Search for Baryon Number Violation in Neutron Oscillations

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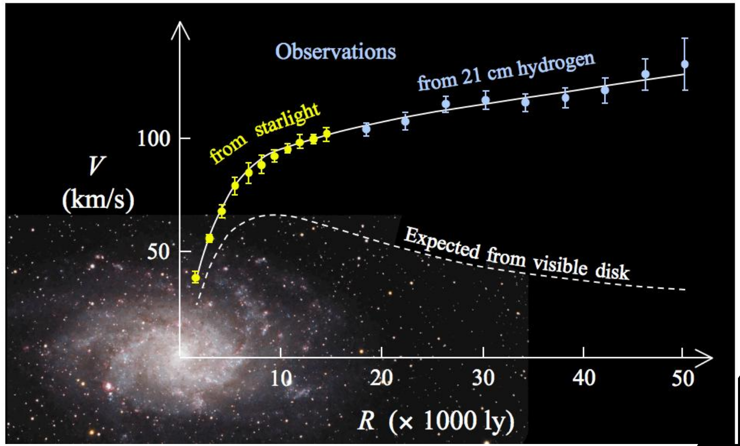
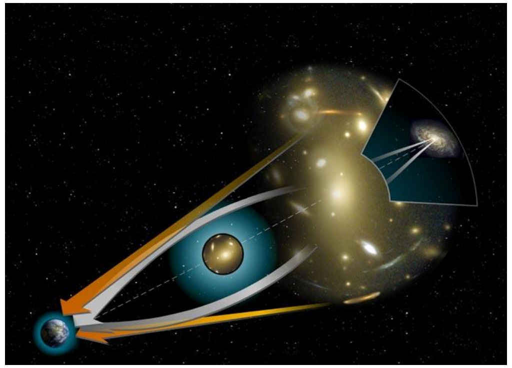
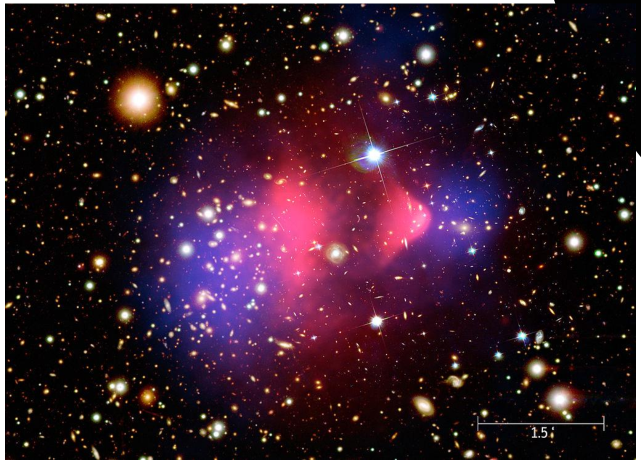




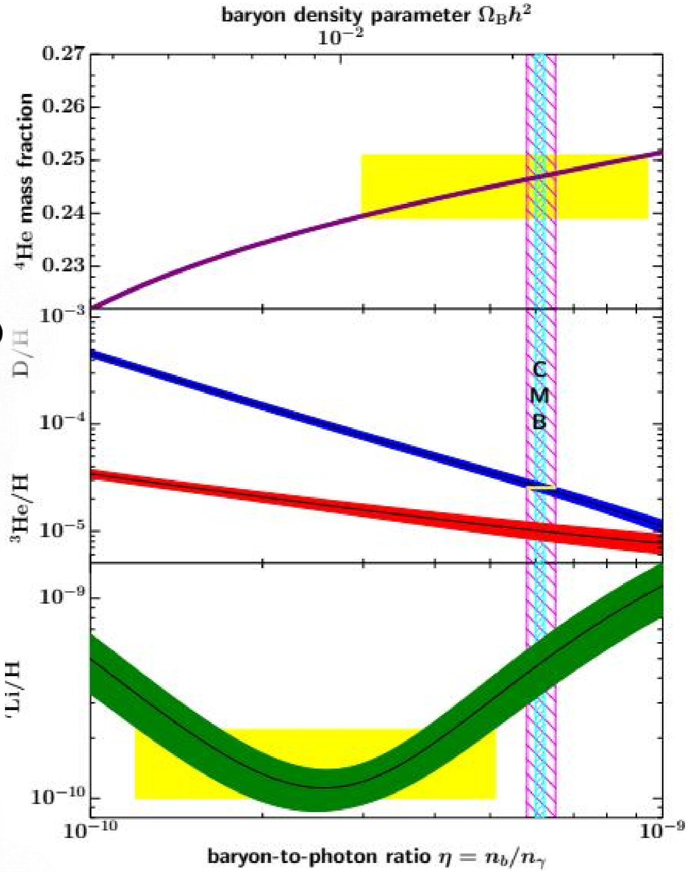


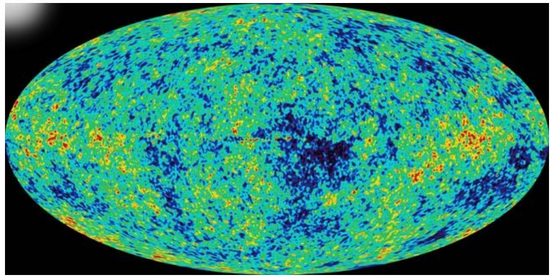
What makes up 85% of matter in the universe?

Why is there no antimatter in the universe?

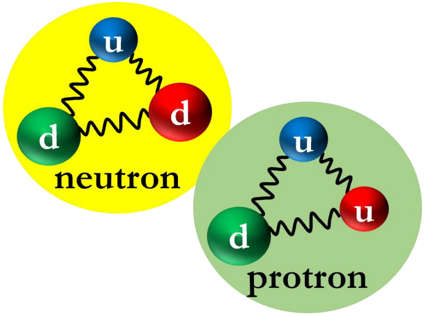
Symmetry tests, rare processes, and precision measurements

Vecteezy.co

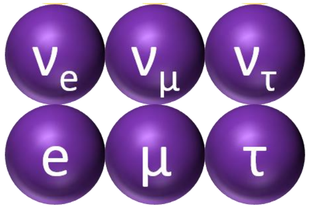




Baryon and Lepton Number



Quarks: **B = +⅓**
Antiquarks: **B = -⅓**



Electrons/
Neutrinos: **L = +1**
Anti-electrons/
Anti-neutrinos: **L = -1**

Andrei Sakharov

"We must have a process that does not conserve **B** [or **L**] to create an excess of matter in the universe!"

…and we might expect these to be violated! $\boldsymbol{B-L}$ conserved in the SM

$$\Delta B \neq 0, \Delta L = 0,\ \Delta[B-L] \neq 0$$

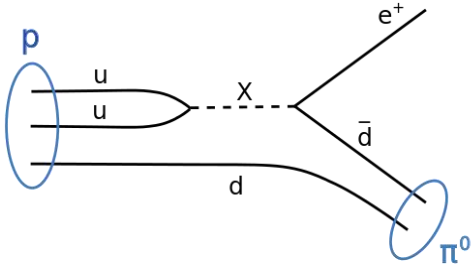
$$\Delta B = 0, \Delta L \neq 0,\ \Delta[B-L] \neq 0$$

$$\Delta B \neq 0, \Delta L \neq 0,\ \Delta[B-L] = 0$$

Searches for Violation of B and L

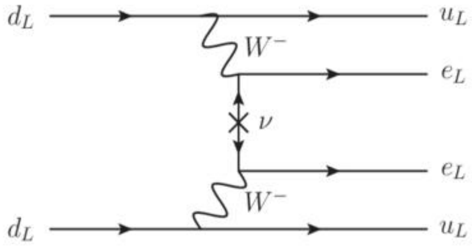
- **Proton Decay**: Originally motivated massive detectors!
  - But limit is now > 10^{34} years
  - Universe is 10^{10} years old

$$p \rightarrow e^{+} + \pi^{0}$$
$$\Delta B \neq 0, \Delta L \neq 0$$
Δ[ɑ − ɜ] = 0



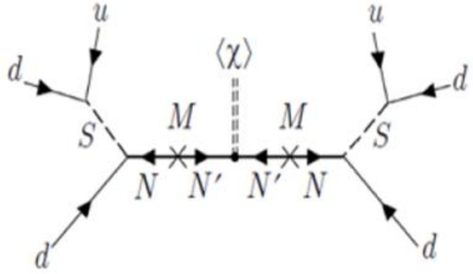
- **Neutrinoless double-beta decay**: vibrant worldwide program already ongoing!

$$0\upsilon 2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$
$$\Delta[B - L] \neq 0$$



- Complementary approach: **Neutron – antineutron oscillations**

$$n \rightarrow \overline{n}$$
$$\Delta B = 2, \Delta L = 0$$
$$\Delta[B - L] \neq 0$$



Neutron oscillations $n \rightarrow \bar{n}$

- Two-state mixing

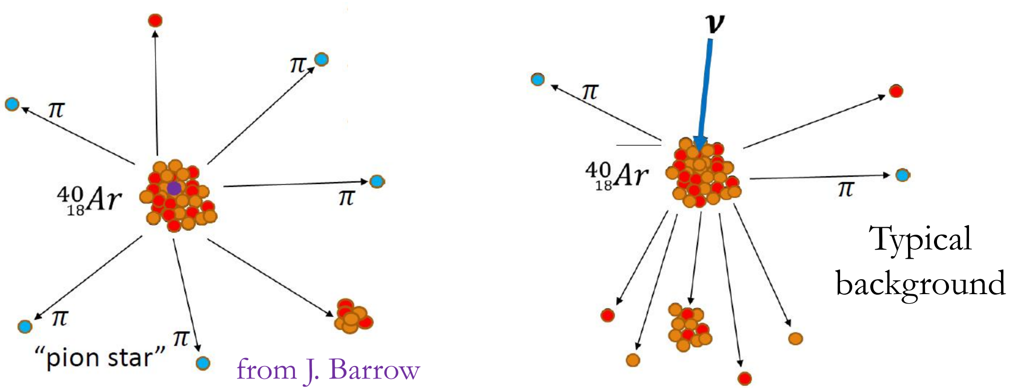
$$\hat{H}\psi = \begin{pmatrix} H_n & \epsilon \\ \epsilon & H_{\bar{n}} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad H_n = m_n + \frac{p^2}{2m_n} + \mu_n(\vec{\sigma} \cdot \vec{B}) + V - i\,W - \frac{i}{2\tau_n}$$

Antiparticles have opposite magnetic moments

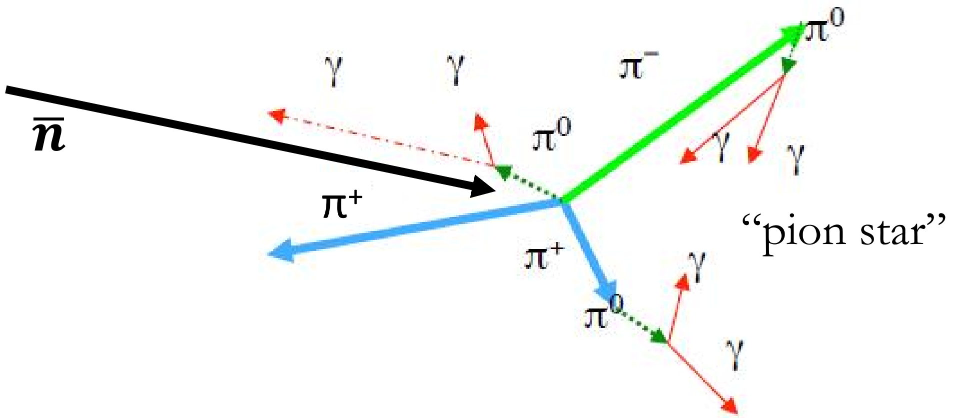
Different material potentials

- Oscillations are suppressed unless energy difference $\ll \epsilon < 10^{-29}$ MeV
- Use uncertainty principle $\Delta E \Delta t \ll \hbar$ to operate in "quasi-free limit" NIMA 320 (1992) 569
- Free neutrons
  - Earth magnetic potential $\mu \cdot B$ (10^{-18} MeV)
  - Free neutron TOF ~ 0.1 s → B~10 nT
  - $P_{n \rightarrow \bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n \rightarrow \bar{n}}}\right)^2$
- Free neutron Hamiltonian

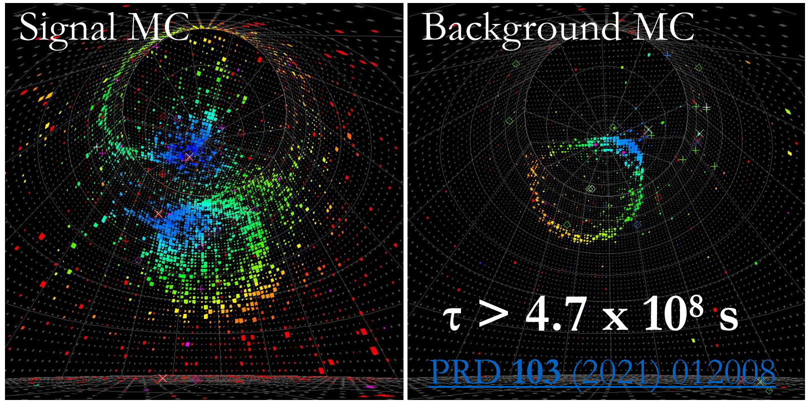
Signature of $n \to \bar{n}$



from J. Barrow

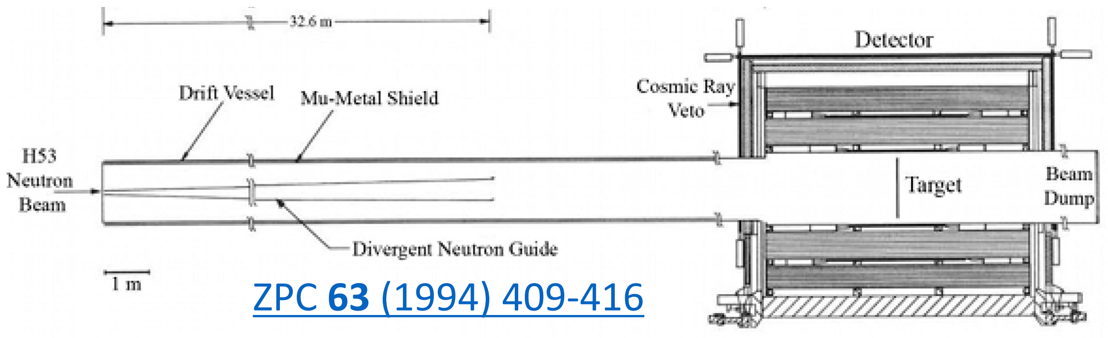


- Best published limits from **Super-K**
  - 11 candidate events, 9.3 expected bkgds



PRD **103** (2021) 012008

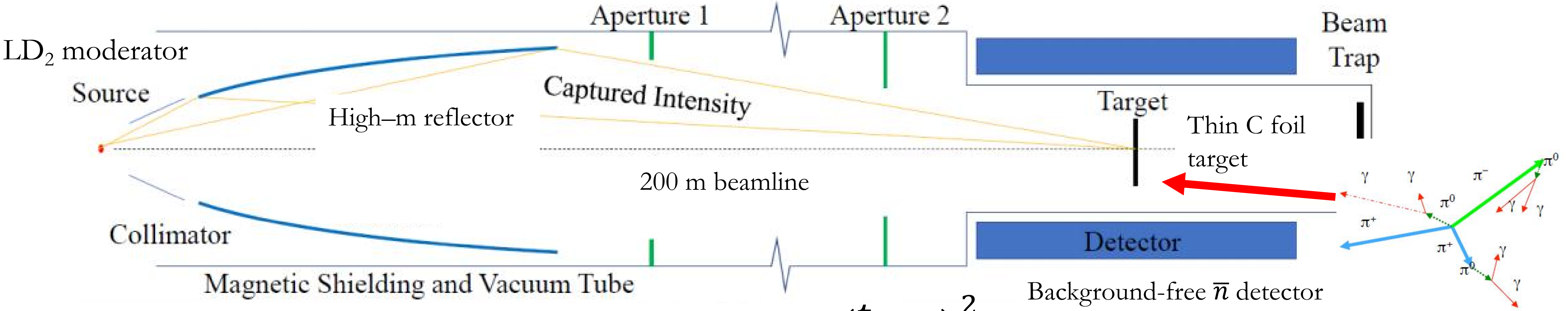
$\tau_{n\to\bar{n}} > 0.86 \times 10^8$s



ZPC **63** (1994) 409-416

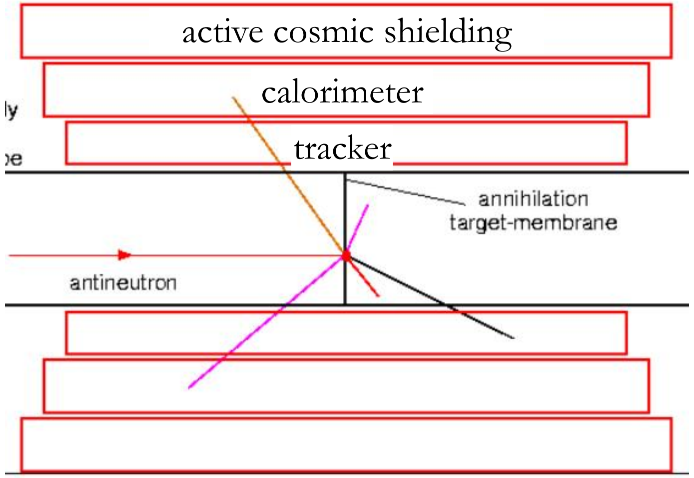
- **DUNE future reach:** $\tau_{n\to\bar{n}} > 5.53 \times 10^8$ s arXiv:2002.03005

The NNBAR Experiment

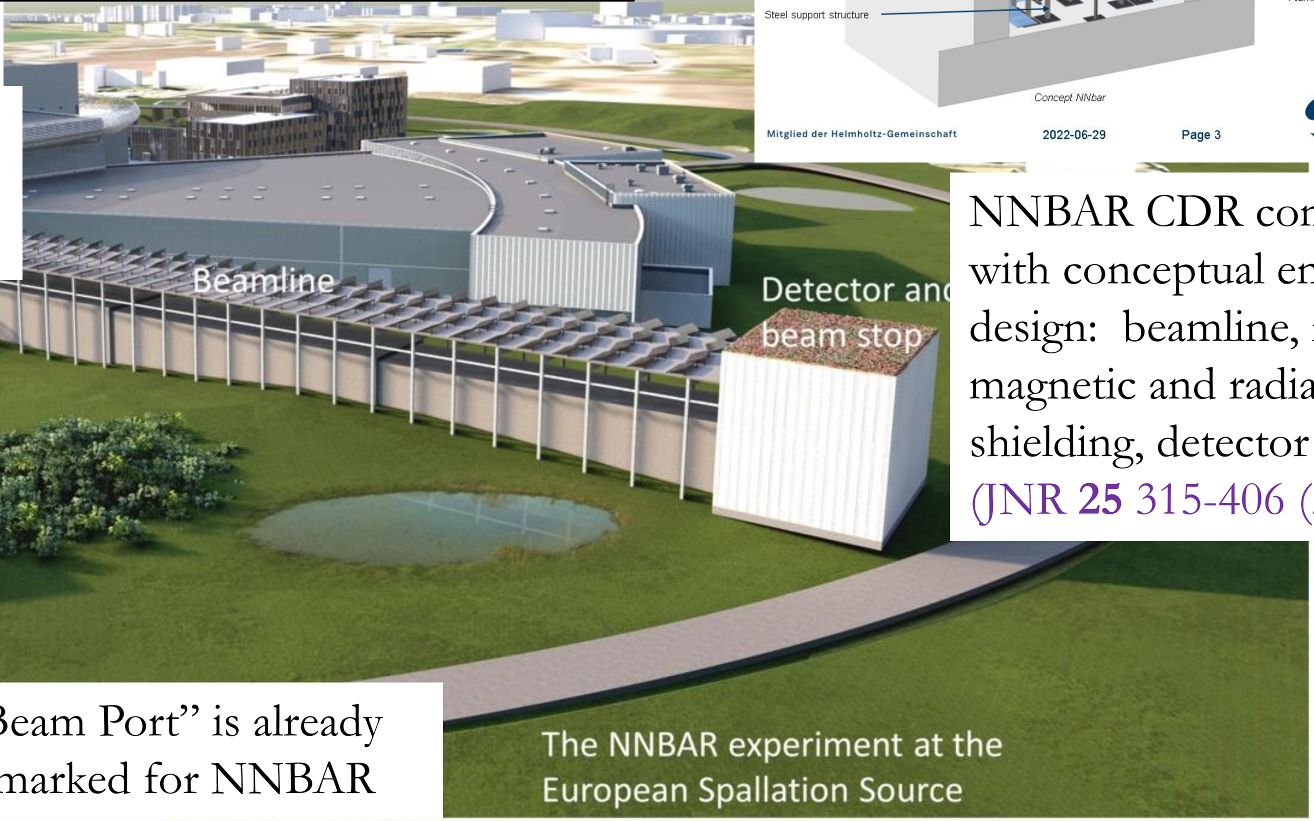


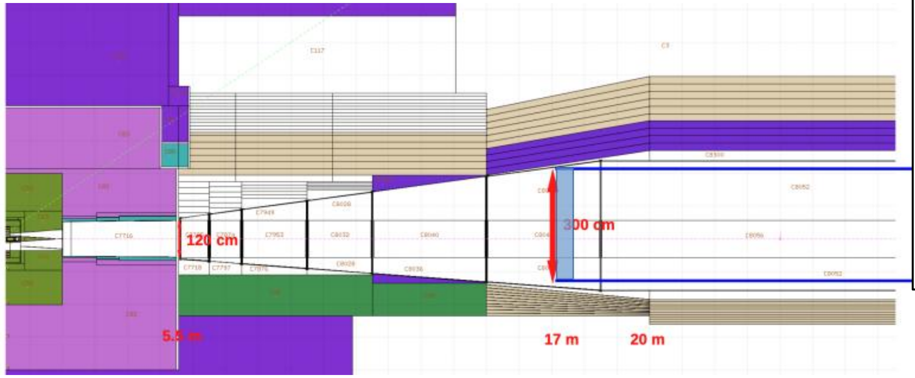
$$P_{n\to\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\to\bar{n}}}\right)^2$$

Goal: 1000x sensitivity of ILL. Discovery if (at least) **one** antineutron detected!



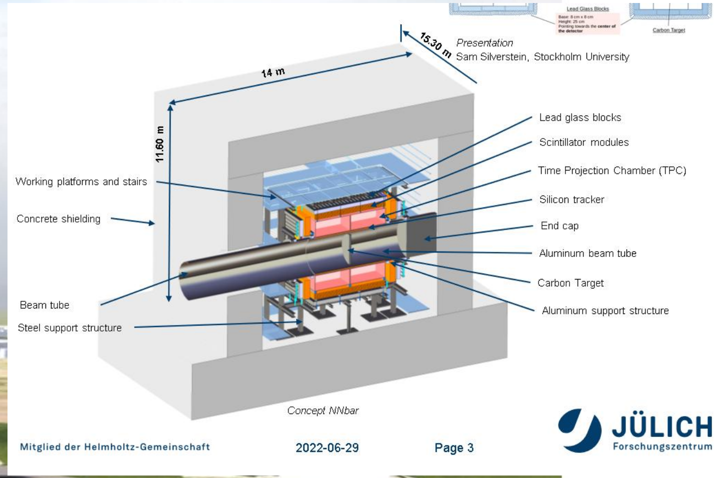
Recent NNBAR progress



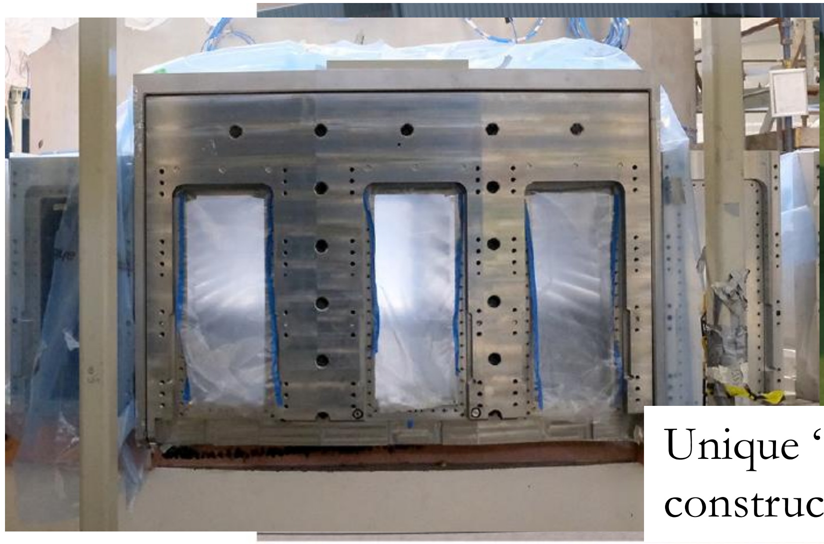


Proposed sensitivity can be achieved even with ESS at 2 MW

Complete engineering design of ESS second cold neutron source, optimized for fundamental physics HighNESS CDR Vol 1: [arXiv:2309.17333]()



NNBAR CDR completed with conceptual engineering design: beamline, reflector, magnetic and radiation shielding, detector (JNR **25** 315-406 (2024))



Unique "Large Beam Port" is already constructed, earmarked for NNBAR

Antineutrons and dark neutrons?

- NNBAR = well motivated large-scale O(100M€) project planned for >2030
- Complementary science on a shorter timescale: $\Delta B = 1$ neutron oscillations
- Straightforward extension of formalism: consider $n \to \bar{n},\ n', \bar{n}'$

$$|\phi_n\rangle = \begin{vmatrix} n \\ n' \\ \bar{n}' \\ \bar{n} \end{matrix}\bigg\rangle$$

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

- Connection to cobaryogenesis
  IJMP **33** 1844034 (2018)
- "Shortcut" for neutron-antineutron oscillations via dark sector EPJC **81** (2021) 33
- Opportunity for NNBAR R&D needed now in detector prototyping, data selection algorithms, interface of beamline and detector

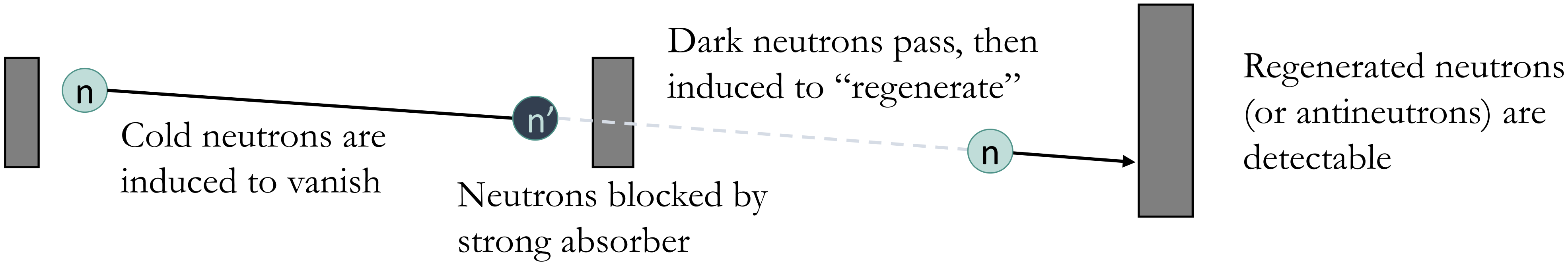
Staged Program to NNBAR

- Increasingly complex searches:
  1. $n \to n' \to n$ with different assumptions:
     A. Mass splitting between n' and n
     B. “Transition magnetic moment” enhances probability
     C. “Traditional” search for $n \to n' \to n$
  2. $n \to n' \to \bar{n}$ in HIBEAM
  3. $n \to \bar{n}$ in NNBAR

Perform at ORNL using existing neutron scattering instruments

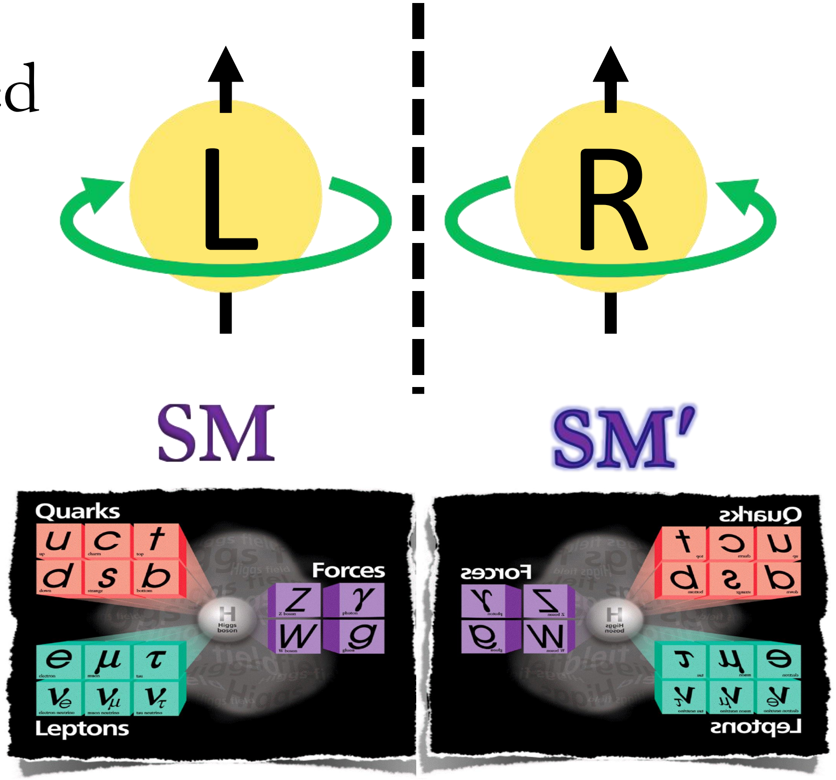
Perform at ESS using dedicated instrument for high sensitivity

- Cold neutron regeneration technique demonstrated at ORNL



Mirror matter and mirror neutrons

- Decades of searches for dark matter: no confirmed detection. New avenues needed!
- Mirror Matter: identical particles/forces, opposite parity [Phys.Usp. **50** (2007) 380-389, From Fields to Strings **3** (2015) 2147, Phys.Rev. **104** (1956) 254-258]
- Only interacts with known particles via gravity [Sov.J.Nucl.Phys. **3** (1966) 6]
- A "hidden sector" which could help explain dark matter [PLB **503** (2001) 362, IJMPA **29** (2014) 1430013]
- **Experimental observable**: predictions of neutron oscillations in Mirror Matter models PRL 96 081801 (2006); related to cobaryogenesis IJMP **33** 1844034 (2018)
- Neutron could be one of a few portals to a dark sector!



Neutron oscillations $n \rightarrow n'$

- Two state mixing
- Free neutron Hamiltonian

$$\hat{H}\psi = \begin{pmatrix} H_n & \epsilon \\ \epsilon & H_{\bar{n}} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad H_n = m_n + \frac{p^2}{2m_n} + \mu_n(\vec{\sigma} \cdot \vec{B}) + V - i\,W - \frac{i}{2\tau_n}$$

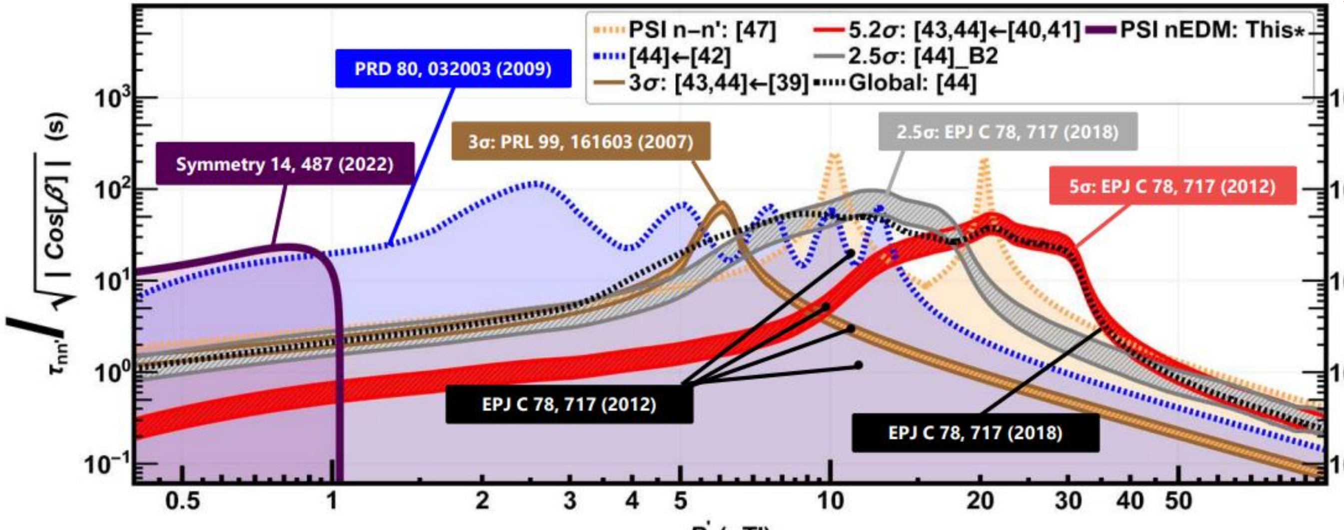
Different Higgs VEV between n, n'

Local matter/mirror matter

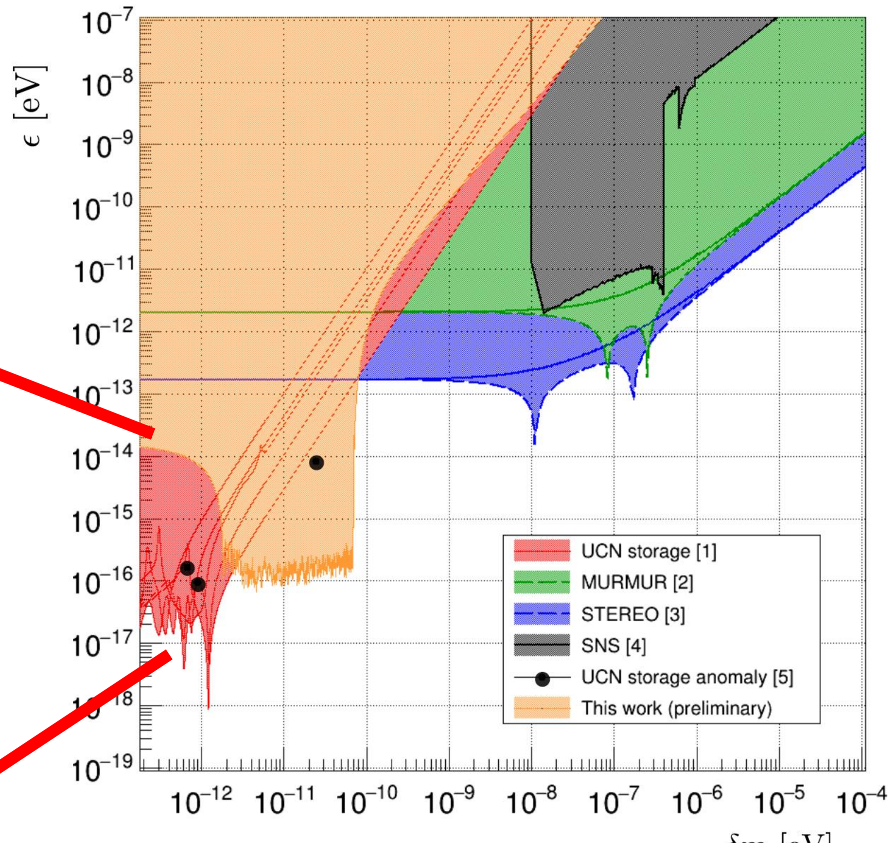
- As before, as $\Delta E \rightarrow 0$, probability for oscillation resonantly enhanced
- Rare process, but not background-free. Tune laboratory B or V to look for evidence of Δm, B', $\epsilon_{nn'}$…

Prior/ongoing searches for mirror neutrons

- Strong limits from B dependence of stored ultracold neutrons
  - $\tau_{nn'} > 448$ s (90% CL) assuming $\Delta E=0$ (e.g. no mirror field B') NIMA **611** (2008) 137
  - Anomalies manifest on reanalysis when relaxing $B' \neq 0$
    EPJC **72** (2012) 1974, EPJC 78 (2018) 717, data of PRL 99 (2007) 161603
  - Exclusions from other searches PRD 80 (2009) 032003, PLB 812 (2021) 135993, Sym 14 (2022) 487
- Recently, more searches assuming larger $n\ n'$ mass difference EPJC **81** 17 (2021), PRL **131** 191801 (2023), PRL **128** 061801 (2022)



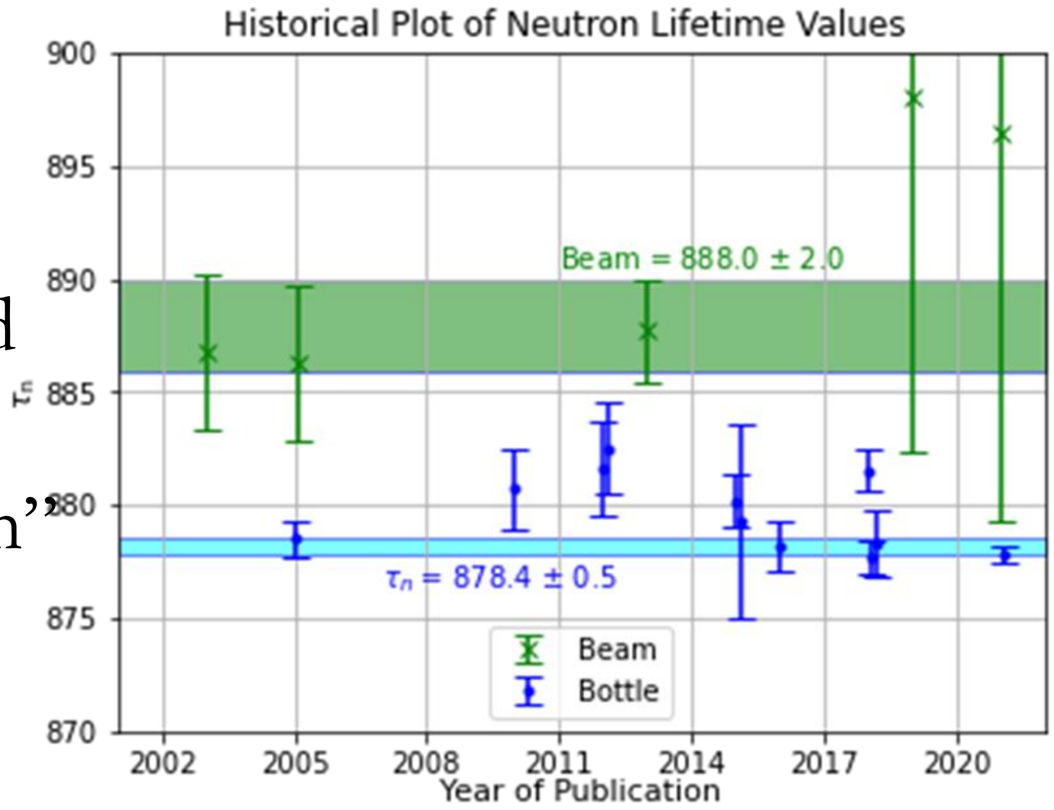
Plot from P Mohanmurthy, CIPANP22



Plot from M Jentschel, PSI22

Can $n - n'$ explain n lifetime anomaly?

- "Bottle" technique:: use a bottle of ultracold neutrons, observe surviving neutrons
- "Beam" technique: use a beam of cold neutrons, count decays into protons
- 4σ discrepancy persists between "beam" and "bottle" measurements [Atoms 6 (2018) 4]
- Do neutrons disappear into something other than protons?



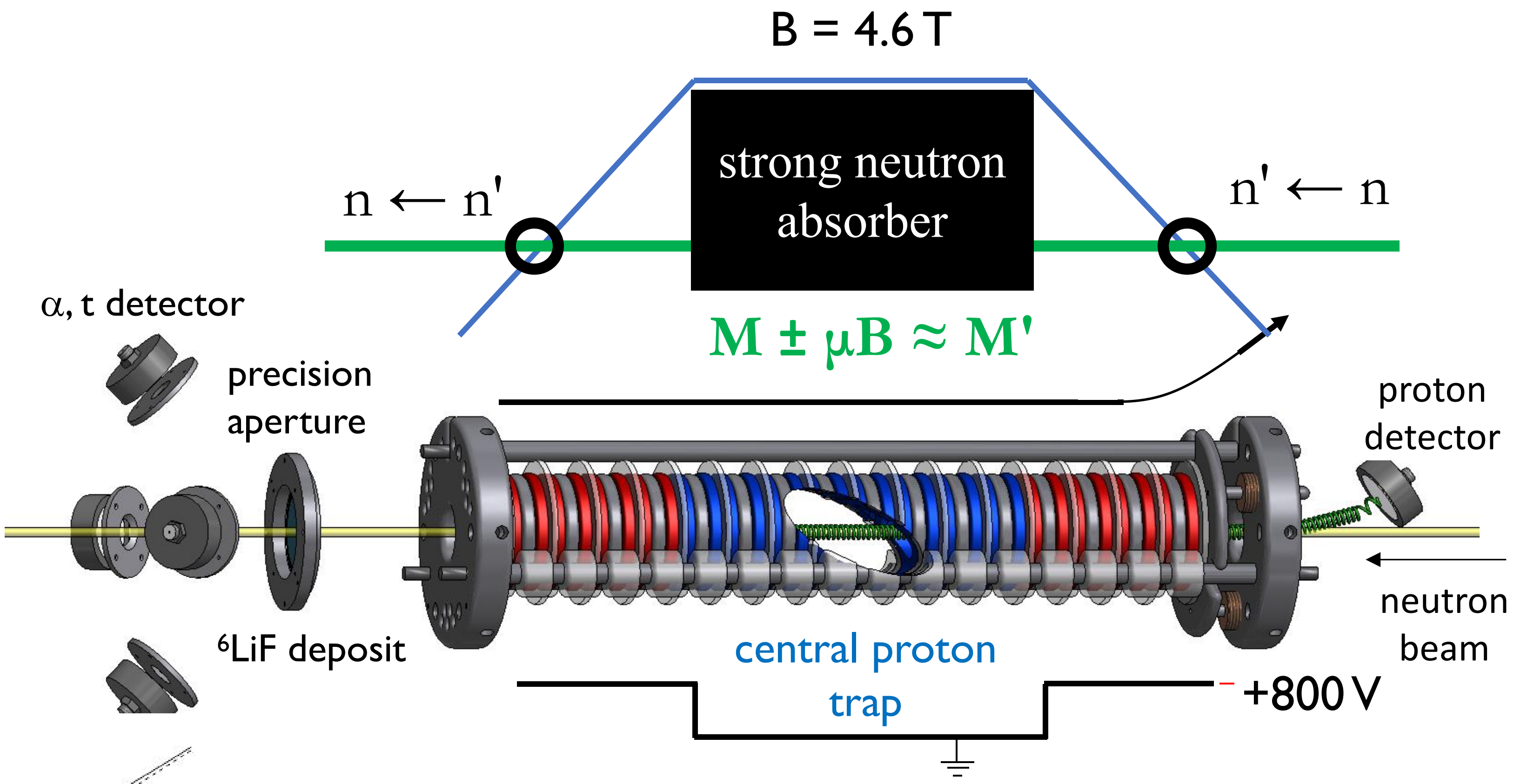
$n \to n'$ in the NIST Beam Lifetime experiment

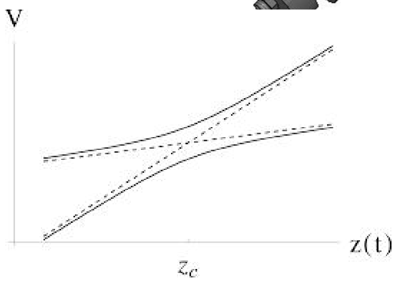
Measure neutron flux and proton decay rate:

$$\dot{N}_p = \epsilon_p \frac{A\,L}{\tau_n} \int \frac{\varphi(v)}{v} dv$$

$$\dot{N}_n = \epsilon_n A v_n \int \frac{\varphi(v)}{v} dv$$

$$\dot{N}_p = \dot{N}_n \left(\frac{L}{\tau_n}\right) \frac{\epsilon_p}{\epsilon_n v_n}$$





Landau-Zener transition: enhanced transition probability for non-adiabatic zero-crossing of energy difference

PRC 71 (2005) 055502, PRL 111 (2013) 222501

EPJC 79 (2019) 484

$n \to n'$ in the NIST Beam Lifetime experiment

- Calculated evolution through NIST beam lifetime B profile PRC 71 (2005) 055502

$$\boxed{\frac{\partial}{\partial t}\hat{\rho} = -i[\hat{H}\cdot\hat{\rho}] = -i\hat{H}\hat{\rho} + i\hat{\rho}\hat{H}^{\dagger}}$$

Liouville–von Neumann equation

$$\hat{H} = \begin{pmatrix} \Delta m + V - iW \pm \mu B & \epsilon \\ \epsilon & 0 \end{pmatrix}$$

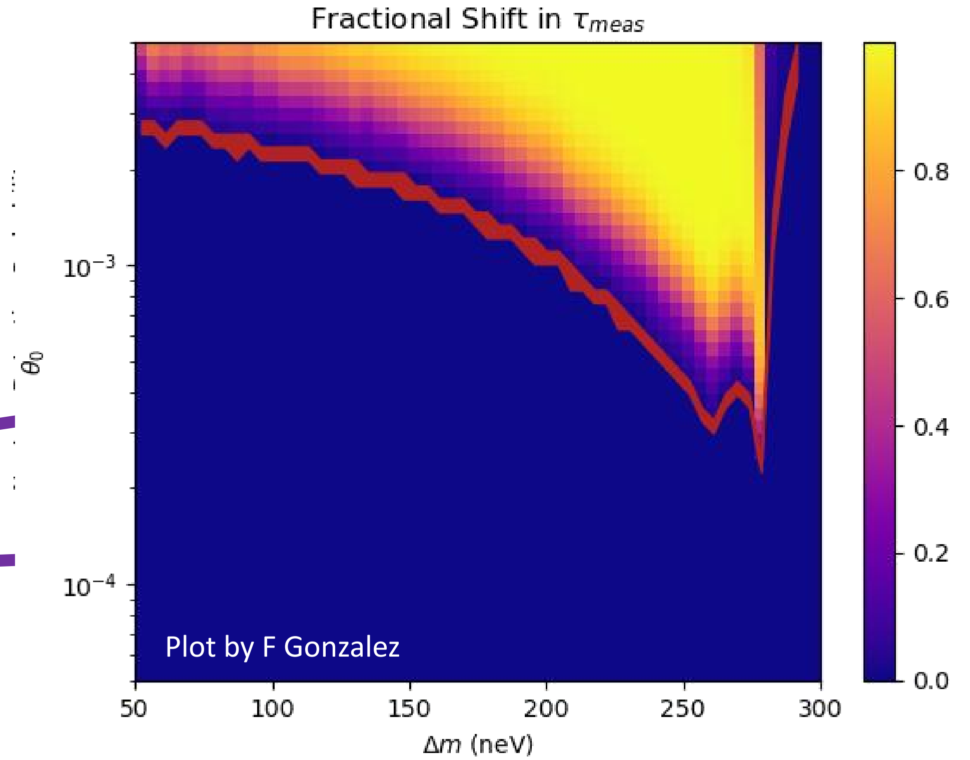
$$\hat{\rho}(0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = n$$

- Combine calculated shift in $\dot{N}_p, \dot{N}_n$ to find a lifetime shift

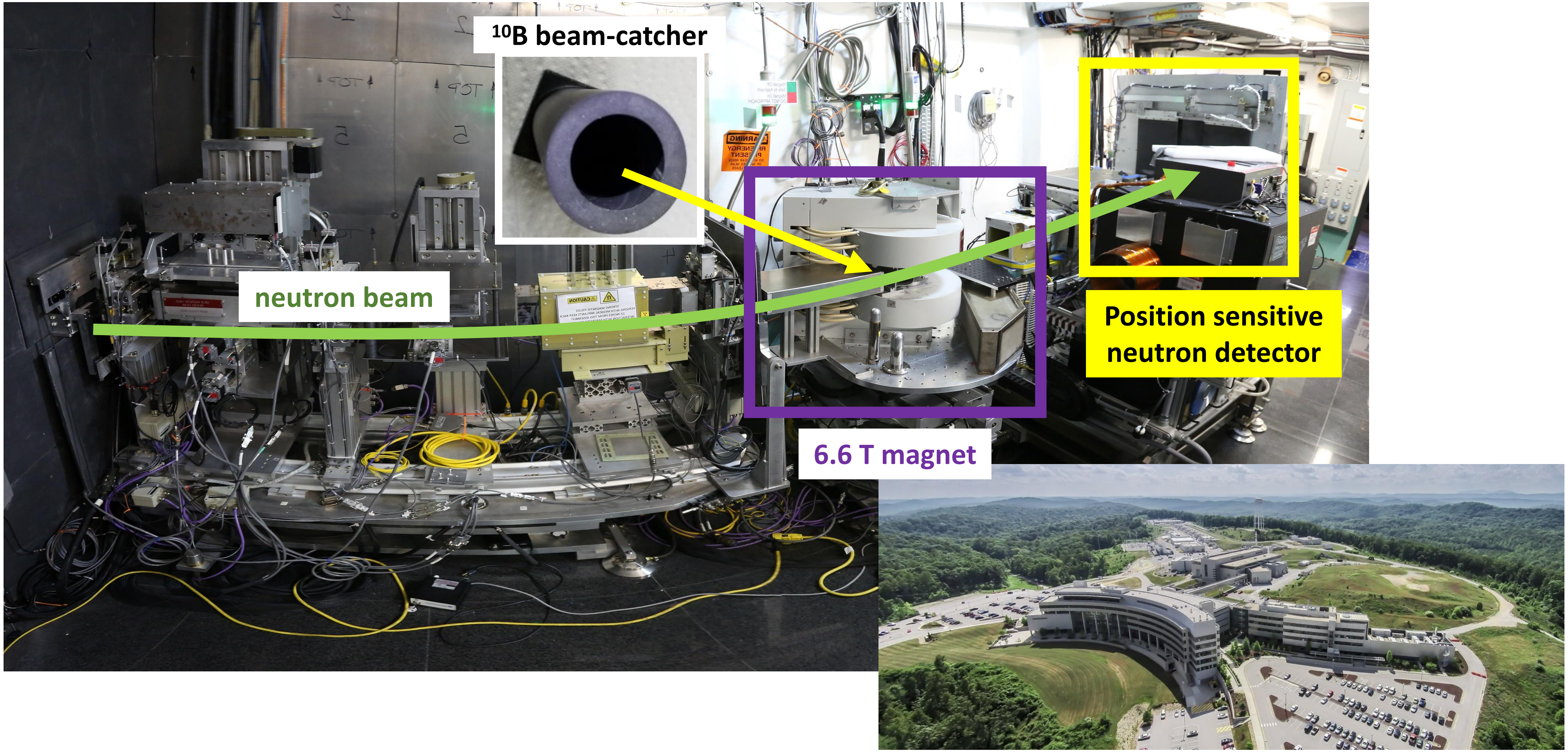
$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

- Region of interest for $n \to n'$:
  - When $\delta\tau_{meas}/\tau_n \sim 1\%$

Landau-Zener transition when $\Delta E = 0$



$n \to n' \to n$@SNS experiment approach

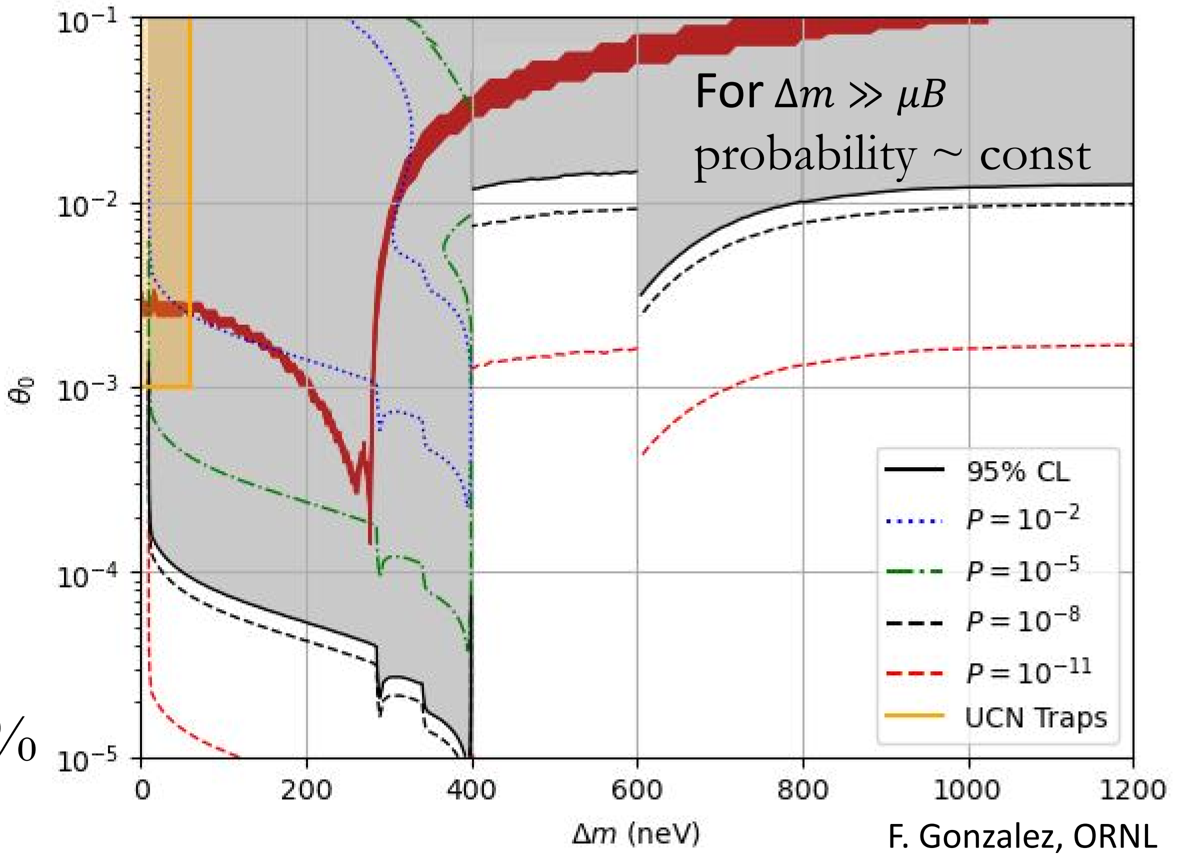


Impact for neutron lifetime anomaly

B Field at B4C	B4C Position	Total Cts in ROI	Charge	Cts / 5C
+4.8 T	center	7748 ± 88	13.8 C	2805 ± 32
-4.8 T	center	4976 ± 70	8.8 C	2823 ± 40
0 T	center	6631 ± 81	11.9 C	2791 ± 34
3.33 T	center	1017 ± 32	1.8 C	2817 ± 88
+6.6 T	peak B	1010 ± 32	1.8 C	2804 ± 88
-6.6 T	peak B	1120 ± 33	2.0 C	2863 ± 86
0 T	peak B	4916 ± 70	8.7 C	2815 ± 40

- Excluded transmission < 2.5 x 10^{-8} (95% C.L.) (grey region)
- **Conclusion**: this exotic process does not explain neutron lifetime anomaly

PRL 128 (2022) 212503



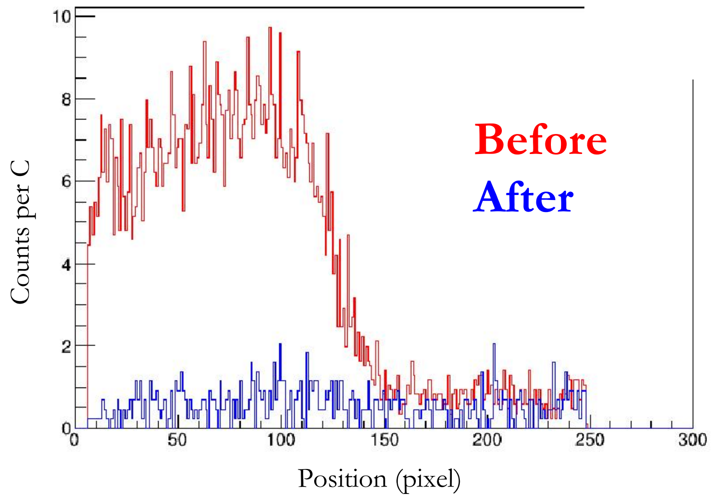
F. Gonzalez, ORNL

Gray – Excluded region from our experiment (95% CL)
Red – 1% ± 0.2% difference in neutron lifetime
Dashed – Probability bands

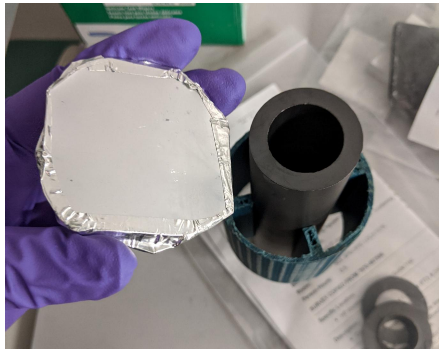
Improved search for $n \to n'$@ SNS

- ×10 reduction in detector background
- Higher intensity (better neutron beam acceptance) and improved analysis
- Improved understanding of neutron oscillations in matter → better choice of material for full sensitivity

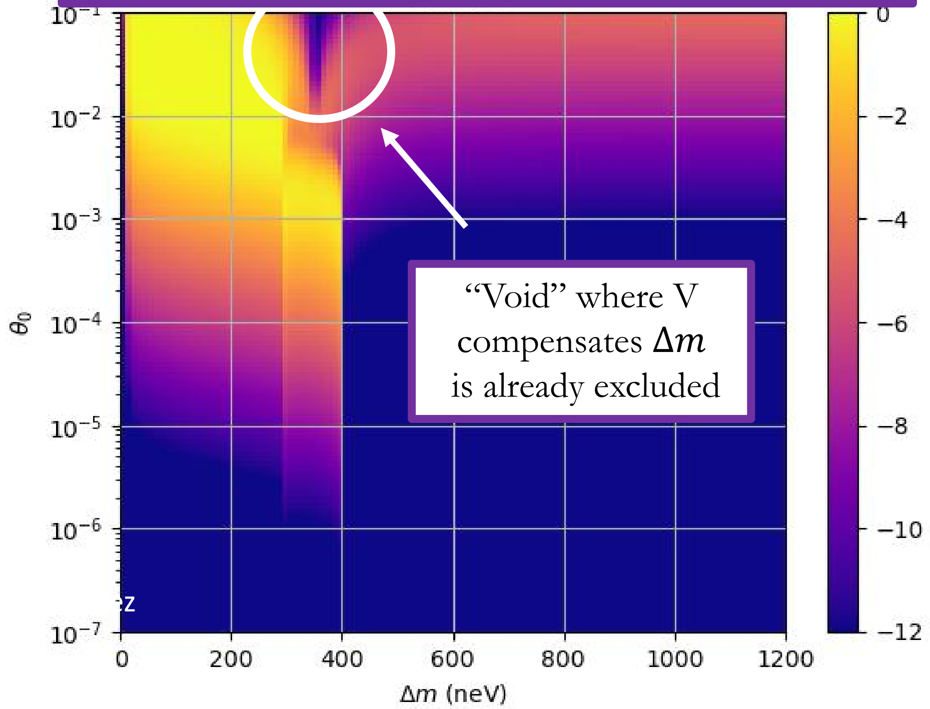
Detector backgrounds



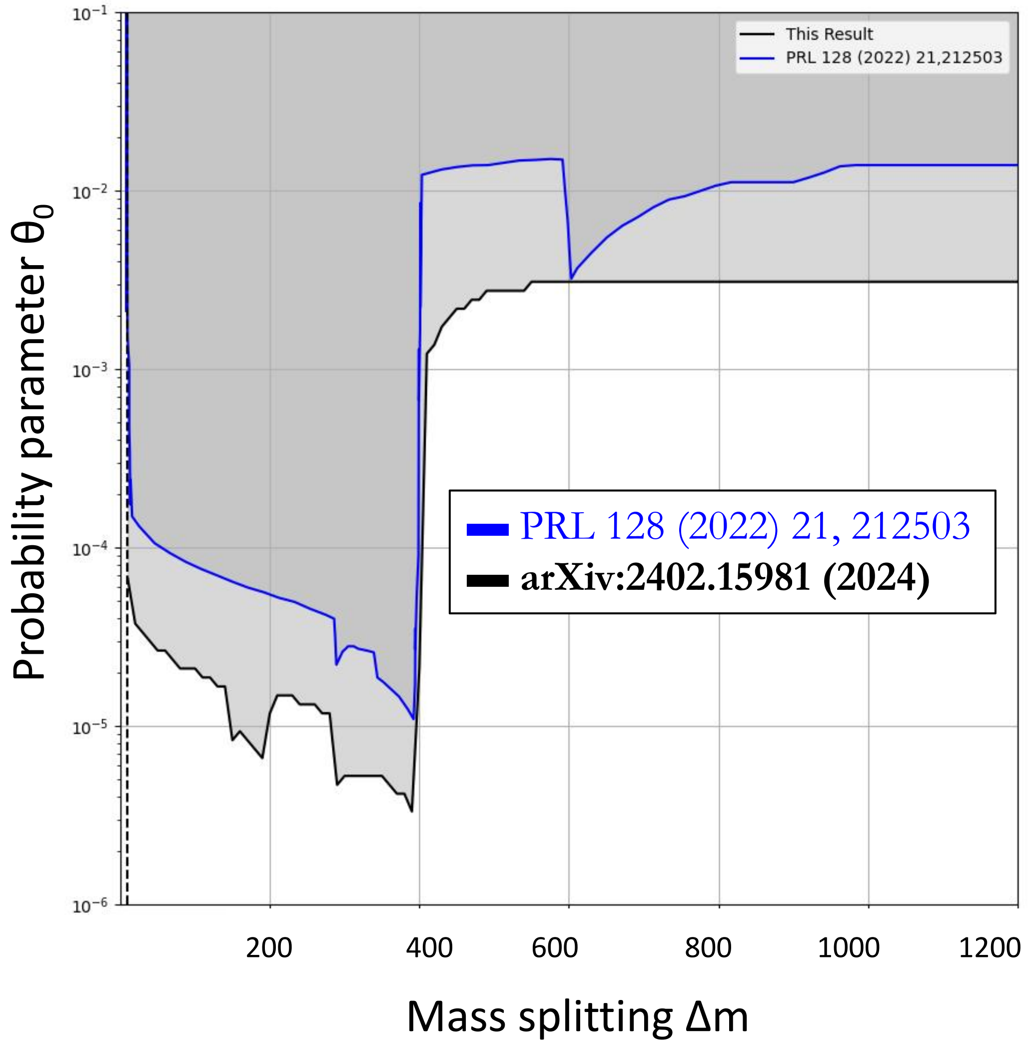
Cadmium neutron absorber

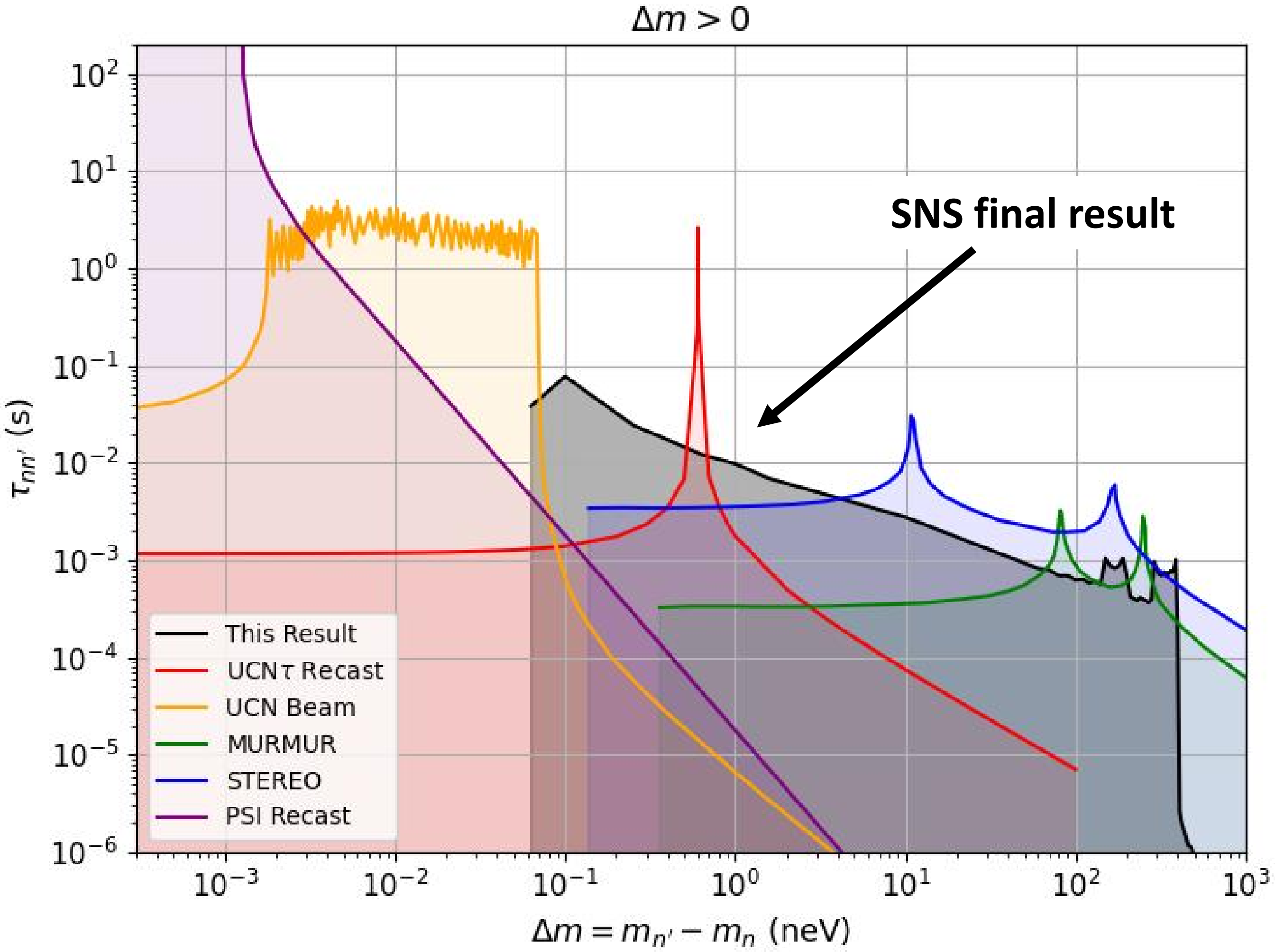


Probability for neutron regeneration with Cd beamstop



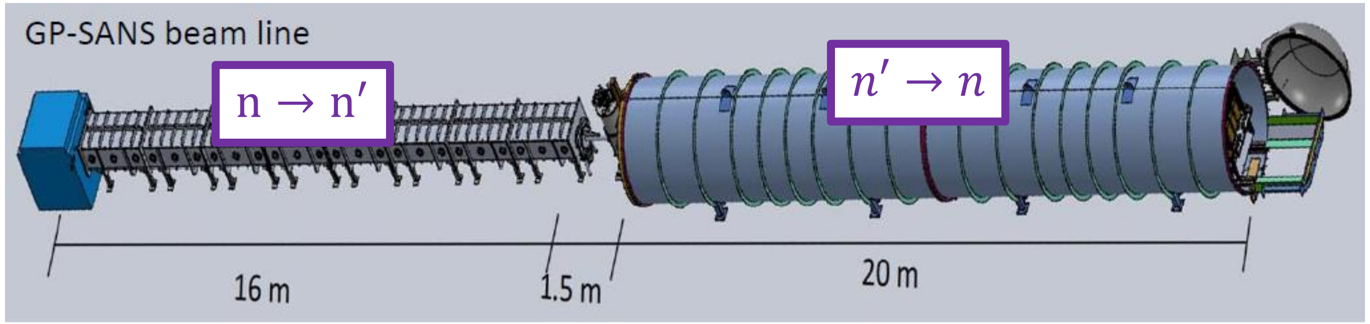
Final result for $n \to n'$@ SNS

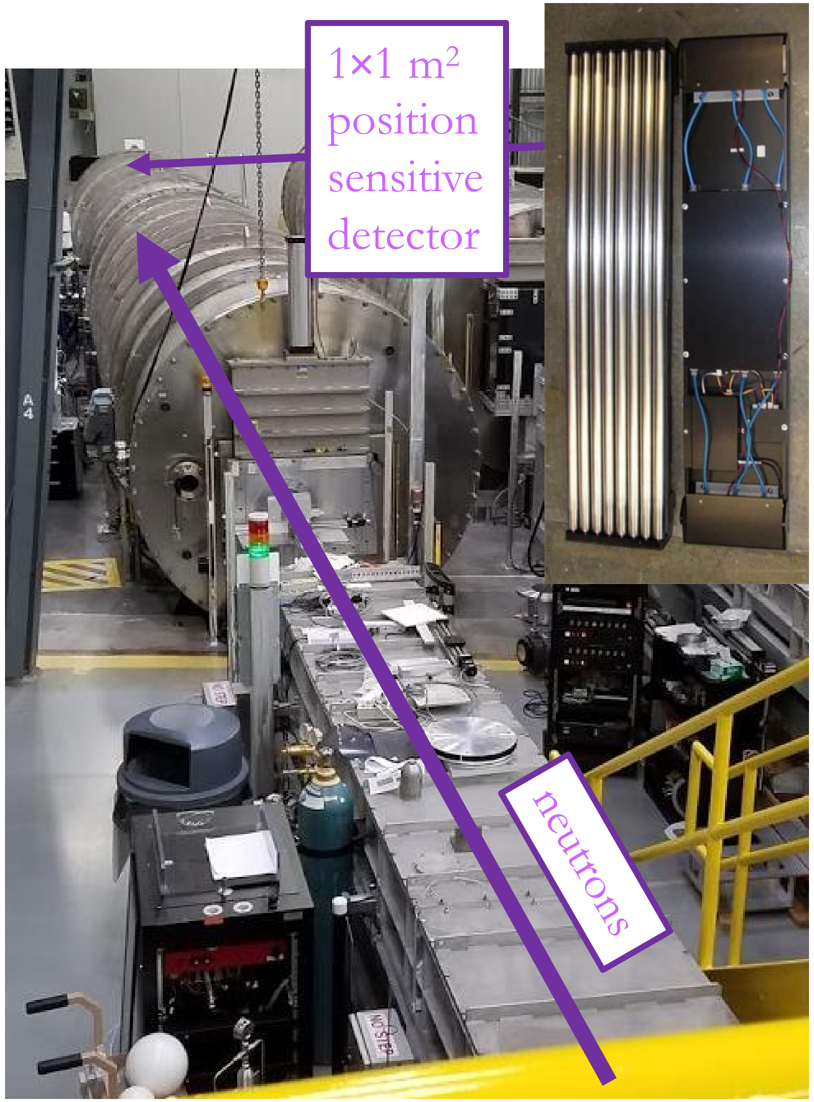




Next: searches for $n \rightarrow n'$@ HFIR

- High Flux Isotope Reactor - 85 MW: highest reactor-based source of neutrons for research in US
  - ~10,000× more neutron intensity than SNS
  - Lower backgrounds: ^{3}He neutron detector in Cd shielded tank
  - 15 m and 20 m long beamguides for "disappearance" and "regeneration"



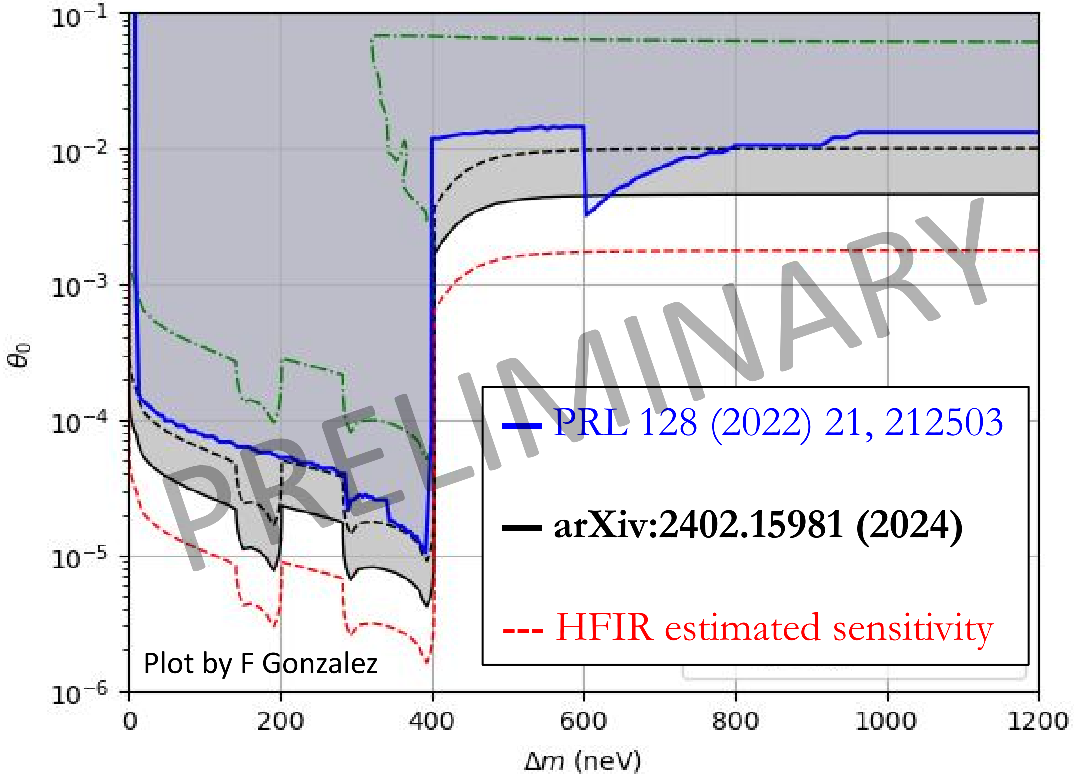


$n \to n'$@ HFIR program now launched

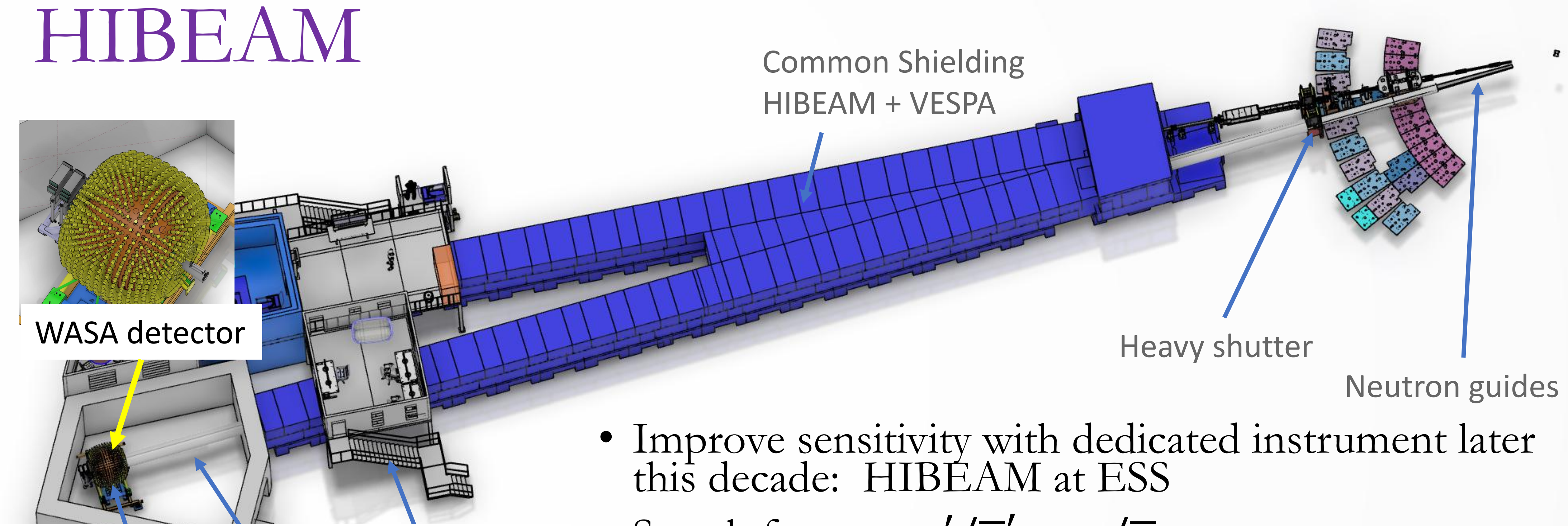
- SNS experiment setup moved to HFIR and completed data-taking in January 2024
  - Sensitivity gain primarily due to higher neutron flux
  - Stage 1A complete!
- Now prototyping apparatus to test Stage 1B: does neutron have Transition Magnetic Moment?
  - Proposed to explain neutron "bottle" lifetime [MDPI Phys, 1 (2019) 271-289]

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

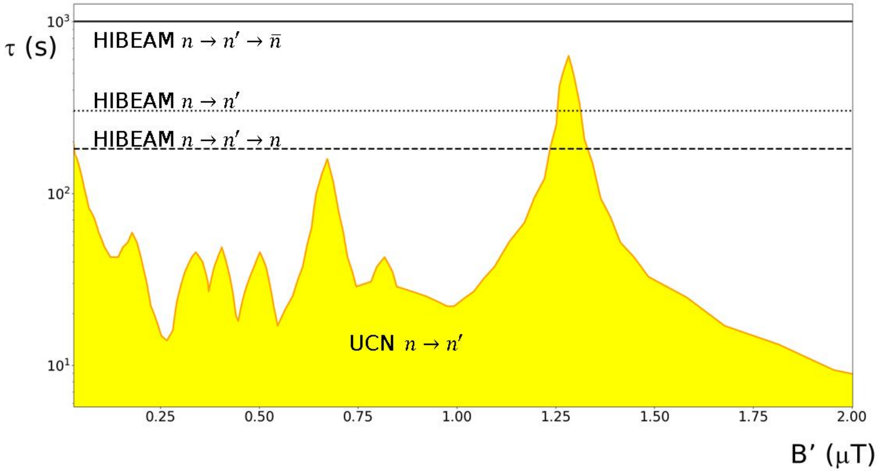
- Seeking funding for Stage 1C at HFIR: search for $n \to n'$ assuming no mass splitting (but small magnetic field splitting)

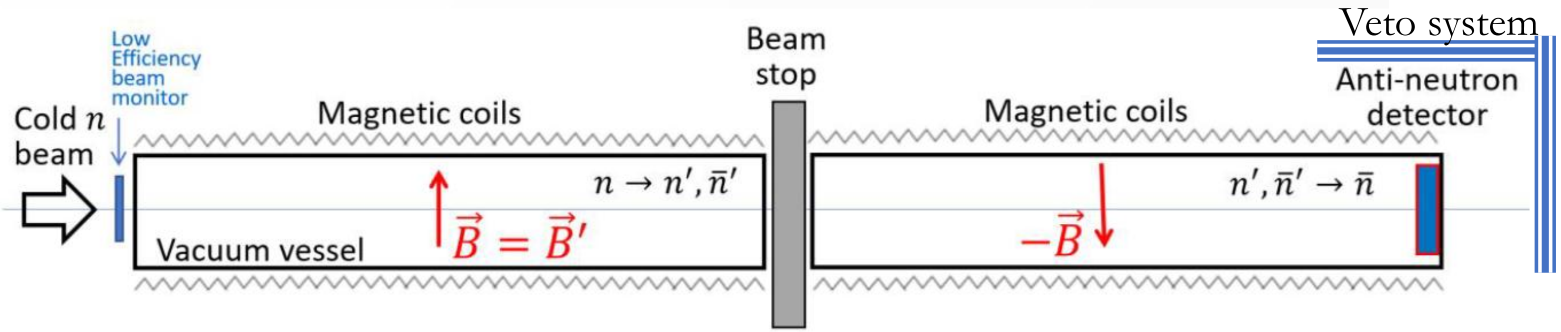


HIBEAM



- Improve sensitivity with dedicated instrument later this decade: HIBEAM at ESS
- Search for $n \to n'/\bar{n}' \to n/\bar{n}$





- Important R&D opportunity for NNBAR!

arXiv:2311.08326

Summary

- Searches for dark matter and baryon number violation strongly motivated! Neutrons are under-explored territory in worldwide BLV/dark matter programs
- NNBAR promises 1000x sensitivity improvement to neutron oscillations. Significant recent engineering design progress for CDR
- Cold neutron regeneration technique used at ORNL to exclude one theory that $n - n'$ oscillations caused the neutron lifetime puzzle, with more sensitive searches for this dark matter candidate recently completed
- ORNL's High Flux Isotope Reactor provides early R&D for high sensitivity program in dedicated instrument at ESS, with HIBEAM and NNBAR

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Parallel universe breakthrough: Scientists begin work on finding a 'mirrorverse'
SCIENTISTS are hoping to open a port
undoubtedly be the biggest
P-magazine, Belgium
for a mi
arallel universe breakthrough:
ists begin work on finding a
TL;DR
1 minute read
Naukowcy próbują odnaleźć lustrzane uniwersa rodem ze Star Treka
R, MIRROR"
Two Experiments Might Soon Show If So-Called Mirror Matte
CIEN
Science Physics
Scientists are trying to open a portal to a
style MIRRORVERSE
Scientists believe there could be a parallel universe as real as our own, but almost completely
www.mirro
BY
STRANGER THINGS
ARÁN
d A Mirror
netgreen.club
WAIT WAIT... DON'T TELL ME!
FROM NPR & WBEZ CHICAGO
Natalia Bogucka 04.07.19 (11:38)
Naukowcy próbują otworzy
do równoległe
chświata
Choć brzmi to jak historia z film
Laboratory w Tennessee wierz
odzwierciedleniem naszego.
portal, który ich do niego prze
de EE UU intentarán abrir un portal
screenrant.com/
elo
Demogorgons, Spock with a goatee, you know the rest
July 3, 2019 9:11 AM Subscribe
Leah Broussard, Oak Ridge National Laboratory, and the search for "mirror matter". In a series of experiments she plans to run at Oak Ridge this summer, Broussard will send a beam of subatomic particles down a 50-foot tunnel, past a powerful magnet and into an impenetrable wall. If the setup is just right — and if the universe cooperates — some of those particles will transform into mirror-image versions of themselves, allowing them to tunnel right through the wall. And if that happens, Broussard will have uncovered the first evidence of a mirror world right alongside our own.
el equipo y física Leah Broussard a la caden
e existence of a mirror universe is
t will be in Tennessee
hursday, July 4th 2019
fox17.com/

Bonus

- About 100 (mostly clickbait) stories on the experiment
- Hundreds of thousands of tweets/other social media
- 2 posted letters
- 1 piece of art
- Response from the public
    - 1/3 enthusiastic public
    - 1/3 “alternative physicists”
    - 1/3 *volunteers to go through the portal*

I have a Google new alert setup for @leahjbroussard and every time it goes off I am excited and scared all at the same time.
Did she do it??
Did she do it and now we are all going to die??

@leahjbroussard have you considered what might come through the portal?... regardless, please proceed.

@leahjbroussard Not that I don't doubt you'll make excellent progress with your experiment, but I hope that you'll be taking every precaution should 'something' try to follow the particles back. Be really cautious and have failsafes to shut it down if need be.

I'm an excited hobbyist (sharing with my 6 year old son and 4 year old daughter) and wish you the best.

Hello Goodmorning, I saw your experiment recently and just wanted to let you know if you ever reach a point you want to see if you can mirror humans. I volunteer as a guinea pig.

Find us a better timeline! You're our only hope @leahjbroussard

I really encourage you and your team to watch Stranger Things before attempting to open the gate to a mirror universe.
Sent from my iPhone

Thank you!