FPSTS-19 Workshop at ORNL • July 27, 2019

Neutron Oscillation searches

Yuri Kamyshkov / UTK
email: kamyshkov@utk.edu

Neutron Oscillations are hypothetical process that can occur in Nature and related to fundamental science questions.

$n \leftrightarrow \bar{n}$

- Violates Baryon number B by 2 units;
- Violates $(B - L)$ by -2 units;
- Can occur below E-W transition energy scale;
- Best testable candidate for BAU and baryogenesis.
- Experimentally limited to $\tau \gtrsim 10^8$ s

Review: D.G. Phillips et al., Phys. Rept. 612 (2016)

$n \leftrightarrow n'$

- n'particle from (sterile, parallel, hidden) mirror sector;
- Violates B by -1, and B' by +1. Global $\tilde{B}$ conserved;
- May be part or whole of the Dark Matter in universe;
- Experimentally can be $\tau \lesssim 1000$ s;
- Has a reach phenomenology due to MM connection;
- It may be the process revealing the nature of DM.

Z. Berezhiani et al., Phys. Rev. Lett. 96 (2006) 081801 + …

In vacuum in the absence of any fields

and neglecting n decay

$n \leftrightarrow \bar{n}$:

$$i\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} m & \varepsilon \\ \varepsilon & m \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

$P_{nn} = cos^2(\varepsilon t)$ $\quad$ $P_{n\bar{n}} = sin^2(\varepsilon t)$

$n \leftrightarrow n'$:

$$i\frac{\partial}{\partial t}\begin{pmatrix} n \\ n' \end{pmatrix} = \begin{pmatrix} m & \epsilon \\ \epsilon & m \end{pmatrix}\begin{pmatrix} n \\ n' \end{pmatrix}$$

$P_{nn} = cos^2(\epsilon t)$ $\quad$ $P_{nn'} = sin^2(\epsilon t)$

$n \leftrightarrow \bar{n}$:

$$\mathcal{H} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \varepsilon \\ \varepsilon & m - \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} \end{pmatrix}$$

$$P_{n\bar{n}} = \frac{\varepsilon^2}{\varepsilon^2 + (\mu B)^2} sin^2\left(t\sqrt{\varepsilon^2 + (\mu B)^2}\right) \xrightarrow{B\rightarrow 0} = (\varepsilon t)^2$$

Large magnetic field B suppresses transformation,
B should be close to zero for $n \leftrightarrow \bar{n}$

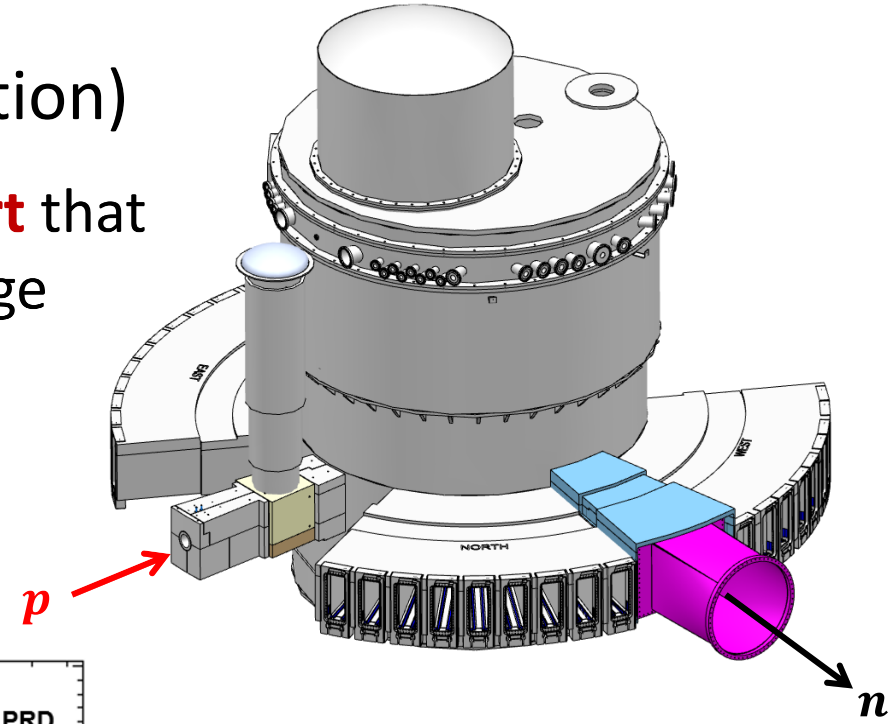
$$P_{n\bar{n}} \cong (\varepsilon t)^2 \equiv (t/\tau)^2 \approx 10^{-18} \quad \leftarrow Nt^2 = \text{“sensitivity”}$$

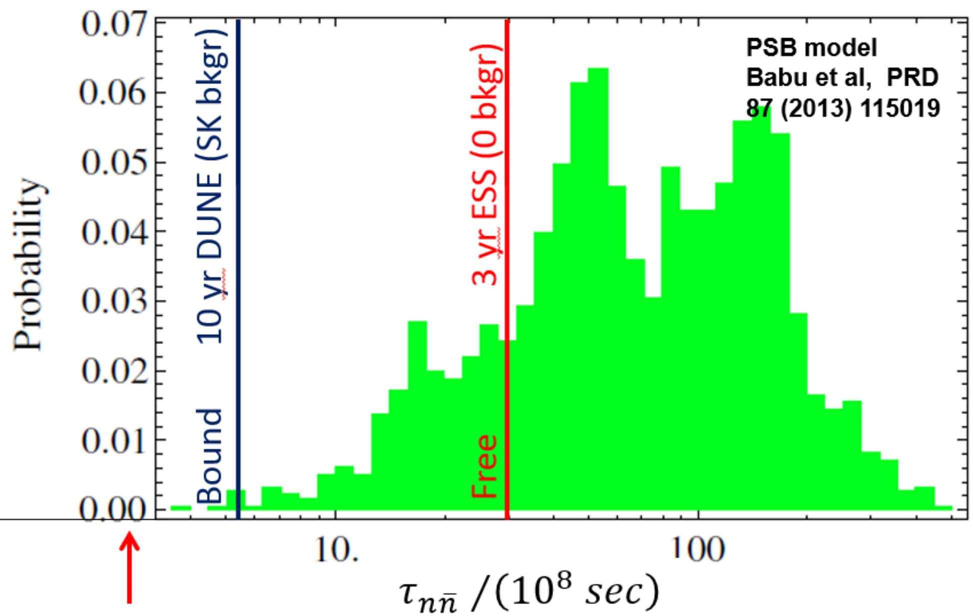
Best free-n search at ILL (1994) $\tau_{n\bar{n}}(ILL) > 0.86 \times 10^8 s$

M. Baldo-Ceolin et al., Z.Phys. C63 (1994) 409-416

$\boldsymbol{n} \leftrightarrow \overline{\boldsymbol{n}}$ (NNbar/ESS Collaboration)

ESS is constructing a **Large Beam Port** that will provide source for the future large $n \rightarrow \bar{n}$ search experiment with sensitivity 1000 times that of the previous ILL experiment



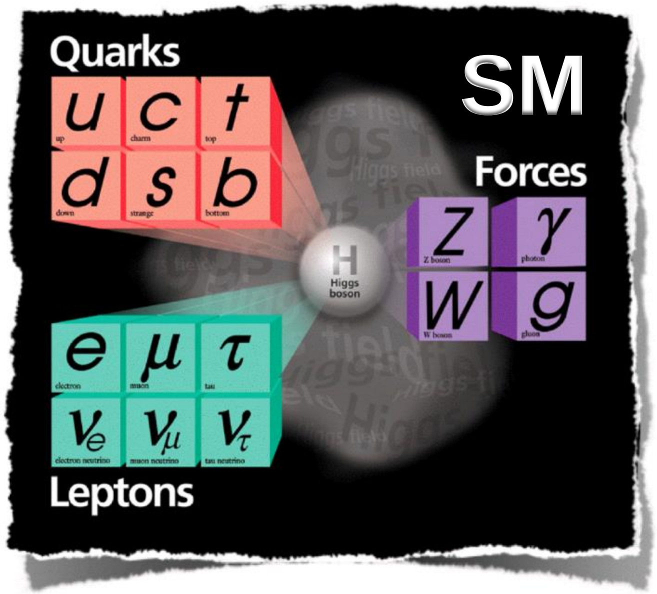


Current free n ILL limit

Current bound n SK limit

- $n \rightarrow \bar{n}$ is a large-scale experiment of a large European Collaboration for ≥ 3 yrs running time.
- $n \rightarrow \bar{n}$ is not feasible for STS at ORNL.

$n \to n'$ can be part of Mirror Matter world comprised in DM



$\mathcal{L}_{mix}$

- Two identical gauge factors, $\mathbb{G} \times \mathbb{G}'$, with identical particles and fields content, e.g. like $SU(5) \times SU(5)'$

$$\mathcal{L}_{tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{mix}$$

- Can naturally emerge in string theory: O and M matter fields are localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$
- Mirror Matter is dark for us, but its particle physics in mirror sector is known exactly – no new parameters!

$\mathcal{L}_{mix}$: $n \leftrightarrow n'$ transformation in the presence of matter and external fields in MM model

(decay is neglected)

$$\begin{pmatrix} m + T + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} + V_F & \epsilon + \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] \\ \epsilon + \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] & m' + T' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' + V_F' \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}$$

ϵ – mixing mass parameter of $n \leftrightarrow n'$: $\epsilon = 1/\tau$, where τ – oscillation time;
$\mu = \mu'$ usual neutron magnetic moment $\mu = -1.91\ \mu_N$
η – transitional magnetic moment, sign is unknown, assumed that $|\eta| \ll |\mu|$
$\pm$ is due to unknown possibly different relative parity of $\boldsymbol{B}$ and $\boldsymbol{B}'$

Models:

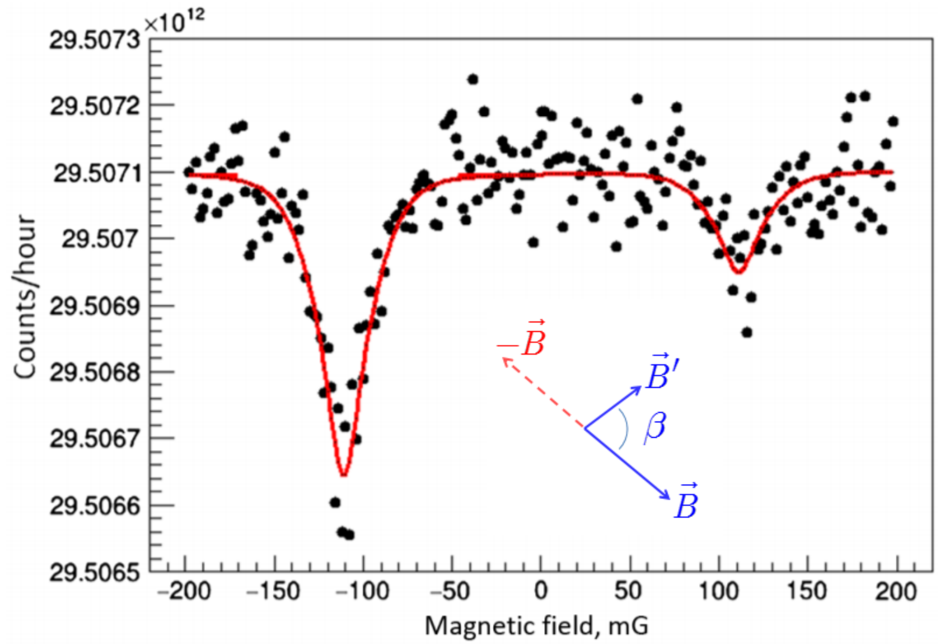
- $|m - m'| \sim 100\ neV$ non degeneracy: Z. Berezhiani, Eur. Phys. J. C79 (2019) no. 6, 484
- $B' \neq 0$ can be as strong as Earth B Z. Berezhiani, Eur. Phys. J. C64 (2009) 421-431
- nTMM and V_F compensation with B Z. Berezhiani et al., arXiv:1812.11141 [nucl-th]

experiments based on these ideas might help to resolve n lifetime beam-trap puzzle and provide explanations for some other UCN effects. They can demonstrate existence of “mirror neutrons” and “mirror photons” – two components of the Dark Matter.
Many “easy” measurable effects.

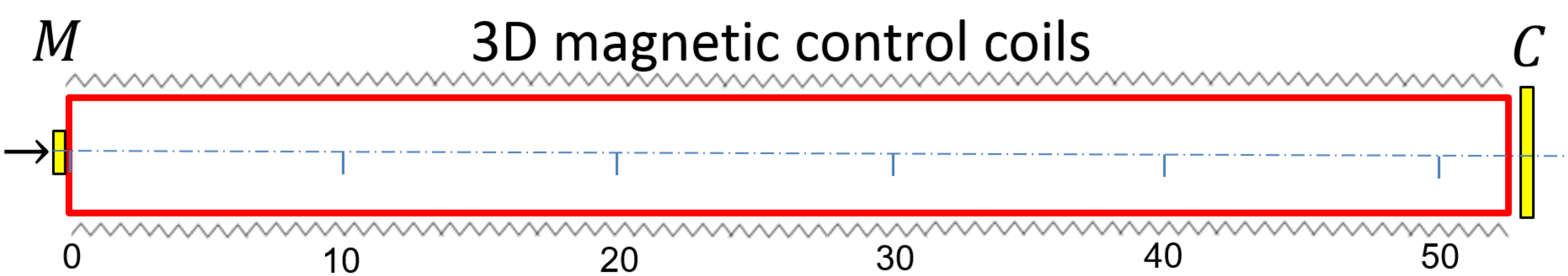
$n \to n'$ leads to neutron disappearance

- it is method used for $n \to n'$ searches with UCN:
  summarized in Z. Berezhiani et al., Eur. Phys. J. C78 (2018) no.9, 717

- it can be used with cold beams at STS with higher sensitivity:
  see Z. Berezhiani et al., Phys. Rev. D96 (2017) no.3, 035039

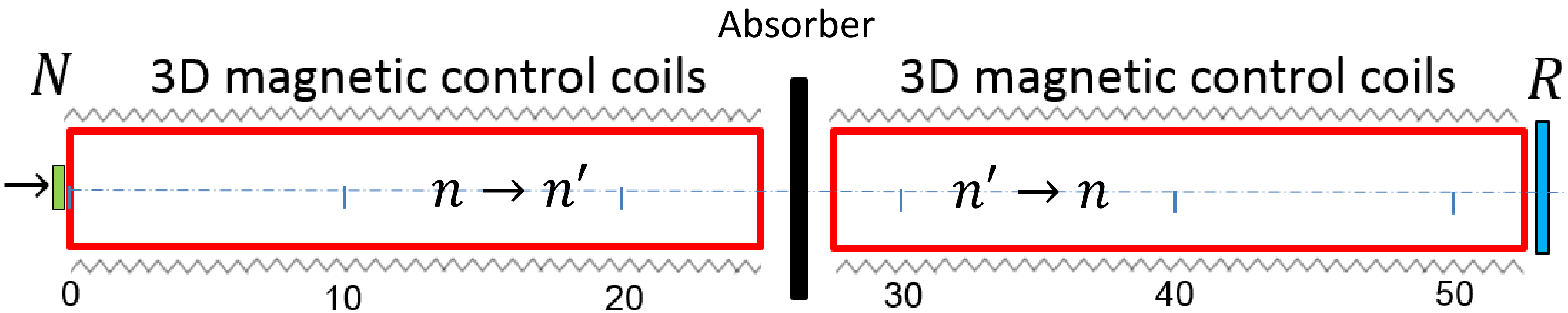


Illustrative example of disappearance detection

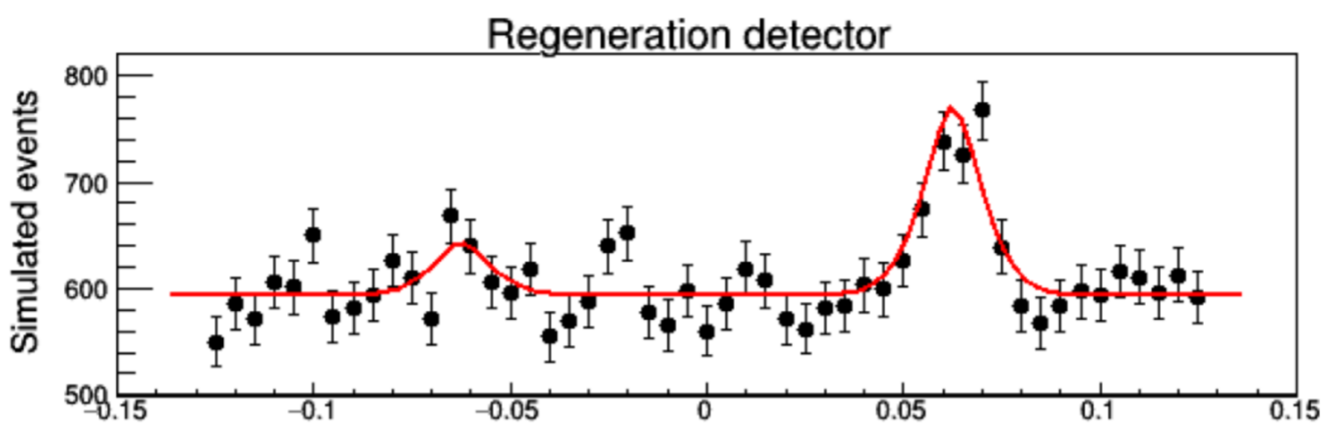


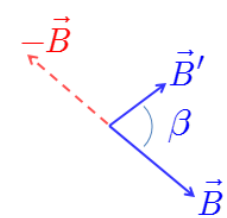
New method $n \to n' \to n$ Regeneration

see L. Broussard et al., arXiv:1710.00767 [hep-ex]



$$\boldsymbol{B}_1 = \boldsymbol{B}_2$$

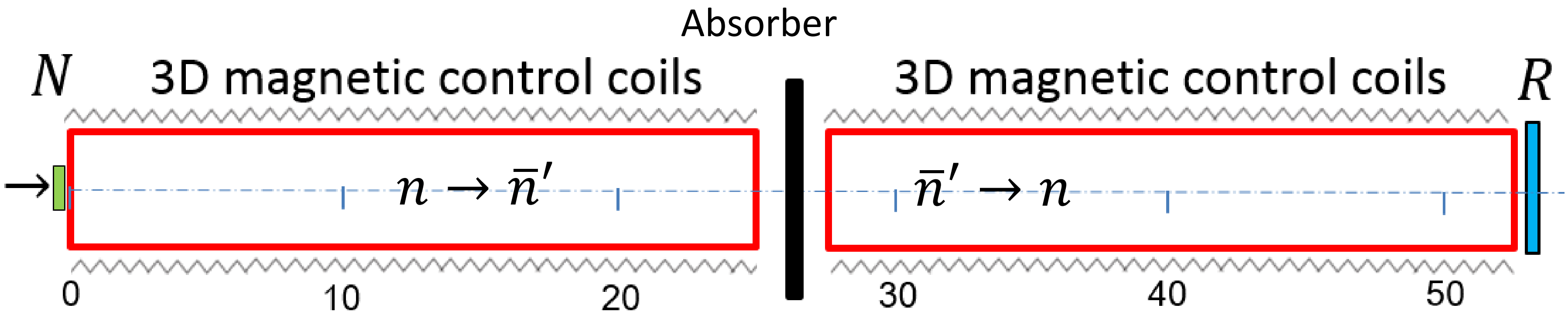




Field in scan, G

What if n' is mirror antineutron?

This idea is favored by the possibility of co-baryogenesis of Ordinary and Mirror sectors, see Z. Berezhiani, Int. J. Mod. Phys. A33 (2018) no.31, 1844034



In this case resonance will be seen for $\boldsymbol{B}_1 = -\boldsymbol{B}_2$

The nn' Collaboration

K Bailey, B Bailey, K Berry, L Broussard, L DeBeer-Schmitt, M Fitzsimmons, A Galindo-Uribarri, F Gallmeier, E Iverson, S Penttila Oak Ridge National Laboratory

J Barrow, M Frost, L Heilbronn, Y Kamyshkov, S Vavra University of Tennessee Knoxville

A Young, D Davis North Carolina State University

R Pattie East Tennessee State University

A Holley Tennessee Technological Institute

W Snow, C-Y Liu Indiana University

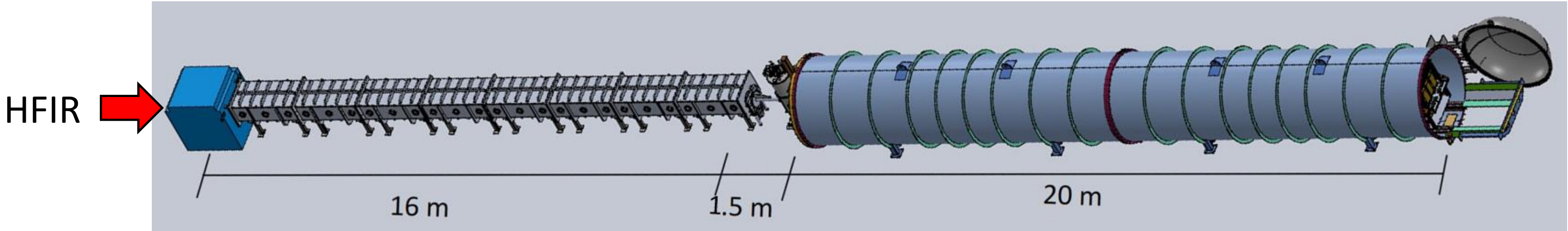
A Blose, C Crawford University of Kentucky Lexington

I Novikov Western Kentucky University

The $\boldsymbol{nn'}$ Collaboration

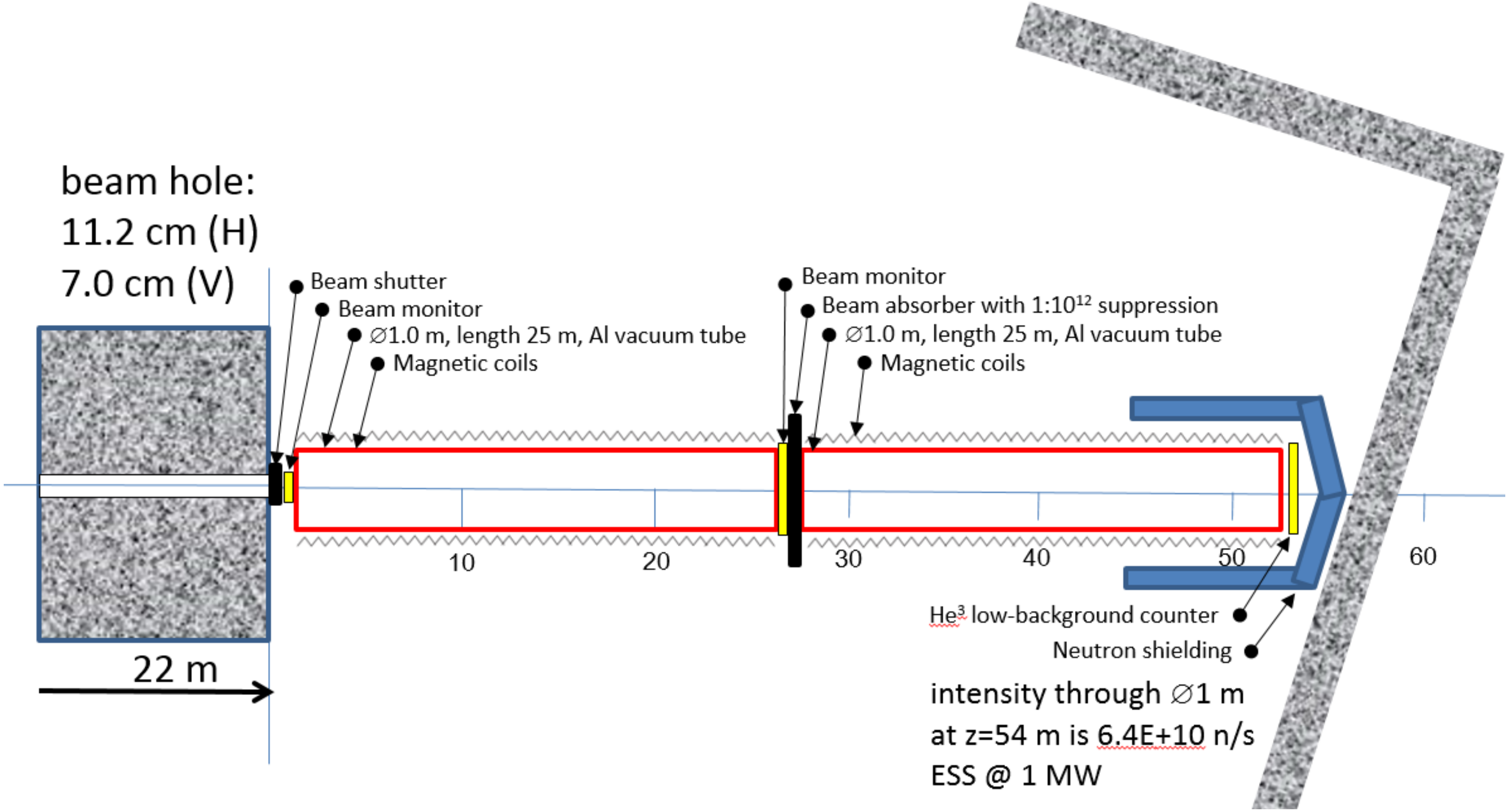
- Starts small experiment at SNS next week to test non-degeneracy $|m - m'| \neq 0$ model.

- Has sent proposal to DOE/HEP to address new ideas in DM search. Proposal is for 2 years development of several experiment options at HFIR using GP-SANS instrument.



GP-SANS at HFIR available beam path $\sim 16 + 20\ m$

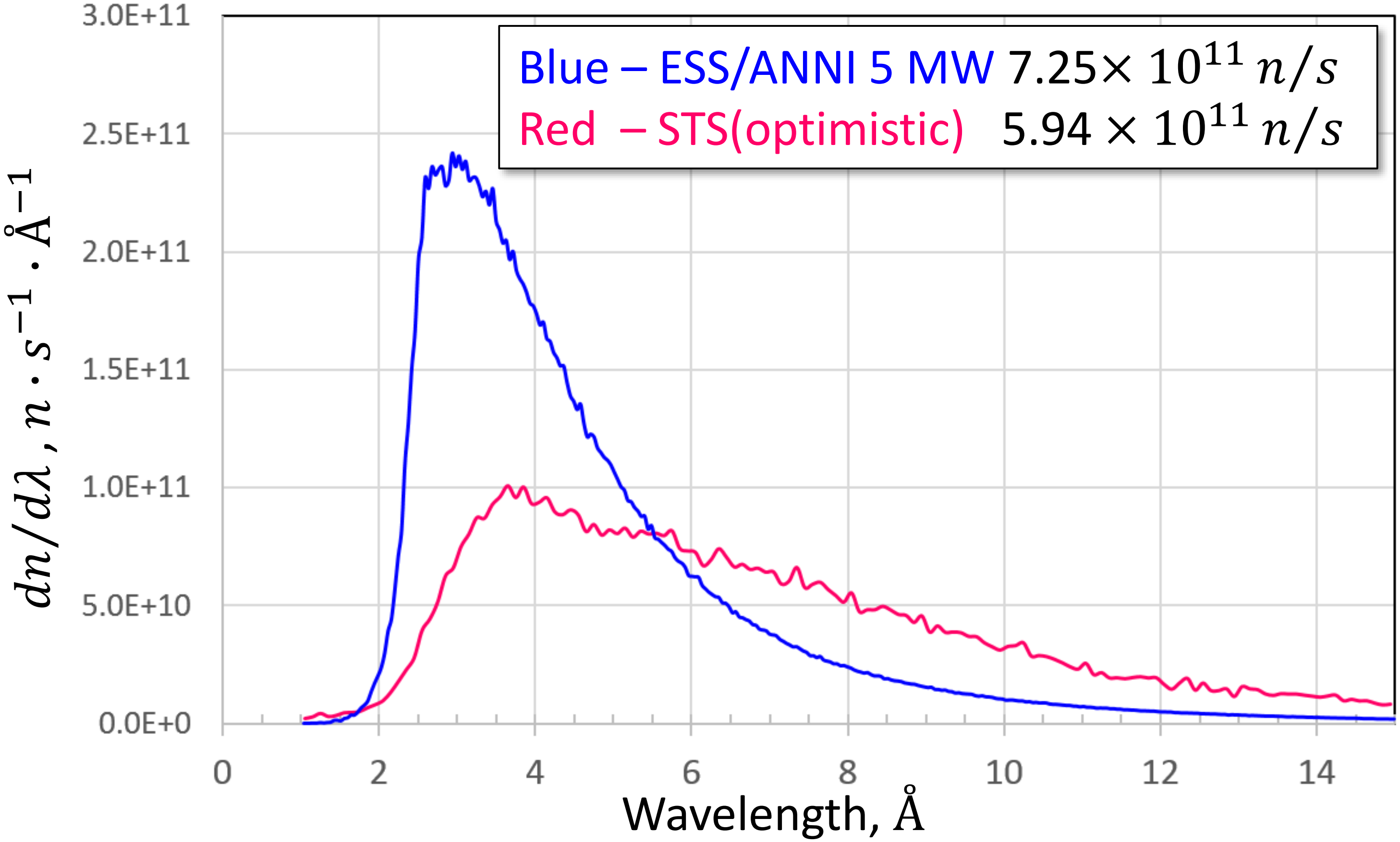
HIBEAM @ ANNI beamline configuration for $n \rightarrow n'$ searches (NNbar/ESS Collaboration)



available distance moderator – end-of-hall at ANNI is 76 m

Available beam path $\sim 54\ m$

Comparison of spectra of ESS/ANNI beamline design and simulation of Leah Broussard for STS beam line (at the exit of beam guide)



ANNI: guide aperture 9×6 cm^2 starting at 1 m and ending at 22 m as 11×7 cm^2

STS: guide 20×30 cm^2 → 40×50 cm^2 → 20×30 cm^2 starting at 1 m ending at 21 m

Setting the limit in regeneration if no effect will be seen

(simplified)

$$\tau > \left[\sqrt{T} \cdot \frac{L^4}{2f\sqrt{\bar{n}_b}} \cdot J_4\right]^{1/4} \qquad J_4 = \int_{200}^{2000} \frac{P \cdot S(v)}{v^4} dv$$

$S(v)$ $[n/(s \cdot MW)]$ intensity on the detector;

$\bar{n}_b$ $[n/s]$ detector background;

$L = L_1 = L_2$ tube length;

T $[s]$ time of measurement with single value of B

2×200 measurement points

v $[m/s]$ neutron velocity;

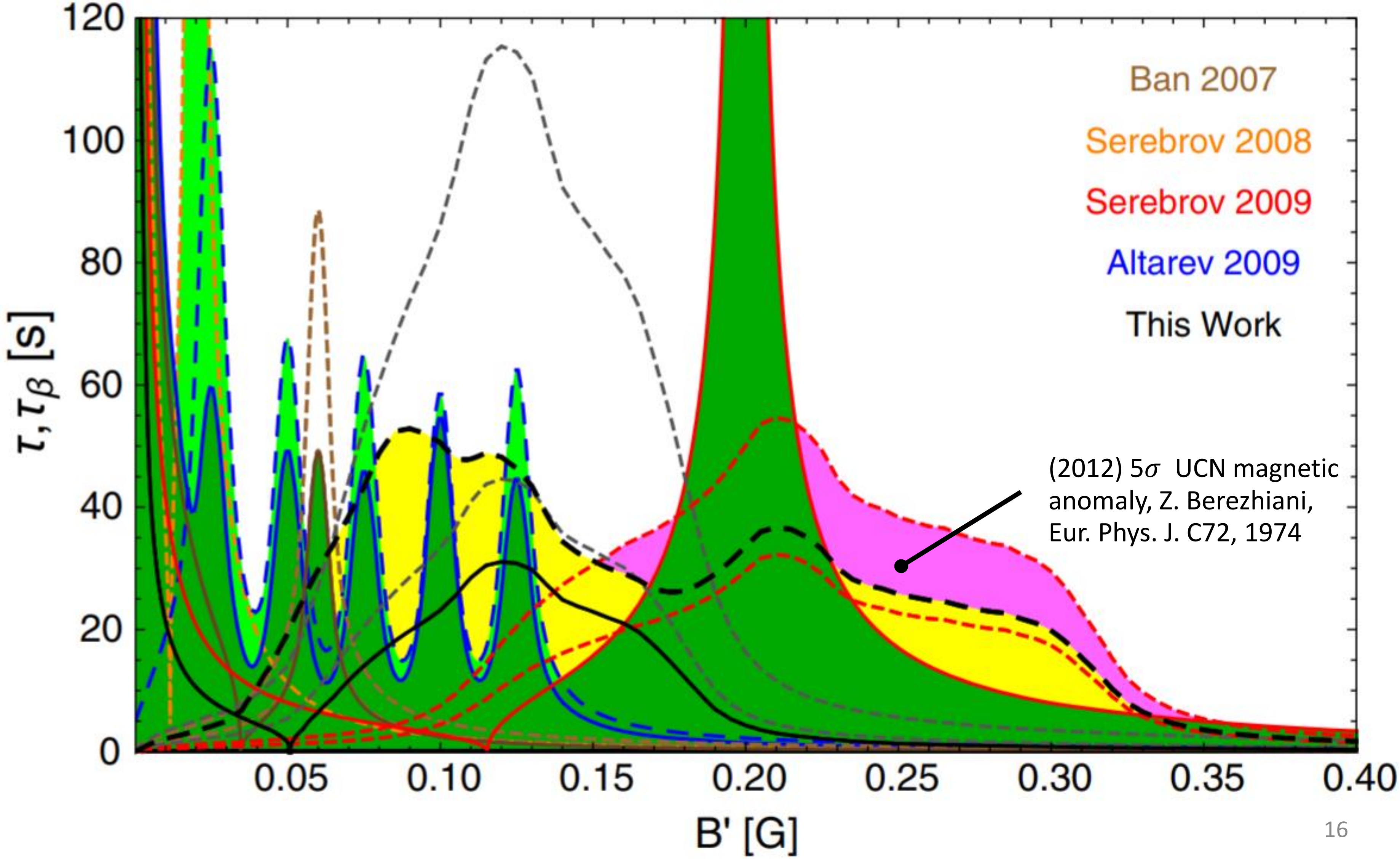
$f = -$ statistical factor for 95% CL (from Monte Carlo)

200 m/s is ~ gravitational cutoff

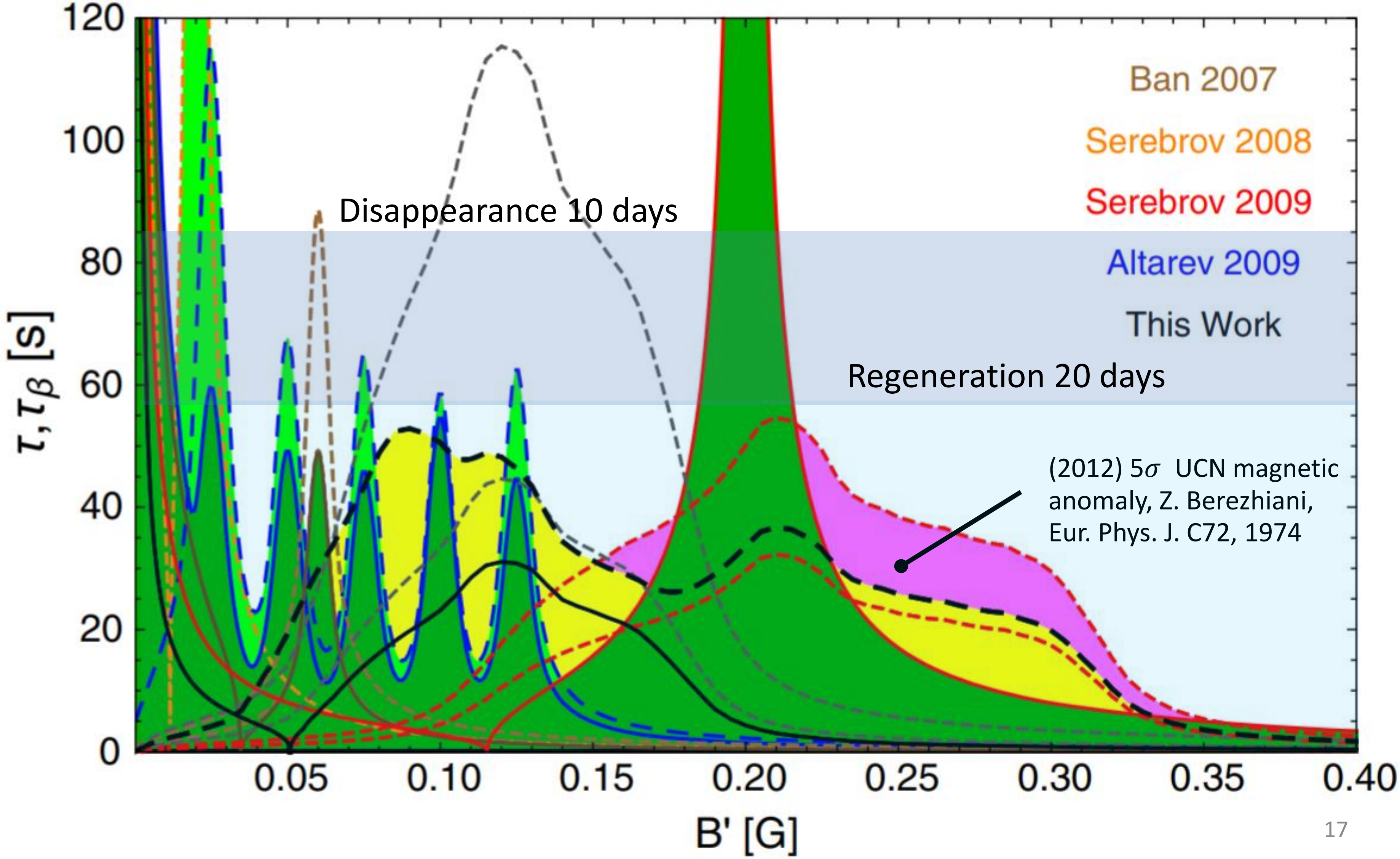
Limit improves linearly with L and with colder spectrum.

Oscillation time τ vs mirror field B' exclusion plot from UCN experiments

Z. Berezhiani et al., Eur. Phys. J. C78 (2018) no.9, 717



HIBEAM/ANNI/ESS 1MW Exclusions



More general view: $\begin{pmatrix} n \\ \bar{n} \end{pmatrix} \leftrightarrow \begin{pmatrix} n' \\ \bar{n}' \end{pmatrix}$

Berezhiani (2019)

$$i\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix} = \begin{pmatrix} E & \varepsilon & \alpha & \beta \\ \varepsilon & E & \beta & \alpha \\ \alpha & \beta & E & \varepsilon \\ \beta & \alpha & \varepsilon & E \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix}$$

$$P_{n\bar{n}} = \varepsilon^2 t^2 + 16\alpha^2\beta^2 t^4$$

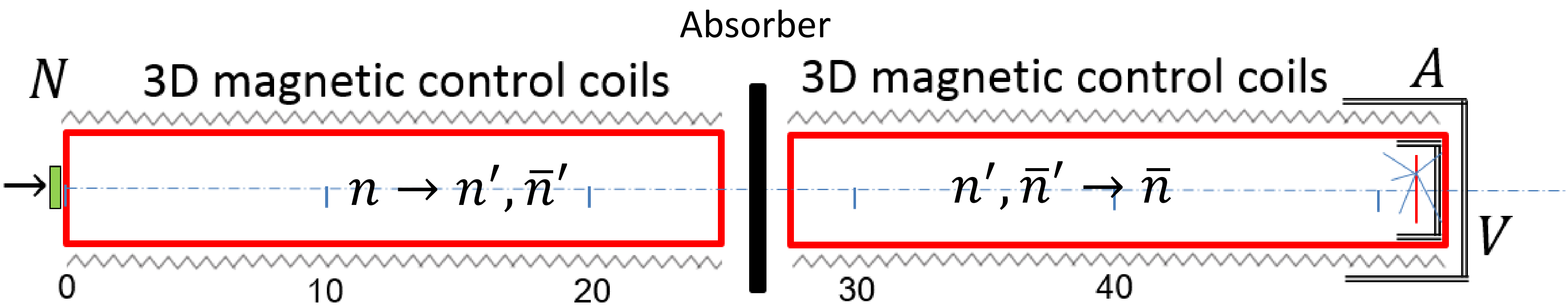
In vacuum, in absence of magnetic fields

"Conventional" $n \to \bar{n}$

$n \to n' \to \bar{n}$ and $n \to \bar{n}' \to \bar{n}$

We can imagine that $\varepsilon \ll \alpha, \beta$ and mirror magnetic field B' is present.
Then ILL $n \to \bar{n}$ limit will not determine real values of $\alpha\beta$.
One will need tune B in order to compensate suppression due to B'.

$n \to \bar{n}$ transformation through mirror regeneration



Then in regeneration antineutron counting rate can be around 1 per hour (estimate)

First stage for such measurement should be detection of disappearance, that will fix $B = B'$
(better will be equate vector values: $\boldsymbol{B} = \pm\boldsymbol{B}'$)

Other interesting possible effect of regeneration based on the nTMM

Z. Berezhiani et al., arXiv:1812.11141 [nucl-th]

for simplicity assume $\epsilon = 0, B' = 0, V_F$, and consider only one neutron polarization

$$\hat{H} = \begin{pmatrix} -\mu B & \eta B \\ \eta B & 0 \end{pmatrix}$$

$$\bar{P}_{nn'}(t) \cong \frac{2\eta^2}{\mu^2}$$

- If magnetic field B is larger than few mG then probability $n \to n'$ is constant and doesn't depend on the magnetic field.
- if resonance at $B = B'$ is present nTMM enhances it. Outside resonance probability again constant.

Compensation of V_F with μB (ignore scattering and absorption)

Z. Berezhiani et al., arXiv:1812.11141 [nucl-th]

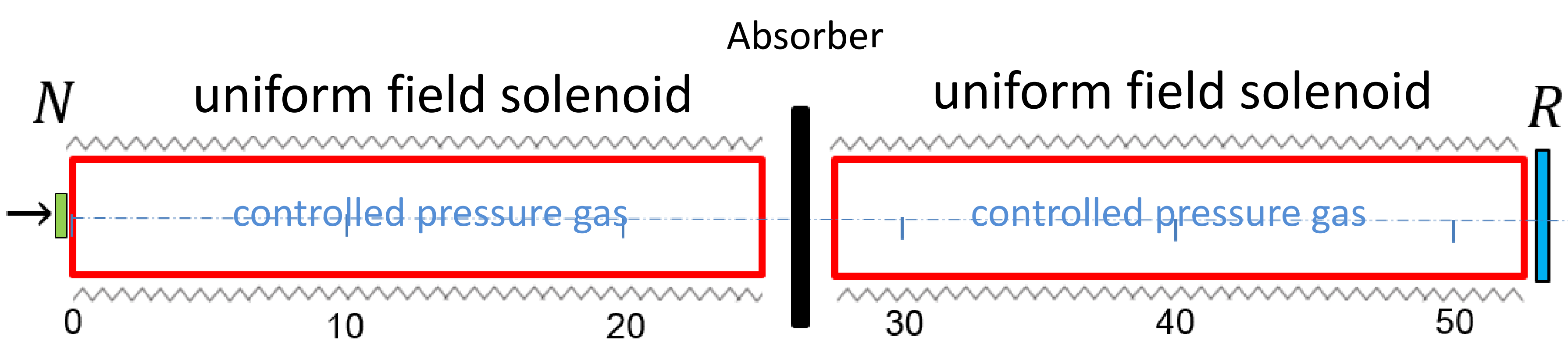
$$\hat{H} = \begin{pmatrix} V_F - \mu B & \epsilon + \eta B \\ \epsilon + \eta B & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & \epsilon + \eta B \\ \epsilon + \eta B & 0 \end{pmatrix}$$

For one polarization in the resonance $V_F - \mu B$ that corresponds to pure unsuppressed oscillations:

$$P_{nn'}(t) = sin^2(\epsilon + \eta B)t$$

For example, air at NTP corresponds to the field 10 G

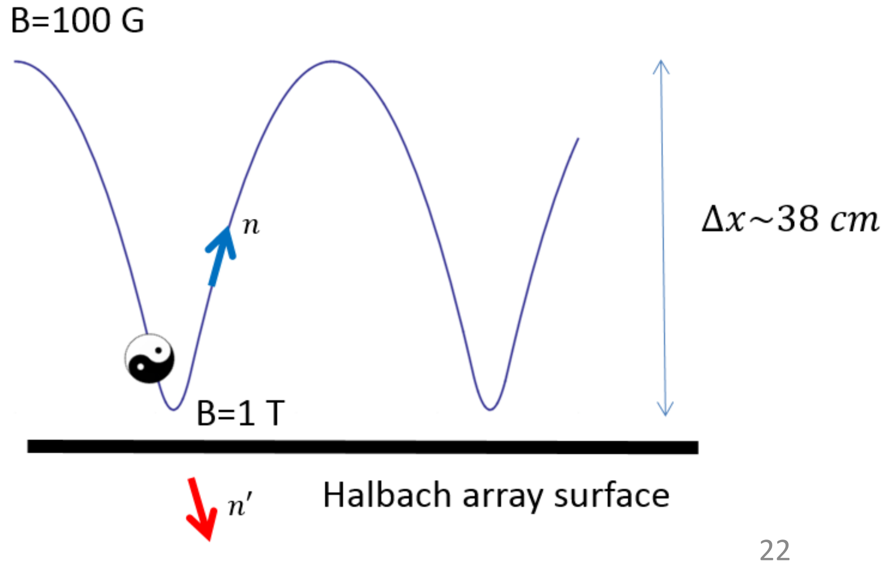
That seems to be the very sensitive method for measurement of nTMM η.



$\binom{n}{n'}$ is a wonderful Quantum system

- Gravity force is common for both components;
- Gradient of magnetic field $\nabla\mu B$ in classical sense is a force different for neutron and mirror neutron;
- Decoherence effects can be caused by the field gradients;
- What gradient of B do you need to apply to collapse the entangled (n, n') system to either n or n' state?
- Several schemes of the field gradient design are used to test the predictions of nTMM

Example of decoherence of nn' system in UCNτ experiment



Desirable parameters of STS beam for $n \to n'$ search

- Total intensity on the detector is more important than brightness
- Enhanced cold spectrum $\Delta\lambda$ from 2Å to 20Å ✓
- Beam length $\geq$ 76 m (moderator – wall) ?
- Divergence for 90% of intensity $\pm 0.5°$?