrons with creation of phonons (or magnons) in e.g. sD_2, sO_2, sCH_4
  - Creation of rotons in super-fluid He



Intensity proton machines