Experimental Searches for $n \to \bar{n}$ Oscillations

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Snowmass Community Planning Meeting

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European Spallation Source, Lund, Sweden: Construction 70% Completed

Violation of Baryon Number *B*

- B, L are accidental symmetries
  - Violated at non-perturbative level
  - $B - L$ conserved in the SM
- BNV could explain BAU

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

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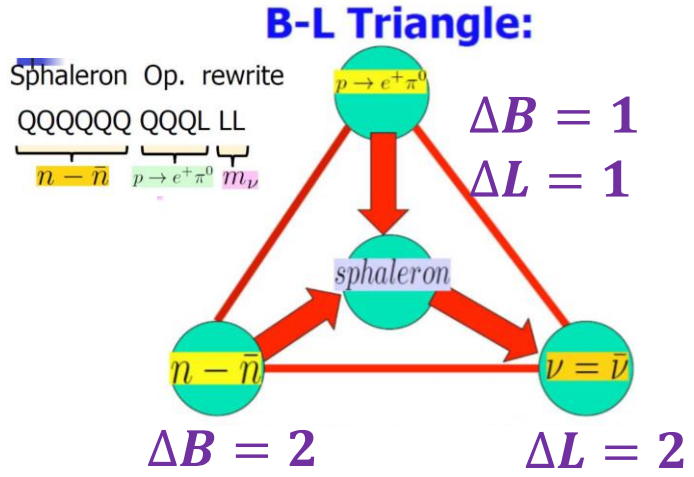
- Target $\boldsymbol{\Delta B \neq 0\ \&\ \Delta[B-L] \neq 0}$
- $n \to \bar{n}$ attractive to pursue
  - Cleaner approach than dinucleon decays
  - B-L violation: avoid "washing out" B-asymmetry by sphalerons

- Complementary approaches: proton decay, 0νββ, $n \to \bar{n}$ /dinucleon decay



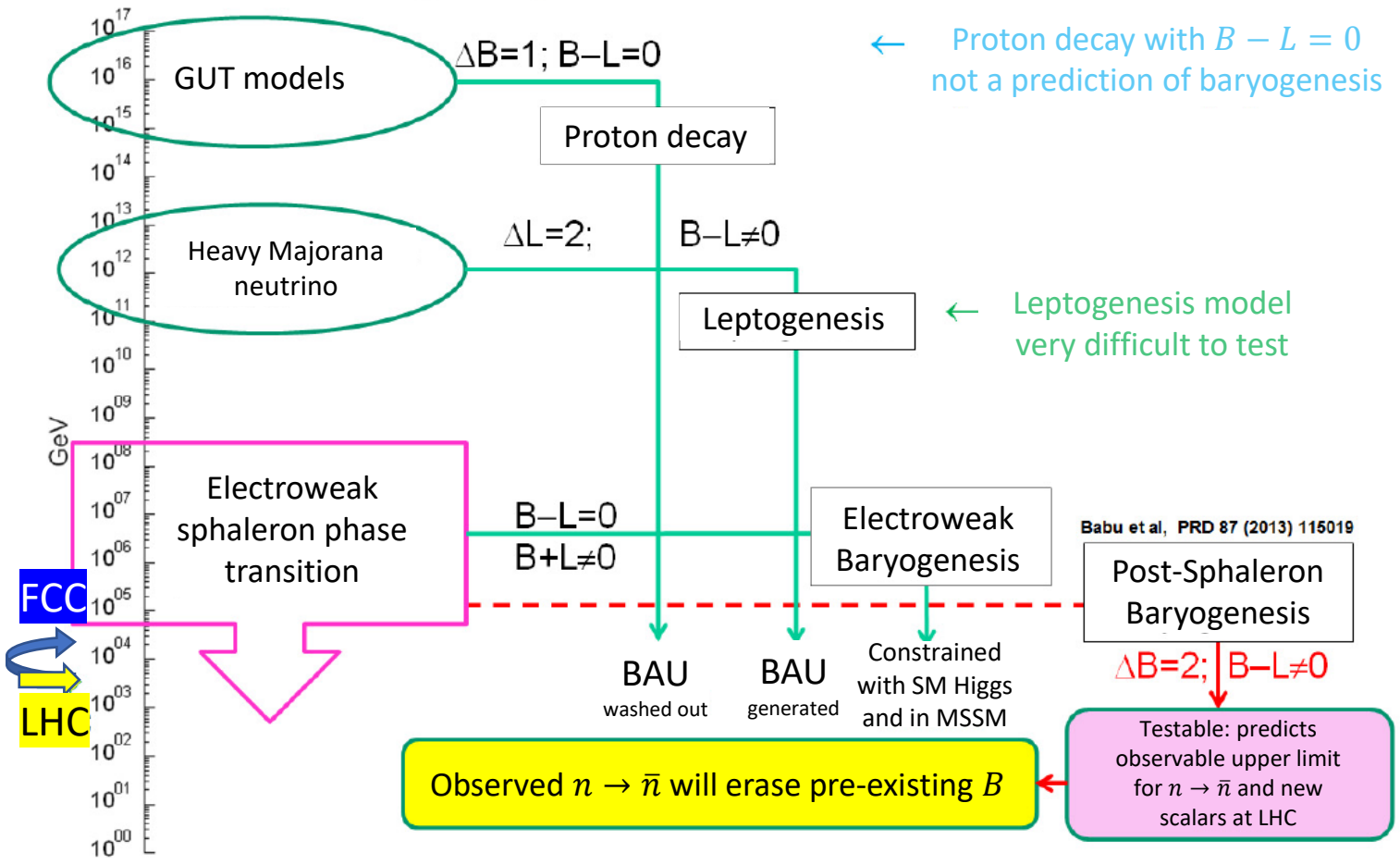
from R. Mohapatra

- Symbiosis with 0νββ: L-R unification theories predict both.
- Neutron oscillations under-explored!

x1000 improvement in sensitivity to $n \to \bar{n}$ on horizon

Baryogenesis models

- Regimes for baryogenesis
  - Leptogenesis: Sphalerons convert L into B
  - Electroweak baryogenesis: T violation near EW scale creates B without L
  - Post-sphaleron baryogenesis: New BNV process below EW phase transition PRD **87** 115019 (2013)
- $n \to \bar{n}$ targets accessible energy scales
  - null result can rule out e.g. PSB



from Y. Kamyshkov

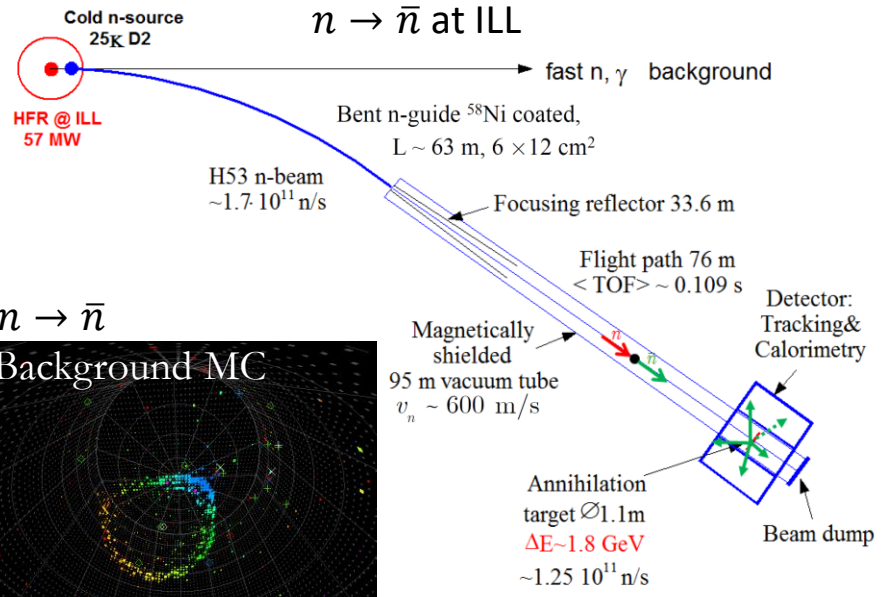
$n \to \bar{n}$: Timely Opportunities

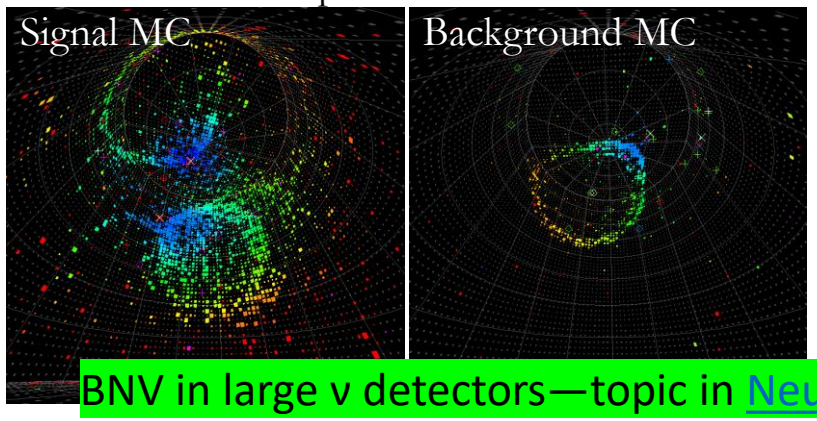
- $n \to \bar{n}$ impacts understanding of BAU without need for additional interpretation
- Strong cross-disciplinary worldwide community support for $n \to \bar{n}$ program
- Opportunities in DUNE and ESS: requires action
  - Possibility to improve free search sensitivity by x1000
  - Complementarity: various models predict different relative strengths for bound vs free $n \to \bar{n}$
- Program of development in last decade and next
  - Bound neutrons: improving analysis and understanding uncertainties in a DUNE search
  - ORNL program—near term activities for $n \to \bar{n}$ R&D with complementary science goals
  - $3M Horizon 2020 EU project for a design study for $n \to \bar{n}$ activities at ESS
- ACFI workshop explored opportunities for ΔB=2 searches (workshop page, indico)
  - Workshop report: arXiv:2010.02299
  - Snowmass LOI on $\Delta B = 2$ physics

Status of $n \to \bar{n}$ Searches

- Free and intranuclear searches: $P_{n\to\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\to\bar{n}}}\right)^2$
  - Free: Figure of merit (zero background): Nt^2
  - Intranuclear: nuclear suppression $\Delta t \approx \hbar/E_{binding} \sim 5 \times 10^{-22}$ s
- Last free neutron search at ILL ZPC **63** (1994) 409-416
  - 0 candidate events, 0 backgrounds, $\tau_{n\to\bar{n}} > 0.86 \times 10^8$ s
  - Major advances in neutronics and detector technology since
- Best published limits from SuperKamiokande PRD **91** (2015) 072006
  - 24 candidate events, 24.1 expected background events
  - T>1.9 x 10^{32} years; R= 0.517×10^{23}/ s; $\tau > 2.7 \times 10^8$ s
- Preliminary SK-I/II/III/IV result:
  - L. Wan, ACFI $\Delta B = 2$ workshop (2020)
  - 11 candidate events, 9.3 expected backgrounds
  - 3.6x10^{32} years at 90% C.L, $\tau > 4.7 \times 10^8$ s
  - Next: tackle neutron multiplicity (SK-Gd)
  - Hyper-K: further study needed on systematics

Nucleus	Experiment	n · year (10^{32})	$\tau_{n\to\bar{n}}$ (10^8 s)
16O	SK-I (2015)	1.9	2.7
16O	Kamikande (1986)	0.4	1.6
2H	SNO (2017)	0.1	1.4
56Fe	Soudan II (2002)	0.7	1.3
56Fe	Frejus (1990)	0.7	1.2
16O	IMB (1984)	0.2	1.2
free n	ILL (1994)	—	0.9

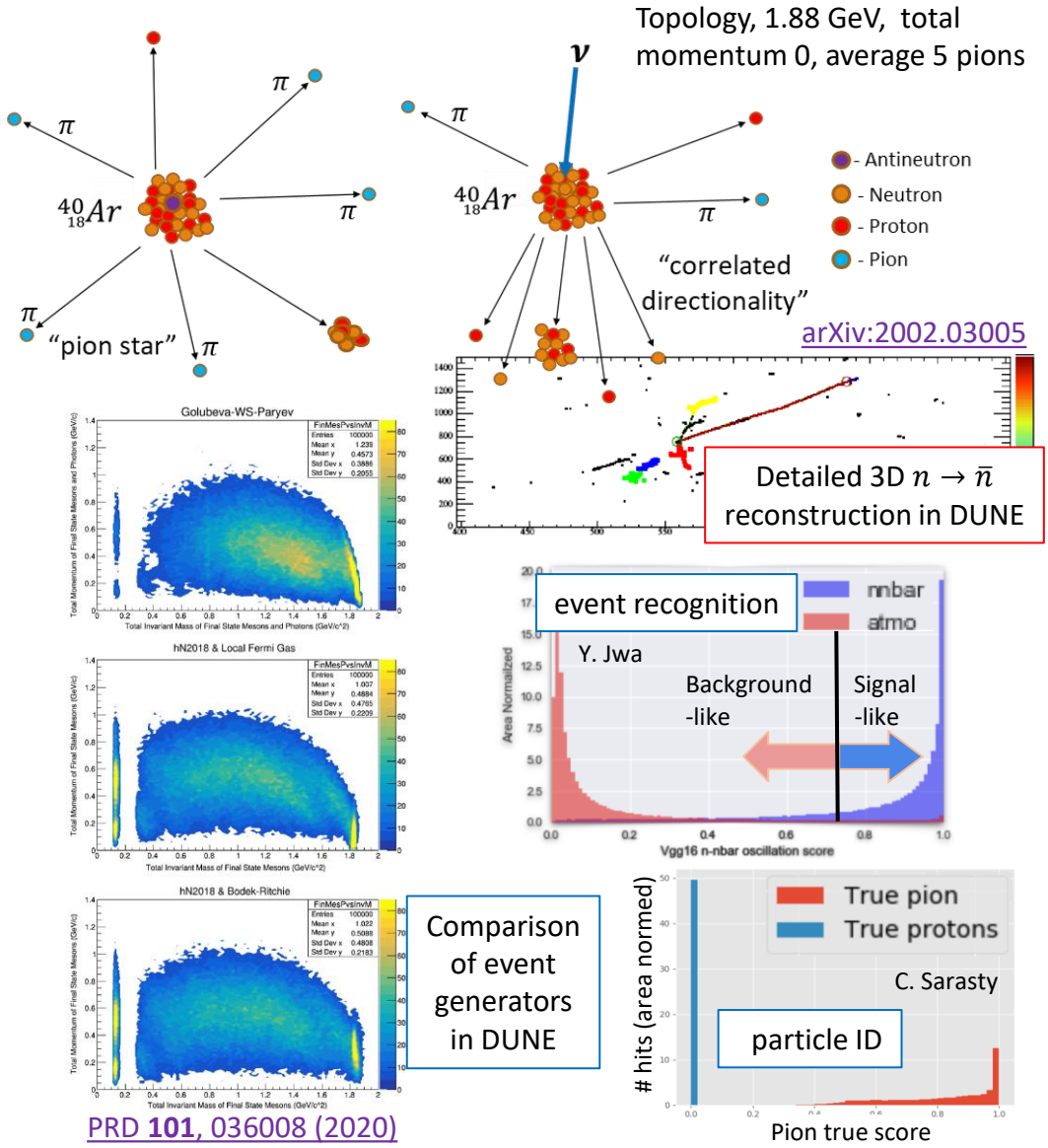




BNV in large ν detectors—topic in Neutrino Frontier, NF03: BSM

Intranuclear $n \to \bar{n}$ Searches in DUNE

- Deep Underground Neutrino Experiment Far Detector: large mass LArTPC
  - Offer lower KE threshold (e.g. protons), higher resolution, bubble chamber-like images, PID & dE/dx capabilities
  - Significant reduction in background rejection rate possible over Super K
  - Expected reach: $\tau_{n\to\bar{n}} > 5.53 \times 10^8$ s
- Improvements in DUNE analysis can further enhance sensitivity
  - Signal and background modeling—study impact of nuclear model configuration on uncertainties
  - Background rejection, event reconstruction and event recognition: BDT with CNN input
  - Promising developments in particle identification
- LOI on $n \to \bar{n}$ at DUNE

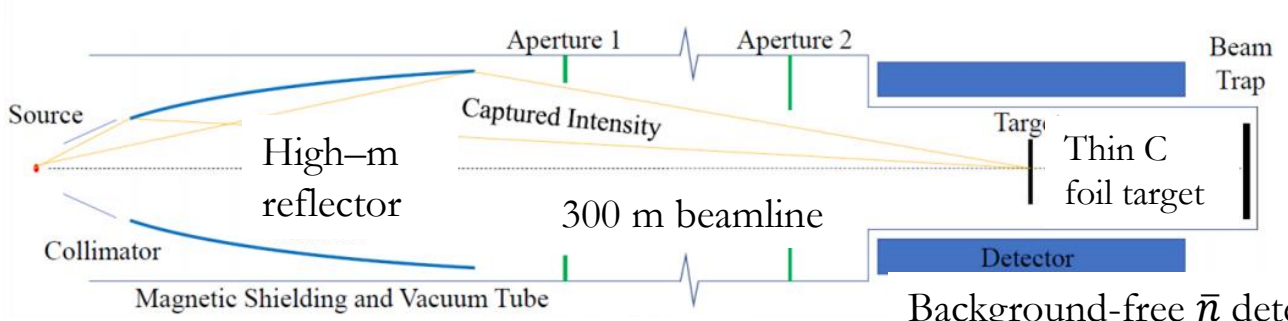


NNBAR: Free Search for $n \to \bar{n}$

- NNBAR: Leverage 3 decades of advances: moderator design, neutronics, detection, reconstruction techniques ×**1000** sensitivity of ILL arXiv:2006.04907
  - Collaboration: 26 institutions across 8 countries
- European Spallation Source (5MW in 2030+): Large Beam Port constructed specifically for NNBAR
  - NNBAR highlighted in Monday plenary on European Strategy
- HighNESS (3M€ EU grant): moderator study, $\bar{n}$ detector prototyping, CDR for upgrade of the ESS including NNBAR beamline+experiment
- Staged program ORNL – HIBEAM - NNBAR

LOI on NNBAR

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		**≥ 1000**



Background-free $\bar{n}$ detector

"The Large Beam Port is an opportunity to broaden the ESS mission"

Rikard Linander, Head of the ESS Target Division

R&D for NNBAR

- Detector prototyping; improved neutronics; novel concepts ("phase non-reset" PRL **122** (2019) 221802) to reduce complexity of experiment
- Access complementary physics: neutron portal to dark sector $n \to n' \to n$ PRL **96** (2006) 081801
- $n \to n'$ searches with ultracold neutrons PLB **663** (2008) 181, NIMA **611** (2009) 137, PRL **99** (2007) 161603, PRD **80** (2009) 032003
  - Some anomalous signals reported! EPJC **72** (2012) 1974, EPJC **78** (2018) 717
- Possible connection to 4σ neutron lifetime anomaly EPJC **79**, 484 (2019); MDPI Physics **1**, 271 (2019)
- Possible mixing of sterile/antipartners ($n \to n' \to \bar{n}$) offer opportunities for NNBar R&D arXiv:2002.05609
- Use existing BES facilities at ORNL: first experiment completed at SNS & in analysis, now characterizing HFIR beamline for second experiment EPJ Web Conf **219**, 07002 (2019)
- Improved sensitivity at ANNI/HIBEAM @ESS arXiv:2006.04907

LOI on $n \to n'$ searches, submitted to RF6 Dark Sector

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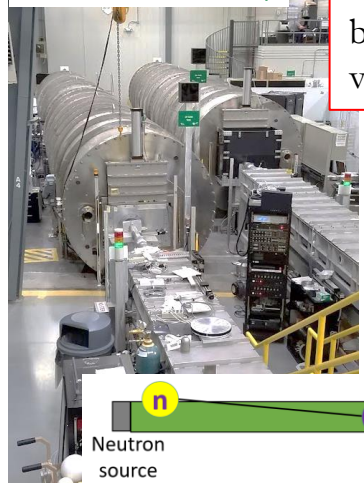
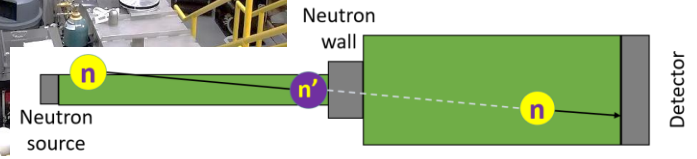


ONGOING:
20m+15m long beamline + low background detectors available via ORNL User Program

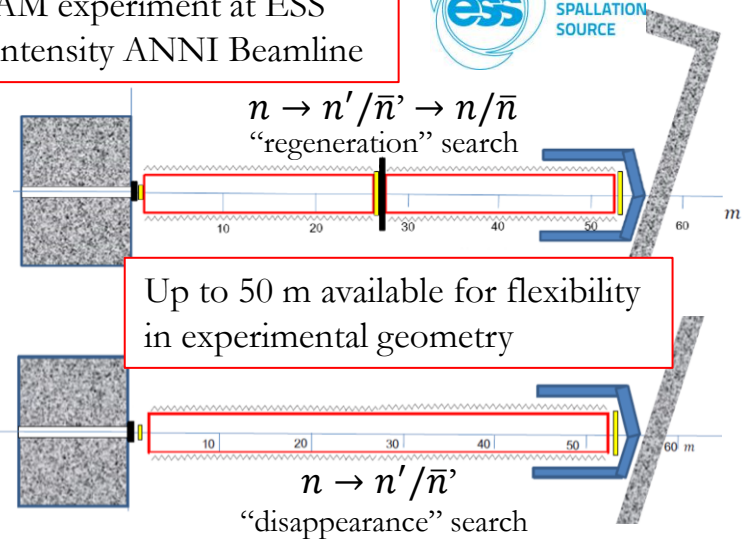
Now planning for HFIR upgrade!



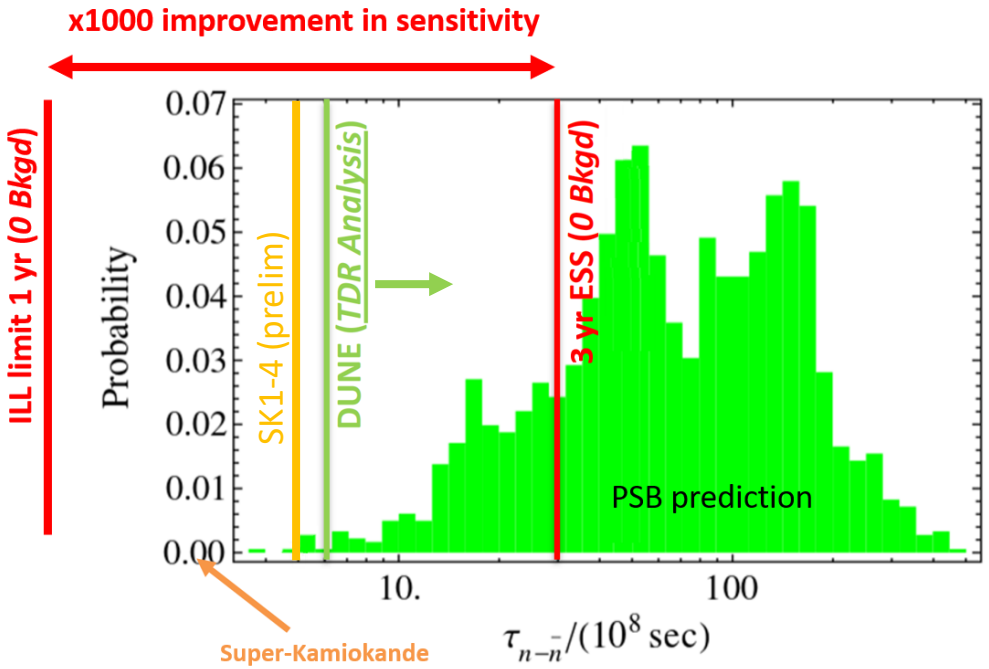
Shining neutrons through a wall

2023 – 2027:
HIBEAM experiment at ESS lower intensity ANNI Beamline

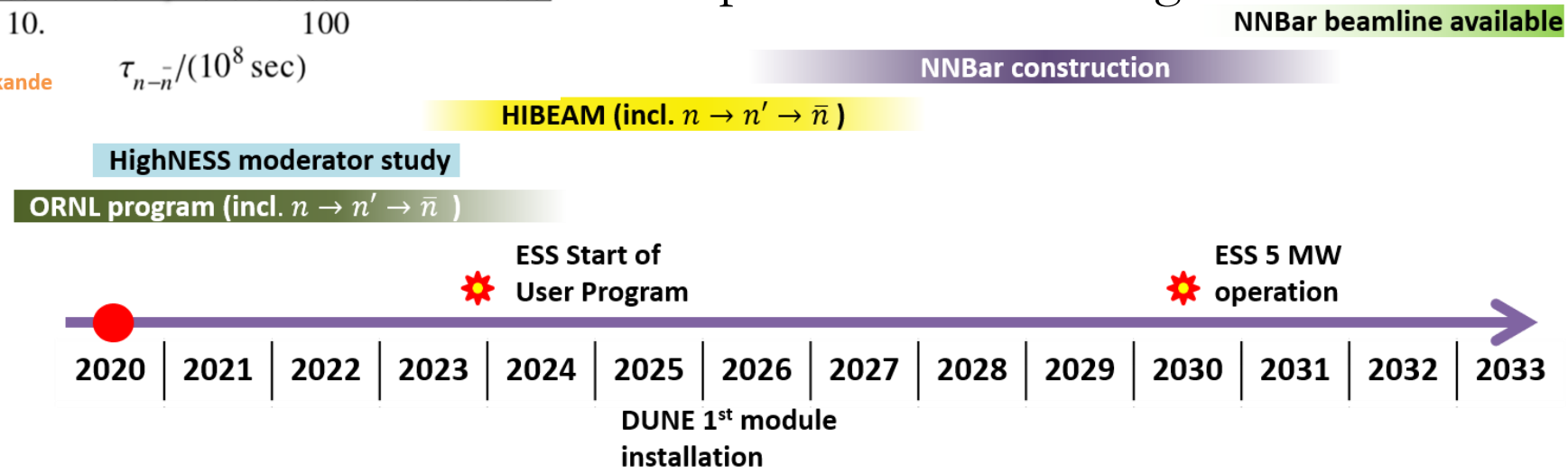
EUROPEAN SPALLATION SOURCE



Outlook



- Green: range predicted by Post Sphaleron Baryogenesis model PRD 87 115019 (2013)
- Recent preliminary Super-K result L. Wan, ACFI $\Delta B = 2$ workshop (2020) approaching that of lower DUNE limit arXiv:2002.03005
- Free neutron search complementary and competitive—zero backgrounds arXiv:2006.04907



Summary

- Searches for Baryon Number Violation strongly motivated
  - Neutron oscillations access underexplored space in worldwide program
  - Resolution of questions on baryon asymmetry of universe, alternate models of dark matter
- Strong limits from complementary approaches: free and bound neutron searches
  - Activity ongoing with preliminary results from SK and R&D towards NNBar
- Future large detectors like DUNE represent great opportunity
  - Goal to aggressively push down backgrounds, promising analysis developments on horizon
- Mature concept for large scale free search in NNBar at ESS
  - Large Beam Port now constructed; investigation of experiment implementation underway
  - Staged program beginning at ORNL can pave the path to a successful BNV program
- Strong interdisciplinary community in nuclear physics and neutronics—timely opportunities for US HEP leadership!

- LOI's: $\Delta B = 2$, DUNE, NNBAR, $n \to n'$