Searches for neutron oscillations with HIBEAM and NNBAR

Leah Broussard
Oak Ridge National Laboratory

14th Conference on the Intersections of Particle and Nuclear Physics

Lake Buena Vista, FL   Aug 29-Sept 4, 2022

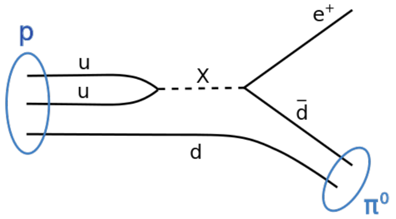
European Spallation Source, Lund, Sweden

Violation of Baryon Number B

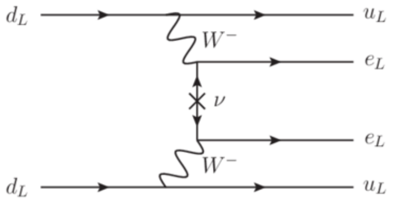
- B, L are accidental symmetries; $B - L$ conserved in the SM
- Global symmetry; BNV not forbidden
- Broadly, SM extensions to explain BAU contain BNV
  - GUT – B necessarily violated (proton decay)
  - RPV SUSY, extra dimensions
  - L-R unification theories, $n \to \bar{n}$ symbiosis with $0\nu\beta\beta$ ($\Delta L = 0$)
  - Post-sphaleron baryogenesis
  - Co-baryogenesis scenarios, mirror matter
- Not if, but at what scale is BNV?

Complementary Approaches

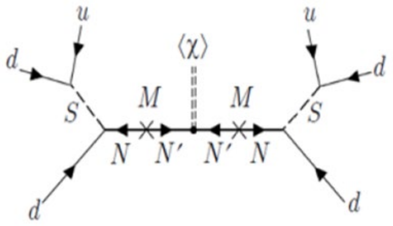
$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$



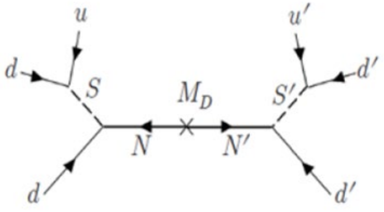
$$0\upsilon\beta\beta$$
$$\Delta B = 0, \Delta L \neq 0$$



$$n \to \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$



$$n \to n'$$
$$\Delta B = 1, \Delta L = 0$$



- p decay, 0νββ, n conversions probe different selection rules

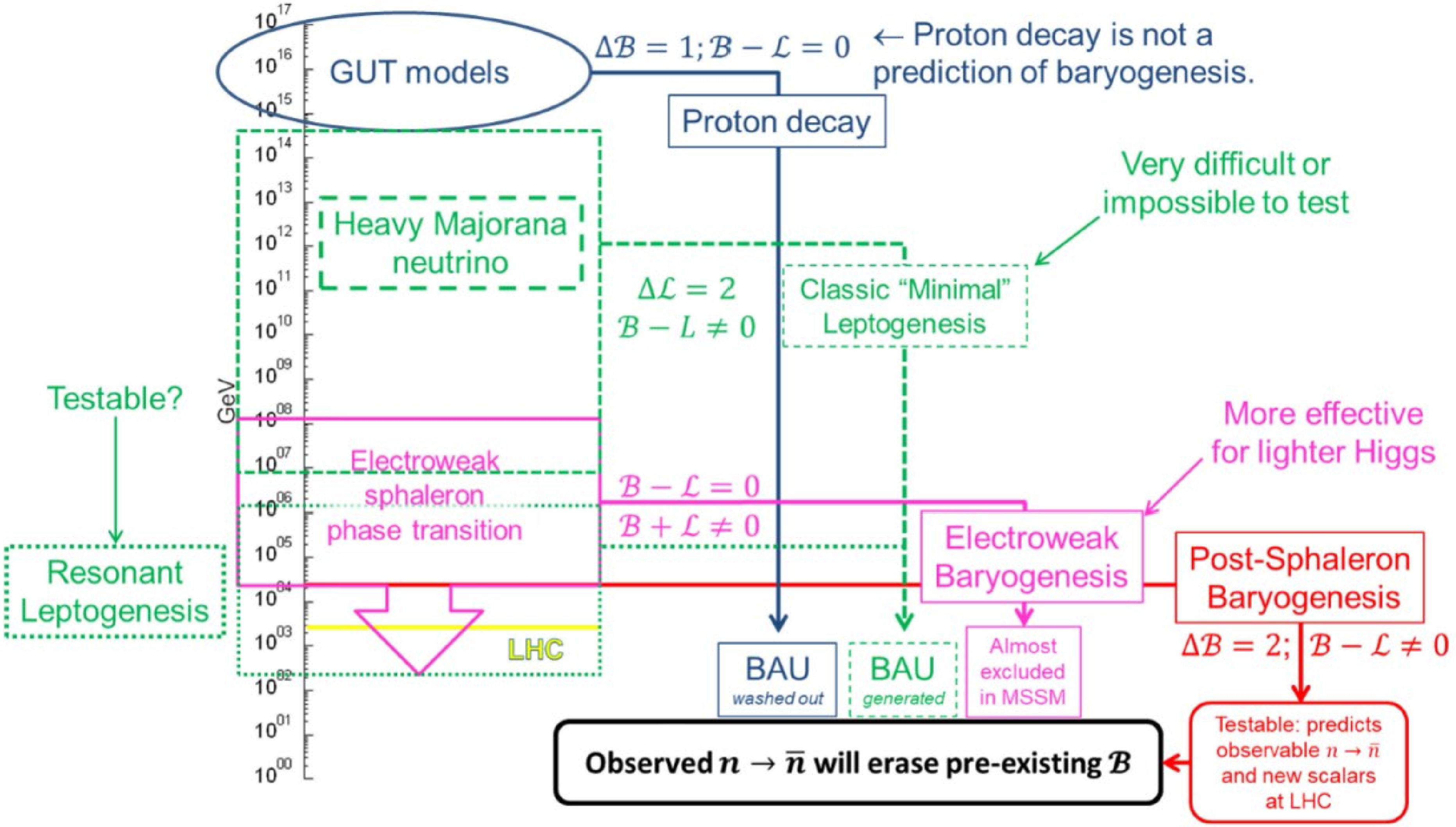
$$\Delta B \neq 0, \Delta L \neq 0, \Delta[B - L] = 0$$

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

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

- $n \to \bar{n}$, dinucleon decays sensitive to BNV-only
- x1000 improvement in $n \to \bar{n}$ sensitivity on horizon
- Neutral particle can mix with dark matter, $n \to n'$ and $n \to n' \to \bar{n}$

Baryogenesis models



from Y. Kamyshkov and J. Barrow

$n \to \bar{n}$ oscillations

- 2 state system with potential difference for neutron vs antineutron
  - Neutron inside nucleus: ~100 MeV
  - Free neutron in Earth's magnetic potential $\mu \cdot B$ (10^{-18} MeV)

$$\hat{H} = \begin{pmatrix} m + \vec{\mu}(\vec{B} \cdot \vec{\sigma}) & \varepsilon \\ \varepsilon & m - \vec{\mu}(\vec{B} \cdot \vec{\sigma}) \end{pmatrix} \qquad \psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

- Strong limits on $\tau_{n\to\bar{n}}$: Mass splitting from nonzero V >> off-diagonal term ε

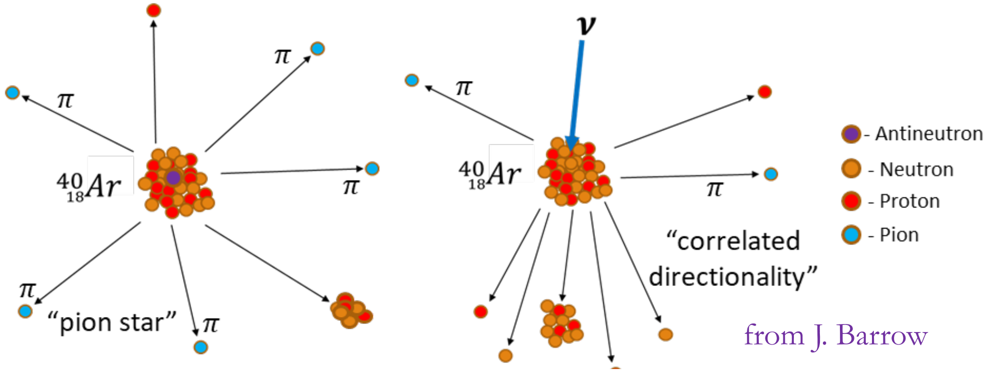
$$\Delta E(1\,nT) = E_n - E_{\bar{n}} = 2\mu B \sim 10^{-22} \text{ MeV} \qquad \varepsilon < 10^{-29} \text{ MeV}$$

- Need "Quasi-free limit": Uncertainty principle $\Delta E \Delta \mathrm{t} \ll \hbar$
  - Free neutron TOF ~ 0.1 s → B~10 nT   NIMA 320 (1992) 569
  - Bound neutrons "free" inside nucleons for $\Delta t \approx \hbar / E_{binding} \sim 5 \times 10^{-22}$ s (nuclear suppression factor)

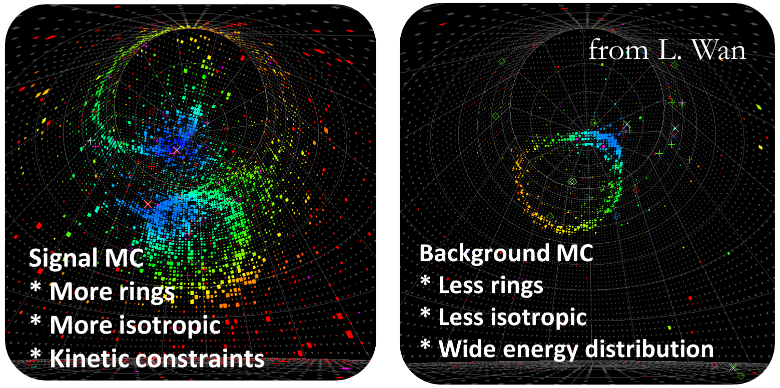
- In this limit $P_{n\to\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\to\bar{n}}}\right)^2 \qquad \frac{1}{\tau_{n\to\bar{n}}} = \varepsilon$ (Figure of Merit)

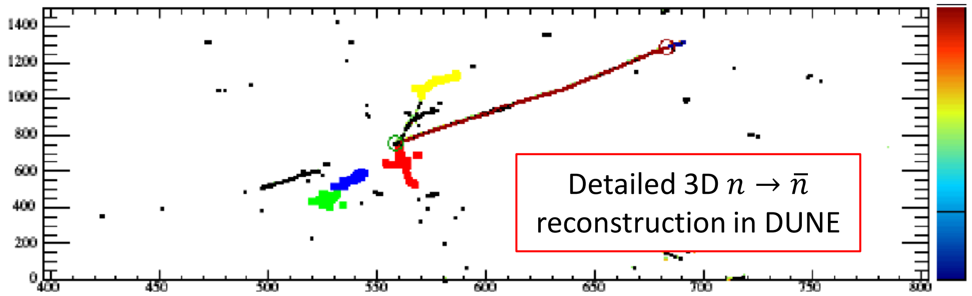
Searches for $n \to \bar{n}$ in nuclei

- Task: distinguish characteristic $\bar{n}$ signature ("pion star") from backgrounds such as ν_{atm} background
  - Constraints: topology, 1.88 GeV, total momentum 0, average 5 pions
- Super-K Runs I/II/III/IV **PRD 103 (2021) 012008**
  - 11 candidate events, 9.3 expected backgrounds
  - 3.6x10^{32} years at 90% C.L, **τ > 4.7 x 10^{8} s**
- Sensitive searches potentially possible in Hyper-K, NOvA, MicroBooNE
- DUNE: improved background rejection **arXiv:2002.03005**
  - Offer lower KE threshold (e.g. protons), higher resolution, bubble chamber-like images, PID & dE/dx
  - Expected reach: $\boldsymbol{\tau_{n\to\bar{n}} > 5.53 \times 10^{8}}$ **s**



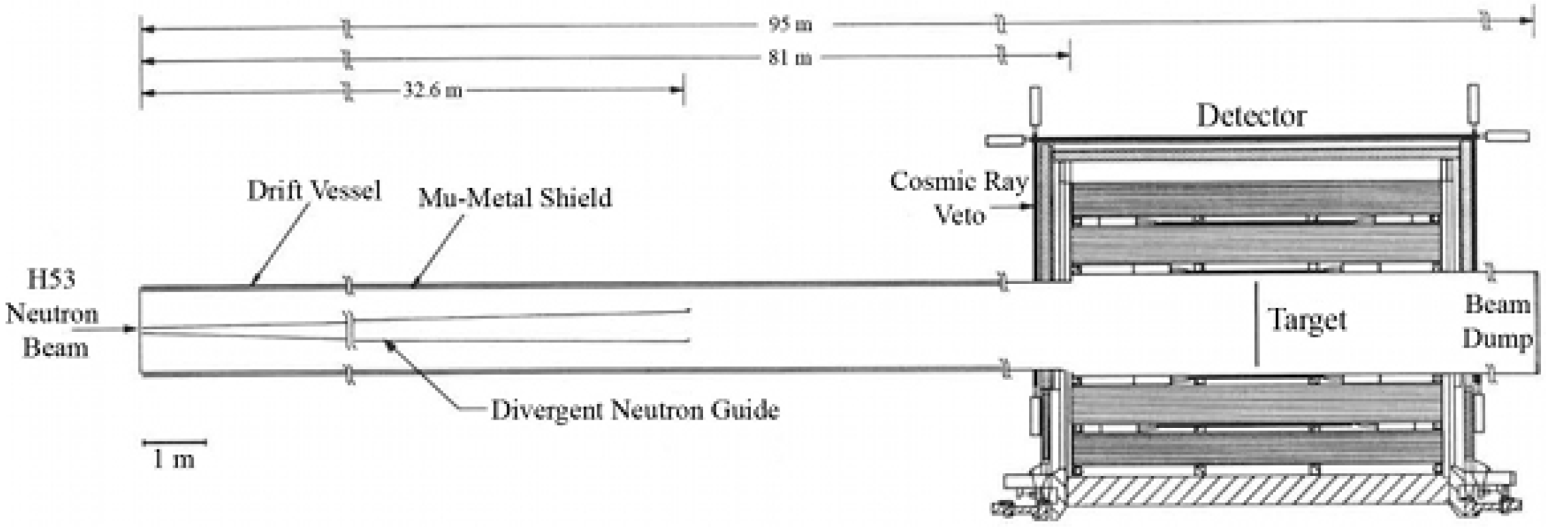
from J. Barrow

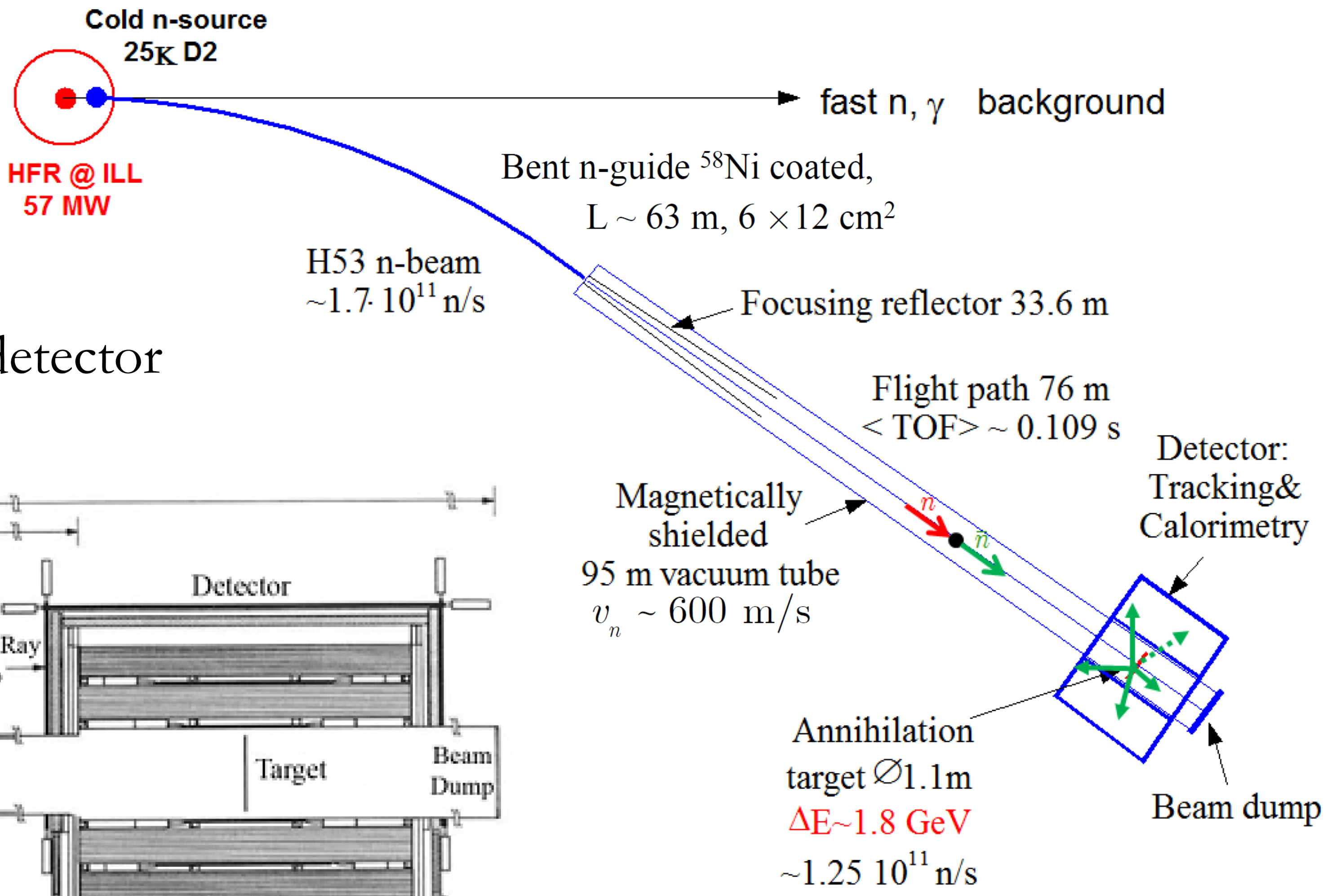




Free $n \to \bar{n}$ search at ILL

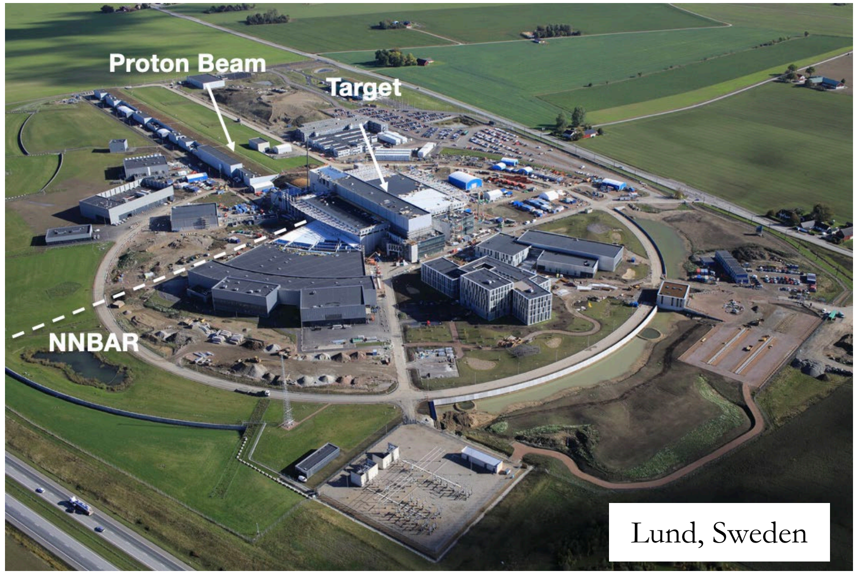
- Last free neutron search at ILL
  ZPC **63** (1994) 409-416
  - 0 candidate events, 0 backgrounds
  - 1 year running: $\boldsymbol{\tau_{n\to\bar{n}} > 0.86 \times 10^8 s}$
- Major advances in neutronics and detector technology in 3 decades since

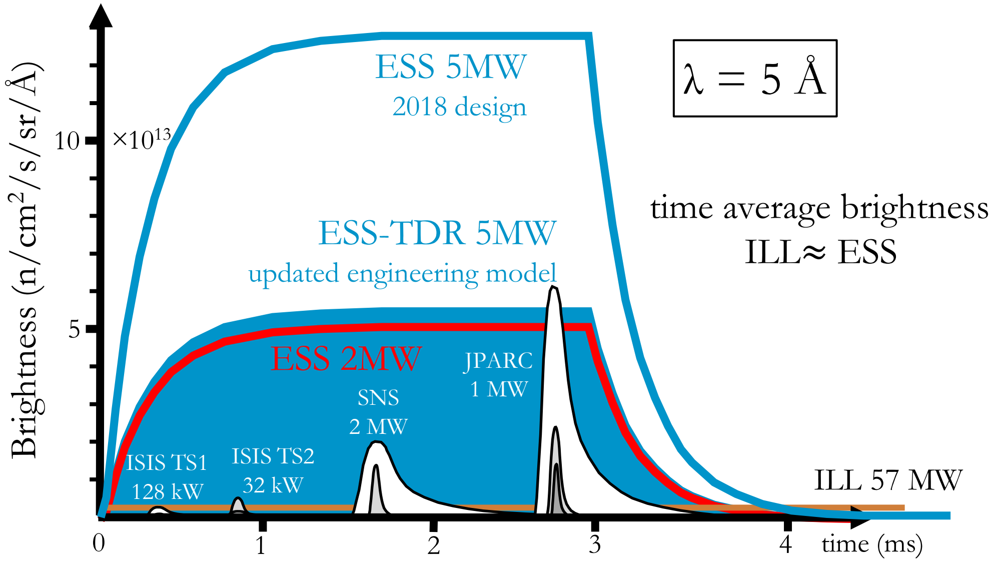




The European Spallation Source

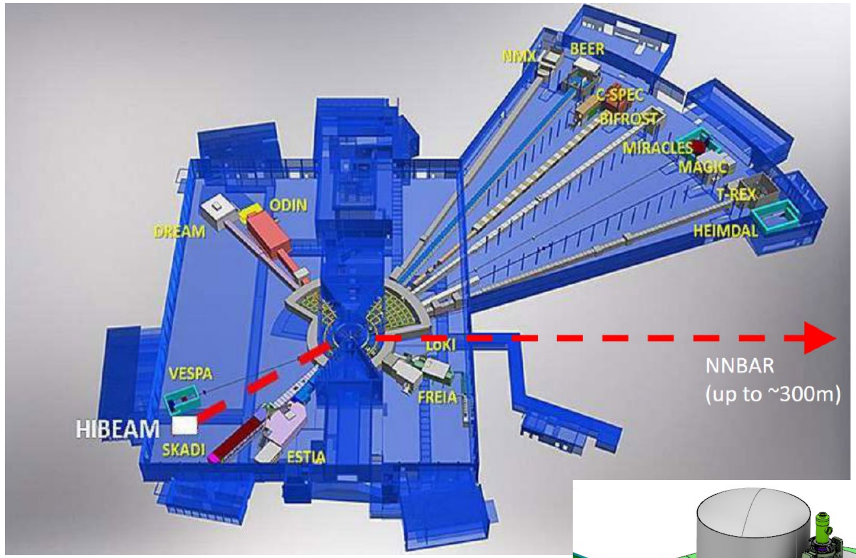
- World's most powerful neutron spallation source, primarily serves neutron scattering community
- 2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target
- 2 MW beam on target ~ 2027, upper moderator, first suite of 15 instruments in user program
- 22 instruments, lower moderator > 2027
- Possibility to upgrade to 5 MW in future project
- 2018 Capability Gap Analysis: inclusion of particle physics given highest priority (with 1 other) => particle physics beamline in TDR of 22 instruments

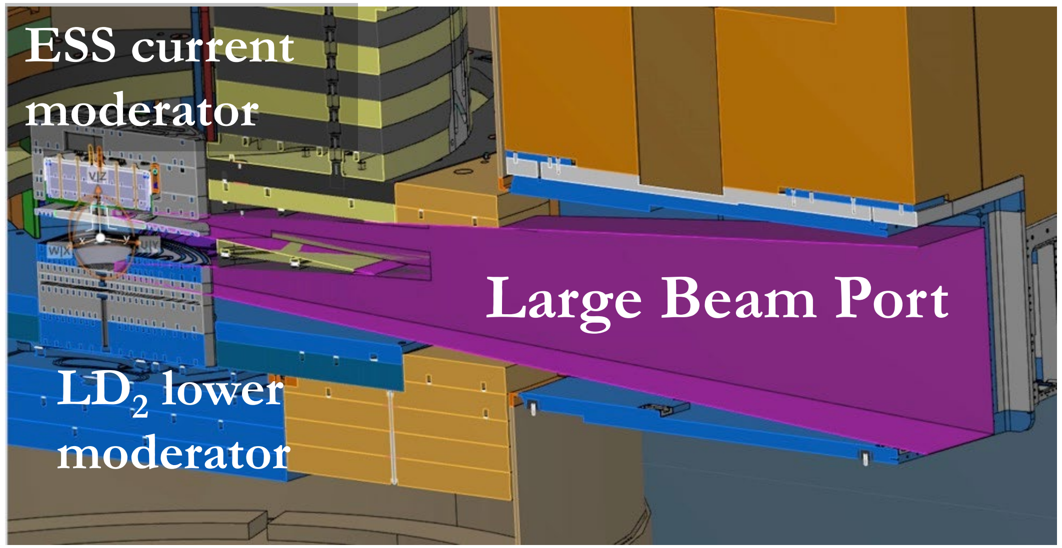


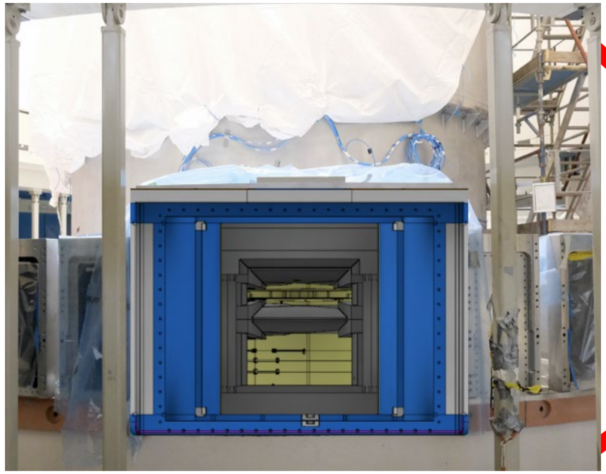


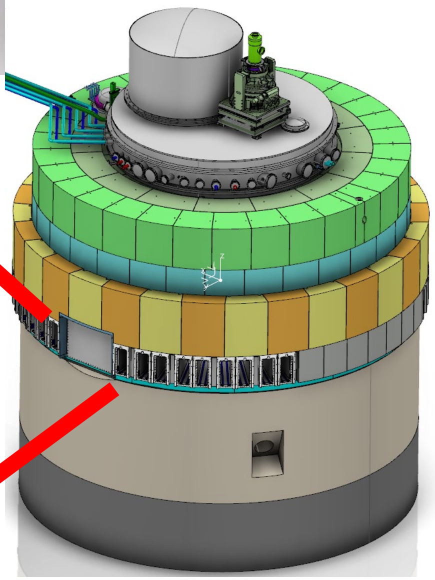
Golden opportunity for $n \to \bar{n}$ at ESS

- Substantial investment from ESS with $n \to \bar{n}$ in mind, to maximize FOM: $N\langle t^2 \rangle$
  - "Large Beam Port" now constructed
  - Up to 300 m beamline
- Fundamental Physics leading design of LD_2 lower moderator [J Phys G 48 070501 (2021)]



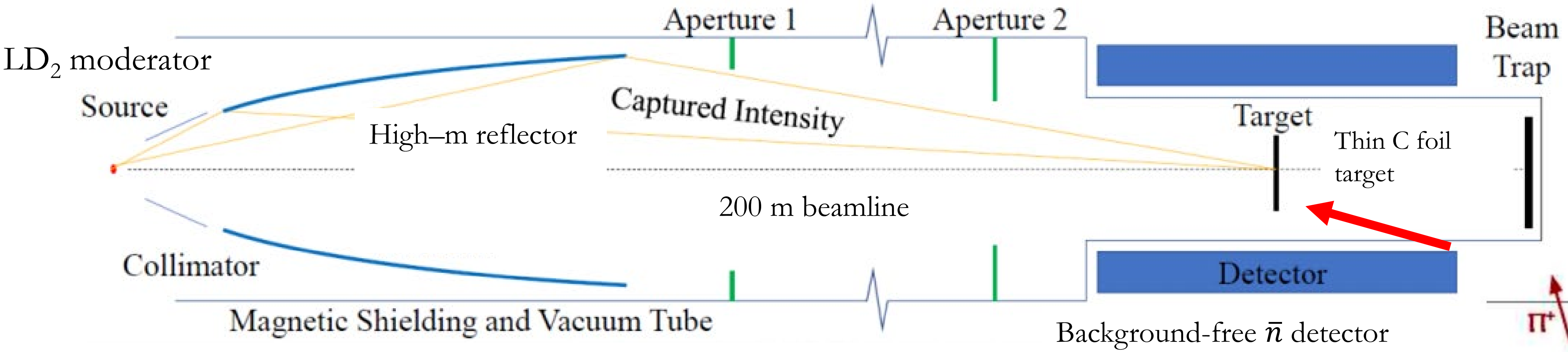




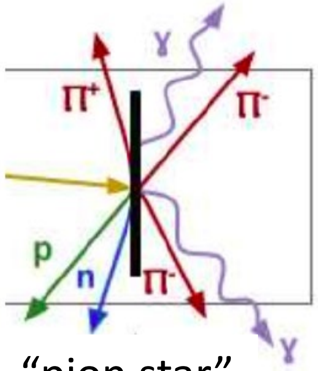


The NNBAR Experiment

- NNBAR at ESS: Leverage 3 decades of advances: moderator design, neutronics, detection, reconstruction techniques ×**1000** sensitivity of ILL J Phys G 48 070501 (2021)



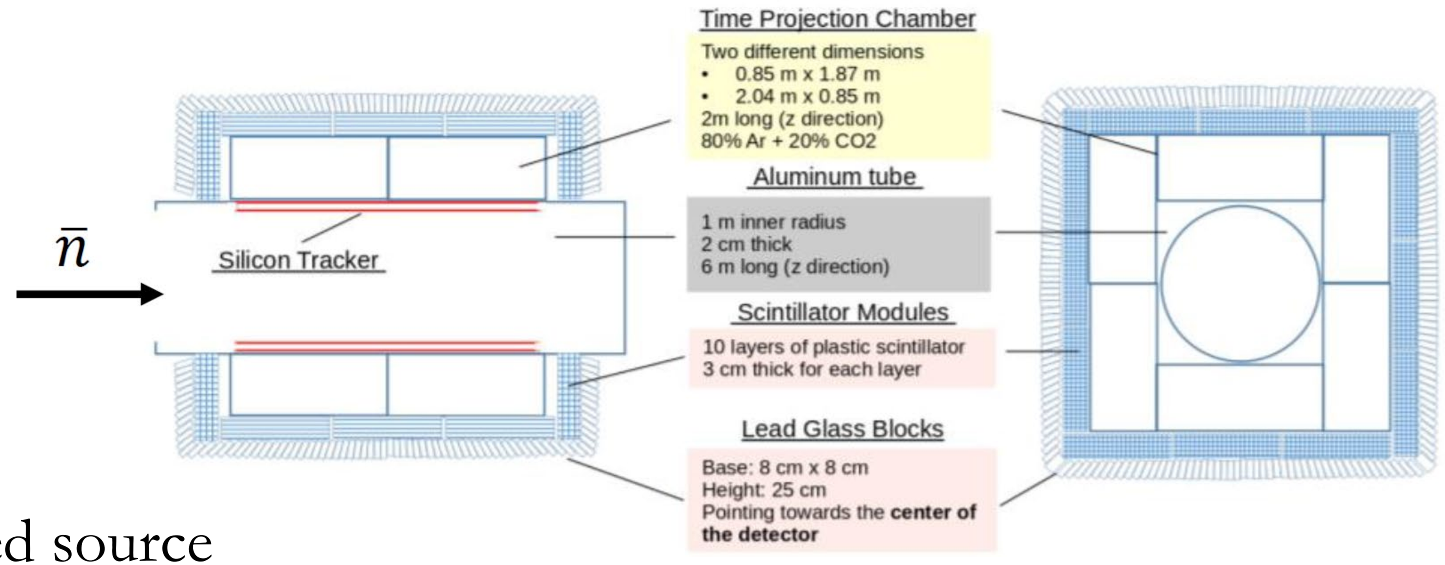
- HighNESS (3M€ EU grant): moderator study, $\bar{n}$ detector prototyping
  - EPJ Web Conf 251 02062 (2021), Sym 14 1 (2022), arXiv:2204.04051
  - Goal: CDR in 2023 for LD_2 moderator, NNBAR
- Staged R&D program ORNL – HIBEAM – NNBAR

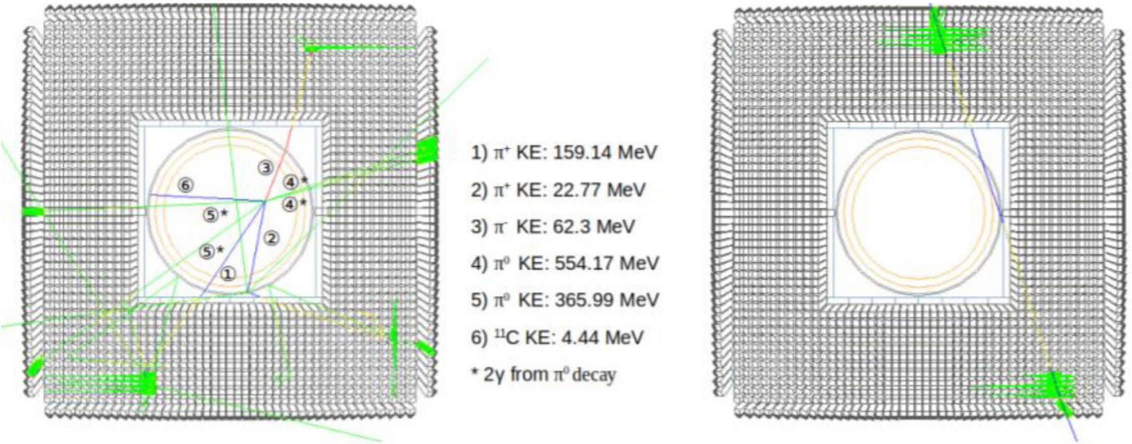


"pion star"

NNBAR Detector

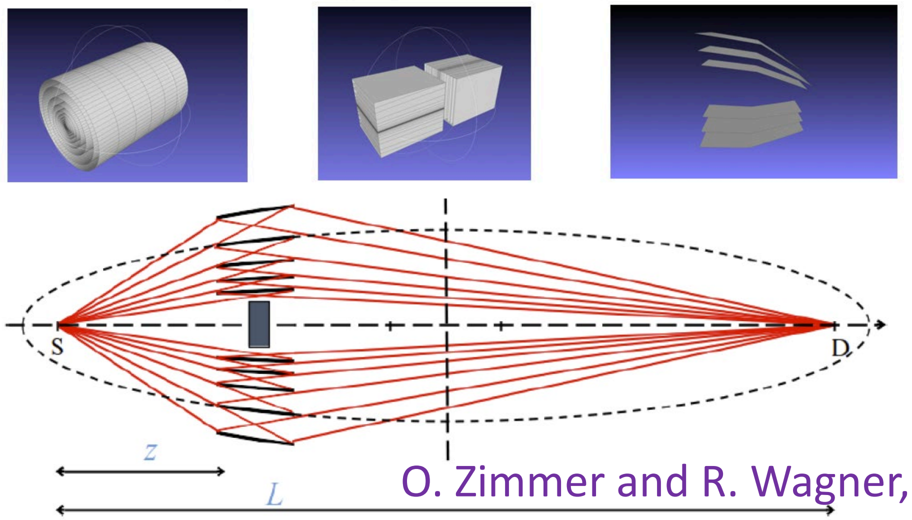
- Detector concept:
  - Silicon inner tracker
  - TPC
  - Scintillator range detector
  - Lead-glass calorimeter
- Strong constraints: 1-2 GeV, 4-7 pions, precise vertex, pulsed source
- Requirements:
  - Reconstruct multi-pion final state
  - Invariant mass reconstruction
  - Particle ID
  - Timing sensitivity for background rejection
- EPJ Web Conf 251 02062 (2021), Sym 14 1 (2022), arXiv:2107.02147





Factors improvement in NNBAR over ILL

Brightness		≥ 1
Moderator Temperature	Colder neutron <TOF>, quadratic sensitivity	≥ 1
Moderator Area	Large aperture required	2
Angular Acceptance	2D = quadratic sensitivity	40
Length	∝ time, quadratic sensitivity	5
Run Time	ILL run = 1 year	3
Total gain vs ILL	Figure of merit: Nt^2	**≥ 1000**



O. Zimmer and R. Wagner, ILL

- Assumes ESS @ 5 MW, optimized moderator + 2 MW may be similar; 200 m baseline, 50% detection efficiency (as in ILL), no bounces
- Large gains from neutron reflector: supermirror reflectors now commercially available (m=6); advanced concepts like nested reflectors JNR 30 (2018) 91
- × 1000 increase in sensitivity, reaching $\tau \sim$ 2-3×10^9s
- Multiple reflections? PLB 795 (2019) 362-365; PRL 122 (2019) 221802; PLB 808 (2020) 135636

Road to NNBAR

- R&D, $\bar{n}$ detector prototype
- CDR for LD_2 moderator, HIBEAM/NNBAR
- ORNL $n \to n'$ program

- TDR
- Small scale experiments at ESS Test Beamline

2022 2024 2028

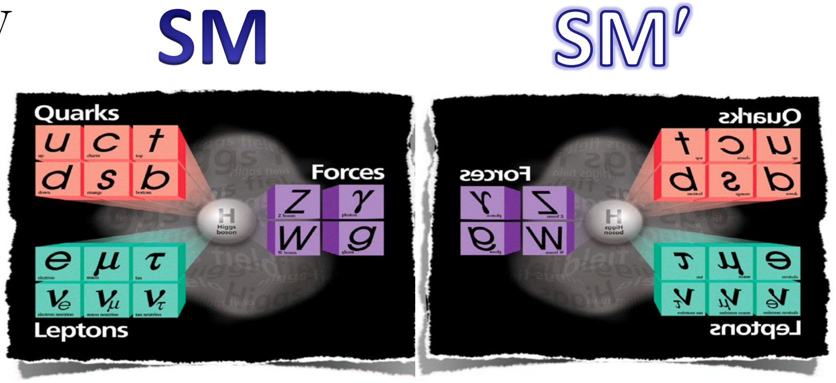
- HIBEAM high precision $n \to n'$ program
- Low sensitivity $n \to \bar{n}$

- NNBAR high sensitivity $n \to \bar{n}$ (×1000 ILL)

>2028 >2030

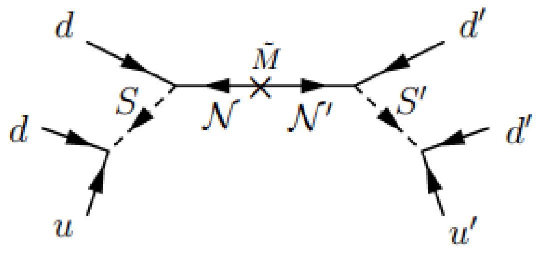
Sterile neutrons

- Mirror matter: identical copy of SM with opposite parity [Phys.Usp. **50** (2007) 380-389, From Fields to Strings **3** (2015) 2147]
  - Mirror sector was proposed to restore L-R symmetry [Phys.Rev. **104** (1956) 254-258]
  - No new parameters. Z_2 symmetry
  - MM and SM don't interact via known SM interactions except gravity [Sov.J.Nucl.Phys. **3** (1966) 6]



- MM a viable DM candidate [PLB **503** (2001) 362, IJMPA **29** (2014) 1430013]
  - Possibly related to sterile neutrino anomaly, GZK limit
- Predictions of nn' mixing in Mirror Matter models PRL 96 081801 (2006)
  - Apparent BNV: Global $\mathcal{B} = \mathcal{B} + \mathcal{B}'$?
- Recent activity: searches using PSI nEDM apparatus Sym 14 503 (2022), STEREO hidden neutron search PRL 128 061801 (2022), UCN-based search at ILL Saenz, Moriond-EW (2022), SNS regeneration search PRL 128 212503 (2022)

$n \rightarrow n'$ Oscillations



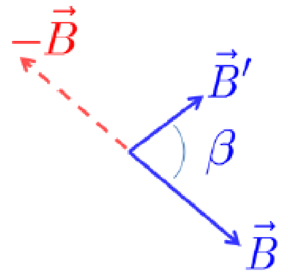
- Similar concept to $n - \bar{n}$: mixing of neutron with sterile twin
- Small mirror magnetic field $\boldsymbol{B'}$ possible from MM captured by earth

$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \epsilon \\ \epsilon & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B'} \end{pmatrix} \qquad \text{oscillation time } \tau_{nn'} = \frac{1}{\epsilon}$$

- $n - n'$ mass splitting (10^{-24} GeV) or magnetic field (mG) can strongly suppress oscillation:
- Not sensitive to large $\Delta m_{nn'}$ in laboratory, control $\vec{B}$ for resonance in probability:

$$\mathrm{P}(n \rightarrow n') = \frac{\sin^2[(\omega-\omega')t]}{[(\omega-\omega')]^2 2\tau^2} + \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2} + \cos\beta\left[\frac{\sin^2[(\omega-\omega')t]}{(\omega-\omega')^2 2\tau^2} - \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2}\right]$$

$$\omega = \frac{1}{2}|\mu B|,\ \omega' = \frac{1}{2}|\mu' B'|,\ \ \mu = \mu' \text{ and } \tau = \frac{1}{\varepsilon}$$

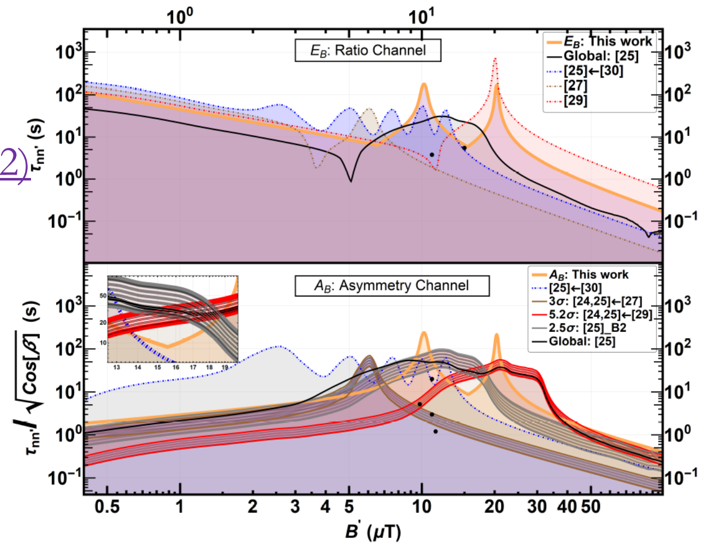


- Near $B \approx B'$ resonance: $\mathrm{P}(n \rightarrow n') \propto \left(\frac{t_{free}}{\tau_{n\rightarrow n'}}\right)^2$. Signal maximum when $\cos\beta = 1$

Berezhiani and Bento *PRL* **96** 081801 (2006), Berezhiani *EPJC* **64** 421 (2009), Berezhiani *EPJC* **72** 1974 (2012)

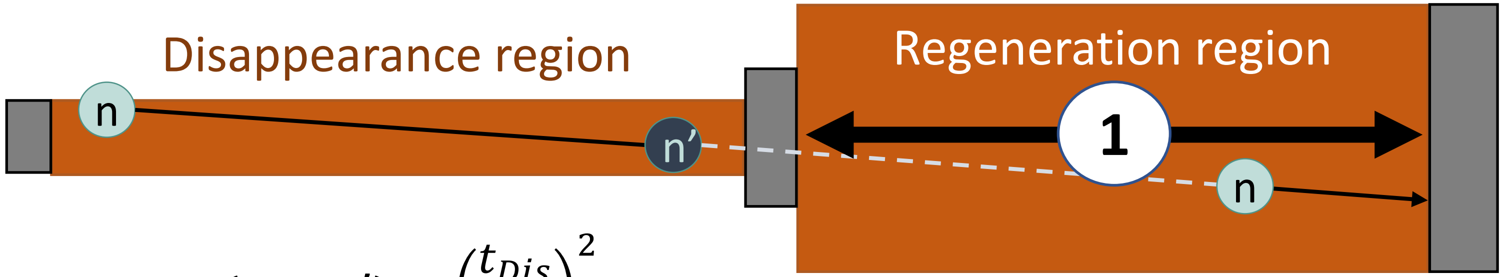
Complementary approaches: UCN vs CN

- Strongest limits from UCN disappearance searches, but some anomalies observed NIMA **611** (2008) 137-140, EPJC **72** (2012) 1974, EPJC 78 (2018) 717, PRD 80 (2009) 032003, PLB 812 (2021) 135993, arXiv:2111.02794
  - P Mohanmurthy talk Thursday
- CN intensities much higher; UCNs=1000's bounces
- CN experiments need long, large area beam tubes; UCN bottles much smaller
- CN robust alternative using "regeneration" technique PRD 96 (2017) 035039
- First regeneration search attempt with 6m flight path: $\tau_{nn'} > 2.7$ s Schmidt 2007

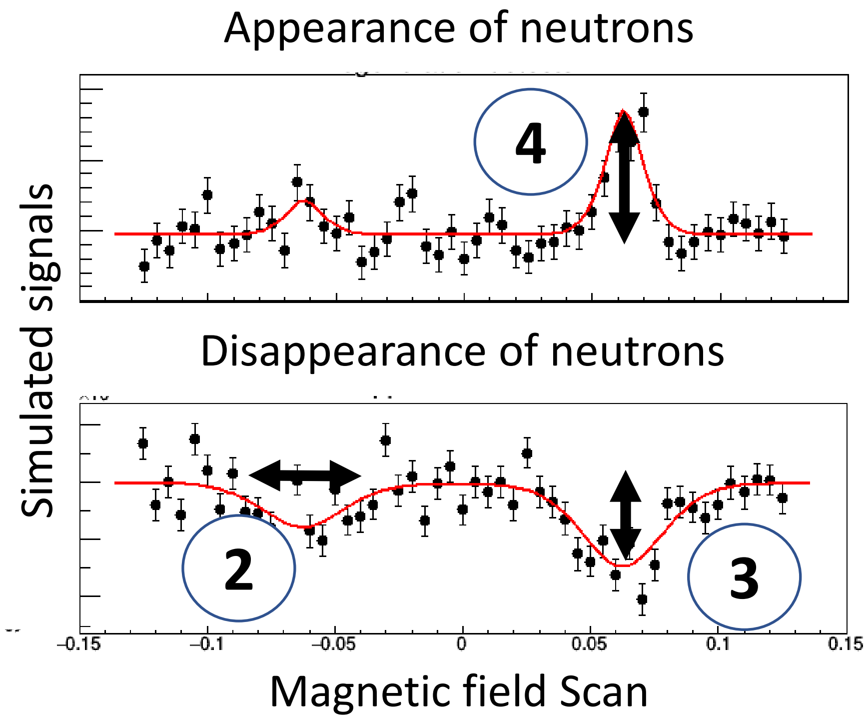


$n \to n' \to n$ Disappearance and Regeneration

$$P(n \to n' \to n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



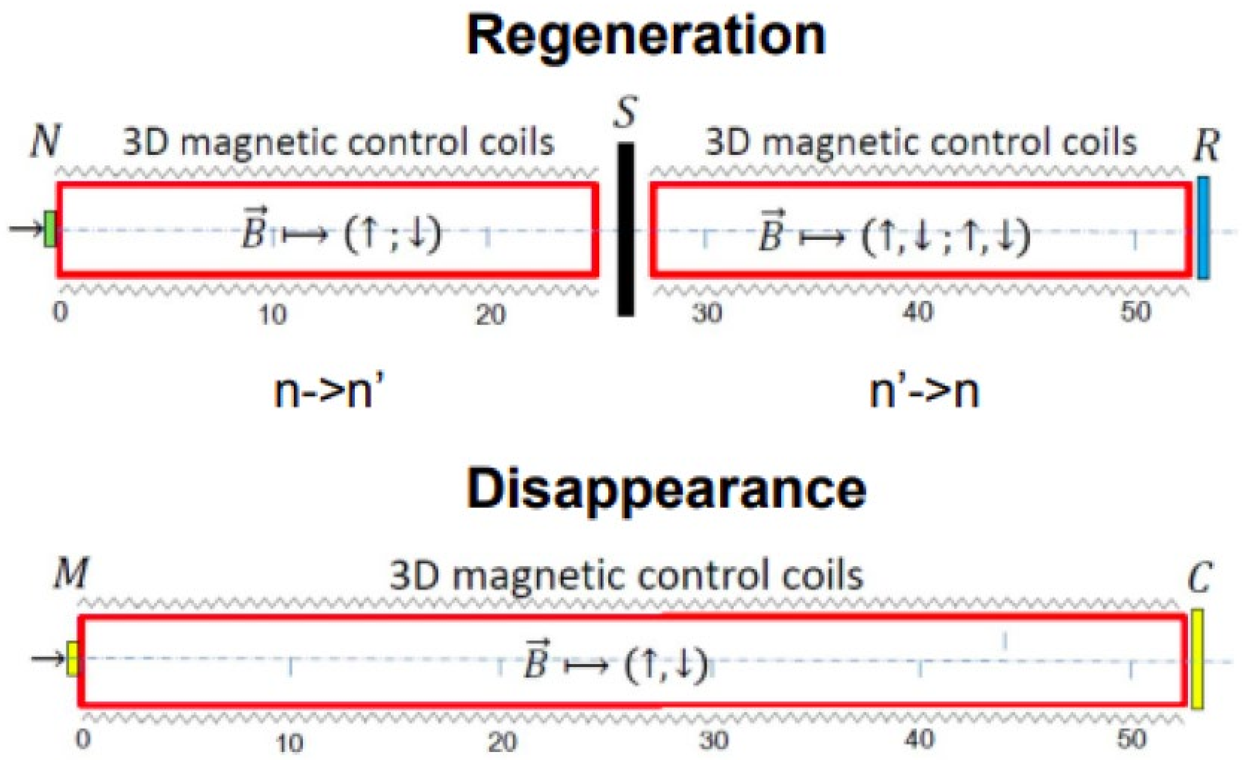
$$P(n \to n') \propto \left(\frac{t_{Dis}}{\tau}\right)^2$$

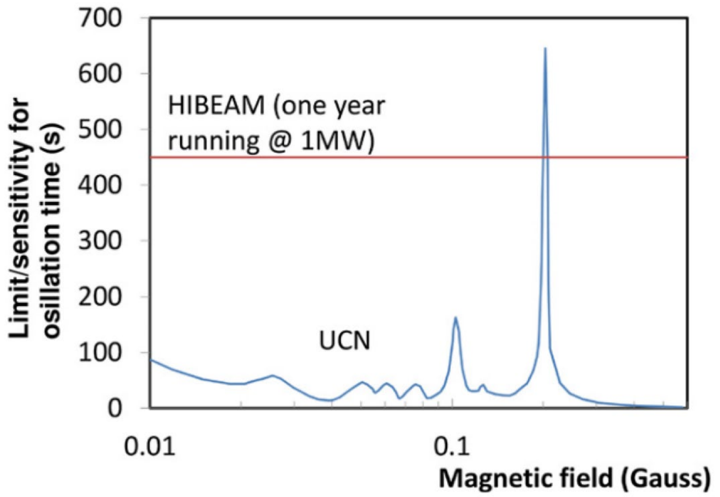


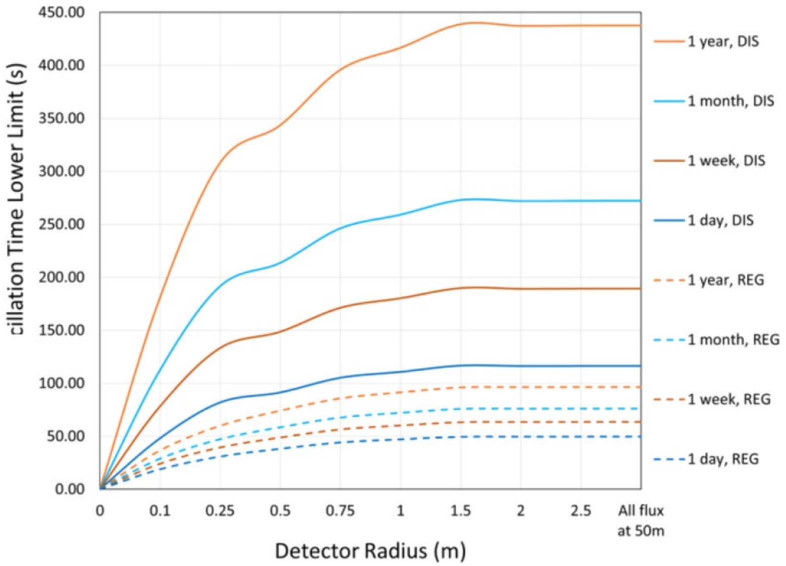
1. High neutron flux + long, large area guides
2. Magnetic field uniformity and control (~mG)
3. Precise monitoring of changes in transmission
4. Regeneration: large area, low bkgd detector

HIBEAM sensitivity to $n \rightarrow n'$

- Assume ESS@1MW, 50m, 1 year operation, 1 n/s bkgd



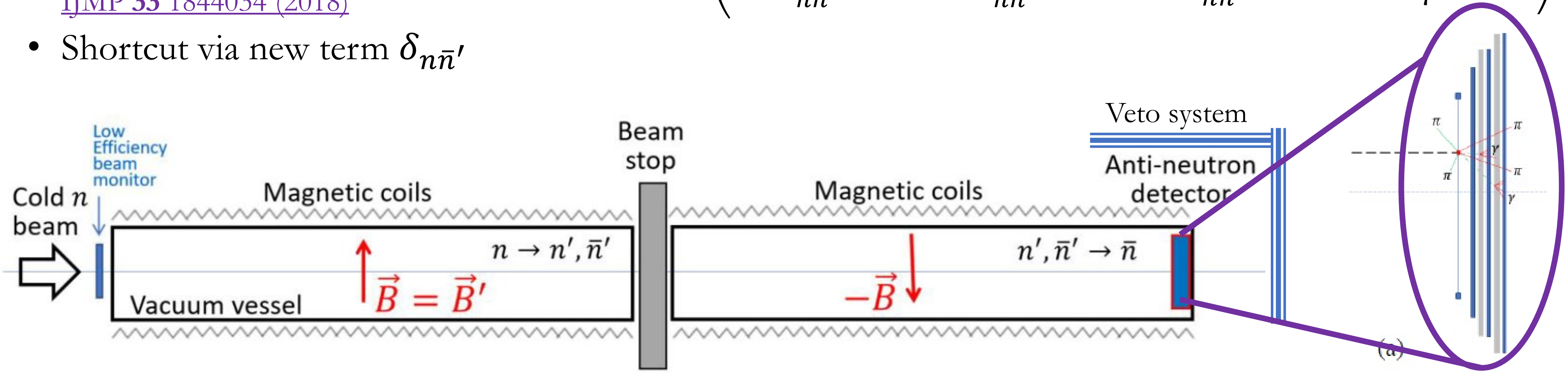




Mirror neutrons and antineutrons

- Straightforward extension of formalism to consider $n \rightarrow \bar{n}, n', \bar{n}'$
- Mirror neutrons provide shortcut for neutron-antineutron oscillations
  [EPJC 81 (2021) 33]
  - Connection to cobaryogenesis
    [IJMP **33** 1844034 (2018)]
  - Shortcut via new term $\delta_{n\bar{n}'}$

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

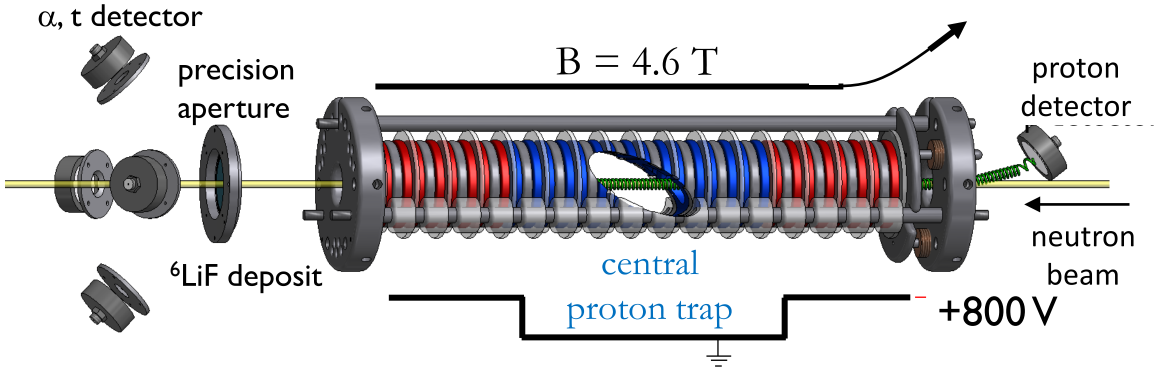


- Staged approach for R&D for new $n \rightarrow \bar{n}$ experiment, similar sensitivity as ILL

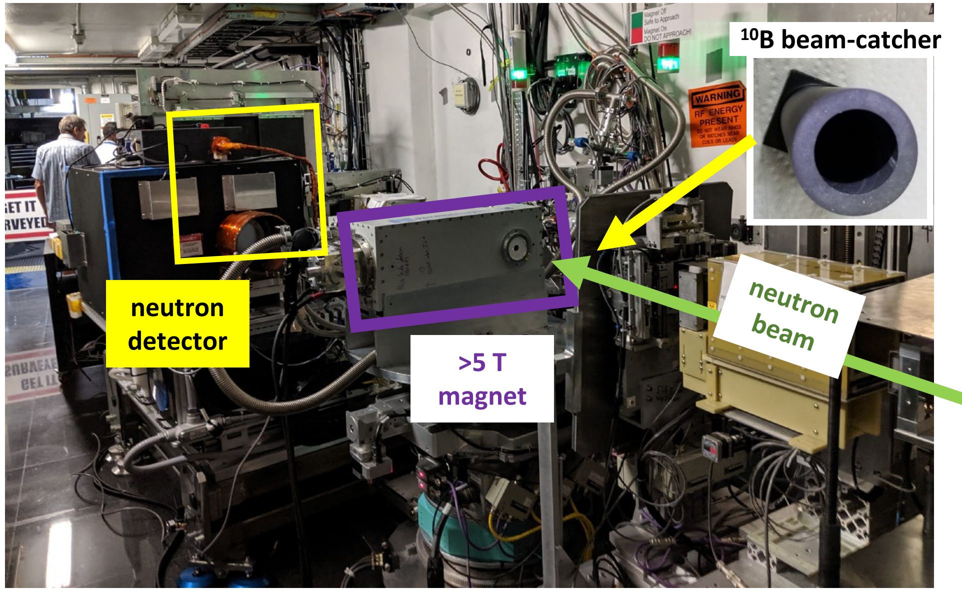
$n \to n'$ at ORNL

- Neutron Lifetime precision improves (see R Pattie talk), but UCN/CN discrepancy unresolved
- Small mass splitting in n, n' could cause a too-high NIST Beam Lifetime result EPJC 79 (2019) 484
- Search conducted at ORNL SNS using neutron scattering instrument MagRef
- Probed full parameter space to confirm/refute explanation PRL 128 (2022) 212503 more sensitive searches in progress (see F Gonzalez talk) arXiv:1710.00767, EPJWebConf 219 (2019) 07002

NIST Beam Lifetime

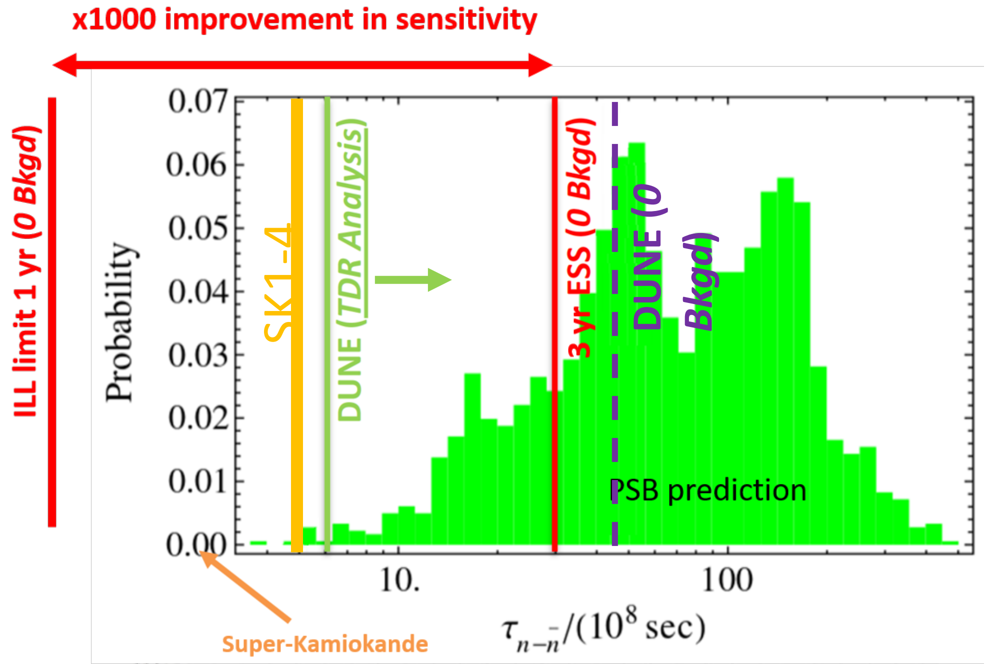


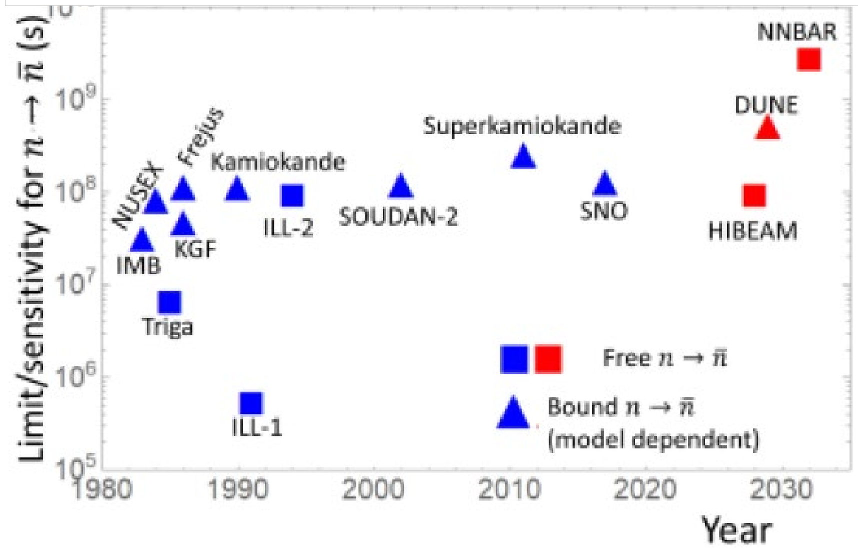
PRC 71 (2005) 055502, PRL 111 (2013) 222501



Outlook for $n \to \bar{n}$

- Green: range predicted by PSB model **PRD 87 115019 (2013)**
- Recent Super-K result **PRD 103 (2021) 012008** approaching that of lower DUNE limit **arXiv:2002.03005**
- NNBAR free neutron search complementary, with discovery potential





Summary

- Searches for Baryon Number Violation is strongly motivated
  - Neutrons are under-explored territory in worldwide BLV program
- Fundamental physics program enabled by investments in Large Beam Port and LD_2 lower moderator optimization
- Searches for $n \to n'$ and $n \to n' \to \bar{n}$ in HIBEAM address BNV and dark matter, enable unique opportunity for early R&D for future high sensitivity search for $n \to \bar{n}$
- NNBAR can produce the world leading limit on $n \to \bar{n}$ oscillations
- Strong interdisciplinary community in nuclear physics, particle physics and neutronics—exciting opportunities ahead!

HIBEAM/NNBAR Collaboration

- 26 institutions in 8 countries signed NNBAR LOI (2015)
- HIBEAM-NNBAR white-paper (J. Phys. G: Nucl. Part. Phys. 48 (2021)) with over 100 authors.
- Conceptual Design Report to be delivered by end of 2023.
- Currently funded by EU grant (EUR 3M), Swedish Research council (total of ~ EUR 1.3M)
- Current focus of the work are simulations and the detector prototype
- Potential for institutions to getting involved (only "in-kind" contributions expected)


arXiv:2006.04907v1 [physics.ins-det] 8 Jun 2020

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P. Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[be], G. Ichikawa[bf], T. M. Ito[ab], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[s], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[l], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,bn], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,av], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[a]Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA, USA
[b]INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy
[c]Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA
[d]Department of Physics, Indiana University, 727 E. Third St., Bloomington, IN, USA, 47405
[e]Indiana University Center for Exploration of Energy & Matter, Bloomington, IN 47408, USA
[f]Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA
[g]Department of Physics, Boston University, Boston, MA 02215, USA
[h]Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China

*Corresponding author: david.milstead@fysik.su.se

Preprint submitted to Elsevier June 11, 2020