Experimental Searches for $n \rightarrow n'$ Oscillations at the Spallation Neutron Source

FRANK GONZALEZ

OAK RIDGE NATIONAL LABORATORY

CONFERENCE ON THE INTERSECTION OF PARTICLE AND NUCLEAR PHYSICS

SEPTEMBER 1, 2022

Standard Model Extension: Mirror Matter

Introduce a new hidden sector SM copy

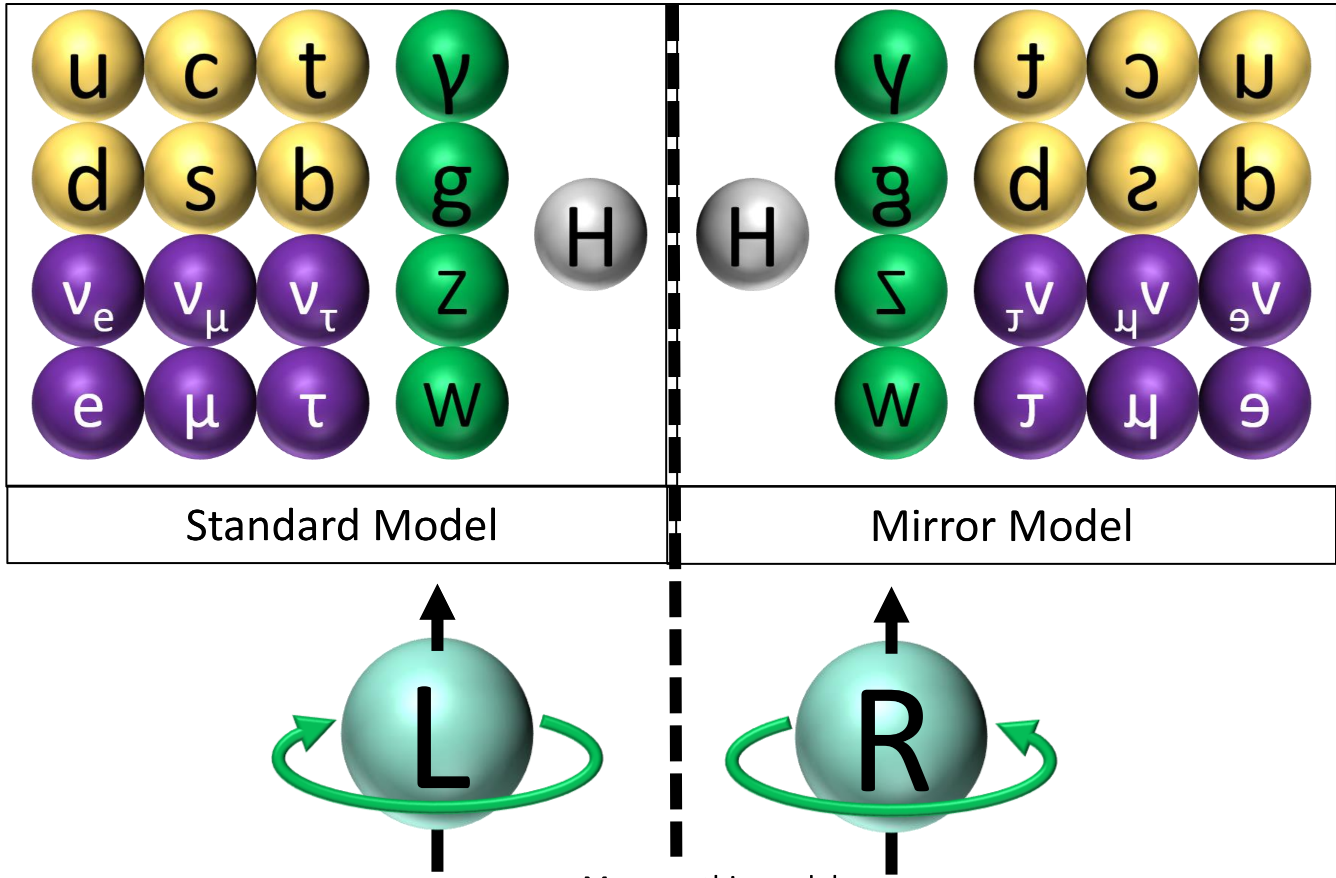
- Restore global parity with right-handed weak interactions
- Mirror composite particles (p', n')
- Interaction through gravity

Normal and Mirror Model mixing

- $i\frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} \Delta E(\Delta m, B, B', V) & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix} |\Psi(t)\rangle$
  - Δm from different Higgs VEV

In lab can control fields (B) and materials (V)

- Look for resonance at $\Delta E = 0$



More on this model:

- Berezhiani, Z., and Bento, L., PRL 96 081801 (2006)

Standard Model Extension: Mirror Matter

Introduce a new hidden sector SM copy

- Restore global parity with right-handed weak interactions
- Mirror composite particles (p', n')
- Interaction through gravity

Normal and Mirror Model mixing

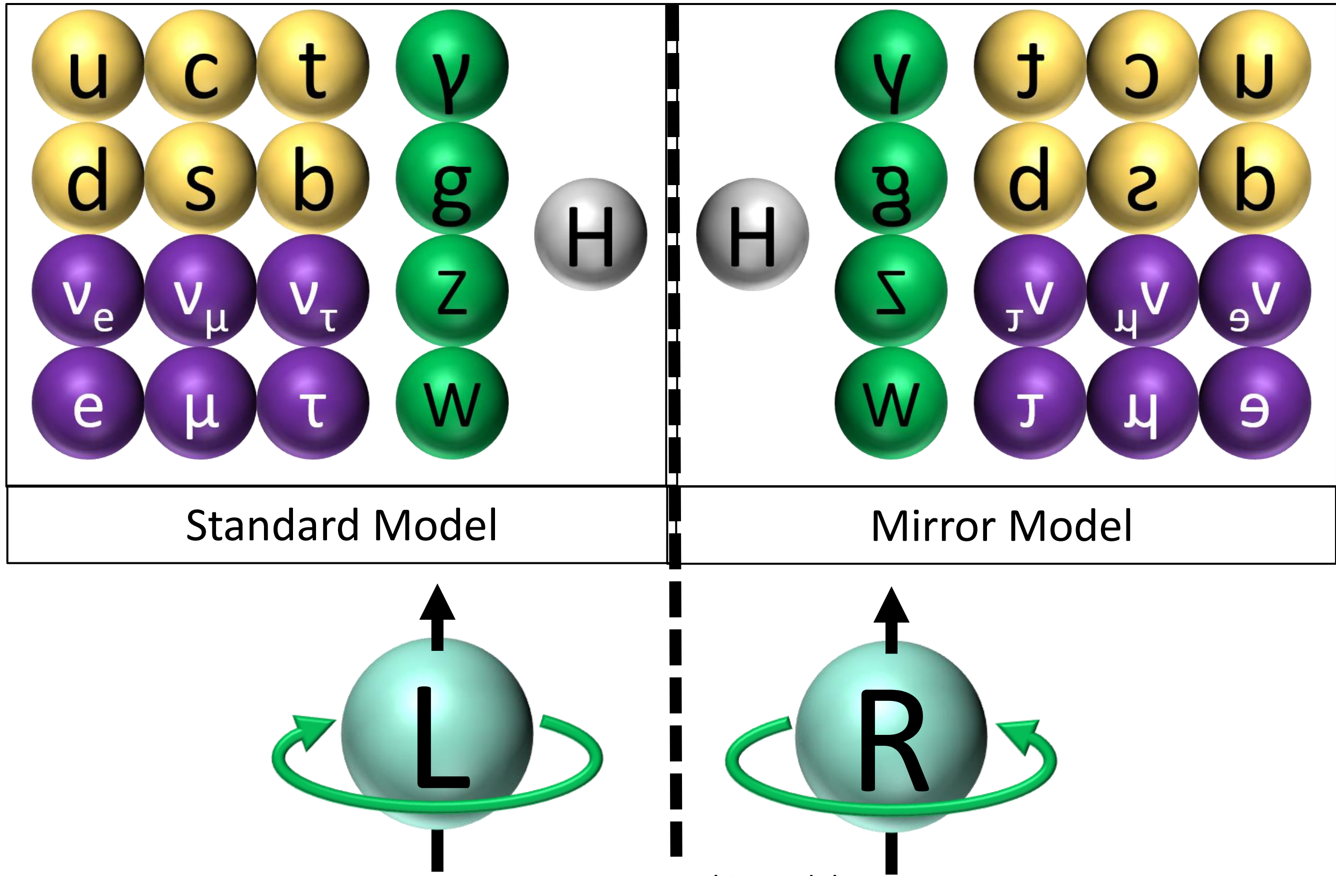
- $i \frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} \Delta E(\Delta m, B, B', V) & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix} |\Psi(t)\rangle$
  - Δm from different Higgs VEV

In lab can control fields (B) and materials (V)

- Look for resonance at $\Delta E = 0$

For B' see:

- P. Mohanmurthy



More on this model:

- Berezhiani, Z., and Bento, L., PRL 96 081801 (2006)

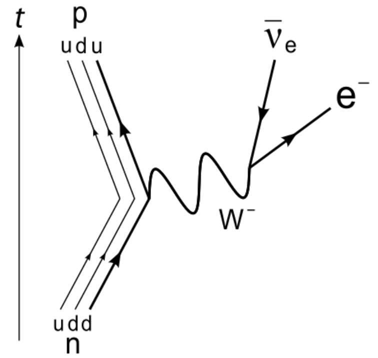
The Weak Interaction and Neutron Decay

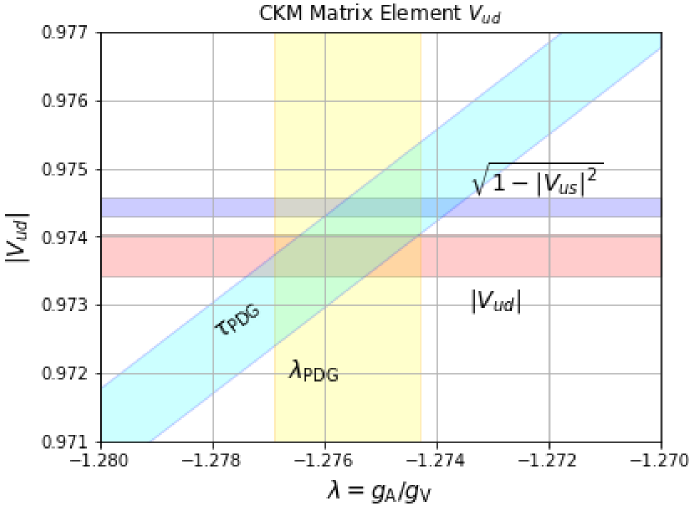
Neutron β-decay:

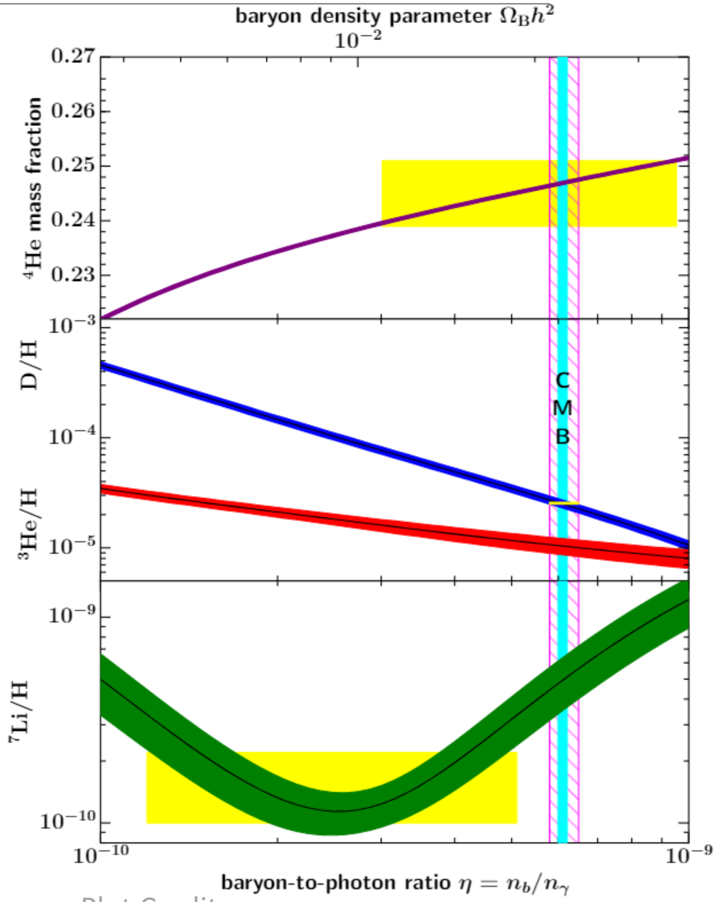
- $n \rightarrow p^{+} + e^{-} + \overline{\nu_e}$
- $|V_{ud}|^2 = \dfrac{5099.3\text{ s}}{\tau_n\,(1+3\,\lambda^2)(1+\Delta_R)}$

Precision Measurements of τ_n

- Big Bang Nucleosynthesis
- CKM (quark-mixing) Matrix:
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{BSM}$







Plot Credit:
Workman, R. L. *et al*, Particle Data Group (2022)

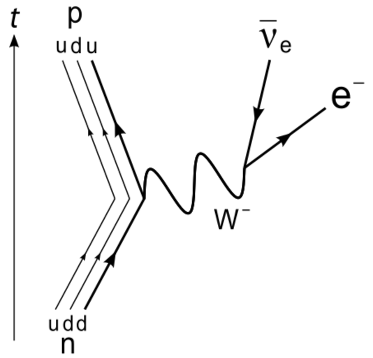
The Weak Interaction and Neutron Decay

Neutron β-decay:

- $n \rightarrow p^+ + e^- + \overline{\nu_e}$
- $|V_{ud}|^2 = \frac{5099.3\ \mathrm{s}}{\tau_n\ (1+3\ \lambda^2)(1+\Delta_R)}$

Radiative Corrections:

- L. Hayen (EW-3)

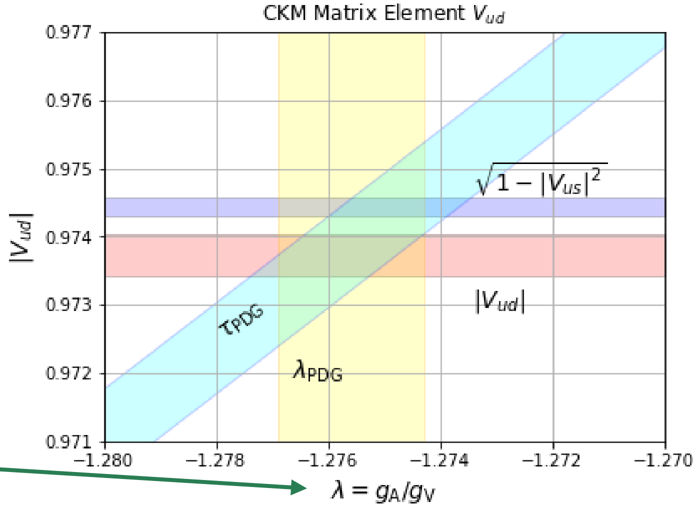


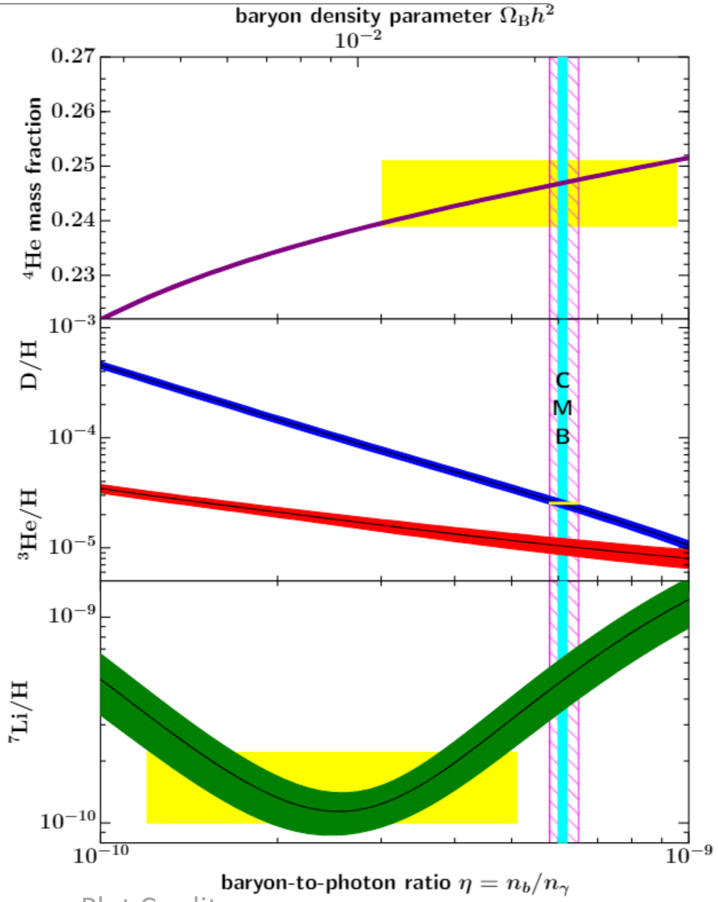
Precision Measurements of τ_n

- Big Bang Nucleosynthesis
- CKM (quark-mixing) Matrix:
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{BSM}$

Also in this session:

- F. Wietfeldt (aCORN)
- R. Mammei (Nab)
- B. Märkisch (PERKEO III/PERC)
- S. Baeßler (aSPECT)



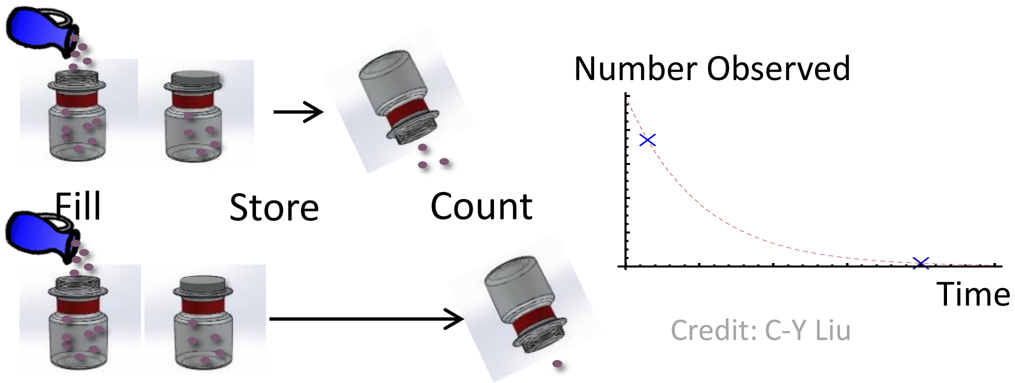


Plot Credit:
Workman, R. L. *et al*, Particle Data Group (2022)

How to Measure a Lifetime? Count the Living or Count the Dead

"Bottle experiment":

- Counting the ~~living~~ neutrons
- $Y(t) = Y_0 e^{-t\,/\,\tau_{meas}}$

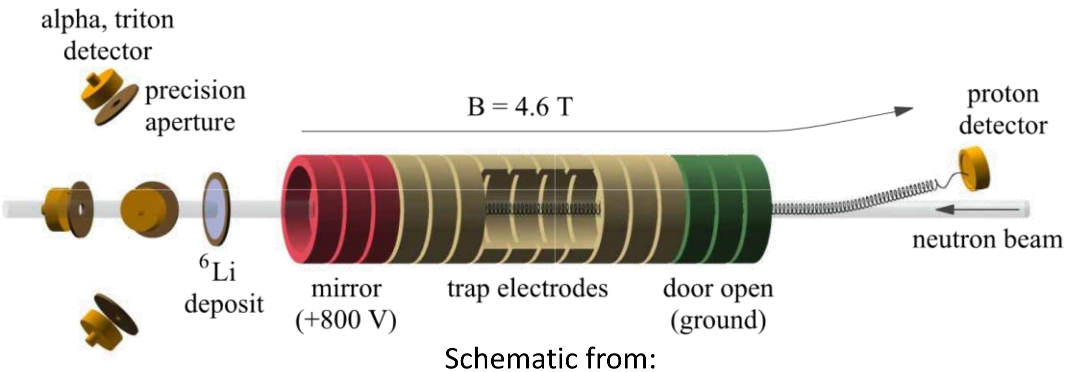


Systematics:

- Relative measurements of rates
- *Unaccounted for sources of loss give a lower lifetime!*

"Beam experiment":

- Counting the ~~dead~~ decay products
- $\tau_{meas} = \frac{L}{v_n} \frac{\dot{N}_n / \epsilon_n}{\dot{N}_p / \epsilon_p}$



Schematic from:

- [Nico, J. S. *et* al, Phys. Rev. C 71, 055502 (2005)]

Systematics:

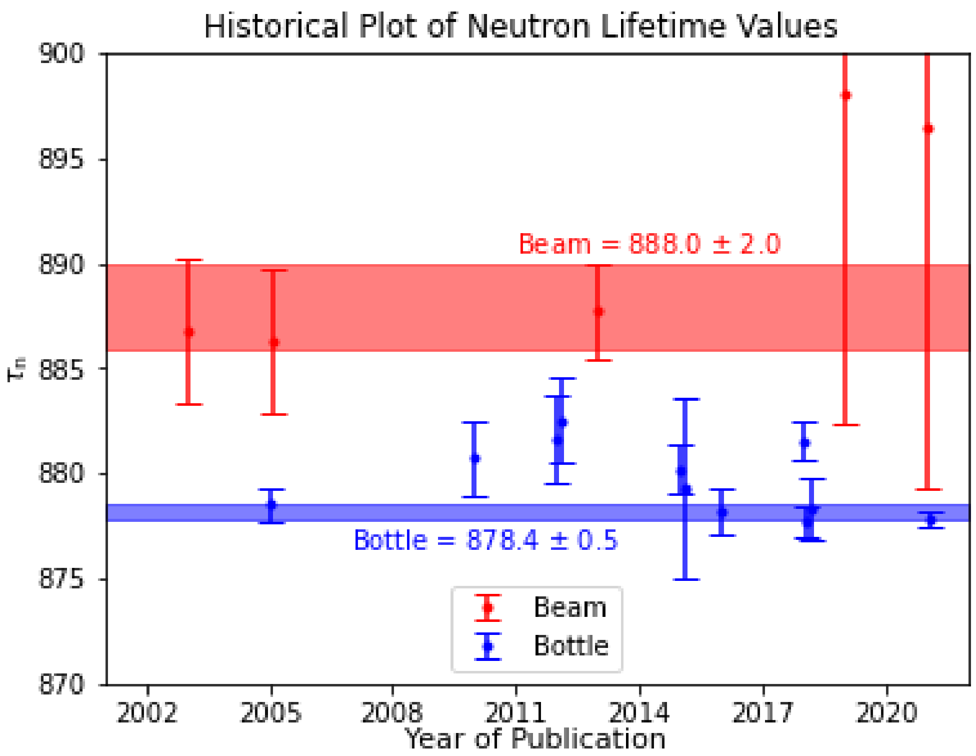
- Absolute measurements of p^+ and n rates
- *Need to calibrate two detectors*

How to Measure a Lifetime?
Count the Living or Count the Dead

"Bottle experiment":
- Counting the ~~living~~ neutrons

"Beam experiment":
- Counting the ~~dead~~ decay products

Beam > Bottle (~4σ)

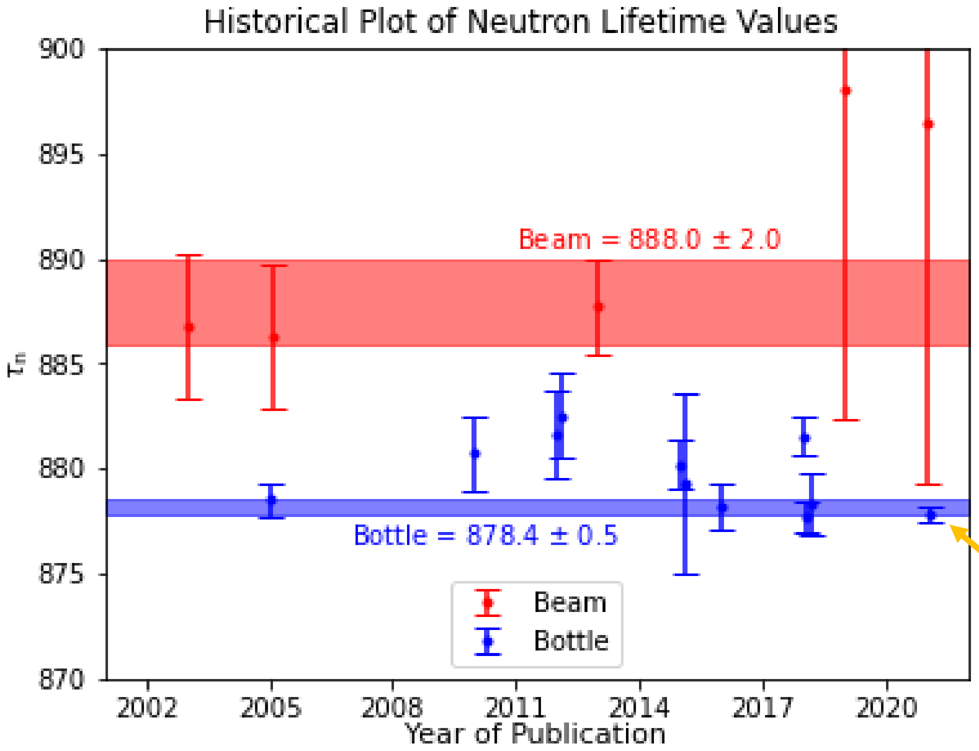


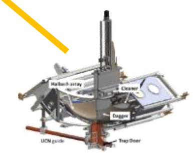
How to Measure a Lifetime?
Count the Living or Count the Dead

"Bottle experiment":
- Counting the ~~living~~ neutrons

"Beam experiment":
- Counting the ~~dead~~ decay products

Beam > Bottle ($\sim 4\sigma$)





UCNτ Experiment:
- [R. Pattie (Plenary)]

UCNProBe(ing) the discrepancy:
- [Z. Tang (EW-3)]

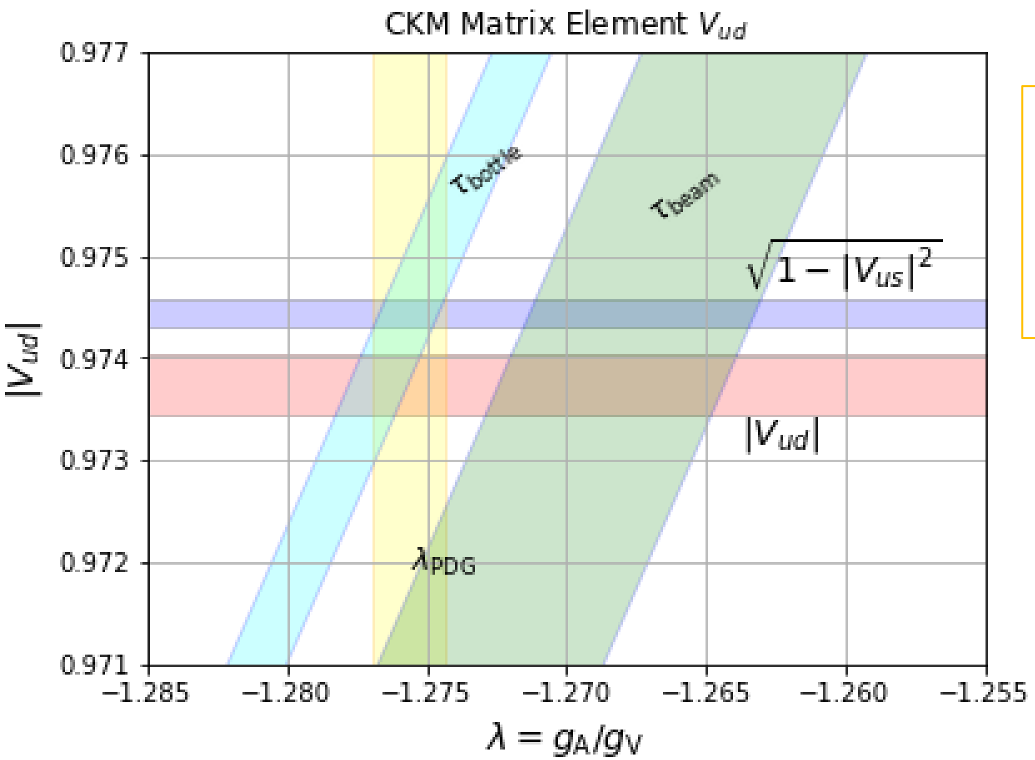
Gonzalez, F. M. *et al*, Phys. Rev. Lett. 127, 162501 (2021)

How to Measure a Lifetime? Count the Living or Count the Dead

"Bottle experiment":
- Counting the ~~living~~ neutrons

"Beam experiment":
- Counting the ~~dead~~ decay products

Beam > Bottle ($\sim 4\sigma$)

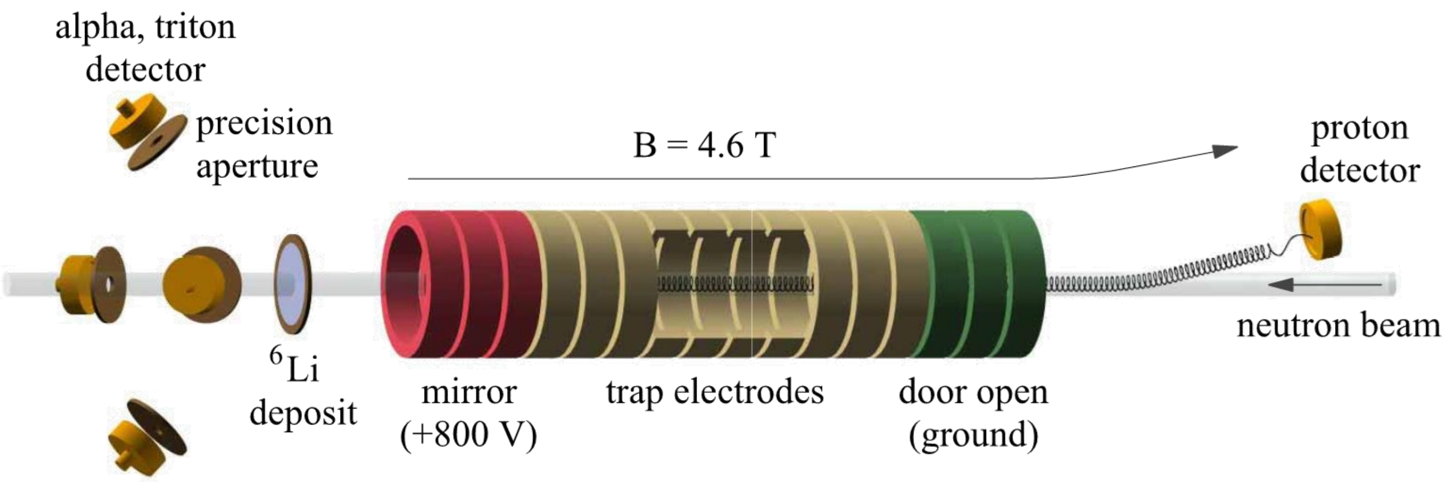


Can be explained if $n \rightarrow \chi$, where χ is not a proton
- But CKM Unitarity constraints agree with τ_{bottle}…

How to Measure Lifetime?
The Beam Lifetime

Two particle fluxes ($\dot{N}_p$,$\dot{N}_n$) required:

$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$



Most precise beam:
- [Yue, A. T. *et al*. PRL 111, 222501 (2013)]

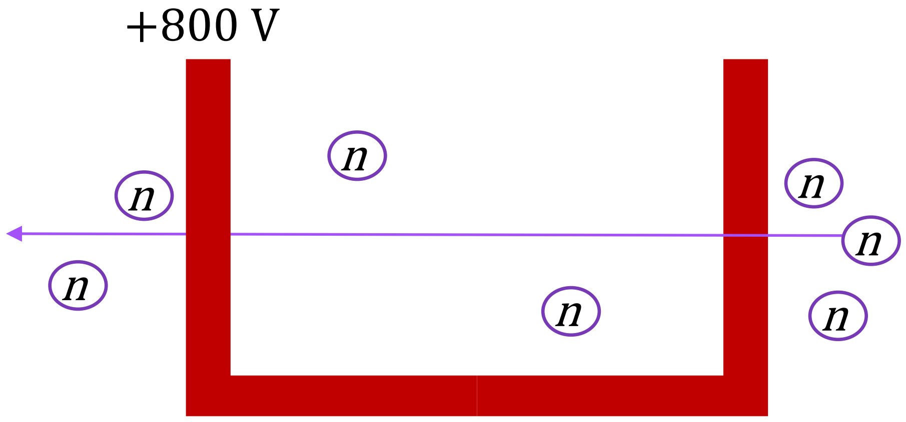
How to Measure Lifetime?
The Beam Lifetime

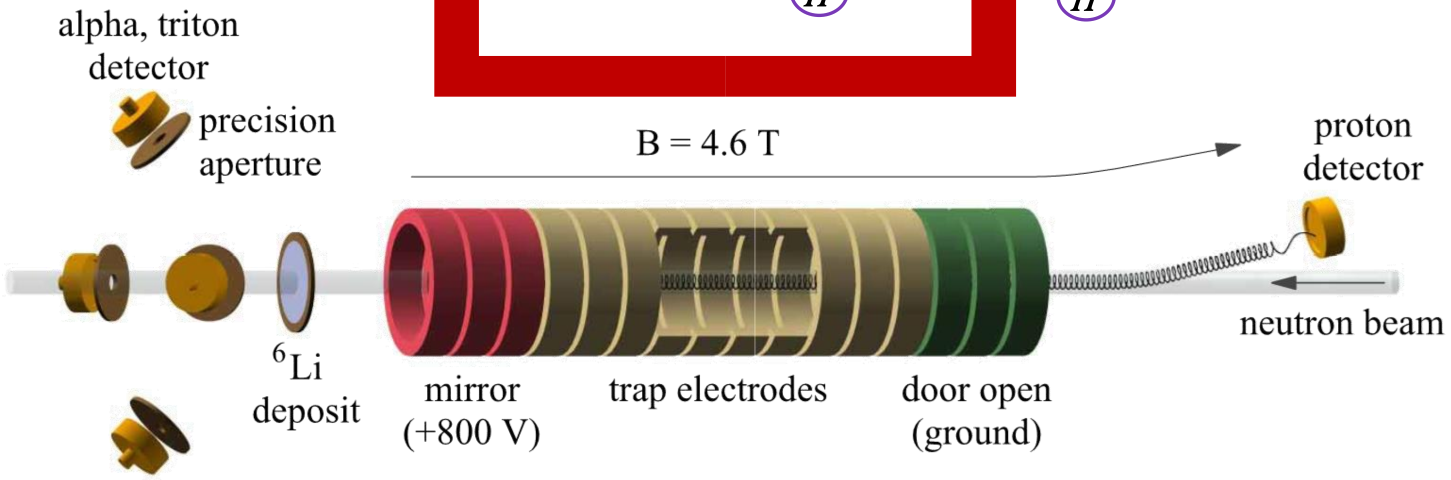
Two particle fluxes ($\dot{N}_p$,$\dot{N}_n$) required:

$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

Beam of n passes through electrodes

- $\dot{N}_n$ measured at end with ^{6}Li





Most precise beam:
- Yue, A. T. *et al*. PRL 111, 222501 (2013)

How to Measure Lifetime? The Beam Lifetime

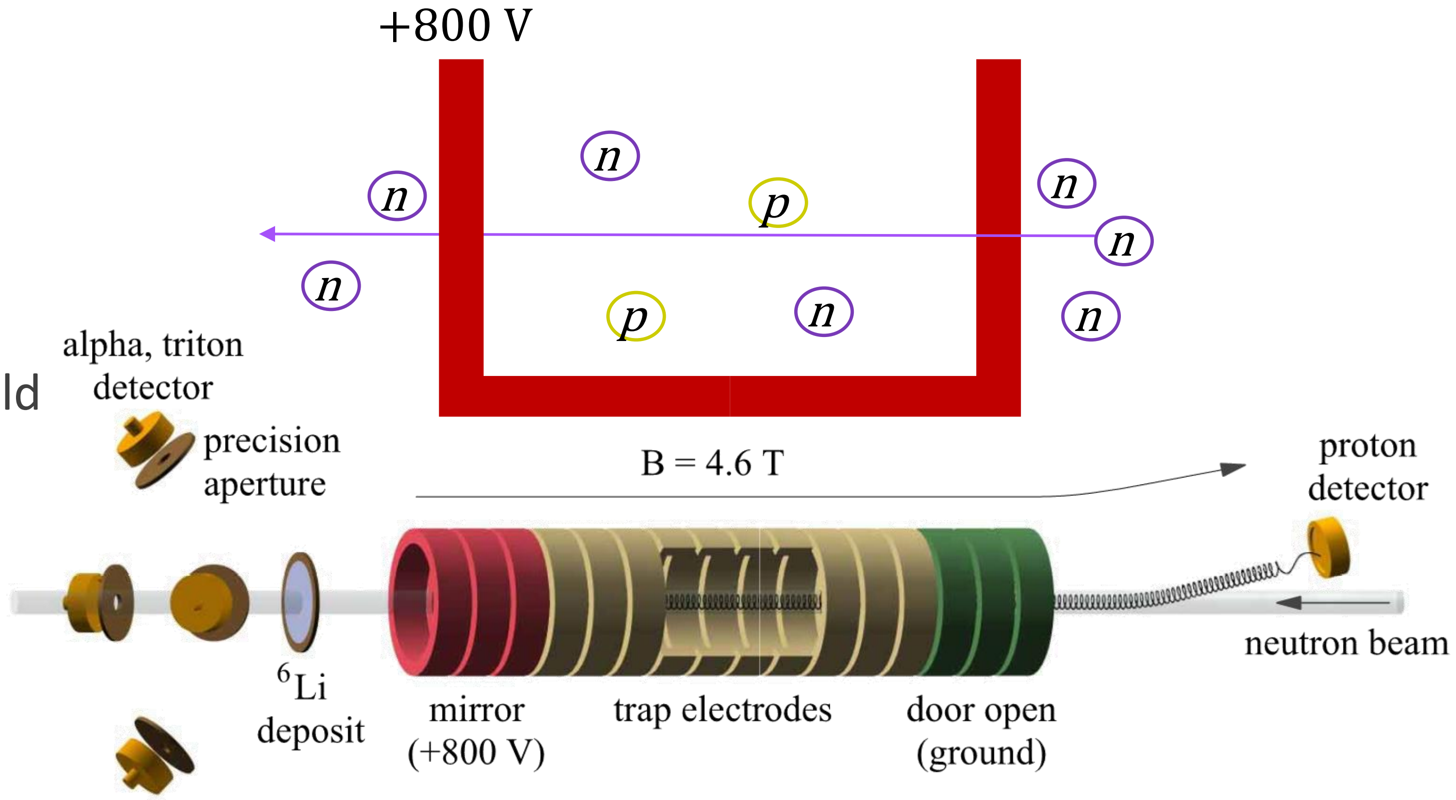
Two particle fluxes ($\dot{N}_p$,$\dot{N}_n$) required:

$$\tau_{meas} = \frac{L}{v_n} \frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

Beam of n passes through electrodes

- $\dot{N}_n$ measured at end with ^{6}Li

Decay product p^+ trapped inside E field



Most precise beam:

- Yue, A. T. *et al*. PRL 111, 222501 (2013)

How to Measure Lifetime?
The Beam Lifetime

Two particle fluxes ($\dot{N}_p$,$\dot{N}_n$) required:

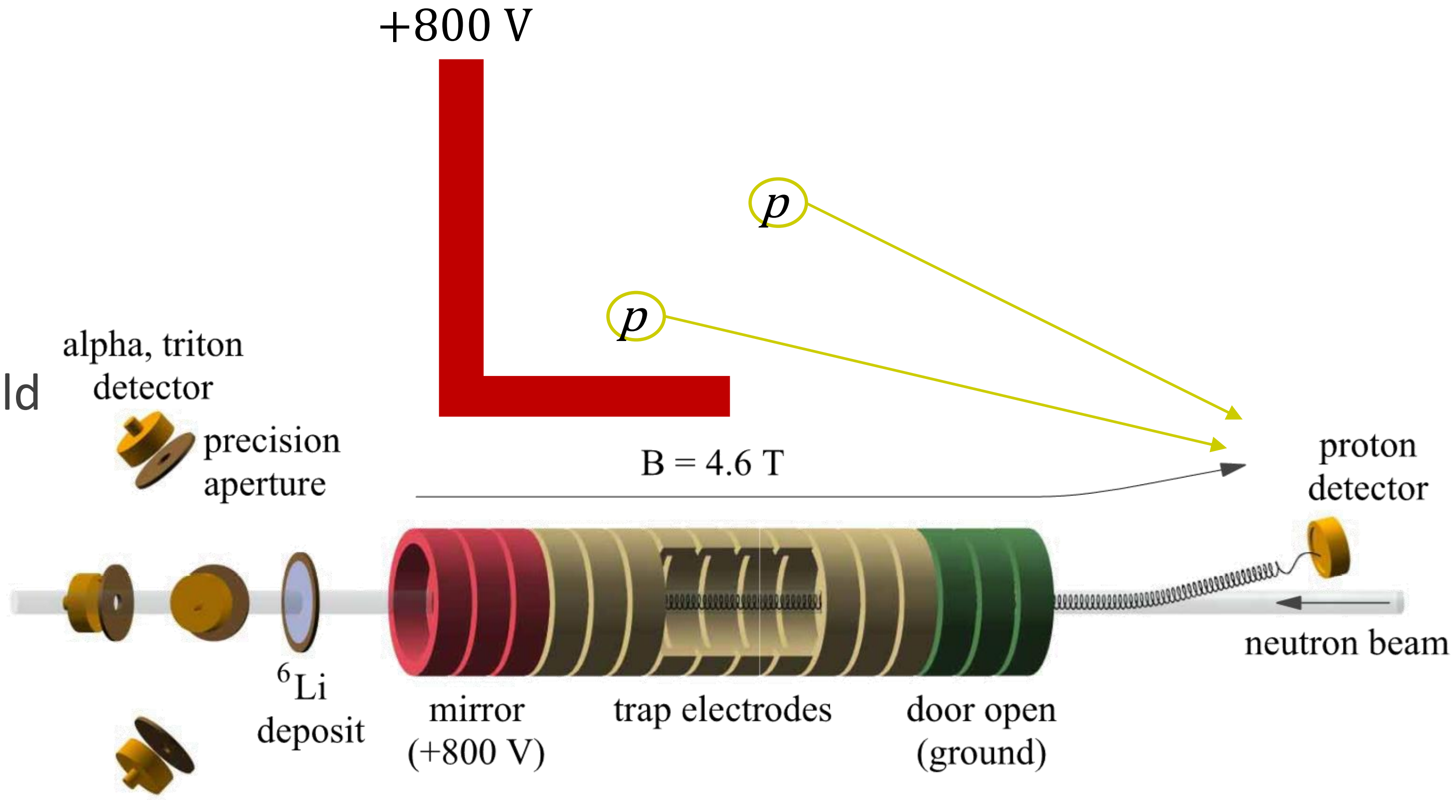
$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

Beam of n passes through electrodes

- $\dot{N}_n$ measured at end with ^{6}Li

Decay product p^+ trapped inside E field

External detector to measure $\dot{N}_p$



Most precise beam:

- Yue, A. T. *et al*. PRL 111, 222501 (2013)

How to Measure Lifetime?
The Beam Lifetime

Two particle fluxes ($\dot{N}_p$,$\dot{N}_n$) required:

$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

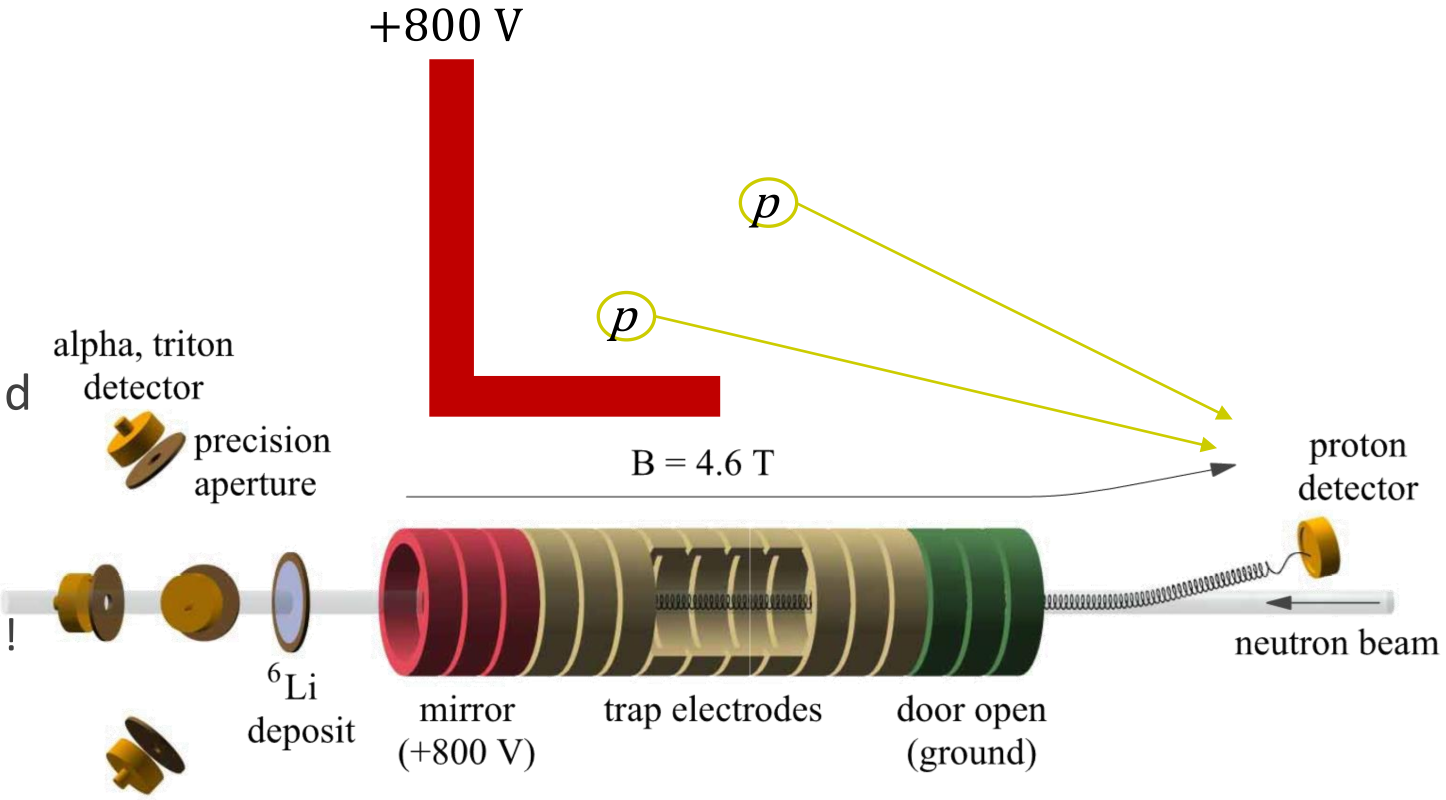
Beam of n passes through electrodes

- $\dot{N}_n$ measured at end with ^{6}Li

Decay product p^+ trapped inside E field

External detector to measure $\dot{N}_p$

- Guided to detector with $B = 4.6$ T
- Compensation for energy difference ΔE!

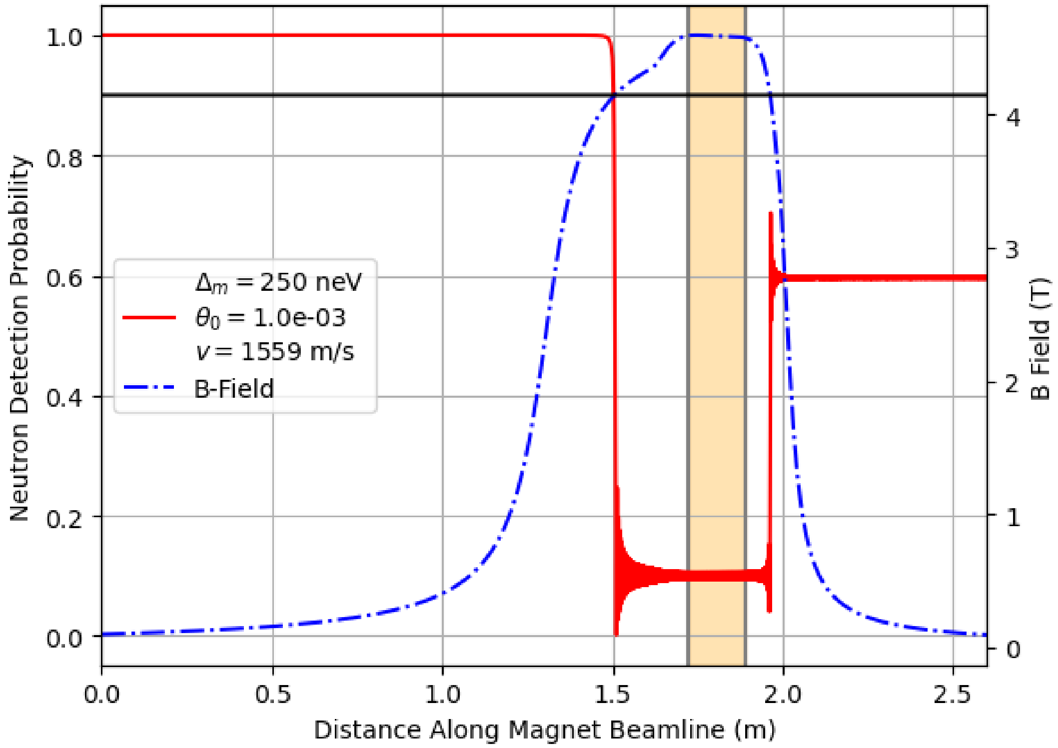


Most precise beam:

- Yue, A. T. *et al*. PRL 111, 222501 (2013)

$n \rightarrow n'$ in the Beam Lifetime

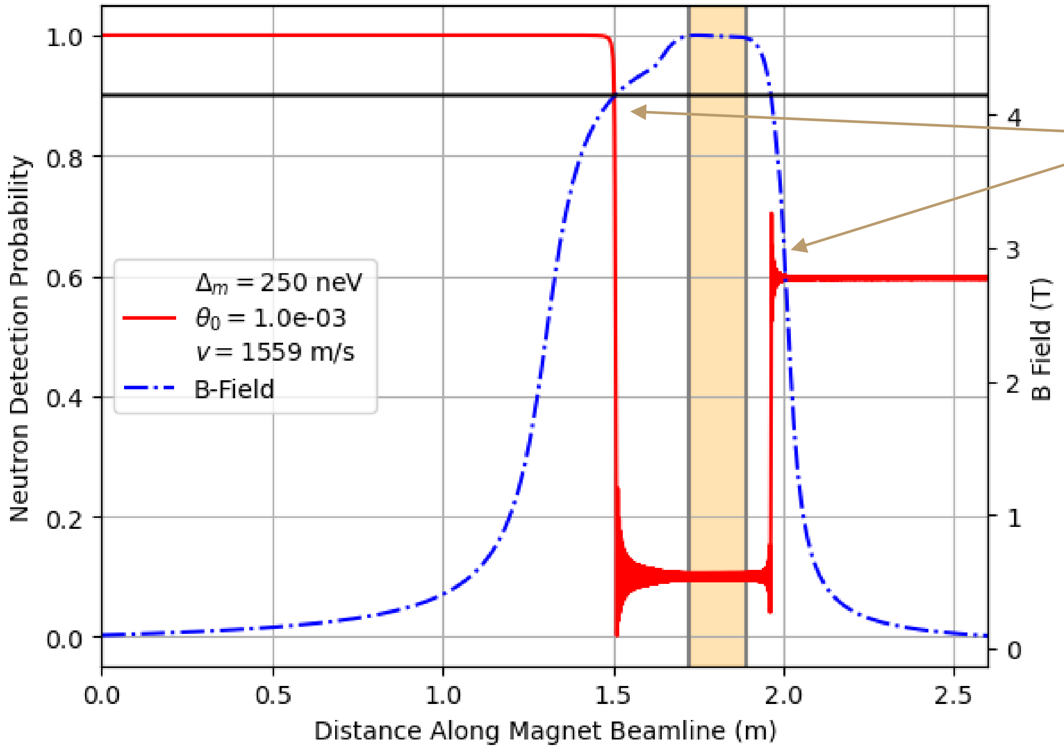
$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$



Neutron Beam

$n \rightarrow n'$ in the Beam Lifetime

$$\tau_{meas} = \frac{L}{v_n} \frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

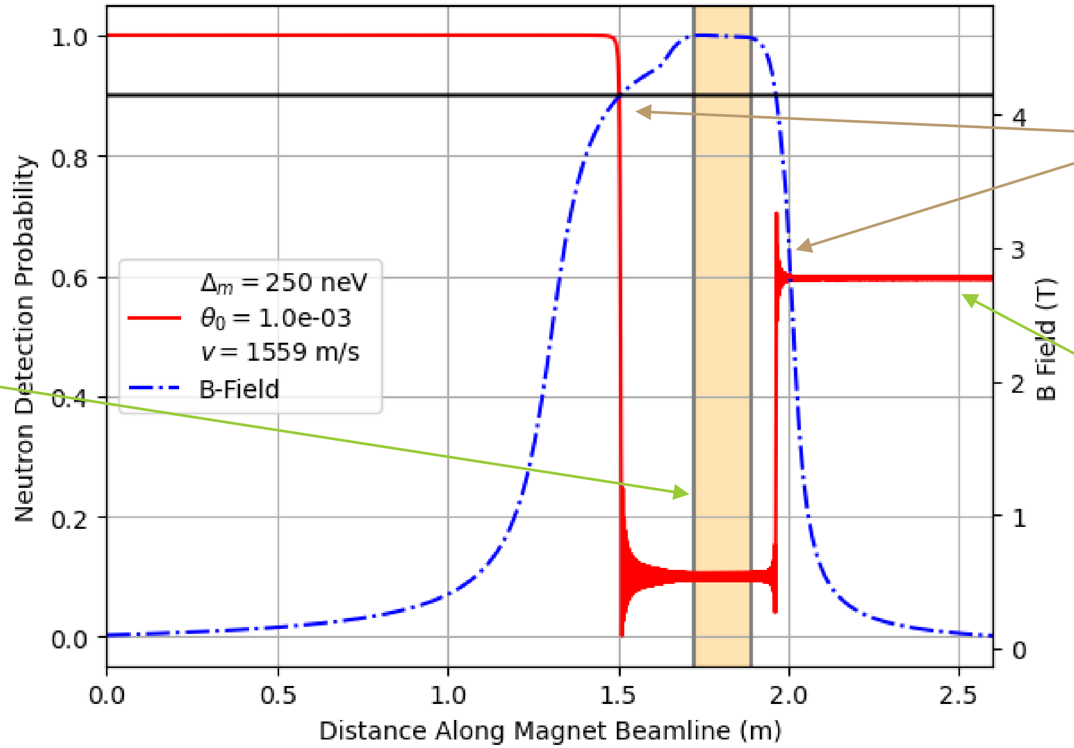


Landau-Zener Transitions when $\Delta\mathrm{E} = 0$

Neutron Beam

$n \to n'$ in the Beam Lifetime

$$\tau_{meas} = \frac{L}{v_n} \frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$



Landau-Zener Transitions when $\Delta\mathrm{E} = 0$

p^+ counted in this region

n counted after magnet

Neutron Beam

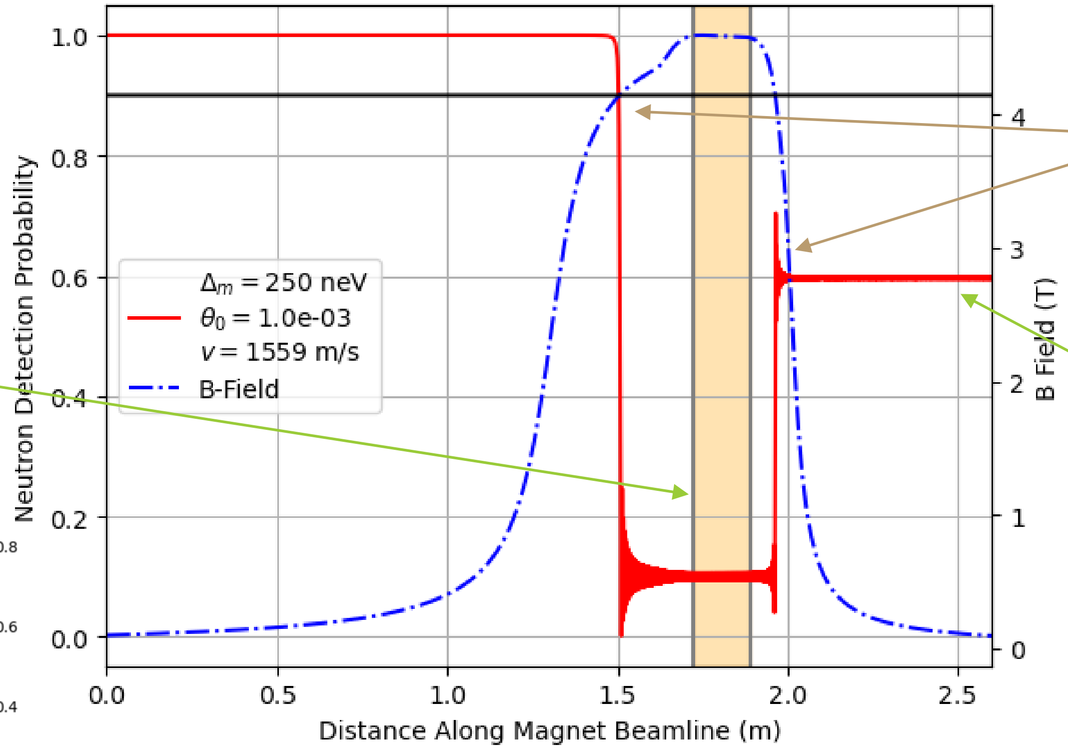
$n \to n'$ in the Beam Lifetime

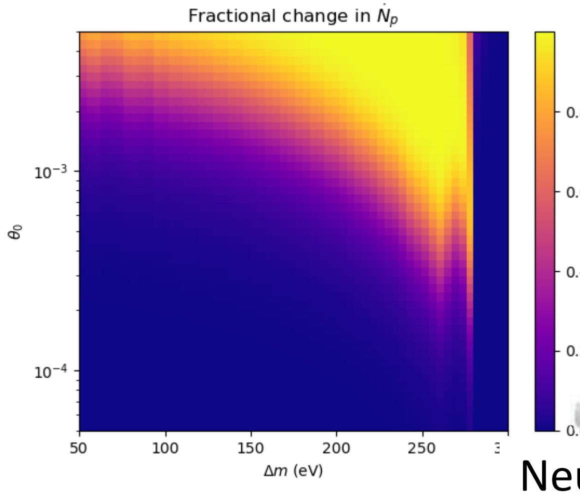
$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

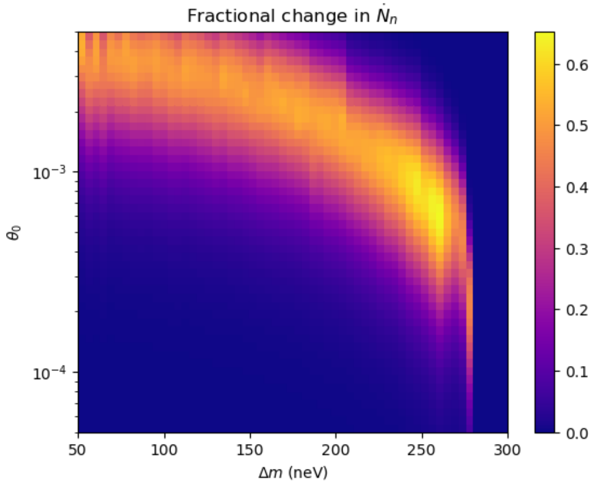
Landau-Zener Transitions when $\Delta\text{E} = 0$

p^+ counted in this region

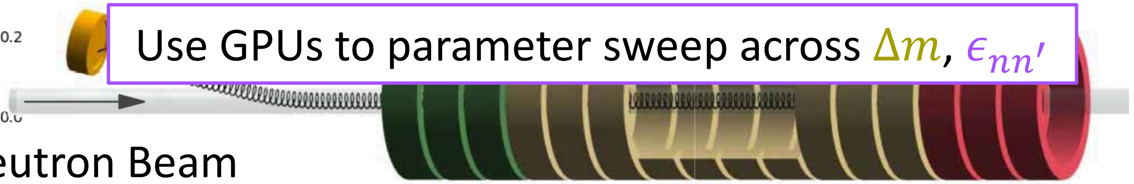
n counted after magnet







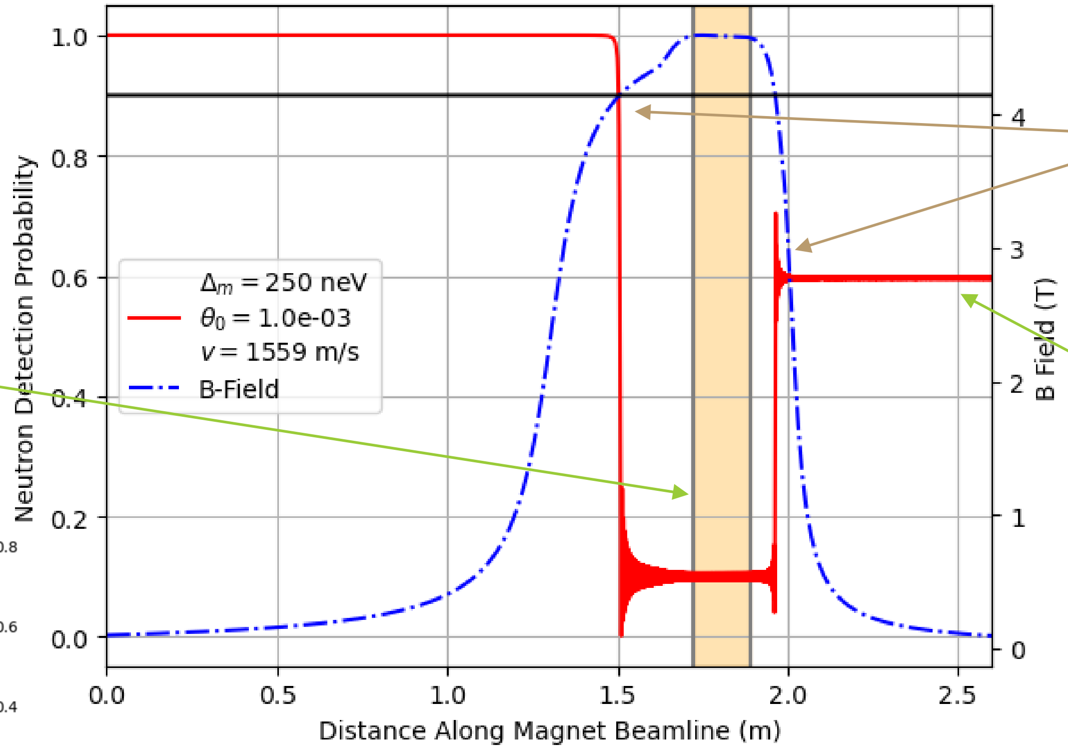
Use GPUs to parameter sweep across Δm, $\epsilon_{nn'}$



Neutron Beam

$n \to n'$ in the Beam Lifetime

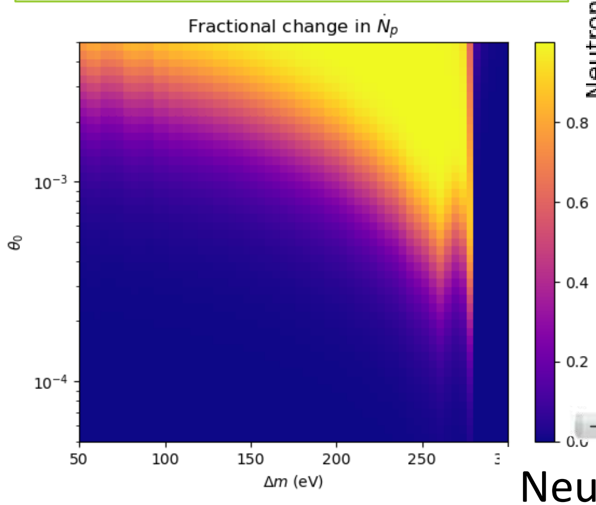
$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

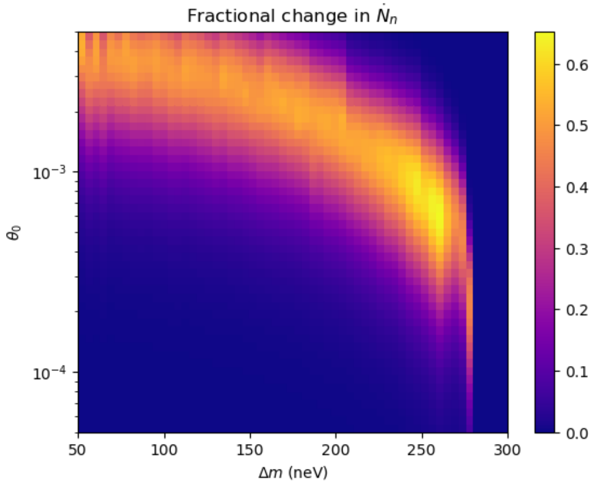


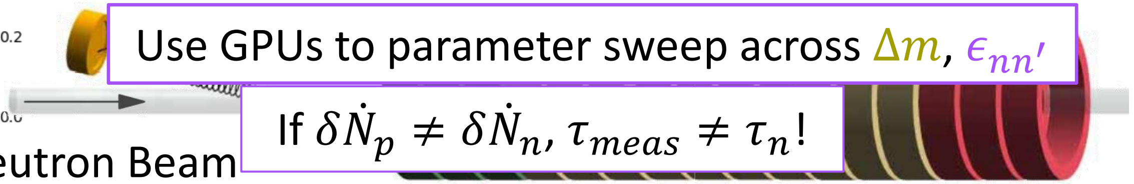
Landau-Zener Transitions when $\Delta \mathrm{E} = 0$

p^+ counted in this region

n counted after magnet





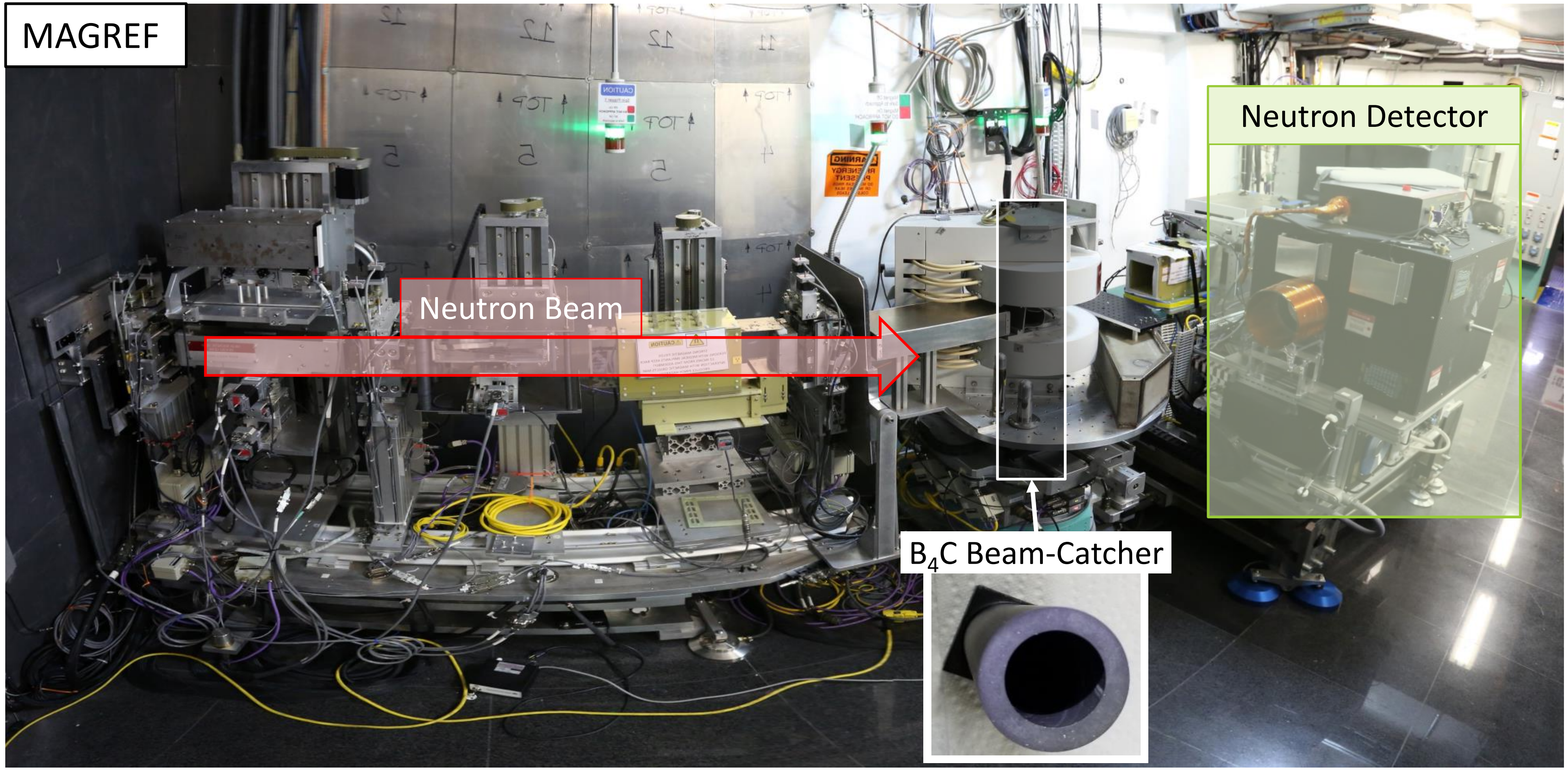


Use GPUs to parameter sweep across Δm, $\epsilon_{nn'}$

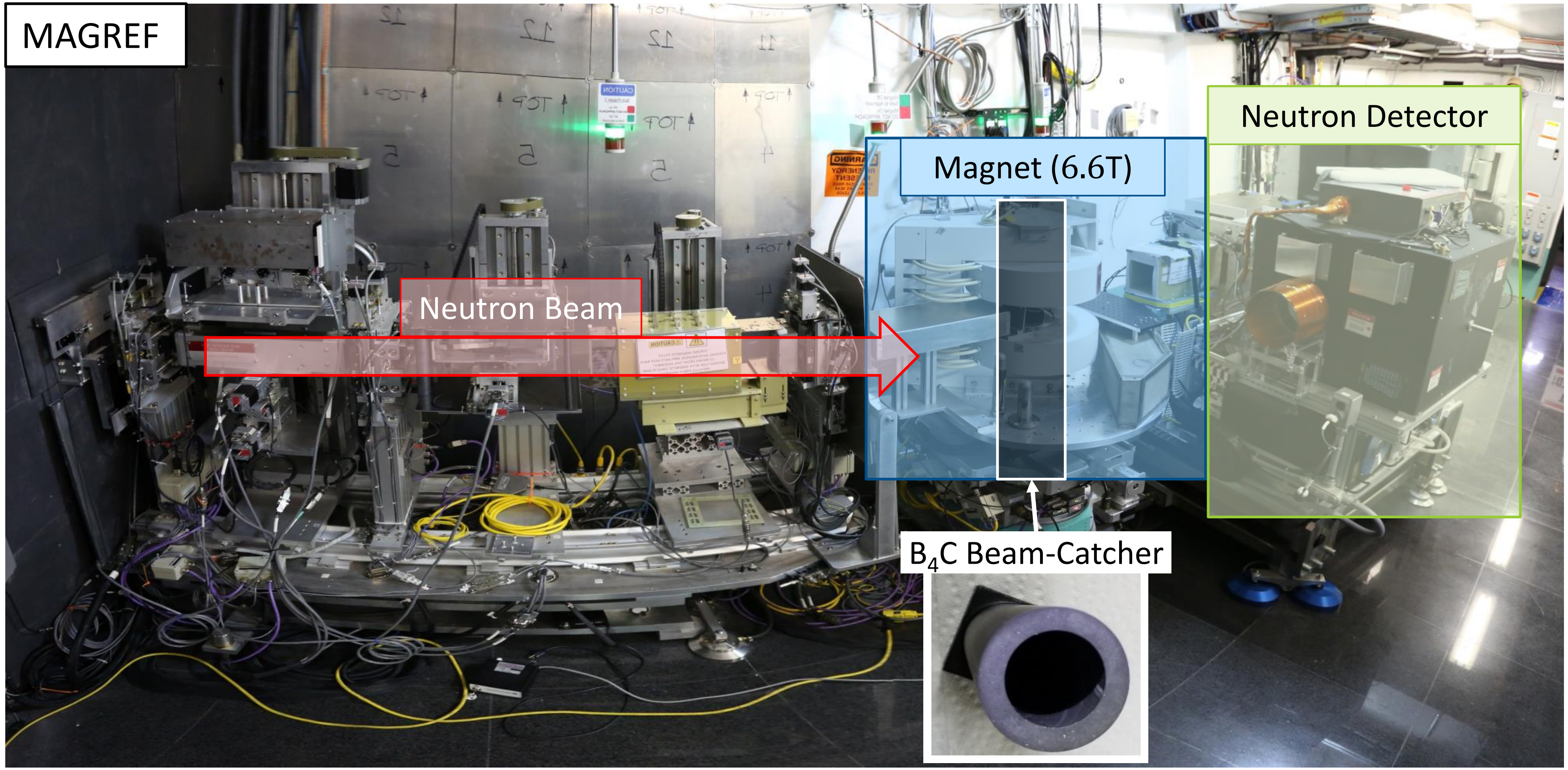
If $\delta\dot{N}_p \neq \delta\dot{N}_n$, $\tau_{meas} \neq \tau_n$!

Neutron Beam

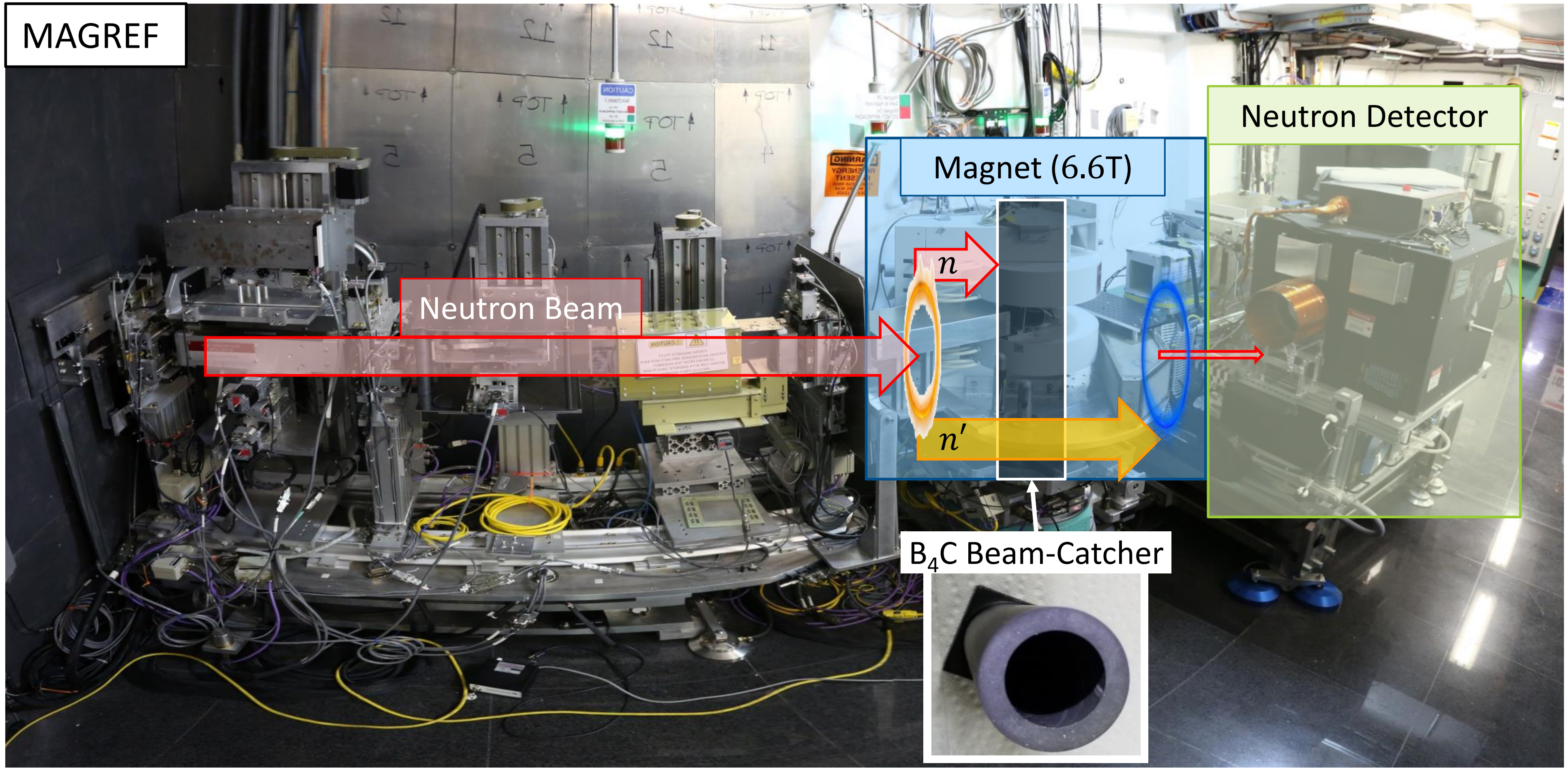
Experimental Apparatus: Shooting Neutrons Through a Wall



Experimental Apparatus: Shooting Neutrons Through a Wall

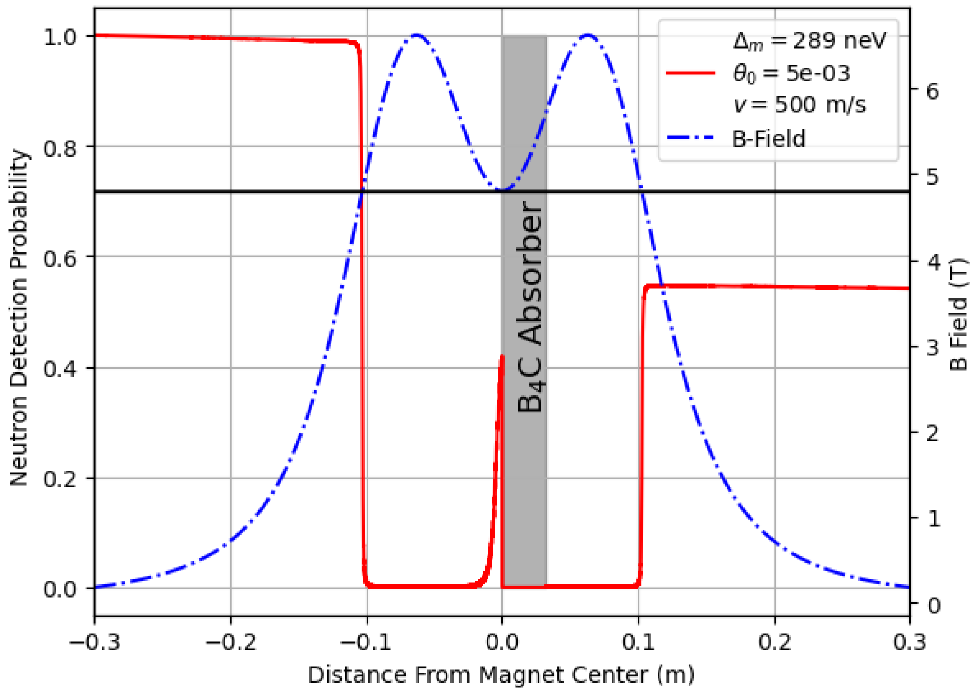


Experimental Apparatus: Shooting Neutrons Through a Wall

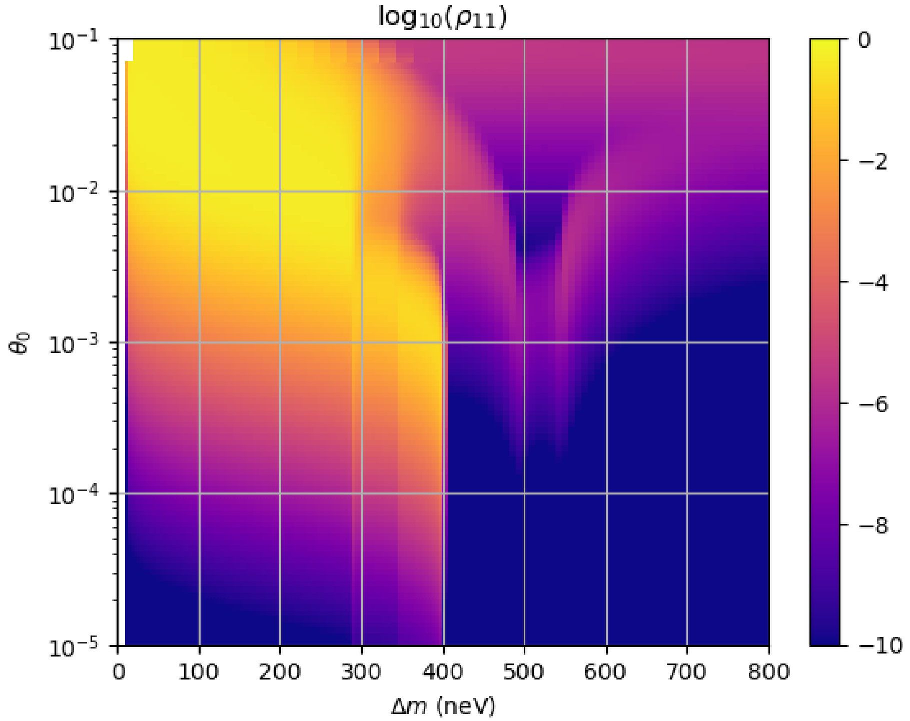


Searching for $n \rightarrow n'$ at ORNL

Double solenoid with B_4C absorber inside
- Absorber blocks transmission of n
- Doesn't block n'!



Calculate the probability of n':
- Use GPU codes to parameter sweep Δm and θ
- Exclude regions without enough transmission



Does $n \rightarrow n'$ Explain the Neutron Lifetime Discrepancy?

Does $n \rightarrow n'$ Explain the Neutron Lifetime Discrepancy?

NO!

Does $n \to n'$ Explain the Neutron Lifetime Discrepancy?

NO!

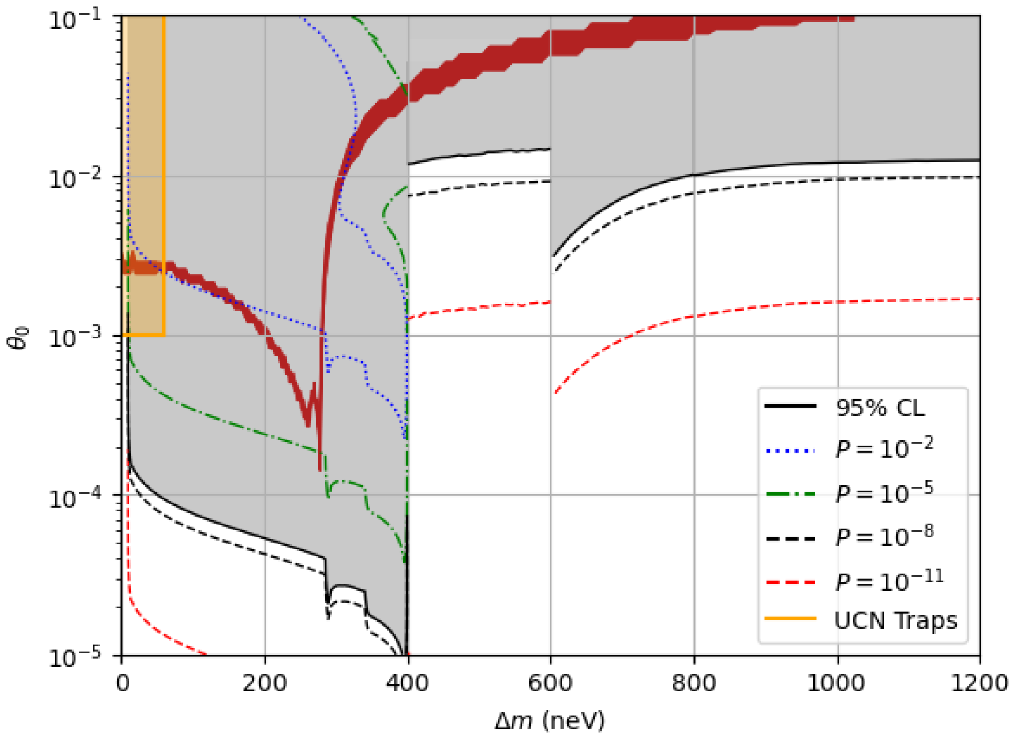
No counts observed above background!

- No transmission $< 2.5 \times 10^{-8}$ (95% CL)
- Excludes gray parameter space

Difference between Beam Lifetime and τ_n (red band)

Mirror neutrons do NOT explain the lifetime shift

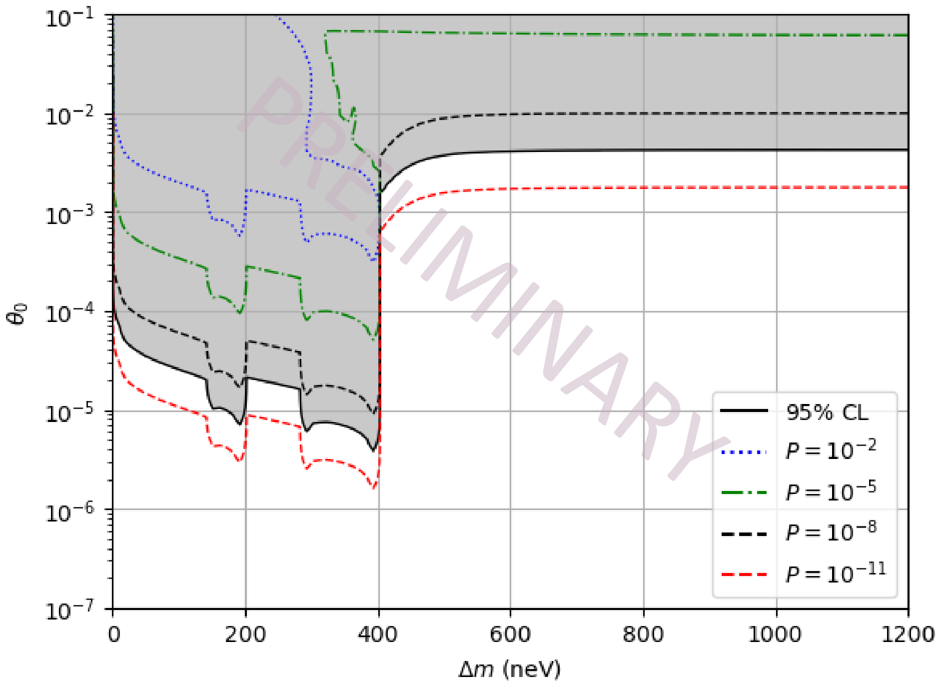
- [Broussard, L.J. *et al.* Phys. Rev. Lett. 128, 212503 (2022).]



Looking Forwards: More Neutrons and Better Limits

Spallation Neutron Source (MAGREF)

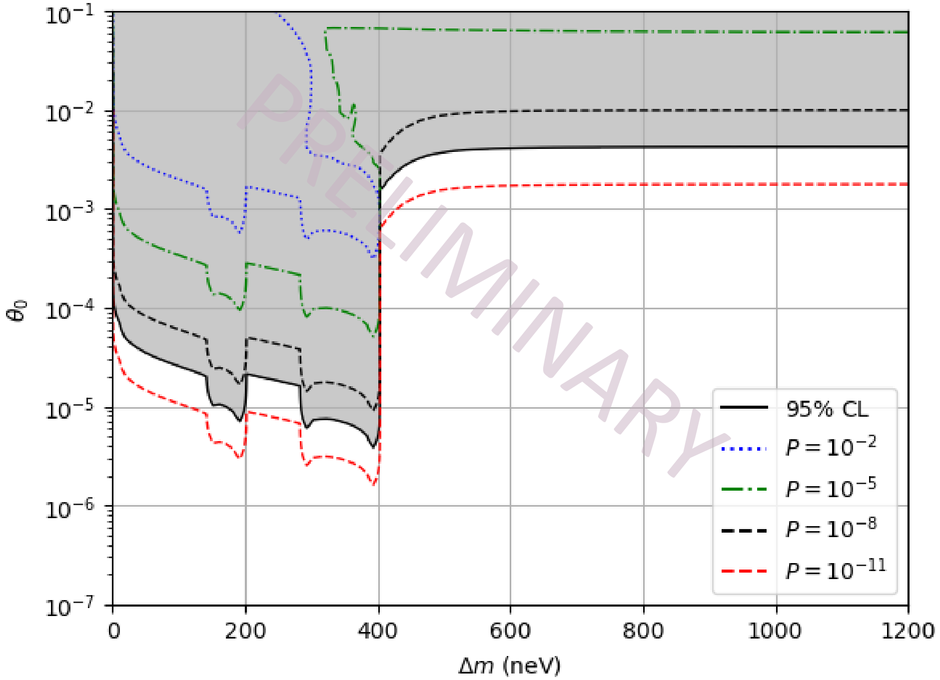
- Different absorber, better shielding, different magnetic fields
- Transmission $< 4.35 \times 10^{-10}$ (95% CL)



Looking Forwards:
More Neutrons and Better Limits

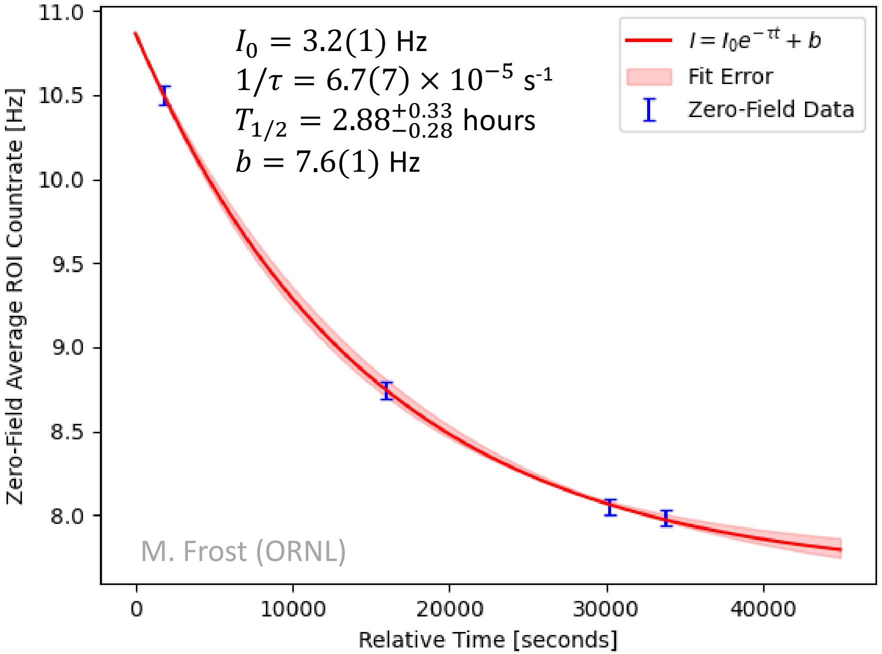
Spallation Neutron Source (MAGREF)

- Different absorber, better shielding, different magnetic fields
- Transmission $< 4.35 \times 10^{-10}$ (95% CL)



High Flux Isotope Reactor (GP-SANS)

- $\times 10^4$ intensity of MAGREF
- So intense we accidentally activated the steel in the detector…
- New detector/beam characterizations at GP-SANS



Further $n \to n'$ Searches at ORNL: Transition magnetic moment

Neutron Transition Magnetic Moment:

- See e.g. $\Sigma^0 \to \Lambda^0 + \gamma$
- $\hat{H} = \begin{pmatrix} \Delta E(\Delta m_n, \vec{B}, V) & \epsilon_{nn'} + \eta\, \vec{\sigma} \cdot \vec{B} \\ \epsilon_{nn'} + \eta\, \vec{\sigma} \cdot \vec{B} & 0 \end{pmatrix}$
- For strong $\vec{B}$, transition probability $P_{nn'} \to 2(\eta/\mu)^2$

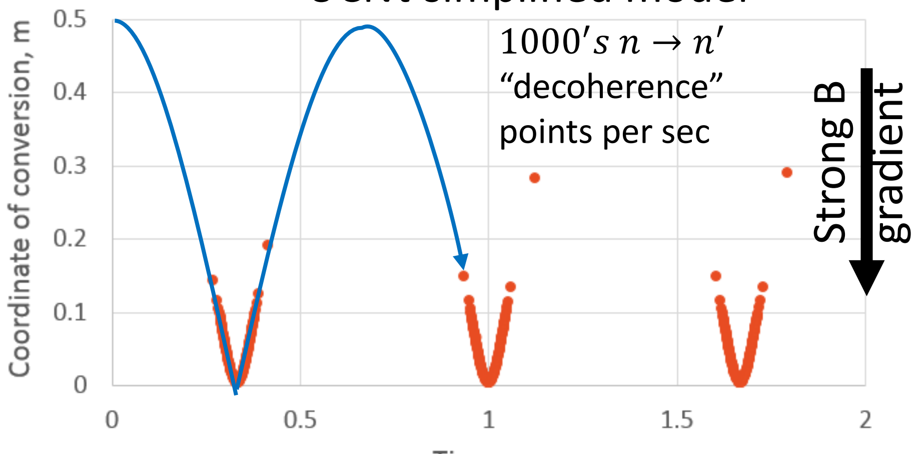
Decoherence in sharp field gradient:

- $\frac{\Delta B}{\Delta x} > \frac{1}{\mu v\,(\Delta t)^2} = \frac{v}{\mu (\Delta x)^2}$

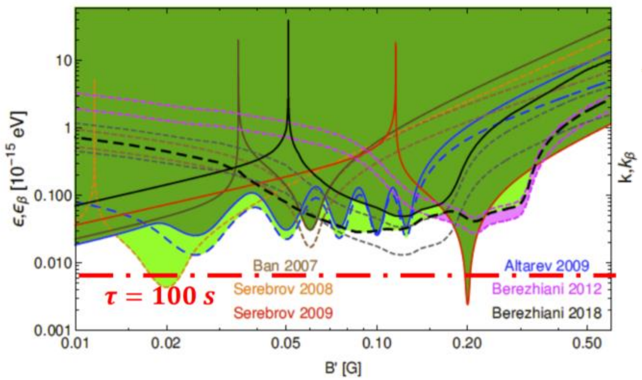
For small, uniform $\vec{B}$ with $\Delta E = 0$:

- $P_{nn'} = \sin^2(\eta\, \vec{\sigma} \cdot \vec{B} \Delta t)$

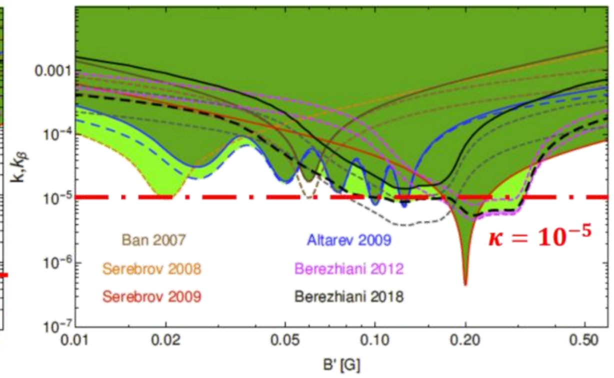
UCNτ simplified model



Current UCN limits in terms of ϵ



Current UCN limits in terms of $k \cdot \mu_n$



Berezhiani, Z. *et al.* Physics, 1(2), 271-289 (2019)

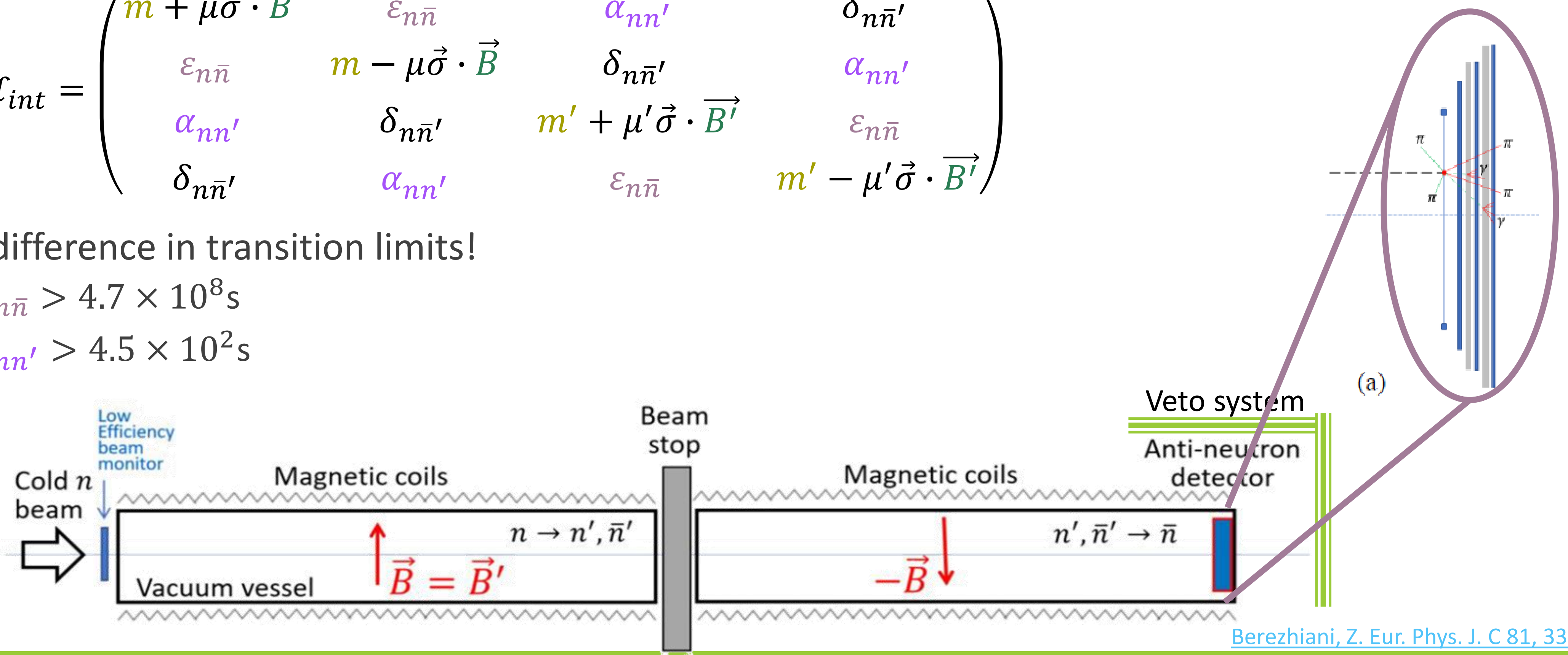
Further $n \to n'$ Searches at ORNL: Searches for $n \to n' \to \bar{n}$

Extend Hamiltonian to account for $n' \to \bar{n}$:

- $$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\vec{\sigma}\cdot\vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \delta_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m - \mu\vec{\sigma}\cdot\vec{B} & \delta_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \delta_{n\bar{n}'} & m' + \mu'\vec{\sigma}\cdot\vec{B'} & \varepsilon_{n\bar{n}} \\ \delta_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m' - \mu'\vec{\sigma}\cdot\vec{B'} \end{pmatrix}$$

Big difference in transition limits!

- $\tau_{n\bar{n}} > 4.7 \times 10^{8}\mathrm{s}$
- $\tau_{nn'} > 4.5 \times 10^{2}\mathrm{s}$



Berezhiani, Z. Eur. Phys. J. C 81, 33 (2021).

Further $n \to n'$ Searches at ORNL: Searches for $n \to n' \to \bar{n}$

Extend Hamiltonian to account for $n' \to \bar{n}$:

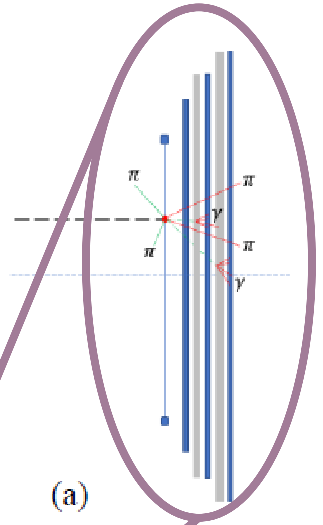
- $$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\vec{\sigma}\cdot\vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \delta_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m - \mu\vec{\sigma}\cdot\vec{B} & \delta_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \delta_{n\bar{n}'} & m' + \mu'\vec{\sigma}\cdot\overrightarrow{B'} & \varepsilon_{n\bar{n}} \\ \delta_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m' - \mu'\vec{\sigma}\cdot\overrightarrow{B'} \end{pmatrix}$$

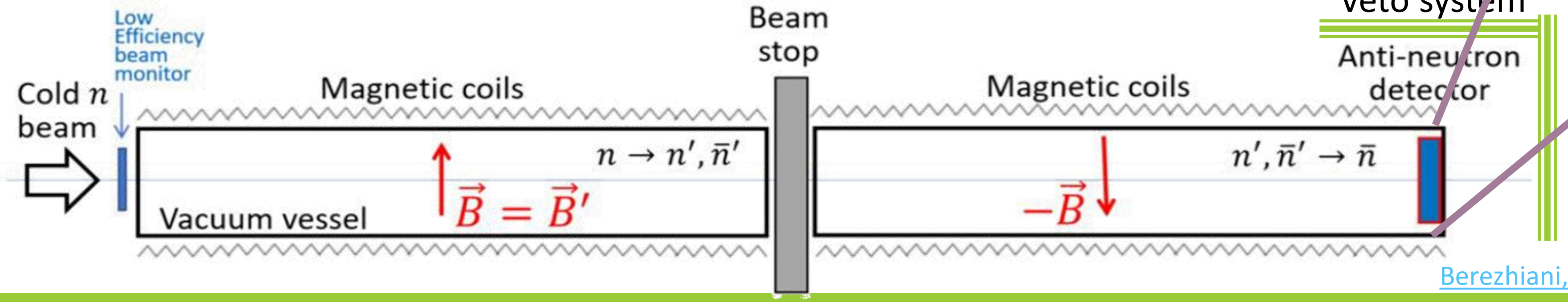
Big difference in transition limits!

- $\tau_{n\bar{n}} > 4.7 \times 10^8\mathrm{s}$
- $\tau_{nn'} > 4.5 \times 10^2\mathrm{s}$

More on the staged program to HIBEAM+NNBAR:

- L. Broussard (HI-3)





Berezhiani, Z. Eur. Phys. J. C 81, 33 (2021).

$n \rightarrow n'$ Collaboration

V. Santoro European Spallation Source

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

M. Kline Ohio State University

L. Varriano University of Chicago

J. Barrow Massachusetts Institute of Technology

B. Chance, L. Heilbronn, Y. Kamyshkov, P. Lewiz, C. Matteson, D. Peffley, C. Redding, A. Ruggles, B. Rybolt, J. Ternullo, L. Townsend, S. Vavra University of Tennessee Knoxville

A. Blose, D. Bowles, C. Crawford University of Kentucky Lexington

T. Dennis East Tennessee State University

I. Novikov Western Kentucky University

W. M. Snow Indiana University

D. Milstead Stockholm University

We gratefully acknowledge the LDRD program of ORNL, the DOE OS NP, and the NSF

EXTRA SLIDES

Duffer, M. and Duffer, R., “Stranger Things”, Netflix Productions

Dark Neutron Decay Limits

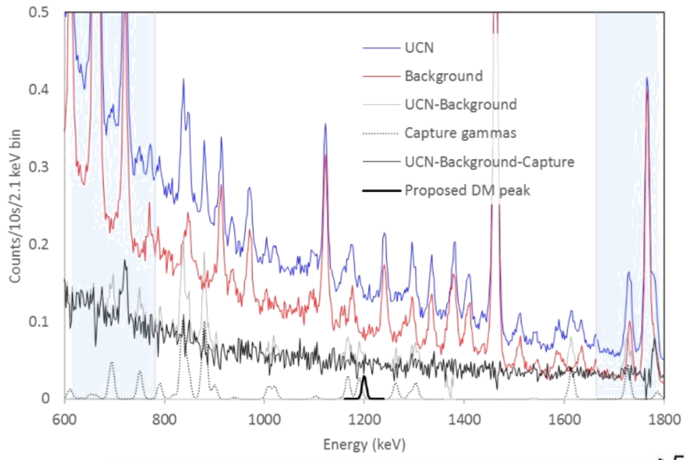
Quickly followed by experimental searches for exotic neutron decay channels

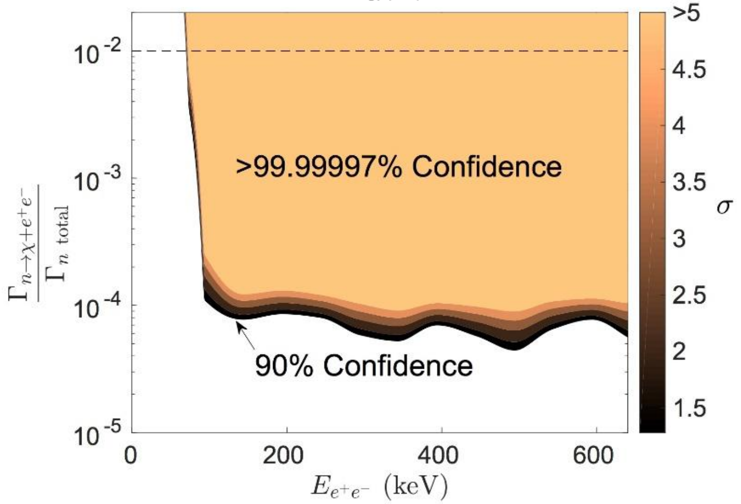
- $n \rightarrow \chi + \gamma$
  - Tang, Z., *et al.* PRL. 121, 022505 (2018).
- $n \rightarrow \chi + e^+e^-$
  - Sun, X. et al., Phys. Rev. C 97, 052501(R) (2018).

Additional nuclear decay limitations

- Neutron star masses require self-interacting χ
  - Baym, B. *et al.* PRL. 121, 061801 (2018)
  - Cline, J. and Cornell, J., JHEP 81, 13180 (2018).
- Proposals to search in ^{11}Li, ^{11}Be decays
  - Ejiri, H. and Vergados, J. D., J. Phys. G, 46.025104 (2019).
  - Riisager, K. *et al.* Eur. Phys. J. A 56, 100 (2020).

Bottle measurement agrees with V_{ud}!





Fornal, B. and Grinstein, B. Mod. Phys. Let. A 35, 31 2030019 (2020).

Energy Dependence of $n \to n'$

Write a two-state mixing Hamiltonian and solve the Schrödinger equation:

- $i\frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} H_n(m_n, B, \ldots) & \epsilon_{nn'} \\ \epsilon_{nn'} & H_{n'}(m_{n'}, B', \ldots) \end{pmatrix}|\Psi(t)\rangle$

$$H_n = m_n + \frac{p^2}{2m_n} + \mu_n(\vec{\sigma}\cdot\vec{B}) + V - i\,W - \frac{i}{2\tau_n}$$

Different Higgs VEV between n, n'

Local matter/mirror matter

Equivalent to difference between energy states

- $i\frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} \Delta E(\Delta m, B, B', \ldots) & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix}|\Psi(t)\rangle$
- $\Delta E = \Delta m + \mu_n(\vec{\sigma}\cdot\vec{B}) - \mu_{n'}(\vec{\sigma}\cdot\overrightarrow{B'}) + (V - V')$

Traditionally, diagonalize the matrix with a rotation:

$$\tan 2\theta = 2\frac{\epsilon_{nn'}}{\Delta E}$$

Solving for the probability of $n \to n'$ transition:

- $P_{n\to n'}(t) = \sin^2 2\theta\,[1 - \cos(\Delta E t)] = \frac{4\epsilon_{nn'}^2}{\Delta E^2}\sin^2\left(\frac{\Delta E}{2}t\right)$

When $\Delta E \to 0$, we expect a resonance!

- Tune B to look for evidence of Δm, B', $\epsilon_{nn'}$...

Kamyshkov Y. et al., Symmetry, *14*(2), 230 (2022)

Simulating The Beam Lifetime

Amplitude of transitions depends on $\Delta E, \theta, v$:

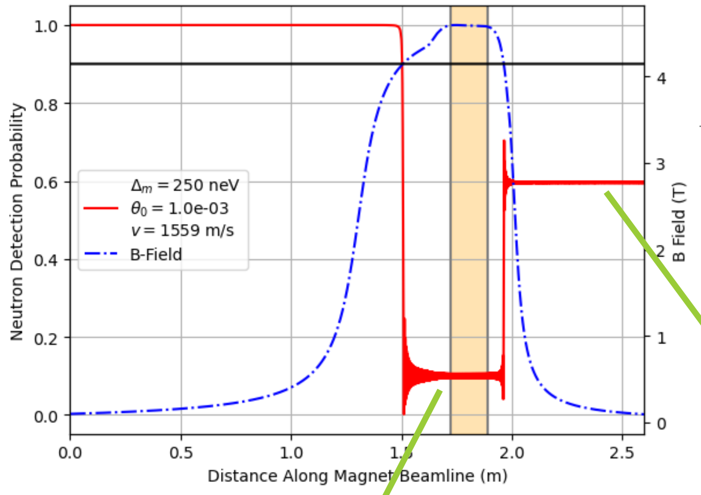
- $\Delta E = \Delta m \pm \mu_n B$
- $\tan 2\theta = 2\frac{\epsilon_{nn'}}{\Delta E}$
- Parameter sweep over Δm, θ with known v distribution

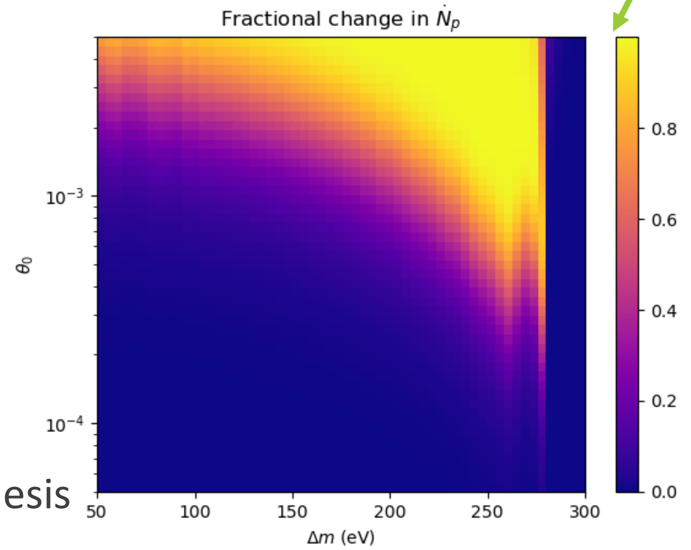
Numerically integrating density matrix with Liouville-von Neumann equation:

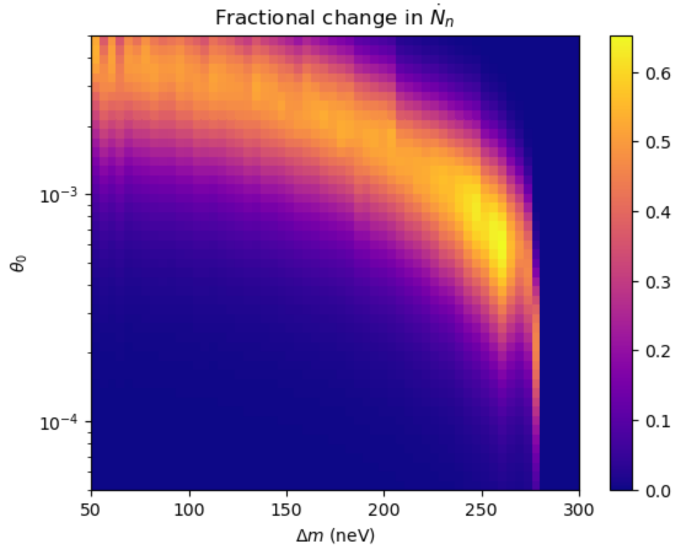
- $\frac{\partial}{\partial t}\hat{\rho} = -i[\hat{H} \cdot \hat{\rho}] = -i\hat{H}\hat{\rho} + i\hat{\rho}\hat{H}^{\dagger}$
- GPU (CUDA) parallelized code
  - Undergraduate project! Michael Kline, OSU
- Determine change in measured rates

Region of interest for $n \to n'$:

- When $\delta\tau_{meas}/\tau_n \sim 1\%$
- Lower shifts possible for dark matter, baryogenesis







Improvements at the SNS: Material Potentials

Recall:

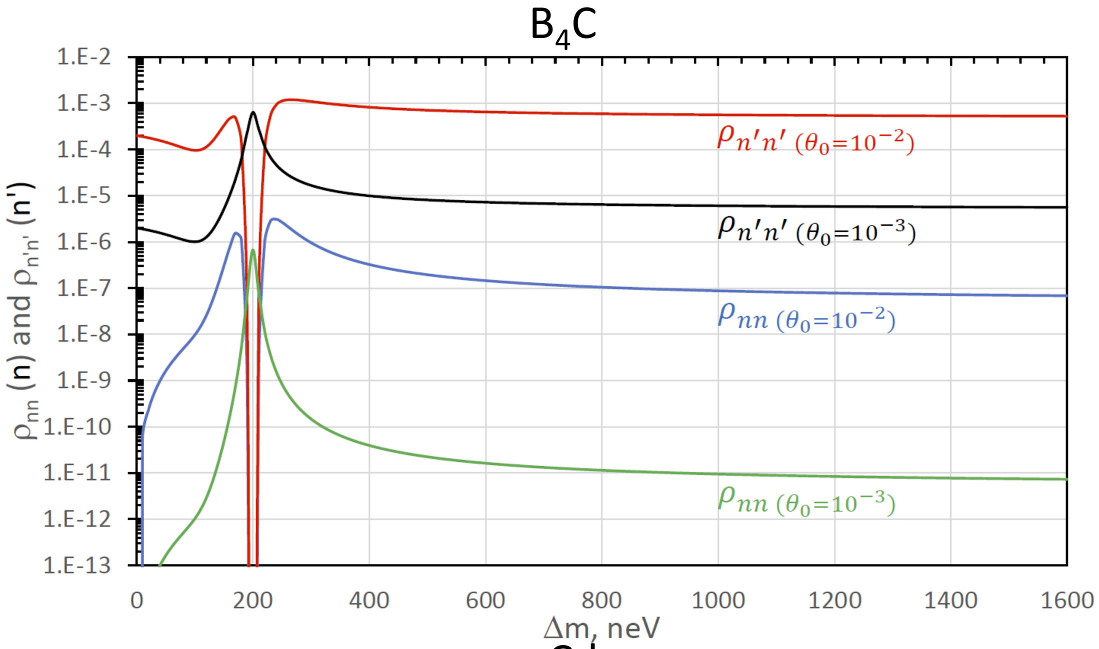
- $H_n = m_n + \frac{p^2}{2m_n} + \mu_n(\vec{\sigma} \cdot \vec{B}) + V - i\,W - \frac{i}{2\tau_n}$
- Looking at $\Delta E(n, n')$

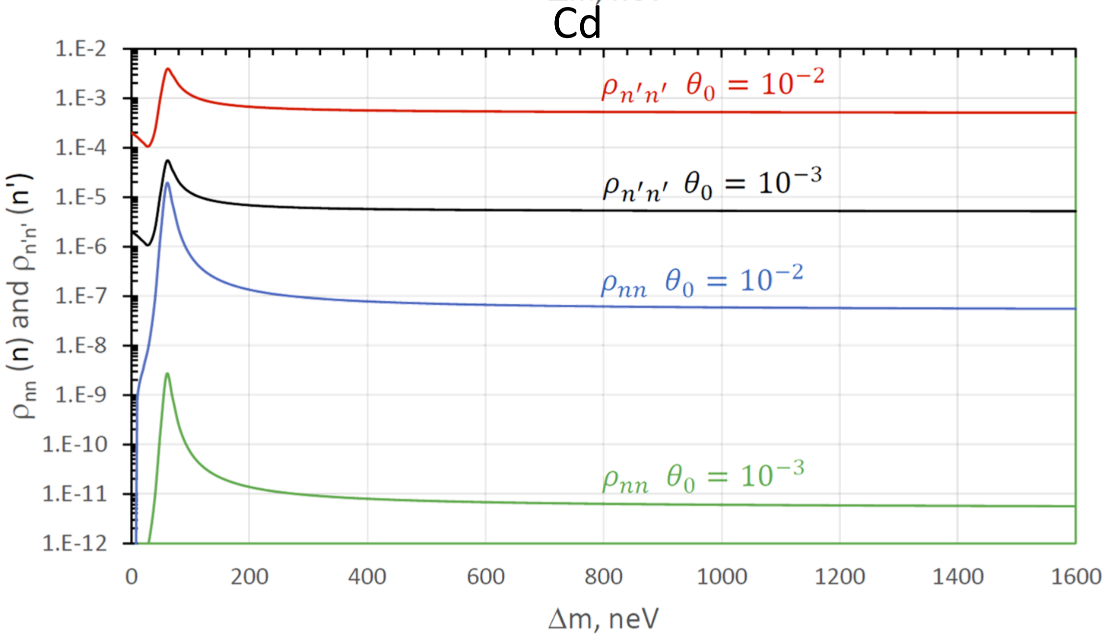
Lower sensitivity when $\Delta E(\Delta m, B) \approx V$

- $V_{B_4C} = 199.2$ neV
- $V_{Cd} = 58.8$ neV

More data taken at SNS:

- Lower material potential
- Lower background ($\times$ 10)





Kamyshkov Y. et al., Symmetry, *14*(2), 230 (2022)

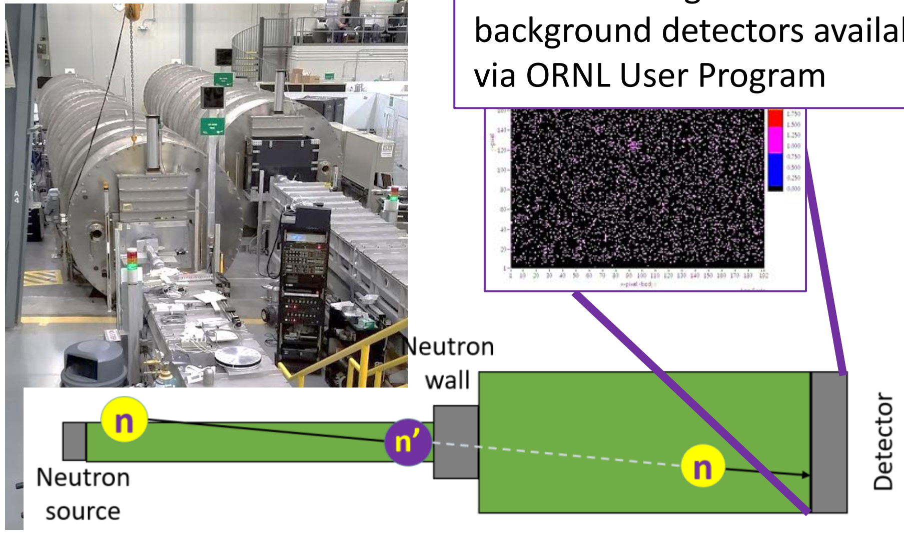
Staged Program from ORNL to NNBAR

ORNL:

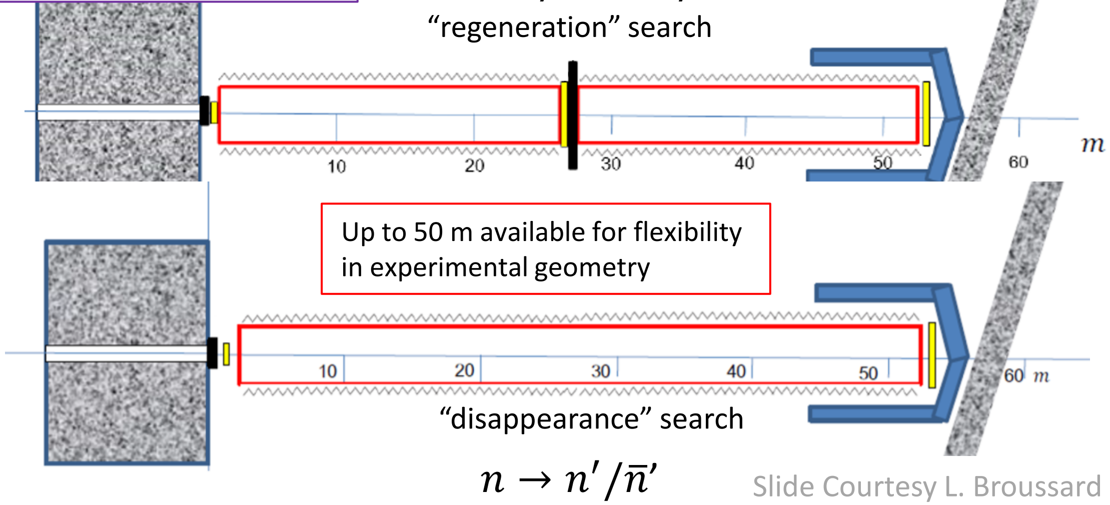
- Uses existing neutron scattering facilities (MAGREF, GP-SANS)
- GP-SANS has long, large area beam guides with low background detector

Move to HIBEAM experiment at ESS

Early Stage:
20m+15m long beamline + low background detectors available via ORNL User Program



Middle Stage:
HIBEAM experiment at ESS



Slide Courtesy L. Broussard

Another Type of B Violation: $n \to \bar{n}$

Similar idea to $n \to n'$:

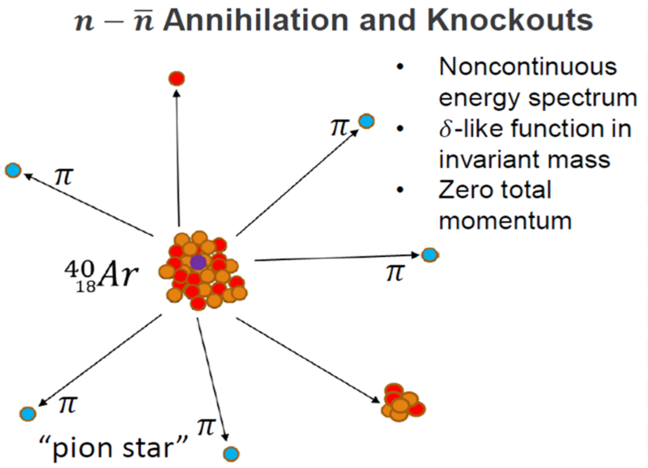
- $\hat{H} = \begin{pmatrix} m_n + \mu_n B & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}} & m_n - \mu_n B \end{pmatrix}$

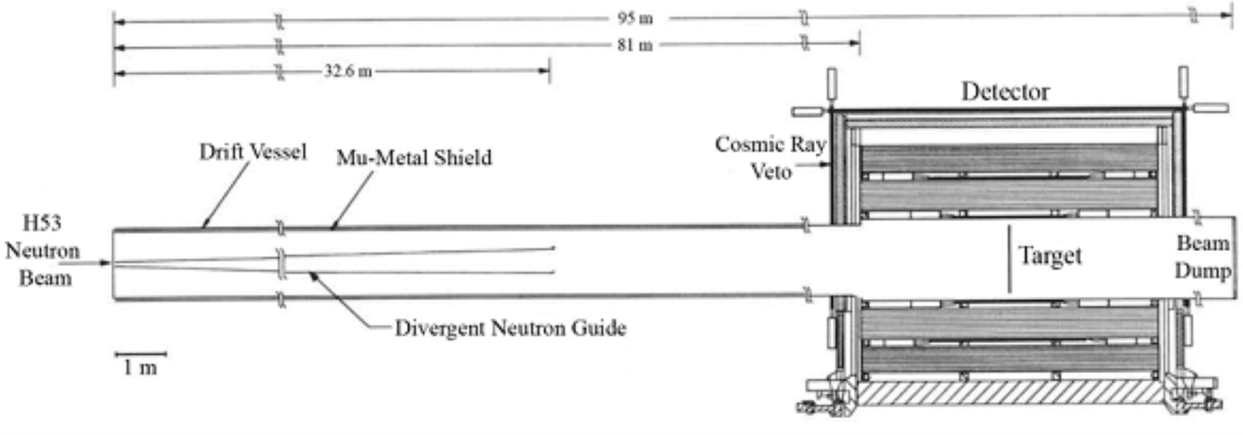
Nuclear transitions:

- $\tau_{n\bar{n}} > 4.7 \times 10^8$s (90% C. L.)
- Use $n \to \bar{n}$ in oxygen nucleus
- Super Kamiokande, Phys. Rev. D 103. 012008 (2021).

"Free" n beam limit:

- $\tau_{n\bar{n}} > 0.86 \times 10^8$s (90% C. L.)
- Baldo-Ceolin, M. *et al.*, Z. Phys. C - Particles and Fields 63, 409–416 (1994).





Golubeva, E. S., Barrow, J. L. and Ladd, C. G., Phys. Rev. D 99, 035002 (2021).