Neutron Mirror-Neutron oscillations at high magnetic fields

William Sáenz Arévalo

PhD director: T. Lefort

GDR-InF annual workshop

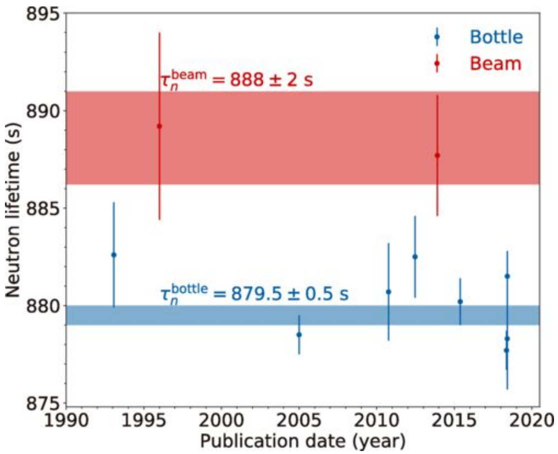
Nov 15 – 17, 2021
LPNHE

Outline

- Why a mirror universe?
- Theoretical background
- State of the art
- Experimental setup
- Preliminary results

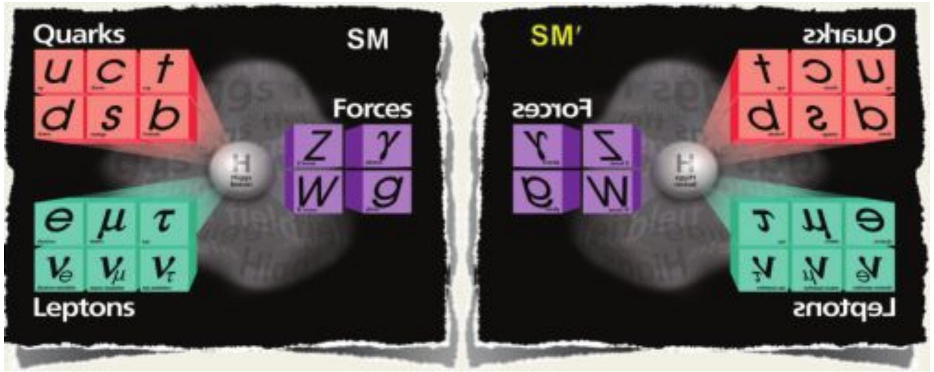
Why a mirror universe?

- An alternative solution to
  - P-symmetry breaking in a global sense
  - new sources of CP violation (baryogenesis)
  - neutron lifetime puzzle
  - dark matter



[Jack T. Wilson, et al, Phys. Rev. Res 2, 023316 (2020)]

- Hypothesis: there is a mirror coexisting universe where all particles would have a mirror twin



$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$

Theoretical background

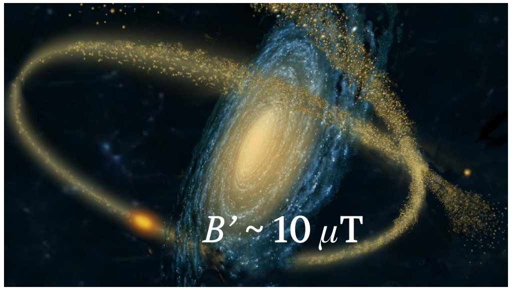
- Mixing between universe and mirror universe would be possible for neutral particles
- In particular, for neutrons under magnetic fields:

[Berezhiani, Z. (2009). Eur. Phys. Jou C, 64(3)]

$$\hat{H} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & \mu\vec{\sigma}\cdot\vec{B'} \end{pmatrix}$$

Mixing term (measured quantity)

Mirror magnetic field



Theoretical background

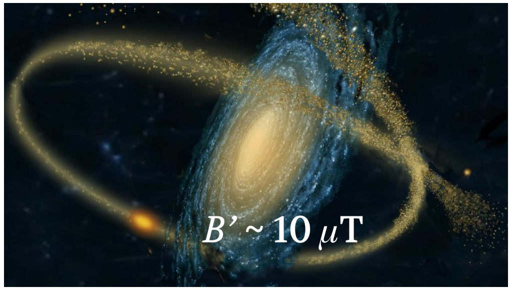
- Mixing between universe and mirror universe would be possible for neutral particles
- In particular, for neutrons under magnetic fields:

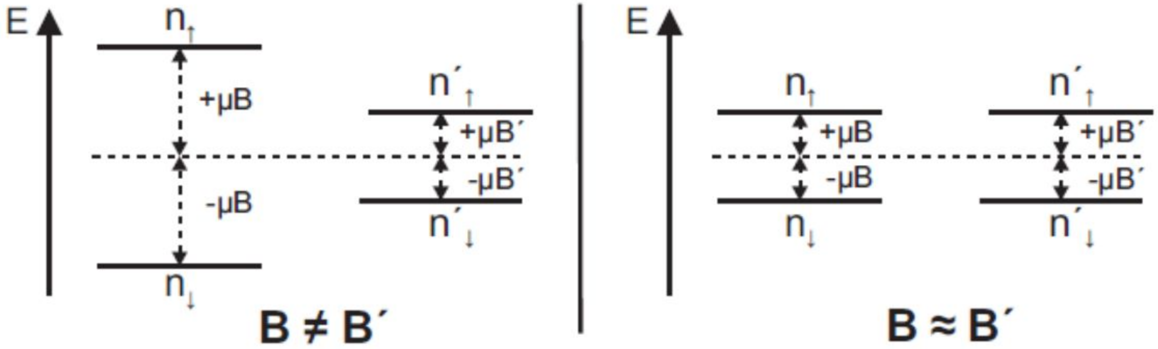
[Berezhiani, Z. (2009). Eur. Phys. Jou C, 64(3)]

Mixing term (measured quantity)

$$\hat{H} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & \mu\vec{\sigma}\cdot\vec{B'} \end{pmatrix}$$

Mirror magnetic field





Theoretical background

- **Mixing between universe and mirror universe would be possible for neutral particles**
- **In particular, for neutrons under magnetic fields:**
  [Berezhiani, Z. (2009). Eur. Phys. Jou C, 64(3)]

$$\hat{H} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & \mu\vec{\sigma}\cdot\vec{B}' \end{pmatrix}$$

Mixing term (measured quantity)

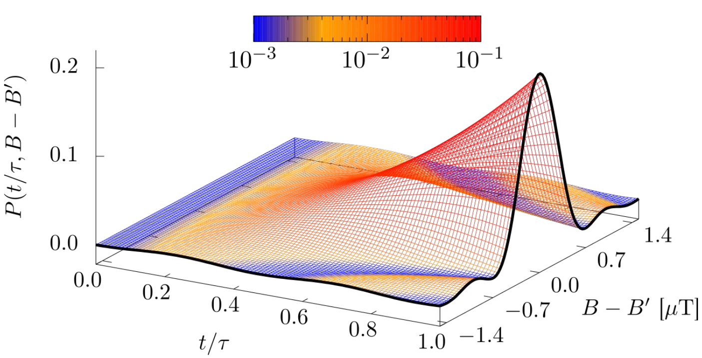
Mirror magnetic field

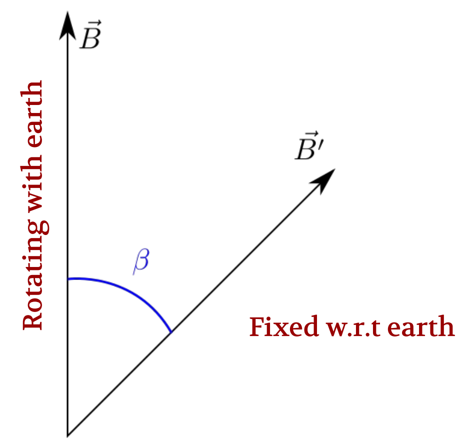
- **Oscillation probability given by**

$$P_{nn'}(t) = \mathcal{P}_{\vec{B}}(t) + \mathcal{D}_{\vec{B}}(t)\cos\beta$$

$$\mathcal{P}_{\vec{B}}(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau_{nn'}^2(\omega-\omega')^2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau_{nn'}^2(\omega+\omega')^2}$$

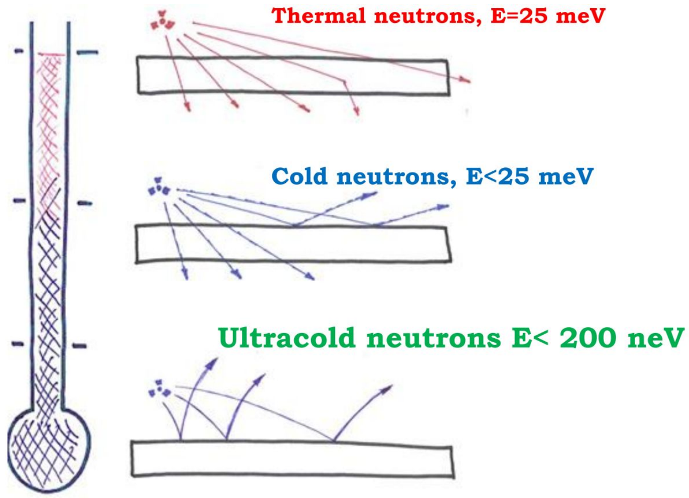
$$\mathcal{D}_{\vec{B}}(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau_{nn'}^2(\omega-\omega')^2} - \frac{\sin^2[(\omega+\omega')t]}{2\tau_{nn'}^2(\omega+\omega')^2}.$$



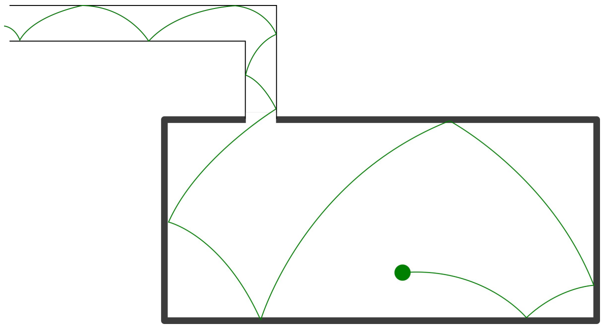


Theoretical background

- Why working with ultra-cold neutrons (UCN) ?

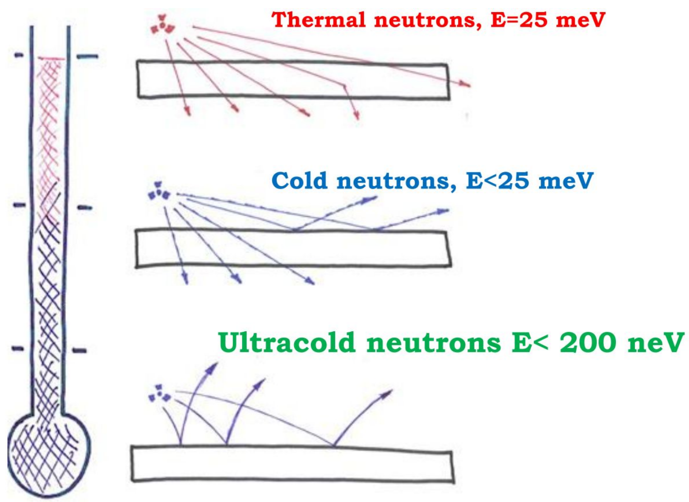


$K_{ucn} < V_F \sim 200$ neV $\rightarrow$ Total reflection

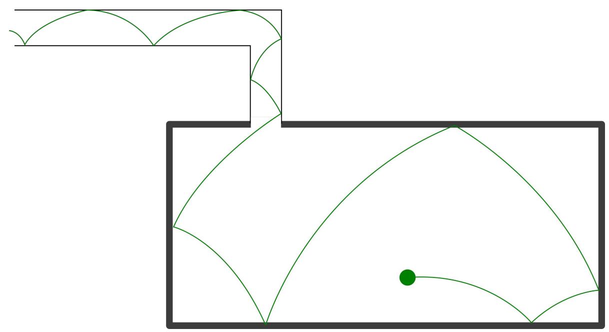


Theoretical background

- Why working with ultra-cold neutrons (UCN) ?



$K_{ucn} < V_F \sim 200$ neV $\rightarrow$ Total reflection



$$N(t) = N_0 \exp(-R_{\text{tot}} t_s)$$

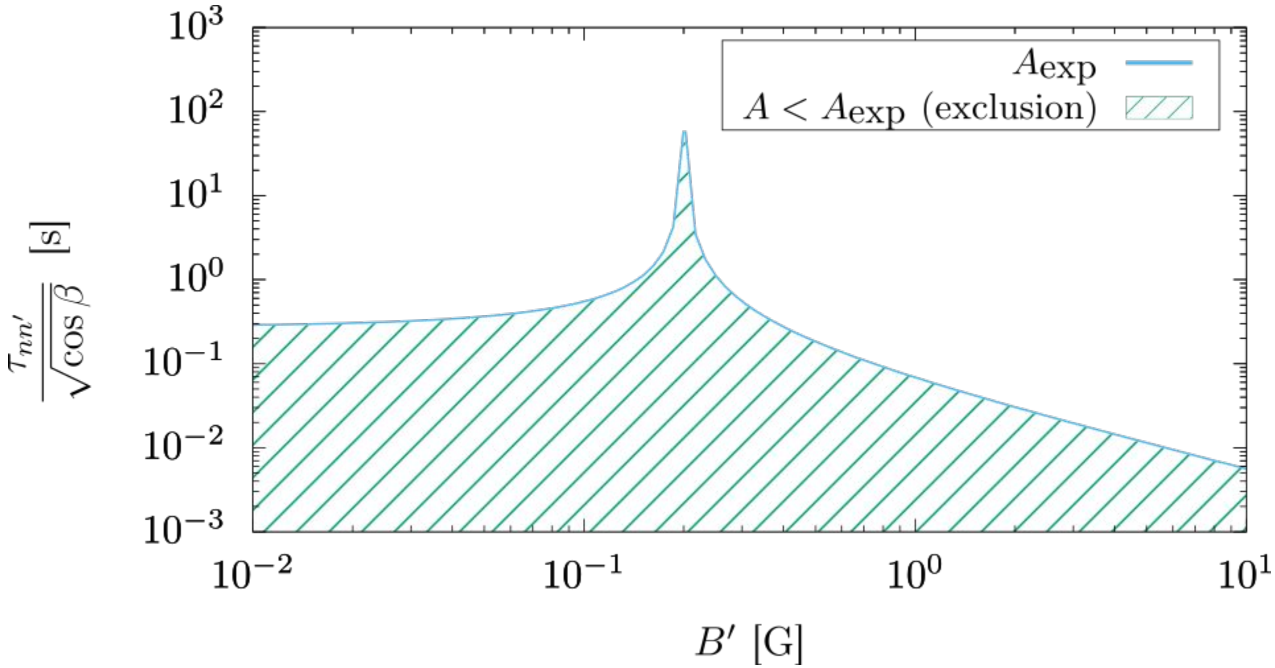
$$R_{\text{tot}} = R^{\beta} + R^{\text{up-scattering}} + R^{\text{absorption}} + R_B^{nn'}$$

… the asymmetry A depends only on the terms sensitive to *B:*

$$A = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx n_s \bar{D}_{\vec{B}} \cos\beta = n_s \frac{\langle \sin^2[(\omega - \omega')t_f] \rangle}{2\tau_{nn'}^2 (\omega - \omega')^2} \cos\beta$$

n_s : number of wall collisions

Theoretical background

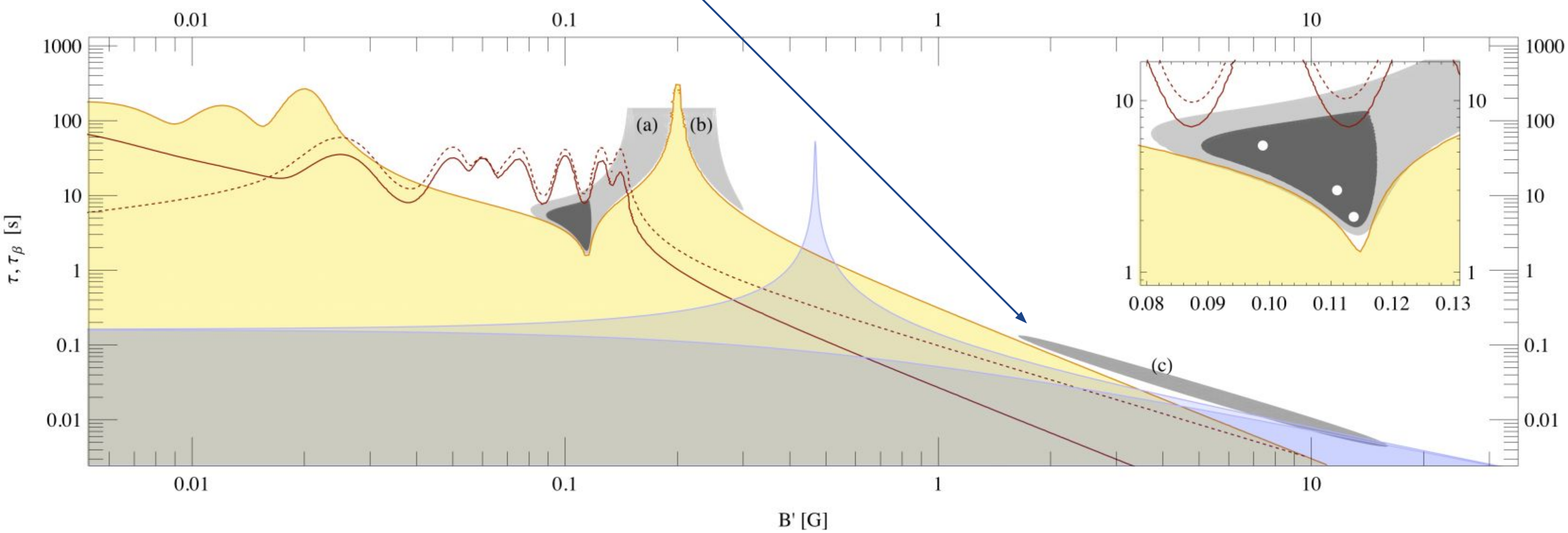


$$A = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx n_s \bar{\mathcal{D}}_{\vec{B}} \cos\beta = n_s \frac{\left\langle \sin^2[(\omega - \omega')t_f] \right\rangle}{2\tau_{nn'}^2 (\omega - \omega')^2} \cos\beta$$

exclusion regions in the oscillation parameters space

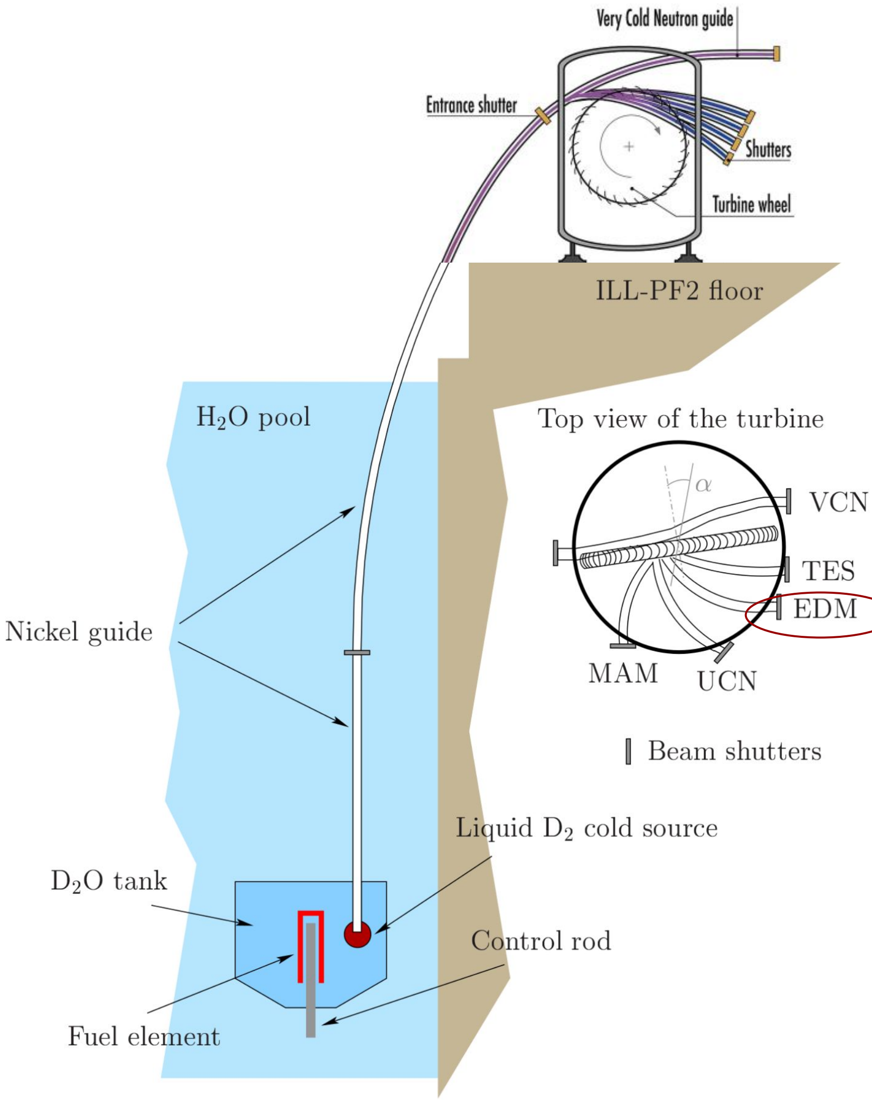
State-of-the-art

- Past UCN trap experiments have shaped the parameter space
- A 5σ anomaly [Berezhiani, 2012] proposed three regions of interest (a), (b) and (c)
  - (a) and (b) were recently revised without positive confirmation
  - region (c) is the aim of this work

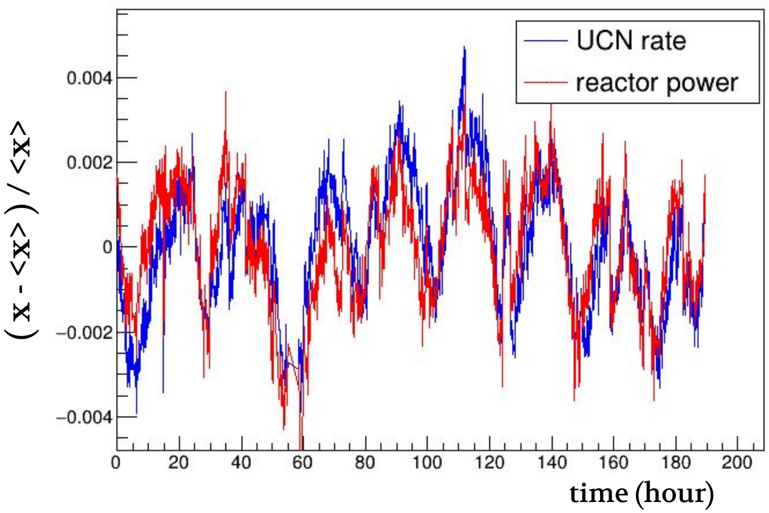


[Berezhiani, Z., & Nesti, F. (2012). Eur. Phys. Jour. C, 72(4).]

UCN source

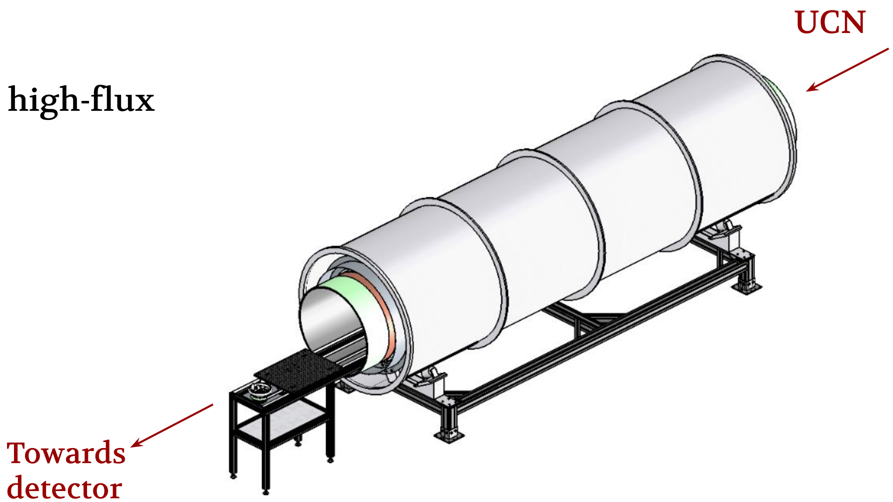


- Neutrons from ^{235}U fission at ILL's reactor
- Neutron flux: 1.5×10^{15} $cm^{-2}s^{-1}$, with a thermal power of 58.3 MW
- UCN flux: 3.3×10^4 $cm^{-2}s^{-1}$ for $v_z < 7$ m/s
- UCN flux at experiment port: ~ 4×10^5 s^{-1}



Experimental setup

- N-N' oscillations at B in 50 - 1000 μT
- No UCN storage → We look at the drop of the high-flux UCN beam



- Uniform B-field applied at the UCN guide
  - Solenoid
    - StdDev ~ 30 nT with I=1.7 A
    - 4.8 m long
    - 80 cm diameter
  - Compensation coils at both ends (I = 2.5 A)
  - Mu-metal shielding:

Measuring technique

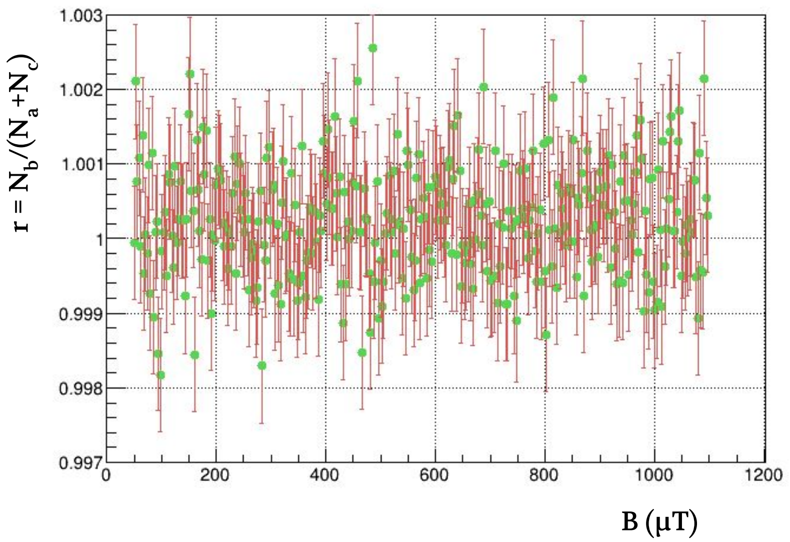
- UCN Flux drop at field B relative to A and C

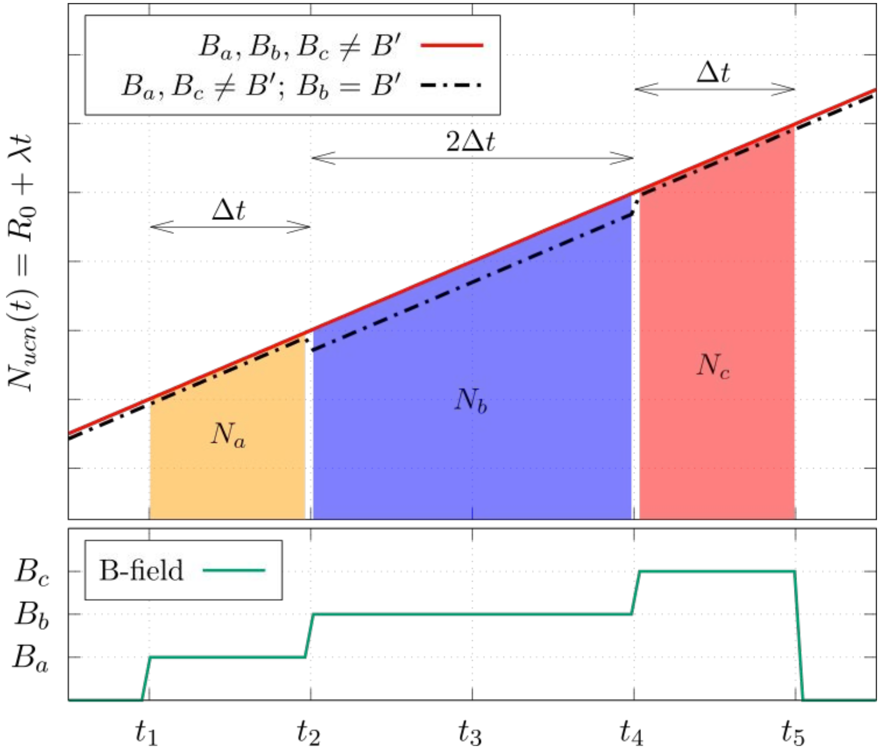
$$r = \frac{N_b}{N_a + N_c}$$

- Experimental sensitivity

$$r \approx 1 - \frac{t_f t_{\rm tot}}{\tau_{nn'}^2} \qquad \tau > \sqrt{\frac{t_f t_{\rm tot}}{1 - r + 1.65\Delta r}}$$

if t_f = 50 ms, t_{tot} = 1 s, and $\Delta r = 5 * 10^{-4}$: **$\tau_{nn'}$ > 4 s**

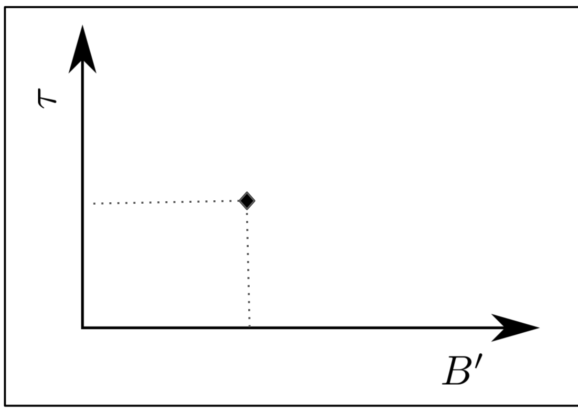


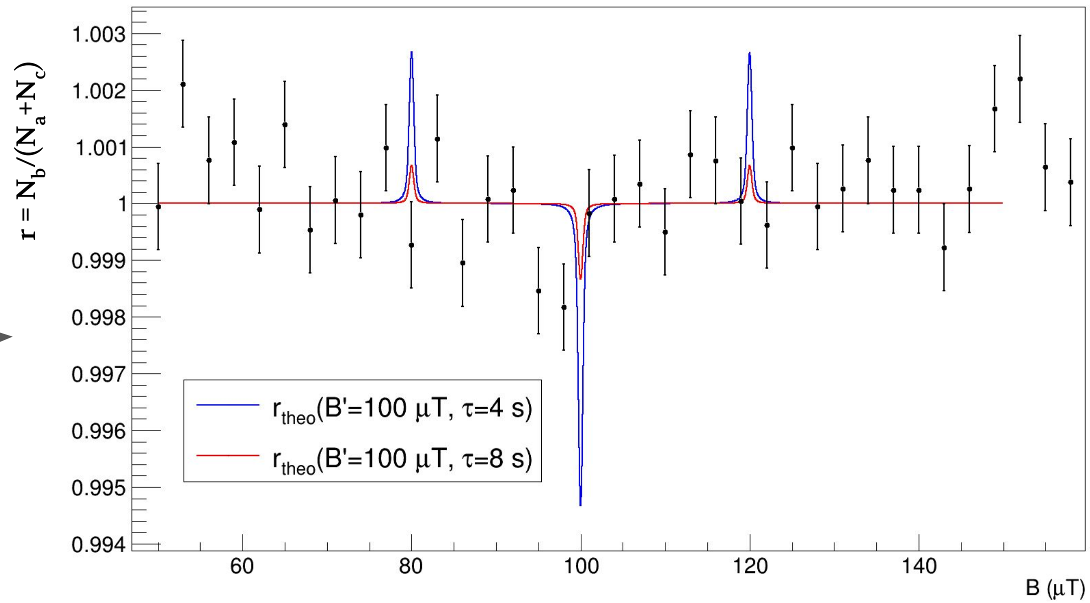


From $N_b/(N_a+N_c)$ to parameter exclusion

- We compare model predictions within the parameter space region of interest to data and produce exclusion plots

If resonance at (B', τ), r should look like….

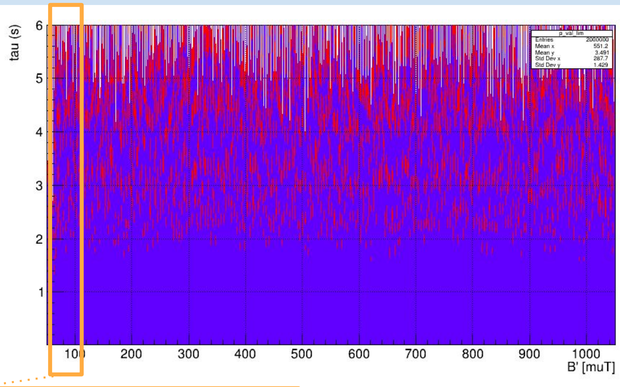




- Triple signal pattern due to construction of r: resonance could happen at $B = B_a$, B_b or B_c

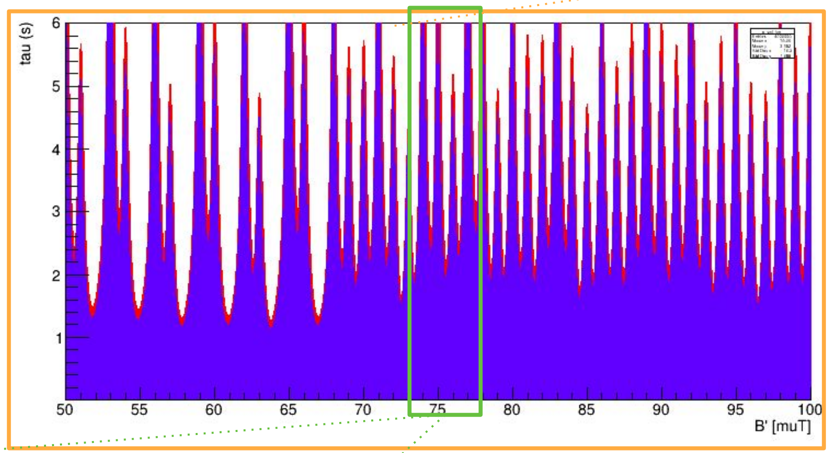
- If τ too big, possible signals hidden in statistical fluctuations

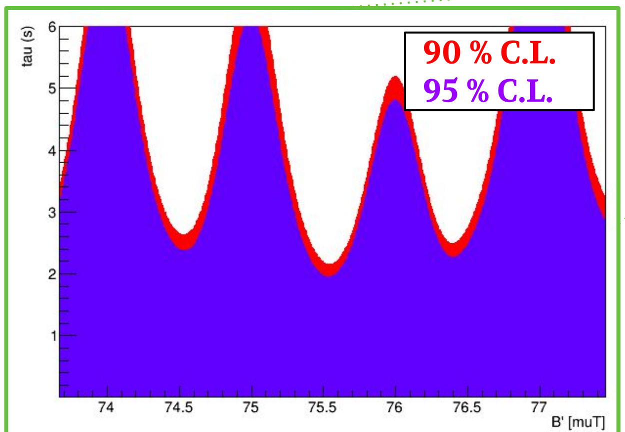
Parameter space exclusion



Preliminary analysis:

- Exclusion from statistics $\chi^2 = \Sigma(r_{exp} - r_{theo})^2/\delta r_{exp}^2$
- Each maximum corresponds to a single cycle (data point)

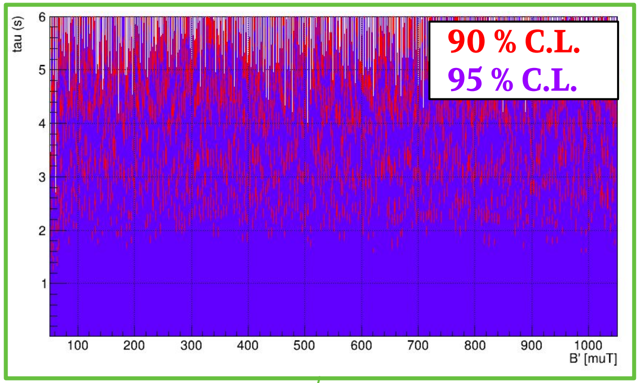


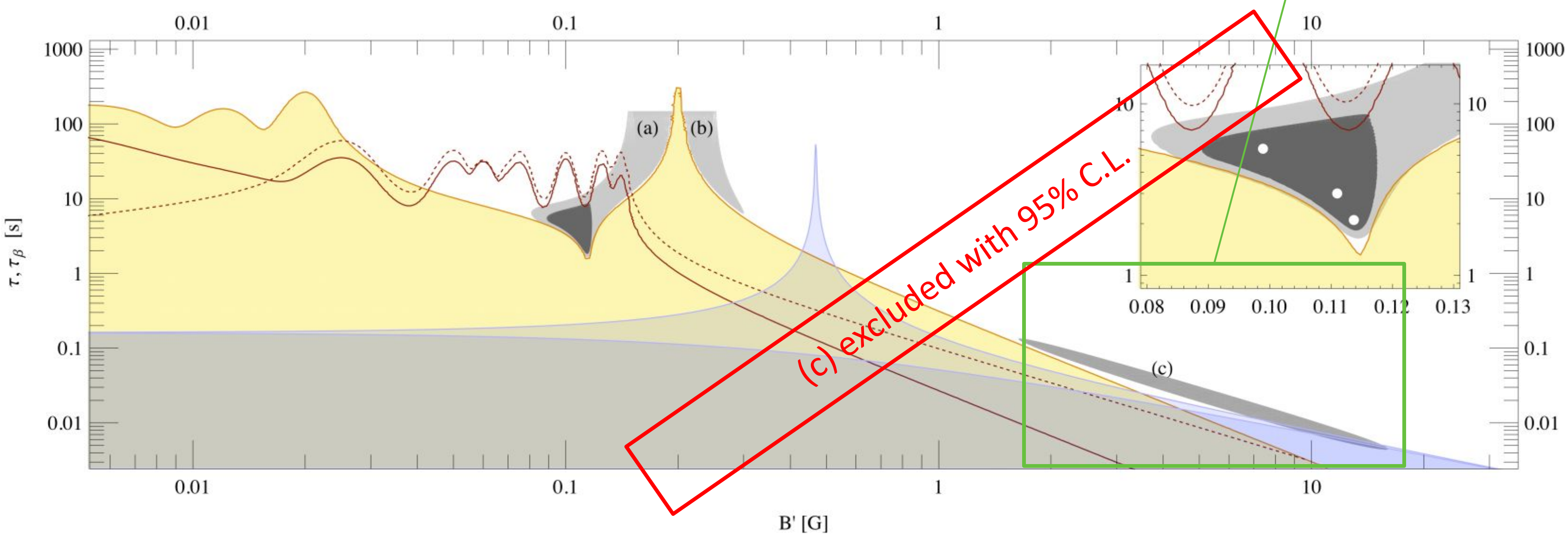


Parameter space exclusion

Preliminary analysis:

- Exclusion from statistics $\chi^2 = \Sigma(r_{exp} - r_{theo})^2/\delta r_{exp}^2$
- Each maximum corresponds to a single cycle (data point)
- Region (c) excluded!





Thank you

Spare

Scanning high magnetic fields: UCN detection

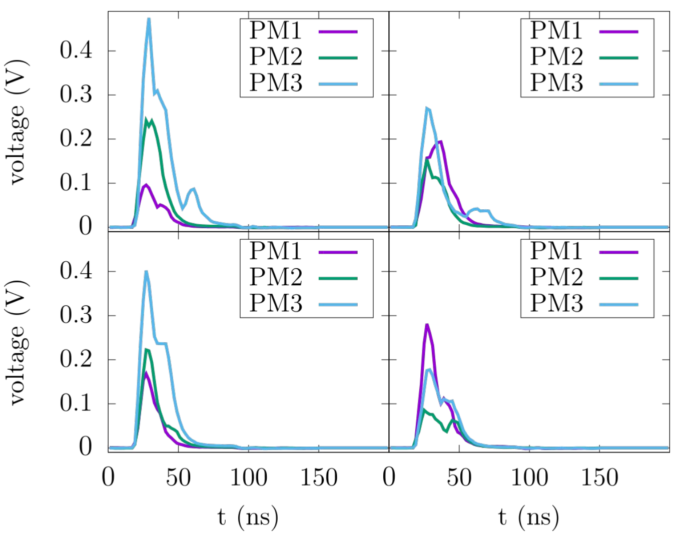
GADGET detector developed at LPC
^{3}He and CF_4 gas mixture:

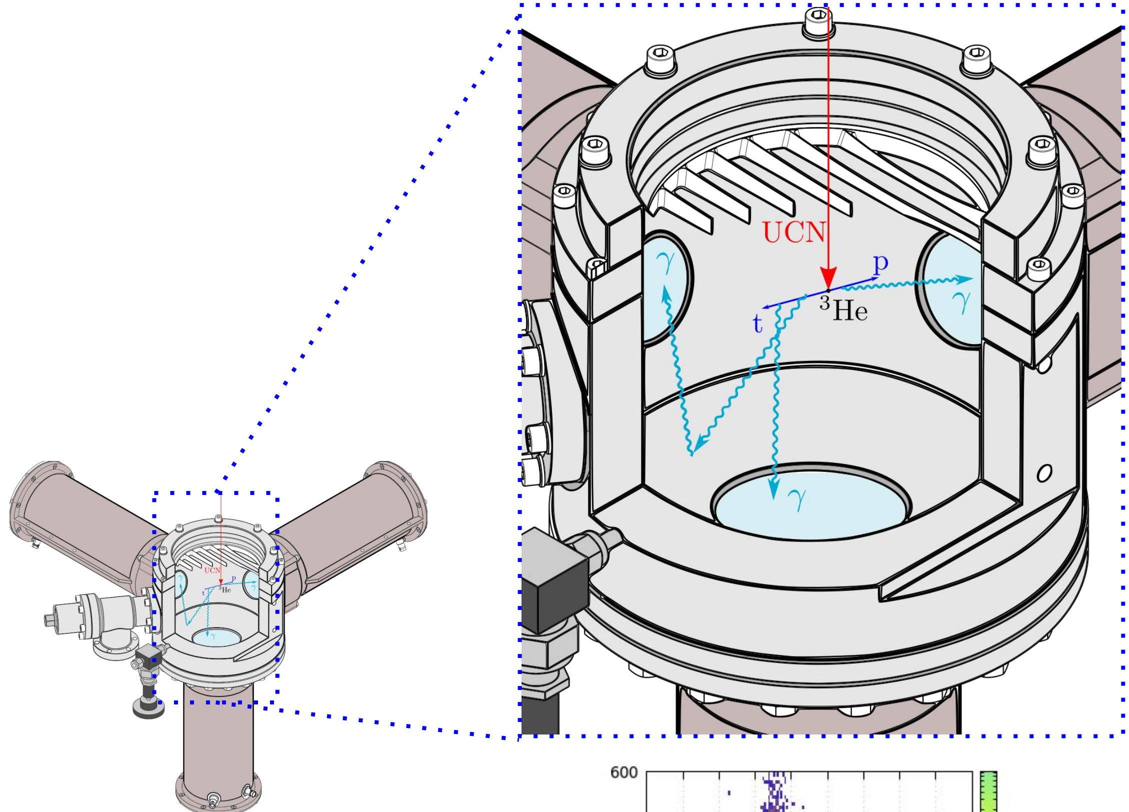
1. UCN absorption

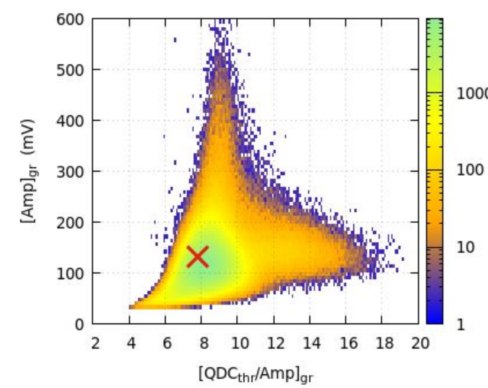
   $n + {}^3He \rightarrow p\ (0.57\ MeV) + t\ (0.19\ MeV)$

2. **CF_4 scintillation due to p and t ionization/excitation.**

3. Light collection by 3 PM tubes working in coincidences







State-of-the-art

- Mixing between universe and mirror universe would be possible for neutral particles
- In particular, for neutrons under magnetic fields, the Hamiltonian is expressed as

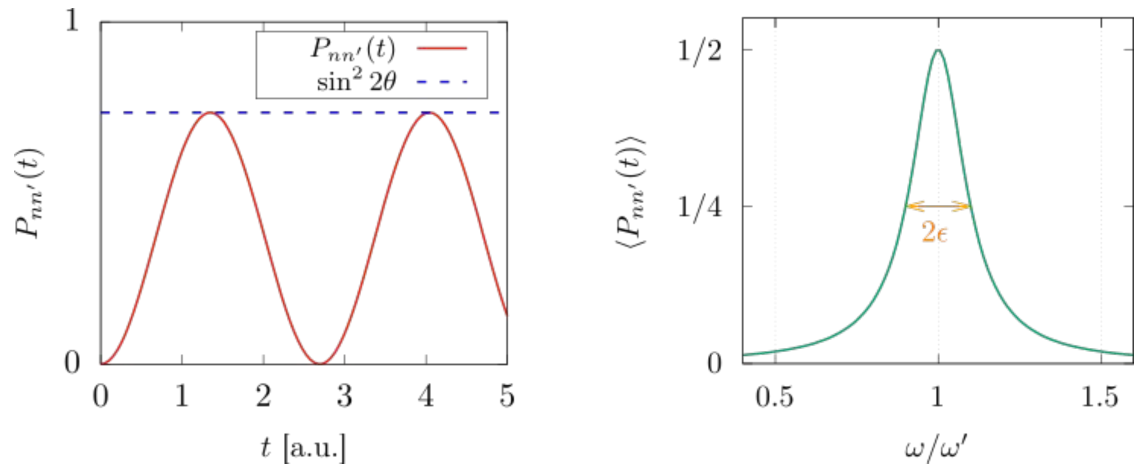
$$\hat{H} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & \mu\vec{\sigma}\cdot\vec{B'} \end{pmatrix} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & \epsilon \\ \epsilon & \mu\vec{\sigma}\cdot\vec{B'} \end{pmatrix}$$

Mixing term

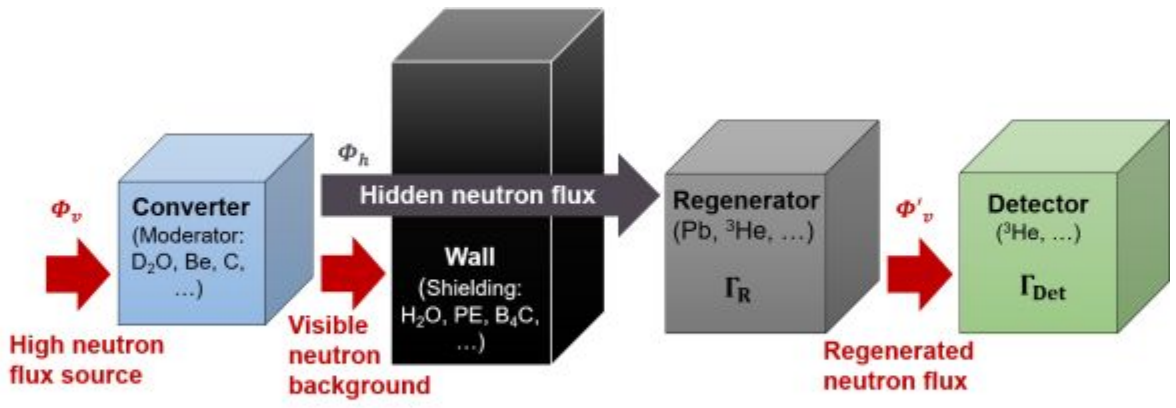
- If B // B' the n-n' oscillation probability takes the form of the Rabi oscillations:

$$P_{nn'}(t) = \frac{\epsilon^2}{\epsilon^2 + (\omega - \omega')^2} \sin^2\left(\sqrt{(\omega - \omega')^2 + \epsilon^2}\,t\right).$$

$$\sin^2 2\theta = \frac{\epsilon^2}{\epsilon^2 + (\omega - \omega')^2}$$



Passing-through-walls neutron experiments



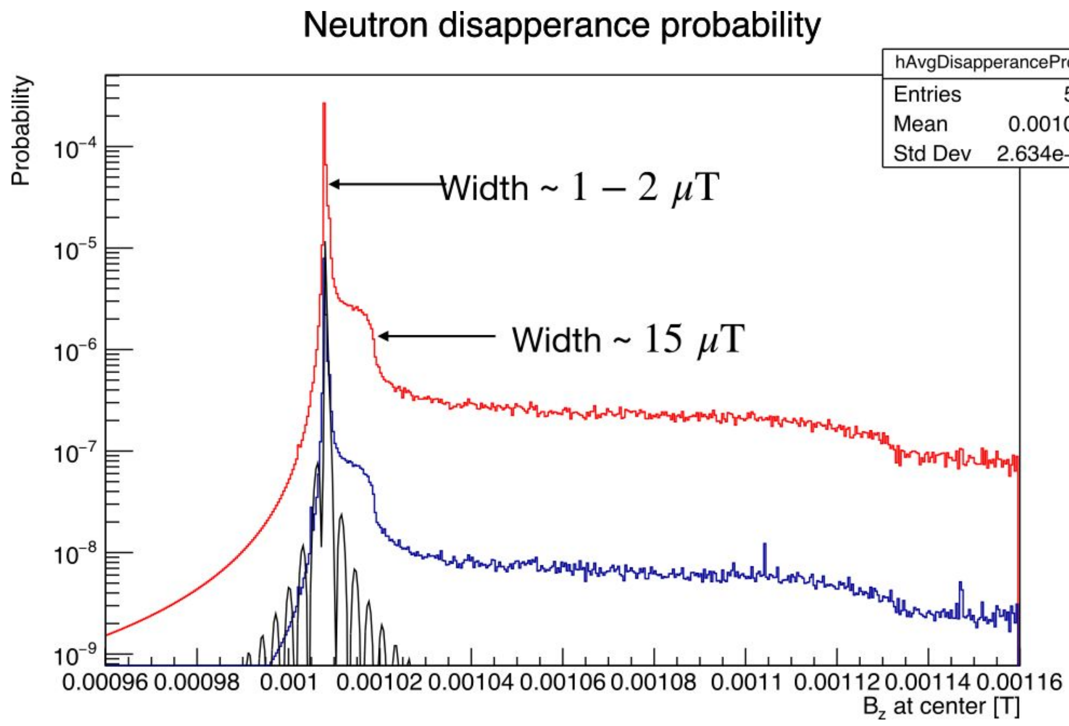
[C. Stasser, *et al.*, Eur. Phys. J. C 81, 17 (2021)]

Size of the B-field step (in a cycle)

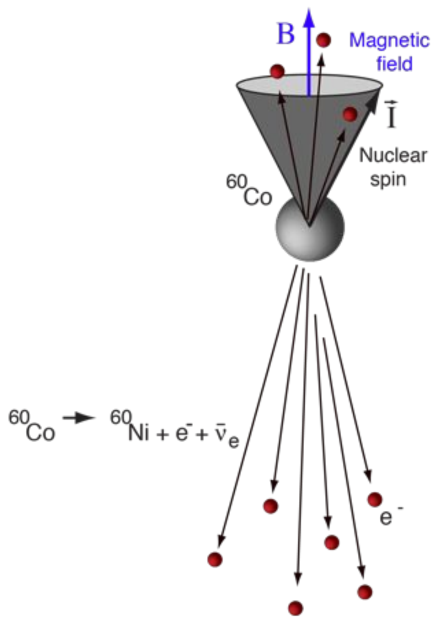
MC simulation of tracks: StarUCN
Field maps: COMSOL

Validation:

B' = 1.008 mT
tau = 10 s



P-violation ?



- 1957 Wu's experiment showed beta emissions had a preferred direction, i.e., beta decay violates P-symmetry

- 7 years later, in order to keep CP invariance, a mirror or "shadow" universe was proposed (SM did not exist yet)

  … then, even if ^{60}Co β -particles prefer direction -B
  ^{60}Co' β'-particles would prefer direction +B'

  so restoring the global P-symmetry!

Reactor power ratio r

- Fluctuation in the detector as big as the ones in the reactor power
- Correlation coefficient: $\rho = 0.42$