Searches for baryon number violation in the HIBEAM-NNBAR experiment at the European Spallation Source

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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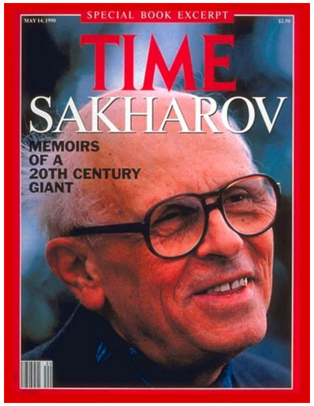

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- These principles have come to be attributed to Sakharov (JETP Lett. 5 1967).
- **Need for BNV is obvious**.

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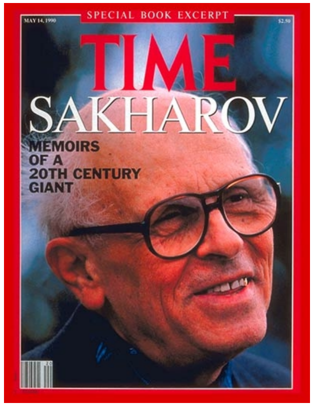
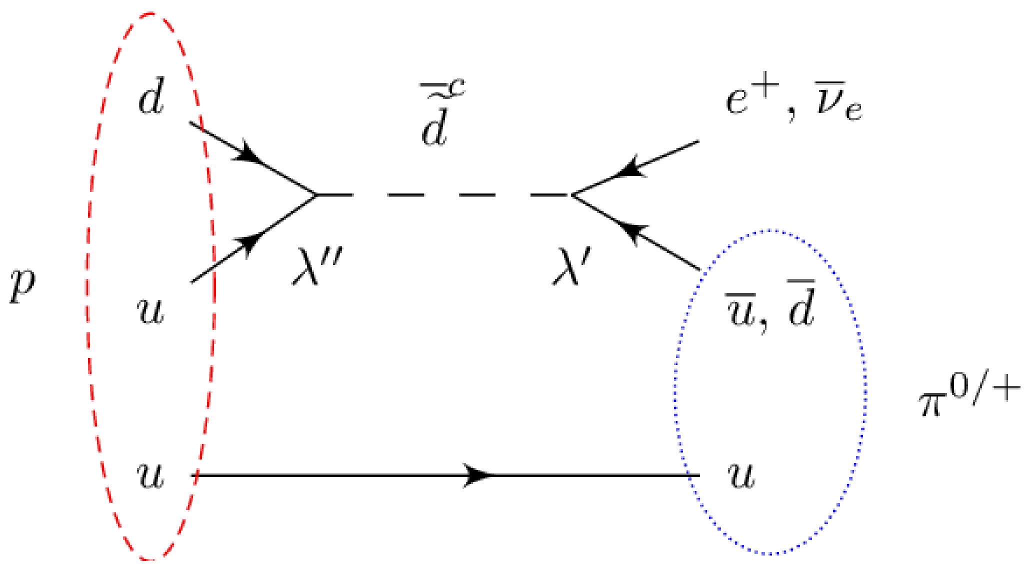


BNV in BSM models

- 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 .

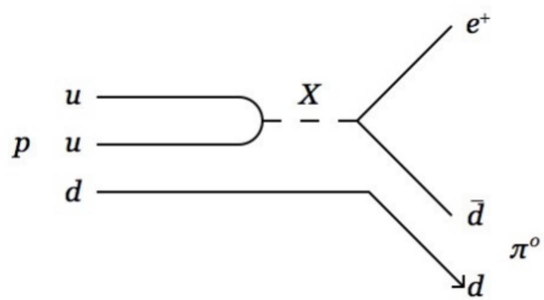
Why neutron oscillations?

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

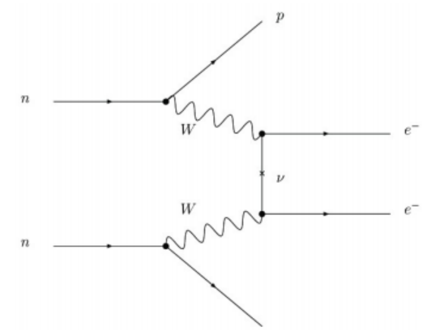
$p \to e^{+} + \pi^{0}$



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

Neutrinoless double beta decay

$0\nu 2\beta$

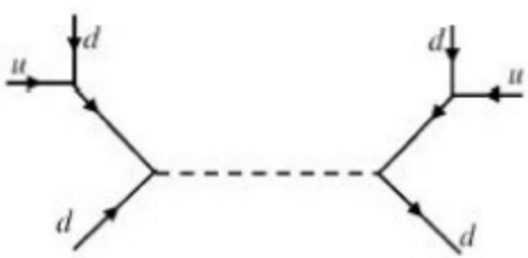


$$\Delta B = 0, \Delta L \neq 0$$

Neutron Oscillation

Neutron antineutron oscillation

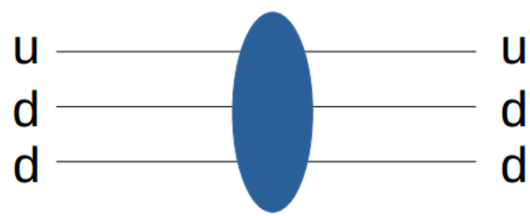
$n \to \bar{n}$



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

Neutron sterile neutron oscillation

$n \to n'$



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

Search for neutron oscillations

- Assumption: baryon number violation (BNV)
- If BNV → $n \rightarrow \bar{n}$ permitted
- How? → bound or free $n \rightarrow \bar{n}$ search
- For bound neutrons:
  signal is annihilation of oscillated antineutron with another nucleon.

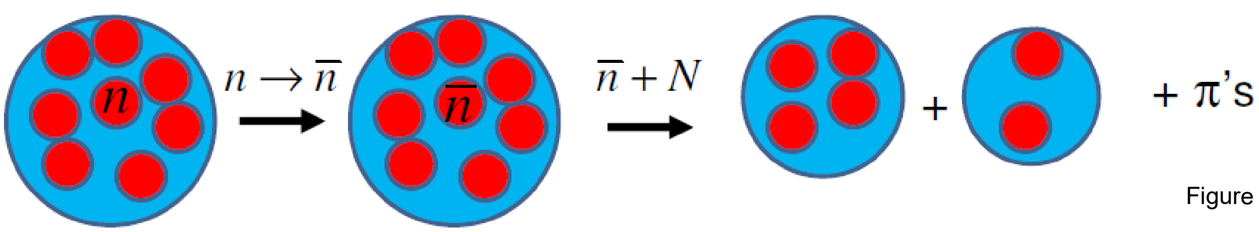


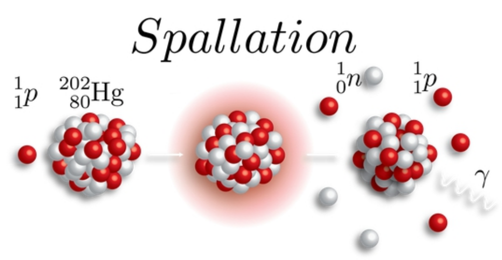
Figure by D. Milstead

- Rate suppressed by nuclear suppression factor R (~10^{23}) w.r.t free neutrons
- Model dependent

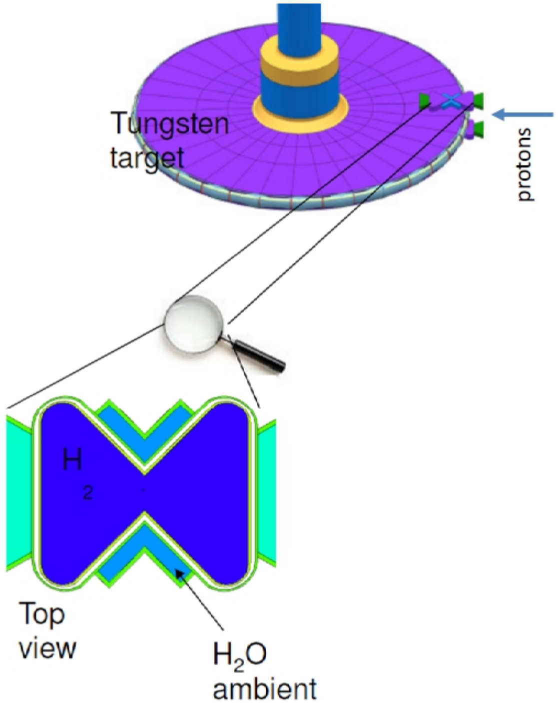
Search for neutron oscillations

- 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



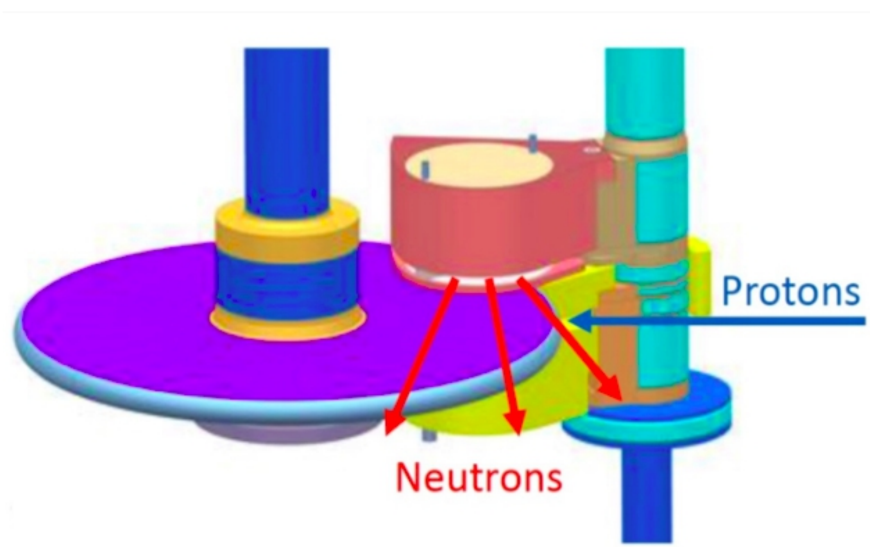
- **To increase *probability of*** $n \rightarrow \bar{n}$:
- t large → slow (a.ka. "cold" → few meV) need lots of collisions → moderators
- We also want as many neutrons as possible.

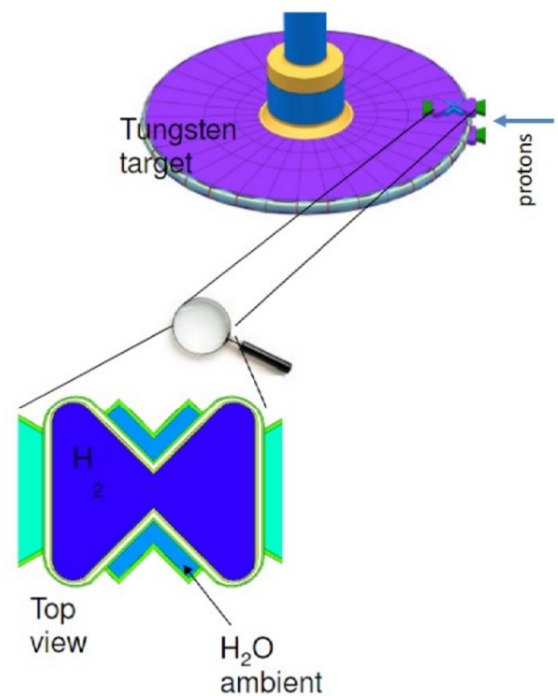
ESS

EUROPEAN SPALLATION SOURCE

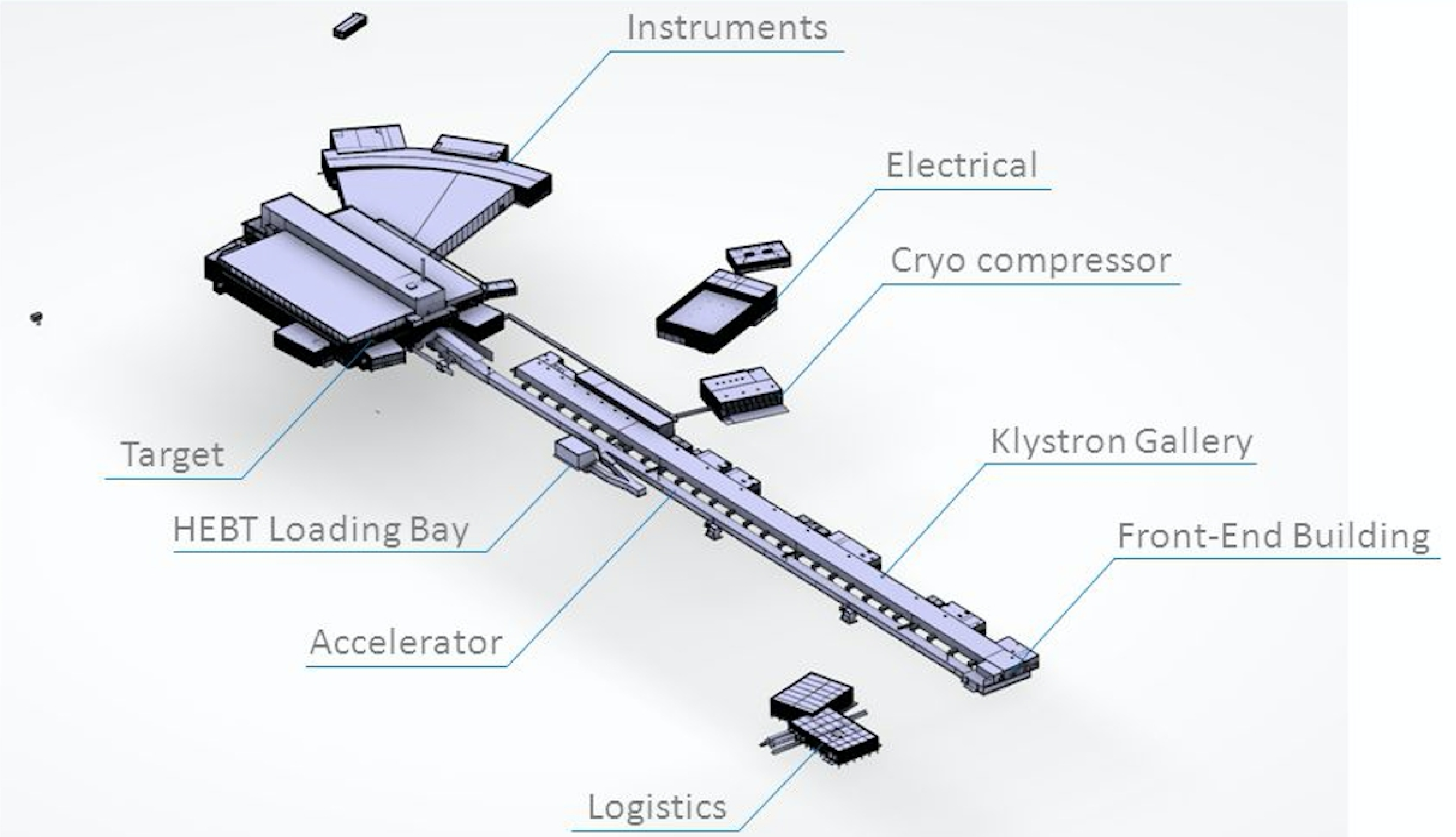
ESS – a neutron factory

- High intensity spallation source
- Place: Lund, Sweden
- Under construction (user program starts 2027)
- 2 GeV protons (3ms long pulse hit rotating tungsten target)
- Cold neutrons after interaction with moderators (~ $10^{12\text{-}13}$ n/s)

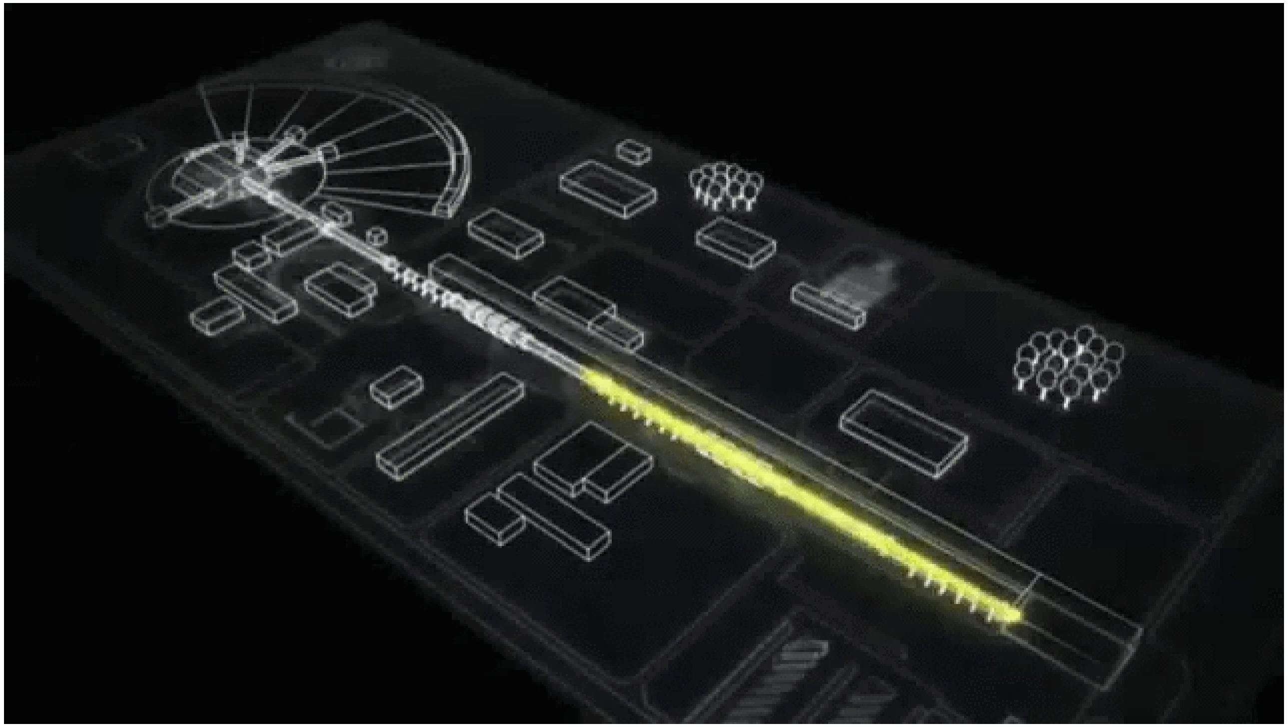




ESS Accelerator (I)



The protons are accelerated to almost the speed of light in pulses hitting the target 14 times per second

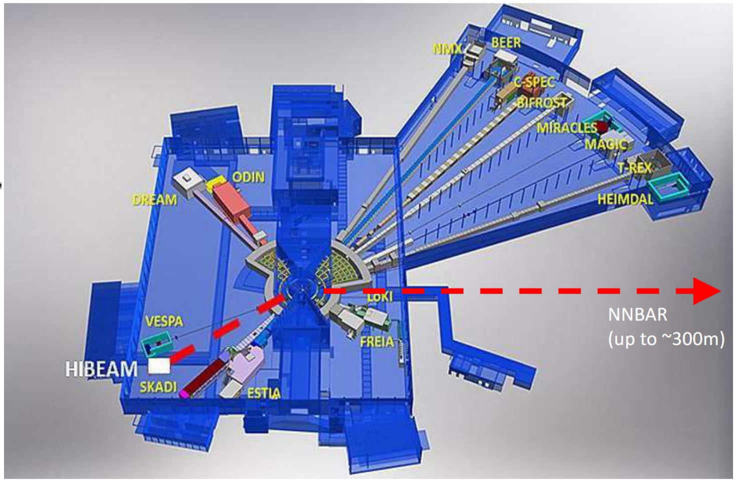


HIBEAM-NNBAR

HIBEAM and NNBAR

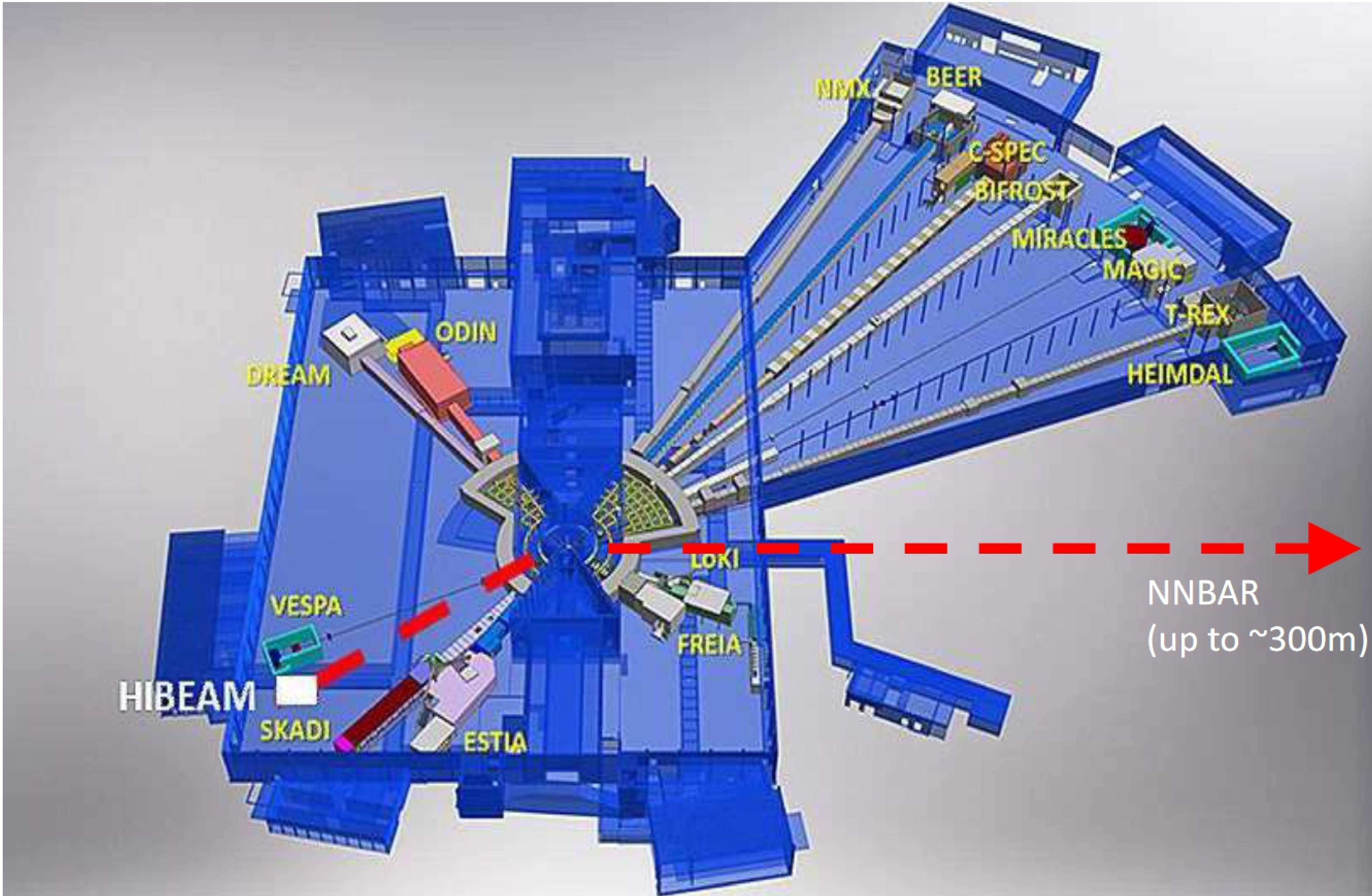
- Staged experiment

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



- 2. NNBAR
  - extremely high precision searches $n \rightarrow \bar{n}$, $n \rightarrow n'$
  - 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
VESPA
FREIA
HIBEAM
SKADI
ESTIA
NNBAR
(up to ~300m)

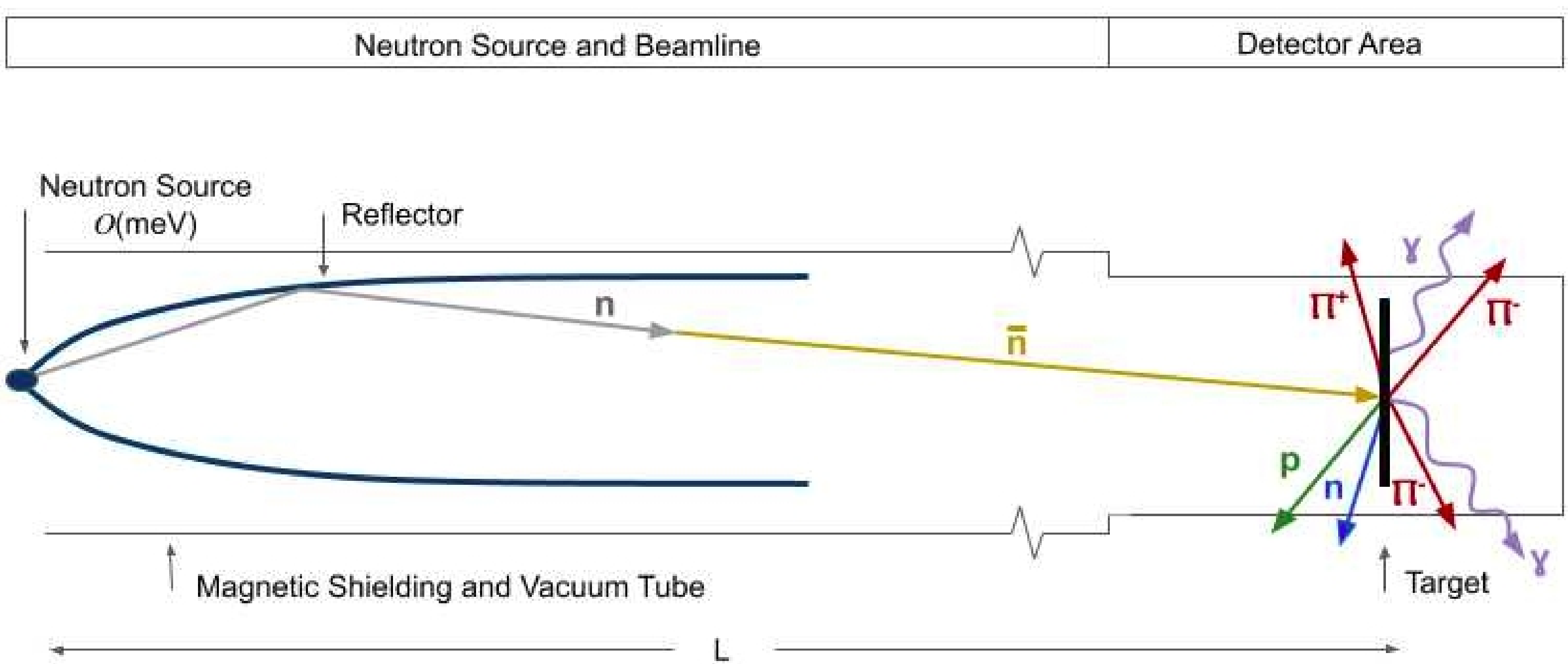
NNBAR

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:

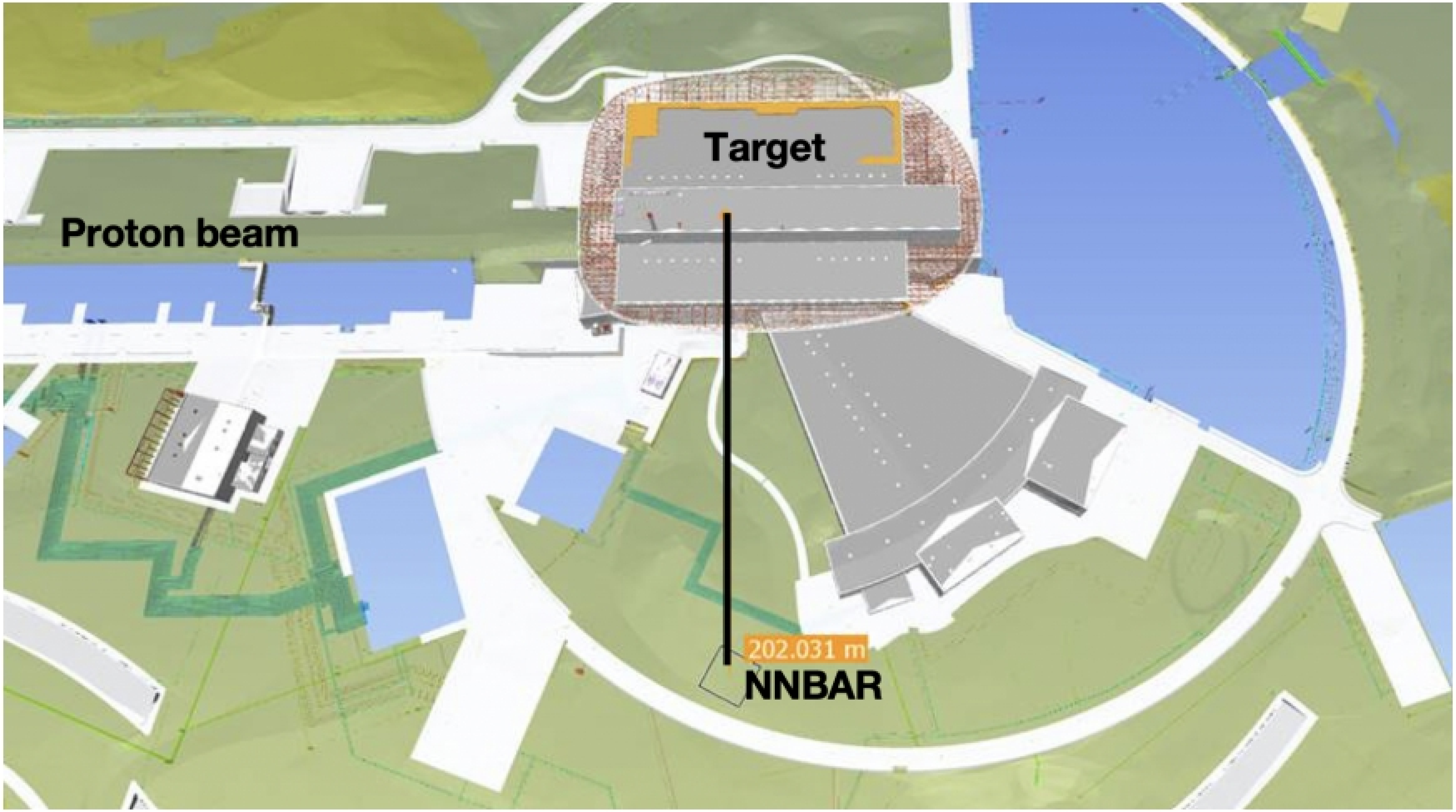
$$P(\bar{n},t)=(t/\tau)^2 \qquad \text{FOM}= Nt^2$$

- $t \rightarrow$ neutron flight time; $\tau \rightarrow$ “oscillation time” (BSM predicted, model dependent)



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

NNBAR@ESS



NNBAR Large Beam Port (LBP)

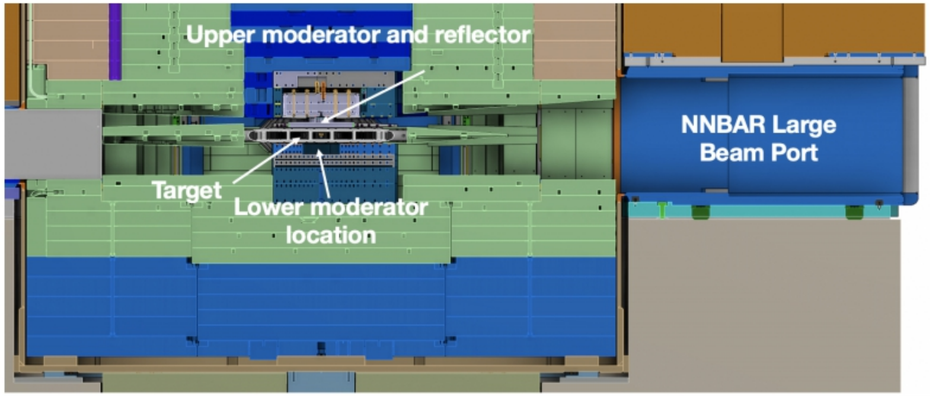


Figure 2: Cross sectional view of the ESS target/moderator area and the inner shielding. In the figure it is shown the location of the ESS upper and lower moderator. The NNBAR experiment will view both moderators.

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

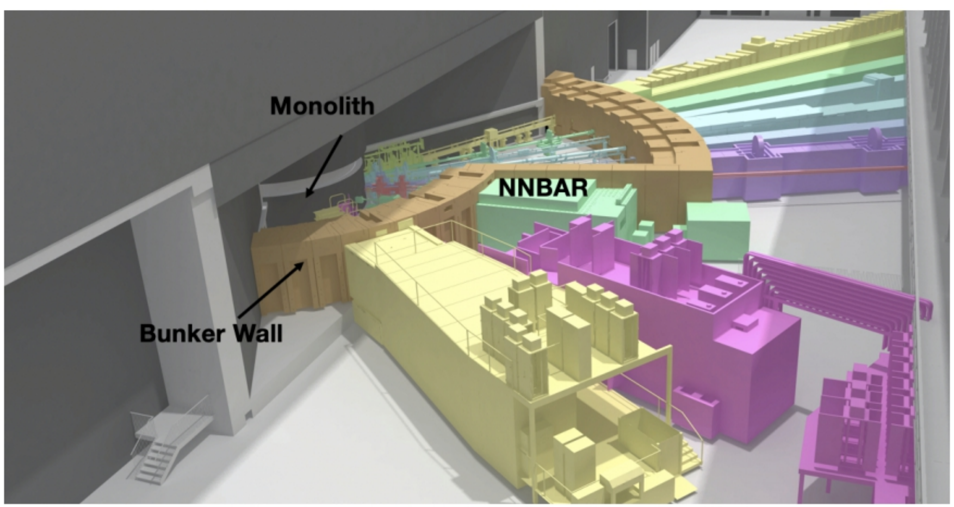


Figure 4: The ESS monolith and bunker area. At the start of ESS operation, the NNBAR location will be occupied by the test beamline, used in the early days of the ESS operation to characterize the target-reflector-moderator system. Also shown in the figure are the caves of the LOKI (purple) and FREIA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

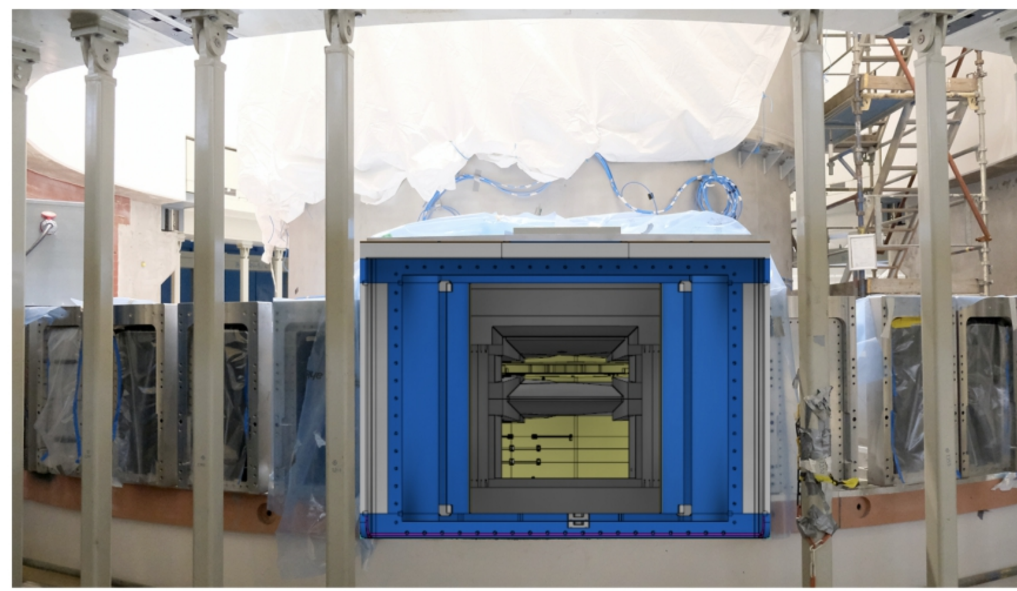


Figure 3: Photograph of the frame of the Large Beam Port being installed in the ESS monolith. A superimposed CAD drawing is showing the field of view of the LBP. The upper moderator, the inner shielding to avoid a direct view of the target, and the space below the target where the high-intensity moderator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

Potential Gains w.r.t. ILL

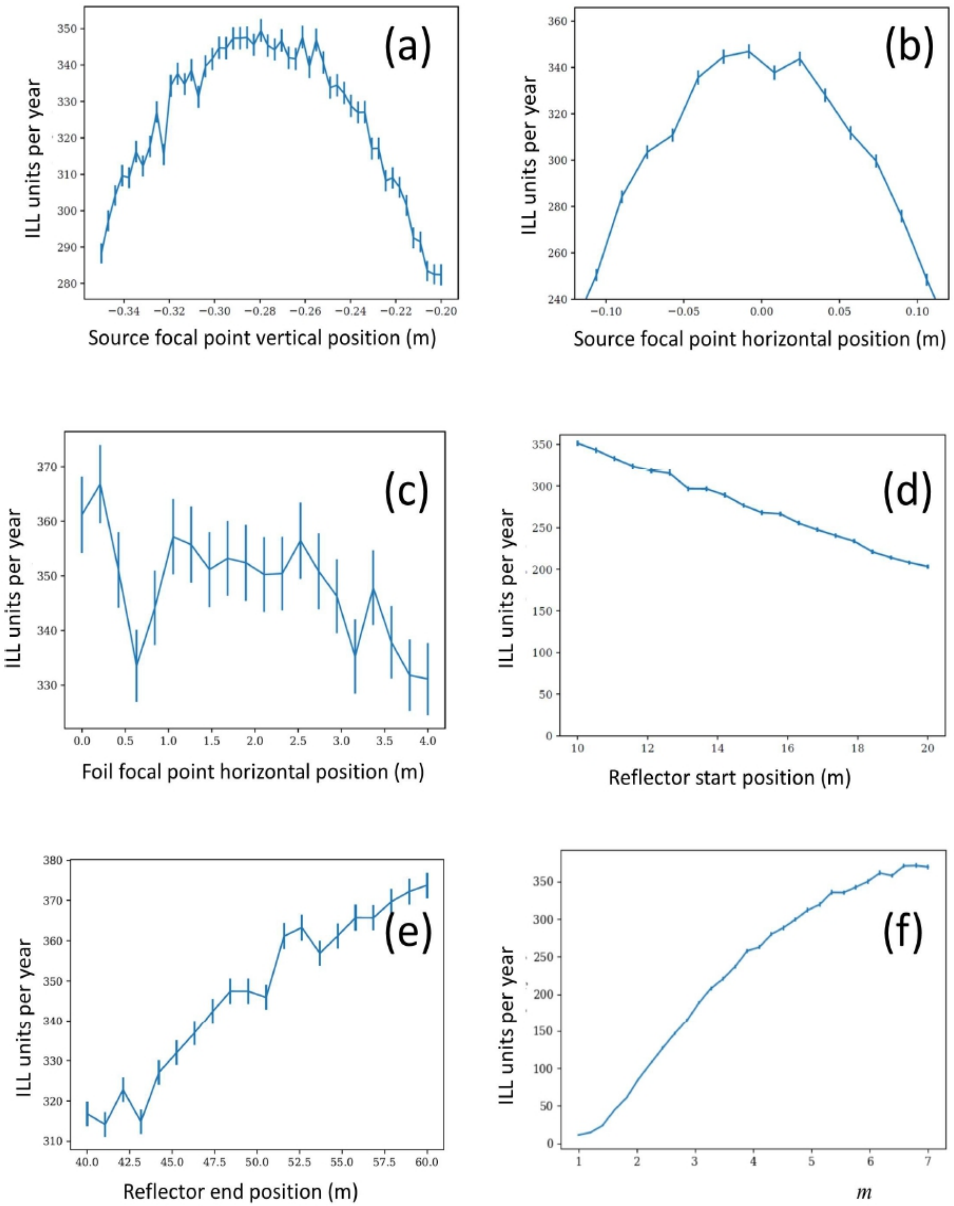
Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

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

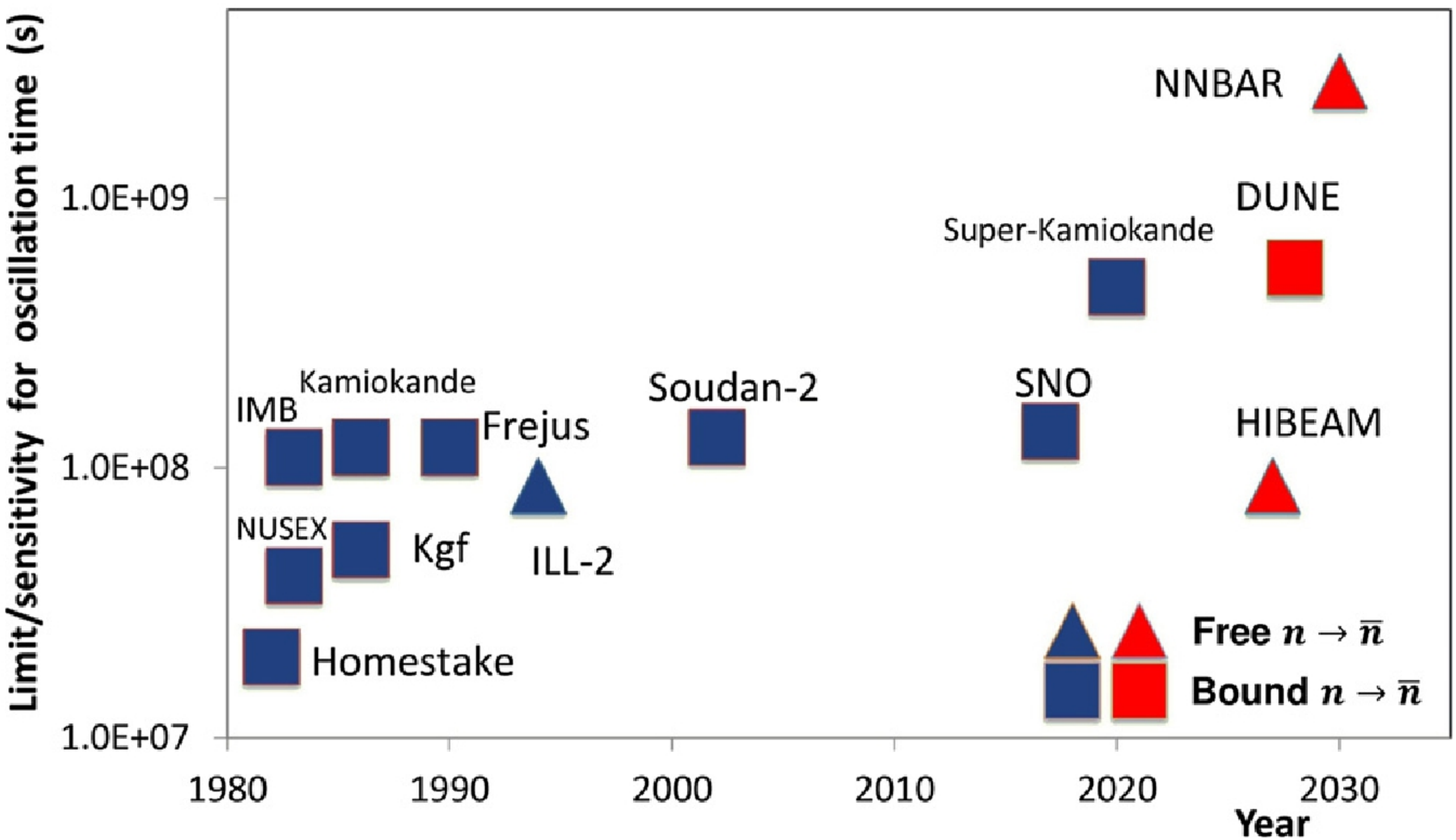
Opportunity to test a global symmetry with three orders of magnitude better precision than previously done is rare!!

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

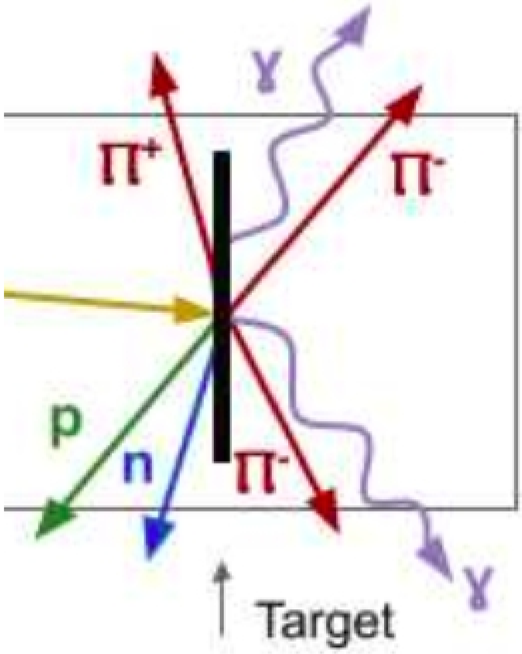


Annihilation detector

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

Detector

- Subsystems annihilation detector (ordered radially outward):
- (i) annihilation target and detector vacuum region;
- (ii) tracker;
- (iii) time of flight systems (before and after the tracker);
- (iv) calorimeter;
- (v) cosmic veto system

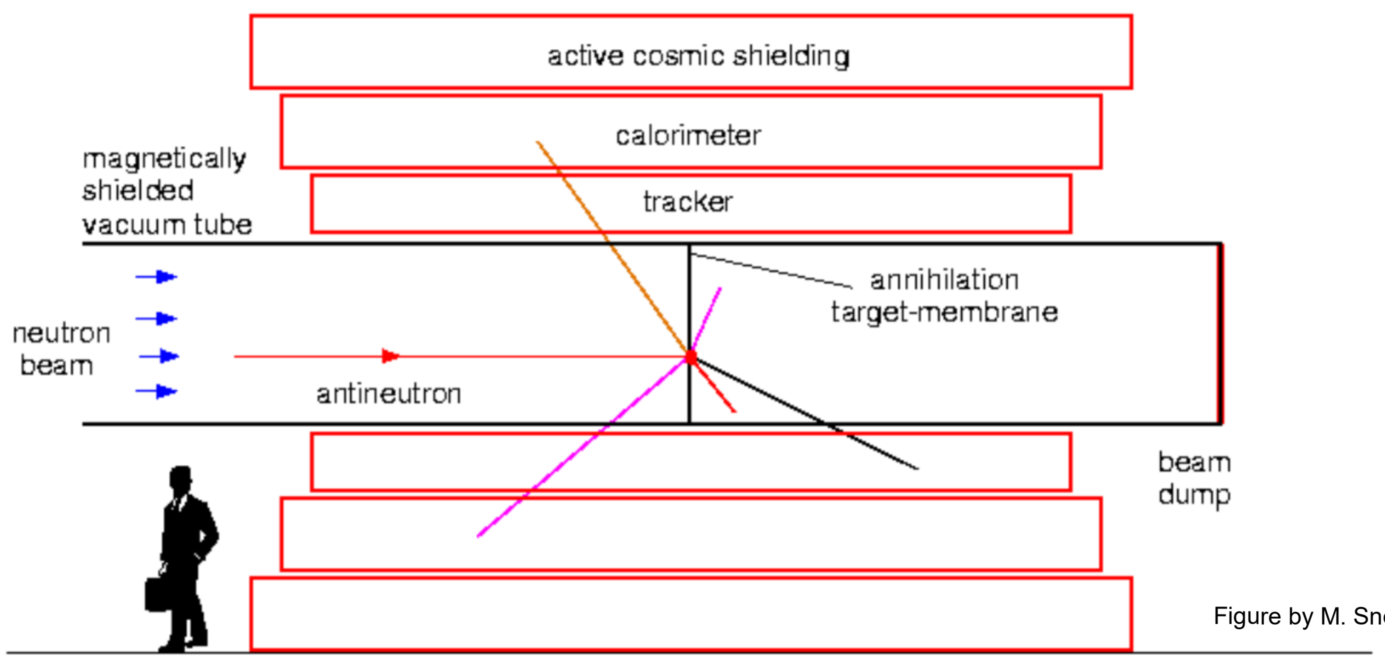


Figure by M. Snow

NNBAR Annihilation Detector – Box Geometry

Time Projection Chamber

Filling gas: 80% Ar, 20% CO_2

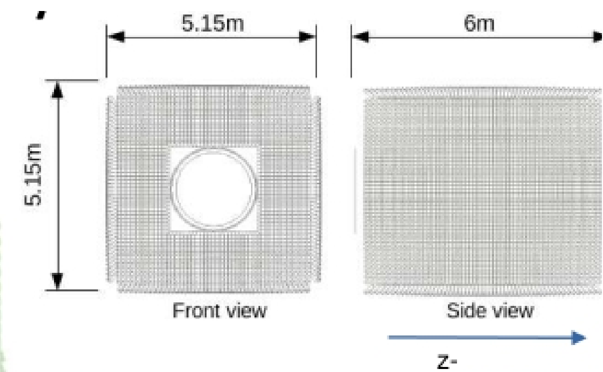
2 different dimensions (x-y):

0.85 m x 1.87 m

2.04 m x 0.85 m

Both:

2 m length in z-direction



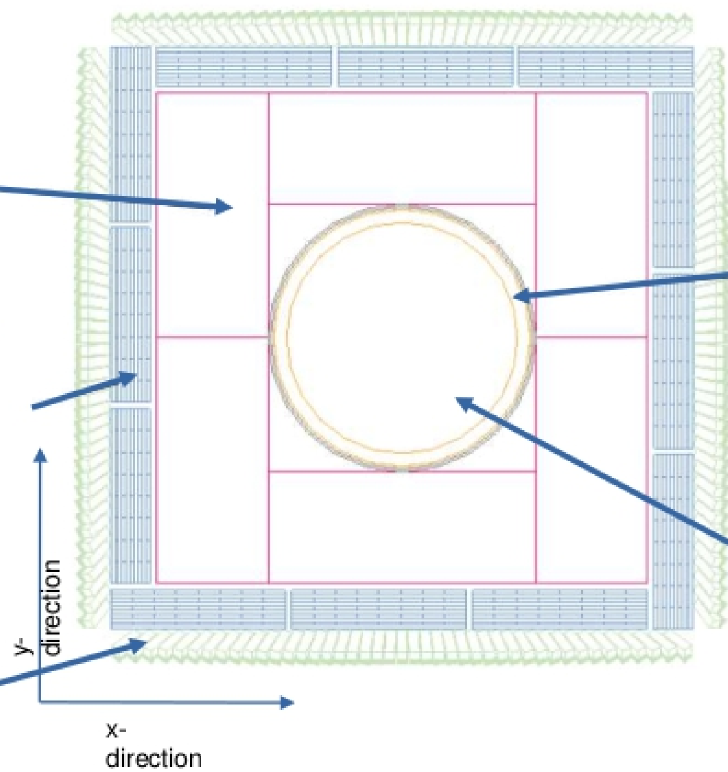
Silicon Trackers

2	layers
6m	length
0.3 cm	thickness

Scintillator Modules (Calorimeter)

10	layers
3 cm	thickness per layer
8	staves per layer

consecutive layers are perpendicular



Vacuum tube

1 m	inner radius
2 cm	wall thickness
6 m	tube length

Lead Glass Blocks

8 x 8 cm base area

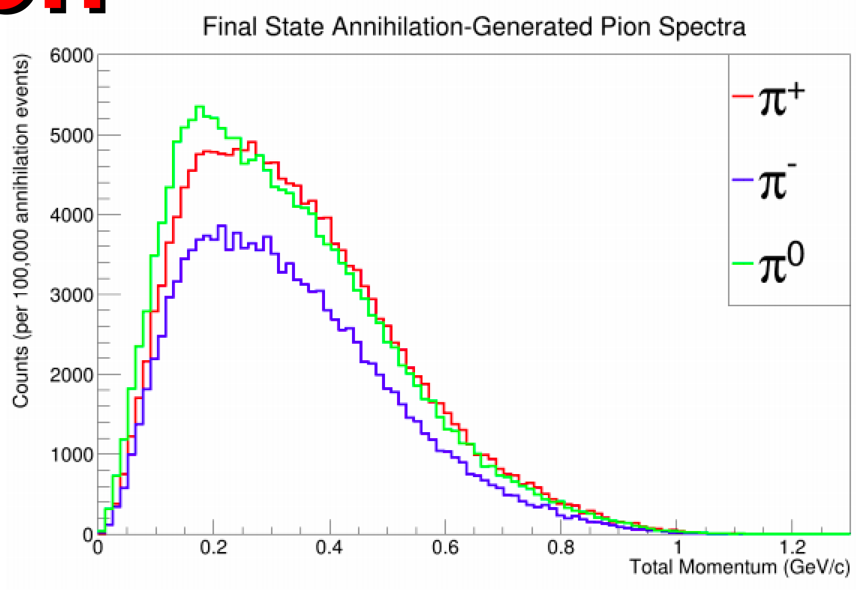
25 cm height

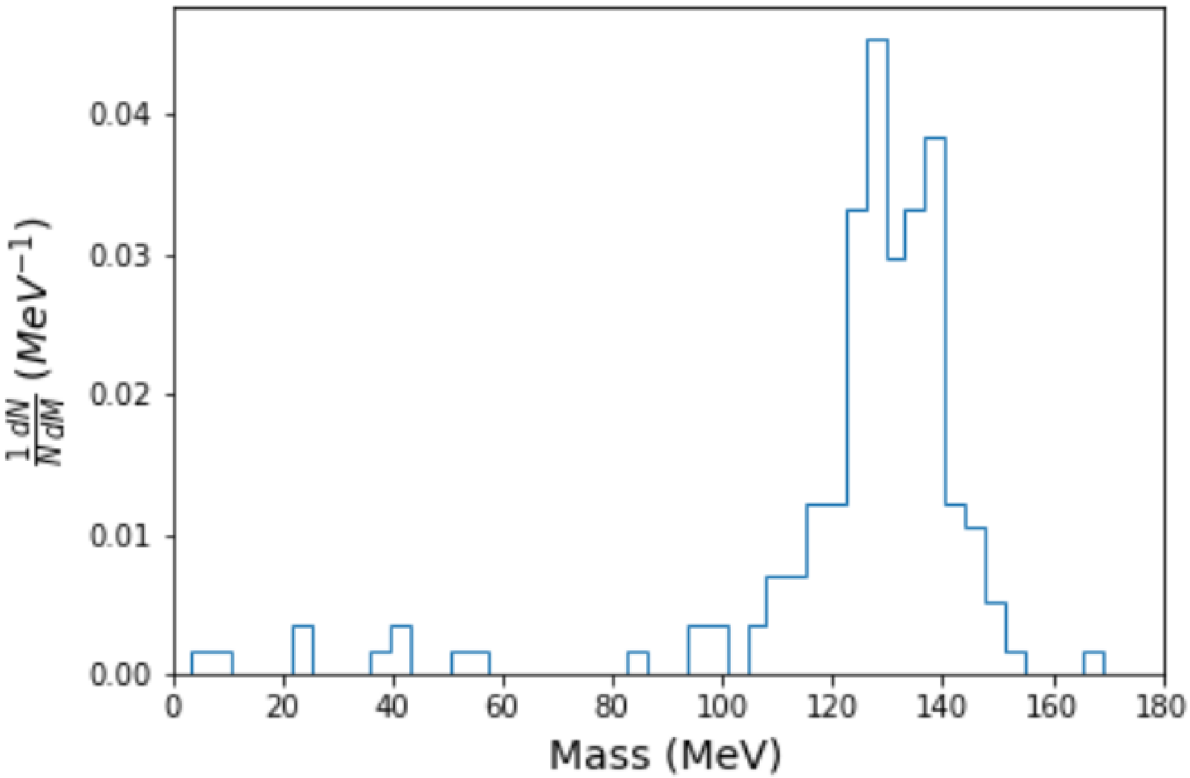
Oriented towards center of detector

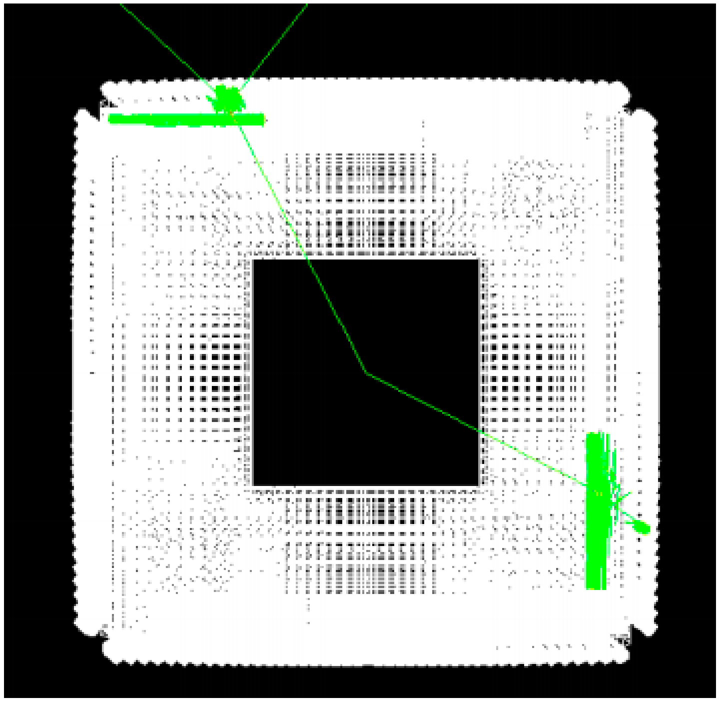
π^0 reconstruction

$$m_0^2 = 2E_1E_2(1 - cos(\theta))$$

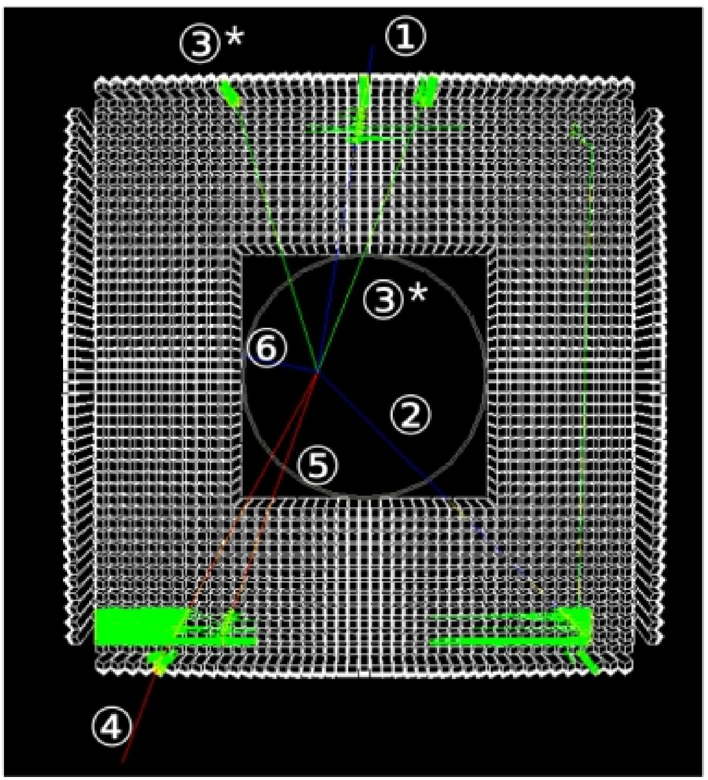
Energy Deposited by gamma 1 and gamma 2 in the calorimeter

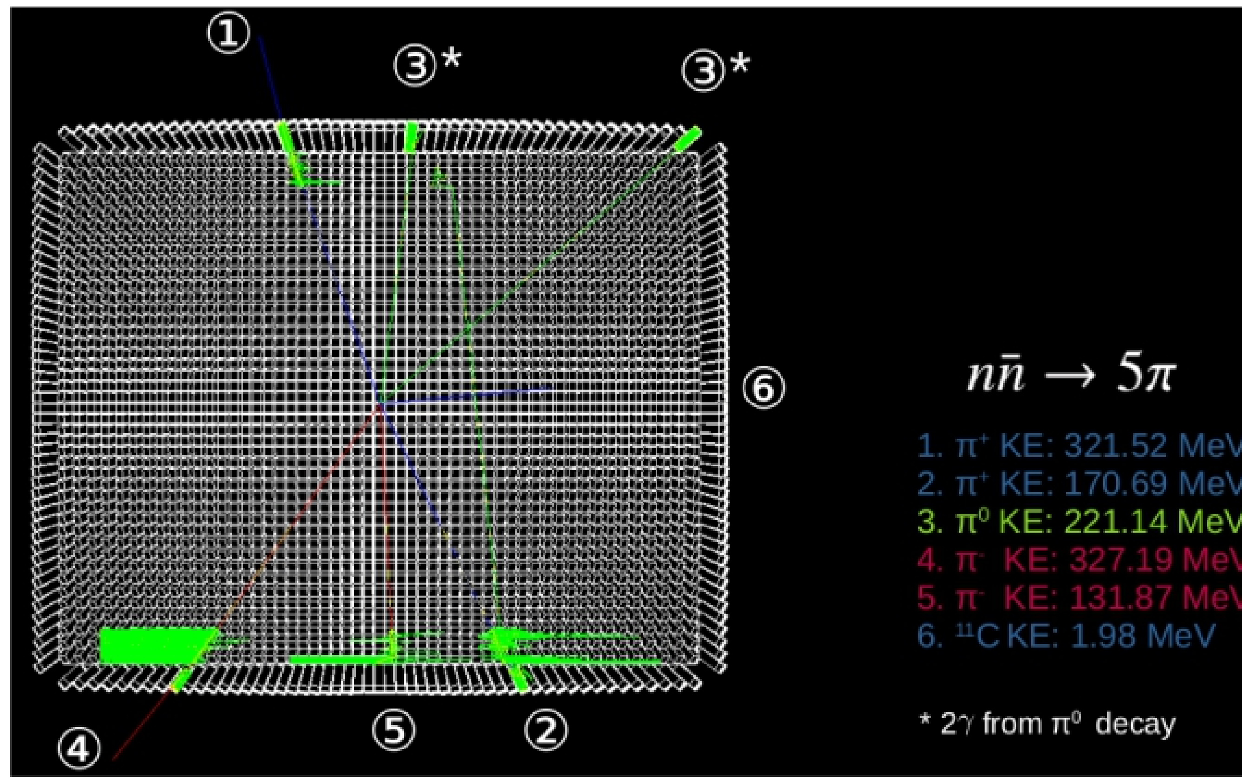






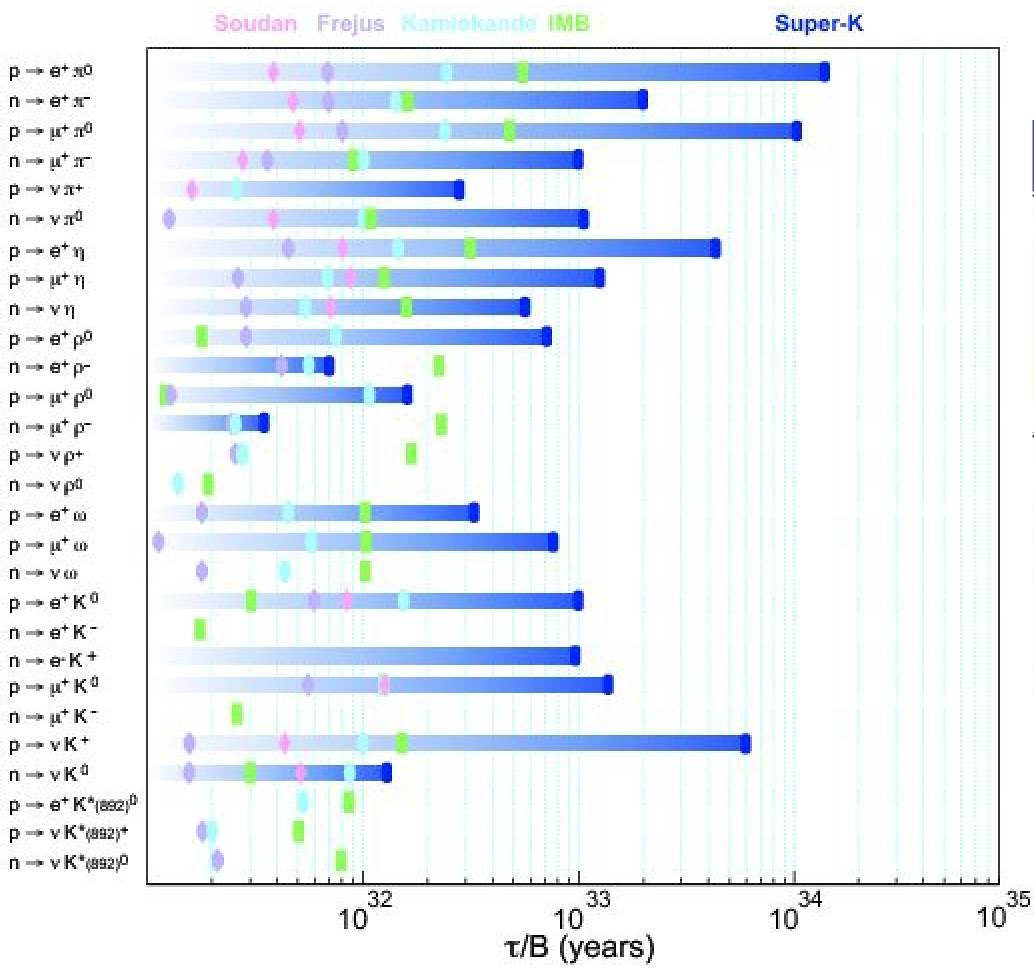
Event display of signal event





Possible future measurements

- Most competitive limits from single nucleon decay searches arise from large volume experiments.
- For neutrons limits ranges from 10^{31} - 10^{33} yrs.
- Hyper-K (data taking 2027) to further explore rare neutron decays (including DM).



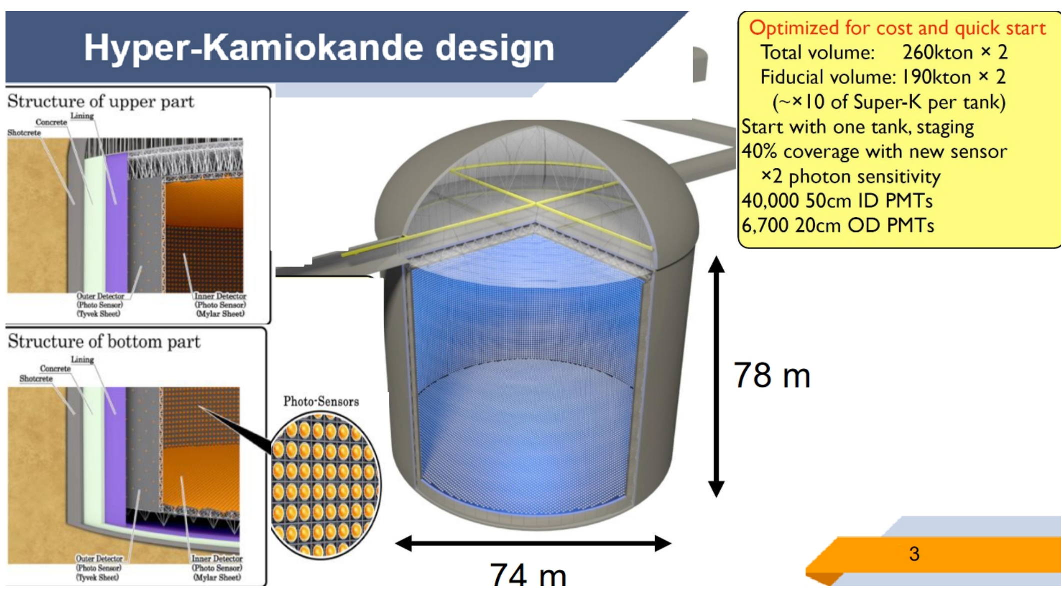


Figure by B. Richards on behalf of Hyper-K

Rare neutron decay searches with HIBEAM-NNBAR detector?

- Annihilation detector can also observe neutron decays.
- Reach cannot in principle compete with Hyper-Kamiokande.
- Unless:

  a) Are there modes which cannot be sought at these experiments?
  b) Limits are applicable for free neutrons?

- Possibly, one could look for, e.g, dark matter in HIBEAM-NNBAR:

$$n \longrightarrow \chi + \gamma$$

$$n \longrightarrow \chi + e^{+} + e^{-}$$

$$n \longrightarrow \chi + \phi$$

Possible rare decays

- Possibility for a range of B,L violating processes*

Mode	ΔB	$\Delta(B-L)$
$n \to \pi^- + e^+$	1	0
$n \to \pi^- + \mu^+$	1	0
$n \to \rho^- + e^+$	1	0
$n \to \rho^- + \mu^+$	1	0
$n \to \pi^- + \pi^0 + e^+$	1	0
$n \to \pi^+ + \pi^0 + e^-$	1	2
$n \to \pi^- + \pi^0 + \mu^+$	1	0
$n \to \pi^+ + \pi^0 + \mu^-$	1	2

- * see: D. Milstead - "Rare decays at HIBEAM?" - nnbar at ESS workshop – 12-13 December 2019

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 $n \rightarrow \bar{n}$ search.
- NNBAR – world leading neutron-antineutron oscillation searches.
- Rare neutron decays under investigation.

LUNDS UNIVERSITET

NNBAR

Stockholm University

Thanks!