Search for Neutron Regeneration $n \to n' \to n$ via Sterile Neutron with Cold Beam at HFIR

Presented by Carolyn Haviland, University of Tennessee, Knoxville

On behalf of UTK-ORNL-UKY-Lund nn' Collaboration

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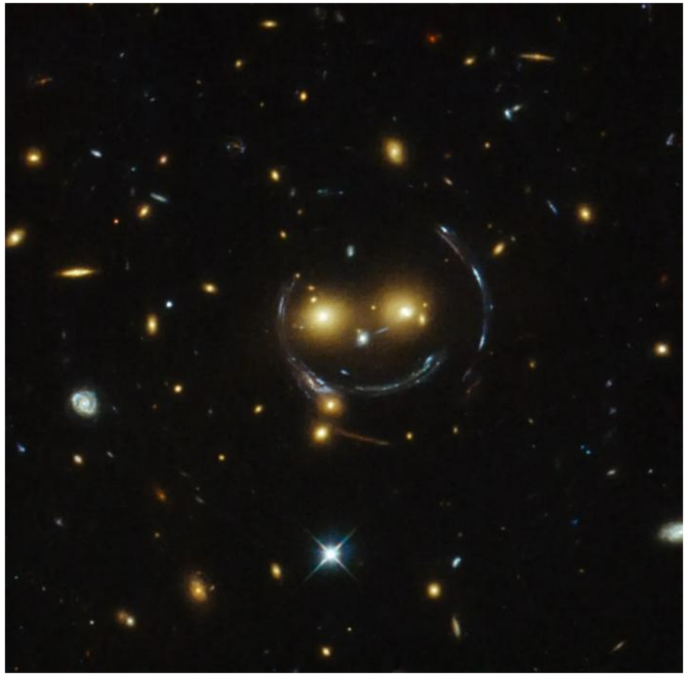
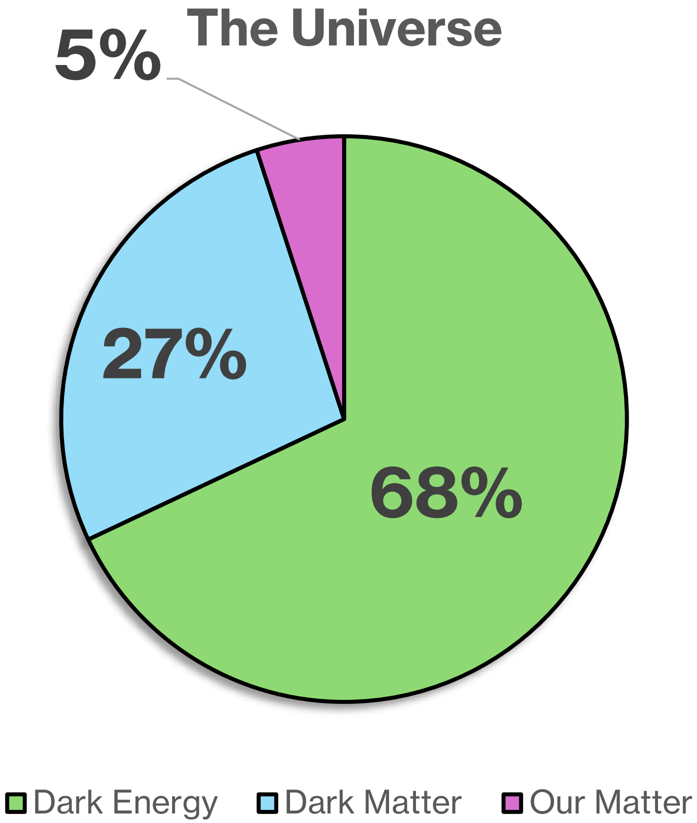
Dark Matter in the Universe

- There is strong evidence of dark matter (CMBR, gravitational lensing, galactic rotational curves, etc.)
- **Its nature is unknown**



Hubble Sees a Smiling Lens - NASA Science

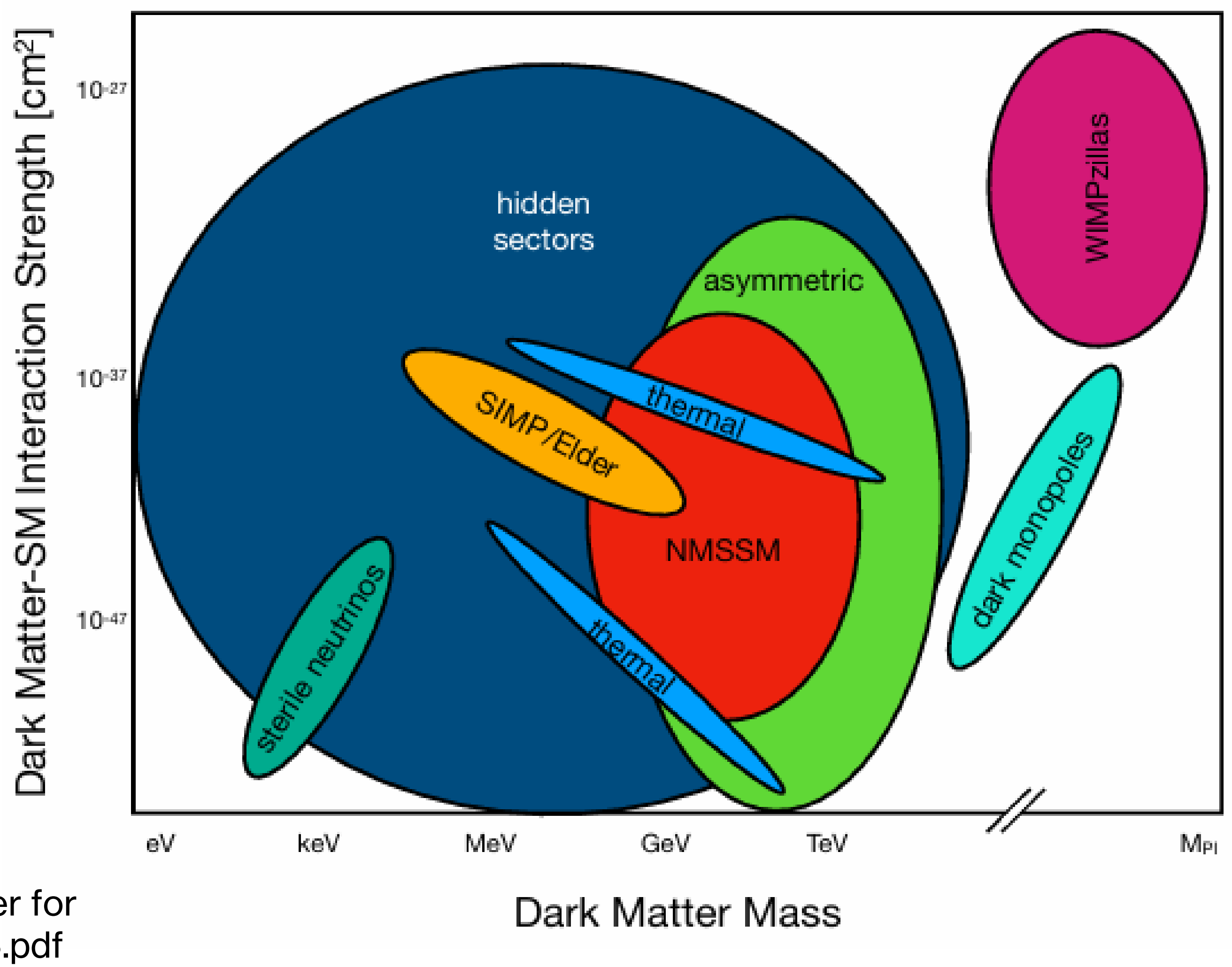


There are many models looking to explain DM

Most models look for particle DM with possibility of direct search

2 major unknown parameters in DM search

- Mass of DM particle
- Strength of interaction with our matter (OM)



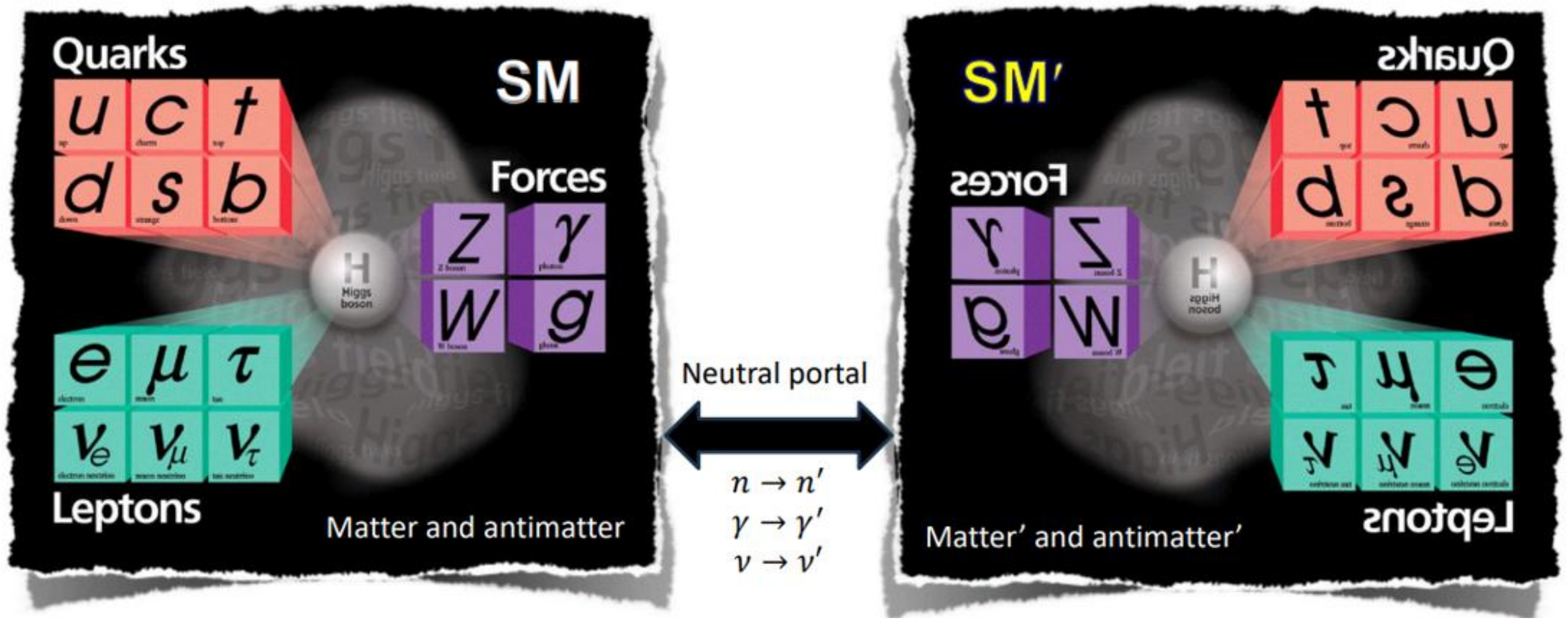
Report of the Topical Group on Particle Dark Matter for Snowmass 2021 https://arxiv.org/pdf/2209.07426.pdf

Mirror Matter (MM) is one of the viable DM Models

Lee & Yang – 1956, Okun – 2006, Foot - 2007, Berezhiani - 2000

OM and MM can be two coexisting worlds in our Universe

In MM model all what is happening with OM particles can happen with MM particles



In this model neutron can oscillate into mirror neutron ($n \leftrightarrow n'$) *Berezhiani - 2006*

Our nn' collaboration focuses on two main models of investigation *Berezhiani - 2019*

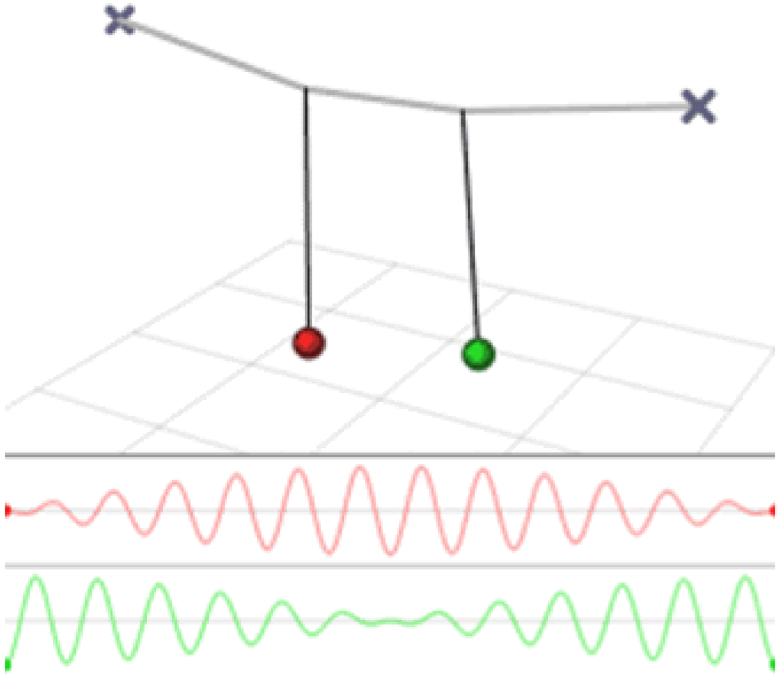
1. MM "Δm" model – could explain neutron lifetime anomaly
2. MM "$nTMM$" model – transition magnetic moment on neutron enhances probability of nn'

Berezhiani - 2018

Oscillations occur due to neutron mixing nn'

- Quantum mechanically neutron oscillations can be understood as a two-level coupled system
- Similar phenomena: neutrino flavor oscillations or neutron-antineutron oscillations
- QM description by Hamiltonian

$$\mathcal{H} = \begin{pmatrix} \mathrm{E_n} & \varepsilon \\ \varepsilon & \mathrm{E_{n'}} \end{pmatrix}$$



Mechanical analogy of coupled system

Mirror matter (n’) doesn't interact with our matter... so how can we experimentally find n→n’?

- Here we consider mixing via Δm model
- Neutron oscillates to mirror neutron in vacuum even in the presence of Δm
- With magnetic field or optical potential, Δm can be compensated

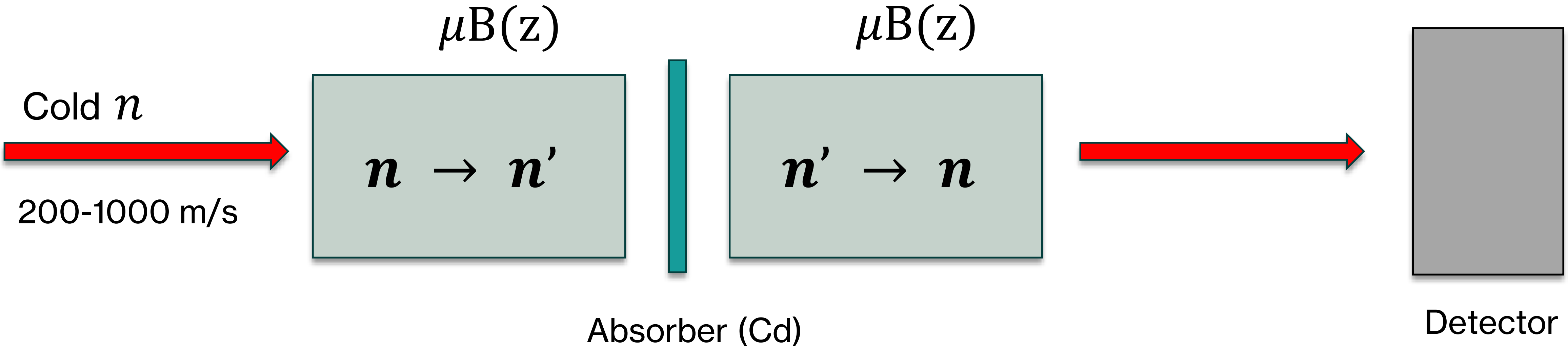
$$\mathcal{H} = \begin{pmatrix} U - iW & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix}$$

$$U = \Delta m \pm \mu B(z) + \mathrm{V_F}$$

$$\tan(2\theta) = \frac{\epsilon_{\mathrm{nn'}}}{\mathrm{U}}$$

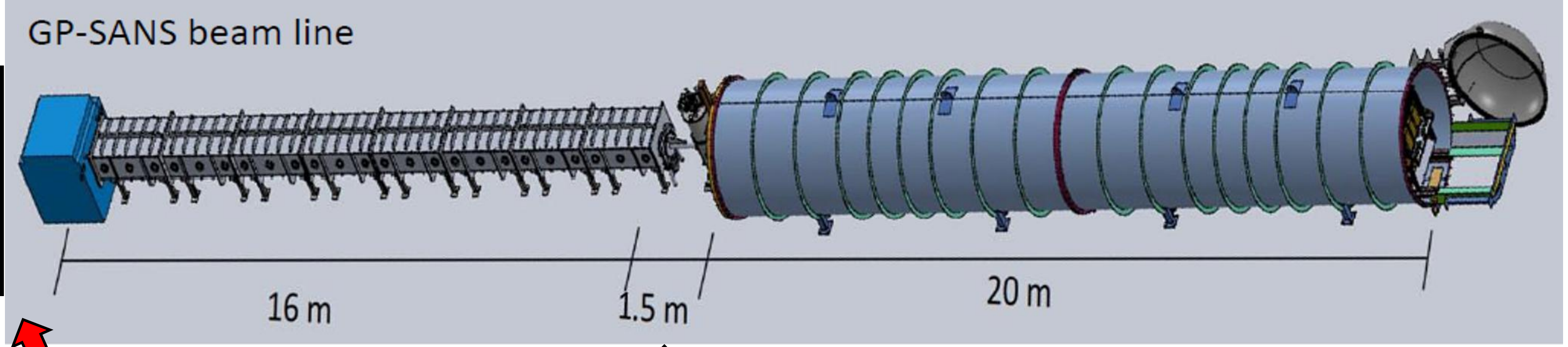
$$\theta_0 = \frac{\epsilon_{\mathrm{nn'}}}{\Delta\mathrm{m}}$$

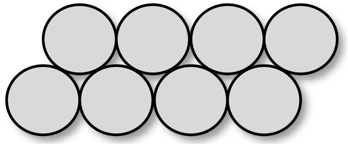
Regeneration Experiment Schematic



Experimental Layout

19 m

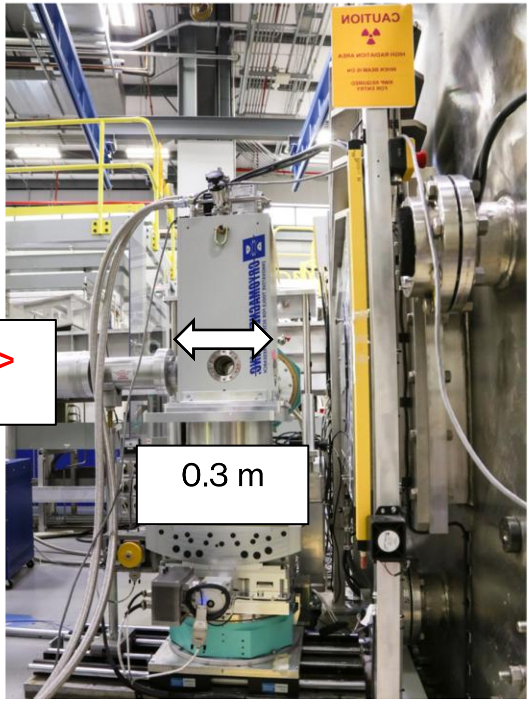




Initial 19 m of guides

Low efficiency monitor (LEM)

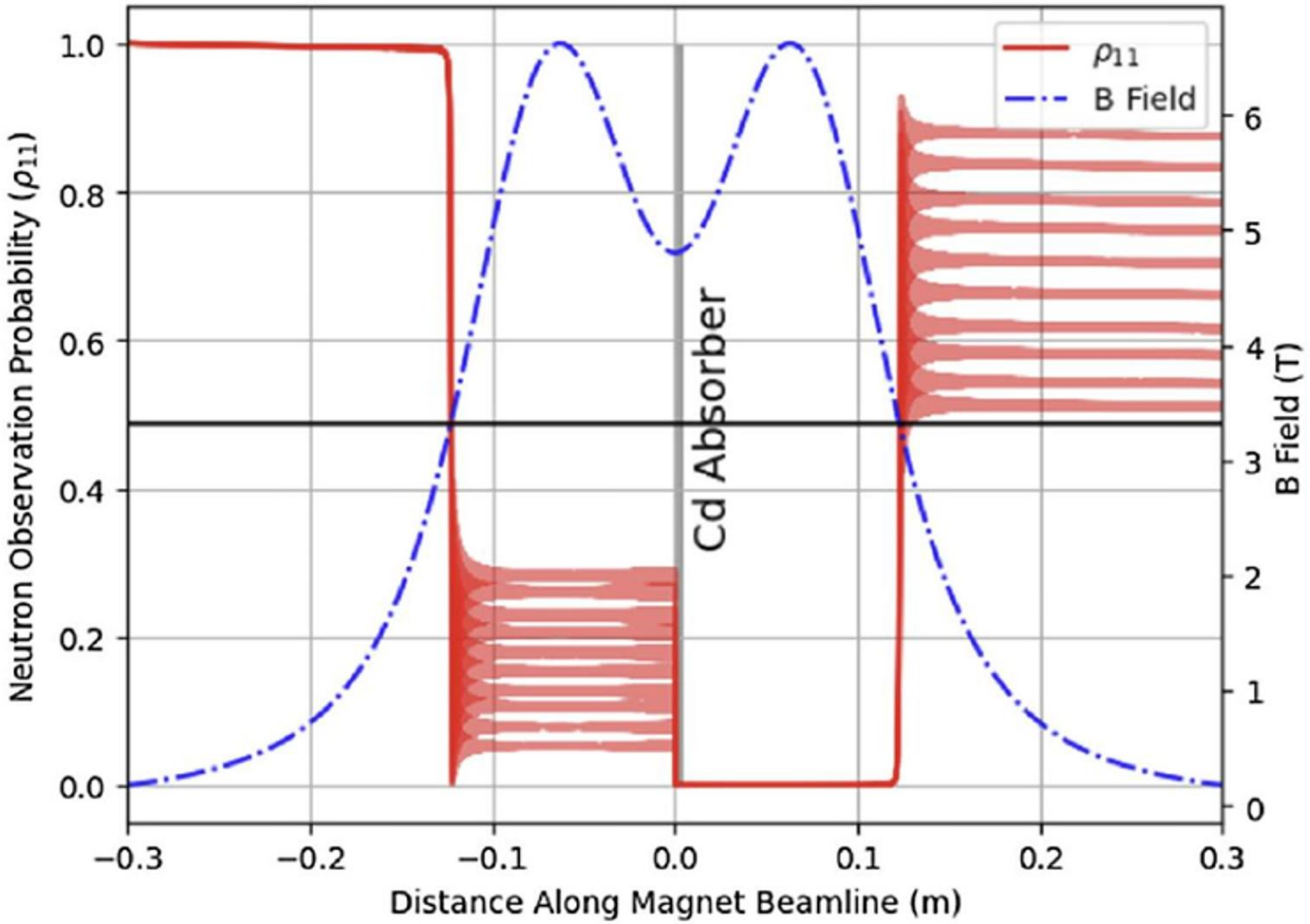
0.3 m superconducting magnet



1x1 m ^{3}He detector

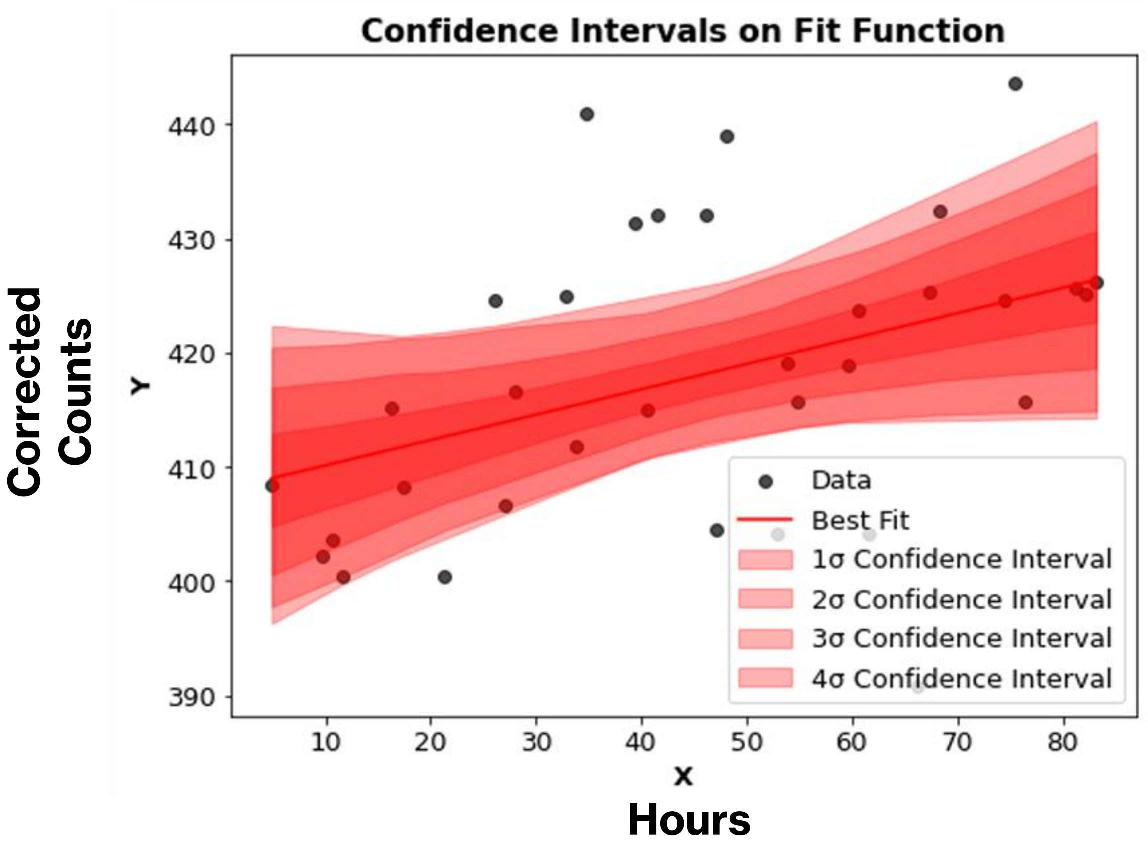
How regeneration transformation occurs

- Landau Zener effect
- Neutron flips energy going through magnetic field
- Different velocities → different probability of neutron being observable
- Result in a spectrum of probabilities for regeneration



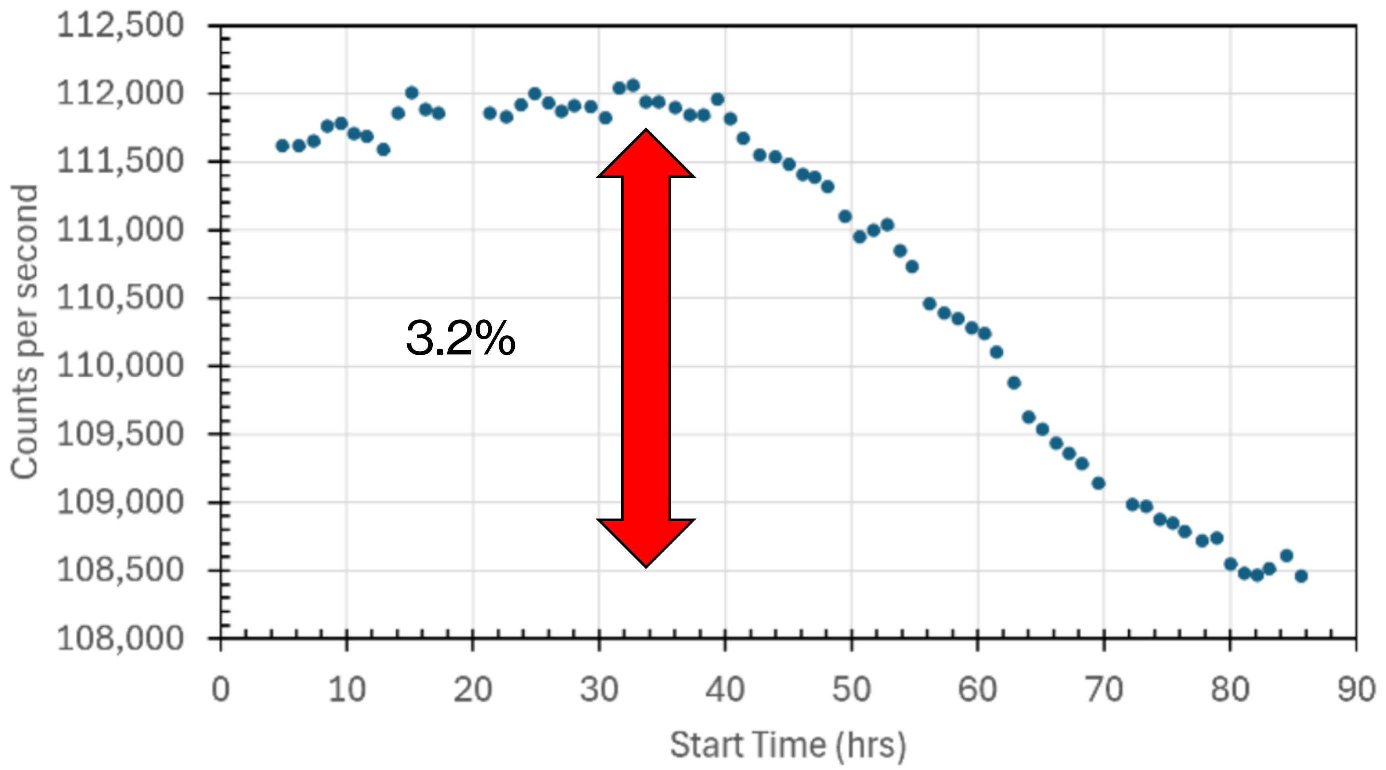
Defining regeneration effect in detector as the difference between applied field and 0 field

- Background runs are B = 0T
- Taken at different time from applied field runs
- Fit background as a function of time
- Predict value and error at any point
- Effect is found as a difference between runs with magnetic field and without magnetic field



Intensity correction for normalization

- Intensity measured by LEM
- Deadtime correction: 15%
- Reactor decreasing intensity
- Window attenuation factors



Intensity

- Intensity on the target after corrections: **2.3e12 per hour**
- or **6.4e8 per second**

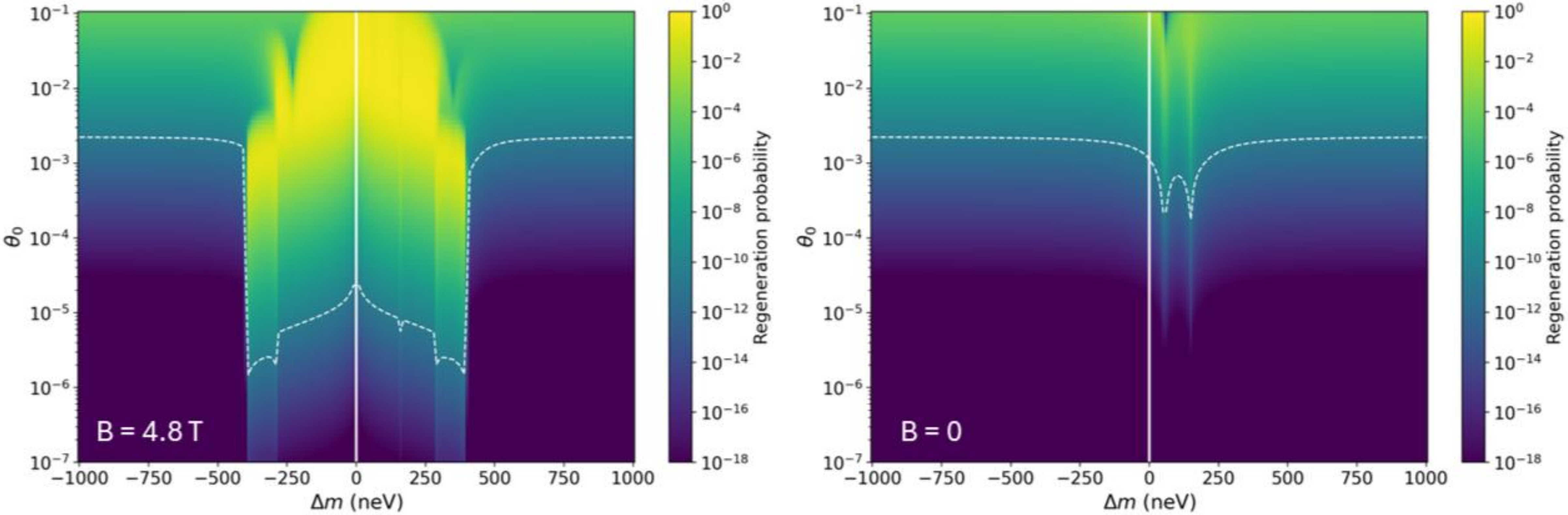
Final Results

- For 3.5 days of active beam time
- **No positive effect seen**
- Improved limits from two previous experiments of collaboration at SNS

Probability of regeneration

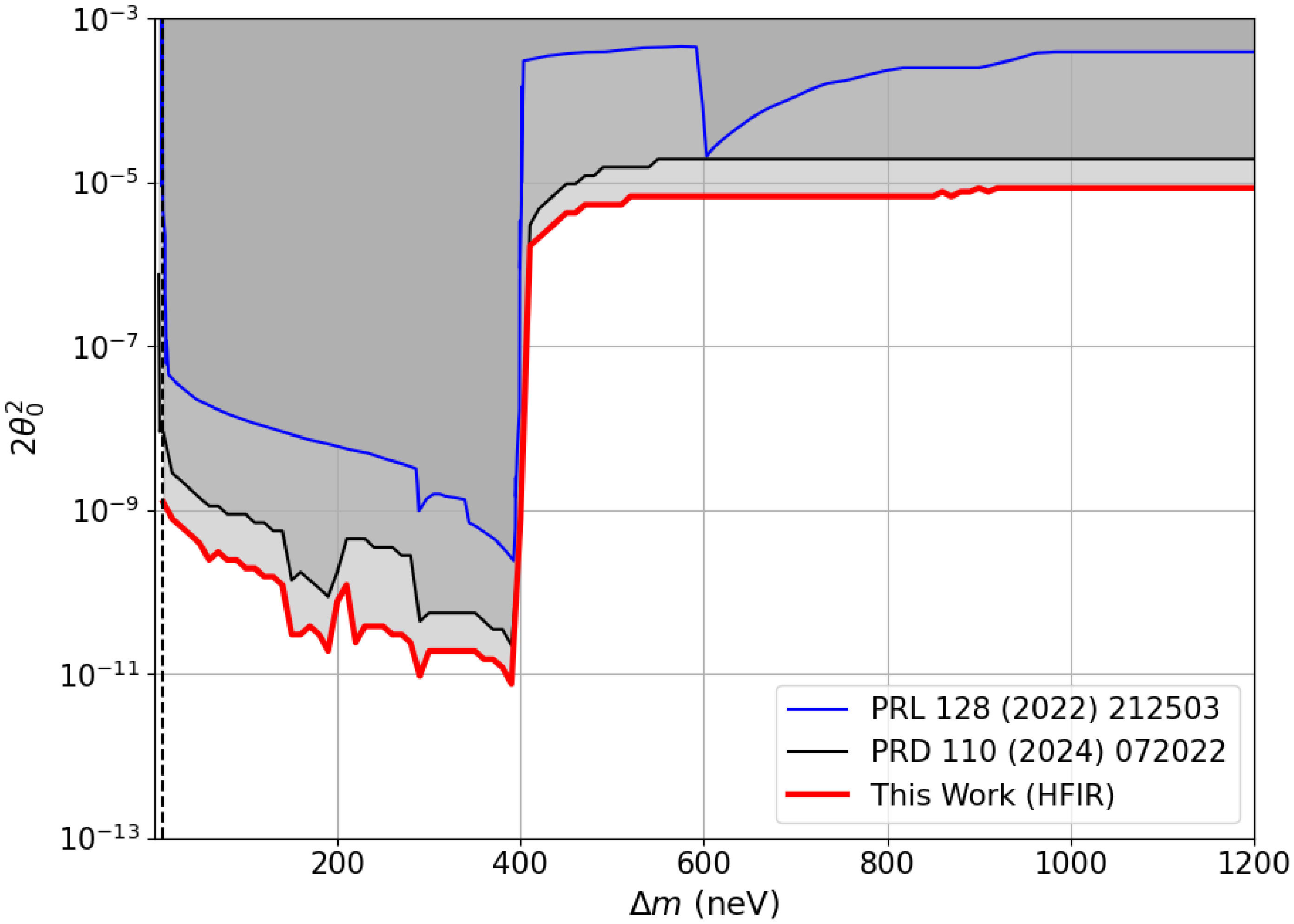
B-Field (T)	Counts (h^{-1})	Signal ($\times 10^{-12}$)	95% CL Limit (Feldman-Cousins)
0	24.4 ± 49.2	5.1 ± 10.3	1.25×10^{-11}
2.4	−9 ± 21	−6.34 ± 14.7	2.28×10^{-11}
3.6	13 ± 20	9.1 ± 14	3.65×10^{-11}
4.8	−3 ± 20	−2.1 ± 14	2.55×10^{-11}

What the limits mean for the model in terms of parameters Δm and vacuum θ_0?

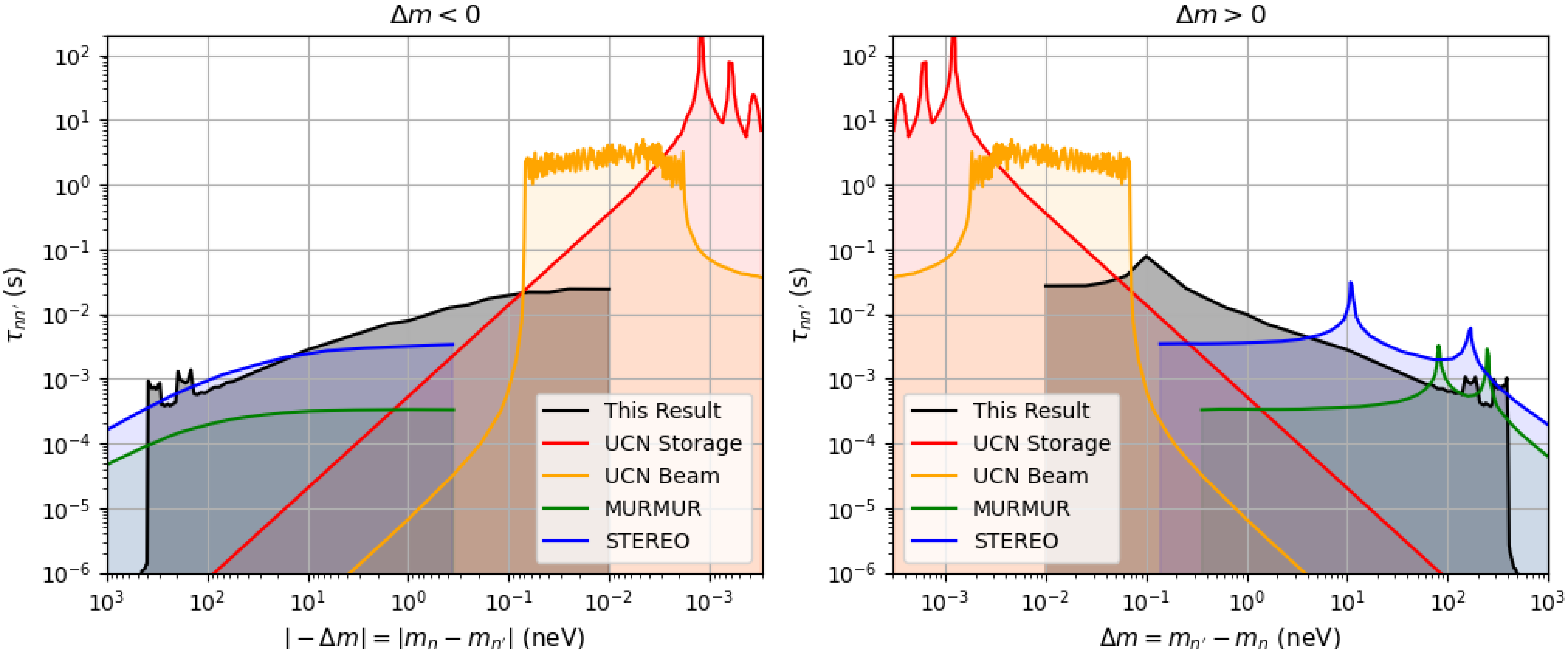


Probability of regeneration as a function of two parameters. Our result is dashed line (to be included). Excludes results above line for 4.8T and 0T

Progress in limits from SNS1, SNS2, and HFIR



Other experiments on $n \to n'$ search



Conclusion

- New limits on regeneration process $n \to n' \to n$ were obtained
- These limits agree with the limits obtained with UCN neutron
- In view of neutron lifetime anomaly (difference between UCN and beam measurement) our search provides complementary measurement of neutron with cold beam compared to UCN data

I would like to thank my colleagues of nn' Collaboration

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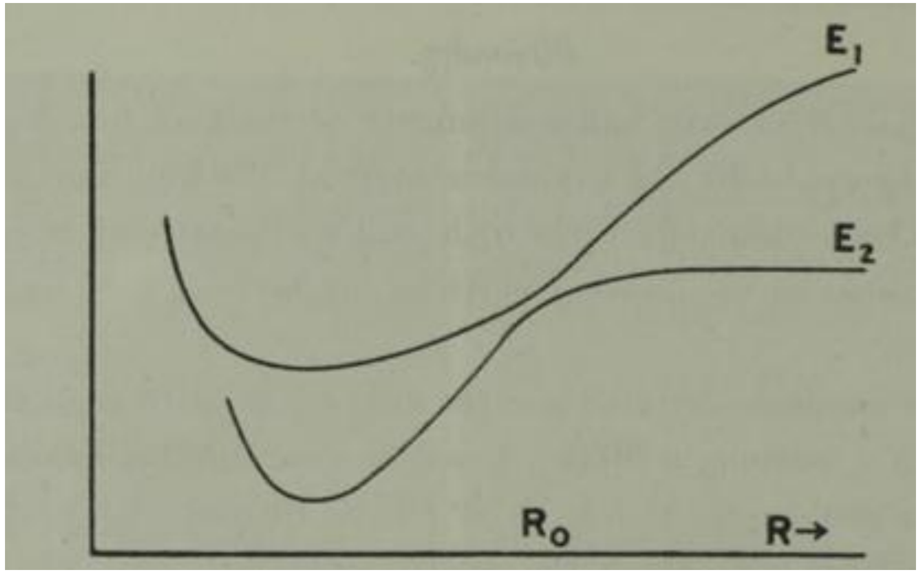
Backup

$$P_{n\to n'} = \frac{\varepsilon^2}{\varepsilon^2+\omega^2}\sin(\frac{\omega t}{\hbar})^2$$

$$\text{no } B, V_F \;\rightarrow\; \omega = \Delta m \;=\; U$$

$$\Psi n(0) \;=\; \cos\theta\cdot n + \sin\theta\cdot n'$$



Zener - 1932