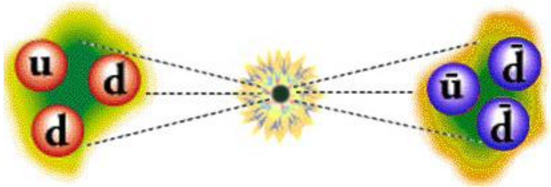
Raby Fest Conference • UMD • October 20-21, 2022

Prospects of Neutron Oscillation Search



Yuri Kamyshkov/ University of Tennessee
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I am grateful to Rabi for his impact on my scientific life.

VOLUME 44, NUMBER 20 PHYSICAL REVIEW LETTERS 19 MAY 1980

Local $B-L$ Symmetry of Electroweak Interactions, Majorana Neutrinos, and Neutron Oscillations

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and

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(Received 11 January 1980)

Interpretation of the U(1) generator of the left-right-symmetric electroweak model in terms of $B-L$ enables us to study the spontaneous breaking of local $B-L$ symmetry. The same Higgs mechanism at the "partial unification" level of $SU(2)_L \otimes SU(2)_R \otimes SU(4')$ that produces $\Delta_L = 2$ processes (e.g., Majorana neutrinos) also yields $\Delta B = 2$ processes (e.g., "neutron oscillations"). The observation of "neutrinoless" double β decay and $\Delta B = 2$ nucleon transitions without proton decay would favor this model and an intermediate mass scale.

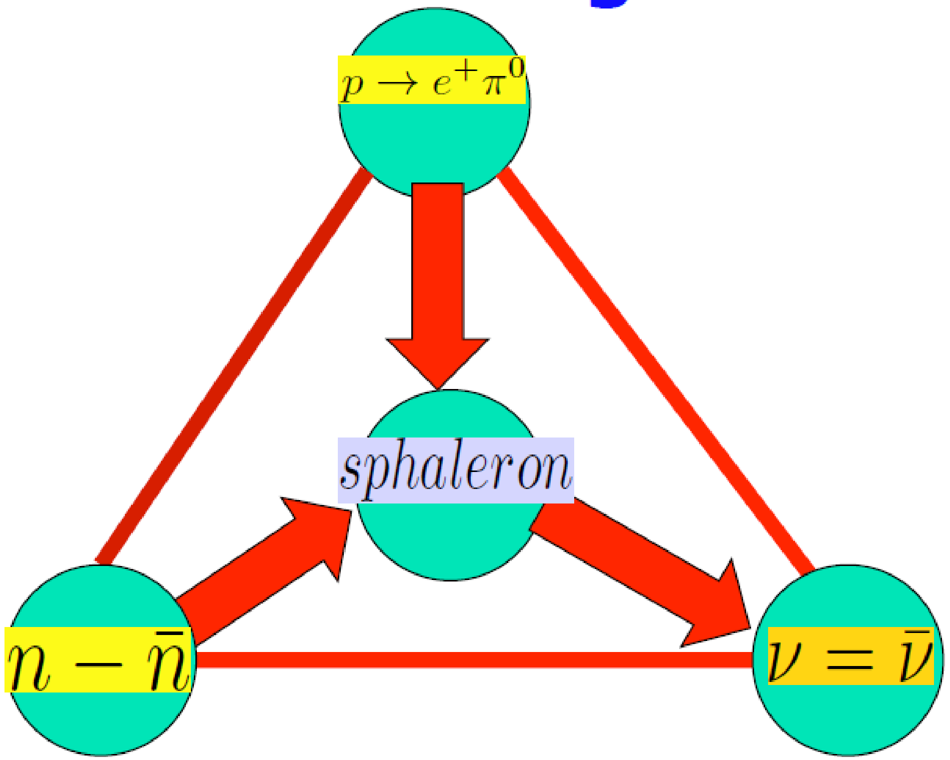
From NNbar to Majorana neutrino via sphalerons

- Sphaleron Op. rewrite

QQQQQQ QQQL LL

$\underbrace{QQQQQQ}_{n-\bar{n}}\ \underbrace{QQQL}_{p\to e^+\pi^0}\ \underbrace{LL}_{m_\nu}$

B-L Triangle:



Observe p-decay and nn-bar→Neutrino Majorana

Short history of $n \to \bar{n}$ experiments

1980

Experiments in Italy and at ILL France

ORNL and LANL Proposals for $n \to \bar{n}$ experiments (1982)

Intranuclear searches: IMB (1984),Kamiokande (1986), Fréjus (1990), Soudan-2(2002), SNO(2017), S-K (2015)

Experiment at ILL (M. Baldo-Ceolin, D. Dubbers, et al, 1994) [free n]

New Research Reactor at ORNL "ANS"

Existing HFIR Reactor at ORNL

Workshop at ORNL (1996) →

SNS at ORNL cannot host the experiment

First "BLV" workshop at LBNL (2007)

Vertical $n \to \bar{n}$ experiment proposal for Sanford Lab

Search for International facilities (India, China, Russia, Argentina)

Project-X at FNAL

P5 2015: "$n \to \bar{n}$ addresses HEP drivers; but no priority"

DOE/HEP: "$n \to \bar{n}$ is not HEP" (2021)

Latest Super-K result(K. Abe et al, PRD 2021) [bound n]

Developments at European Spallation Source

Small experiments at ORNL (SNS & HFIR)

2022


DEC 11 1996
ADV MATLS, PHYSICAL, & NEUTRON SCIENCES

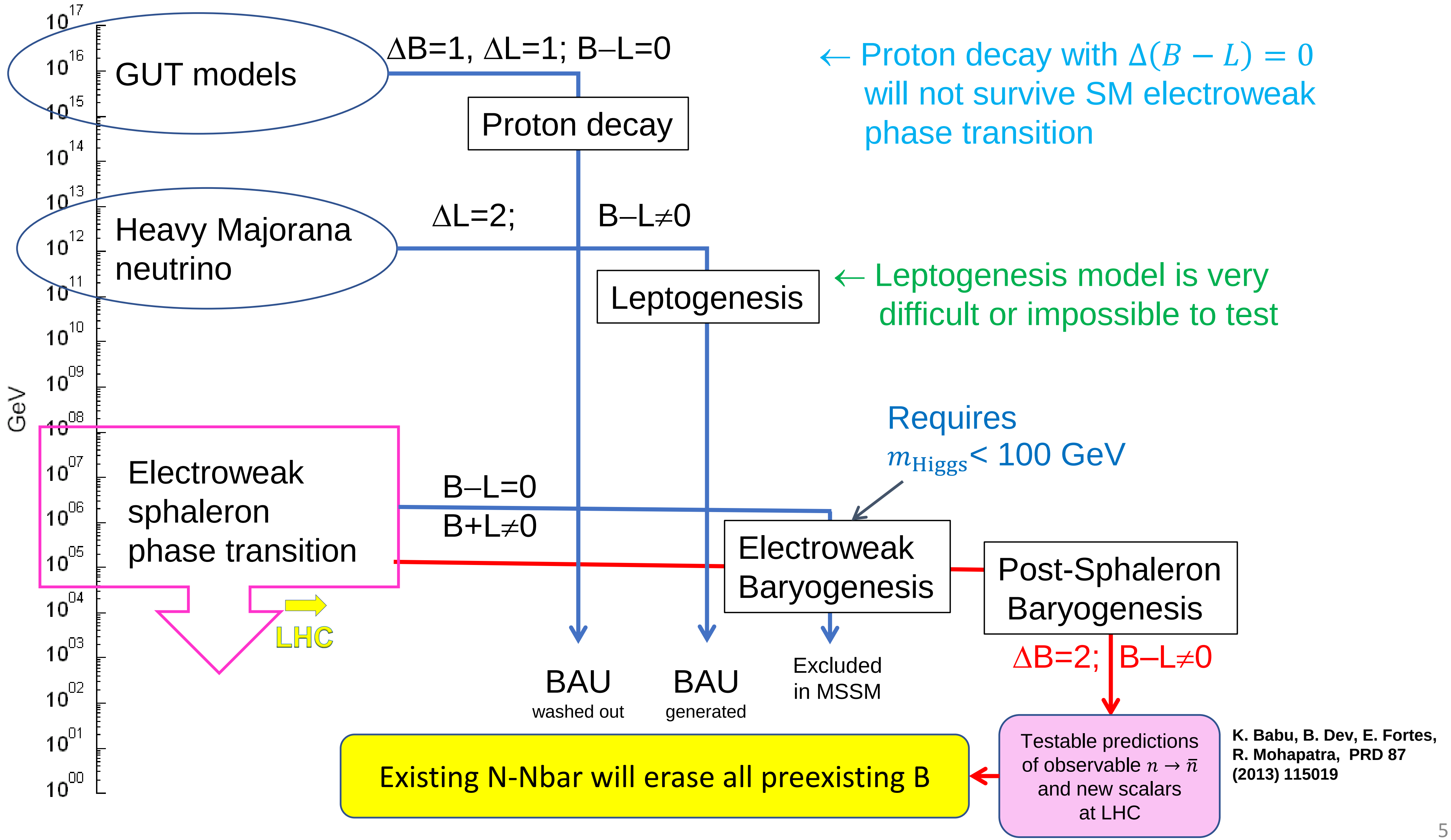
ORNL-6910

FUTURE PROSPECTS
OF BARYON INSTABILITY SEARCH
IN p-DECAY AND n → n̄ OSCILLATION EXPERIMENTS

Proceedings of the International Workshop on Future Prospects of Baryon Instability Search in p-Decay and n → n̄ Oscillation Experiments
Oak Ridge, Tennessee, U.S.A., March 28-30, 1996

Edited by
S. J. BALL and Y. A. KAMYSHKOV
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831, U.S.A.

Baryogenesis Models



$n \to \bar{n}$

- Means a transformation of matter to antimatter;
- Means that neutron has a Majorana component that evolves with time;
- It violates baryon number by two units $\Delta B = 2$;
- It violates $(B - L)$ by 2 units;
- Testable PSB model: K. Babu, B. Dev, E. Fortes, R. Mohapatra (2013)
- Experimentally possible to approach $n \to \bar{n}$ by (a) observation of free n transformations in vacuum and (b) the decay of bound neutrons in underground experiments

Recent reviews “Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects”, D. Phillips + 57 authors, Physics Reports, Volume 612 (2016) https://arxiv.org/abs/1410.1100 and “New high-sensitivity searched …”, A. Addazi + 90 authors https://arxiv.org/abs/2006.04907 (2020)

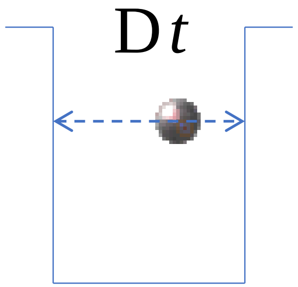
Both reviews are with essential Rabi’s contributions

Intranuclear bound vs free $n \to \overline{n}$

Intranuclear (exponential) decay time $\tau_A = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2$

$[R]$ = 1/s

$\Delta t \approx \frac{\hbar}{30\ MeV}$



Known nuclear suppression factors from nuclear theory

Nuclei	R, s^{-1}
^{56}Fe	1.4×10^{23}
^{16}O	5.17×10^{22}
^{40}Ar	5.6×10^{22}
^{2}D	2.5×10^{22}

Most recent (2021) Super-K intranuclear $n \to \bar{n}$ limit

$\tau_A > 3.6 \cdot 10^{32}$ yr

$\tau_{n\bar{n}} > 4.7 \cdot 10^{8}$ s $(\sim 15\ yr)$

based on 11 observed events

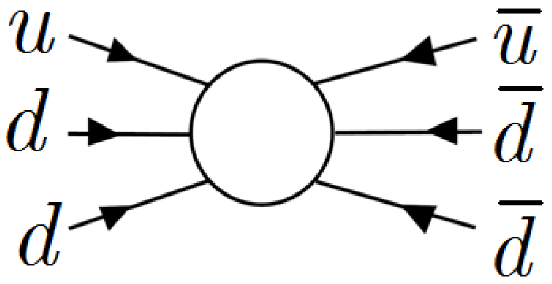
with expected background 9.3 events

Nuclear suppression factor R can be calculated with $\pm 15\%$ by nuclear theory

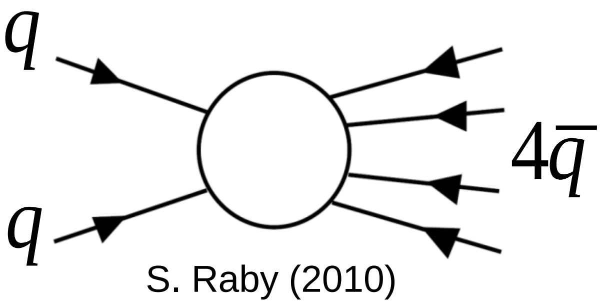
e. g. J. Barrow et al., https://arxiv.org/abs/1906.02833 (2020)

Some of my colleagues insist that free and bound $n \to \bar{n}$ are two different processes

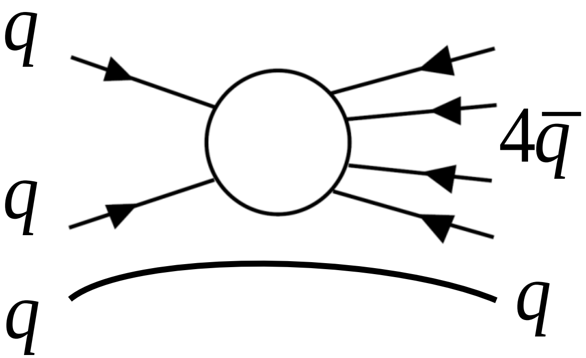
For example



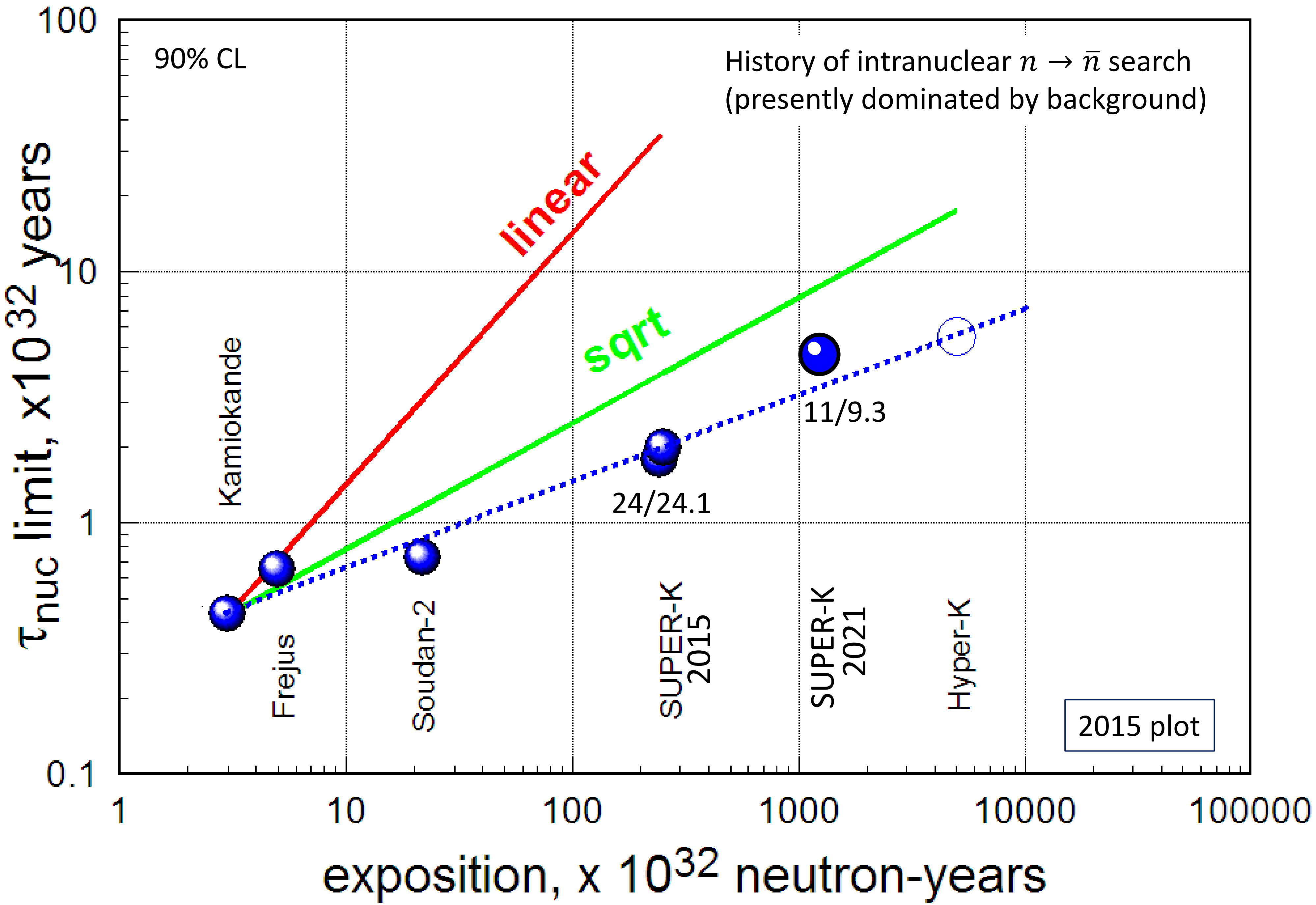
$n \to \bar{n}$



cross – symmetry channel



Can occur within nuclei but not with the free neutron



90% CL
History of intranuclear $n \to \bar{n}$ search
(presently dominated by background)
linear
sqrt
Kamiokande
Frejus
Soudan-2
SUPER-K 2015
SUPER-K 2021
Hyper-K
24/24.1
11/9.3
2015 plot
τ_{nuc} limit, $x10^{32}$ years
exposition, x 10^{32} neutron-years
100
10
1
0.1
1
10
100
1000
10000
100000

Free beam of neutrons in vacuum

$$P_{n\to\bar{n}}(t) = \frac{\epsilon^2}{\epsilon^2 + V^2} \cdot sin^2\left(\frac{\sqrt{\epsilon^2 + V^2}}{\hbar} \cdot t\right)$$

$\tau_{osc} \equiv \frac{\hbar}{\epsilon}$ - oscillation time

t - time of free neutron flight

free neutrons in the magnetic field $V = \mu\vec{\sigma} \cdot \vec{B}$ The probability can be suppressed if $V \gg \epsilon$. However, if $\omega t < 1$, $\sin \omega t \approx \omega t$ (called "quasi-free" condition)

$$P_{n\to\bar{n}}(t) = \left(\frac{\epsilon t}{\hbar}\right)^2 = \left(\frac{t}{\tau_{osc}}\right)^2$$ is the same as for $V = 0$

$P_{n\to\bar{n}} \sim t^2$

Sensitivity

$\sim N\bar{t}^2$

if $\epsilon \approx 10^{-24}\, eV$ (~current limit) and $t = 1\, sec$, i. e. $P_{n\to\bar{n}} \approx 5 \times 10^{-18}$ per neutron

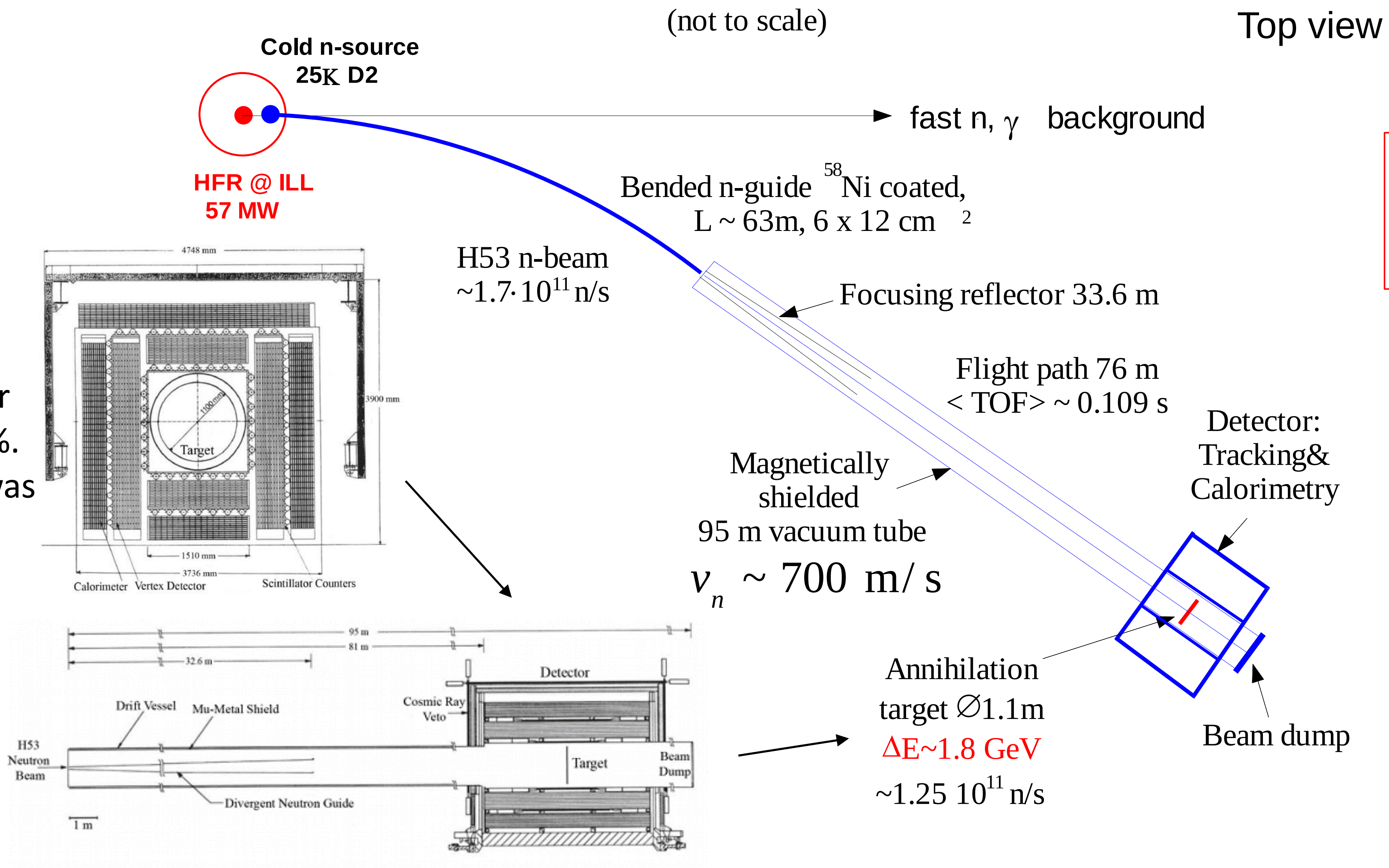
B should be $< 10\, nT$, i. e. 5,000 times less than Earth mag. field $B \approx 50\, \mu T$

$$\Uparrow V = \mu \cdot B = 6 \times 10^{-16} eV \gg \epsilon$$

N-Nbar search experiment with free neutrons

at ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409



Overall detector efficiency ~ 50%.
Running time was 1 year.

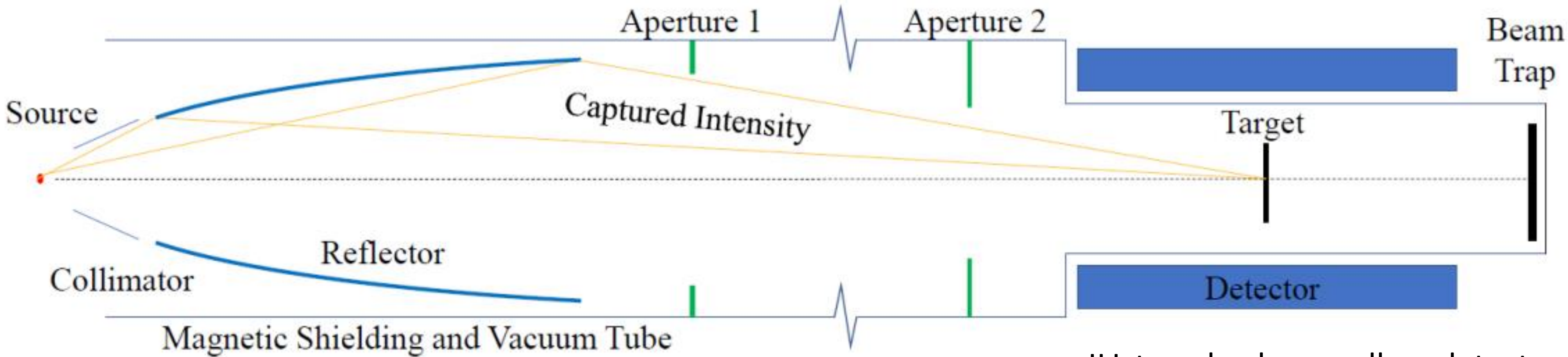
Sensitivity

$\sim N\bar{t}^2$

$P_{n\to\bar{n}} \approx 5\times10^{-18}$ per neutron

$\tau_{free} > 0.86\times10^{8}$ s

Schematically ESS $n \rightarrow \bar{n}$ experiment will be configured similar to ILL



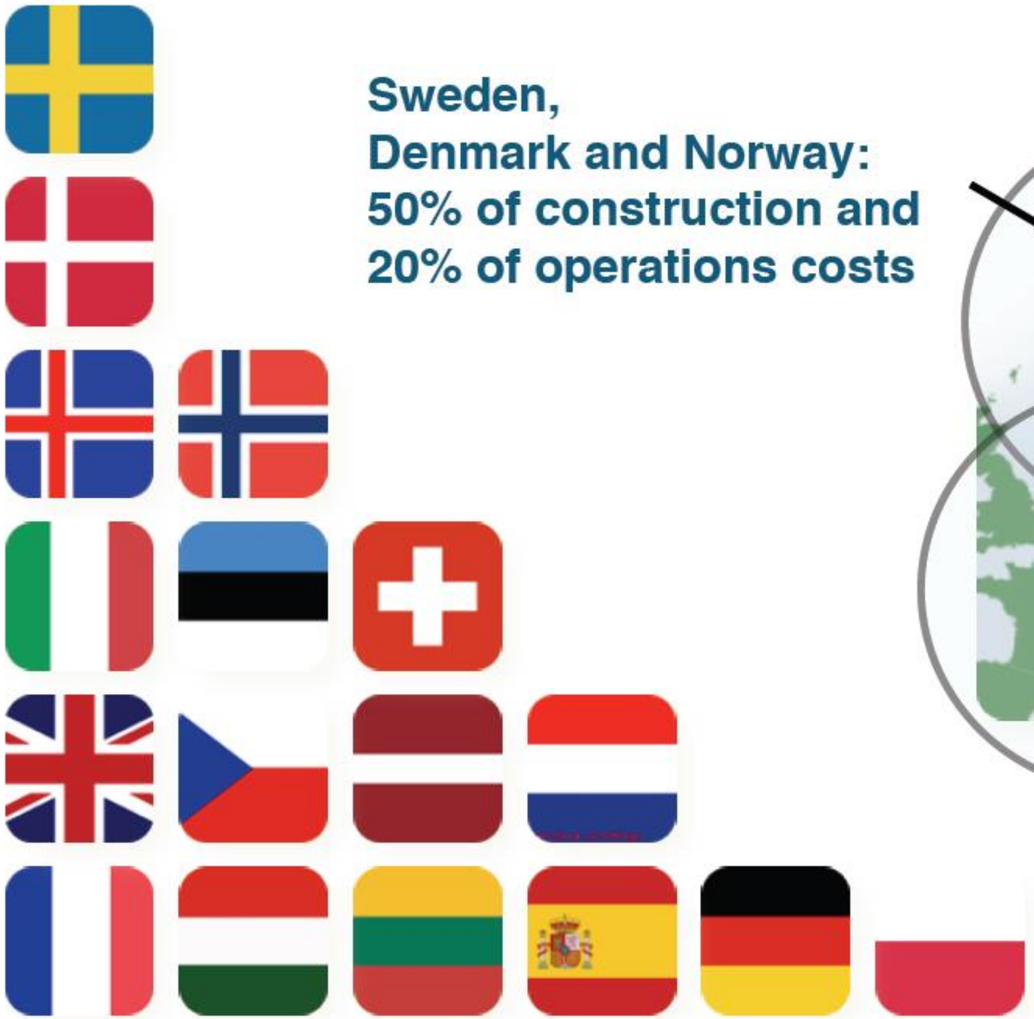
ILL type backgroundless detector

Factors of improvement:

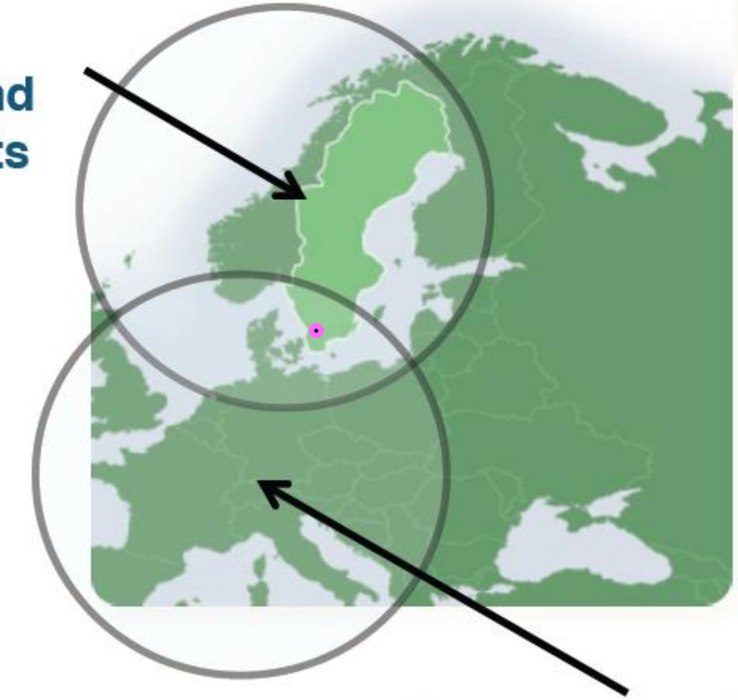
- Cold more intense source
- Large solid angle of emission
- Super-mirror focusing reflector
- Large flight distance
- Larger annihilation target
- Operation time $\geq$ 3 yr

→ Large increase $N\bar{t}^2$

An International Collaboration



**Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs**



**European partners
pay the rest**

14 Hz 3 ms proton pulses
0.8 GeV/2MW

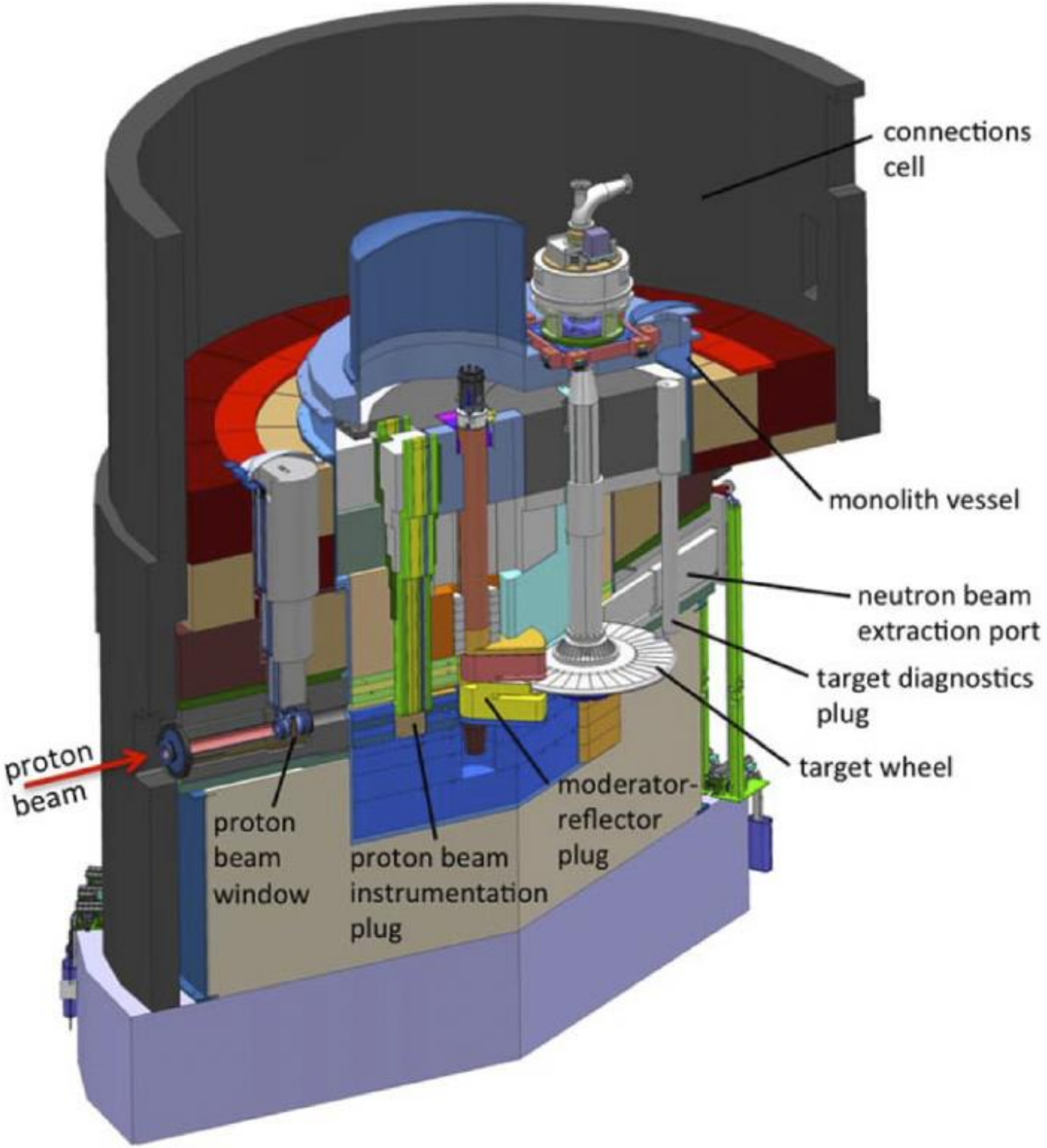
Construction site overview: A seven-year-long civil construction project, where ESS and Skanska have worked in close collaboration, has now been successfully completed.

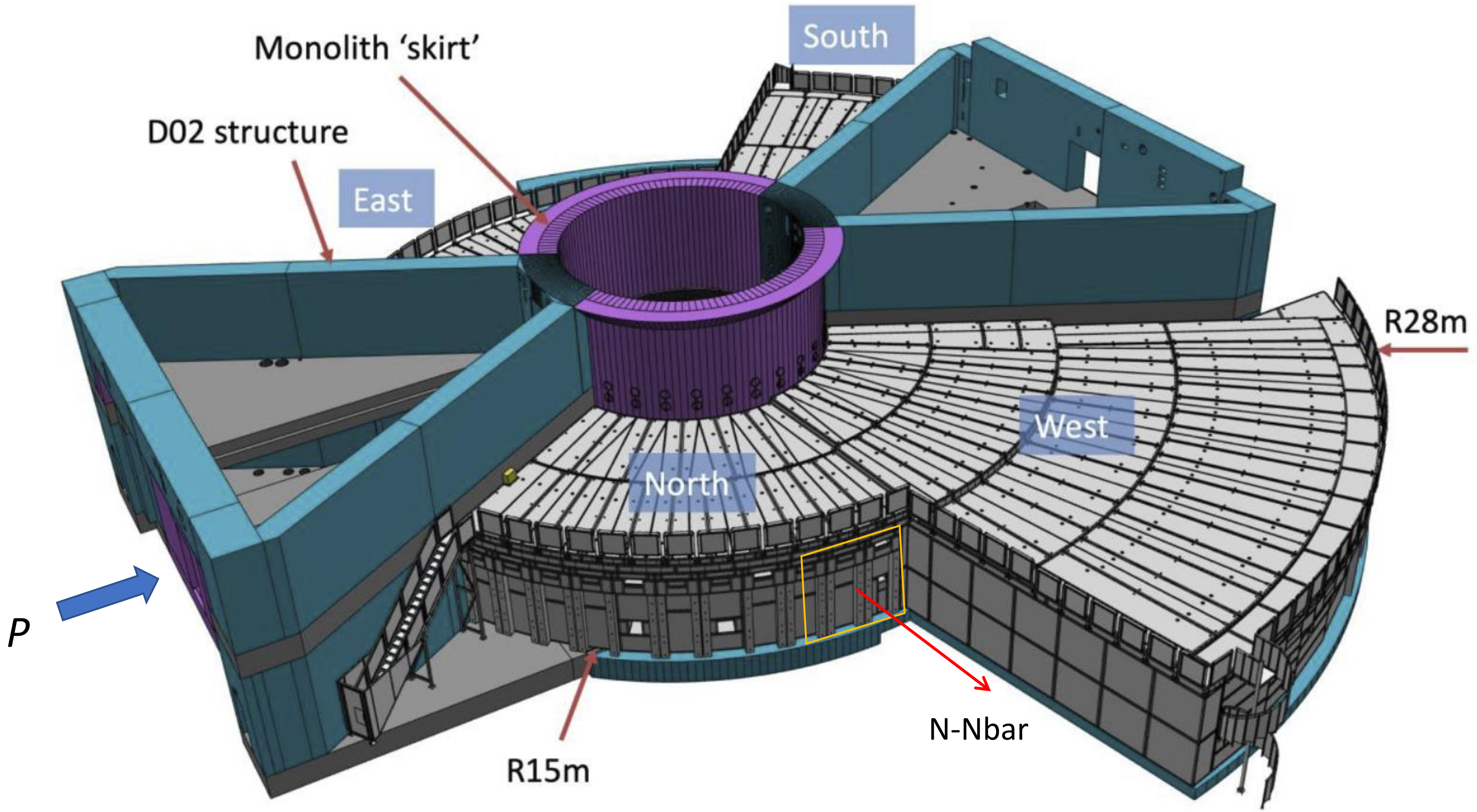
Photo: Perry Nordeng/ESS.

Spallation source ESS

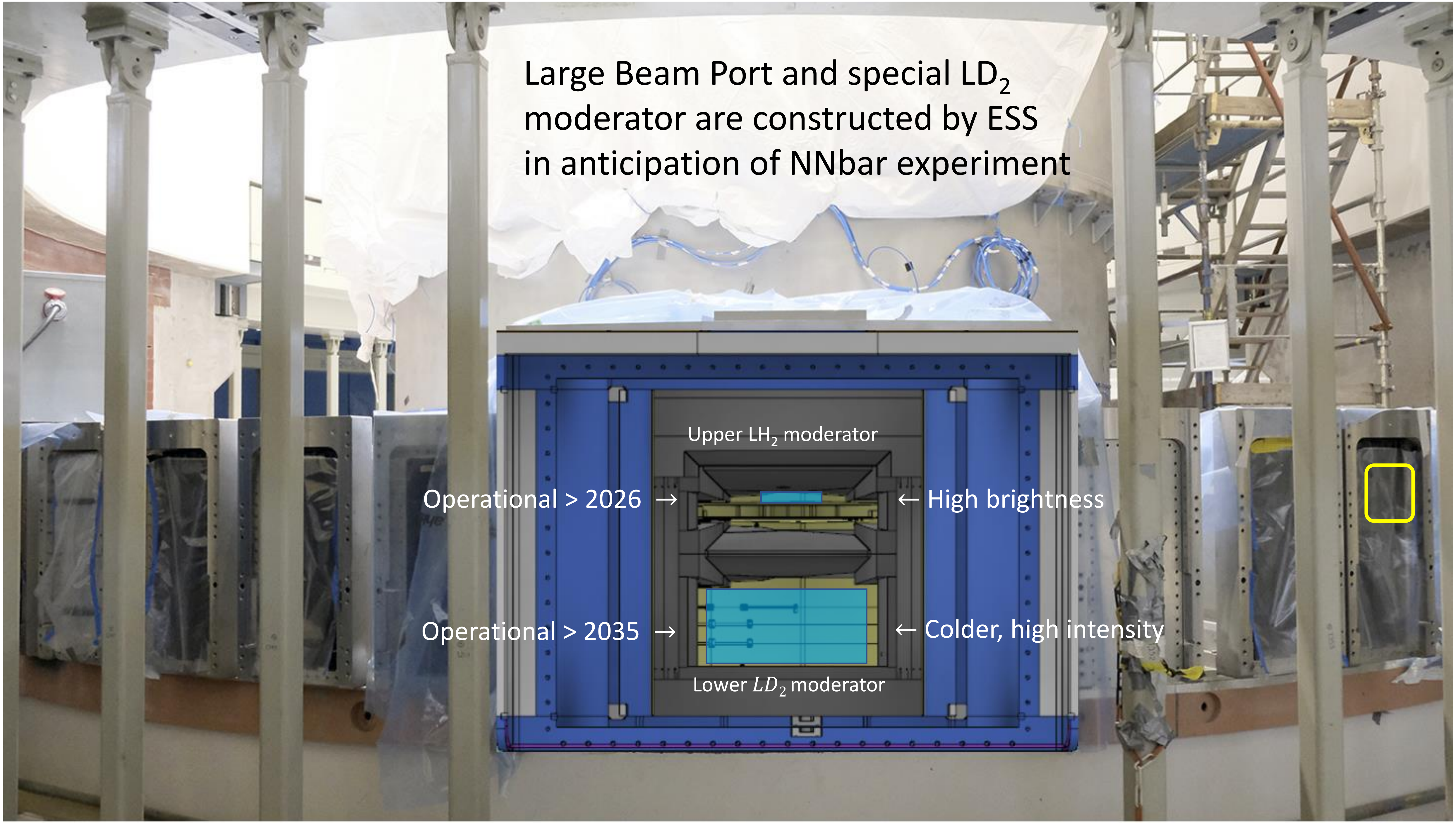
Proton beam 0.8 GeV (1-st stage) 2026-2035 , 2 MW

Proton beam 2.0 GeV (2-nd stage) > 2035, 5 MW





South
Monolith 'skirt'
D02 structure
East
R28m
West
North
P
N-Nbar
R15m



Large Beam Port and special LD_2 moderator are constructed by ESS in anticipation of NNbar experiment
Upper LH_2 moderator
Operational > 2026 →
← High brightness
Operational > 2035 →
← Colder, high intensity
Lower LD_2 moderator


ESS North-West experimental hall in June 2022

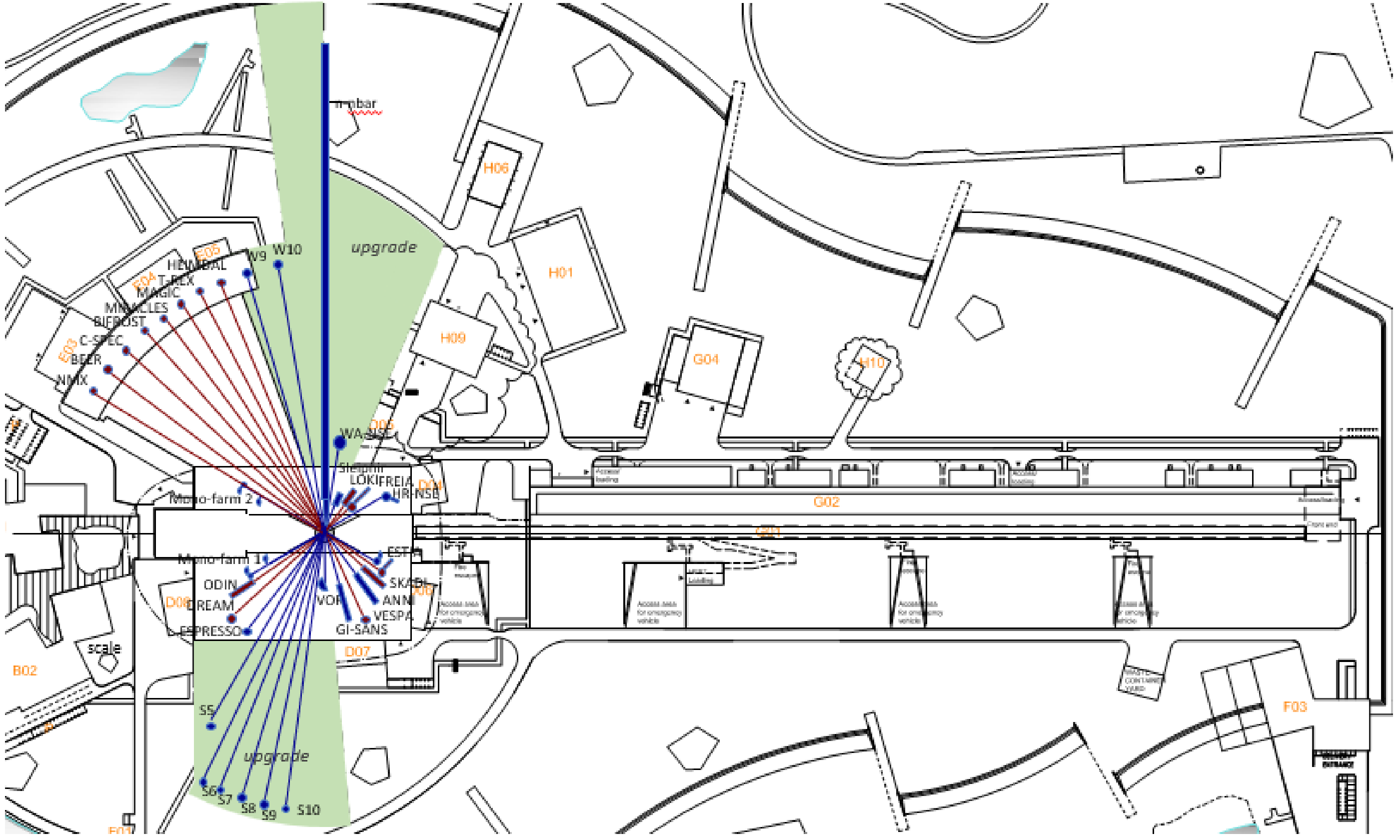
Upgradeability of ESS

Initially planned for 5 MW
ESS will start in 2026 producing cold neutrons at 2 MW with 0.8 GeV LINAC

14 Hz operation with 3 ms Proton pulses and with upper cold moderator operation will start in 2026-2027

Lower moderator can be installed after 2030
Upgrade to 5 MW (2 GeV p) will be in $\gtrsim$ 2035

Unique possibility for designing NNbar experiment together with the design of the source and beamline.



The green part show the upgrade area

HighNess

NNBAR

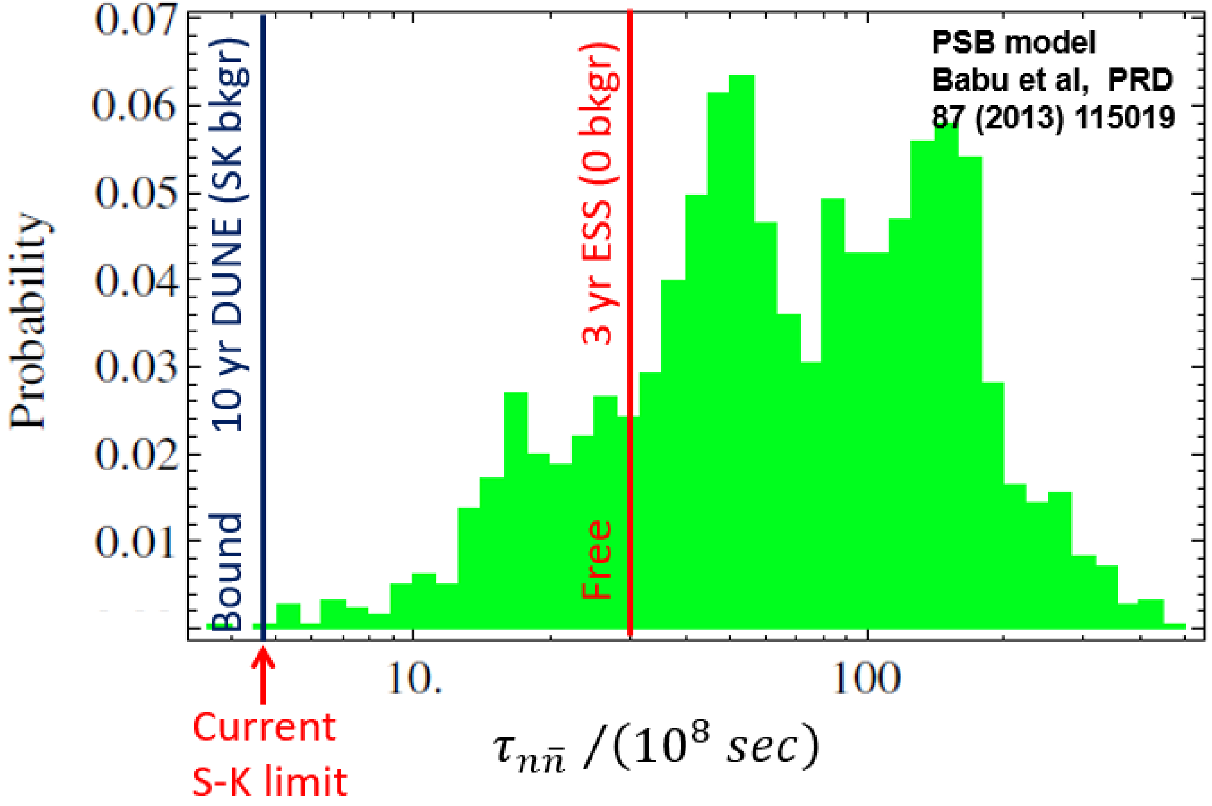
HighNESS Collaboration meeting
at ESS • Lund • 21-22 June 2022

Highness/ESS Design Project develops lower LD_2 Cold Source and beamline for NNbar

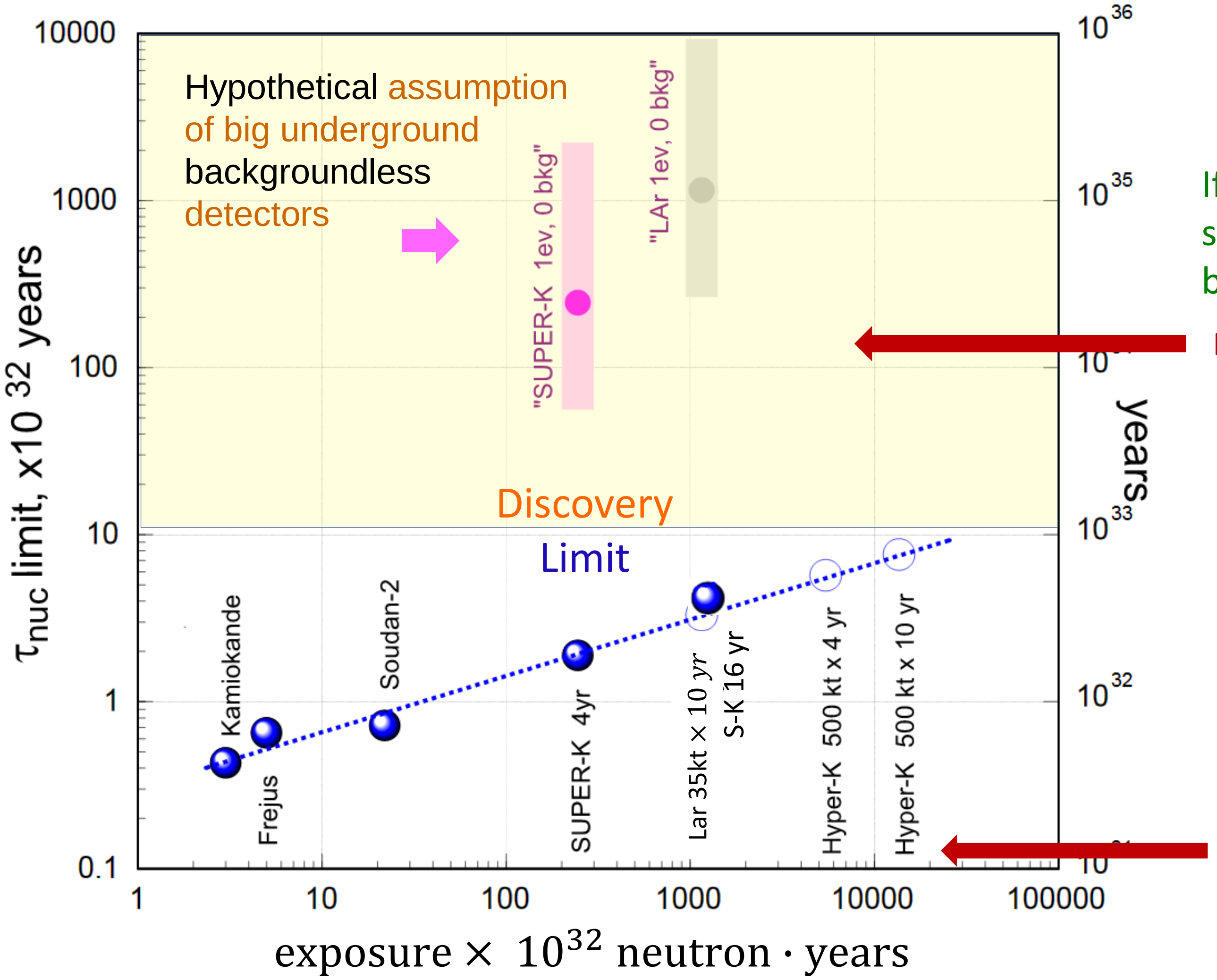
NNbar Collaboration sub-group meeting
at ESS • Lund • 23 June 2022

NNbar Collaboration has several working groups on the detector study, prototypes construction/test, neutronics, shielding, simulations, mag. field, and recently on project Engineering.

The goal of International NNbar Collaboration at ESS is to increase $N\bar{t}^2$ compared to ILL experiment (=1 unit of sensitivity) by factor of $\times$1,000 for **3** years of operation at power **5 MW**, or for **5** years at power **2 MW**, if it will be possible to start experiment before 2035. Factor 1,000 of ILL units will be equivalent to oscillation time $\tau_{n\bar{n}} = 3 \times 10^9$s . In the design we currently achieved factor of ~ 100 per MW·year taking ILL as a prototype of the backgroundless experiment. We anticipate to perform in this experiment a first test the PSB Model of Rabi and his colleagues.



Prospects of intranuclear n-nbar search are background dependent



Demonstrated backgrounds

If we believe in nuclear suppression theory for bound to free relation

ESS 3-yr goal for ~ 2035

$$\tau_A = R \times \tau_{n\bar{n}}^2$$

Current ILL limit

11 candidate events and 9.3 events background – best S-K result 2021 (0.37 kt-yr)

DUNE experiment will not be backgroundless (Josh Barrow, UT PhD thesis, 2021)

- In the transition time 2026-2030 Collaboration plans to pursue at ESS a smaller project HIBEAM with lower intensity cold neutrons through reduced Large Beam Port from only upper moderator. Goal of several smaller-size experiments there will be to search for for the neutron to mirror neutron oscillations $(n \to n')$ and the detector prototyping for future $(n \to \bar{n})$ experiment. Interesting possibility will be to search for $(n \to n' \to \bar{n})$ in the magnetic field.

We are glad that creativity of Rabi and his colleagues extends to the testable ideas of Mirror Matter and $(n \to n')$

- Before 2026 we pursue a program to explore the $(n \to n')$ oscillations in a few small experiments using SNS and HFIR neutron sources at ORNL. European members of NNbar are trying to join us in these experiment. The results of the first $(n \to n')$ search experiment from ORNL are published L. Broussard and others, *Phys.Rev.Lett.* 128 (2022) 21, 212503
More analyses and results will follow.

$n \to n'$ search as complementary to $n \to \bar{n}$

$n \to \bar{n}$ is described by propagation of eigenstates $\begin{pmatrix} m + \mu\boldsymbol{\sigma}\boldsymbol{B} & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}} & m - \mu\boldsymbol{\sigma}\boldsymbol{B} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$

More effects can be present for $n \to n'$ $\begin{pmatrix} m + V + \mu\boldsymbol{\sigma}\boldsymbol{B} & \epsilon_{nn'} + \eta\boldsymbol{\sigma}\boldsymbol{B} + \eta'\boldsymbol{\sigma}\boldsymbol{B}' \\ \epsilon_{nn'} + \eta\boldsymbol{\sigma}\boldsymbol{B} + \eta'\boldsymbol{\sigma}\boldsymbol{B}' & m' + V' + \mu'\boldsymbol{\sigma}\boldsymbol{B}' \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}$

Recent paper of I. Goldman, R. Mohapatra, S. Nussinov, Y. Zhang, PRL 129, 061103 (2022) from the n-stars cooling discuss as possible value $\epsilon_{nn'} \sim \mathcal{O}(10^{-17}\text{eV})$. In ESS experiments we plan to explore down to smaller $\epsilon_{nn'}$ $(\tau_{nn'} > 100\ s)$ provided that we understand and take experimentally under control other possible parameters of $n \to n'$ oscillations

- $\Delta m = m' - m$ of neutrons — Z. Berezhiani, *Eur.Phys.J.C* 79 (2019) 6, 484
- η – neutron Transition Magnetic Moment — Z. Berezhiani, R. Biondi, YK, L. Varriano *MDPI Physics* 1 (2019) 2, 271-289
- B' – presence of mirror magnetic field — Z. Berezhiani, *Eur.Phys.J.C* 64 (2009) 421-431
- $(V - V')$ – presence of Fermi potentials of materials — YK, J. Ternulo, L. Varriano, Z. Berehiani, *Symmetry* 14 (2022) 2, 230

$n \to \bar{n}$ transformation through mirror states in the presence of magnetic field

Z. Berezhiani, *Eur.Phys.J.C* 81 (2021) 1, 33

More general view: $\begin{pmatrix} n \\ \bar{n} \end{pmatrix} \leftrightarrow \begin{pmatrix} n' \\ \bar{n}' \end{pmatrix}$

$$\begin{pmatrix} E & \epsilon & \alpha & \beta \\ \epsilon & E & \beta & \alpha \\ \alpha & \beta & E & \epsilon \\ \beta & \alpha & \epsilon & E \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix}$$

$$P_{n\bar{n}} = \epsilon^2 t^2 + 16\alpha^2\beta^2 t^4$$

In vacuum, in the absence of magnetic fields

"Conventional" $n \to \bar{n}$

$n \to n' \to \bar{n}$ and $n \to \bar{n}' \to \bar{n}$

We can imagine that $\epsilon \ll \alpha, \beta$ and the mirror magnetic field B' is present.
Then ILL $n \to \bar{n}$ limit will not determine the real values of $\alpha\beta$.
One will need to tune B in order to compensate suppression due to B'.
In the resonance $B = B'$ probability $P_{n\bar{n}} \sim \mathcal{O}(10^{-10})$ is not excluded.
This can be testable at ESS.

The n - oscillations allow a range of new experiments at ORNL→ ESS inspired by your Theories and addressing BSM physics of observation of baryon number violation by 2 $(n \rightarrow \bar{n})$ or 1 units $(n \rightarrow n')$, the mechanism of baryogenesis (PSB), and the nature of Dark Matter (n')

We are building Collaboration including Europe, Japan, and US. Currently 5 US senior scientists (UT, NCSU, IU, Columbia, ORNL) are participating in the project. No support yet from funding agencies. ORNL, as specialized neutron Lab, is interested to participate. In Europe we are hoping that Swedish Funding Agencies will sponsor HIBEAM and NNbar as a substantial Sweden contribution to the science at ESS.

As emissary of NNbar-HIBEAM-NN'ORNL Collaboration I appeal to the experimentalists in your institutions – join us

Rabi will continue work with us on the neutron oscillation search !

$*$ I am grateful to the Stockholm University and Swedish Research Council, who are supporting my travel to Rabi Fest