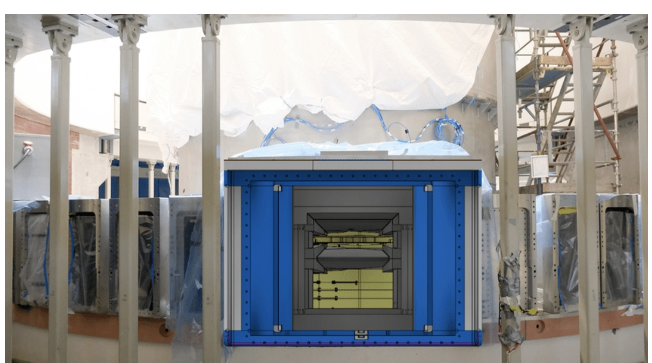
HIBEAM Project Status

Bernhard Meirose
(on behalf of the HIBEAM-NNBAR Collaboration)

A bit of history

- HIBEAM: first stage of HIBEAM-NNBAR program
- NNBAR itself goes back many years (~ 2015 LOI)
- Driven by:
  1) unprecedented free neutron flux (ESS);
  2) advancements in neutronics;
  3) Large beam port (4M SEK investment by ESS);
  4) long beamline availability
- HIBEAM (since ~ 2017): unique magnetically controlled fundamental physics beamline
- First n → nbar search for >30 years
  + range of other activities



EUROPEAN SPALLATION SOURCE

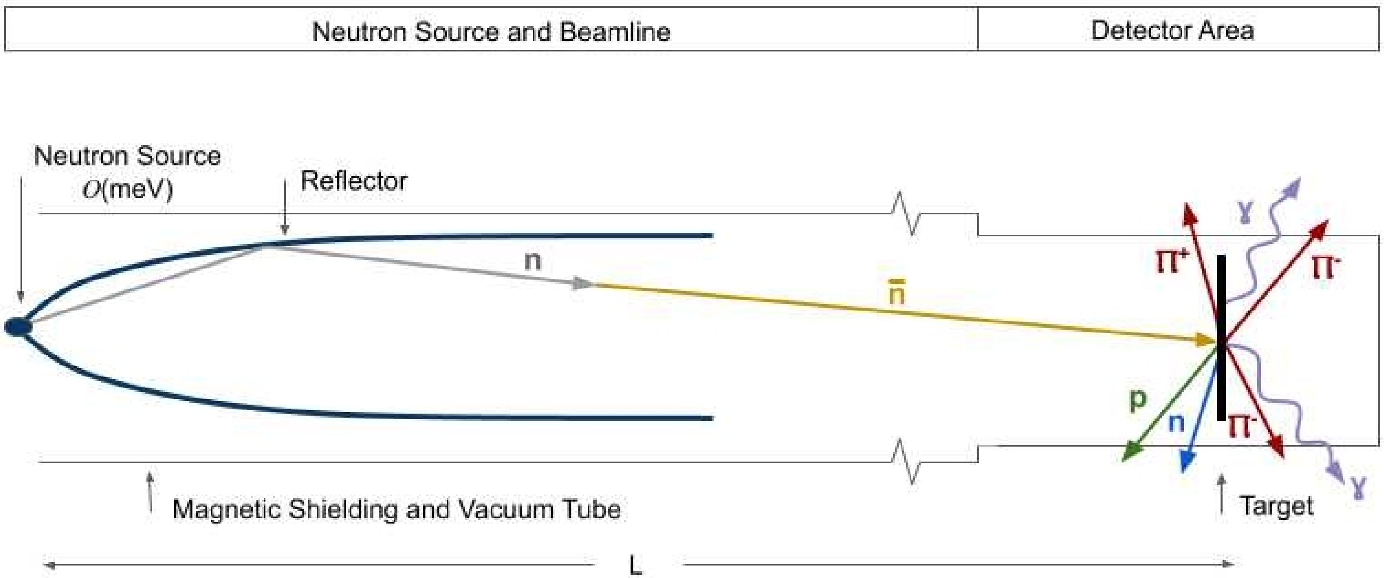
2014/2015 Round   Instrument Construction Proposal
Revision Date   25/04/2019

	Name	Affiliation
Main proposer	Gustaaf Brooijmans	Columbia University
Co-proposers	David Baxter	Indiana University
	Lorenzo Calibbi	Université Libre de Bruxelles
	Luis Castellanos	University of Tennessee
	Joakim Cederkäll	Lund University
	Brian Cole	Columbia University
	Gabriele Ferretti	Chalmers University of Technology
	Peter Fierlinger	TU Munich
	Matthew Frost	University of Tennessee
	Franz Gallmeier	University of Tennessee, Oak Ridge National Laboratory
	Kenneth Ganezer	California State University Dominguez Hills
	Richard Hall-Wilton	ESS
	Lawrence Heilbronn	University of Tennessee
	Go Ishikawa	Nagoya University
	Tord Johansson	Uppsala University
	Leif Jönsson	Lund University
	Yuri Kamyshkov	University of Tennessee
	Masaaki Kitaguchi	Nagoya University
	Esben Klinkby	ESS
	Mats Lindroos	ESS
	Bernhard Meirose	University of Texas Dallas
	David Milstead	Stockholm University
	Rabindra Mohapatra	University of Maryland
	Thomas Nilsson	Chalmers University of Technology
	Anders Oskarsson	Lund University
	Robert Pattie	Los Alamos National Laboratory
	Christoffer Petersson	Chalmers University of Technology
	David Phillips	North Carolina State University
	Amlan Ray	VECC, Kolkata, India
	Filippo Resnati	CERN
	Arthur Ruggles	University of Tennessee
	Utpal Sarkar	Physical Research Laboratory, Ahmedabad, India
	Alexander Saunders	Los Alamos National Laboratory
	Hirohiko M. Shimizu	Nagoya University
	Robert Shrock	Stony Brook University
	Samuel Silverstein	Stockholm University
	Camille Theroine	ESS
	Lawrence Townsend	University of Tennessee
	Rick Van Kooten	Indiana University
	Albert Young	North Carolina State University
ESS coordinator	Camille Theroine	ESS

NNBAR

Why neutron oscillations?

- Baryon number violation (BNV) only process
- BN conservation is accidental symmetry of the SM (broken in extensions)
- BNV is most obvious condition for baryogenesis
- Last free neutron experiment at ILL in the 90's ($\tau > 8.7\ 10^{7}$s)
- NNBAR: ~10^3× ILL sensitivity
- HIBEAM: ~10× ILL sensitivity (after new neutron optics simulations)



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

FOM= Nt^2

European Spallation Source (ESS)

EUROPEAN SPALLATION SOURCE

- Will be most powerful spallation neutron source
- Place: Lund, Sweden
- Under construction: start of user program in 2027

NNBAR Conceptual Design Report

Journal of Neutron Research 25 (2023) 315–406
DOI 10.3233/JNR-230951
IOS Press

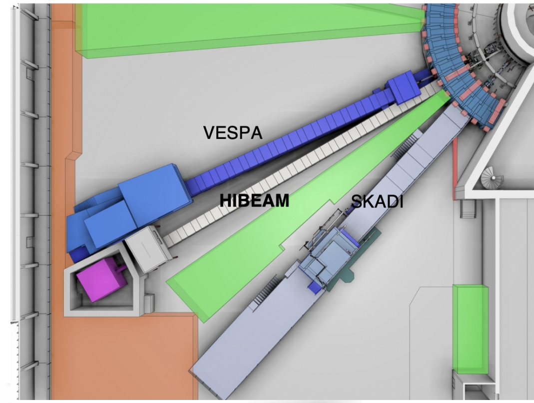
HighNESS conceptual design report: Volume II. The NNBAR experiment.

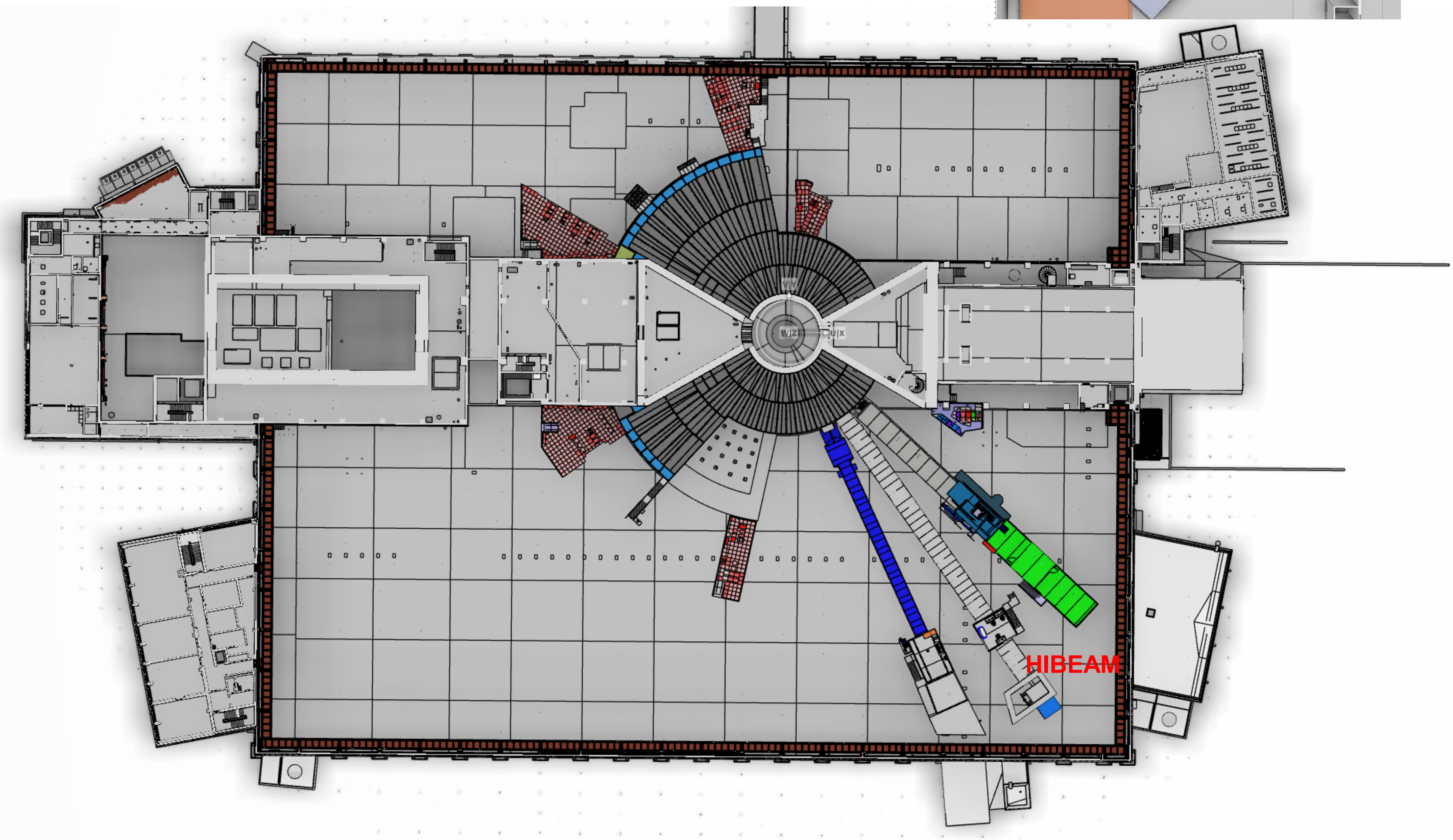
V. Santoro[a,b,*], O. Abou El Kheir[c], D. Acharya[c], M. Akhyani[d], K.H. Andersen[e], J. Barrow[f,g], P. Bentley[a], M. Bernasconi[c], M. Bertelsen[a], Y. Beßler[h], A. Bianchi[a], G. Brooijmans[i], L. Broussard[e], T. Brys[a], M. Busi[j], D. Campi[c], A. Chambon[k], J. Chen[h], V. Czamler[l], P. Deen[a], D.D. DiJulio[a], E. Dian[m,n], L. Draskovits[n], K. Dunne[o], M. El Barbari[h], M.J. Ferreira[a], P. Fierlinger[p], V.T. Fröst[q], B.T. Folsom[a,c], U. Friman-Gayer[a], A. Gaye[a], G. Gorini[c], A. Gustafsson[q], T. Gutberlet[h], C. Happe[h], X. Han[r,s,t], M. Hartl[a], M. Holl[a], A. Jackson[a], E. Kemp[u], Y. Kamyshkov[v], T. Kittelmann[a], E.B. Klinkby[k], R. Kolevatov[w], S.I. Laporte[c], B. Lauritzen[k], W. Lejon[o], R. Linander[a], M. Lindroos[a], M. Marko[n], J.I. Márquez Damián[a], T.C. McClanahan[e], B. Meirose[o,b], F. Mezei[m], K. Michel[a], D. Milstead[o], G. Muhrer[a], A. Nepomuceno[x], V. Neshvizhevsky[l], T. Nilsson[y], U. Odén[a], T. Plivelic[z], K. Ramic[a], B. Rataj[a,b], I. Remec[e], N. Rizzi[k], J. Rogers[v], E. Rosenthal[h], L. Rosta[n], U. Rücker[h], S. Samothrakitis[j], A. Schreyer[aa], J.R. Selknaes[a], H. Shuai[m], S. Silverstein[o], W.M. Snow[ab], M. Strobl[j], M. Strothmann[h], A. Takibayev[a], R. Wagner[l], P. Willendrup[a,k], S. Xu[a], S.C. Yiu[o], L. Yngwe[q], A.R. Young[ac], M. Wolke[ad], P. Zakalek[h], L. Zavorka[e], L. Zanini[a] and O. Zimmer[l]

Neutron Res. 25 (2024) 3-4, 315-406

Funded by EU: H2020 – 3MEuro HighNESS project

HIBEAM





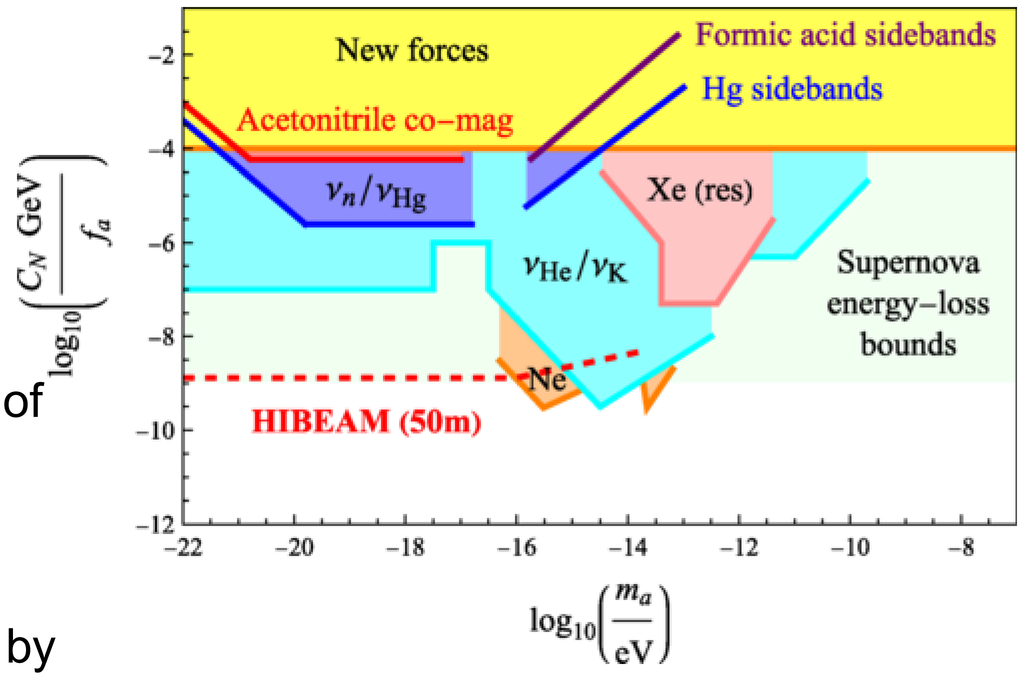
Why HIBEAM?

- Open a new intensity frontier in particle physics
- Magnetically-controlled beamline: searches for rare or forbidden processes
- neutron ↔ antineutron conversions, sterile neutrons, axions, exotic neutron decays
- Only facility worldwide with required neutron flux, propagation length, and magnetic control for these measurements
- First fully Swedish-led ESS instrument — fills a gap in Sweden’s ESS leadership

Physics Program
(beyond neutron-antineutron conversions)

Searches for Ultralight Axion Dark Matter in HIBEAM

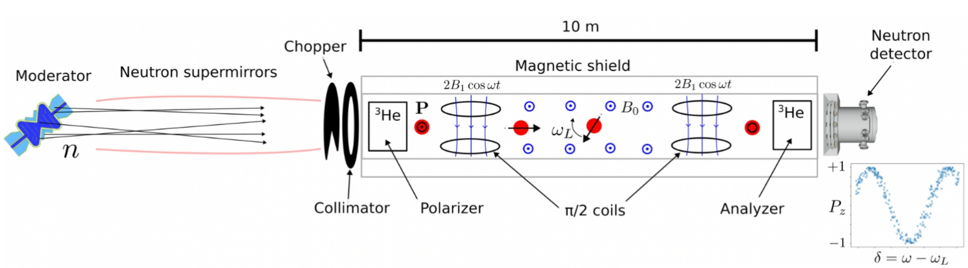
- HIBEAM can search for ultralight axion dark matter (using "short-HIBEAM (~ 10 m))
- Unlike photon-based axion searches, HIBEAM probes the axion–neutron spin coupling.
- axion field creates time-dependent modulation of the Larmor frequency
- This shows up as a shift in the central Ramsey fringe, which oscillates in time
- HIBEAM improves sensitivity to sub-eV axions by 2–3 orders of magnitude over existing laboratory magnetometry.
- One year of running already provides competitive constraints, complementary to astrophysical limits.



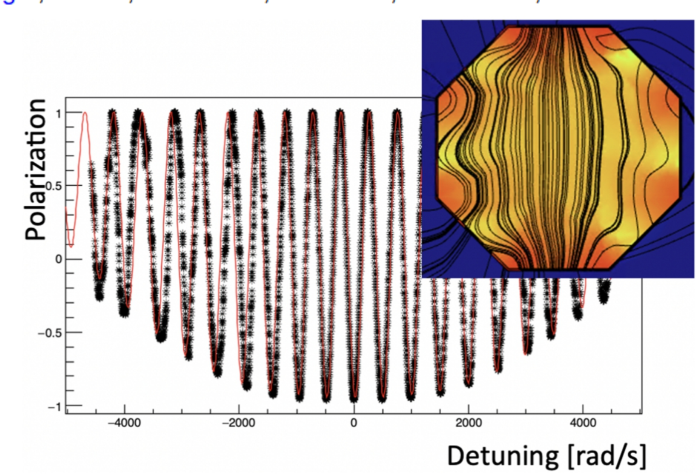
PHYSICAL REVIEW LETTERS **133,** 181001 (2024)

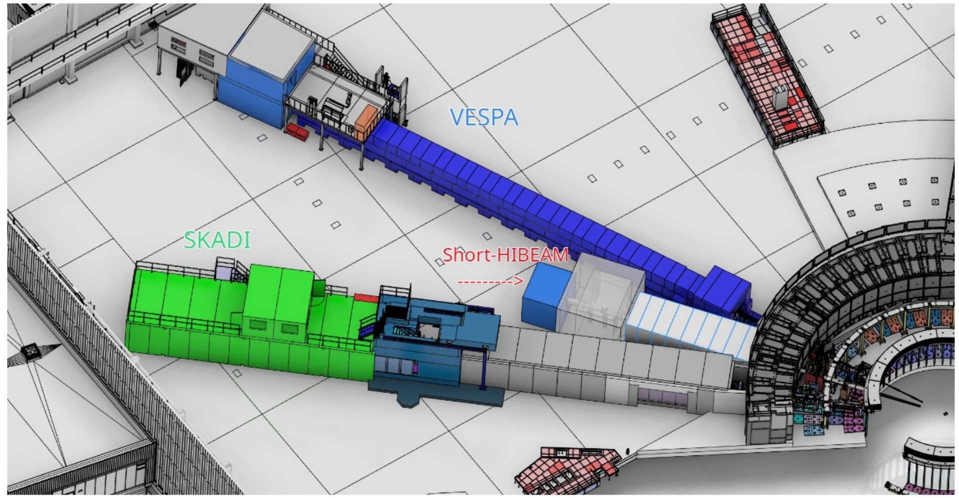
Proposal for a Ramsey Neutron-Beam Experiment to Search for Ultralight Axion Dark Matter at the European Spallation Source

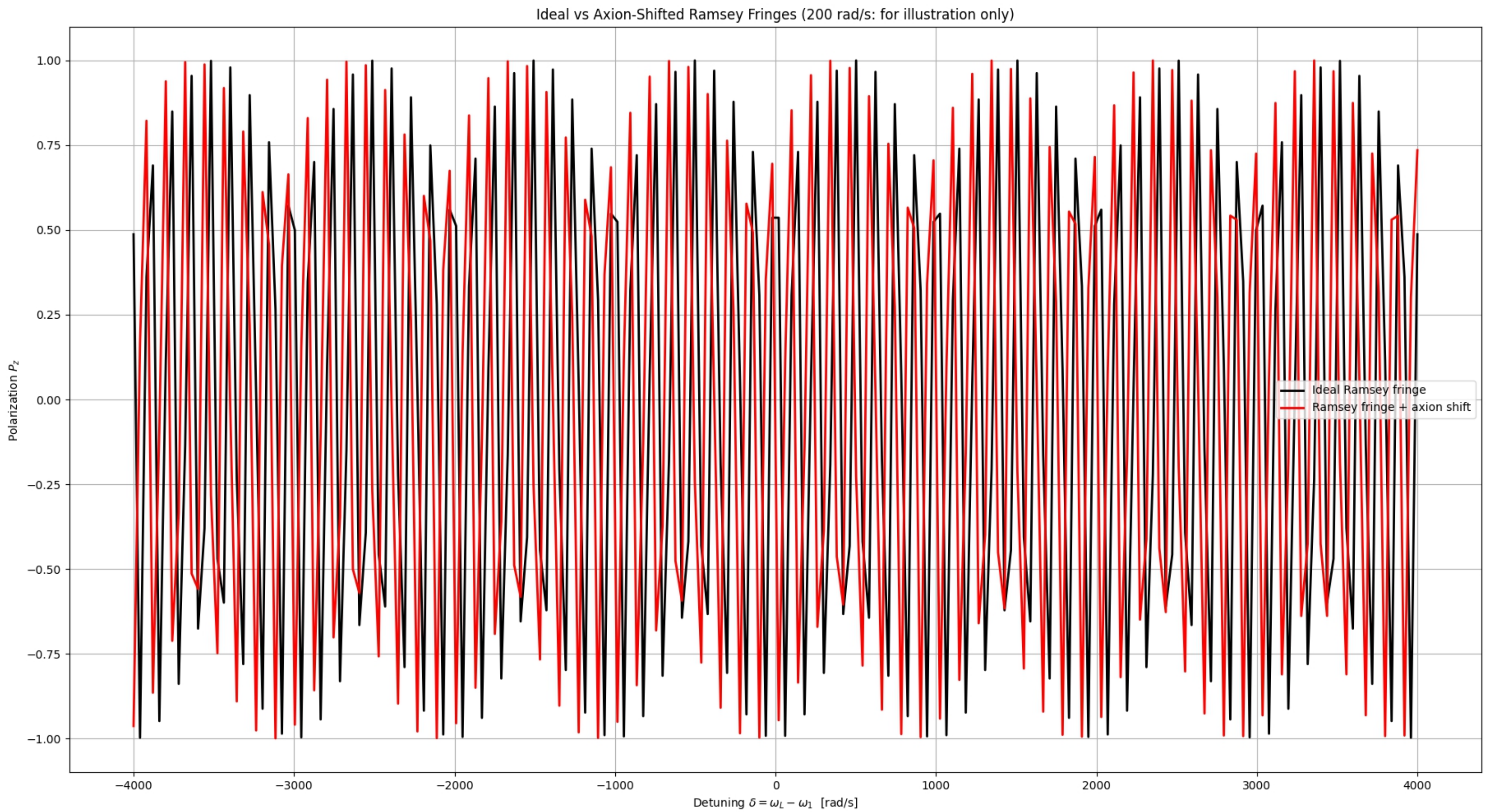
P. Fierlinger, M. Holl, D. Milstead, V. Santoro, W. M. Snow, Y. V. Stadnik



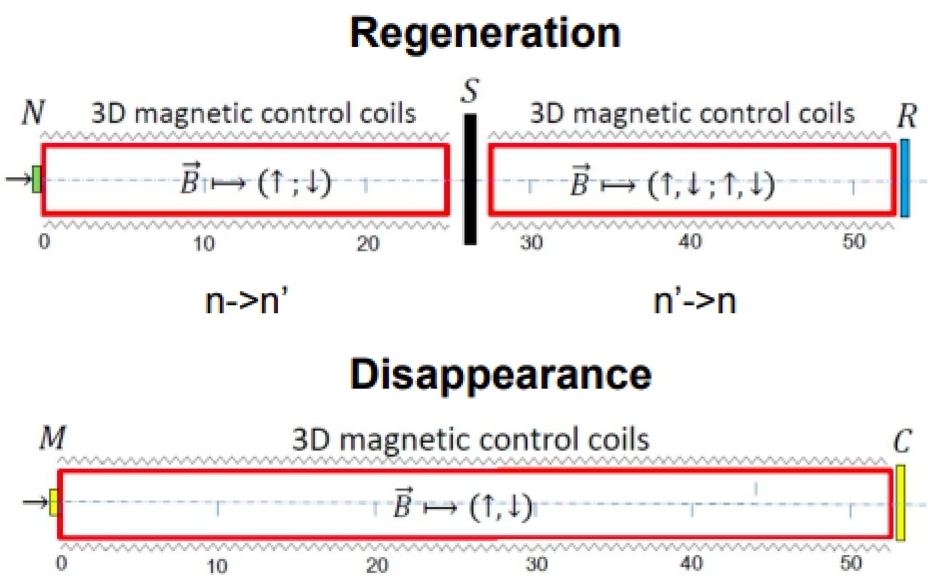
$$P_z(\omega_L, \omega_1) = \frac{1}{2}\left[1 \pm \cos\left(\left(\underbrace{\omega_L - \omega_1}_{\text{detuning}} + \underbrace{\Delta\omega_{\text{ax}}(t_{\text{meas}}, B)}_{\text{axion shift}}\right)T\right)\right]$$




VESPA
SKADI
Short-HIBEAM
------->


Ideal vs Axion-Shifted Ramsey Fringes (200 rad/s: for illustration only)
Polarization P_z
Detuning $\delta = \omega_L - \omega_1$ [rad/s]
Ideal Ramsey fringe
Ramsey fringe + axion shift
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−4000
−3000
−2000
−1000
0
1000
2000
3000
4000

HIBEAM discovery sensitivity



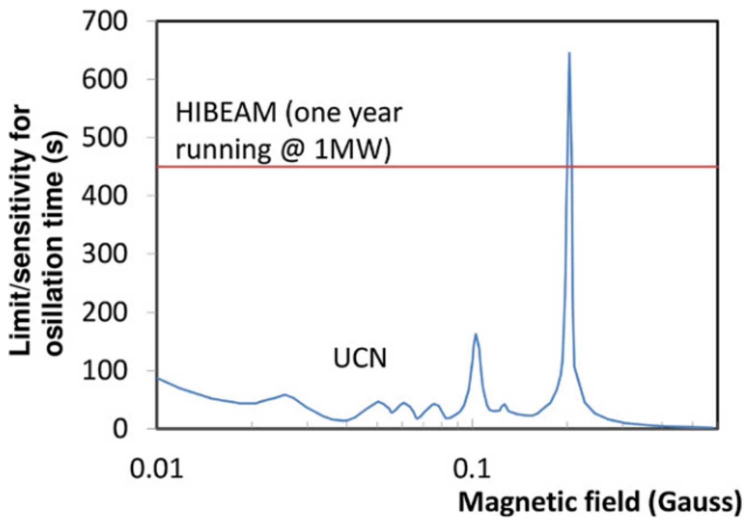


Figure 22. Excluded neutron oscillation times in blue for $n \to n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power of 1 MW.

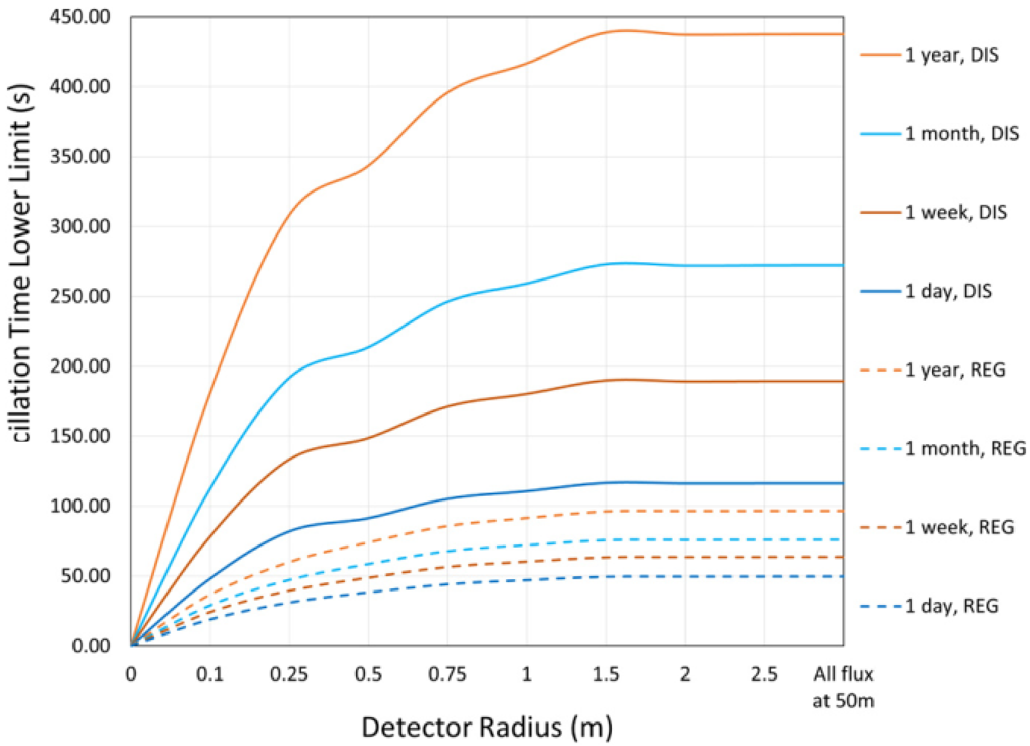
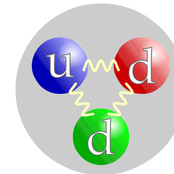


Figure 21. Sensitivity at 95% CL for the discovery of $\tau^{\rm dis}_{n\to n'}$ (disappearance, 'dis') and $\tau^{\rm reg}_{n\to n'}$ (regeneration, 'reg') for various detector radii for the nominal 1 MW HIBEAM/ANNI flux at 50 m. A background rate of 1 n s^{-1} is assumed for the regeneration search. Plots have been smoothed.

NNBAR

Exotic neutron decays



- Ultra-rare decays searched by large-volume experiments
- Lifetime for decay modes > 10^{33} years

$n \rightarrow e^+\pi^-$	0	2.0×10^{33} yrs.	[13]
$n \rightarrow \mu^+\pi^-$	0	1.0×10^{33} yrs.	[13]
$n \rightarrow e^+\rho^-$	0	7.0×10^{31} yrs.	[13]
$n \rightarrow \mu^+\rho^-$	0	3.6×10^{31} yrs.	[13]
$n \rightarrow \nu\pi^0$	$0(\overline{\nu}), 2(\nu)$	1.1×10^{33} yrs.	[38]
$n \rightarrow \nu\gamma$	$0(\overline{\nu}), 2(\nu)$	5.5×10^{32} yrs.	[37]

arXiv:1605.03235 [hep-ex]

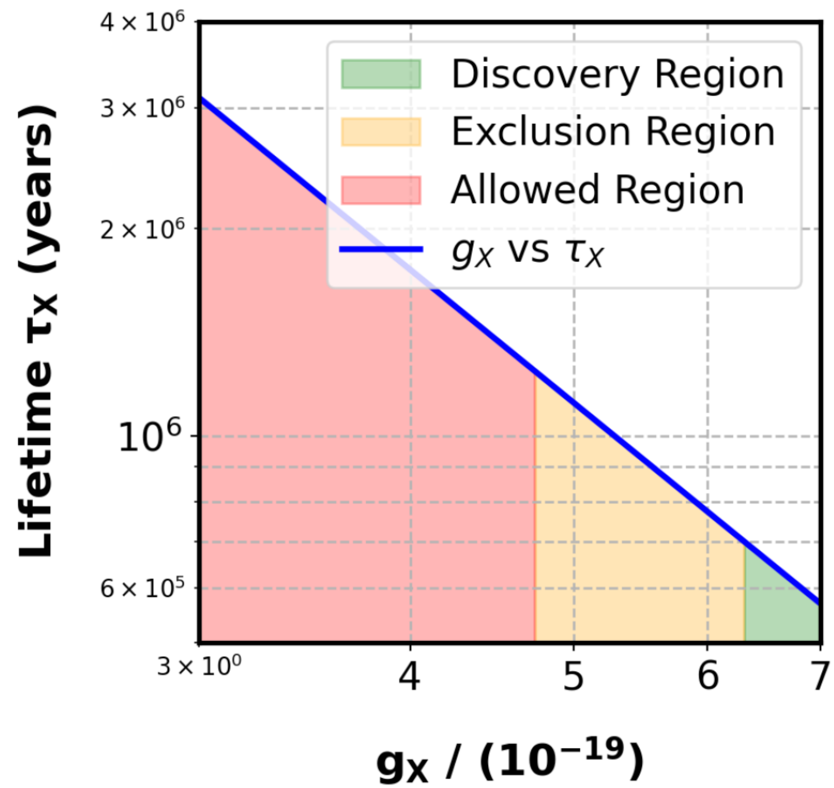
Exotic neutron decays

Searching for long-lived particles in free neutron experiments

B Meirose, R Nieuwenhuis, R Pasechnik, H Gisbert, L Vale Silva and D Milstead

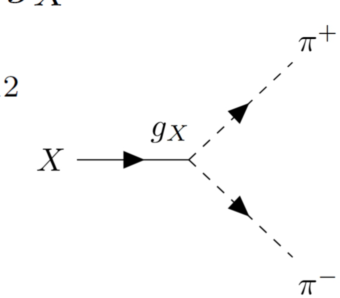
Published 8 July 2025 • © 2025 The Author(s). Published by IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 52, Number 7
Citation B Meirose *et al* 2025 *J. Phys. G: Nucl. Part. Phys.* **52** 075001
DOI 10.1088/1361-6471/ade3f2

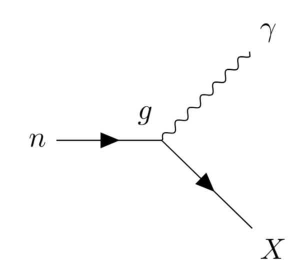
- Large detectors cannot see exotic neutron decays when the exotic particle X is nearly mass-degenerate with the neutron (mass gap $\lesssim$ few keV).
- HIBEAM-NNBAR: huge neutron flux, long flight path + full reconstruction capability: uniquely able to probe these hidden decay channels.
- Constraints from Super-Kamiokande (SK) allow long-lived X with lifetimes 10^5–10^6 years if $M_X \approx M_n$.
- HIBEAM can probe low eff SK channels (e.g., $X \to \nu+\gamma$, $X \to \pi^0+\gamma$).



$$\Gamma_X \sim \frac{M_X}{4\pi} g_X^2$$

$$g = 3 \times 10^{-12}$$





Fit within dark portal scenarios linking dark/hidden sectors with SM

Status

HIBEAM Status & Progress

Journal of Physics G: Nuclear and Particle Physics

MAJOR REPORT • OPEN ACCESS

The HIBEAM instrument at the European spallation source

J. Phys. G: Nucl. Part. Phys. 52 040501 (2025)

- Technical design work advanced; extensive CDR completed
- ESS has invested 1 M€ for crucial beamline insert infrastructure
- Prototype development underway:
  magnetics, annihilation detector, TPC components, veto system
- Early ESS data campaign planned:
  axion search + beam background measurements

Implementation Plan & Path to Construction

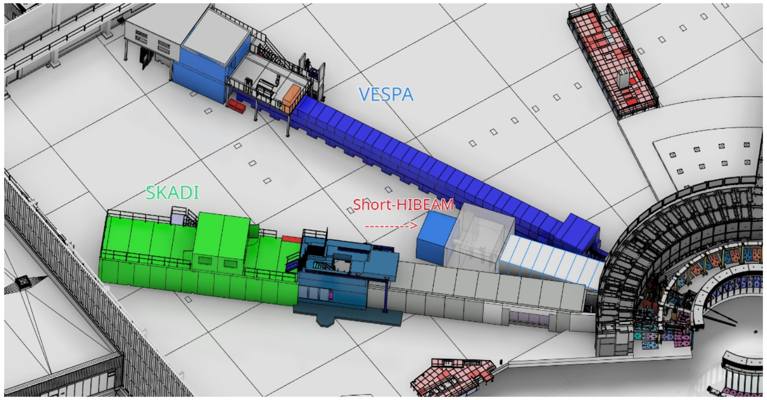
- Located at ESS E5 beam port; staged construction possible

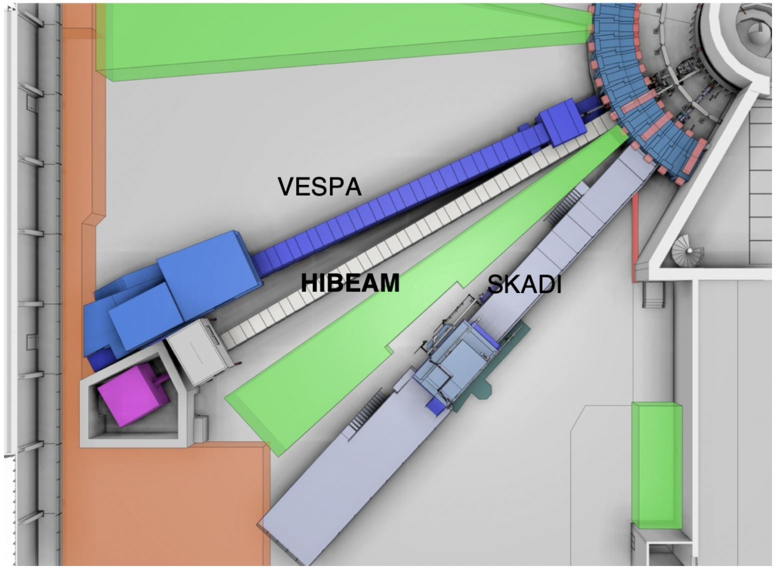
- **Detector suite:**
- Time Projection Chamber (TPC)
- WASA crystal calorimeter
- Scintillator-based cosmic-veto system

- Beamline constructed by ESS engineering teams; *detector systems by collaboration*

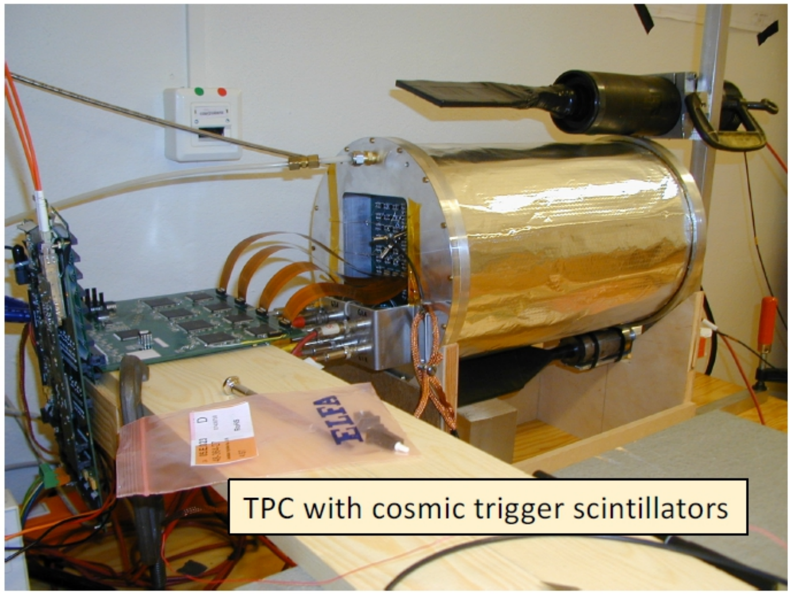
- Long-term vision: HIBEAM as springboard to NNBAR

- Responding to an ESS call for new instruments (deadline Feb 2025) – joint-proposal with ANNI



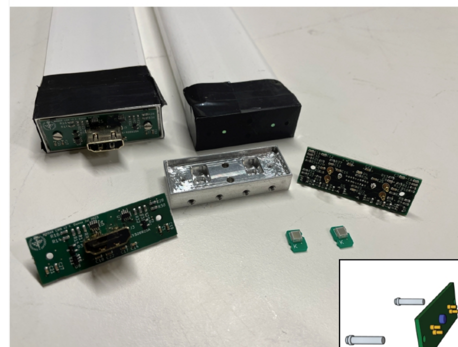


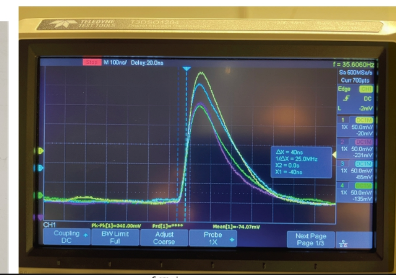
HIBEAM Prototypes

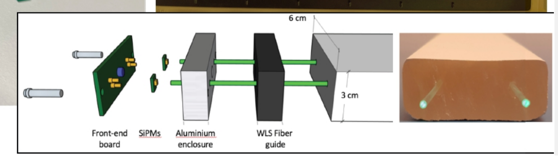


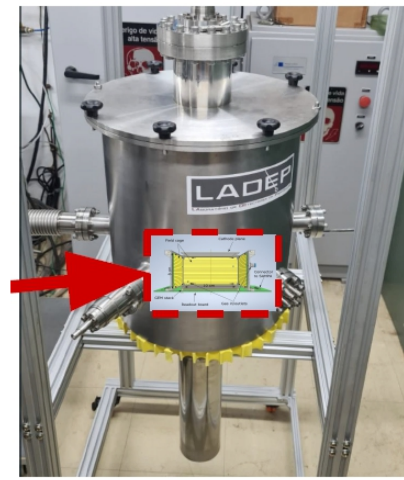
beam tests in Krakow, Poland, in December

HRD prototype

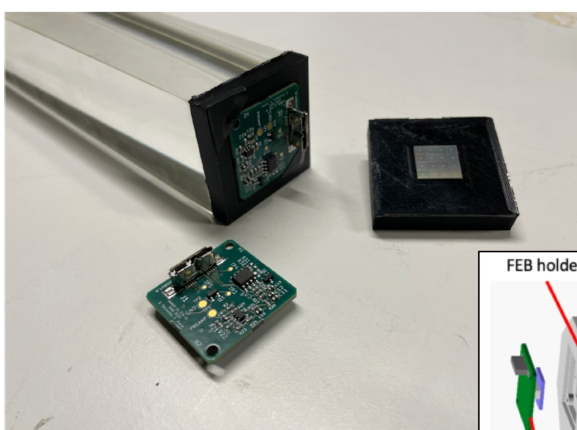




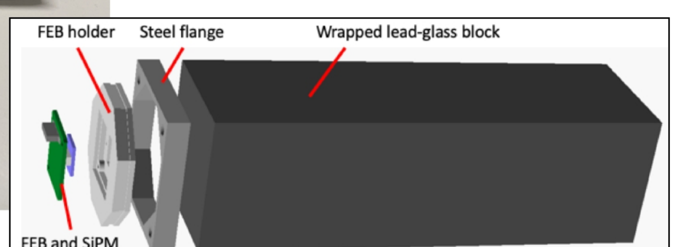




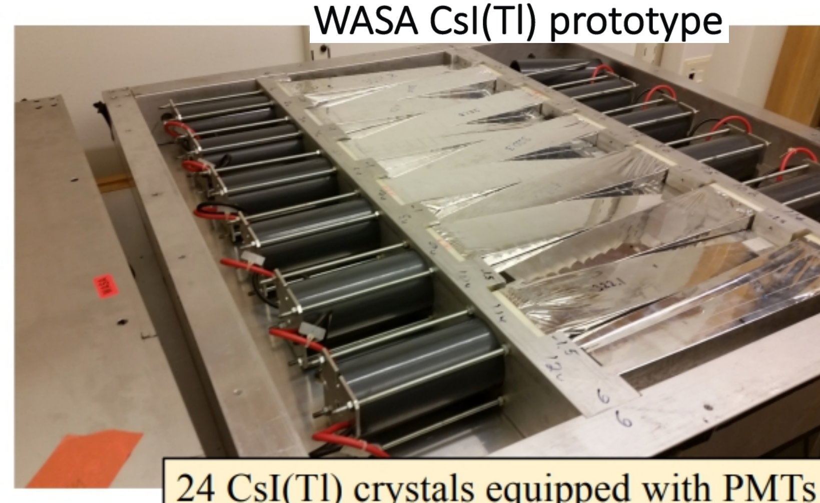
LEC prototype



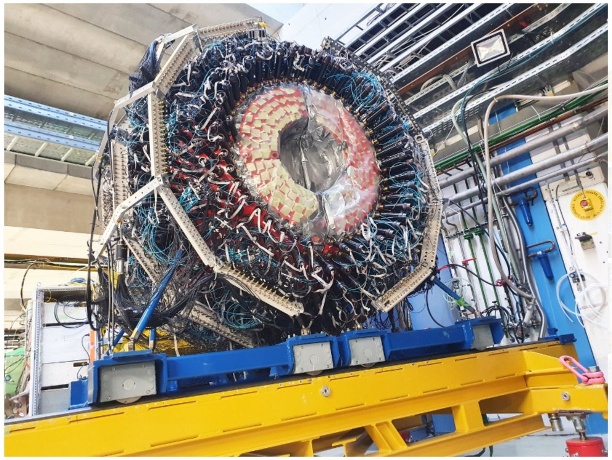
- The LEC front-end board is based on the HRD design.
- We will produce a revised version once the HRD front-end is validated

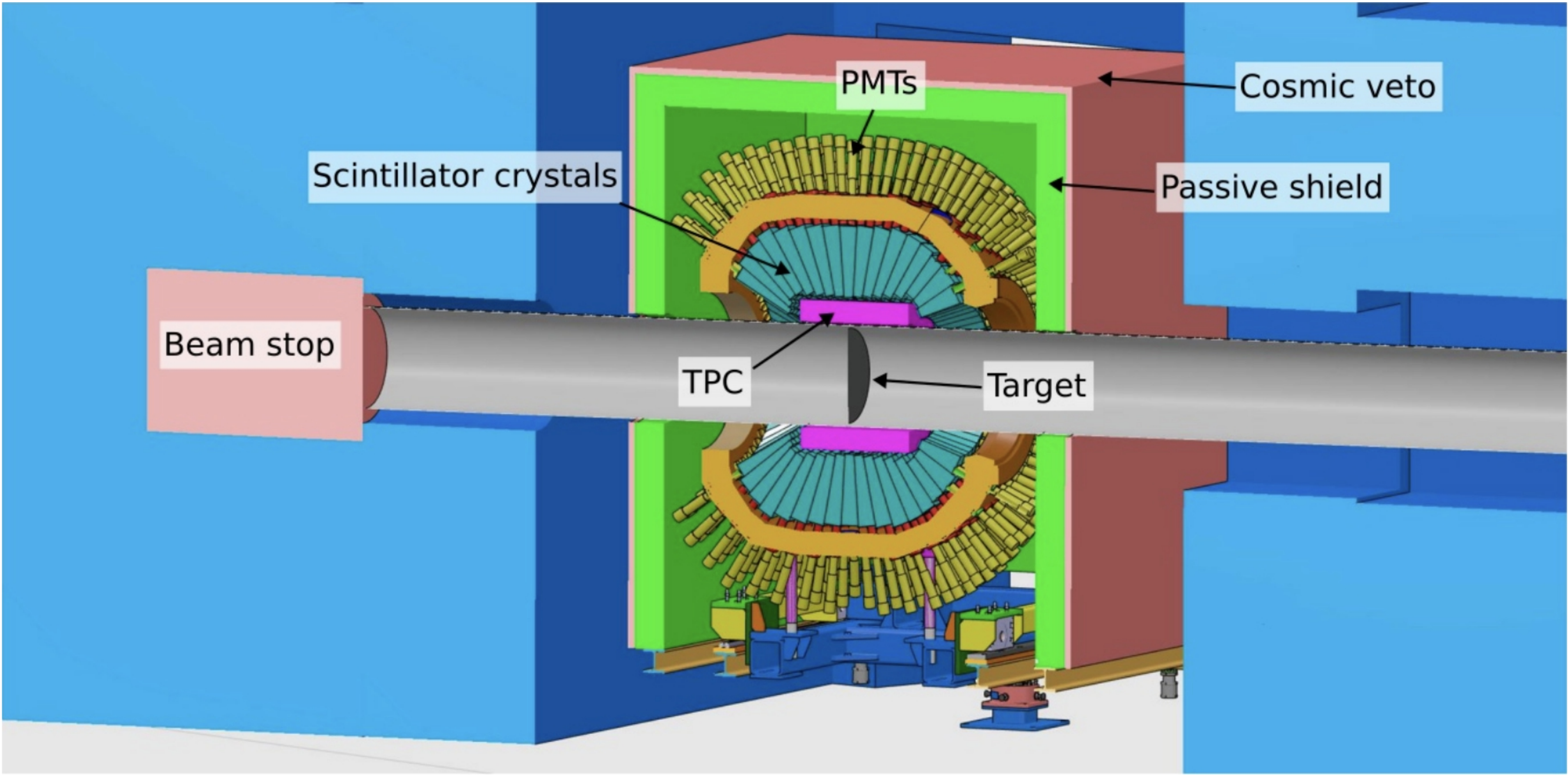


WASA CsI(Tl) prototype



WASA detector





Management

- D. Mistead (SU) and G. Brooijmans (Columbia): co-spokespersons
- Y. Kamyshkov (Tennessee): Lead Scientist
- V. Santoro: Technical Coordinator (LU/ESS)
- B. Meirose (CTU/LU): Detector Simulation and Computing Coordinator
- M. Holl (LU): Prototype Coordinator

Summary and outlook

- HIBEAM is a Swedish-led flagship experiment at ESS, opening a new intensity frontier with the world's brightest neutron source.
- Unique science reach: neutron–antineutron conversions, sterile neutrons, ultralight axions, exotic decays
- Technical readiness is high: major design work completed: prototypes for magnetics, TPC, veto, and annihilation detector are in active development.
- Near-term program: axion search + background studies, within the next few years (we expect to be able to use ESS test beam line)
- Strategic importance for Sweden: cost-effective route to national leadership at ESS
- Responding to an ESS call for new instruments
- Outlook: HIBEAM stands as both a standalone long-term facility and the required first step toward full NNBAR

Tack!

NNBAR

CHALMERS
UNIVERSITY OF TECHNOLOGY

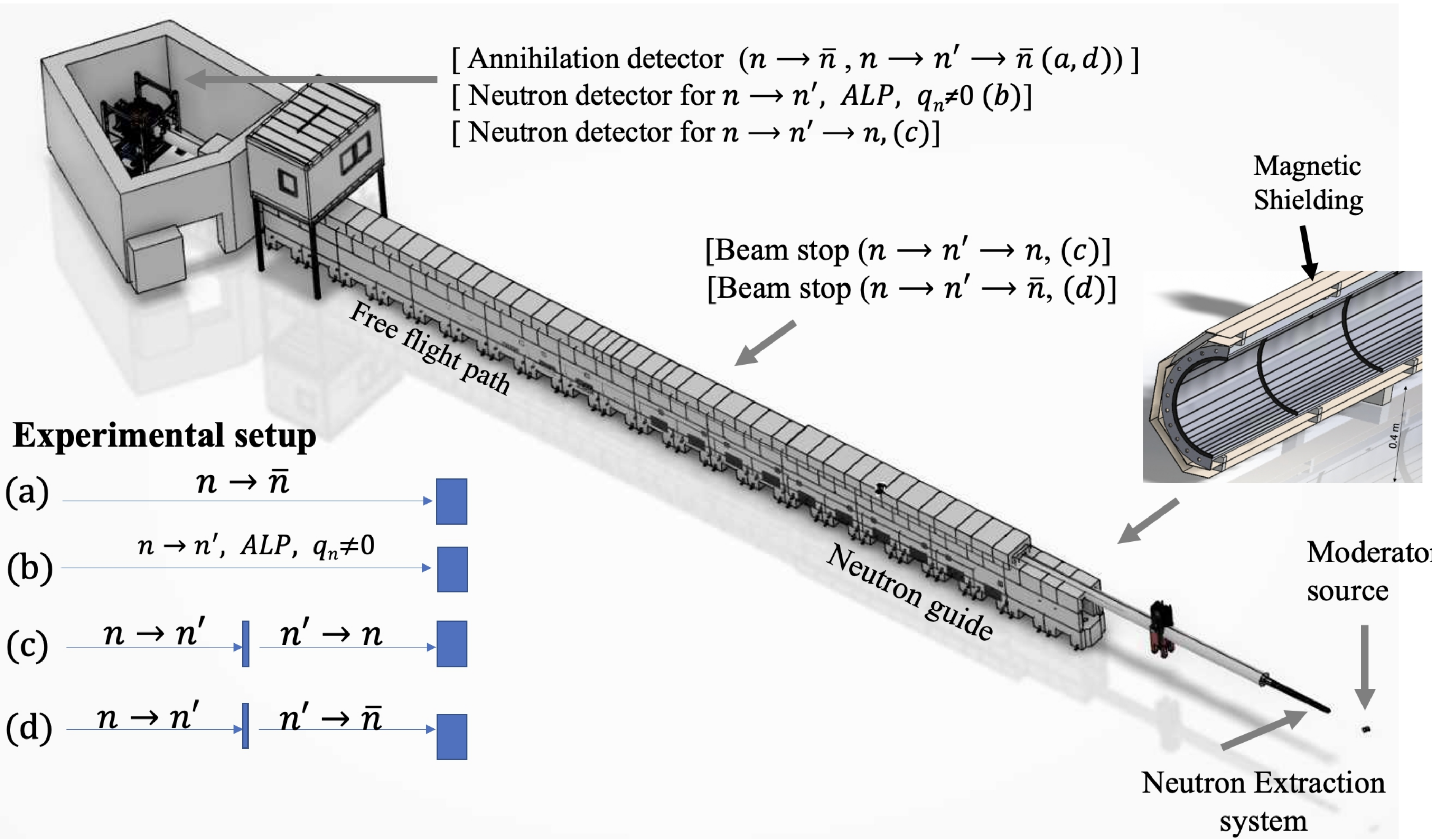
LUNDS UNIVERSITET

Vetenskapsrådet

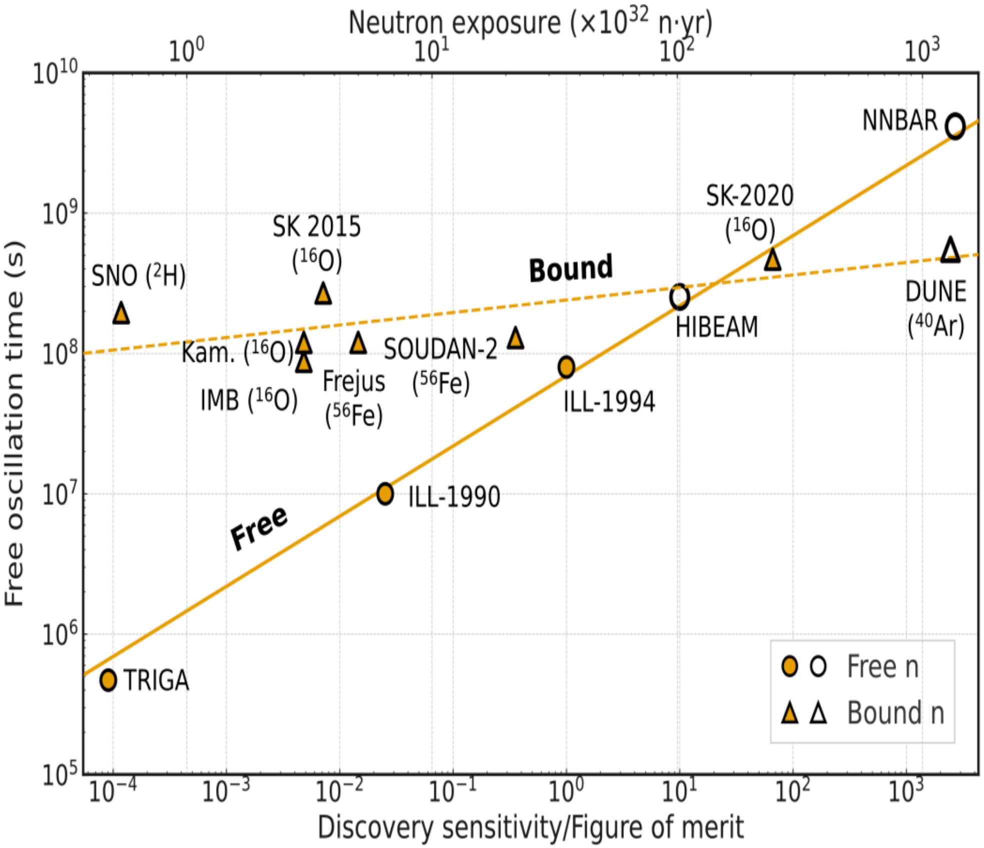
STINT
Stiftelsen för internationalisering av
högre utbildning och forskning
The Swedish Foundation for International
Cooperation in Research and Higher Education

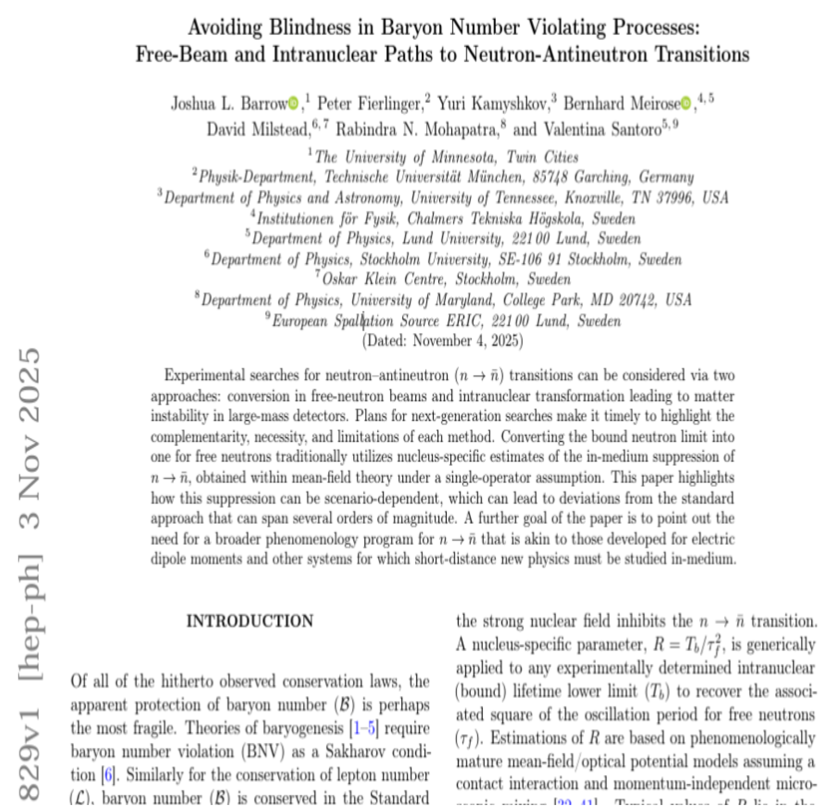
Backup

Sterile neutron search



The future is free





Avoiding Blindness in Baryon Number Violating Processes: Free-Beam and Intranuclear Paths to Neutron-Antineutron Transitions

Joshua L. Barrow,[1] Peter Fierlinger,[2] Yuri Kamyshkov,[3] Bernhard Meirose,[4,5] David Milstead,[6,7] Rabindra N. Mohapatra,[8] and Valentina Santoro[5,9]

[1] *The University of Minnesota, Twin Cities*
[2] *Physik-Department, Technische Universität München, 85748 Garching, Germany*
[3] *Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[4] *Institutionen för Fysik, Chalmers Tekniska Högskola, Sweden*
[5] *Department of Physics, Lund University, 221 00 Lund, Sweden*
[6] *Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden*
[7] *Oskar Klein Centre, Stockholm, Sweden*
[8] *Department of Physics, University of Maryland, College Park, MD 20742, USA*
[9] *European Spallation Source ERIC, 221 00 Lund, Sweden*

(Dated: November 4, 2025)

Experimental searches for neutron–antineutron ($n \to \bar{n}$) transitions can be considered via two approaches: conversion in free-neutron beams and intranuclear transformation leading to matter instability in large-mass detectors. Plans for next-generation searches make it timely to highlight the complementarity, necessity, and limitations of each method. Converting the bound neutron limit into one for free neutrons traditionally utilizes nucleus-specific estimates of the in-medium suppression of $n \to \bar{n}$, obtained within mean-field theory under a single-operator assumption. This paper highlights how this suppression can be scenario-dependent, which can lead to deviations from the standard approach that can span several orders of magnitude. A further goal of the paper is to point out the need for a broader phenomenology program for $n \to \bar{n}$ that is akin to those developed for electric dipole moments and other systems for which short-distance new physics must be studied in-medium.

829v1 [hep-ph] 3 Nov 2025

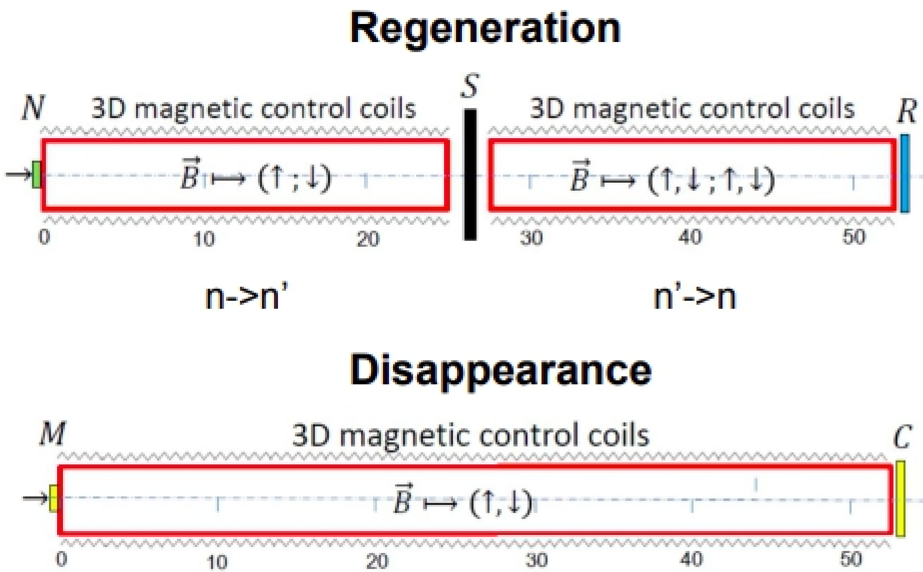
INTRODUCTION

Of all of the hitherto observed conservation laws, the apparent protection of baryon number ($\mathcal{B}$) is perhaps the most fragile. Theories of baryogenesis [1–5] require baryon number violation (BNV) as a Sakharov condition [6]. Similarly for the conservation of lepton number ($\mathcal{L}$), baryon number ($\mathcal{B}$) is conserved in the Standard

the strong nuclear field inhibits the $n \to \bar{n}$ transition. A nucleus-specific parameter, $R = T_b/\tau_f^2$, is generically applied to any experimentally determined intranuclear (bound) lifetime lower limit (T_b) to recover the associated square of the oscillation period for free neutrons (τ_f). Estimations of R are based on phenomenologically mature mean-field/optical potential models assuming a contact interaction and momentum-independent micro-

Free neutron-antineutron searches offer strong sensitivity increases
Limits from free and bound searches are ”apples and pears”.
Multi-operator interference and non-locality can radically shift sensitivities between the two methods.

HIBEAM discovery sensitivity



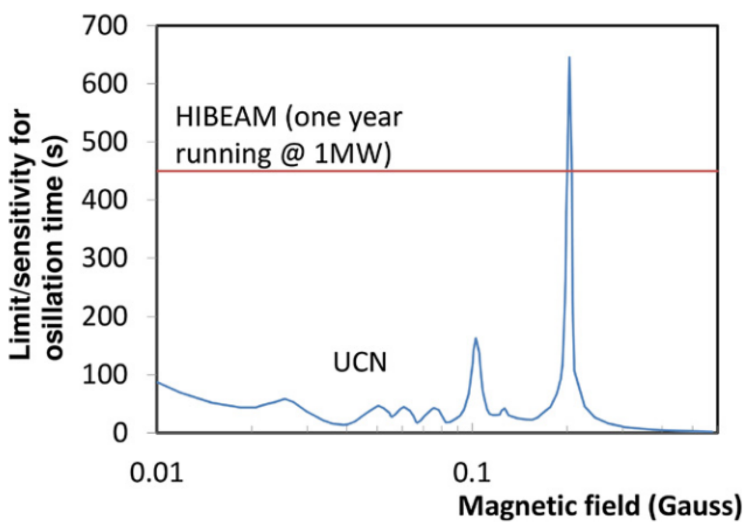


Figure 22. Excluded neutron oscillation times in blue for $n \to n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power of 1 MW.

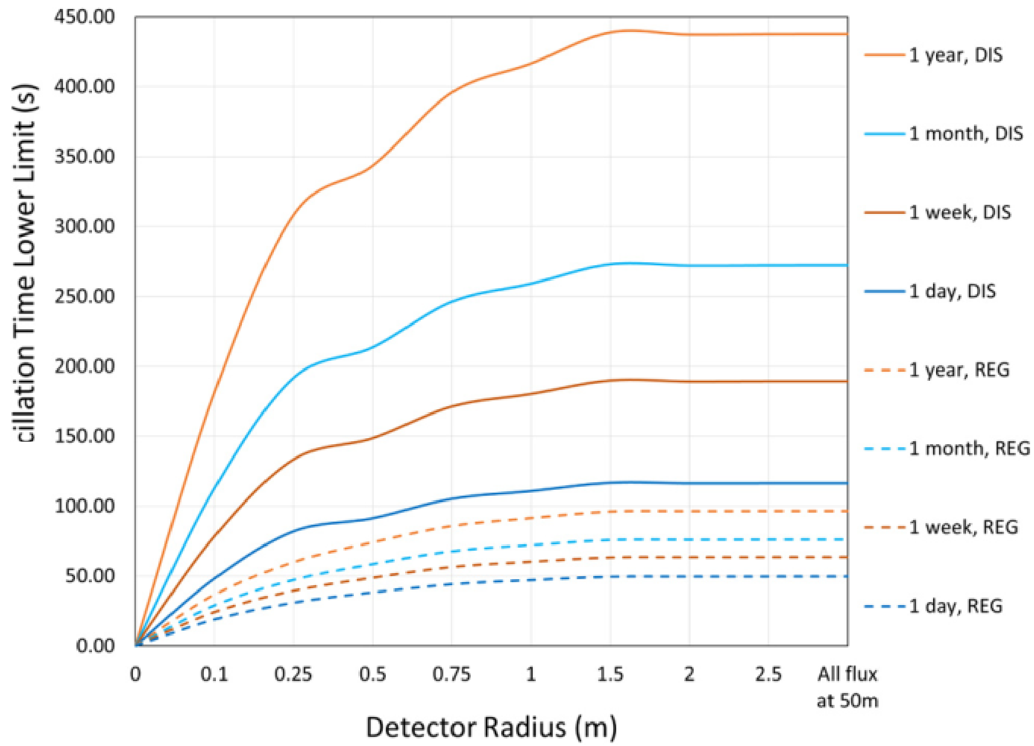
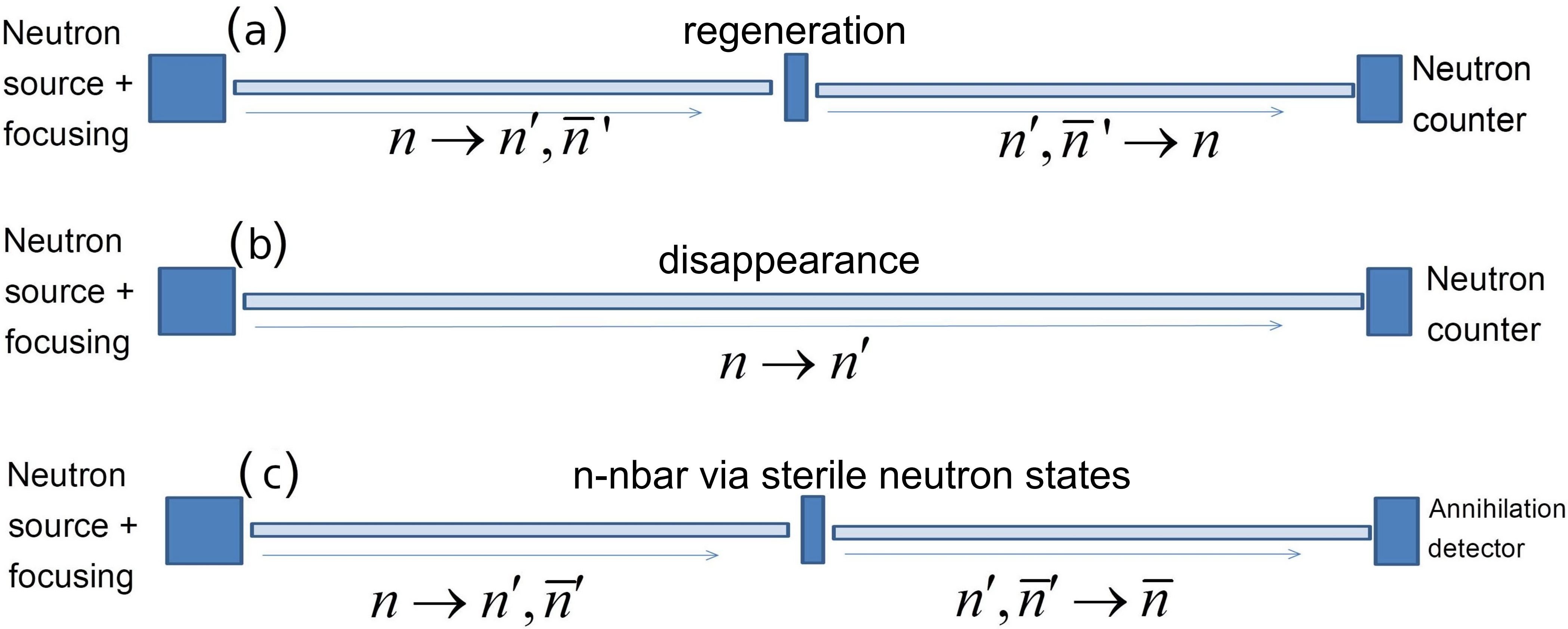


Figure 21. Sensitivity at 95% CL for the discovery of $\tau^{\mathrm{dis}}_{n\to n'}$ (disappearance, 'dis') and $\tau^{\mathrm{reg}}_{n\to n'}$ (regeneration, 'reg') for various detector radii for the nominal 1 MW HIBEAM/ANNI flux at 50 m. A background rate of 1 n s^{-1} is assumed for the regeneration search. Plots have been smoothed.

Sterile neutron search

$n \longrightarrow n'$ possible with a non-zero B-field that must be scanned/optimized to match the B-field in the dark sector



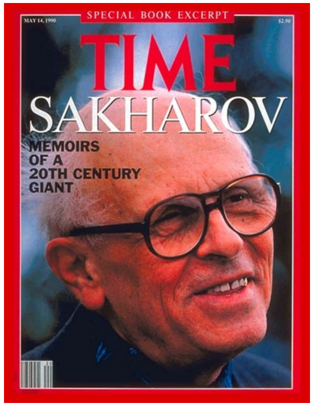
Sakharov conditions for baryogenesis

- Baryogenesis: hypothetical physical process that took place in the early Universe responsible for baryon asymmetry.
- Necessary ingredients needed to create a baryon asymmetry:
- **1. Baryon number violation (BNV)**
- **2. Loss of thermal equilibrium**
- **3. C, CP violation**
- These principles have come to be attributed to Sakharov (JETP Lett. 5 1967).
- **Need for BNV is obvious**.

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

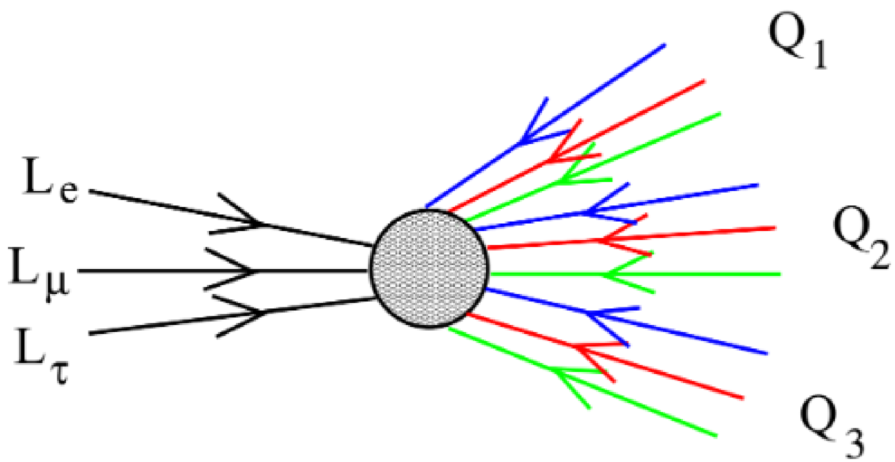
(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]



Baryon number in the SM

- Even within the SM, B is subject only to approximate conservation law.
- In fact only B-L is exactly conserved.
- BNV exists in the SM baryon due to nonperturbative effects (t'Hooft [Phys. Rev. Lett. 37 (1976) 8]).
- Baryon number can be violated by triangle anomaly, where left handed quarks annihilate with leptons.

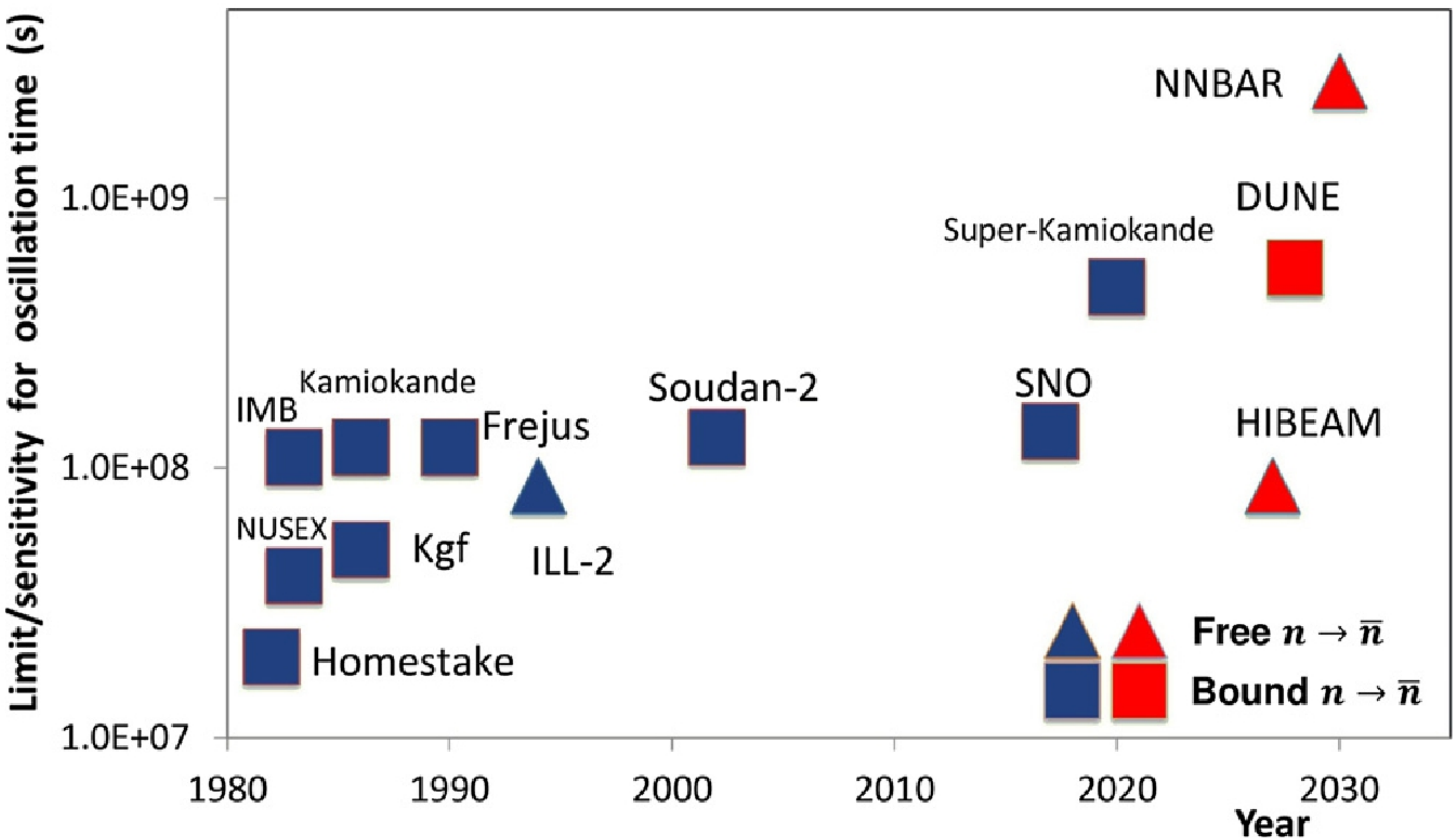
$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g}{32\pi}\epsilon_{\mu\nu\rho\sigma} W_a^{\mu\nu} W_a^{\rho\sigma}$$



$$\Delta B = \Delta L = \pm 3$$

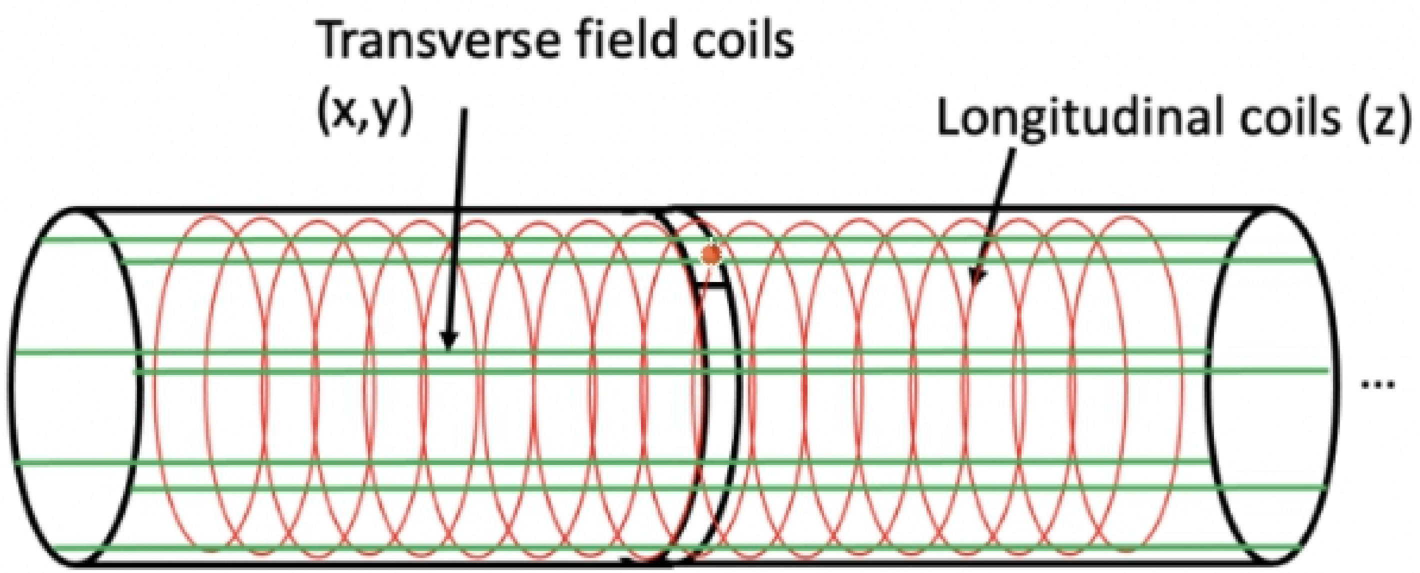
- **1. Tiny effects imply that the minimal Standard Model already has B violation.**
- **2. However: SM B violation too small to produce observed baryon asymmetry!**

Comparison with past and future experiments

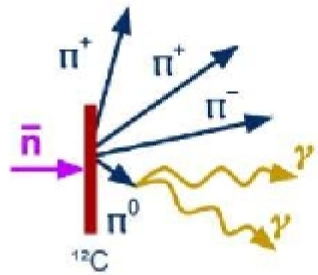


Magnetic control beam line

- Full 3D control of the magnetic field will be needed
- Level of ~2 mG.
- Achieved with 3D current coils
- Non-uniformity reduced with mu-metal shielding



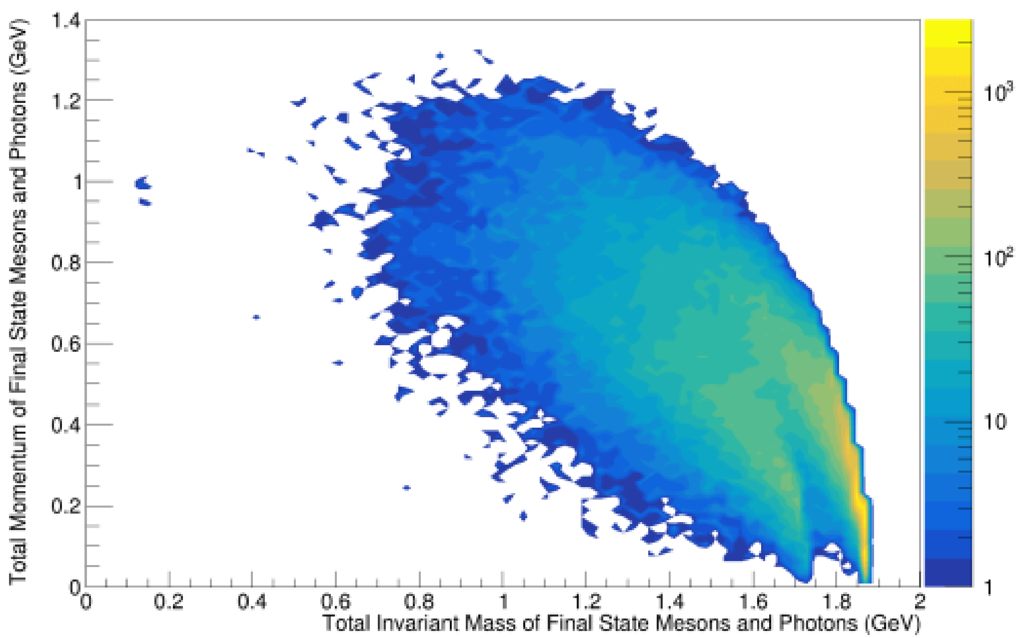
Antineutron annihilation signal

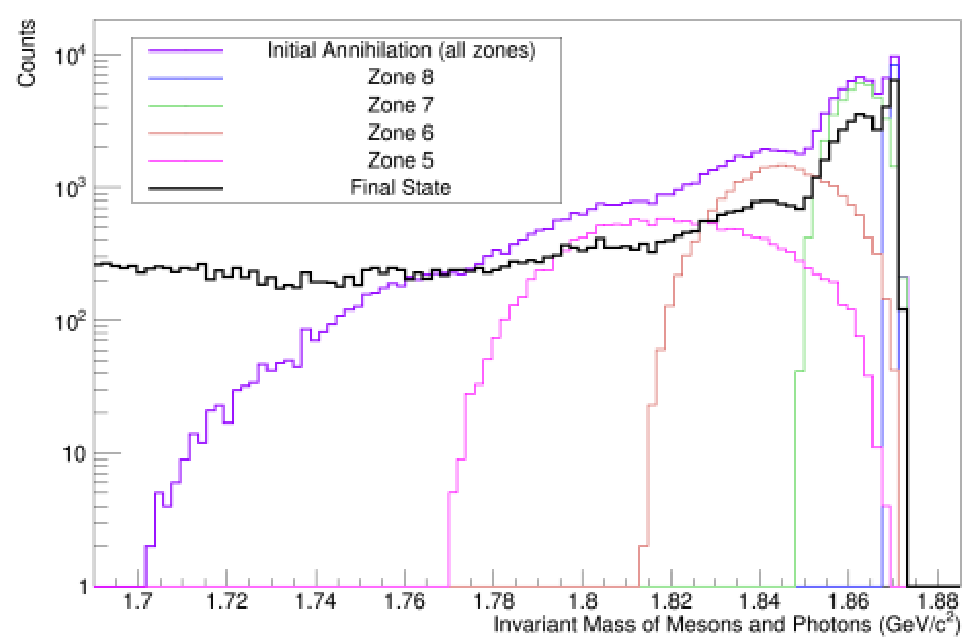


Model of $\bar{n}$ annihilation in experimental searches for $\bar{n}$ transformations

E. S. Golubeva, J. L. Barrow, and C. G. Ladd
Phys. Rev. D **99**, 035002 – Published 5 February 2019

- Energy release of ~ 2*mn ~ 1.88 GeV
- Distributed over several pions (5 in average), e.g.: $n + \bar{n} \rightarrow \pi^+ + \pi^- + 3\pi^0$
- However: in a real experiment antineutron would annihilate inside a nucleus – this is NOT the same as annihilation in free space.
- Neutron is strongly interacting particle - ^{12}C nucleus acts as strong medium

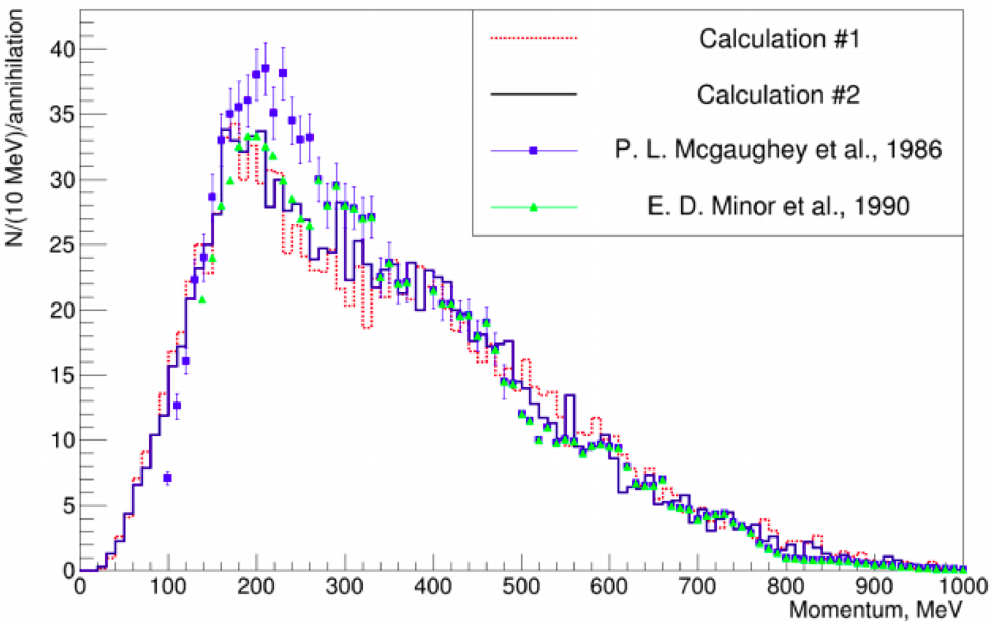




Antineutron annihilation

- Final states extrapolated from antiproton-nucleon:

$\overline{p}C \rightarrow \pi^+$ Spectrum Matches Experiment Well



Based on 10,000 events

See [here] and [here]

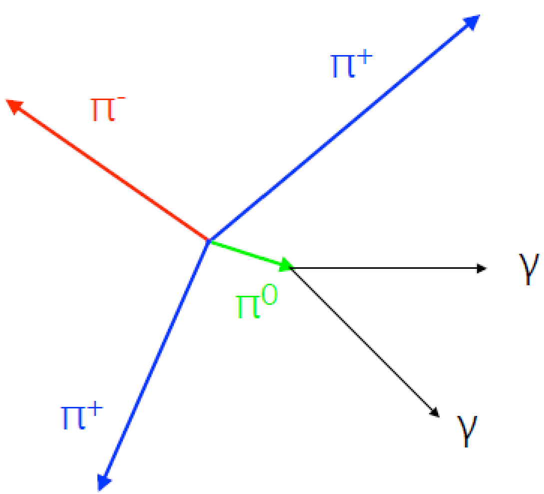
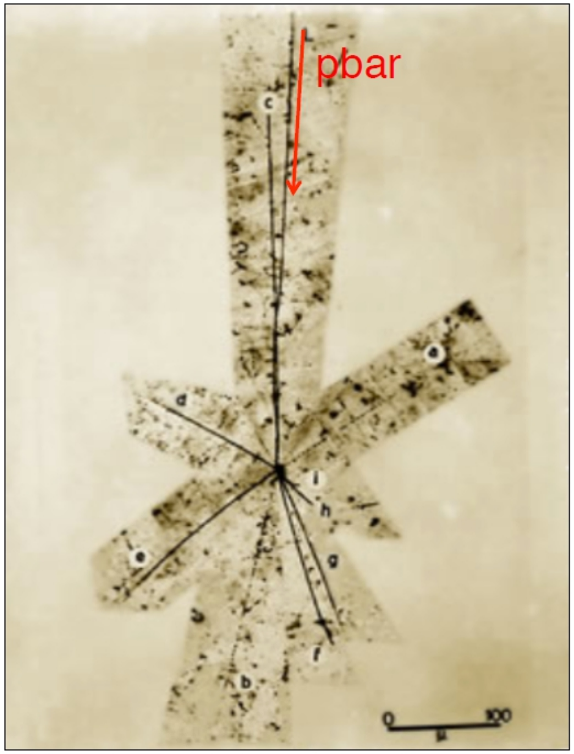


Figure by J. Hewes



Antiproton Star Observed in Emulsion*

O. Chamberlain, W. W. Chupp, G. Goldhaber, E. Segrè, and C. Wiegand, *Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

AND

E. Amaldi, G. Baroni, C. Castagnoli, C. Franzinetti, and A. Manfredini, *Istituto di Fisica della Università, Roma Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy*

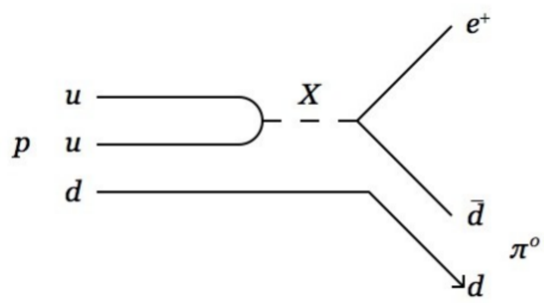
(Received December 16, 1955)

Testing selection rules

- Neutron oscillations provide **clean channel to probe BNV-only process.**
- From a purely experimental point: test different selection rules for BNV and LNV.

Proton decay

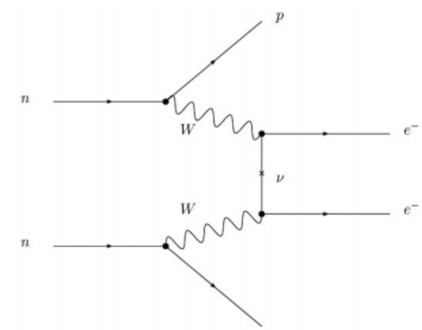
$p \to e^{+} + \pi^{0}$



$\Delta B \neq 0, \Delta L \neq 0$

Neutrinoless double beta decay

$0\nu 2\beta$

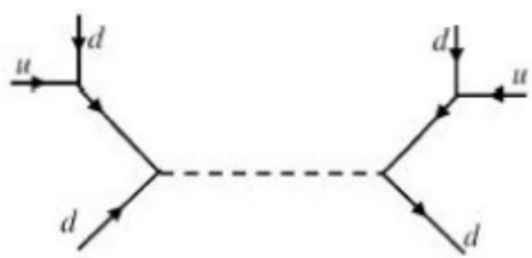


$\Delta B = 0, \Delta L \neq 0$

Neutron Oscillation

Neutron antineutron oscillation

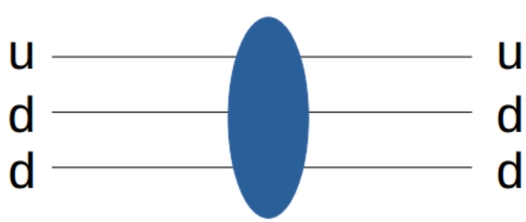
$n \to \bar{n}$



$\Delta B = 2, \Delta L = 0$

Neutron sterile neutron oscillation

$n \to n'$



$\Delta B = 1, \Delta L = 0$

Control of fields in which the neutrons propagate

Eg Free $n \longrightarrow \bar{n}$ state

$$\boldsymbol{\Psi} = \binom{n}{\bar{n}}$$

$$H = \begin{pmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} \end{pmatrix}$$

ε =mixing mass term

Probability to find an antineutron at time t is given by

$$P_{n\bar{n}}(t) = \frac{\varepsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2} \sin^2\left[t\sqrt{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2}\right] e^{-t/\tau_n},$$

$\Delta \text{E} = E_n - E_{\bar{n}}$ Require degeneracy between $n, \bar{n}$

$\Rightarrow$ Zero magnetic field ($<10^{-5}$ G)

Similarly for $n \longrightarrow \text{n}'$
Magnetic field in dark sector
$\Rightarrow$ Scan for -1G <B<+1G in ~mG steps

$n \rightarrow \bar{n}$ probability via sterile neutron

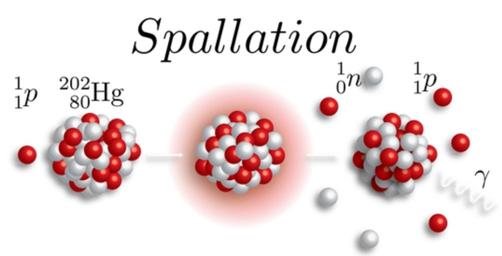
$$P_{n\bar{n}}(t) = \frac{1}{4}\alpha^2_{n\bar{n}'}\alpha^2_{n\bar{n}'}t^4 \sin^2\beta = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4\left(\frac{10^2\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

- Magnetic scans for HIBEAM is analogous to magnetic shielding for NNBAR → reach quasi-free condition
- For NNBAR, $\Delta E \ll t$ (achieved via B < 10 nT)
- For HIBEAM, that's $|\mathbf{B} - \mathbf{B}'| \sim 0$
- B field necessary to compensate B' field to allow $n \rightarrow n' \rightarrow \bar{n}$
- Note: **FOM ~ Nt^4**

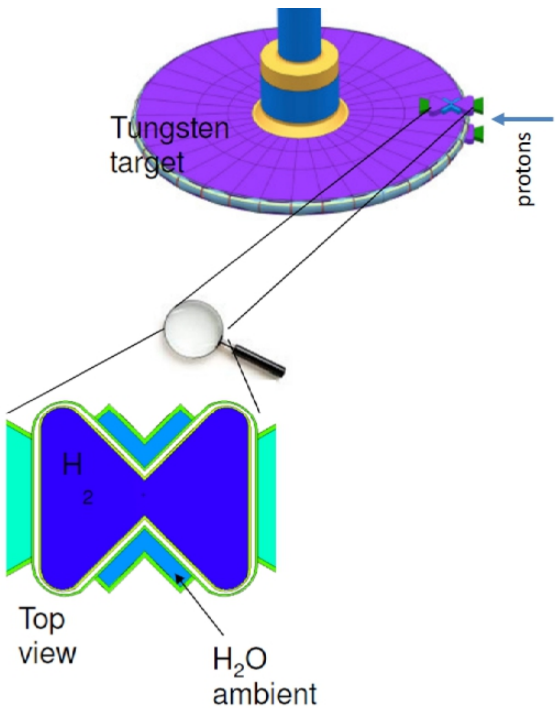
Search for neutron oscillations

- Neutrons are bound in nuclei → several MeV for liberation

→ fission
→ spallation (can be kept under full control)



Extract of figure from Mads Ry Vogel Jørgensen, Aarhus University

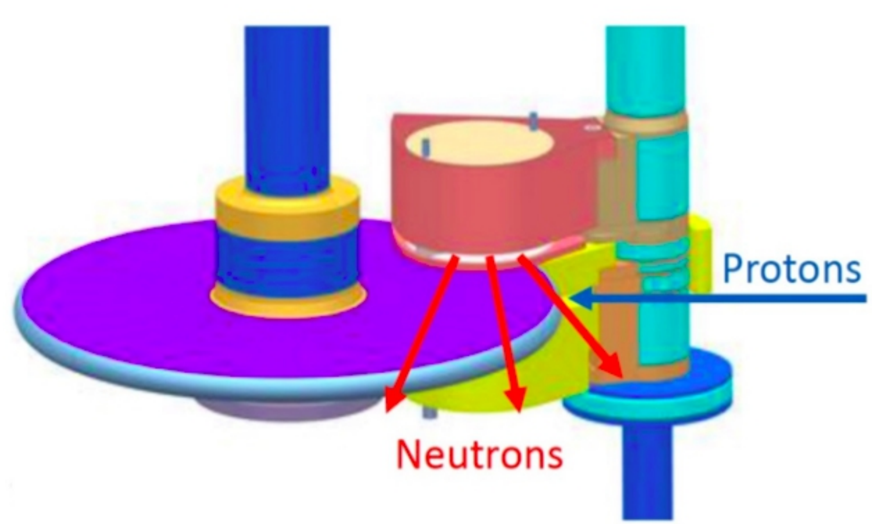


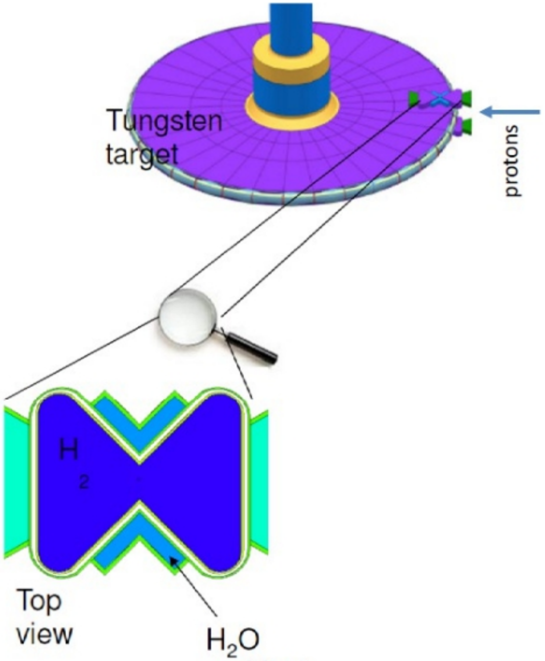
- **To increase *probability of*** $n \rightarrow \bar{n}$:
- *t* large → slow (a.ka. "cold" → few meV) need lots of collisions → moderators
- We also want as many neutrons as possible.

ESS – a neutron factory

EUROPEAN SPALLATION SOURCE

- High intensity spallation source
- 2 GeV protons (3ms long pulse hit rotating tungsten target)
- Cold neutrons after interaction with moderators (~ $10^{12\text{-}13}$ n/s)

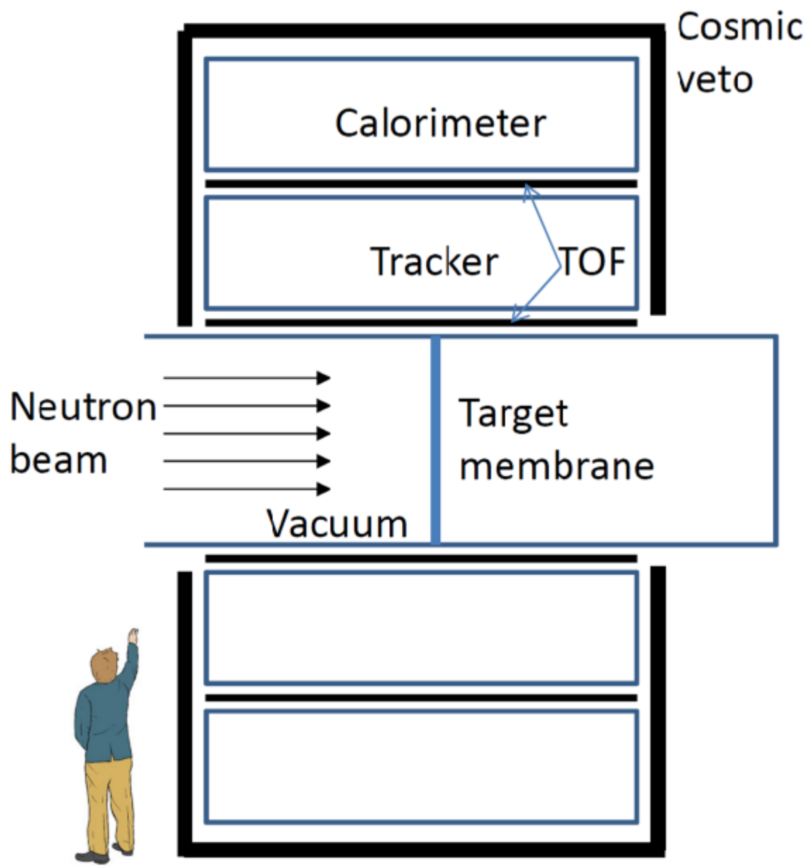




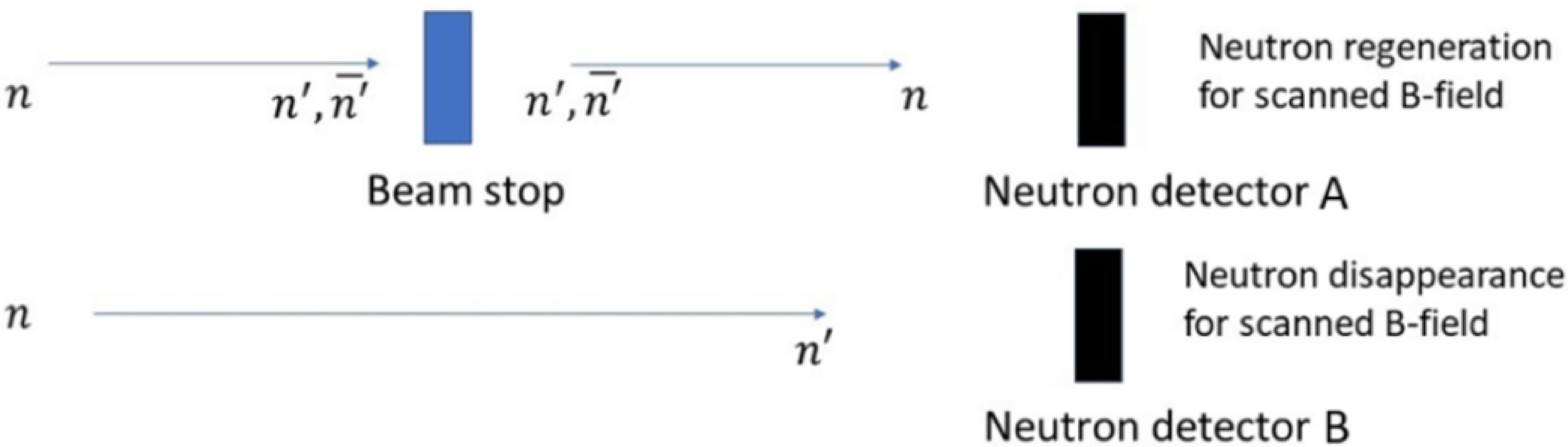
Annihilation target

- Target: 100 μm carbon foil
- Low cross section for absorption

$$\sigma_{annihilation} \sim 4\text{Kb}$$
$$\sigma_{nC,capture} \sim 4\text{mb}$$



Neutron detector design



Two very different experiments with very different neutron detector requirements!

- **detector A**: low-flux, large area position-sensitive neutron detector
- **detector B**: high-flux, high-efficiency neutron detector sensitive to intensity variations of 10^{-7}

Goal of WP4: technology review, candidate selection, costing model(s)

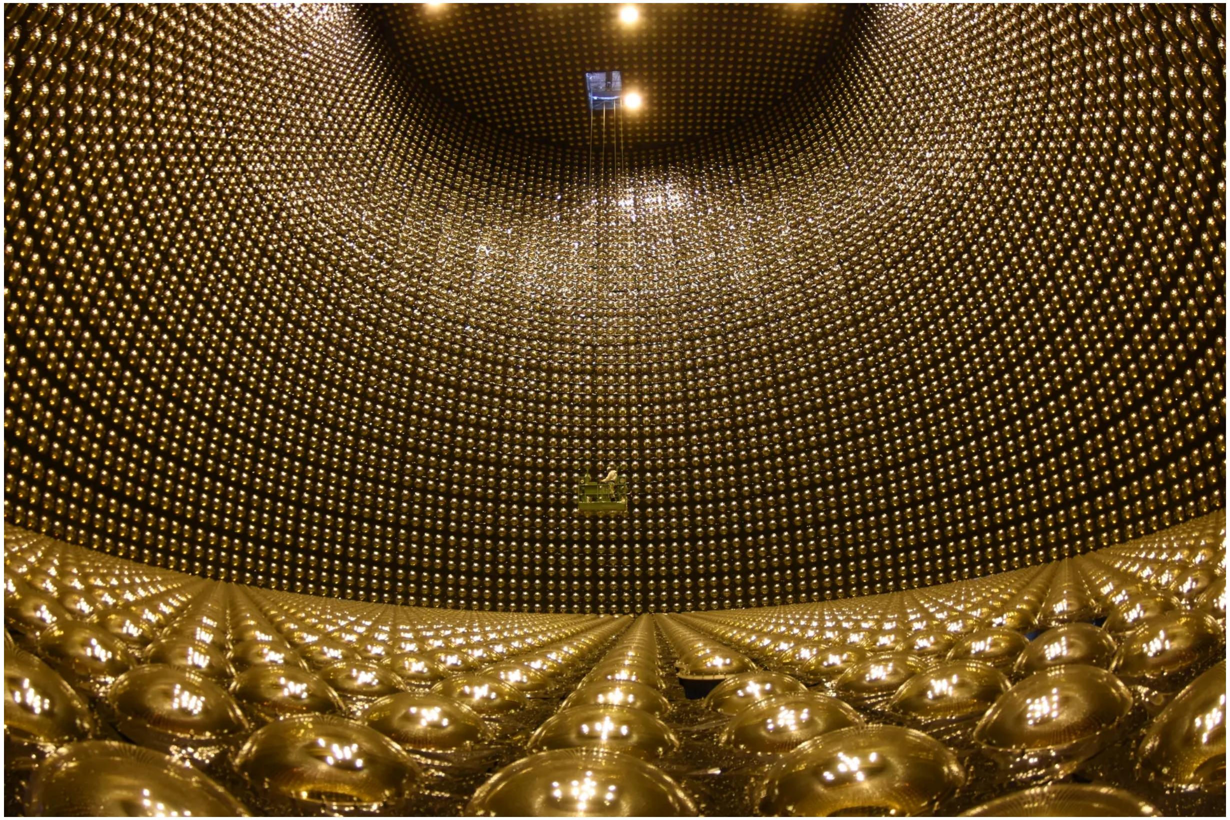
Axion-neutron coupling effect in Ramsey interferometry

$$\mathcal{L}_{\text{int}} = -\frac{C_N}{2f_a}\,\partial_\mu a\,\bar{N}\gamma^\mu\gamma_5 N$$

- Start: spin up along z.
- π/2 pulse: tip spin into x-y plane (say along x).
- Precession: spin rotates in x-y plane → relative phase accumulates (phase = detuning × time).
- Axion field: adds a tiny, oscillating effective magnetic field along some direction → modulates the precession frequency, so total phase = phase + axion-induced phase.
- Second π/2 pulse: maps total phase onto z-axis population.
- Measure z-population over many neutrons → interference pattern shows tiny oscillatory shifts → possible detection of axion interactions.

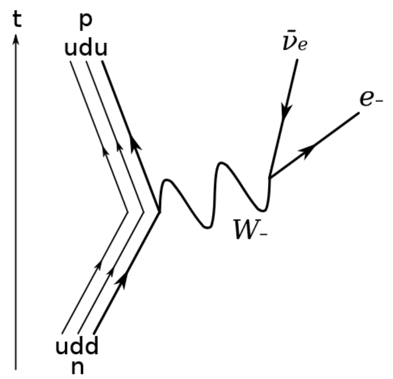
Bound vs. free neutrons

- Large-volume experiments use bound neutrons
- Blind to decays in certain kinematic regions



Super-Kamiokande detector inside view

Bound vs. free neutrons



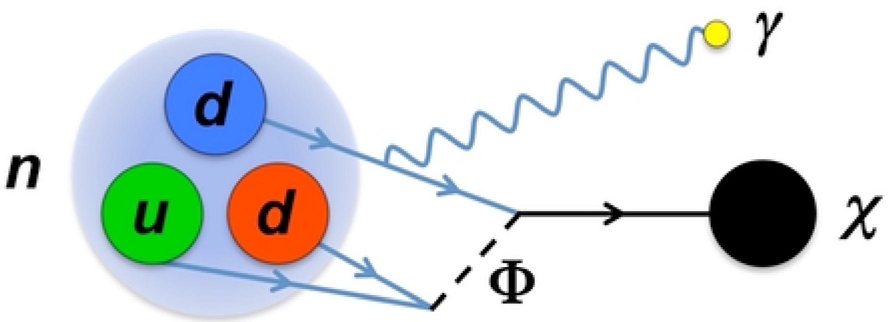
- Free-neutrons decay in ~ 15 minutes
- But bound neutrons are mostly stable
- Energy gained from neutron decay lower than energy needed for extra proton in nuclear core.
- Neutron in shallow potential well
- Direct consequence of semi-degeneracy between proton and neutron in standard beta decay ($n \rightarrow p + e + v_e$)

Exotic neutron decays

- Semi-degeneracy argument restricted to protons (in Standard Model)
- But equally valid in non-standard decays (n → X + …)
- *As long as X's mass is close to the neutron*…
- …there are kinematically suppressed decays for which large-volume experiments are virtually blind
- Full decay must preserve charge and Lorentz invariance

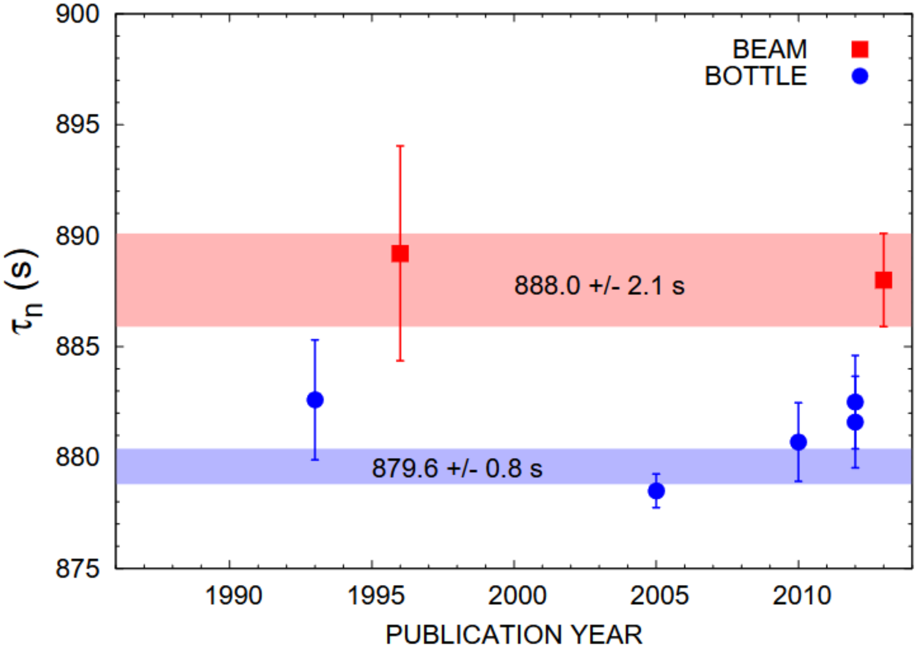
Neutron decay to dark matter?

- Not first time argument is explored
- In Phys. Rev. Lett. 124, 219901 (2020) Fornal and Grinstein explored scenario where neutron to decay to dark matter + γ
- Dark matter particle very close to neutron mass
- $937.900 < m_X < 938.783$ MeV (~ 1.7 MeV "mass gap" from ^{9}Be stability)
- X is a stable fermion



Neutron lifetime puzzle

- Goal of Fornal and Grinstein was explaining "beam vs. bottle" anomaly
- The anomaly: Measurements of the neutron lifetime using two methods —counting decay products in a neutron beam and tracking ultracold neutrons in a trap—differ by about 9 seconds



- However, dark neutron decays excluded (4σ) as an explanation of the neutron anomaly by D. Dubbers et al (Phys. Lett. B 791:6 2019)
- *This is, however, not the end of exotic neutron decays*

Exotic neutron decays revisited

- Free-neutron-exclusive exotic decays still allowed.
- Uncertainty in free neutron decay is *large* (~ 0.1%)
- While *not* an explanation for neutron lifetime anomaly
- Neutrons might still decay to dark matter
- ... *or to some other long-lived exotic particle*

NNBAR

Exotic neutron decays revisited

- If $n \rightarrow X + \ldots$. and $937.900 < m_X < 938.783$
- Condition is met
- As long as X's width (Γ) not too large
- ***otherwise: neutron can decay off-shell***
- With large Γ, exotic decays of X become allowed also at large-volume experiments (the larger Γ, the larger the rates)
- … which is NOT observed.
- So, X may decay as long as its Γ is small enough (long lifetime)
- ***But how small is small enough?***

Maximum width estimation

- Consider n → X + …. and 937.900 < m_X < 938.783
- ***What is maximum Γ consistent with zero events observed in Super-K?***

$$P(X_{\text{off-shell}}) = \int_0^{937.9\,\text{MeV}} \frac{1}{\pi} \cdot \frac{\Gamma_X}{(M_X - M_X^{\text{on-shell}})^2 + \frac{\Gamma_X^2}{4}} \, dM_X$$

$$\Gamma = \Gamma_n \cdot B_r \cdot P(X_{\text{off-shell}})$$

$$B_r = 10^{-3}$$

$$\Gamma_n = 1/878 \text{ Hz}$$

Maximum width estimation

- Data collected by Super-K (1996-2016) ~ 250 kiloton.yrs (~ 10^{35} n)

$$N_{\text{decays}} = N_{\text{SK}} \cdot \Gamma \cdot T_{\text{year}} \cdot \epsilon$$

$$\Gamma = \Gamma_n \cdot B_r \cdot P(X_{\text{off-shell}})$$

$$T_{\text{year}} \sim 3.2 \times 10^7 \text{s} \qquad N_{\text{SK}} = 10^{35}$$

$$\epsilon = 5\%, 10\%, \text{ and } 20\%$$

True for many hadronic channels, e.g., channels with one or more charged pions

Maximum width estimation

Require: **$P_{3\sigma}$ < 0.1 (in 90% of experiments SK below 3σ)**

$$P(X_{\text{off-shell}})_l = 8 \times 10^{-36}$$
$$P(X_{\text{off-shell}})_m = 3 \times 10^{-36}$$
$$P(X_{\text{off-shell}})_t = 1 \times 10^{-36}$$

$$\Gamma_{X_l} \lesssim 4.2 \times 10^{-35}\,\text{MeV}; \quad \tau_{X_l} \approx 5.0 \times 10^{5}\,\text{yrs}$$
$$\Gamma_{X_m} \lesssim 1.7 \times 10^{-35}\,\text{MeV}; \quad \tau_{X_m} \approx 1.2 \times 10^{6}\,\text{yrs}$$
$$\Gamma_{X_t} \lesssim 5.9 \times 10^{-36}\,\text{MeV}; \quad \tau_{X_t} \approx 3.6 \times 10^{6}\,\text{yrs}$$

Compared to ~ 10^{34} years limits imposed by SK!

Can such lifetime be measured? (NNBAR)

- Number of X particles that decay inside detector tube:

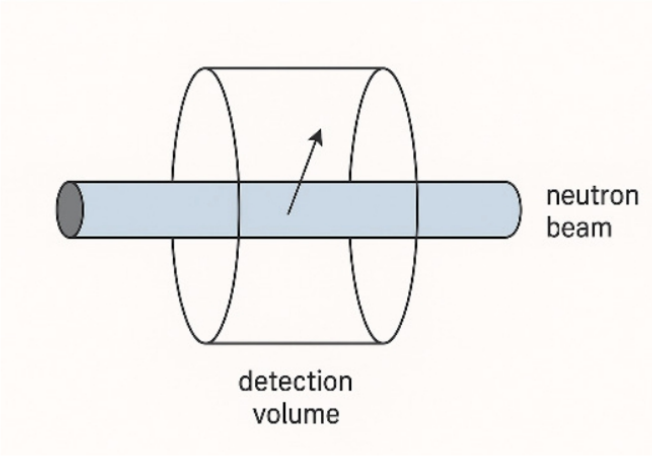
$$N_{\text{total}} = \Phi_X \cdot (1 - e^{-t_{\text{tube}}/\tau_X}) \cdot T$$

$$T = 2 \text{ yrs}$$

$$\Phi_X = 1.1 \times 10^8 \text{ X/s}$$

$$t_{\text{tube}} = \frac{d_{\text{tube}}}{v_X}$$

$$d_{\text{tube}} = 6 \text{ m}$$

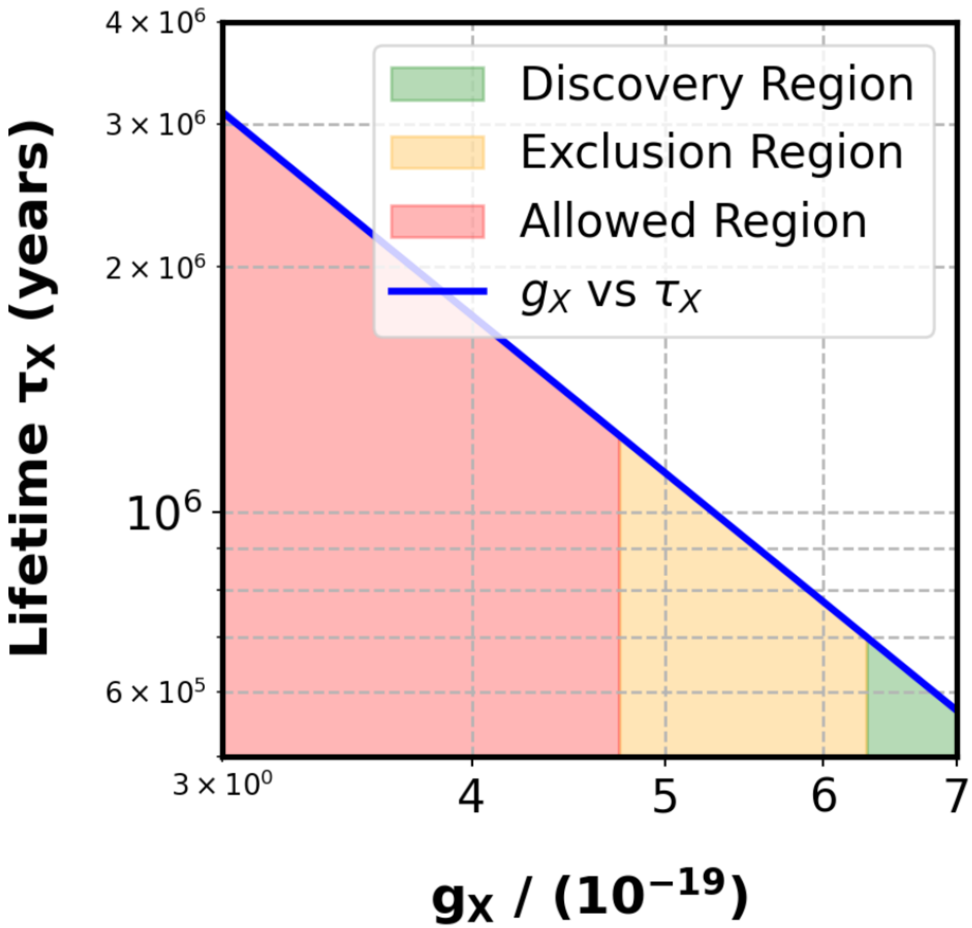


v_x is determined from the kinematics of $n \to X + \gamma$

N_{total} ~ 70 events (assuming $^{16}O \to {}^{15}O$)

NNBAR

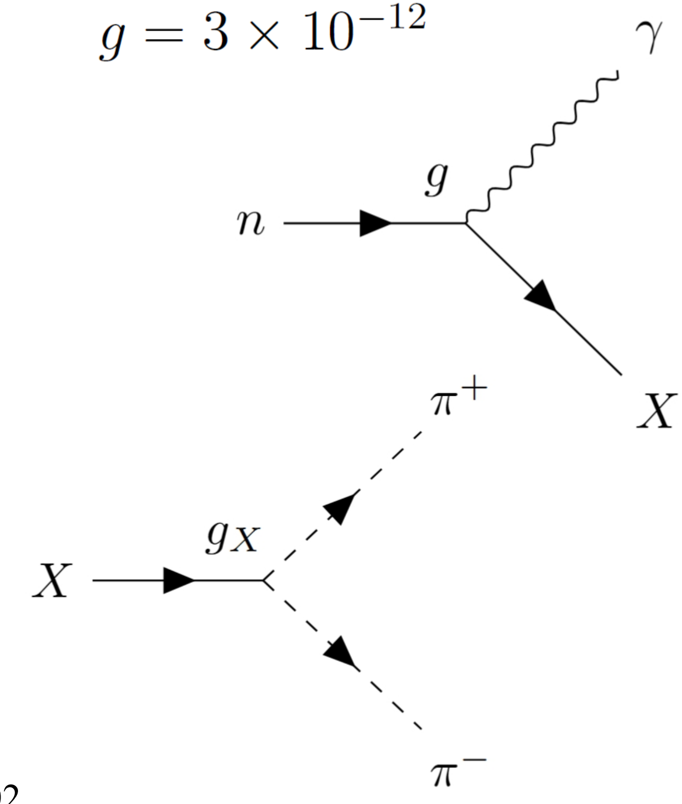
Theoretical parameter space in an effective theory



$$\Gamma_X \sim \frac{M_X}{4\pi} g_X^2$$

$$\Gamma_n \sim \frac{M_n - M_X}{4\pi \cdot \mathrm{BR}} g^2$$

$$g = 3 \times 10^{-12}$$



Motivation for long-lived ~ 1 GeV particles

- Fit within dark portal scenarios linking dark/hidden sectors with SM.
- Natural extension of particle dark matter hypothesis.
- Mass range fairly unconstrained, from MeV to GeV.

- **Hidden Sector models**:
- Suppressed couplings to SM, enabling long lifetimes.
- Can evade high-energy collider detection (e.g., displaced vertices at LHC).
- *Experimental opportunities in rare decay processes* (e.g., NNBAR).

- *Exotic ~1 GeV long-lived particles predicted in many models.*

Two-body Decay Final States

- Given low mass-gap:
  n $\rightarrow$ X + γ (fermionic X)
  n $\rightarrow$ X + ν (scalar/vector X (indistinguishable for low stats))

- **if X is a fermion:**

$$X \rightarrow P^{\pm} + e^{\mp}, \text{ where } P^{\pm} = \pi^{\pm},\ K^{\pm},\ \rho^{\pm}$$

- **if X is a boson:**

$$X \rightarrow \pi^{+,0} + \pi^{-,0}$$

$$X \rightarrow \rho^{\pm,0} + \pi^{\mp,0}$$

$$X \rightarrow K^{\pm,0} + \pi^{\mp,0}$$

$$X \rightarrow \gamma + \gamma$$