

Agenda of September 29 zoom 3:30 pm meeting

1. Yuri 5' Information: Josh Barrow seminar on Wednesday 30 Sept at 3:00 pm in 506
2. Yuri 20' Start writing PRL paper for nTMM

Starting on the paper from nTMM-2 data for submission to PRL

Limiting the Neutron Transition Magnetic Moment with Cold Beam at HFIR

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(Dated: October 1, 2026)

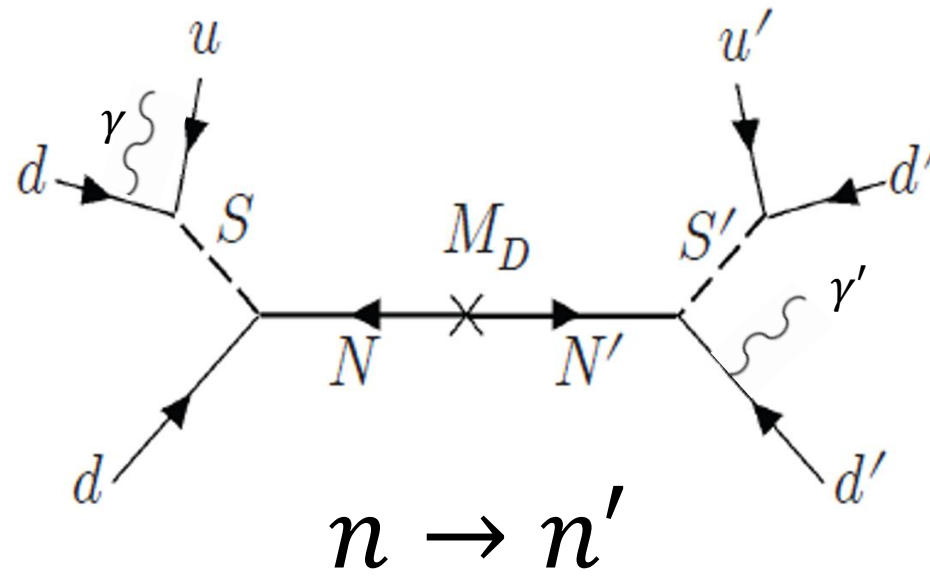
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Abstract

The free neutron n can be a state mixed with the sterile "mirror" neutron n' like that is conjectured in the models of Dark Mirror Matter that allow transformations $n \rightarrow n'$. In this case the neutron transition magnetic moment (n TMM) should exist associated with the electromagnetic property of $n \rightarrow n'$ process. The neutron can be spontaneously converted into mirror neutron n' via the n TMM (in addition to more conventional off-diagonal mass mixing coupling) interacting with the magnetic field $\mathbf{B}$ as well as with hypothetical mirror magnetic field $\mathbf{B}'$. In this letter we report the results of the first attempt to detect n TMM via observation of enhanced $n \rightarrow n'$ transformation in a regeneration type of experiment using the beam of cold neutrons from the reactor. The non-observation of $n \rightarrow n'$ effect allows us setting 95% CL limit on n TMM $\kappa < 2 \times 10^{-6}$ in units of μ_n regular neutron dipole magnetic moment. a

Possible mechanism of TMM in MM Model

simple view:



$$\eta_n = \eta_{n'}$$

$$n\text{TMM} \equiv \eta \equiv \kappa\mu$$

Possible way to understand the n TMM?

In a simple picture, when we describe neutron interaction with magnetic field by a Hamiltonian $H = \boldsymbol{\mu} \cdot \boldsymbol{B}$, for some blink moment oscillating neutron does not interact with B .

Also, there might be a hiccup in the spin rotation angle in magnetic field

General form of $n \leftrightarrow n'$ time evolution with n TMM
in the presence of $\mathbf{B}$ and $\mathbf{B}'$ can be described by Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{int} = \begin{pmatrix} E & \epsilon \\ \epsilon & E \end{pmatrix} + \begin{pmatrix} \mu \boldsymbol{\sigma} \cdot \mathbf{B} & \eta \boldsymbol{\sigma} \cdot [\mathbf{B} \pm \mathbf{B}'] \\ \eta \boldsymbol{\sigma} \cdot [\mathbf{B} \pm \mathbf{B}'] & \mu' \boldsymbol{\sigma} \cdot \mathbf{B}' \end{pmatrix}$$

for the mixed states of $\psi_n = \begin{pmatrix} n \\ n' \end{pmatrix}$

ϵ – mixing parameter of $n \leftrightarrow n'$: $\epsilon = \hbar / \tau$, where τ is $n \leftrightarrow n'$ oscillation time;

$\mu = \mu'$ usual well known neutron dipole magnetic moment $\mu = -1.91 \mu_N$

η – transition magnetic moment, magnitude and sign are unknown, assumed that $|\eta| \ll |\mu|$

$\pm$ is due to unknown and possibly different relative parity of $\mathbf{B}$ and $\mathbf{B}'$

Schrödinger equation for mixed n and n' state coupled with n TMM

μ of $|n\rangle$ interacts with mag field B , but μ' of $|n'\rangle$ does not

That means that B interacts with n' state

$$\begin{cases} i\hbar \frac{\partial}{\partial t} |n\rangle = \mu \boldsymbol{\sigma} \cdot \mathbf{B} |n\rangle \pm \eta \boldsymbol{\sigma} \cdot \mathbf{B}' |n'\rangle + \eta \boldsymbol{\sigma} \cdot \mathbf{B} |n'\rangle \\ i\hbar \frac{\partial}{\partial t} |n'\rangle = \pm \eta \boldsymbol{\sigma} \cdot \mathbf{B}' |n\rangle + \eta \boldsymbol{\sigma} \cdot \mathbf{B} |n\rangle + \mu' \boldsymbol{\sigma} \cdot \mathbf{B}' |n'\rangle \end{cases}$$

That means that B' interacts with neutron

Interaction of Mirror Dark Matter neutron with ordinary B ; the n TMM can be detection mechanism of n'

Simplified Hamiltonian:

$B' = 0, V' = 0$, neglect neutron decay and material absorption.

Also, subtract common real terms from diagonal

Without nTMM For one beam polarization:

$$\mathcal{H} = \begin{pmatrix} V - \mu B \pm \Delta m & \epsilon \\ \epsilon & 0 \end{pmatrix} \quad \text{Resonance: } \mathcal{H} = \begin{pmatrix} 0 & \epsilon \\ \epsilon & 0 \end{pmatrix} \quad \tau_{nn'} = \frac{\hbar}{\epsilon} \quad P_{nn'} = \left(\frac{t}{\tau}\right)^2$$

With nTMM

$$\mathcal{H} = \begin{pmatrix} V - \mu B \pm \Delta m & \epsilon + \eta \boldsymbol{\sigma} \cdot \mathbf{B} \\ \epsilon + \eta \boldsymbol{\sigma} \cdot \mathbf{B} & 0 \end{pmatrix} \quad \mathcal{H} = \begin{pmatrix} 0 & \epsilon + \eta B \\ \epsilon + \eta B & 0 \end{pmatrix}$$

$n \rightarrow n'$ transformation can occur due to nTMM (besides usual mass mixing coupling ϵ)

and can be amplified by magnetic field B since $\eta \boldsymbol{\sigma} \cdot \mathbf{B}$ plays the role of ϵ .

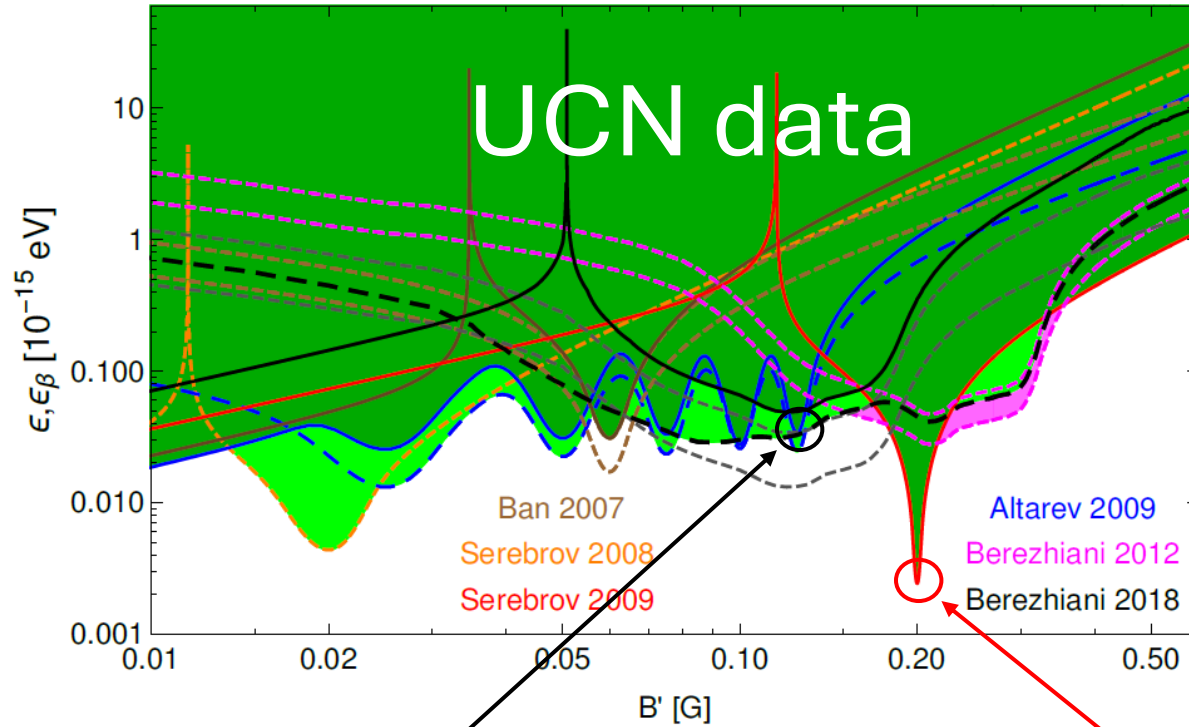
It is possible that $\eta \boldsymbol{\sigma} \cdot \mathbf{B} \gg \epsilon$.

$$P_{nn'} = \left(\frac{t}{\hbar} \kappa \mu B\right)^2$$

nTMM in 2018

Z. Berezghiani et al, On the Neutron Transition Magnetic Moment

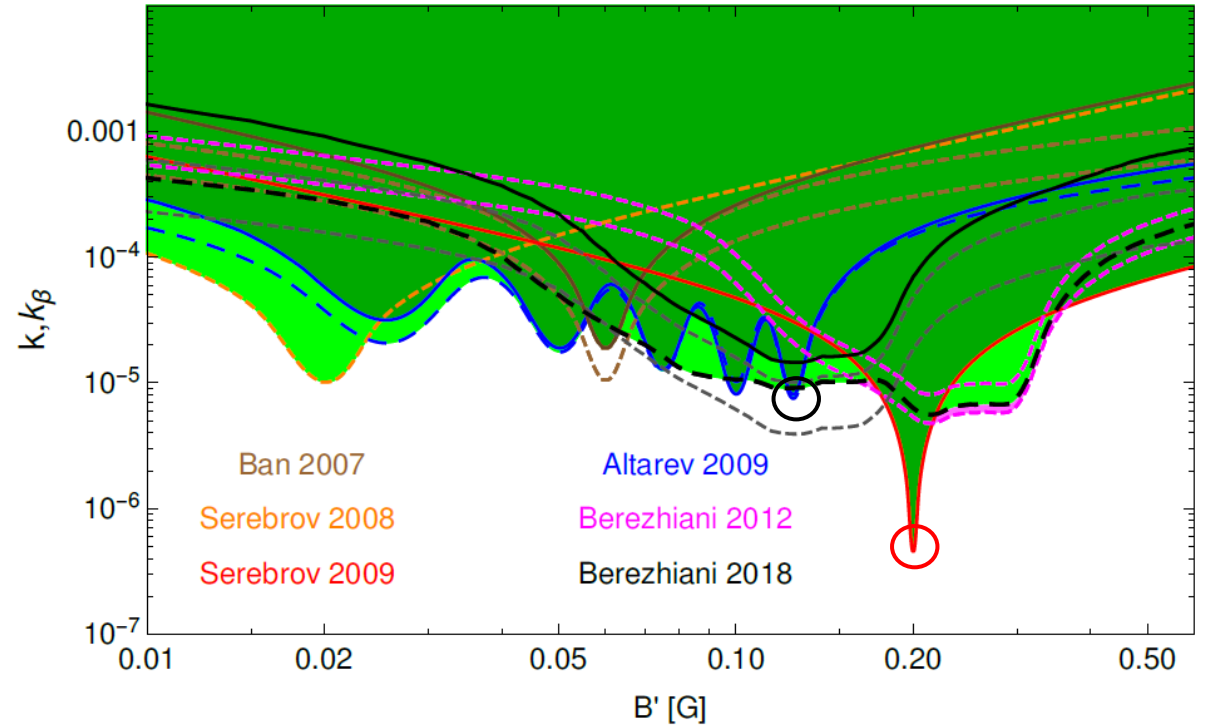
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$\epsilon \sim 3.3 \text{E-}17 \text{ eV}$
at $\sim 0.12 \text{ G}$

" ϵ " = $\kappa\mu(B + B')$

$\epsilon \sim 2.5 \text{E-}18 \text{ eV}$
at $\sim 0.2 \text{ G}$
 $\tau > 260 \text{ s}$



$$\mathcal{H} = \begin{pmatrix} \mu\sigma \cdot \mathbf{B} - \mu\sigma \cdot \mathbf{B}' & \kappa\mu\sigma \cdot (\mathbf{B} + \mathbf{B}') \\ \kappa\mu\sigma \cdot (\mathbf{B} + \mathbf{B}') & 0 \end{pmatrix}$$

$$\kappa (nTMM) = \frac{3.3 \times 10^{-17}}{6 \times 10^{-12} \cdot (0.12 + 0.12)} = 2.3 \times 10^{-5}$$

Plotted $\sim 9 \times 10^{-6}$

$$\kappa (nTMM) = \frac{2.5 \times 10^{-18}}{6 \times 10^{-12} \cdot (0.2 + 0.2)} = 1.04 \times 10^{-6}$$

Plotted $\sim 5 \times 10^{-7}$

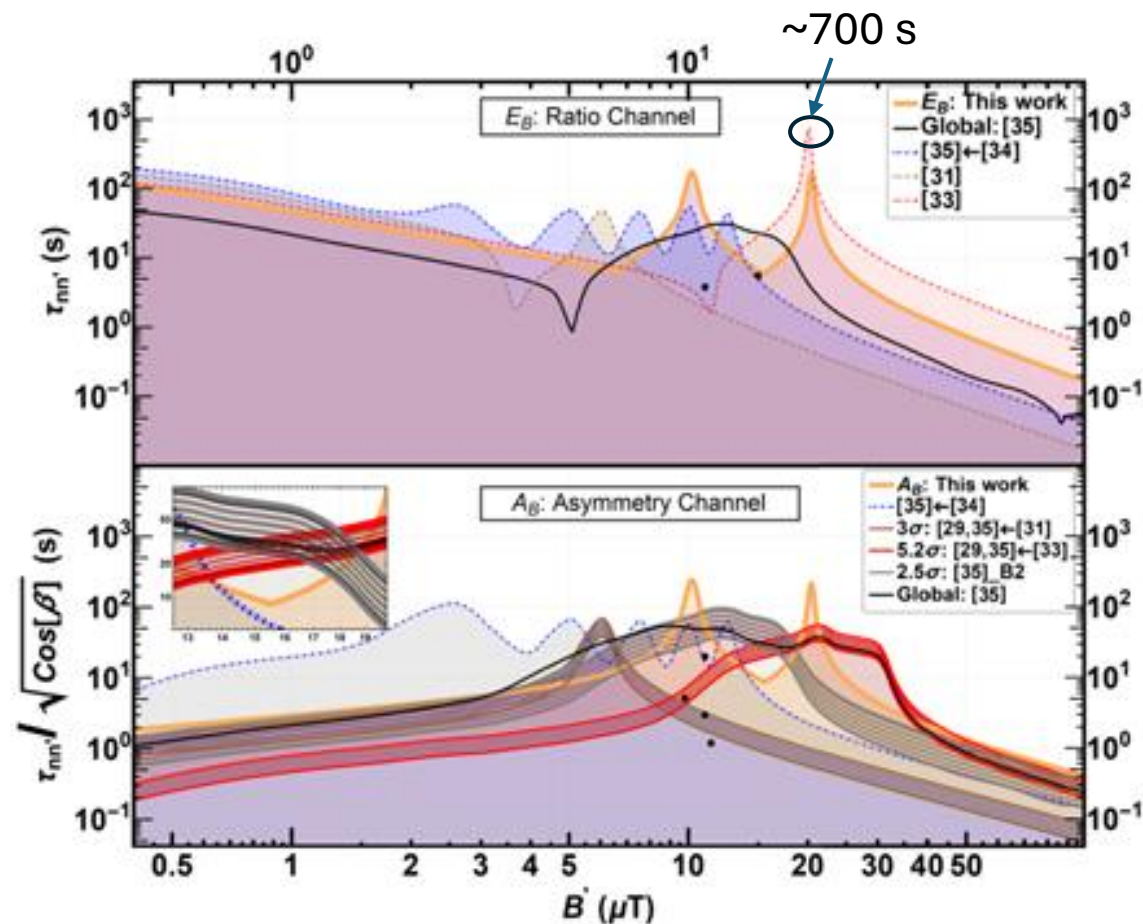


Fig. 3. Lower limits on the $n - n'$ oscillation time, $\tau_{nn'}$, at 95% C.L., using the ratio and asymmetry observables, while assuming $B' \neq 0$. Top (bottom) panel shows the ratio (asymmetry) analysis, where the solid orange curve represents the lower limit on $\tau_{nn'}^{B' \neq 0}$ ($\tau_{nn'}^{B' \neq 0} / \sqrt{\cos \beta}$). (Top): The dot-dashed blue curve represents the lower limit imposed using data in Ref. [34] by Ref. [35]. The black curve represents the global constraint calculated by Ref. [35] which imposes a weighted lower limit using data from Refs. [31,33,34] and the B2 series in Ref. [35]. The dot-dashed brown curve, represents the constraint from Ref. [31]. The dot-dashed red curve represents the constraint from Ref. [33]. The black dots indicate the solution consistent with the statistically significant signals as reported in Ref. [27]. (Bottom): The black curve is the global constraint calculated in Ref. [35]. The dot-dashed blue curve represents the lower limit imposed using data in Ref. [34] by Ref. [35]. The three striped regions are the signals (95% C.L.): (i) the red striped region, is the signal region calculated in Refs. [29,35] from the 5.2σ anomaly in Refs. [33]; (ii) the brown striped region is the signal calculated in Refs. [29,35] from the 3σ anomaly in Ref. [31]; and (iii) the gray striped region is the signal from the 2.5σ anomaly observed in the B2 series of Ref. [35]. The black dots indicate the solution consistent with the statistically significant signals as reported in Ref. [29]. The inset shows an enlarged portion of the bottom plot between the ranges of $12.8 \mu\text{T} < B' < 20 \mu\text{T}$.

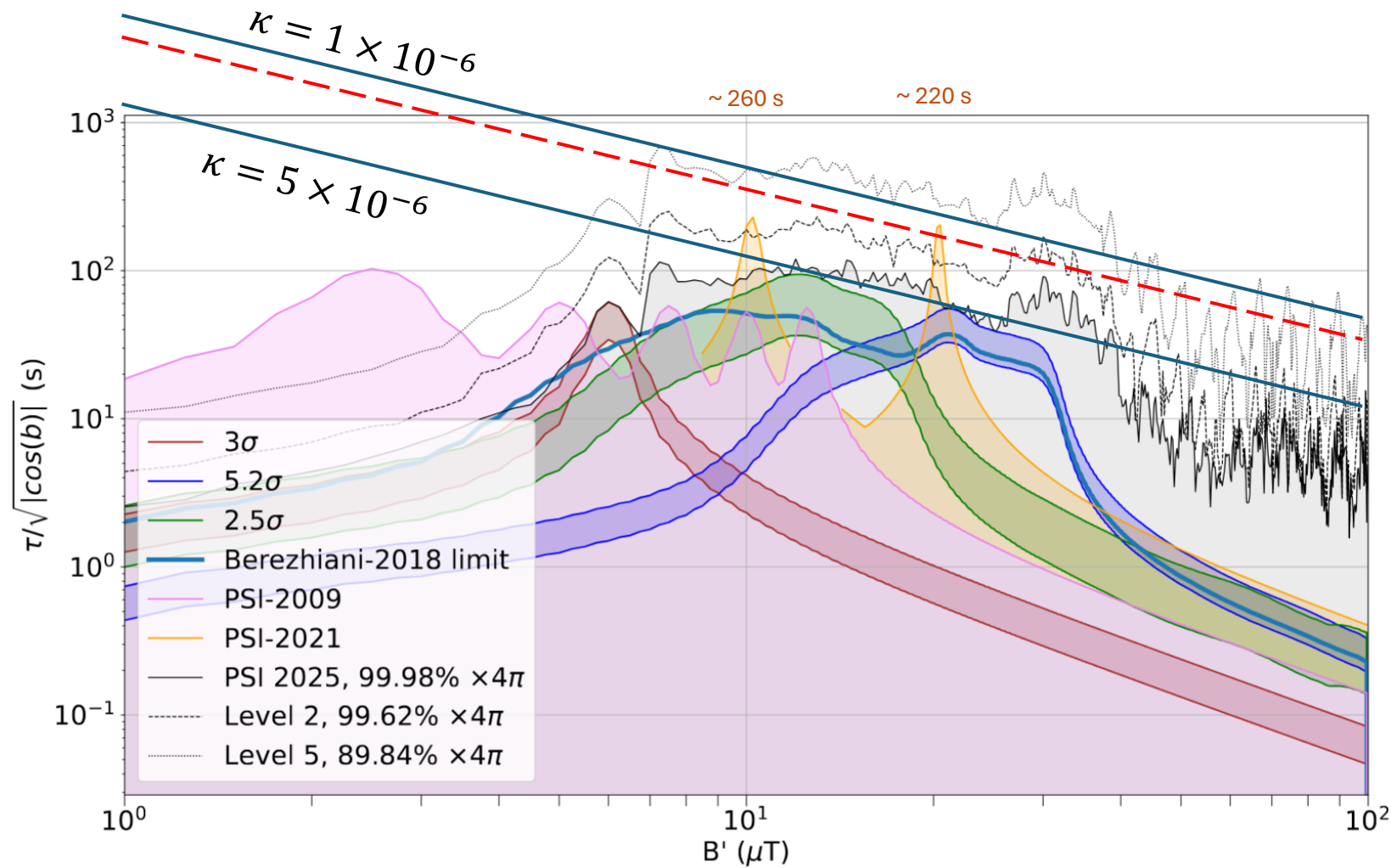


Figure 4: The anomalous signal regions of Berezghiani-2018 [42] from data in [37] (3σ , red), [40] (5.2σ , blue) and [42] (2.5σ , green) together with the 95% C.L. limits on $\tau_{nn'}/\sqrt{|\cos(b)|}$ from PSI-2009 [41], PSI-2021 [43] and this work as a function of the magnitude of the mirror-magnetic-field, B' . Along with the most conservative PSI-2025 limit (black line) excluding 99.98% of the full solid angle (4π), two higher limit curves but with less solid angle exclusion (99.62% and 89.84%) are plotted, corresponding to levels of factor 2 (dashed line) and 5 (dotted line) above the anomalous signals.

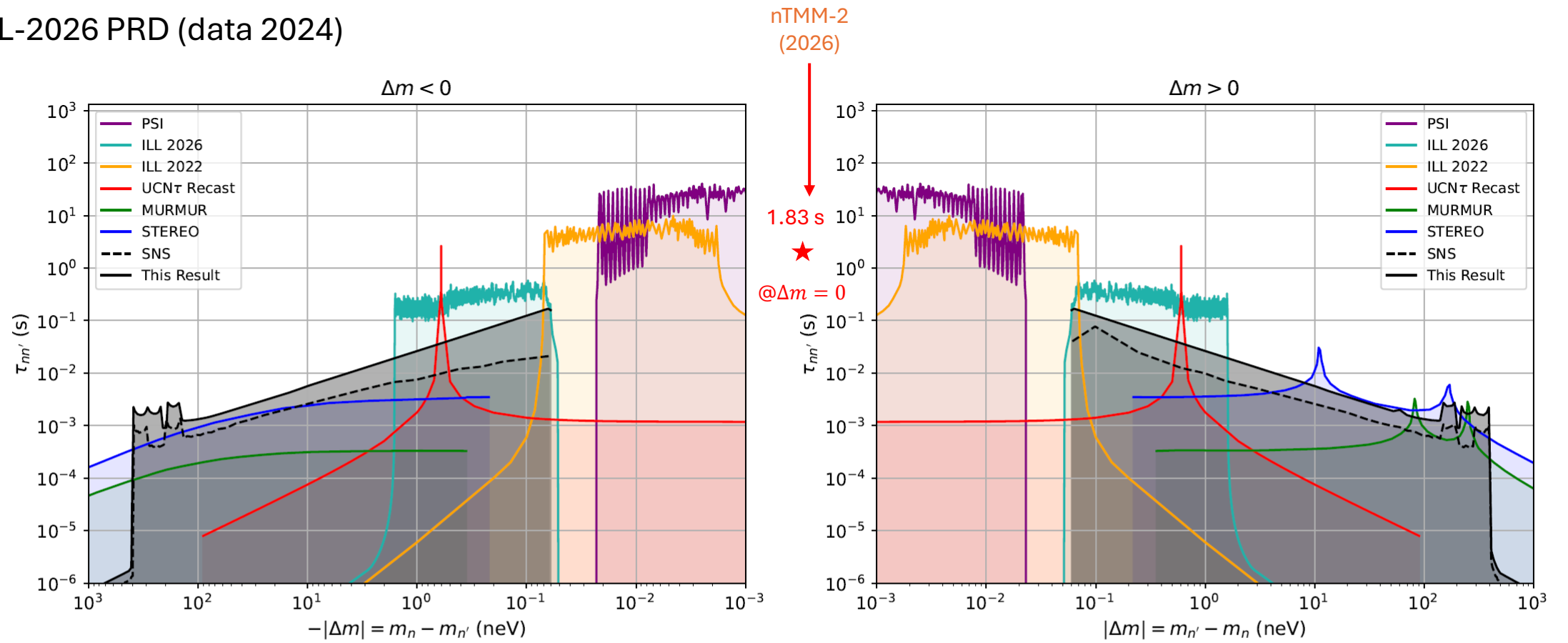


FIG. 10. Summary of most recent $\tau_{nn'}$ limits vs positive and negative Δm range from 10^{-3} neV to 10^{+3} neV. Limits reported in this paper (gray area), overlaid with other searches for sterile neutrons, assuming a unified framework as proposed in [22]. Our previous SNS limits are taken from [9]. The recent 2026 limits marked PSI are results from UCN storage [23, 29]. The limit from UCN τ comes from the non-observation of anomalous losses, as calculated in [22]. UCN beam results marked as ILL 2022 and ILL 2026 use disappearance in the GADGET detector [27, 28]. The STEREO and MURMUR reactor results in terms of $|\Delta m| < 10^3$ neV are also presented from [24, 25]. Limits at lower Δm and the UCN $n \rightarrow n'$ limits [26] from neutron EDM search apparatus are not shown on this plot.