The HIBEAM/NNBAR Experiment at the ESS

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

Why Baryon Number Violation?

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).

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

A. D. Sakharov

(Submitted 23 September 1966)
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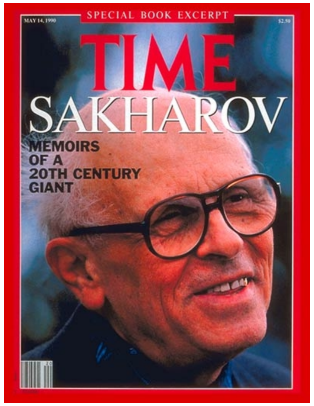
Also S7, pp. 85–88]



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- These principles have come to be attributed to Sakharov (JETP Lett. 5 1967).
- **Need for BNV is obvious.**

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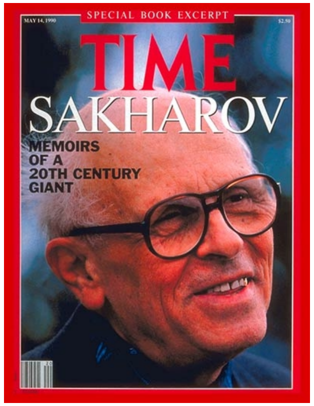
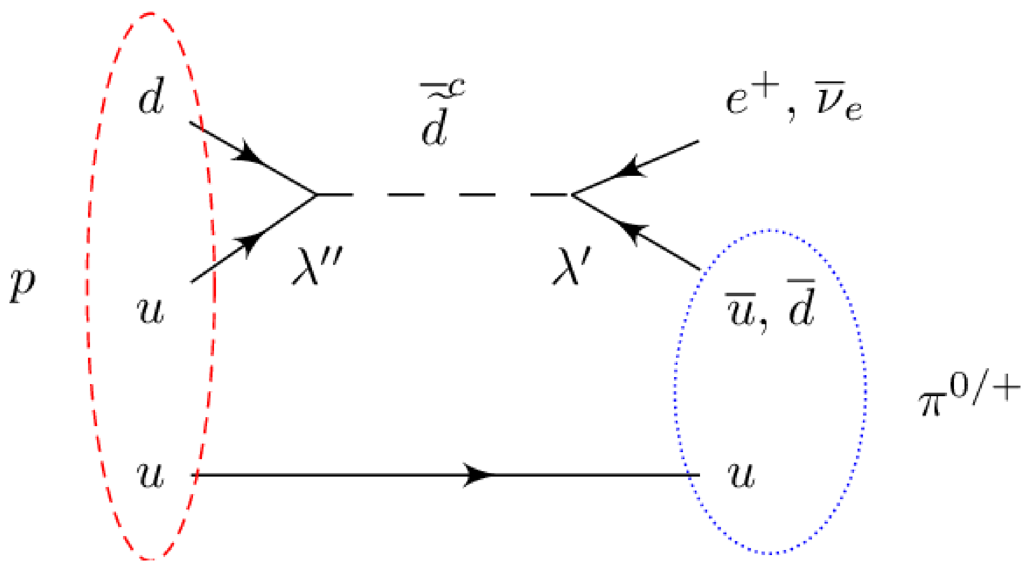


BNV in BSM models

- SM constructed in such a way that B is an accidental symmetry of the Lagrangian.
- Baryon number *broken* in extensions:
- In Grand Unified Theories (GUTs), B is necessarily violated (proton must decay, albeit with a long lifetime > 10^{30} yrs.)
- Other examples: R-parity violating (RPV) supersymmetry, hidden sector models, extra dimensions, etc.



1: Proton decay in general RPV via the lepton number violating coupling λ and the baryon number violating coupling λ .

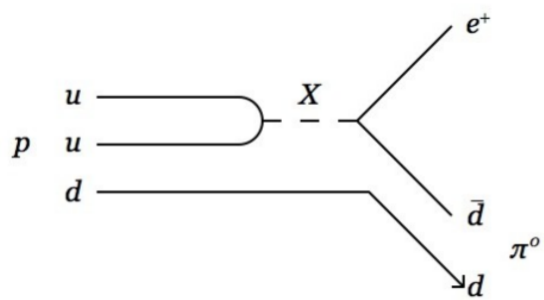
Why neutron oscillations?

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

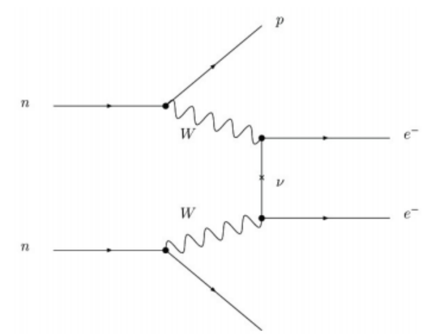
$p \rightarrow e^{+} + \pi^{0}$



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

Neutrinoless double beta decay

$0\nu 2\beta$

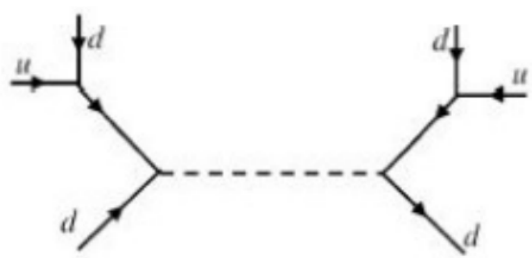


$$\Delta B = 0, \Delta L \neq 0$$

Neutron Oscillation

Neutron antineutron oscillation

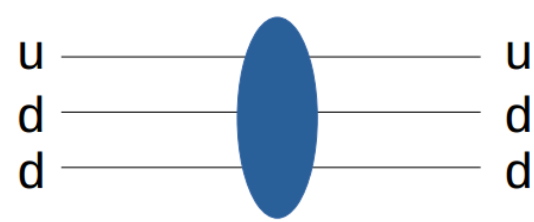
$n \rightarrow \bar{n}$



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

Neutron sterile neutron oscillation

$n \rightarrow n'$

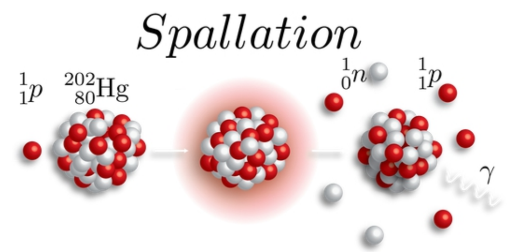


$$\Delta B = 1, \Delta L = 0$$

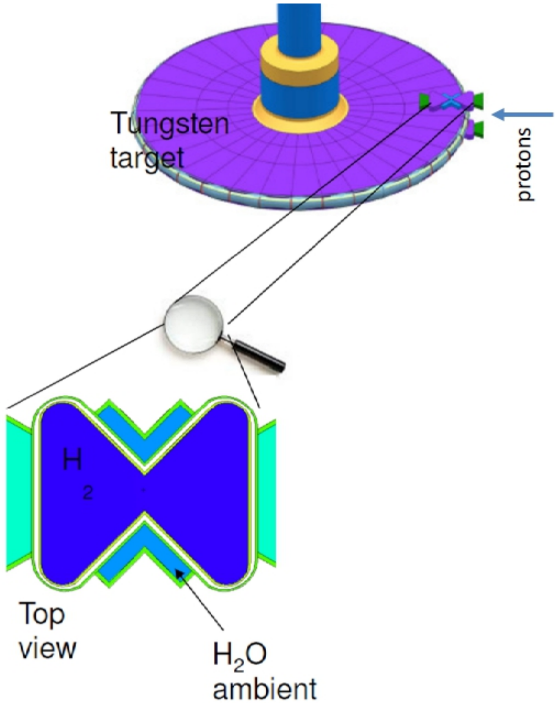
Search for neutron oscillations

- 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.

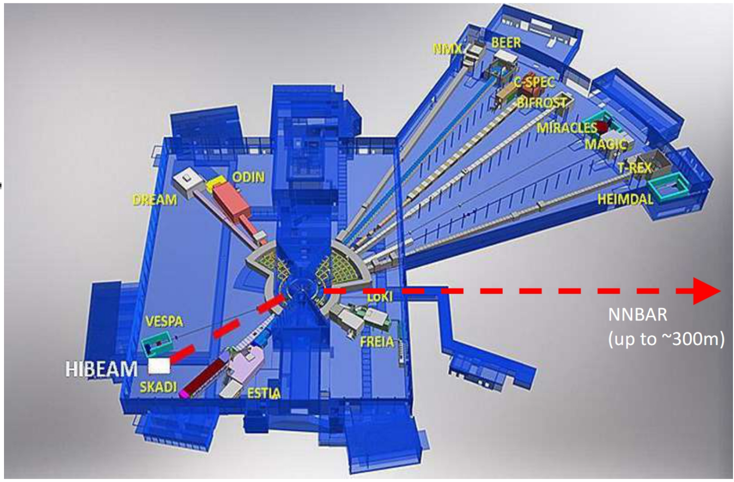
→

HIBEAM-NNBAR

HIBEAM and NNBAR

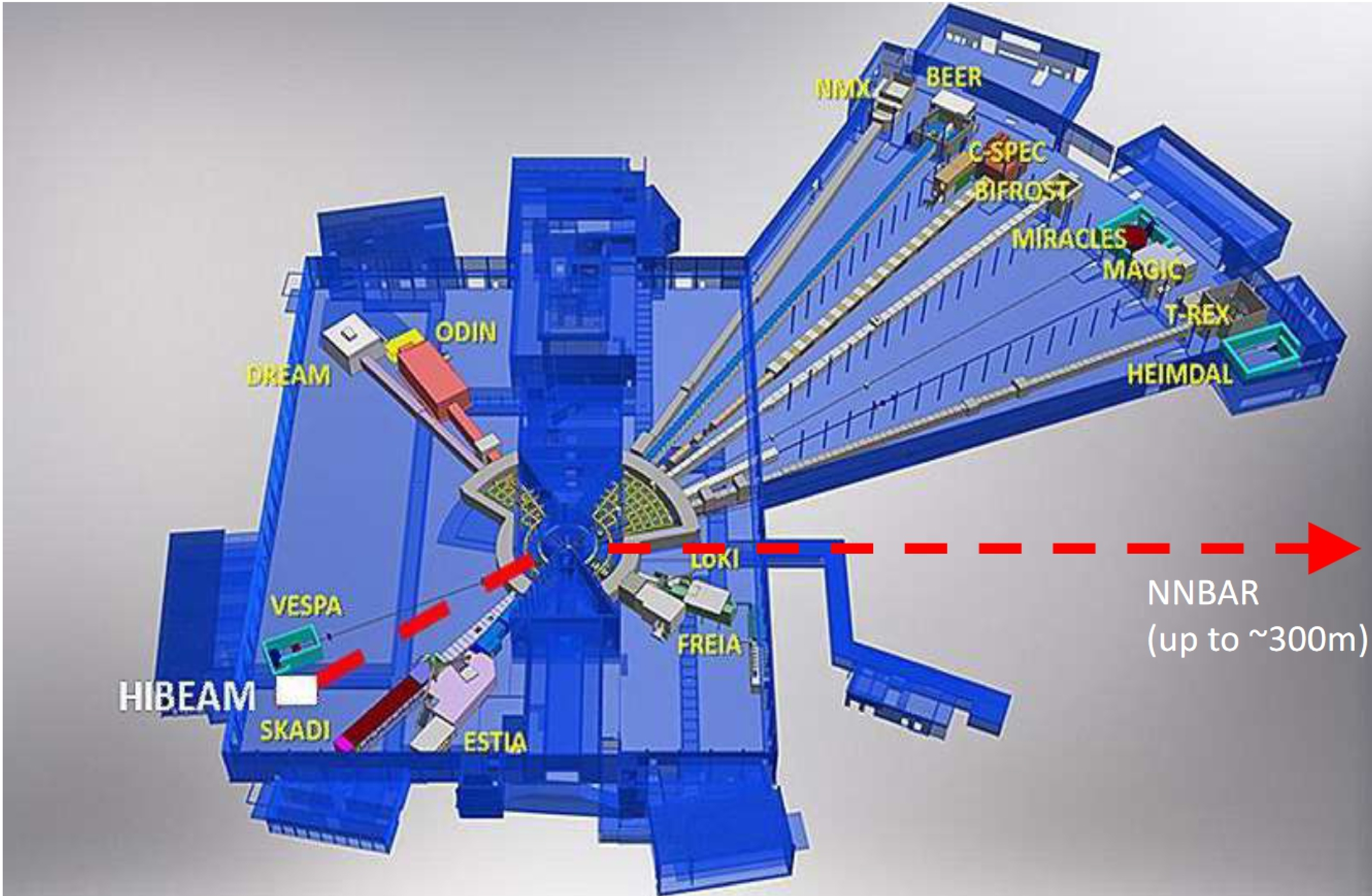
- Staged experiment

- 1. HIBEAM (High Intensity Baryon Extraction and Measurement)
  - late 2020's
  - world leading searches $n \to n'$
  - search for $n \to \bar{n}$ (with lower sensitivity)
  - also search for $n \to \bar{n}$ via sterile neutrons. *First such search*.
  - R&D for full experiment.



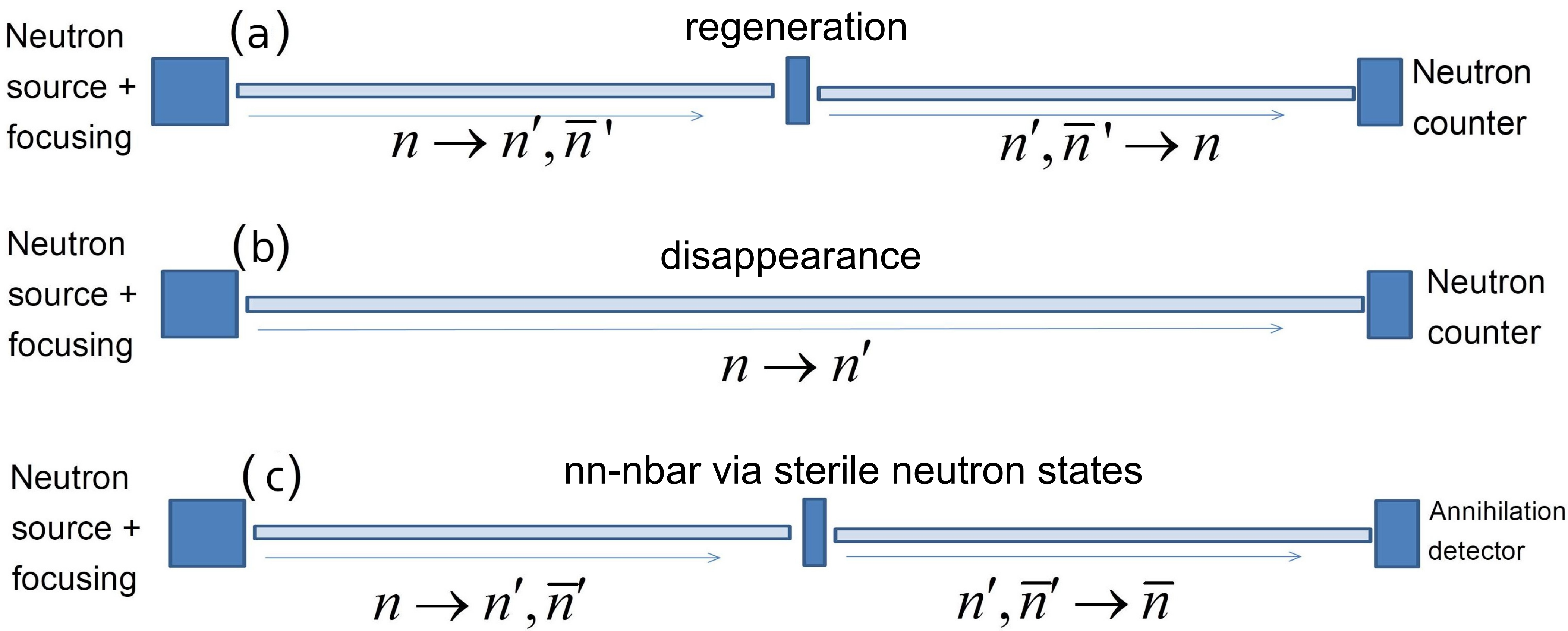
- 2. NNBAR
  - extremely high precision searches $n \to \bar{n}$, $n \to n'$
  - improve sensitivity to oscillation probability by ~ 10^3
  - After 2030

- Prototype/bg tests (cosmic rays) to start as early as 2023.


NMX
BEER
C-SPEC
BIFROST
MIRACLES
MAGIC
T-REX
HEIMDAL
ODIN
DREAM
LoKI
NNBAR
(up to ~300m)
VESPA
FREIA
HIBEAM
SKADI
ESTIA

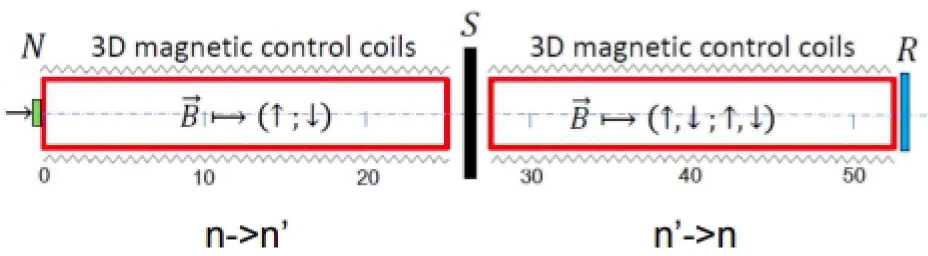
HIBEAM searches

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

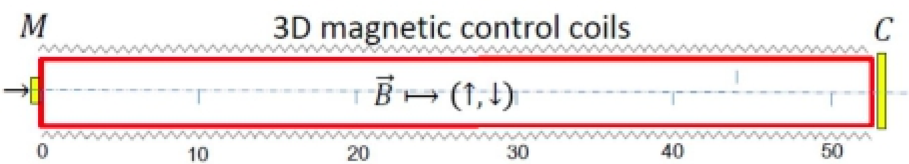


HIBEAM discovery sensitivity

Regeneration



Disappearance



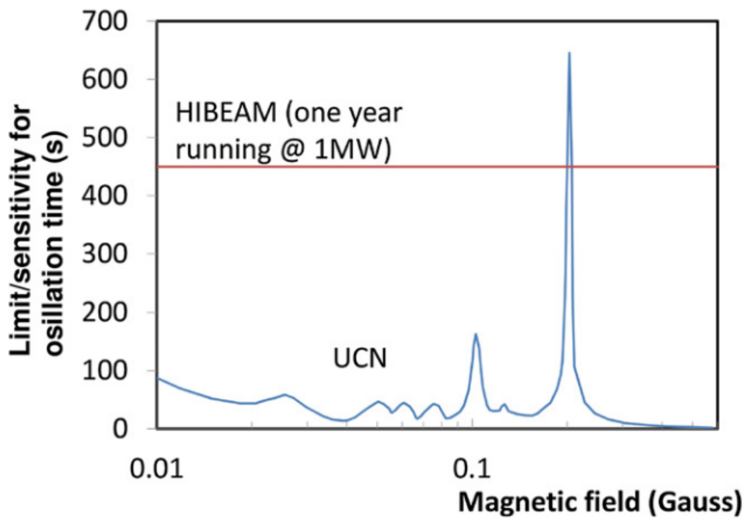


Figure 22. Excluded neutron oscillation times in blue for $n \to n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power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

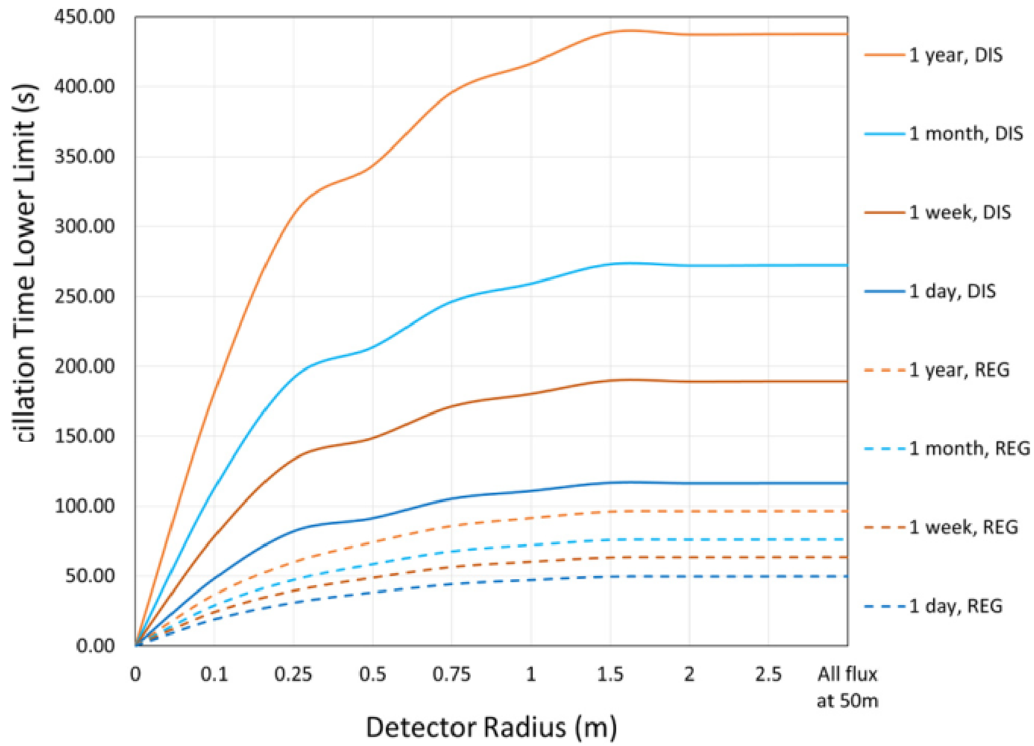


Figure 21. Sensitivity at 95% CL for the discovery of $\tau^{\rm dis}_{n\to n'}$ (disappearance, 'dis') and $\tau^{\rm reg}_{n\to n'}$ (regeneration, 'reg') for various detector radii for the nominal 1 MW HIBEAM/ANNI flux at 50 m. A background rate of 1 n s^{-1} is assumed for the regeneration search.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

NNBAR

NNBAR

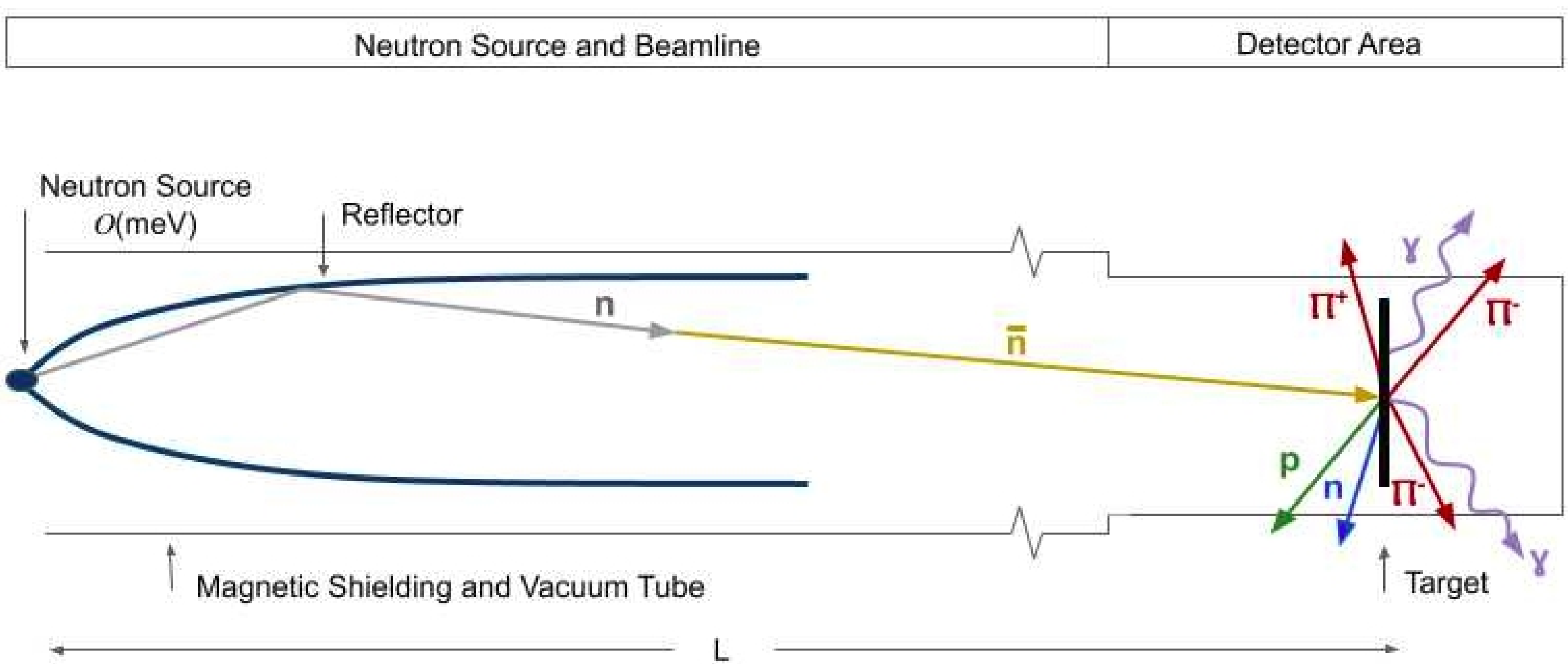
NNBAR experiment

- Goal: observe $n \longrightarrow \bar{n}$ (*only BN is violated by 2 units!*)
- Strategy: let as many neutrons "fly" for as long as possible
- Probability of free neutron transformation into an antineutron:

$$P(\bar{n},t) = (t/\tau)^2$$

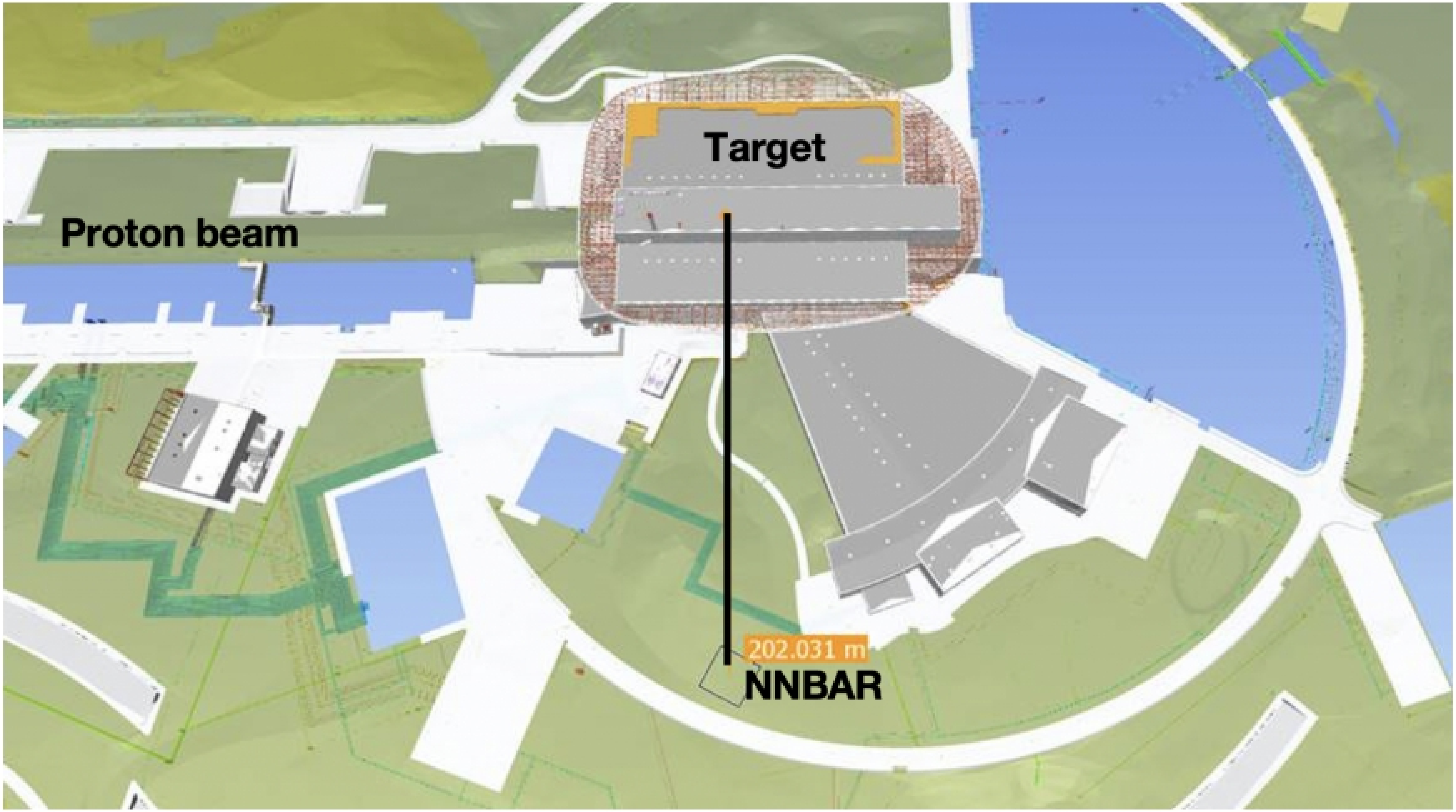
FOM= Nt^2

- t → neutron flight time; τ → "oscillation time" (BSM predicted, model dependent)

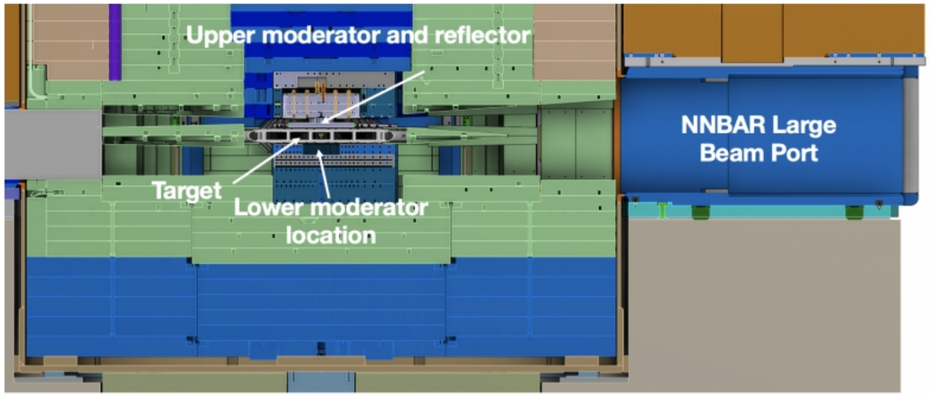


$\tau > 8.7\ 10^7$s (ILL)

NNBAR@ESS



NNBAR Large Beam Port (LBP)



Substantial investment (~4M SEK) from ESS with NNBAR in mind

Figure 2: Cross sectional view of the ESS target/moderator area and the inner shielding. In the figure it is shown the location of the ESS upper and lower moderator. The NNBAR experiment will view both moderators.

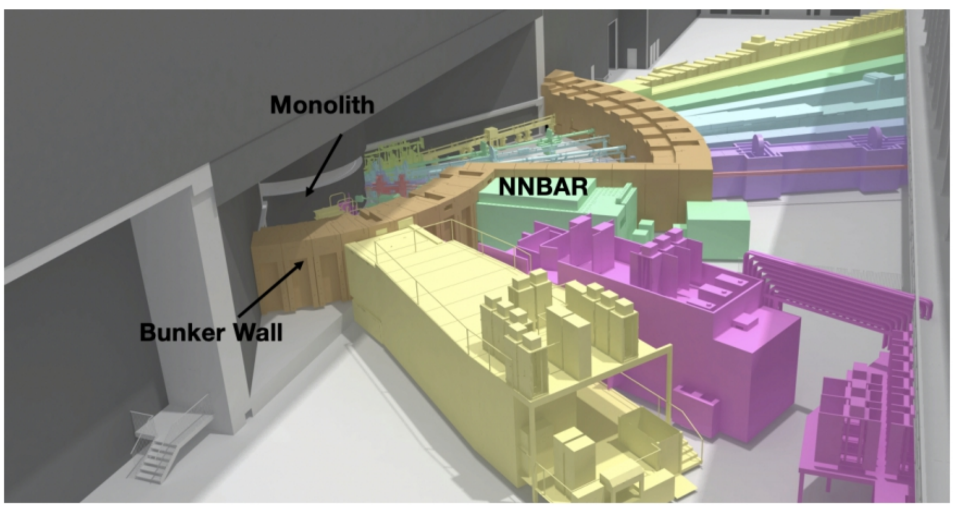


Figure 4: The ESS monolith and bunker area. At the start of ESS operation, the NNBAR location will be occupied by the test beamline, used in the early days of the ESS operation to characterize the target-reflector-moderator system. Also shown in the figure are the caves of the LOKI (purple) and FREIA (yellow) instruments.

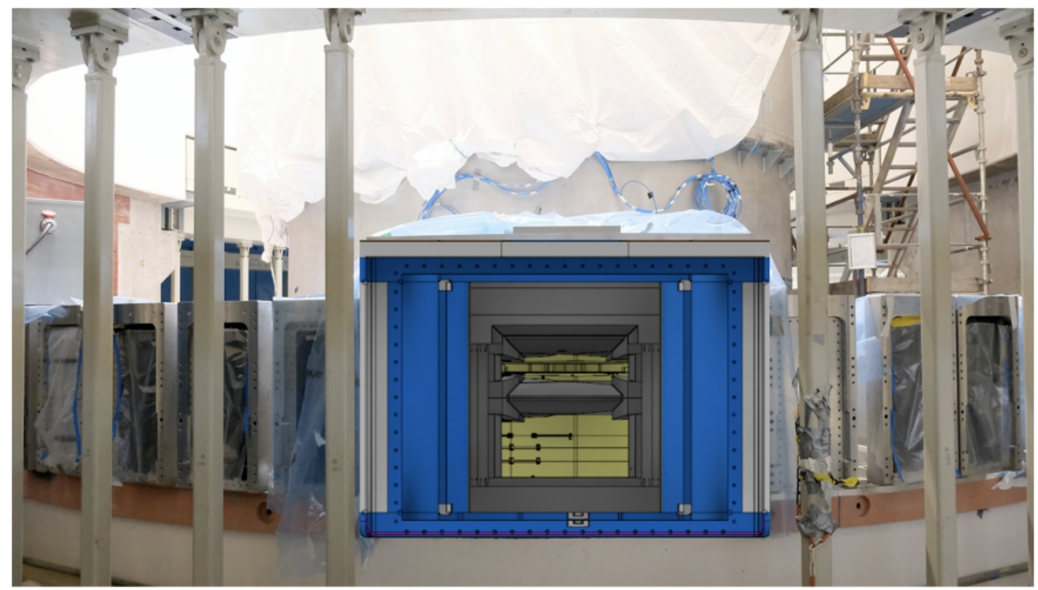


Figure 3: Photograph of the frame of the Large Beam Port being installed in the ESS monolith. A superimposed CAD drawing is showing the field of view of the LBP. The upper moderator, the inner shielding to avoid a direct view of the target, and the space below the target where the high-intensity moderator will be placed, can be clearly seen.

Potential Gains w.r.t. ILL

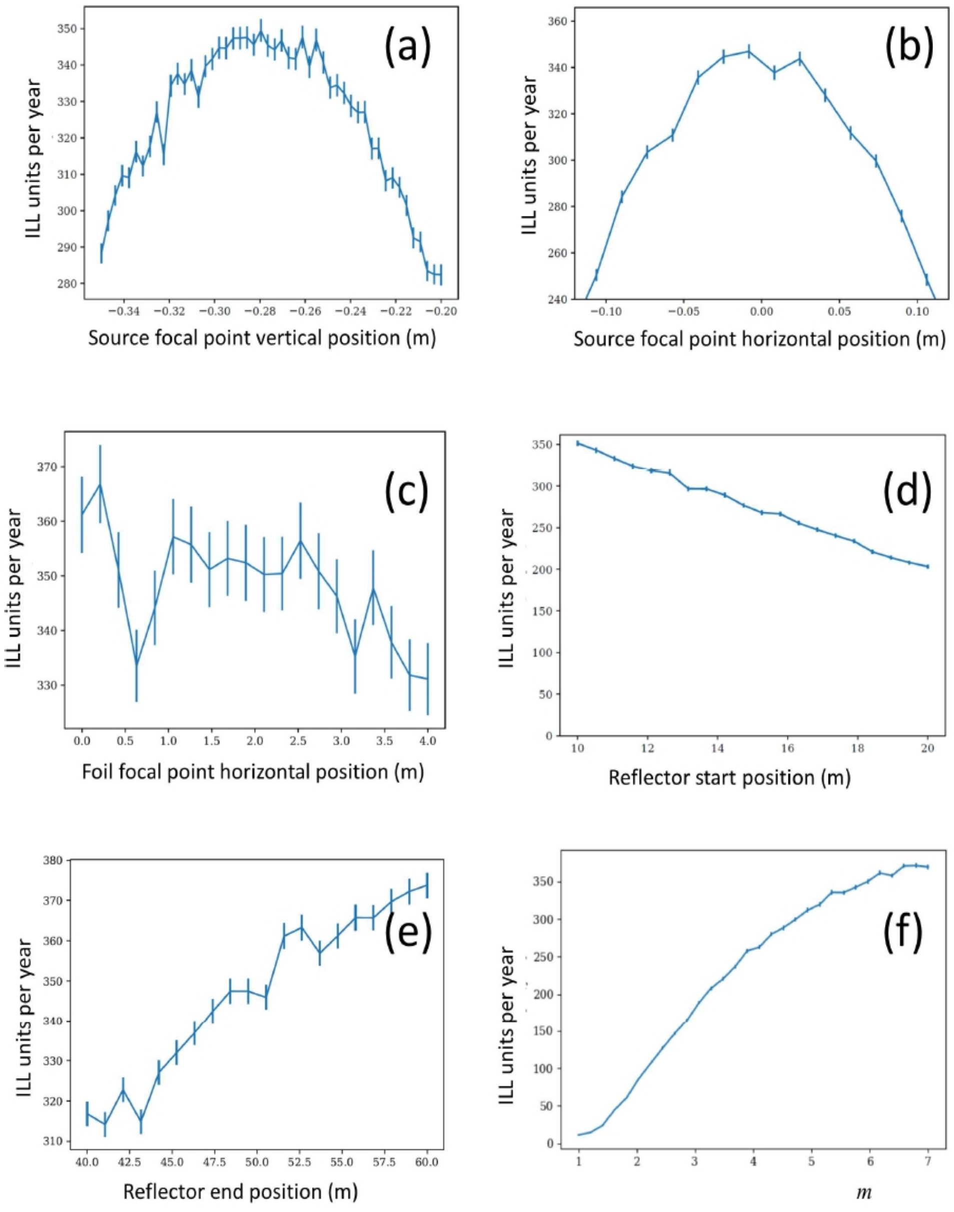
Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

x 1000 in probability, reach $\tau \sim 2\text{-}3 \times 10^9$ s

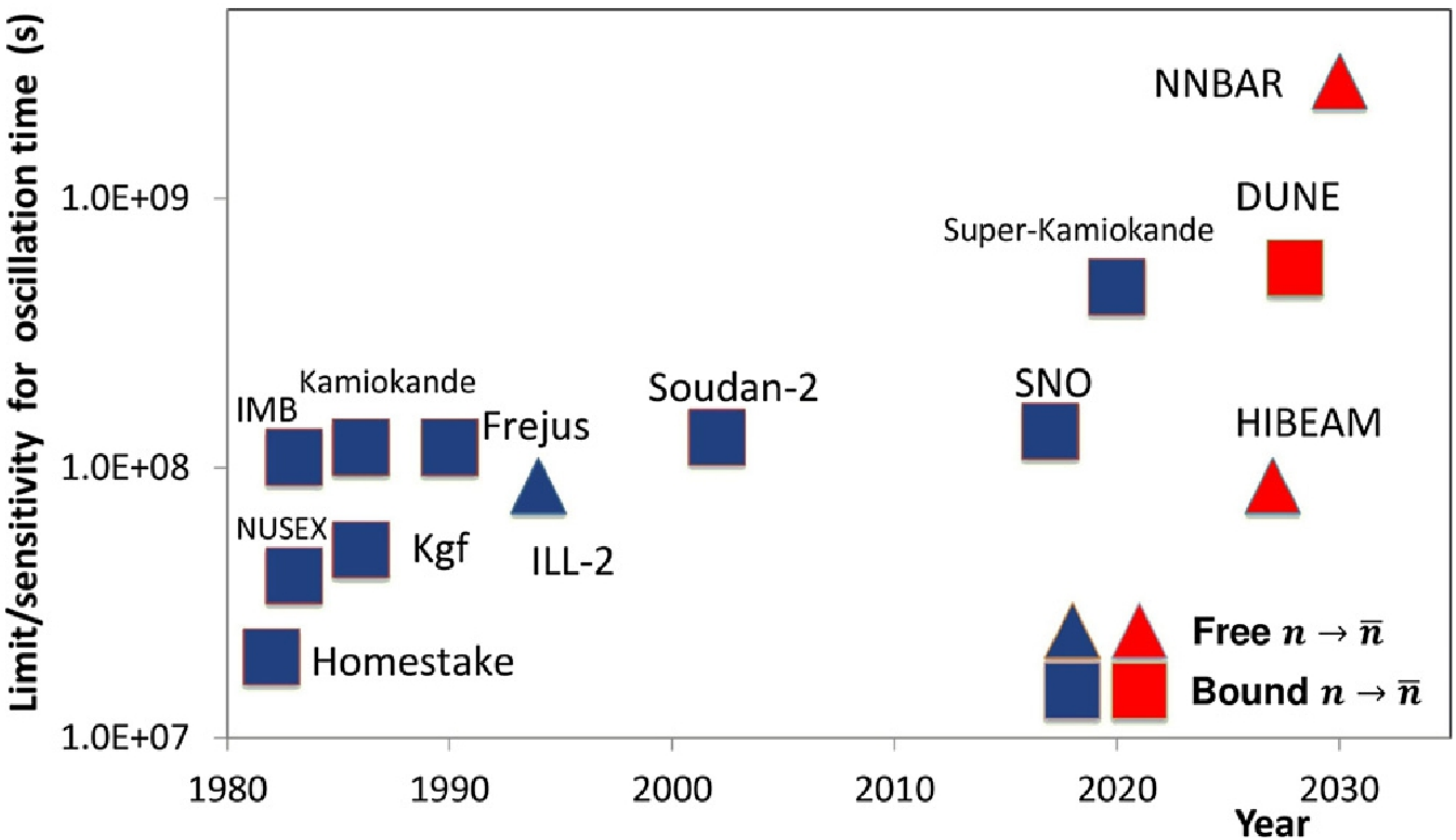
Opportunity to test a global symmetry with three orders of magnitude better precision than previously done is rare!!

NNBAR sensitivity

- With cold LD moderator
- ~350 ILL units per year
- Conservative assumptions
  (e.g. low efficiency)
- Room for surprises, e.g.,
  low ESS power.



Comparison with past and future experiments



Moderator source

NNBAR moderator source

PERFORMANCE

- Integrated intensity for λ > 4 Å : 6.9 × 10^{15} n/s/sr
- Typical values from cylindrical geometry: 3.5 × 10^{15} n/s/sr (24X24 cm^2 opening)
- Original value from 2014 paper arXiv:1401.6003 :
  2.85 × 10^{15} n/s/sr (25X21 cm2 opening)

- The increase is due to:
  - Larger extraction opening: 24X40 cm2
  - Use of box geometry instead of cylindrical
  - Use of Be filter.

- NB all these values are for physics models, the performance will decrease adding engineering details

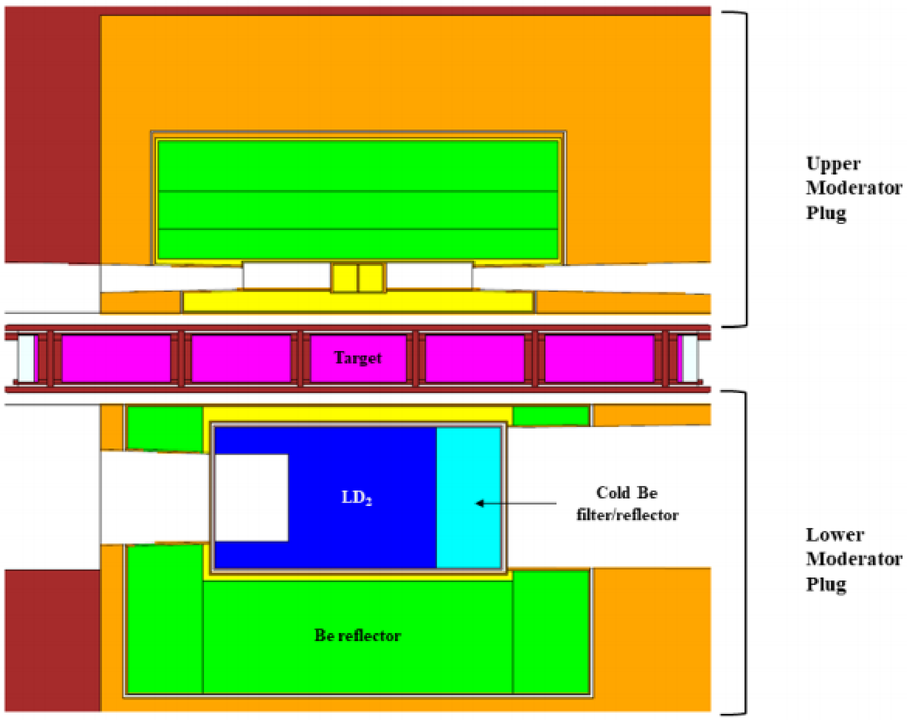
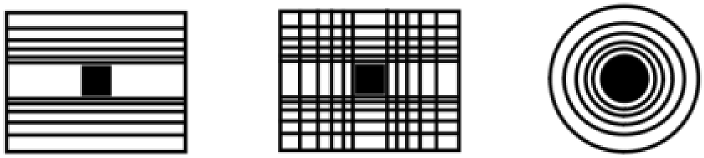


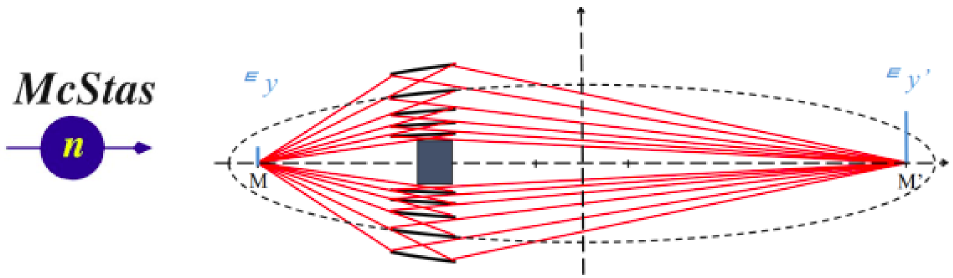
Figure 7: MCNP model of the ESS target with the upper and lower moderator systems. The proton beam is incident on the tungsten spallation target (purple), entering the figure. The NNBAR opening is located on the right side of the moderator while the condensed matter opening is on the left side. Orange and brown = steel (twister frame and inner shielding), green = beryllium reflector, yellow = light water, dark blue = liquid ortho-deuterium, light blue = cold beryllium filter.

NNBAR Optics

Optics

- Design of a nested system of neutron mirrors
- Elliptical mirrors (foci located in moderator and detector) in planar or cylindrical arrangement
- McStas Simulations of performance of a given optical system



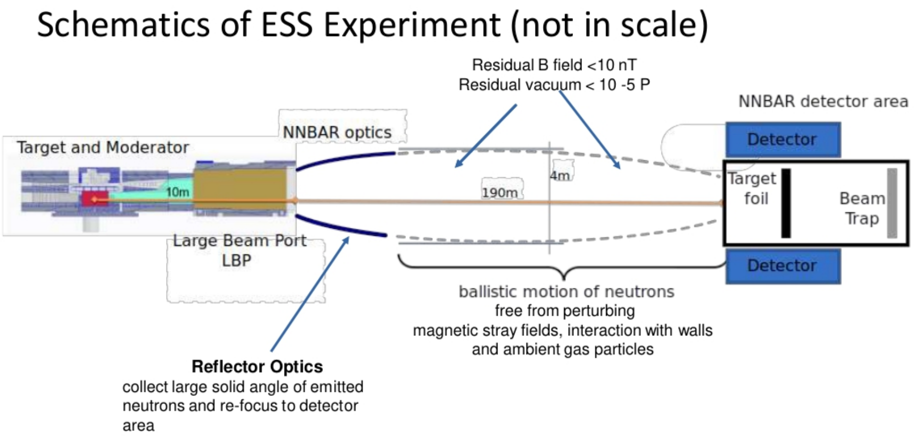


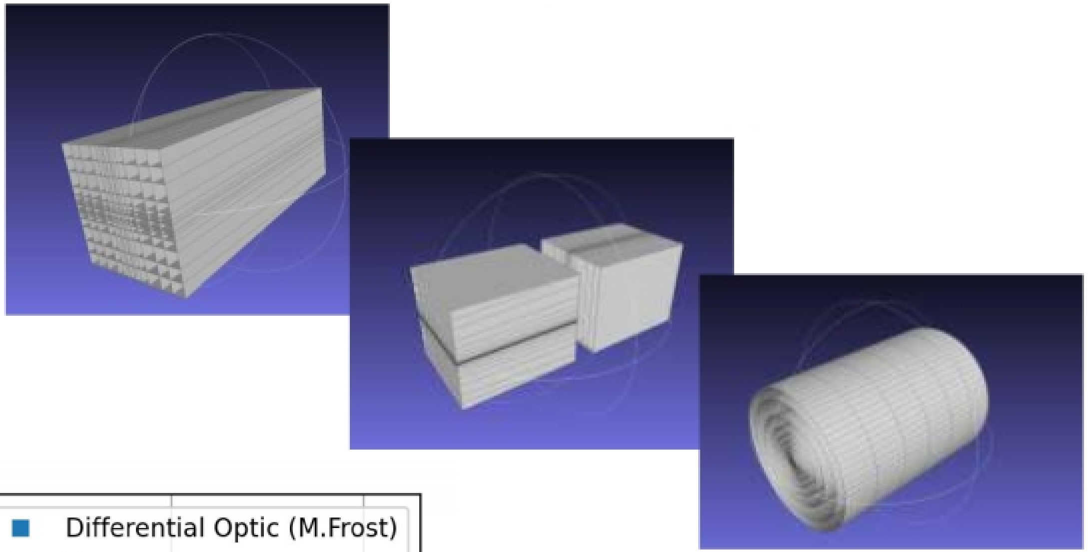
arXiv:1611.07353
Journal of Neutron Research 20 (2018) 91-98

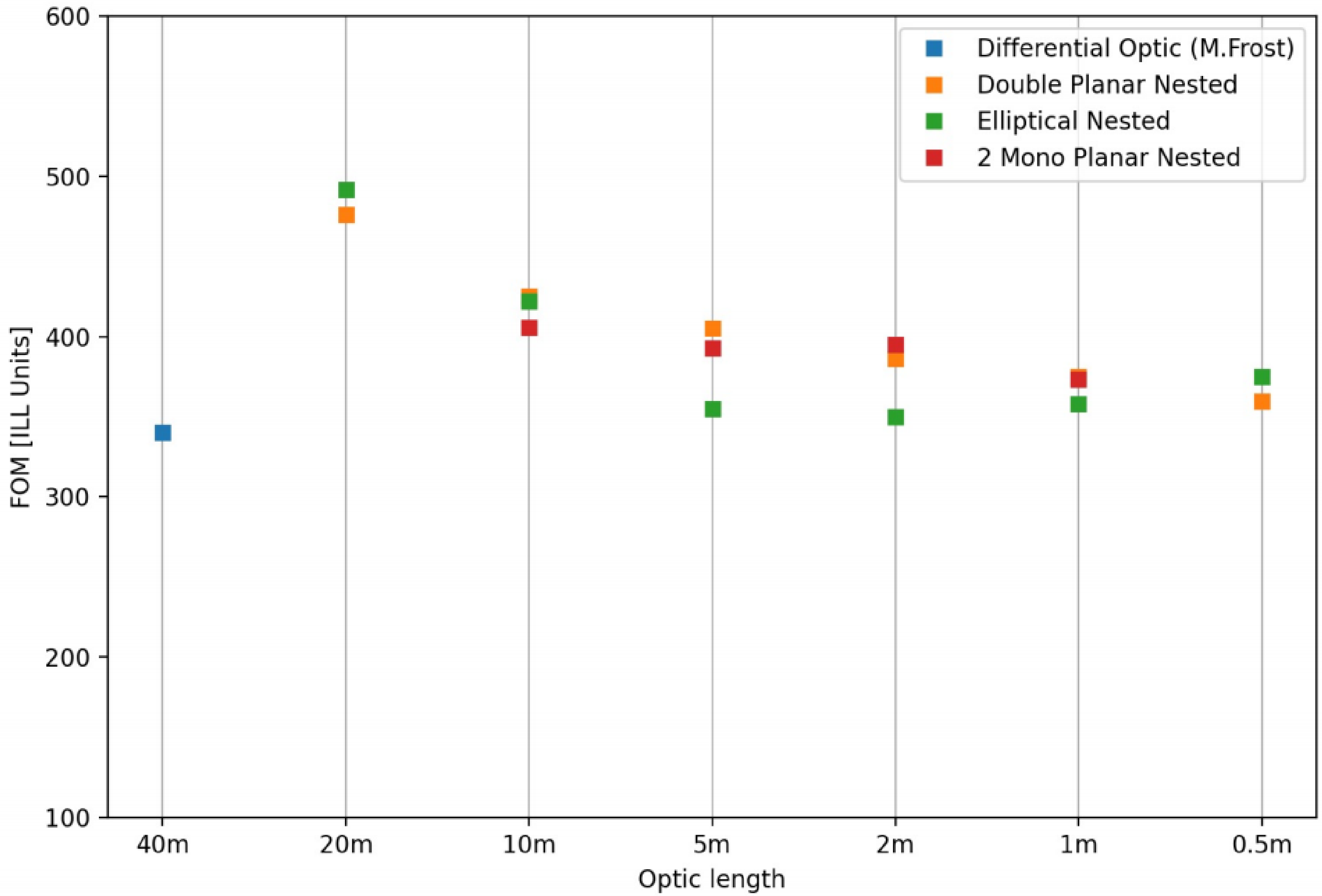
Different optics are compared using the quantity: $FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}}$

Unit is 1991 experiment

NNBAR Optics results





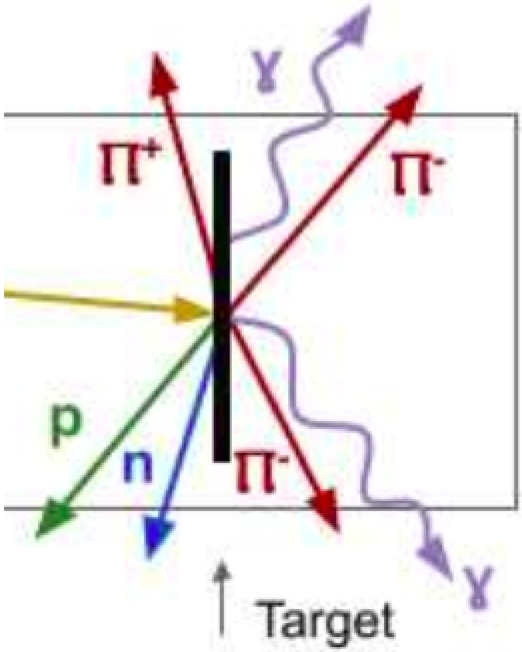


Annihilation detector

Detector requirements

Requirements for the detector:

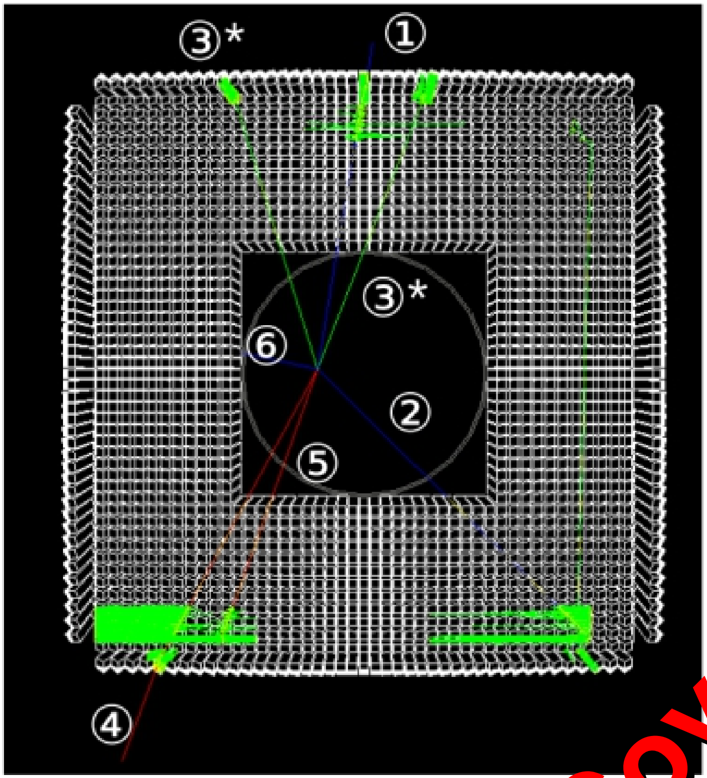
- Reconstruction of multi-pion final state
- Invariant mass reconstruction
- Particle identification
- Timing sensitivity to reject cosmics and other out-of-time backgrounds

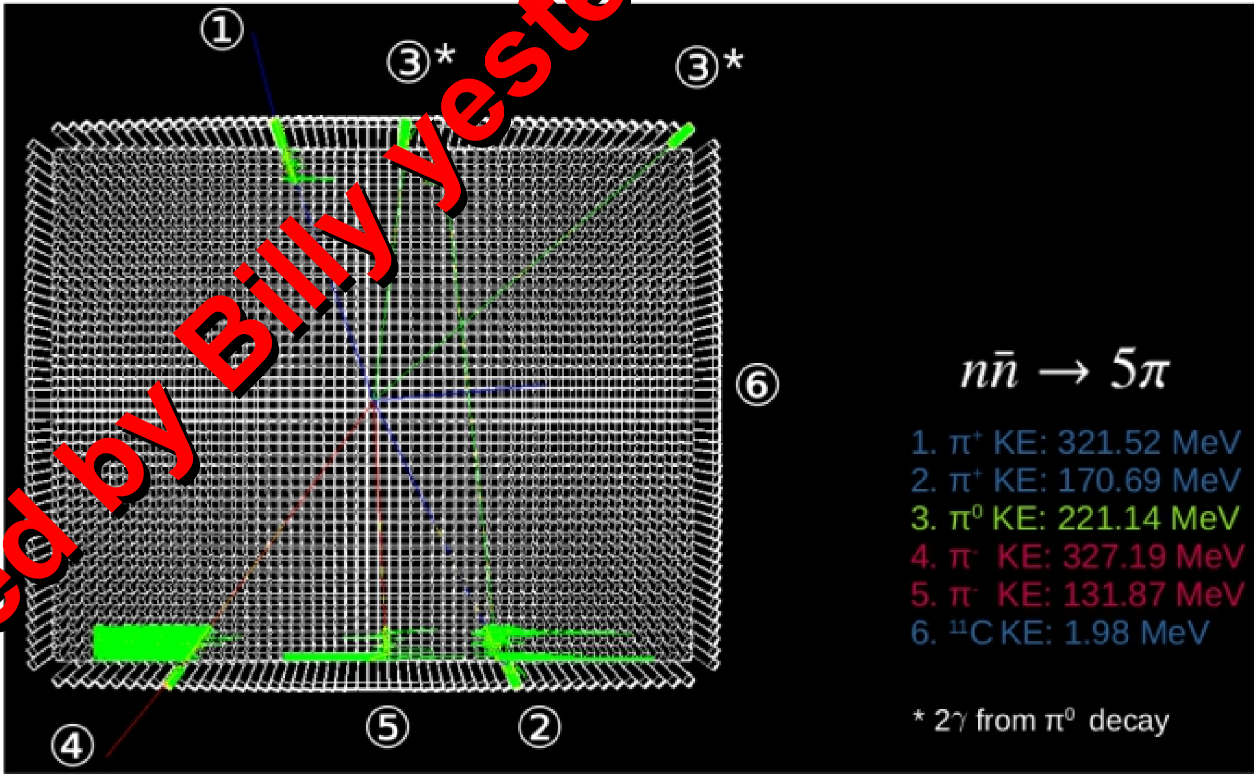


NNBAR

Annihilation detector

Covered by Billy yesterday! :-)

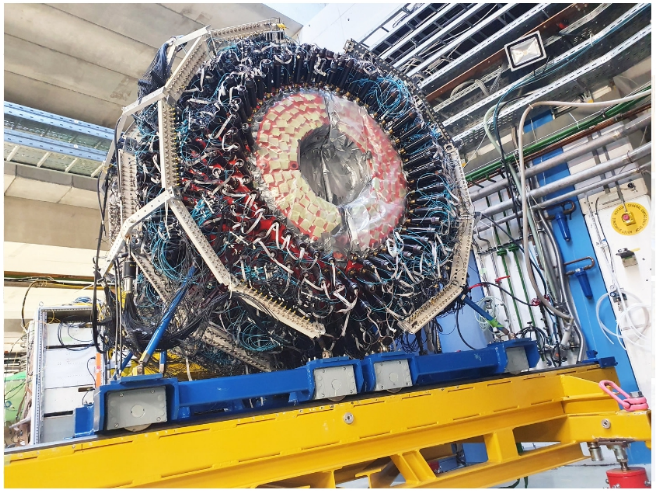


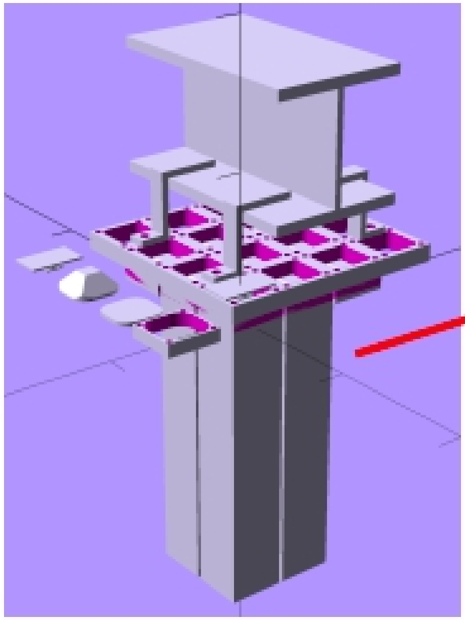


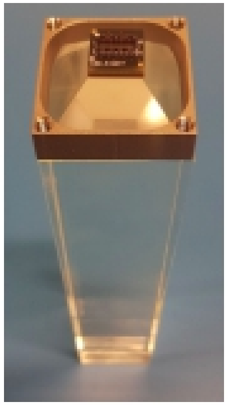
Detector Prototype

Detector prototype

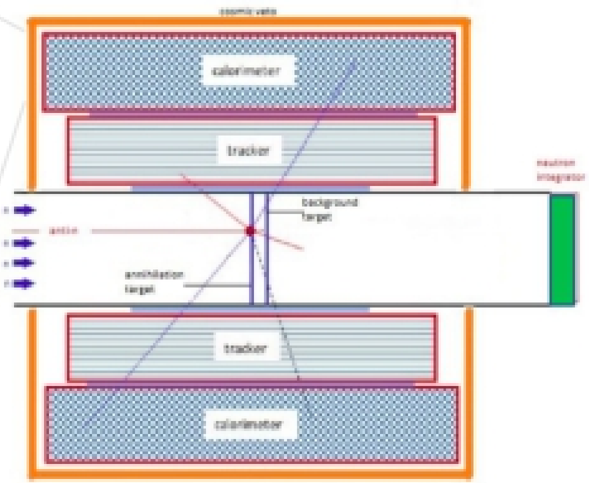
- Calorimeter and TPC prototype already being built!
- Exploring use of WASA calorimeter for HIBEAM.
- DAQ system under development.



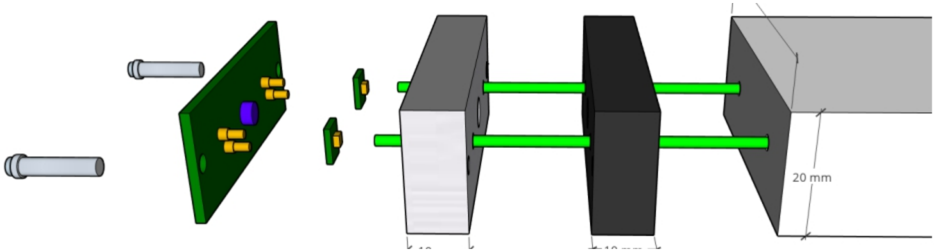




Lead-glass EM calorimeter



Hadronic range detector (plastic scintillator staves)



NNBAR Collaboration

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).

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

A Addazi[1,2], K Anderson[7], S Ansell[8], K S Babu[9], J L Barrow[10], D V Baxter[11,12,13], P M Bentley[14], Z Berezhiani[15,16], R Bevilacqua[14], R Biondi[15], C Bohm[17], G Brooijmans[17], L J Broussard[7], J Cedercäll[18], C Crawford[19], P S B Dev[20], D D DiJulio[14], A D Dolgov[21,22], K Dunne[17], P Fierlinger[3], M R Fitzsimmons[10], A Fomin[23], M J Frost[7], S Gardiner[7], S Gardner[19], A Galindo-Uribarri[7], P Geltenbort[24], S Girmohanta[4], P Golubev[18], E Golubeva[25], G L Greene[10], T Greenshaw[26], V Gudkov[27], R Hall-Wilton[14], L Heilbronn[10], J Herrero-Garcia[28], A Holley[29], G Ichikawa[30], T M Ito[31], E Iverson[7], T Johansson[32], L Jönsson[32], Y-J Jwa[17], Y Kamyshkov[10], K Kanaki[14], E Kearns[33], Z Kokai[14], B Kerbikov[34,35,36], M Kitaguchi[37], T Kittelmann[14], E Klinkby[38], A Kobakhidze[39], L W Koerner[40], B Kopeliovich[22], A Kozela[41], V Kudryavtsev[42], A Kupsc[31], Y T Lee[14], M Lindroos[14], J Makkinje[43], J I Marquez[14], B Meirose[17,18], T M Miller[14], D Milstead[17,*] R N Mohapatra[44], T Morishima[36], G Muhrer[14], H P Mumm[45], K Nagamoto[36], A Nepomuceno[46], F Nesti[16], V V Nesvizhevsky[24], T Nilsson[47], A Oskarsson[18], E Paryev[25], R W Pattie Jr[48], S Penttil[7], H Perrey[18], Y N Pokotilovski[18], I Potashnikovav[40], K Ramic[14], C Redding[49], J-M Richard[50], D Ries[51], E Rinaldi[52,53], N Rizzi[37], N Rossi[15], A Ruggles[49], B Rybolt[54], V Santoro[14], U Sarkar[55], A Saunders[14], G Senjanovic[56,57], A P Serebrov[23], H M Shimizu[36], R Shrock[4], S Silverstein[17], D Silvermyr[18], W M Snow[11,12,13],

A Takibayev[14], I Tkachev[25], L Townsend[58], A Tureanu[59], L Varriano[60], A Vainshtein[61,62], J de Vries[63,64], R Wagner[24], R Woracek[14], Y Yamagata[65], S Yiu[17], A R Young[66], L Zanini[14], Z Zhang[67] and O Zimmer[24]

Summary and outlook

- BNV is expected in Nature.
- Key ingredient to explain baryon asymmetry of the Universe.
- HIBEAM/NNBAR active experimental program for the ESS.
- Addresses BNV ($\Delta B = 1$ and $\Delta B = 2$)!
- HIBEAM – world leading sterile neutron searches + pilot free $n \longrightarrow \bar{n}$ search.
- NNBAR – world leading neutron-antineutron oscillation searches.

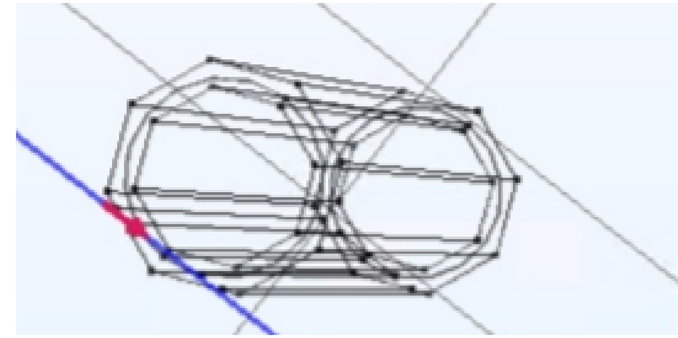
LUNDS UNIVERSITET

NNBAR

Stockholm University

BACKUP

Magnetics



- Shield geometry
  - Outer + inner octagon shield from mu-metal
  - Round steel vacuum chamber: between shields
  - COMSOL simulations
- <10 nT
- Monte Carlo study of inefficiency due to finite magnetic field with field map