Particle Physics with ESS

Valentina Santoro
Lund University and ESS

RECFA visit to Sweden

Outline

1. The ESS fundamental physics program
2. Why fundamental physics at the ESS ?
3. Overview of the different Swedish proposals

The ESS Fundamental Physics Program (I)

- The ESS will be the brightest neutron source in the world enabling new opportunities for many different scientific fields, including materials and life sciences, energy, environmental technology, cultural heritage and fundamental physics

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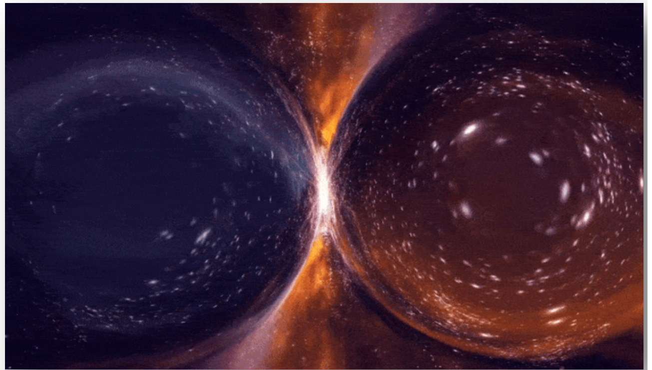
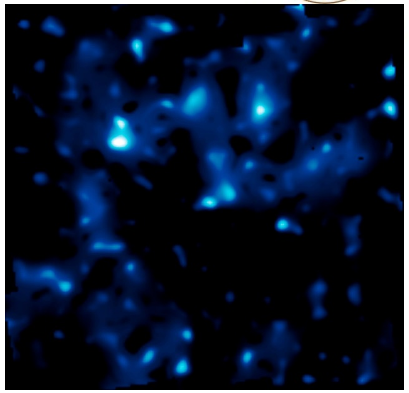
- Sweden has invested ~8BSEK (35% of the construction budget) in the ESS so far
- We are developing a broad fundamental physics program
- This includes mainly
  - Physics with neutrons
  - Physics with neutrinos



The ESS Fundamental Physics Program (II)

- The Dark Sector is more hidden than expected —> direct searches for BSM failed so far at LHC

- Physics at the **High Intensity Frontier** offers unprecedented opportunities for BSM searches in the near future (LHCb/BELLE2 upgrades, MEG, g-2, mu2e, neutrino beams T2k, DUNE. ecc..)



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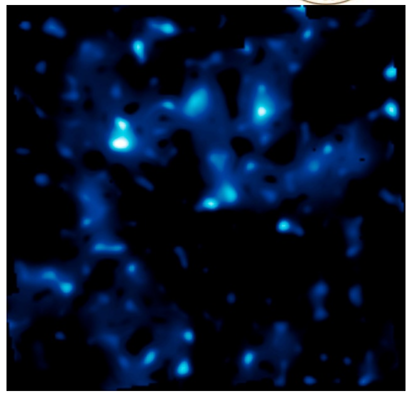

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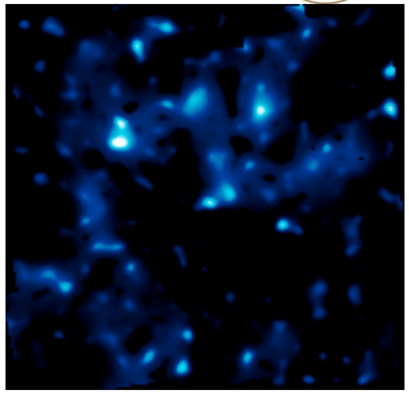

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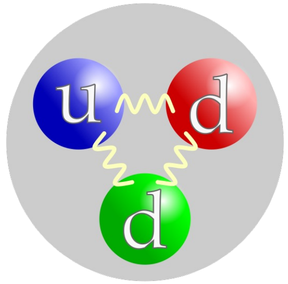
- ESS search can be complementary and competetive with LHC

Fundamental physics possibilities with **neutrons**



Standard Model of particle physics (SM)

Precision experiments

Beyond SM
New interactions

HIBEAM Beamline
Search for neutron oscillations
Search for Axion-like particle
Hadronic parity violation
Electromagnetic properties of the neutron

Search for Neutron antineutron oscillation (NNBAR)

Matter –Antimatter asymmetry of the Universe

Ultra Cold Neutron

Electric Dipole moment of the neutron (EDM)

Gravity resonance spectroscopy

Neutron beta decay

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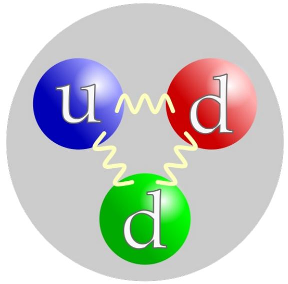

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ESSν
Coherent Elastic Neutrino-Nucleus Scattering at the ESS
High-statistics, precision CEνNS measurements

ESSnuSB
Discover and measure neutrino CPV

Why fundamental physics at the ESS ?

ESS is special

ESS is special particularly for particle physics

ESS is special particularly for particle physics because it is equipped with two superpowers

Superpower number 1

ESS is equipped with an accelerator that could go to 10MW **without extra infrastructure**

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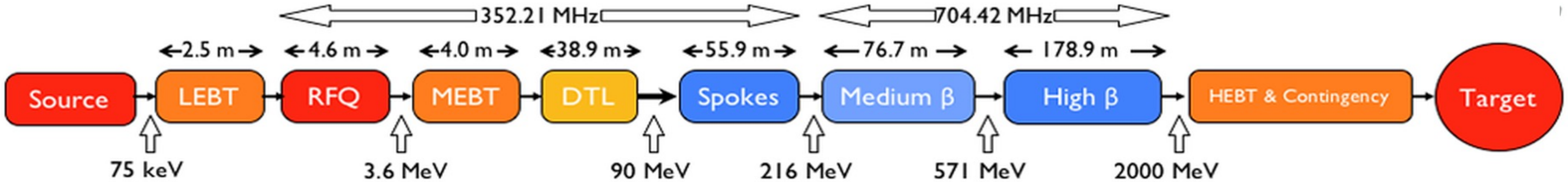
ESS Accelerator design at 2GeV and 5MW power on target



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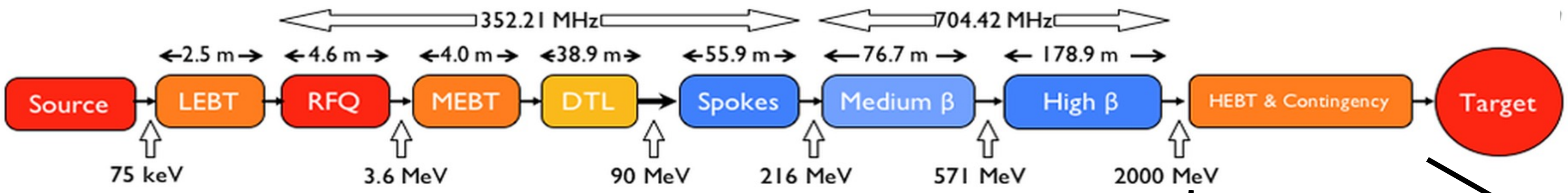
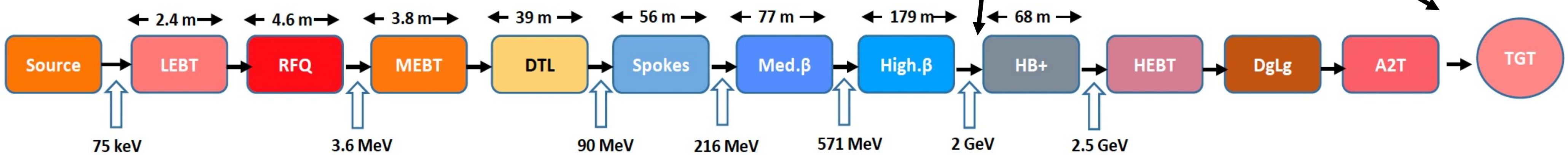


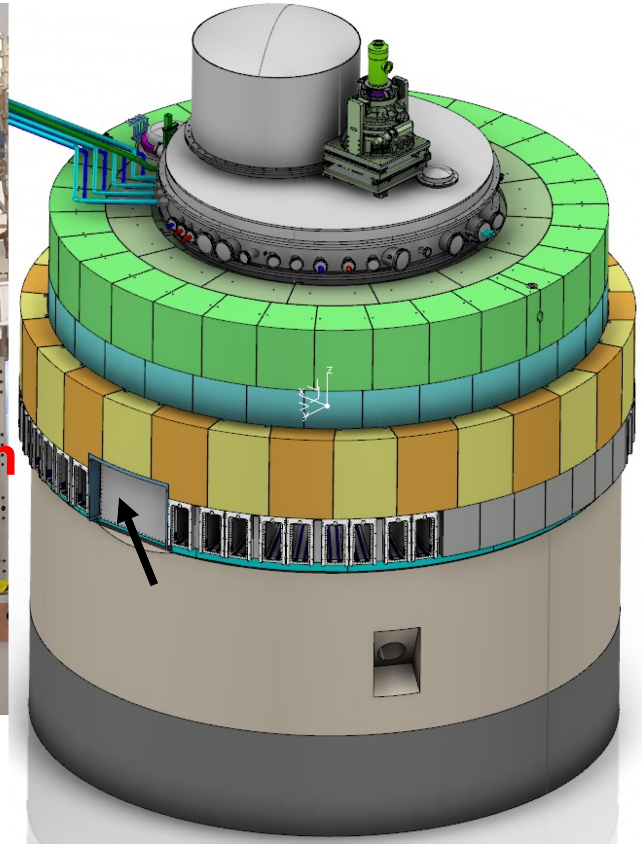
ESS Accelerator coud be “easily” upgraded to 10MW



The world’s most powerful proton accelerator offers unique capabilities by itself. Lots of neutrons, neutrinos…….

Superpower number 2

ESS is equipped with a 1m x 1m neutron beam port



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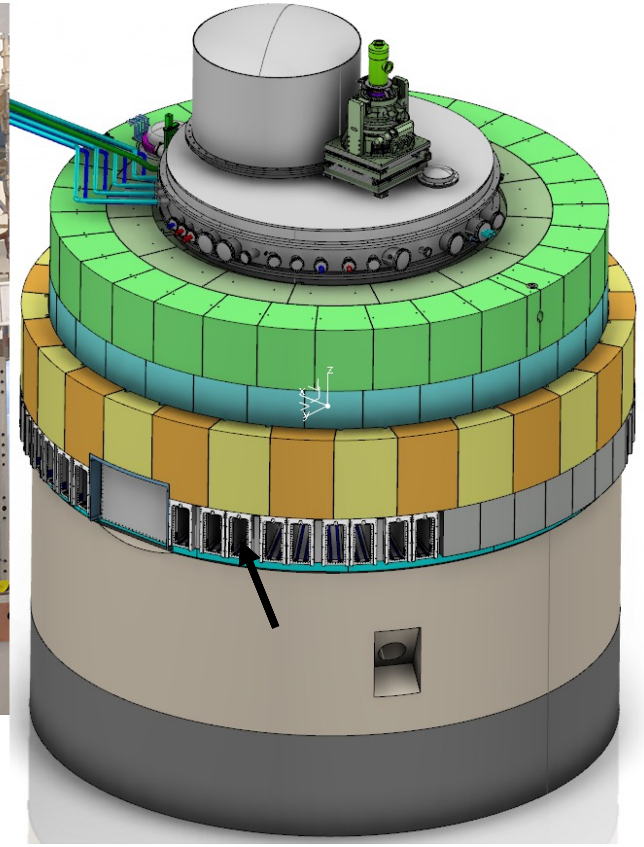

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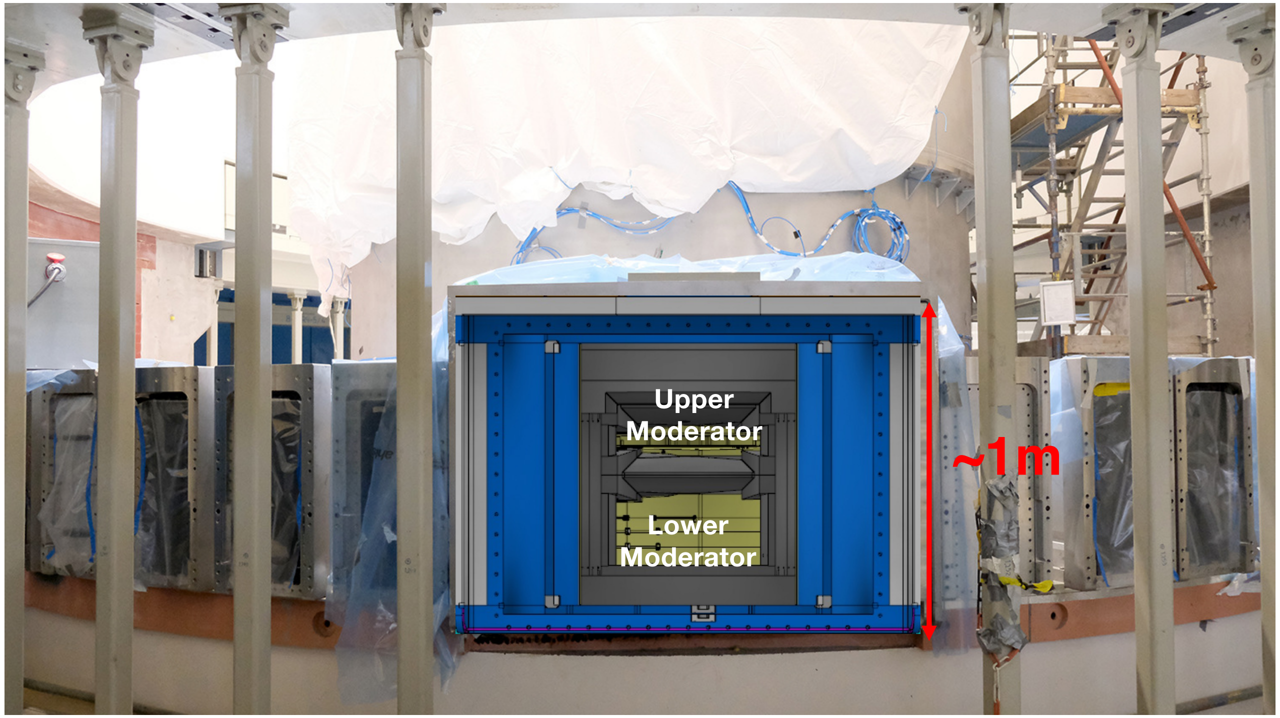

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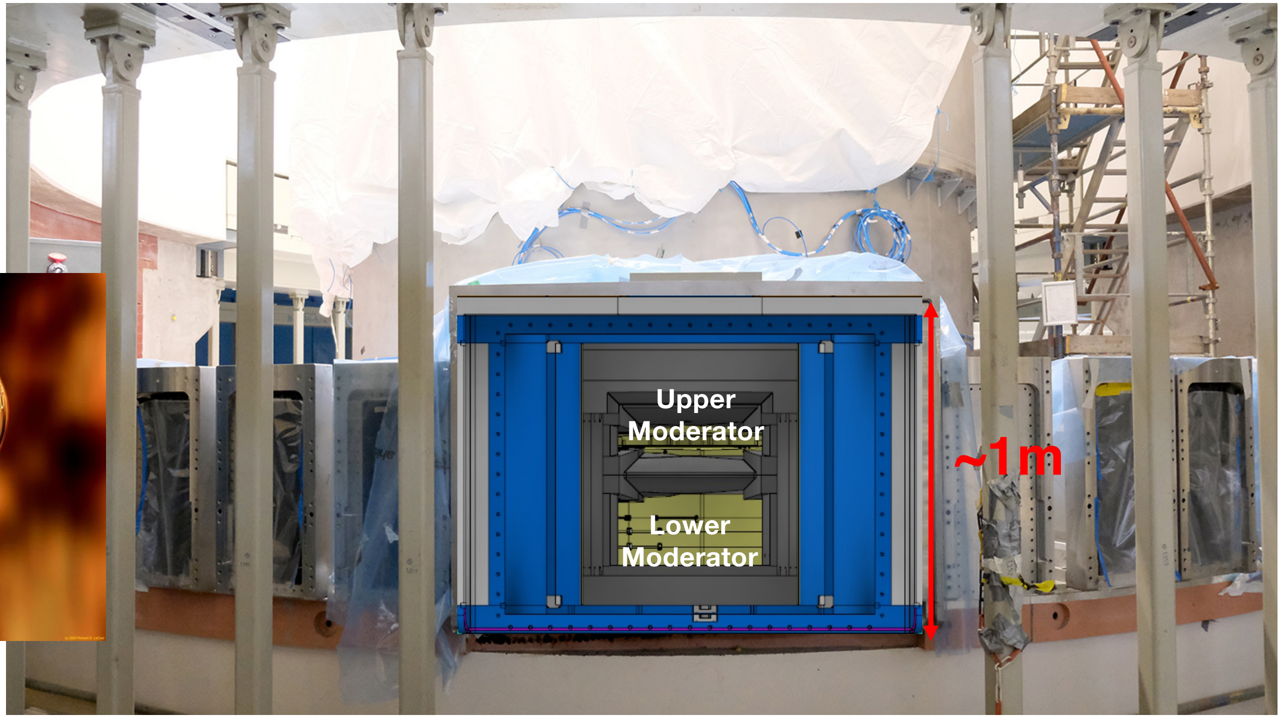
LUND UNIVERSITY



- NNBAR Large Beam Port has been constructed to provide sufficient intensity for $n \rightarrow \bar{n}$ search
- It is able to deliver **1.5x10^{15} n/s** there is no beamline **currently available or planned at any other facility that could reach a flux even close to this number**

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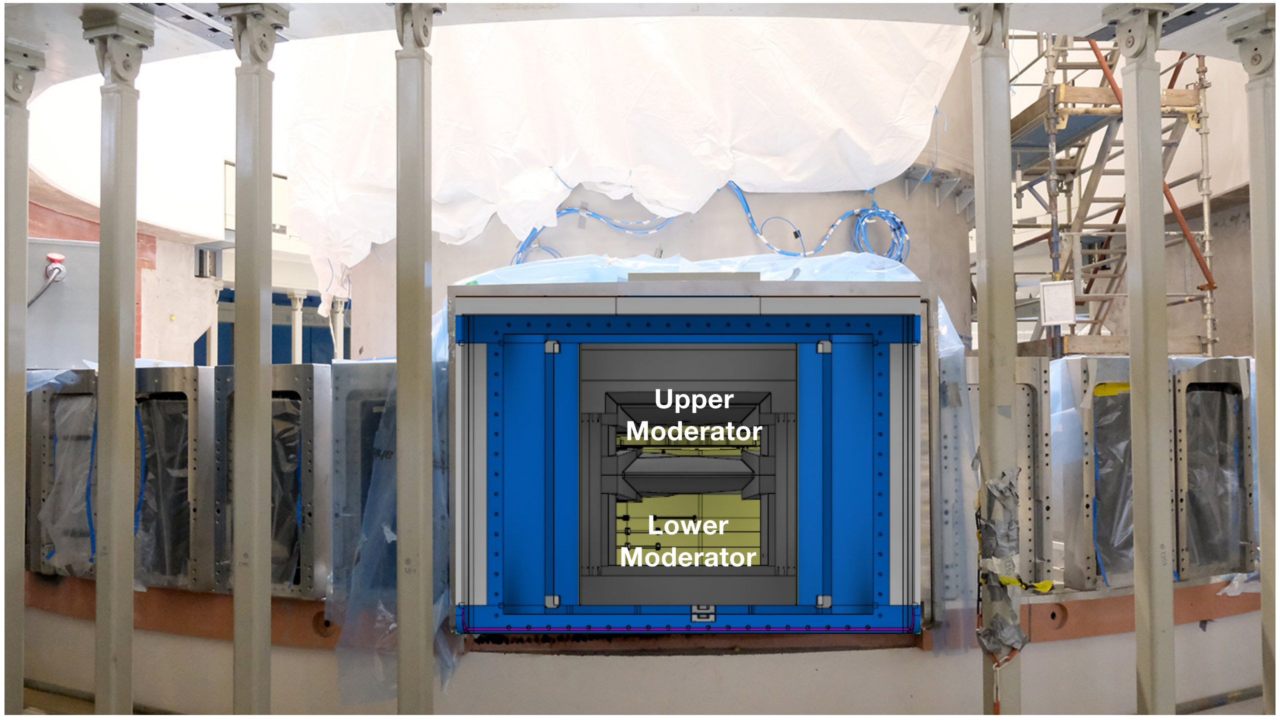

- **The Large Beam Port will allow the NNBAR experiment to achieve more than 10^3 better than previous searches.** Santoro, V. et al. 'HighNESS Conceptual Design Report: Volume II. The NNBAR Experiment.' Journal of Neutron Research, Jan. 2023 : 315 – 406.

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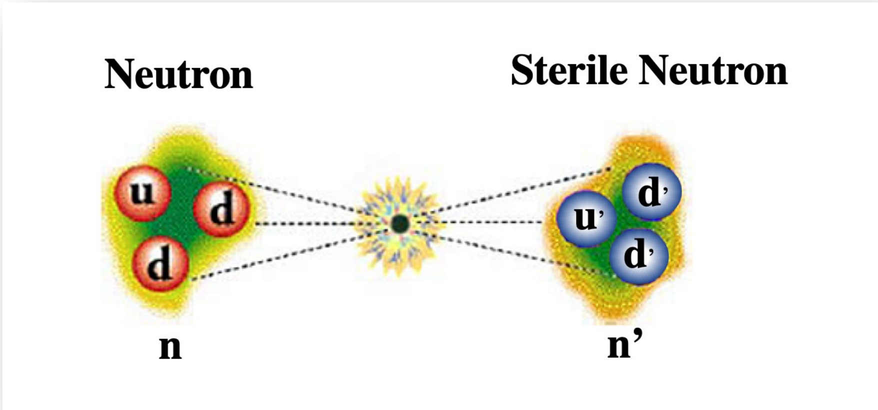
The HIBEAM/NNBAR program search for neutron oscillations



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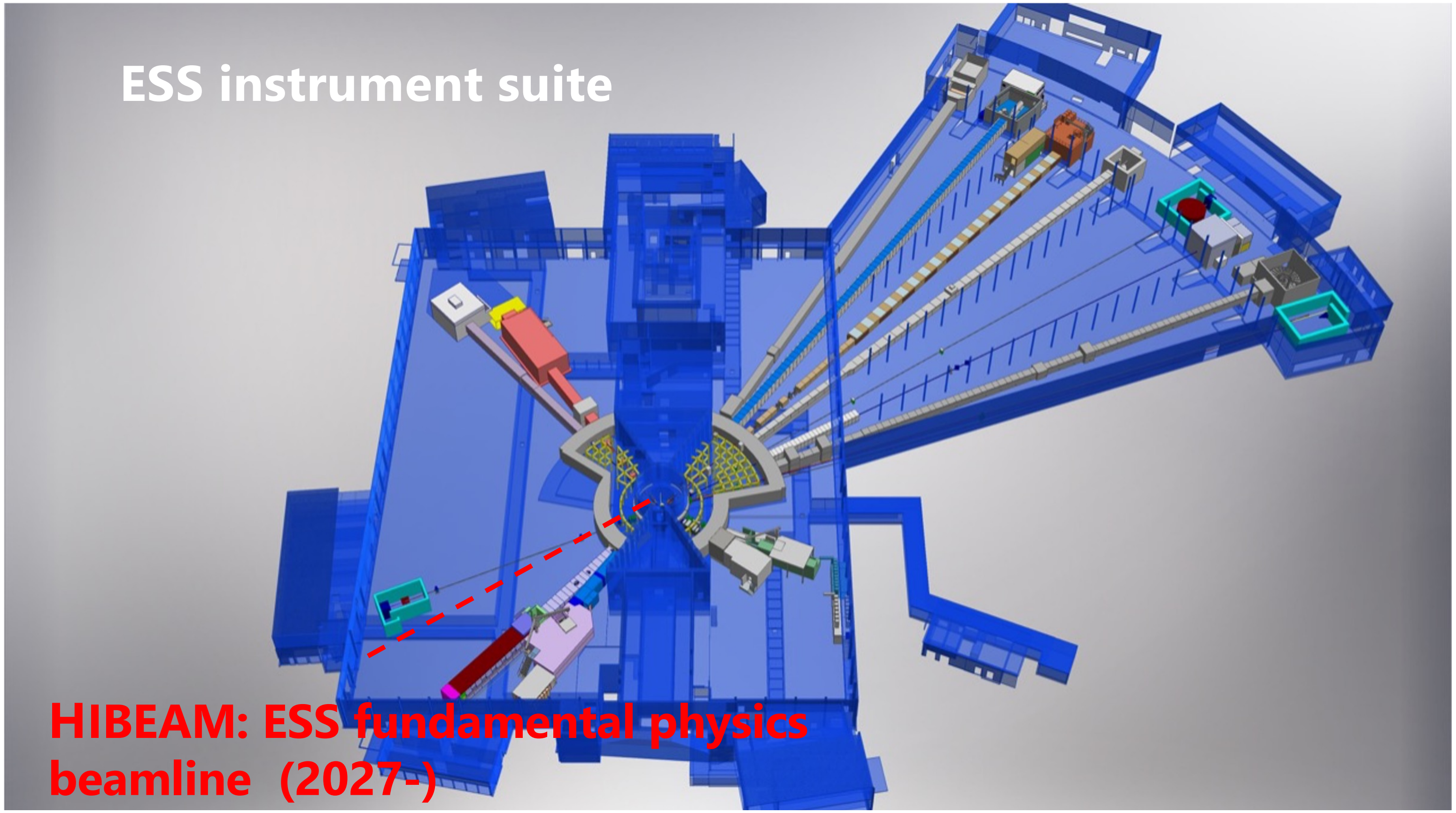
- The HIBEAM/NNBAR program will search for Baryon Number violation through neutron oscillations
- **Two stage program:**
  - HIBEAM will search for **neutron** to antineutron oscillations n→n̄ (|ΔB|=2) sensitivity increase of 10 and for **sterile neutron** oscillation n→n' (|ΔB|=1)
  - NNBAR will search for the n→n̄ with sensitivity increase of 10^3 compared to previous experiments

Future Free Neutron Oscillations Searches at the ESS



Two stage program:

- HIBEAM ($\gtrsim$2027-)

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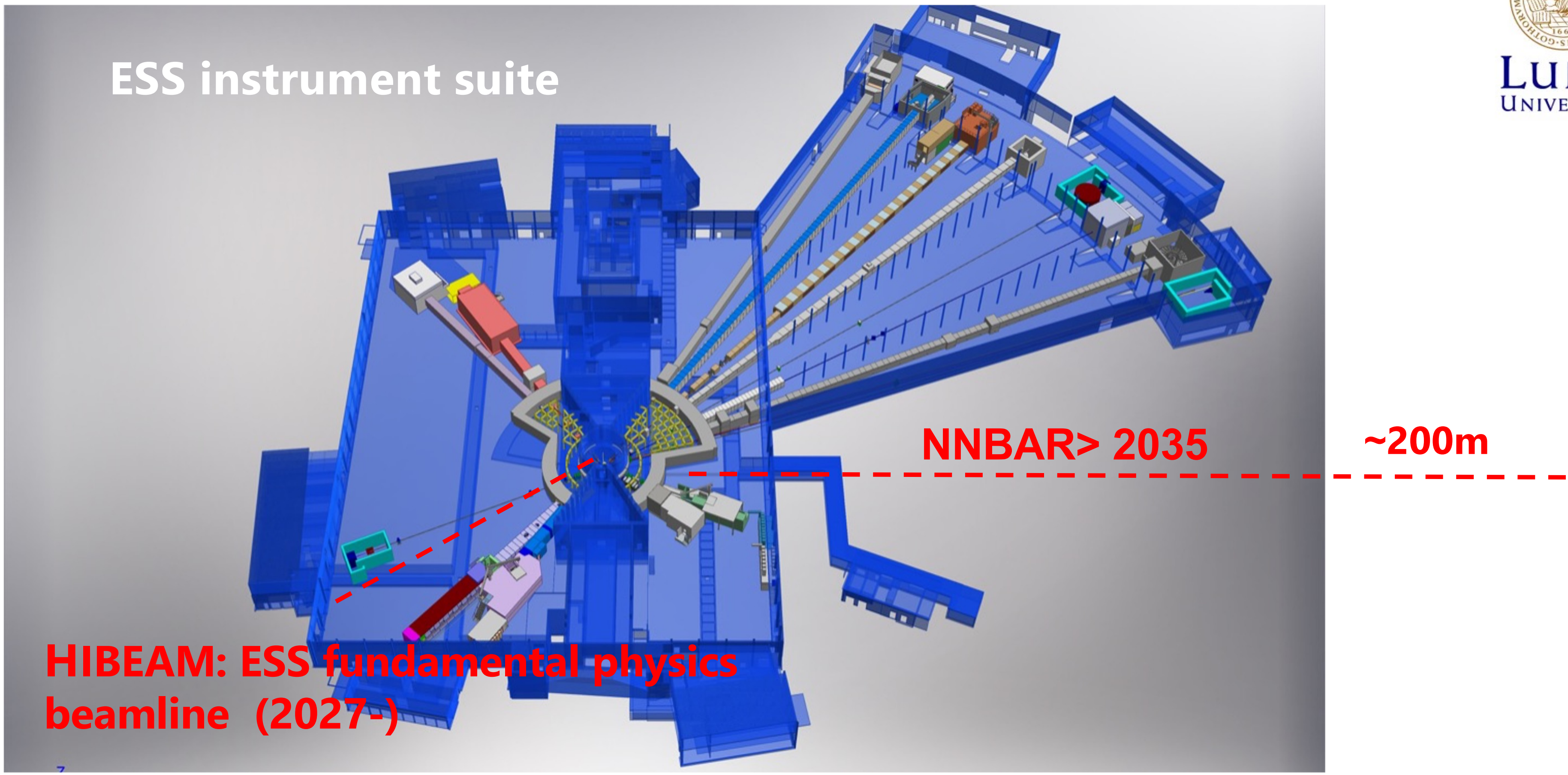


Two stage program:

- HIBEAM (≳2027-)
- NNBAR (>2035): search for $n \to \bar{n}$ oscillations (sensitivity increase of 10^3 compared to previous experiments)

HIBEAM neutron conversions searches

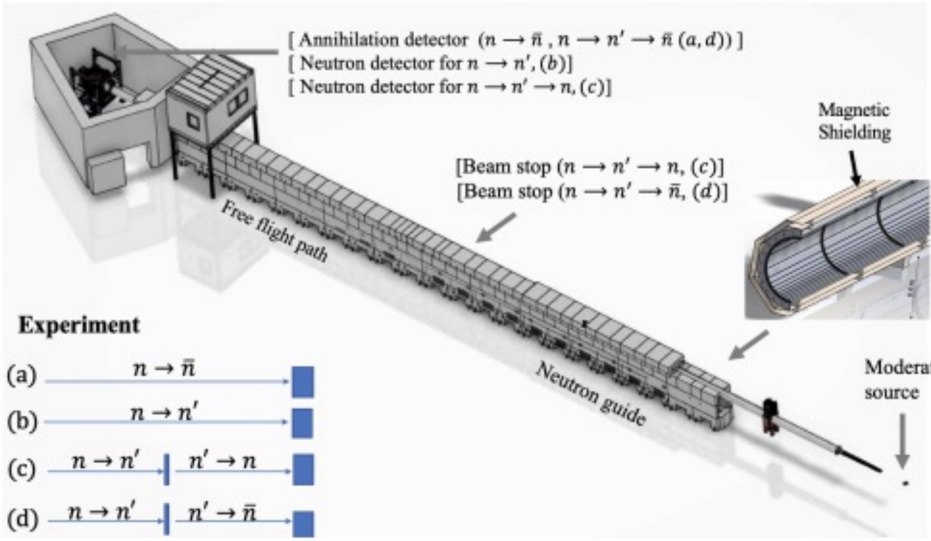
$$\hat{\mathcal{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n'\bar{n}'} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n'\bar{n}'} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$

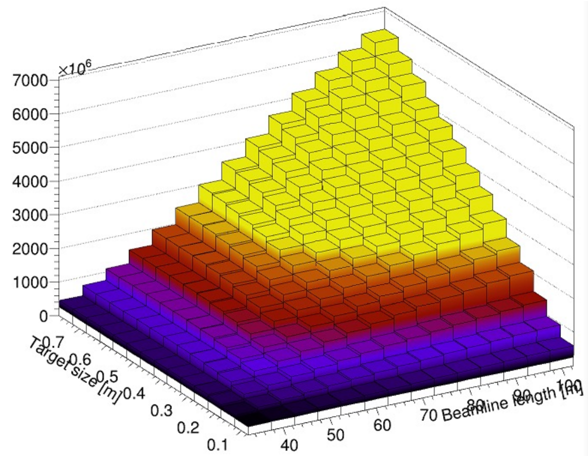
Sensitive to the full mixing Hamiltonian for $n, \bar{n}, n', \overline{n'}$

The signature of the neutron-antineutron transitions is via the annihilation of an $\bar{n}$ on a carbon target → this interaction produce a multipion states (3-5 charged pions and photons from π^0 decay)

An annihilation detector with a TPC, electromagnetic calorimeter and a cosmic veto is needed. Detector studies and simulations have been performed and are ongoing

Factor 10 improvement or higher for free nnbar and sterile neutron searches.





Beyond neutron oscillations

https://arxiv.org/abs/2404.15521v2

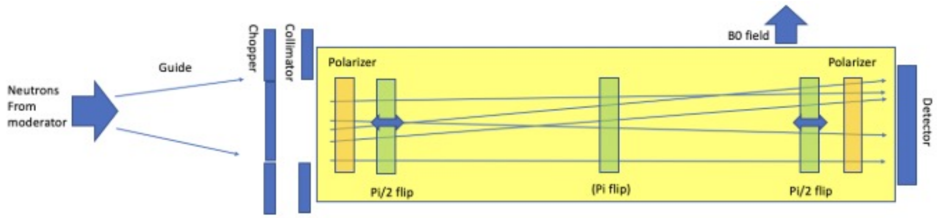
HIBEAM beamline enables a range of physics. E.g. hadronic parity violation, nEDM, **axions**…

$$H_{\text{int}}(t) \approx \frac{C_N a_0}{2 f_a} \sin(m_a t)\, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}$$

Coupling of axions to a nucleon
Axions act as a pseudomagnetic field

Change in Larmor frequency due to axions

Ramsey set up for Larmor frequency

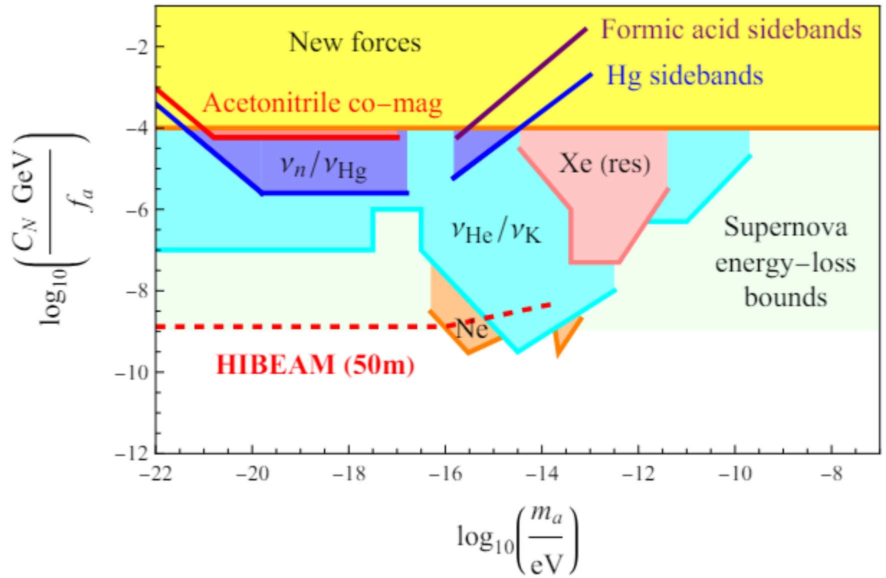


Direct search sensitivity improvement by 2-3 orders of magnitude (indirect searches have model dependence)

Pilot experiment possible with first data.

Most of the kit already acquired (magnetics ..) or can be borrowed.

Can be first ESS particle physics experiment.



HIBEAM current support

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- It is currently supported by the Swedish Research Council (VR) with (10MSEK), by Stiftelsen för Strategisk Forskning (SSF) (15MSEK) grant, by Olle Engkvists Stiftelse and recently VR has funded a new project for the development of the HIBEAM neutron detector.

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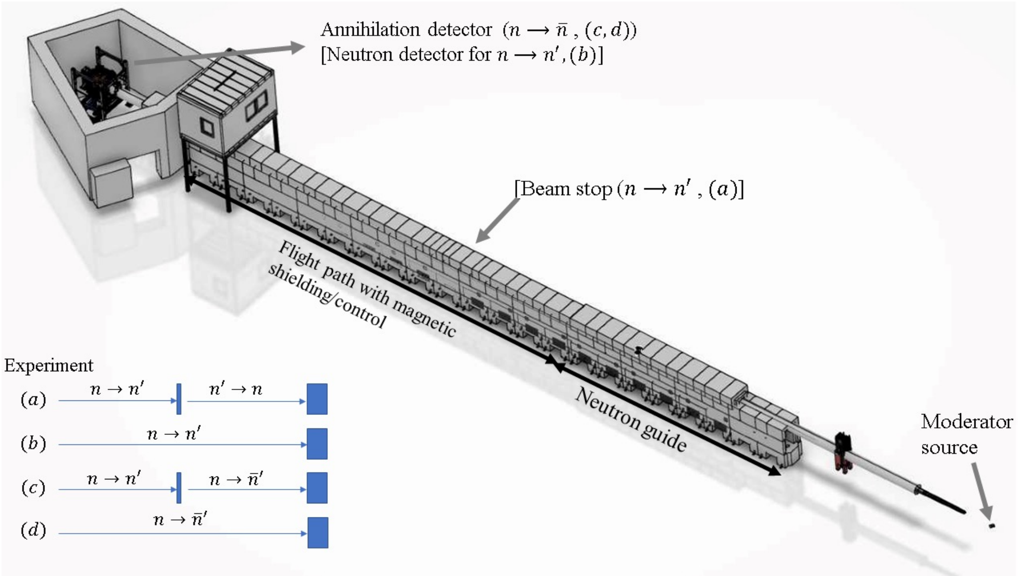
  - Furthermore, the Director General of the ESS, Helmut Schober, has provided a letter of support for an ERC synergy application (November 2023). In the letter, it is stated that ``***The construction of the HIBEAM beamline, with the expected sensitivity increases of one order of magnitude for the proposed searches if realized, represents an extraordinary opportunity not only for neutron science but for the entire particle physics community. It will fully exploit the capability of the ESS***".

EN

HIBEAM current activities

- A technical design report is currently under preparation for a full design for the HIBEAM beamline as final deliverable of the Swedish Research Council (VR) Infrastructure project

- The program is technically mature and the HIBEAM program is ready to move toward the implementation phase if funding is provided



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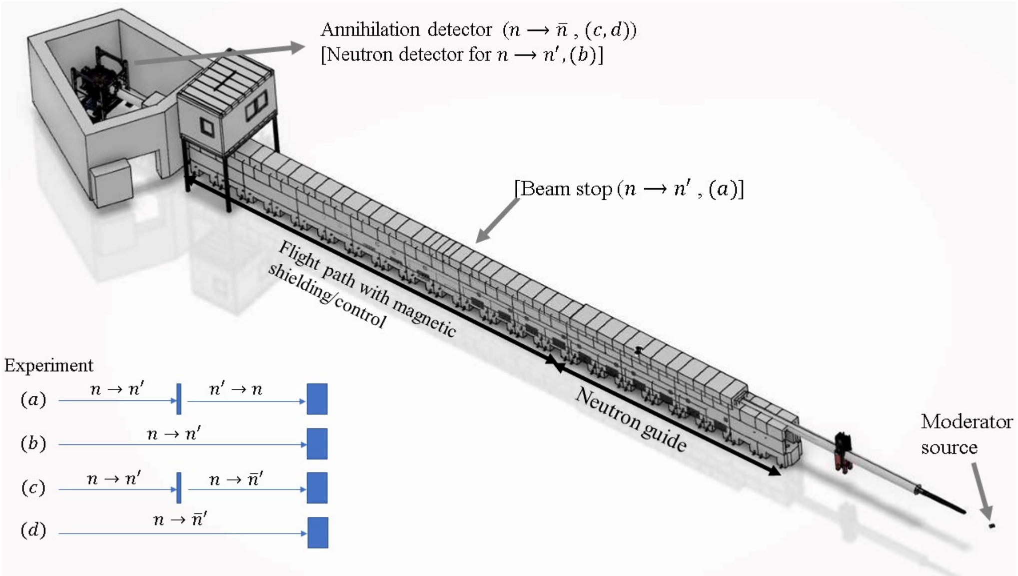
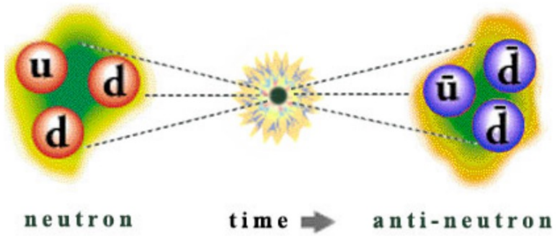
- An application has been submitted to VR RFI for HIBEAM to be included in the behovsinventeringslista (national lists of infrastructure)

- A series of applications have been made to expand the HIBEAM beamline program.



The NNBAR experiment @ ESS



$$\boldsymbol{n \rightarrow \overline{n}}$$

RECFA VISIT TO SWEDEN

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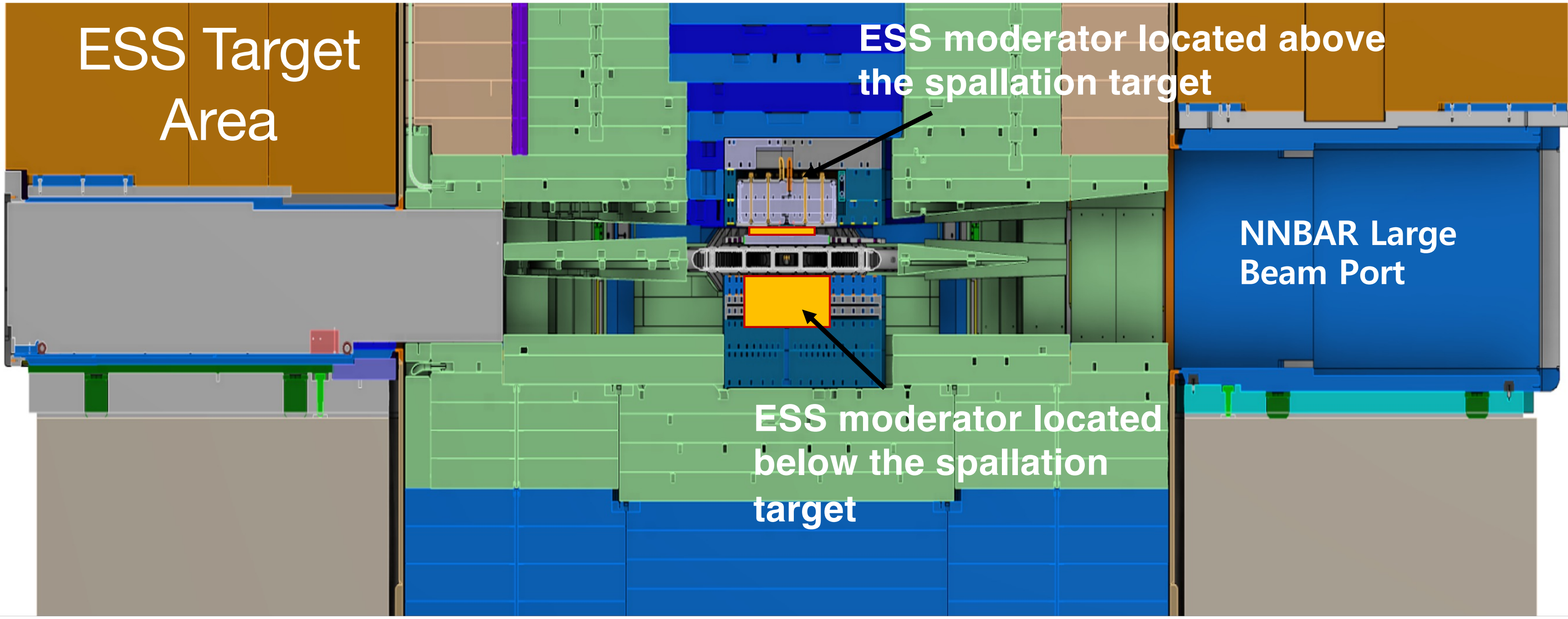

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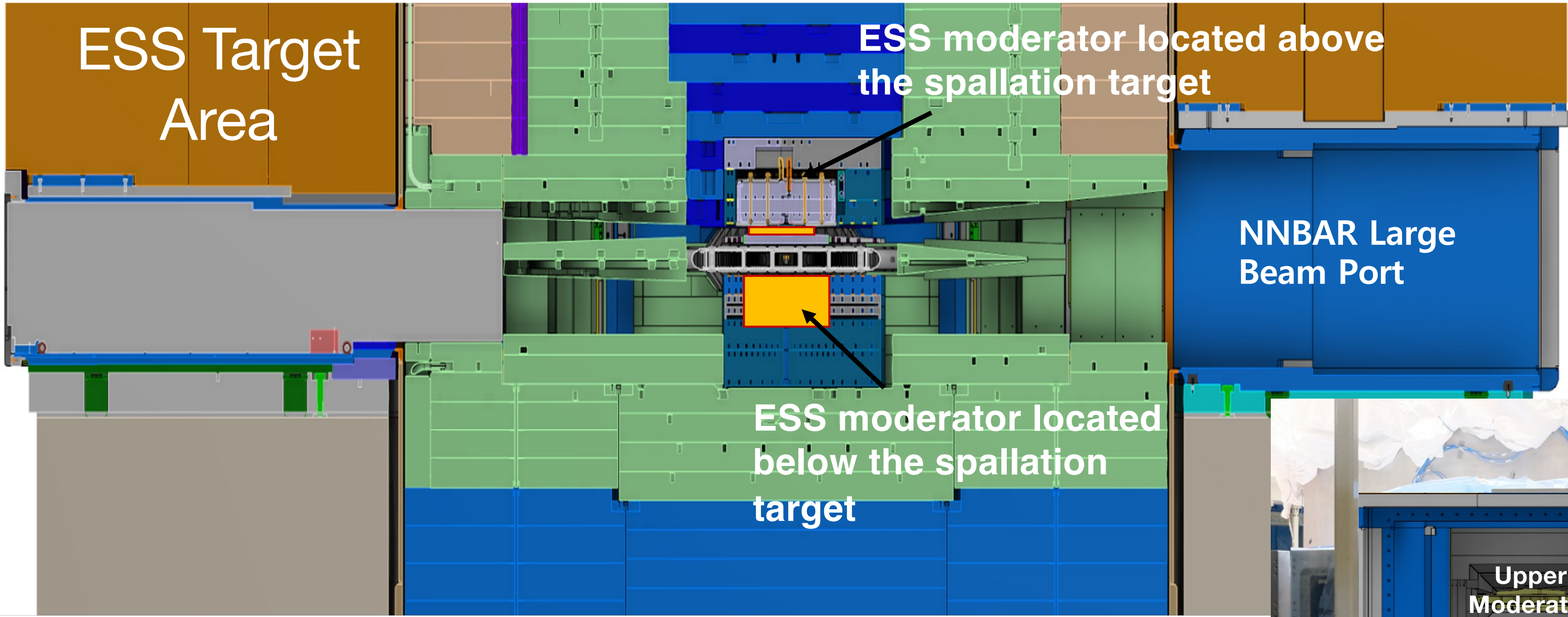
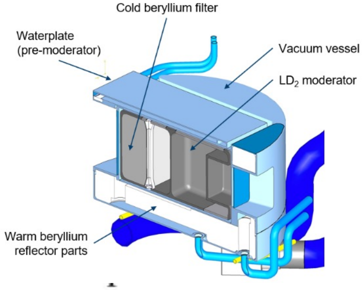


The NNBAR Experiment

The Conceptual Design Report was published two weeks ago as the final deliverable of the European Project HighNESS. All the different parts of the experiment have been addressed



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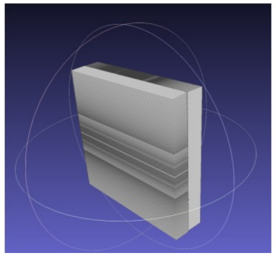

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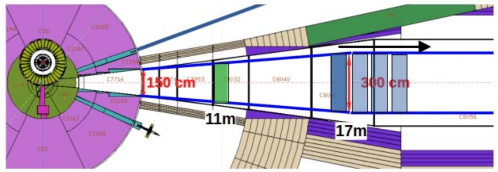

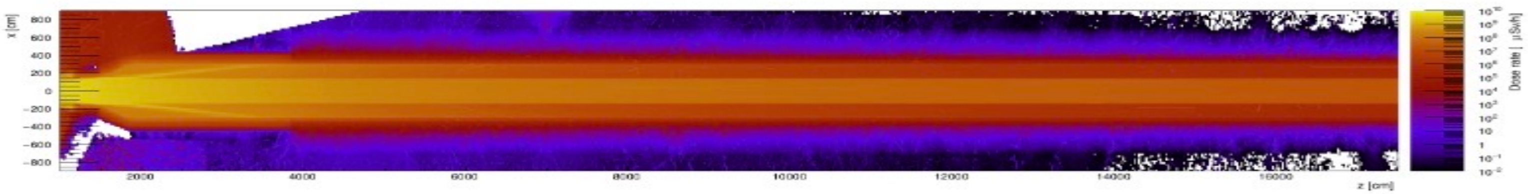

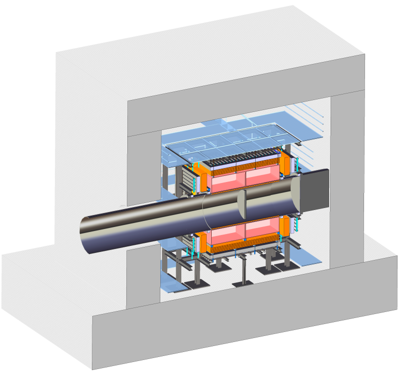

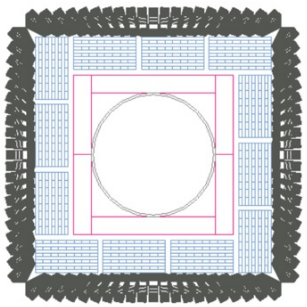

Aluminum tube

0.55 m inner radius
2 cm thick
6 m long (z direction)

Time Projection Chamber

Two different dimensions
- 0.16 m x 0.73 m
- 1.14 m x 0.16 m

2m long (z direction)
80% Ar + 20% CO2

Scintillator Modules

10 layers of plastic scintillator
3 cm thick for each layer

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**

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

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[f] *Massachusetts Institute of Technology (MIT), Cambridge, USA*
[g] *Tel Aviv University, Tel Aviv, Israel*
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[l] *Institut Laue-Langevin ILL, Grenoble, France*
[m] *Mirrotron Ltd., Budapest, Hungary*
[n] *Centre for Energy Research, Budapest, Hungary*
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[p] *Technical University of Munich, Garching, Germany*
[q] *Sweco AB, Malmö, Sweden*
[r] *Institute of High Energy Physics, Chinese Academy of Science, Beijing, 100049, China*
[s] *University of Chinese Academy of Science, Beijing, 100049, China*
[t] *Spallation neutron source science center, Dongguan, 523803, Guangdong, China*
[u] *State University of Campinas, Campinas, Brazil*
[v] *University of Tennessee, Knoxville, USA*
[w] *ESS consultant, Oslo, Norway*
[x] *Departamento de Ciências da Natureza, Universidade Federal Fluminense, Niterói, Brazil*
[y] *Institutionen för Fysik, Chalmers Tekniska Högskola, Sweden*
[z] *MAX IV Synchrotron, Lund University, Lund, Sweden*

NNBAR Status

- Conceptual Design Report of the NNBAR experiment have been delivered and published with support by European Commission Santoro, V. et al. ‘HighNESS Conceptual Design Report: Volume II. The NNBAR Experiment.’ 1 Jan. 2023 : 315 – 406
  - Detector development and design optimization. Design of the NNBAR moderator, optics system, simulations of backgrounds and shielding. Integration in the ESS facility
  - Address uncertainties in cost of experiment
  - Next step is to move from CDR to TDR

HIBEAM/NNBAR Collaboration

- Many active institutes: Stockholm University (D. Milstead co-spokep) , Chalmer Technical University, University of Uppsala ,Lund University (V. Santoro Techinical Coordinator) , TMU (Germany), Tennessee, Columbia (Gustaaf Brooijmans co-spoke) , ORNL, University of Indiana, NC State (US), Brazil (Rio), Italy (University of Milano), Japan (University of Nagoya), Krakow (PL)

- Broad international base and supporters
  ~ 100 authors from 50 institutes in 8 countries. Combines experts in neutronics, magnetics, nuclear and particle physics.

A Ramsey Neutron-Beam Experiment to Search for Ultralight Axion Dark Matter at the ESS, (Arxiv 2404.15521 [hep-ph], submitted to PRL)

HighNESS conceptual design report: Volume II. The NNBAR experiment, , Journal of Neutron Research, vol. 25, no. 3-4, pp. 315-406, 2023

Particle Physics at the European Spallation Source, *Phys.Rept.* 1023 (2023) 1-84

The HIBEAM program: search for neutron oscillations at the ESS, 2311.08326 [physics.ins-det]

The development of the NNBAR experiment, JINST 17 (2022) 10, P10046

Design of an optimized nested-mirror neutron reflector for a NNBAR experiment, Nucl.Instrum.Meth.A 1051 (2023) 168235

The HIBEAM/NNBAR Calorimeter Prototype, J.Phys.Conf.Ser. 2374 (2022) 1, 012014

Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source, Symmetry 14 (2022) 1, 76

Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS, EPJ Web Conf. 251 (2021) 02062

- New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source, *J.Phys.G* 48 (2021) 7, 070501

The ESS neutrino Super Beam (ESSnuSB)

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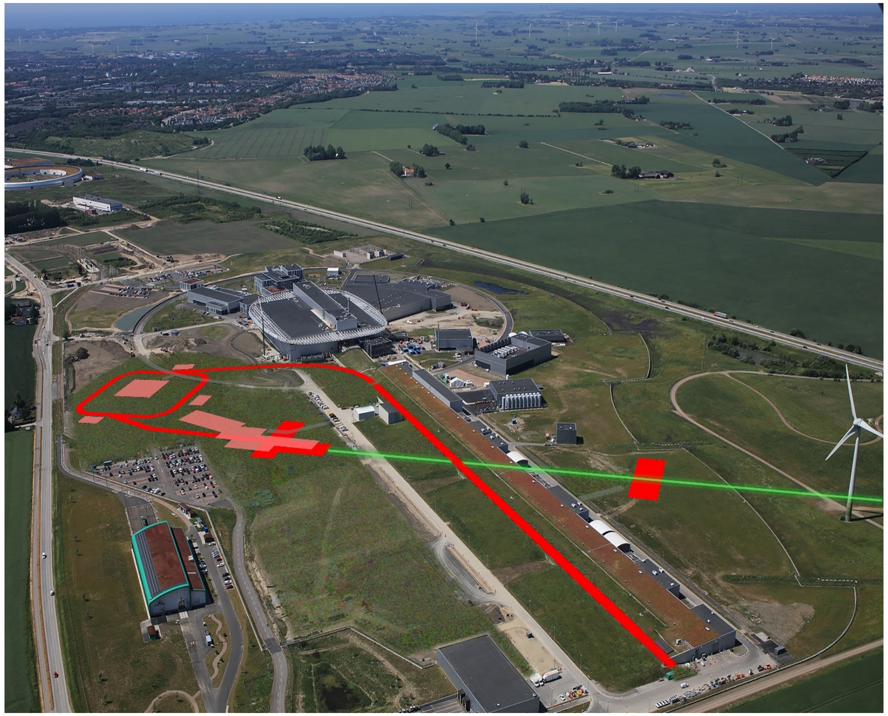
- The ESSnuSB is a proposed accelerator long baseline neutrino experiment at ESS
- The ESSnuSB will search for CP violation in the leptonic sector with higher precision



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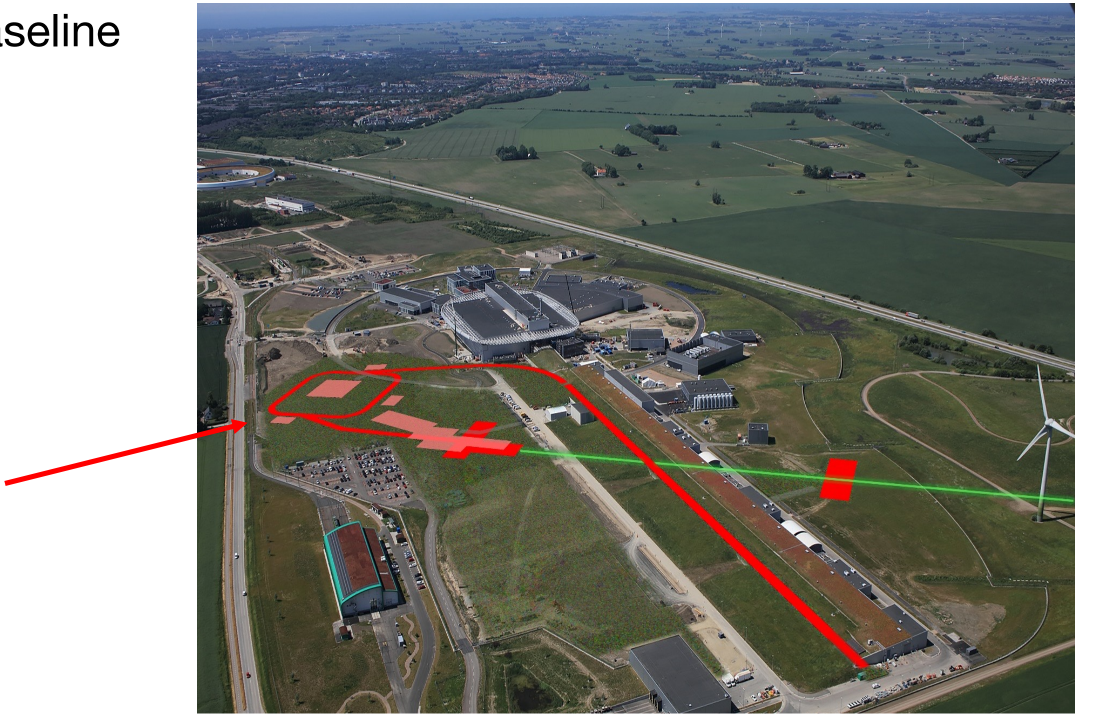
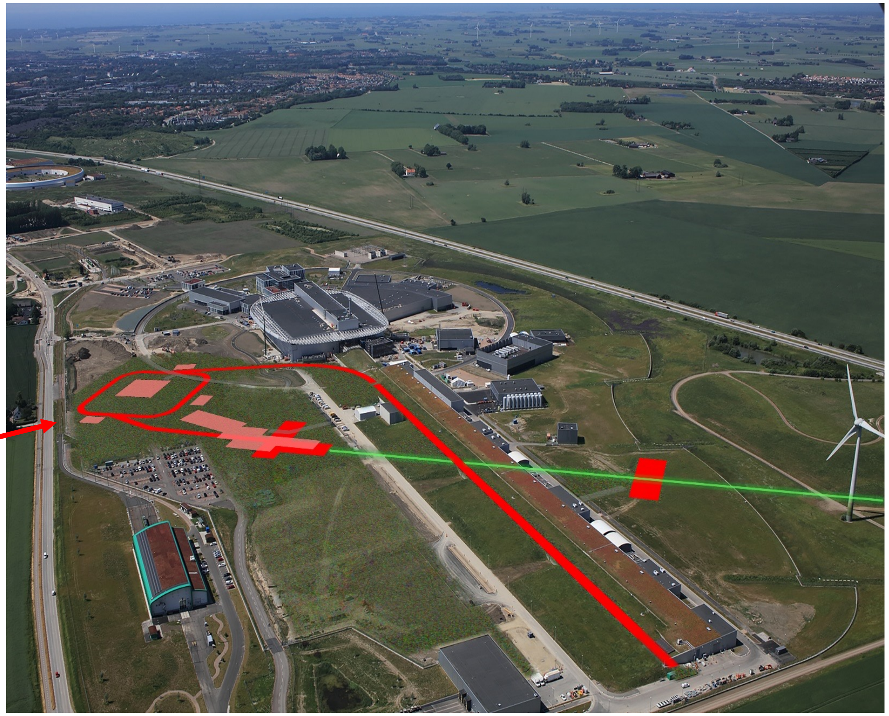
- The ESS accelerator needs to be upgraded

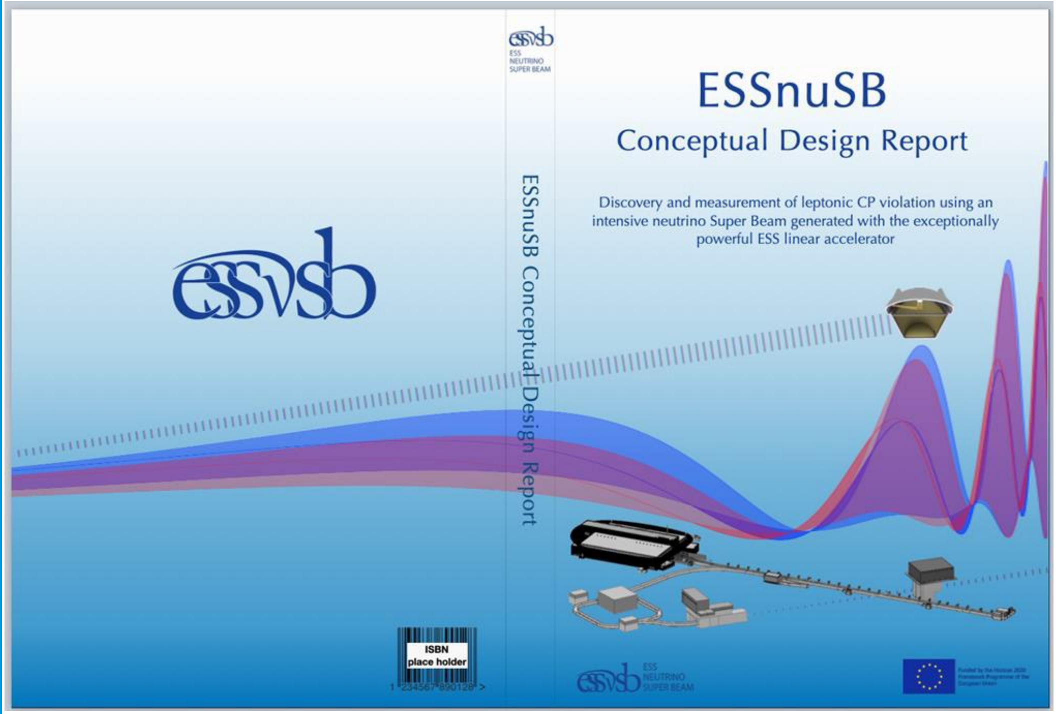


The ESS neutrino Super Beam (ESSnuSB)

- The ESSnuSB is a proposed accelerator long baseline neutrino experiment at ESS
- The ESSnuSB will search for CP violation in the leptonic sector with higher precision
- The ESS accelerator needs to be upgraded
- A neutrino production target station will be built
- There will be a near detector close to the neutrino target station and a far detector in the north of Sweden
- They are supported by 2 European INFRADEV grants



ESSnuSB Conceptual Design Report



Published on arXive 6June 2022:
https://arxiv.org/abs/2206.01208
and in European Physical Journal 6 Nov 2022
Eur. Phys. J. Spec. Top .(3955-3779 :**231** (2022))
https://link.springer.com/article/10.1140/epjs/s11734-00664-022-w

CDR outline:

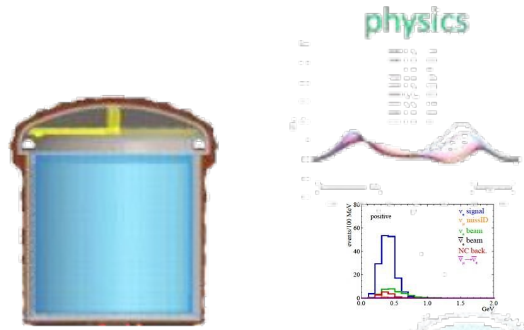
1 Linac upgrade
2 An accumulator ring
3 A target station and 50 m decay tunnel
4 A near detector placed in the neutrino beam Some 250m downstream of the target station
5 A far detector 360 km from the target station consisting of two large underground tanks filled each with 24000m^3 of water
6 Physics performance

The ESSnuSB+ Collaboration

1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UNIVERSITE DE STRASBOURG	FR
3	RUDER BOSKOVIC INSTITUTE	HR
4	TOKAI NATIONAL HIGHER EDUCATION ANDRESEARCH SYSTEM, NATIONAL UNIVERSITY CORPORATION	JP
5	UPPSALA UNIVERSITET	SE
6	LUNDS UNIVERSITET	SE
7	EUROPEAN SPALLATION SOURCE ERIC	SE
8	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
9	UNIVERSITAET HAMBURG	DE
10	UNIVERSITY OF CUKUROVA	TR
11	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
12	ARISTOTELIO PANEPISTIMIO THESSALONIKIS	EL
13	SOFIA UNIVERSITY ST KLIMENT OHRIDSKI	BG
14	LULEA TEKNISKA UNIVERSITET	SE
15	ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE	CH
16	UNIVERSITA DEGLI STUDI ROMA TRE	IT
17	UNIVERSITA' DEGLI STUDI DI MILANO-BICOCCA	IT
18	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
19	UNIVERSITA DEGLI STUDI DI PADOVA	IT
20	CONSORCIO PARA LA CONSTRUCCION, EQUIPAMIENTO Y EXPLOTACION DE LA SEDE ESPANOLA DE LA FUENTE EUROPEA DE NEUTRONES POR ESPALACION	ES

The ESSnuSB Collaboration, currently consisting of ca 80 members from 20 universities and laboratories in 11 European countries has had and has strong support from the European Commission, from ESS and from Zinkgruvan Mining.

Schedule for the ESS-based neutrino Super Beam ESSnuSB



Summary of the ESSnuSB project

- The ESSnuSB is a second generation ESS-based neutrino Super Beam for high precision measurements of the CP violating angle

- The first EU-supported phase of the ESSnuSB conceptual design study 2018-2021 has been successfully concluded, demonstrating the feasibility of the use of the ESS 5 MW linac as proton driver for a long base-line neutrino experiment.

- The second phase of the Design Study is now continuing and the ultimate goal will be to produce an ESSnuSB Technical Design Report by 2028..

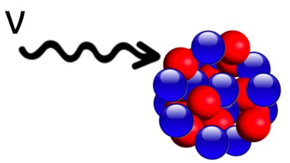
- The collaboration is now consulting with the RFI/VR in view of the intention of the ESSnuSB Consortium to apply in April 2025 for ESSnuSB to be listed in the 2026 ESFRI Roadmap.

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) at the ESS

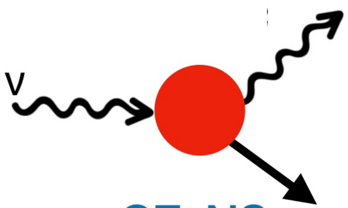
νESS

What is Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)?

Large flux of neutrinos from π+ decay at rest with energies up to 53 MeV (½ m_{μ})

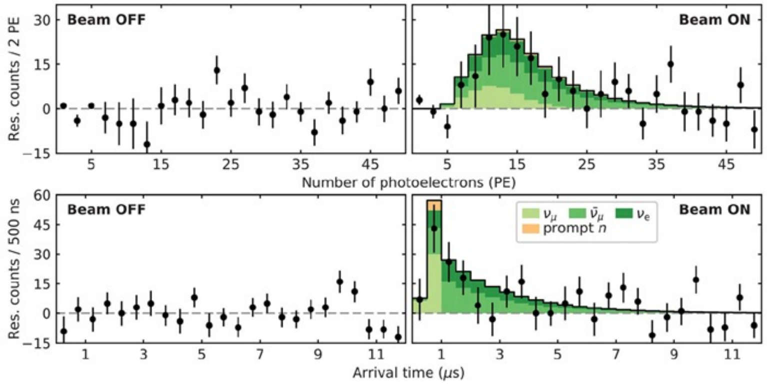


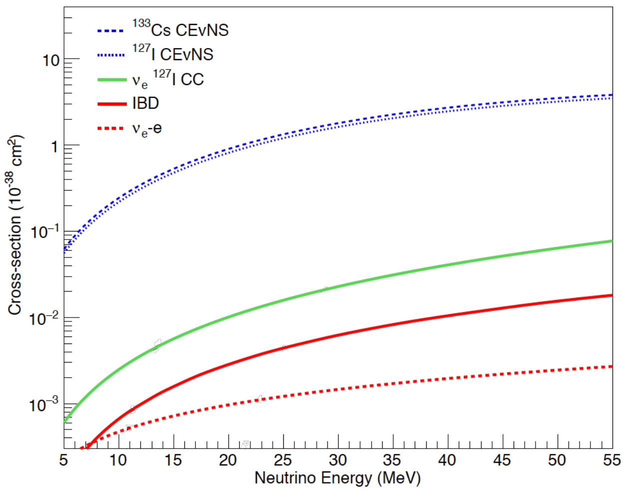
$$\sigma \propto [(1 - sin^2\theta_W)Z - N]^2$$



Long wavelength, "sees" all nucleons simultaneously

Process first observed at SNS in 2017



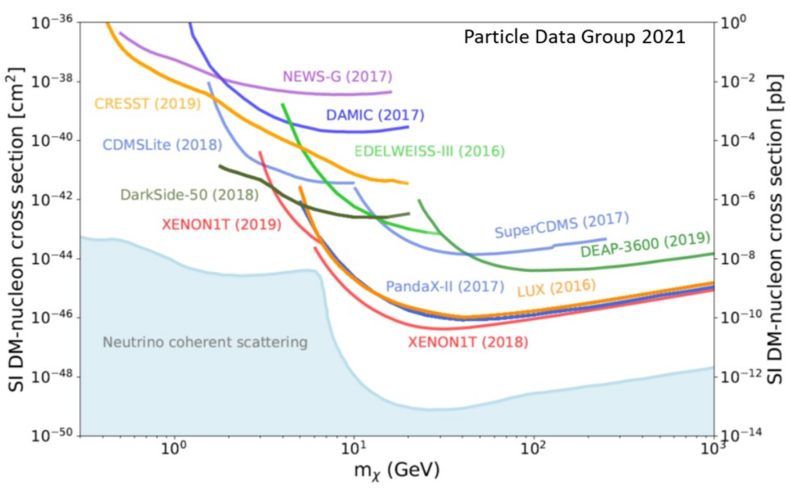


Cross section increases as N². (largest of all -> small detectors) CATCH: sub-keV to few keV recoils are only observable.

Max recoil energy is ≈ $2E_{\nu}^2/M$

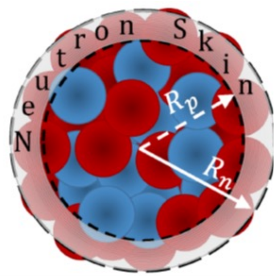
Ar (150keV), Ge (83keV), Cs (45keV)

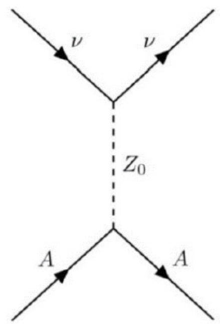
Why is CEνNS important?



Can give input to several research questions, such as:

- ✓ Study of the neutral current and sensitivity to the weak mixing angle and non-standard neutrino interactions.
  - → Especially sensitive to new light mediator particles such as Z′ and φ $(m << m_\mu)$
- ✓ Study of the nuclear structure – minimally disruptive of the nucleus
- ✓ New types of particles such as sterile neutrinos
- ✓ Input to dark matter searches and even sensitivity to new dark matter particles
- ✓ Lepton universality tests
- ✓ Effective neutrino charge radius and neutrino magnetic moment
- ✓ Better understanding of supernovas (where neutrinos carry the energy out first, and CEνNS is the dominant mode)

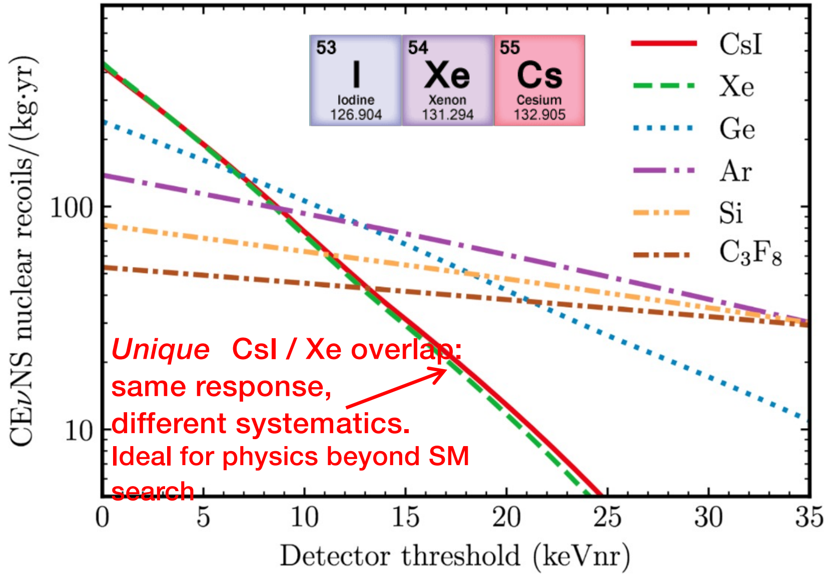




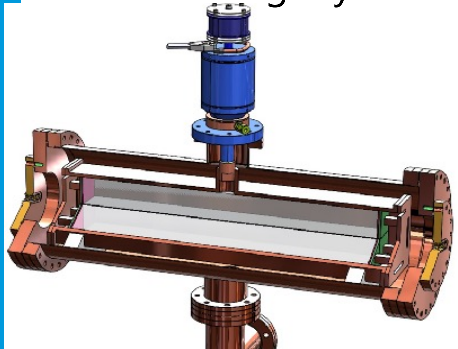
complementary to measurements at the big neutrino experiments!

Detectors for the νESS

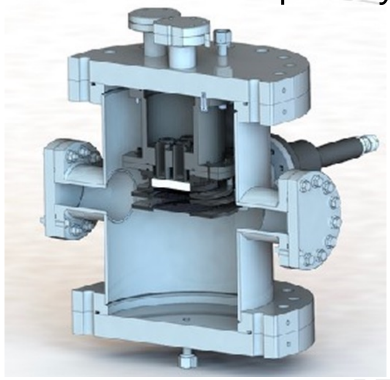
- Combination of technologies to minimise possible systematic effects.
- Use of different nuclei to allow for exploring larger fraction of the phase space, and similar nuclei with different technologies
    - Different nuclei couple to (somewhat) different combinations of couplings
- Right now: tests and development, using CsI, Xe, and Ge
- Important to develop detectors with low threshold for increased sensiti to new physics

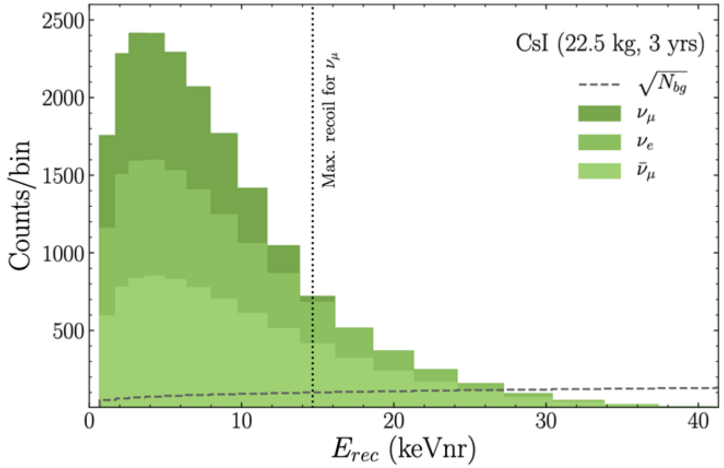


CsI scintillating crystals



Gaseous detector prototype





Time to wrap up my presentation

External funding received for the ESS fundamental physics program

- 1.5 M€ 5 years ERC Starting Grant
- 2 M€ Basque Government
- 2.8 M € ERC Advanced Grant

ESSν

- HighNESS 3M€ (EC)
- HIBEAM RFI Grants (VR) 1.5 M€
- HIBEAM Swedish Foundation Strategic Research 1.5M€

HIBEAM/NNBAR

- ESSnuSB 3 Grants (EC) 4M€ +4M€

ESSnuSB

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ESSnuSB

~ 20M€ of external funding

The ESS Fundamental physics paper

Cross-community initiative "yellow paper" initiative for fundamental physics for the ESS

178 authors, 74 institutions

Phys.Rept. 1023 (2023) 1-84

Led by Swedish institutions

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Particle physics at the European Spallation Source

H. Abele[68], A. Alekou[19], A. Algora[64], K. Andersen[48], S. Baeßler[10,48], L. Barron-Pálos[43], J. Barrow[9,62], E. Baussan[58], P. Bentley[38], Z. Berezhiani[30,29], Y. Beßler[25], A.K. Bhattacharyya[38], A. Bianchi[38], J. Bijnens[37], C. Blanco[52], N. Blaskovic Kraljevic[38], M. Blennow[59,61], K. Bodek[28], M. Bogomilov[57], C. Bohm[60], B. Bolling[38], E. Bouquerel[58], G. Brooijmans[47], L.J. Broussard[48], O. Buchan[38], A. Burgman[35], H. Calén[63], C.J. Carlile[63], J. Cederkall[35], E. Chanel[4], P. Christiansen[35], V. Cirigliano[56], J.I. Collar[11,15], M. Collins[36,38], C.B. Crawford[33], E. Cristaldo Morales[44], P. Cupiał[27], L. D'Alessi[58], J.I. M. Damian[38], H. Danared[38], D. Dancila[63], J.P.A.M. de André[58], J.P. Delahaye[19], S. Degenkolb[24,22], D.D. Di Julio[38], M. Dracos[58], K. Dunne[60], I. Efthymiopoulos[19], T. Ekelöf[63], L. Eklund[63], M. Eshraqi[38], I. Esteban[12,13], G. Fanourakis[3], A. Farricker[66], E. Fernandez-Martinez[40], M.J. Ferreira[38], M. Fertl[42], P. Fierlinger[17], B. Folsom[38], A. Frank[16], A. Fratangelo[4], U. Friman-Gayer[38], T. Fukuda[45], H.O.U. Fynbo[1], A. Garcia Sosa[38], N. Gazis[38], B. Gålnander[38], Th. Geralis[3], M. Ghosh[69], G. Gokbulut[2], J.J. Gomez-Cadenas[15,5], M. Gonzalez-Alonso[64], F. Gonzalez[48], L. Halić[69], C. Happe[25], P. Heil[4], A. Heinz[20], H. Herde[35], M. Holl[38], T. Jenke[22], M. Jenssen[38], E. Jericha[68], H.T. Johansson[20], R. Johansson[38], T. Johansson[63], Y. Kamyshkov[26], A. Kayis Topaksu[2], B. Kildetoft[38], K. Kirch[70,65], B. Kliček[69], E. Klinkby[55], R. Kolevatov[39], G. Konrad[68], M. Kozioł[27], K. Krhač[69], A. Kupść[63,67], Ł. Łacny[27], L. Larizgoitia[15], C.M. Lewis[11,15], M. Lindroos[38], E. Lychagin[16], E. Lytken[35], C. Maiano[38], P. Marciniewski[63], G. Markaj[4], B. Märkisch[18], C. Marrelli[38], C. Martins[38], B. Meirose[60,35], M. Mezzetto[50], N. Milas[38], D. Milstead[60,*], F. Monrabal[15,5], G. Muhrer[38], A. Nepomuceno[54], V. Nesvizhevsky[22], T. Nilsson[20], P. Novella[64], M. Oglakci[2], T. Ohlsson[59,61], M. Olvegård[63], A. Oskarsson[35], T. Ota[40], J. Park[35,a], D. Patrzalek[38], H. Perrey[35], M. Persoz[4], G. Petkov[57], F.M. Piegsa[4], C. Pistillo[4], P. Poussot[58], P. Privitera[11,51], B. Rataj[38], D. Ries[41], N. Rizzi[55], S. Rosauro-Alcaraz[49], D. Rozpedzik[28], D. Saiang[34], V. Santoro[38,35], U. Schmidt[24], H. Schober[38], I. Schulthess[4], S. Silverstein[60], A. Simón[11,15], H. Sina[38], J. Snamina[27], W.M. Snow[6,7,8], T. Soldner[22], G. Stavropoulos[3], M. Stipčević[69], B. Szybiński[27], A. Takibayev[38], Z. Tang[46], R. Tarkeshian[38], C. Theroine[38,22,18], J. Thorne[4].

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https://doi.org/10.1016/j.physrep.2023.06.001

Fitting into the European landscape

LUND UNIVERSITY

The 2020 Update to the European Particle Physics Strategy (“Essential activities)

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

Conclusions (I)

- Several exciting possibilities for fundamental physics at ESS are available
  - CEνNS at ESS and HIBEAM can start in a relatively short amount of time ~ 5 years from approval
  - NNBAR will need of the order of ~ 10 years (both for facility upgrade, beamline design and detector development)
  - ESSnuSB needs a major facility upgrade ~ 15 years
  - **<u>Sweden has invested ~8BSEK (35% of the construction budget) in the ESS so far and there is no Swedish Scientific program</u>**

Conclusions (II)

- We are developing a world leading program for the next 20/30 years

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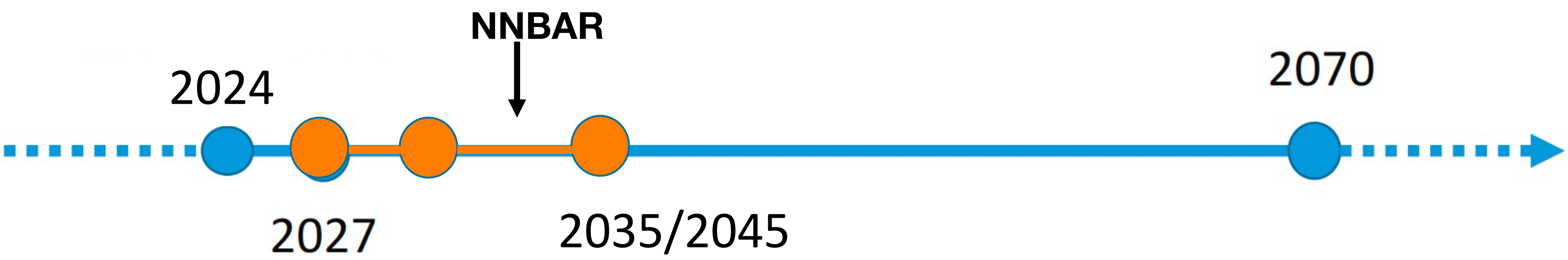

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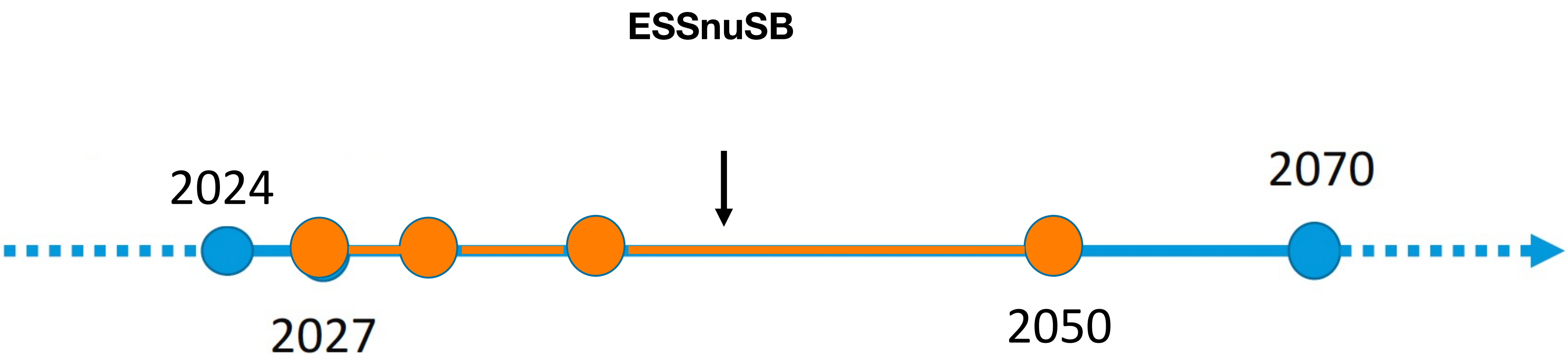

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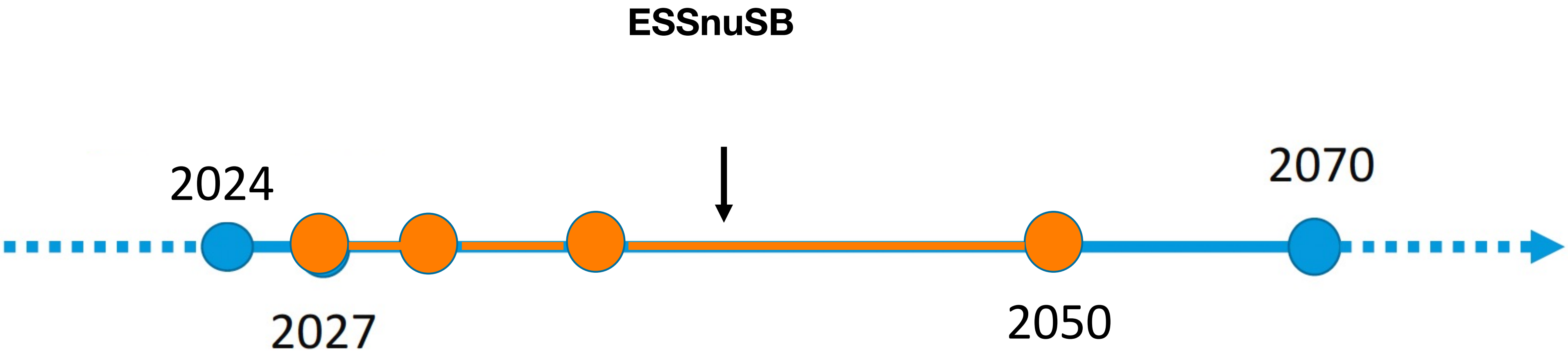


The ESS fundamental physics program is an incredible opportunity for Swedish science that should not be missed

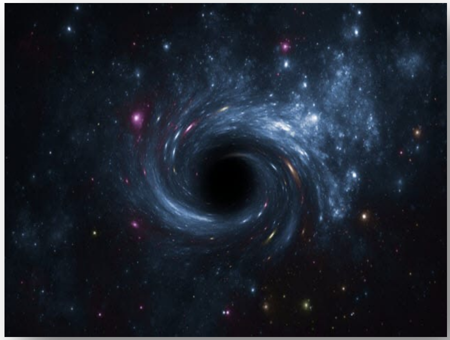
BACK UP SLIDES

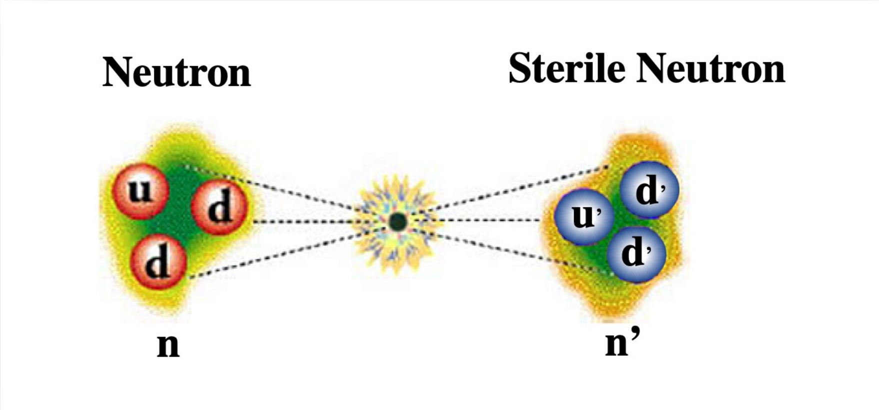
Sterile Neutrons

- Sterile neutrons are states that can belong to a **<u>Dark Sector</u>** of particles that interact via gravity

Sterile Neutrons

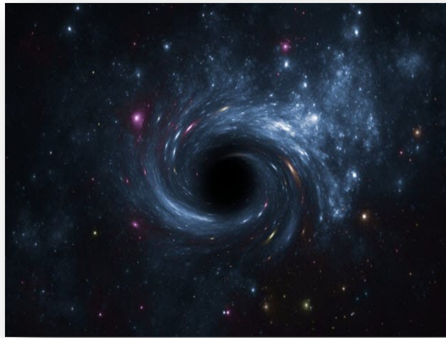
- Sterile neutrons are states that can belong to a **Dark Sector** of particles that interact via gravity



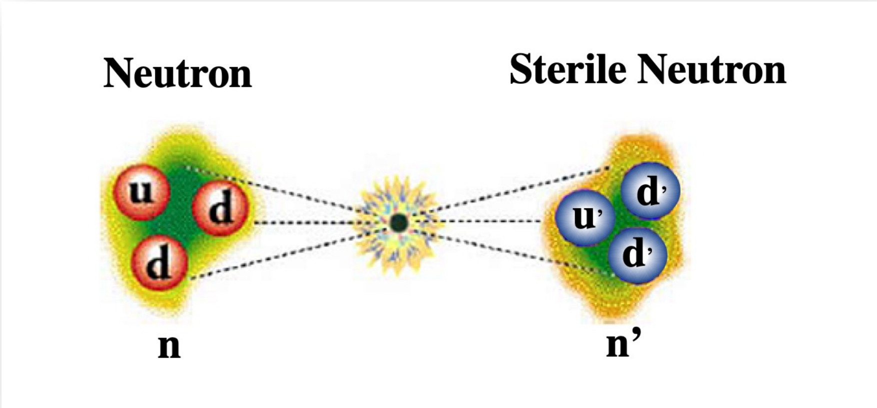


- If they exist, they can be produced in the laboratory by mixing between neutrons in our world and sterile neutrons → **neutrons to sterile neutron oscillations**

Sterile Neutrons



- Sterile neutrons are states that can belong to a **<u>Dark Sector</u>** of particles that interact via gravity



- If they exist, they can be produced in the laboratory by mixing between neutrons in our world and sterile neutrons → **<u>neutrons to sterile neutron oscillations</u>**

- 2020 European Particle Physics Strategy Update ”**<u>searches for dark sector and feebly interacting particles are essential activity”</u>**

Neutron beta decay correlation coefficients

The differential decay probability of the free neutron can be expanded in correlations between the involved particles (momenta or spin) parametrized by correlation coefficients

$n \rightarrow p\ e\ \underline{\nu}_e$

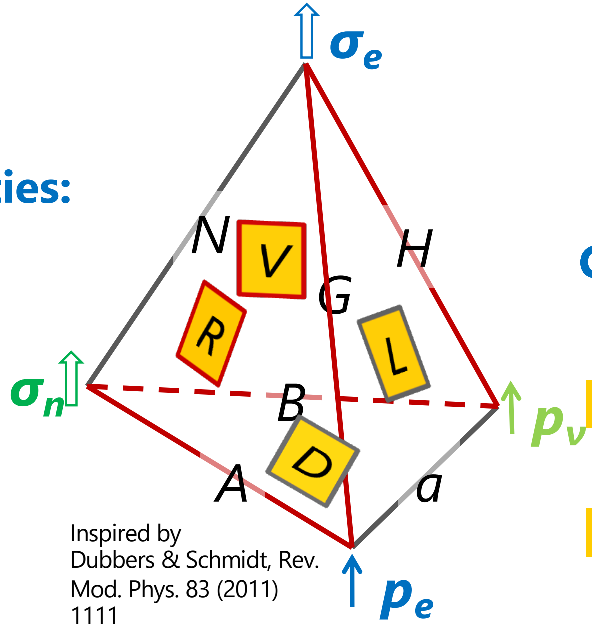
⇧ **4 "detectable" quantities:**

↑ Neutron spin

⇧ Electron momentum

↑ Electron spin

Neutrino momentum



Inspired by Dubbers & Schmidt, Rev. Mod. Phys. 83 (2011) 1111

P conserving

P violating

T violating

Correlations:

6 twofold $\quad \boldsymbol{p}_e\boldsymbol{p}_\nu$, $\boldsymbol{\sigma}_n\boldsymbol{p}_e$

4 threefold $\quad \boldsymbol{\sigma}_n(\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$

5 fourfold $\quad (\boldsymbol{\sigma}_e\boldsymbol{p}_e)(\boldsymbol{p}_e\boldsymbol{p}_\nu)$

1 fivefold $\quad (\boldsymbol{\sigma}_e\boldsymbol{p}_e)(\boldsymbol{\sigma}_n(\boldsymbol{p}_e \times \boldsymbol{p}_\nu))$

+Fierz term (e-spectrum)

+lifetime

+rare decay modes (H, γ)

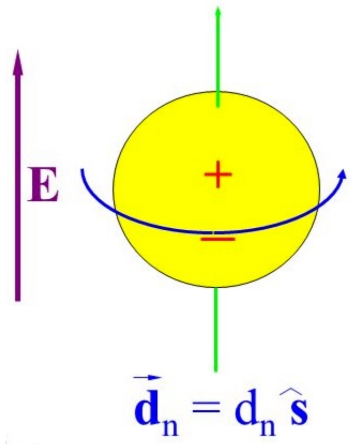
Measuring several correlation coefficients in the neutron beta decay provides broad band probes for physics beyond the standard model

Neutron EDM

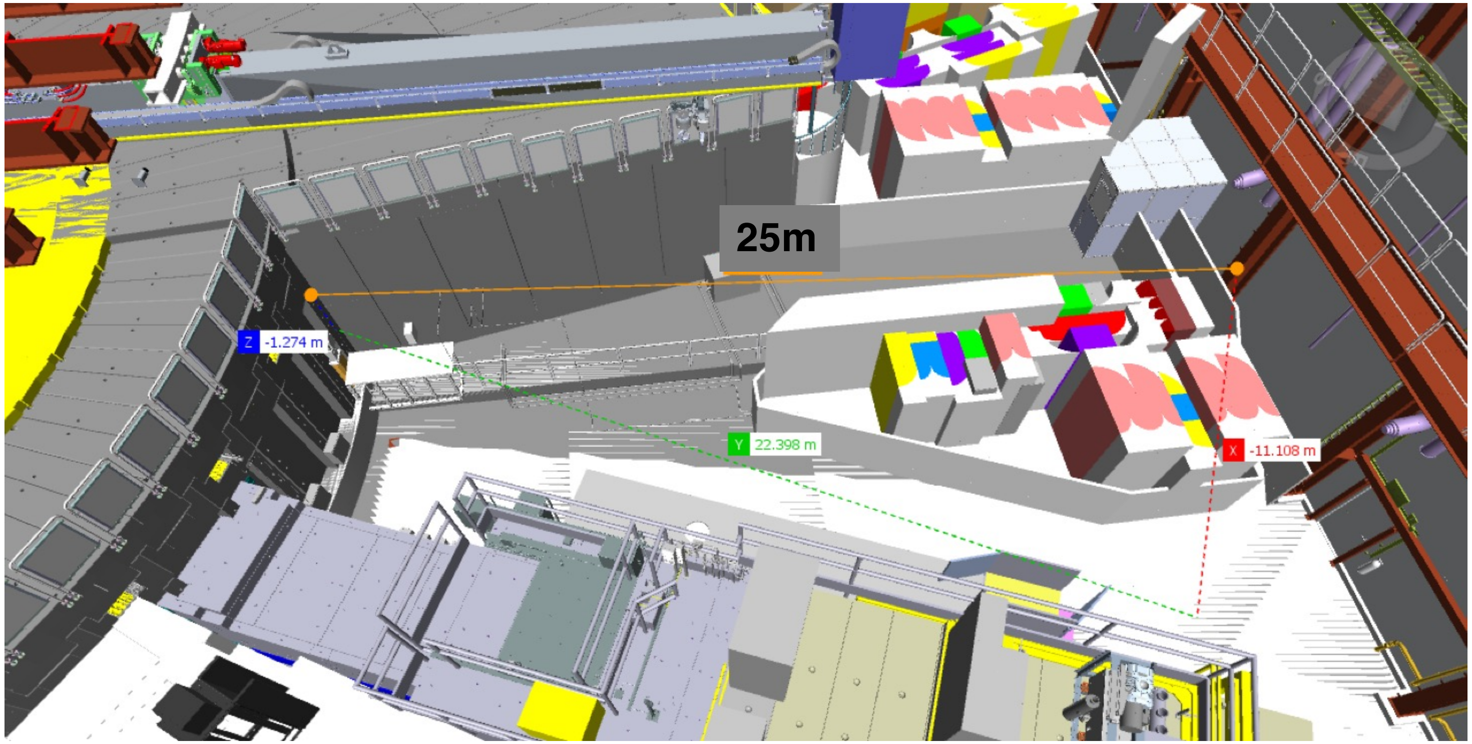
- The electrical neutrality of neutrons are not required by the SM.
- Standard Model EDMs are due to CP violation in the quark mixing matrix CKM
- The neutron EDM is Standard Model is predicted to be **10^{-32} e·cm**
  - The current experimental neutron limit is

    $d_n < 2.9 \cdot 10^{-26}$ e·cm (@ 90% CL)
  - A large class of grand unified theories (with additional CP violation BSM) set a lower bound for the neutron EDM of

    $d_n > 3 \cdot 10^{-28}$ e·cm



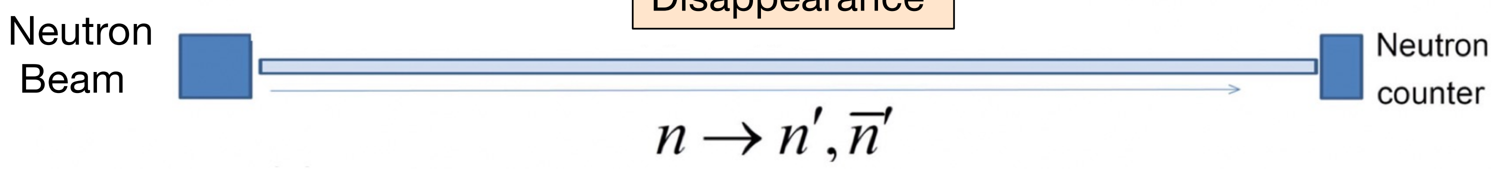
HIBEAM at the test beamline



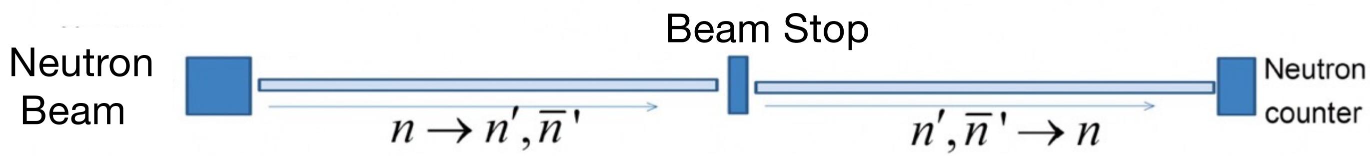
•Sensitivities of the oscillation searches depend linearly on the number of neutrons and quadratically or to the 4th power (depending on the channel) on the flight path
•With a 25m flight path the HIBEAM at the test beamline will have the longer flight path currently available for this kind of searches

Search for sterile neutron oscillations at HIBEAM

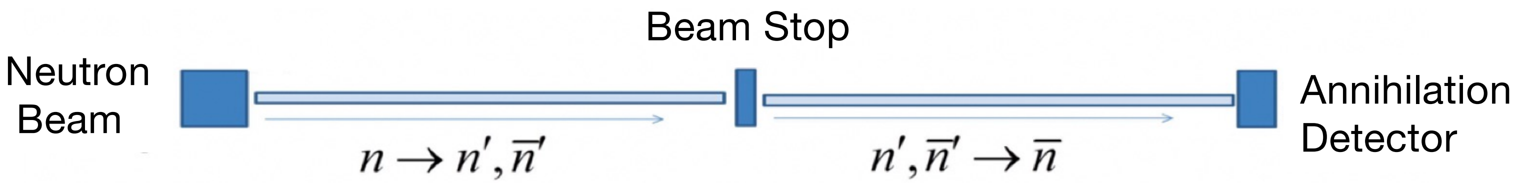
Disappearance



Regeneration $n \to n' \to n$



Neutron antineutron conversion via sterile neutron $n \to n' \to \bar{n}$

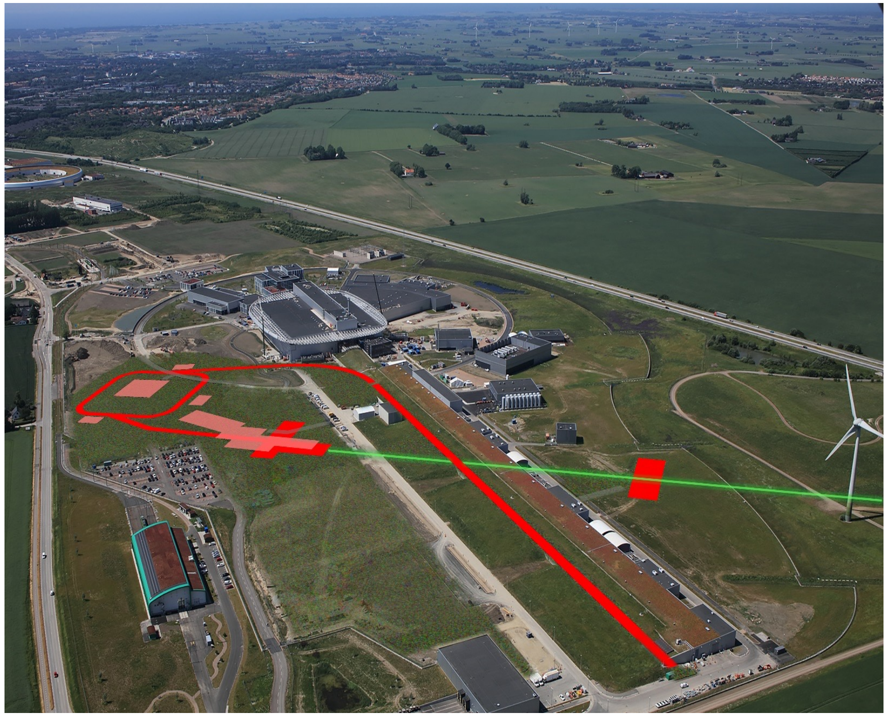


see David Milstead's tallk

Thanks for the Attention

The ESS neutrino Super Beam (ESSnuSB): scientific motivation

In 2012 it was discovered that the neutrino ν_1 and ν_3 mass eigenstates mixing angle $\theta_{13} = 8.8^o$, a value which was much larger than assumed



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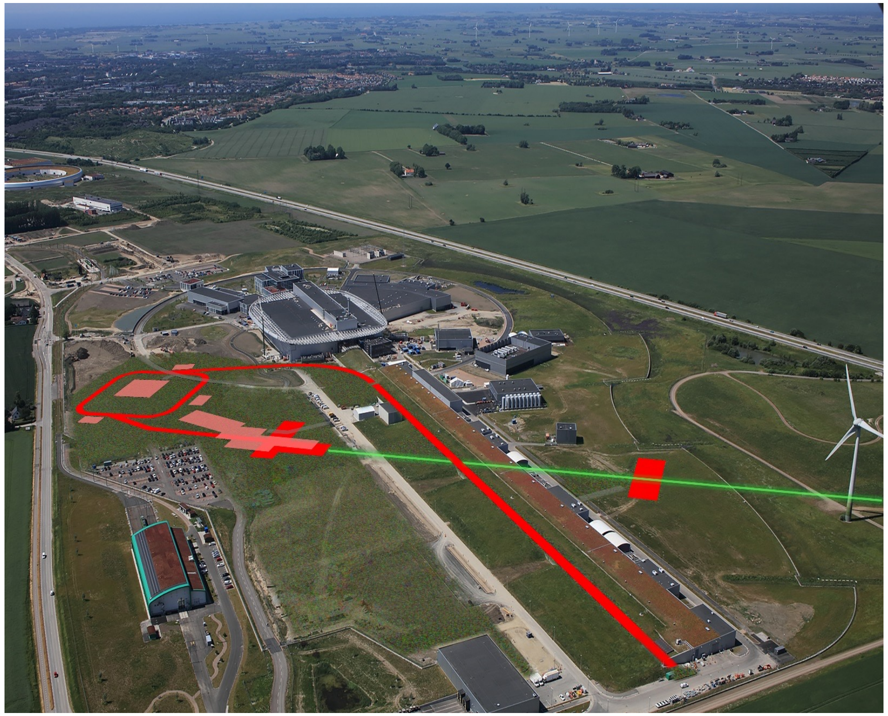
In the light of this finding the sensitivity of CP violation δ_{CP} has a strong enhancement at the second oscillation maximum compared to that at the first oscillation maximum



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LUND UNIVERSITY

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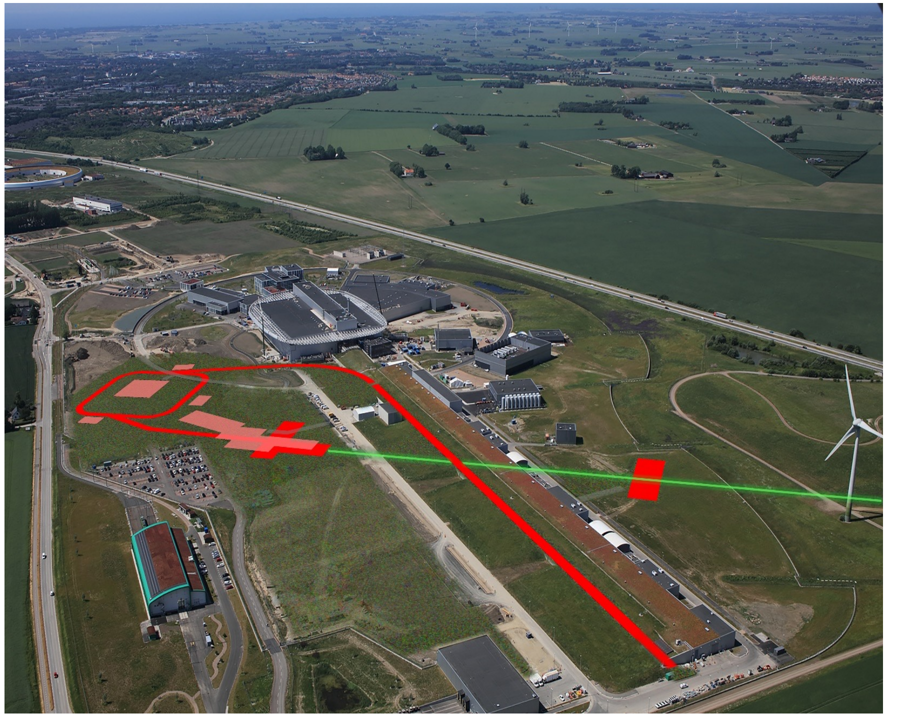
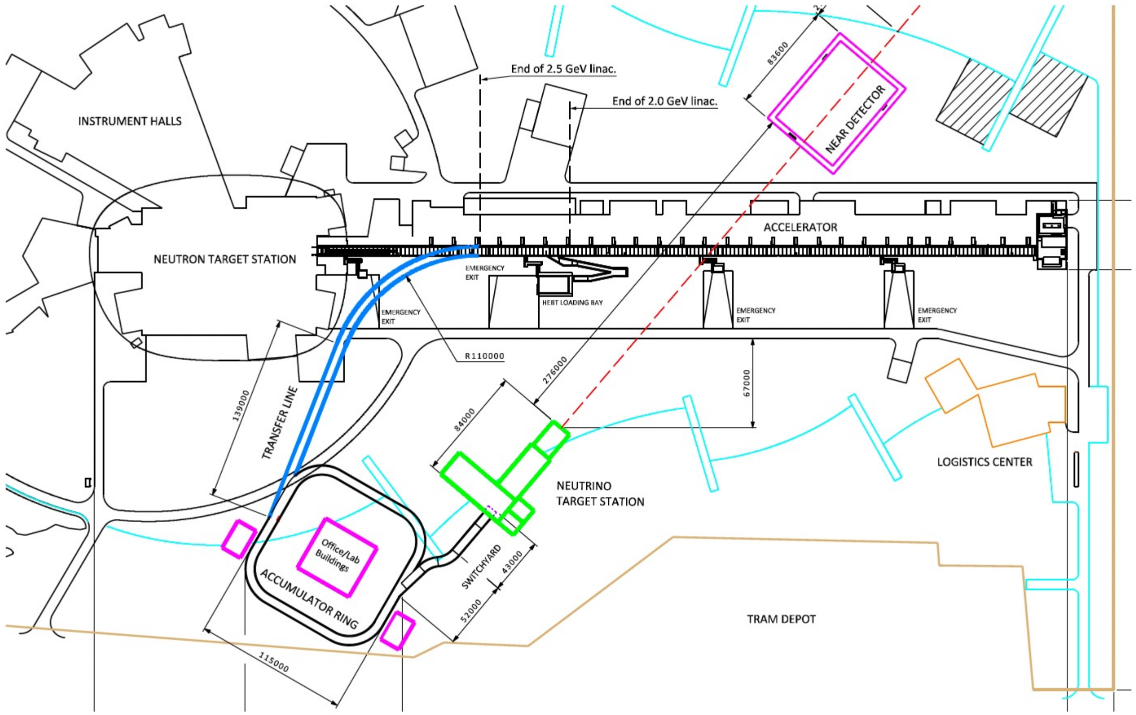
However placing the far detector at the 2nd maximum implies the need of a very high intensity neutrino super beam to compensate for the longer baseline



The ESS neutrino Super Beam (ESSnuSB)

- To produce an intense neutrino beam at the same time of the intense neutron beam it is a needed a major upgrade of the ESS facility
- The ESS accelerator needs to be upgraded to 2.5 GeV energy and power to 10 MW this requires additional H- source and increase of linac duty cycle from 4% to 8%



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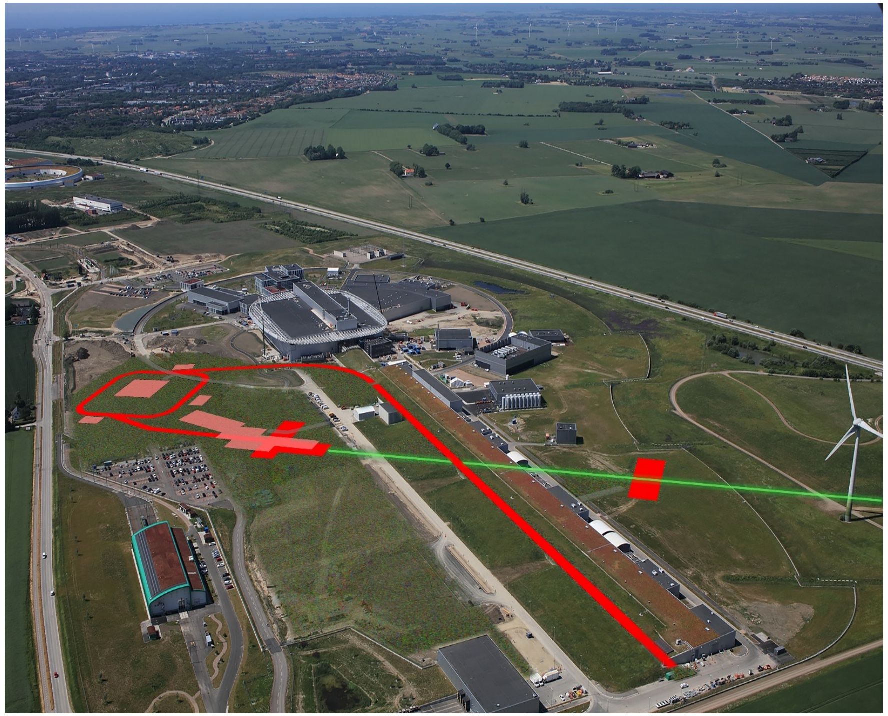
The ESSnuSB is a proposed accelerator based long baseline neutrino experiment at ESS



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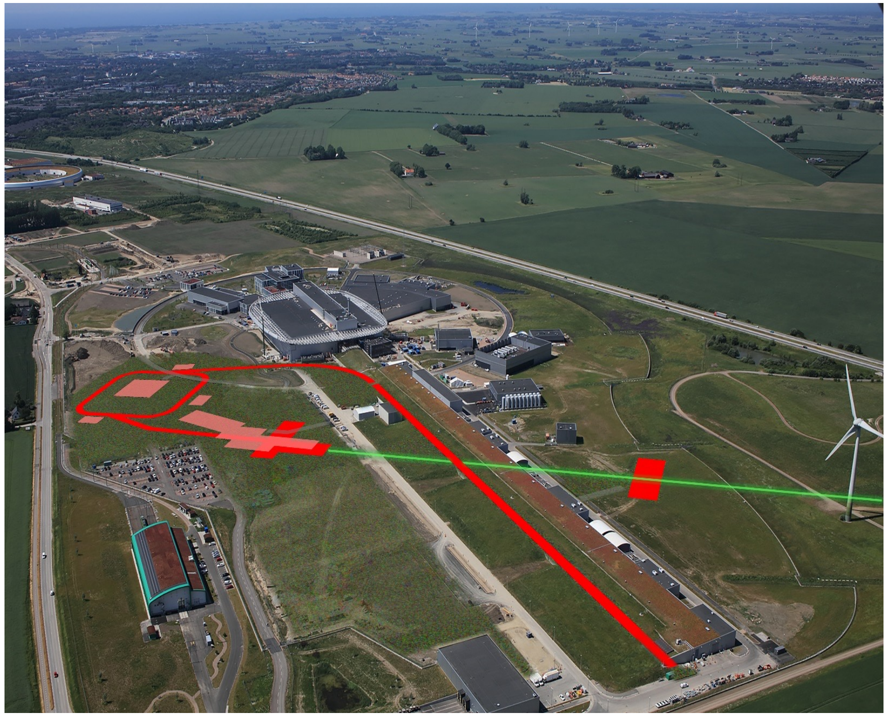

Production, transportation and storage is motivated by the study of several neutron properties:

- **Measurement of the neutron lifetime** (its value impacts the abundance of light chemical elements in big-bang nucleosynthesis)

- **Measurement of the neutron electric dipole moment (EDM**)

- **Observation of the gravitational interactions of the neutrons**

In a previous experiment ILL physicists have observed quantized state of matter under the influence of gravity for the first time.

Nesvizhevsky V et all. Quantum states of neutrons in the Earth's gravitational field. Nature. 2002 Jan 17;415(6869):297-9. doi: 10.1038/415297a. PMID: 11797001.
CopyDownload .nbib

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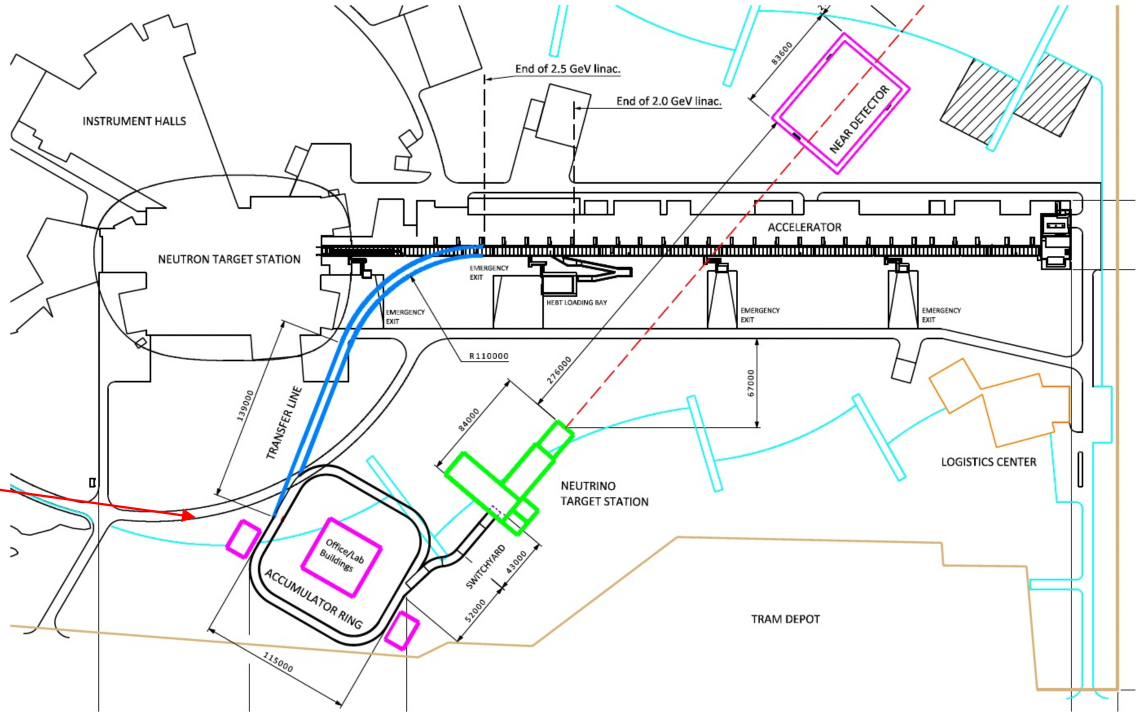
- The ESS accelerator needs to be upgraded to 2.5 GeV energy and power to 10 MW this requires additional H- source and increase of linac duty cycle from 4% to 8%
- An accumulator ring will be built to shorten the ESS pulse to 1.2μs
- A neutrino production target station composed of four identical target will be built



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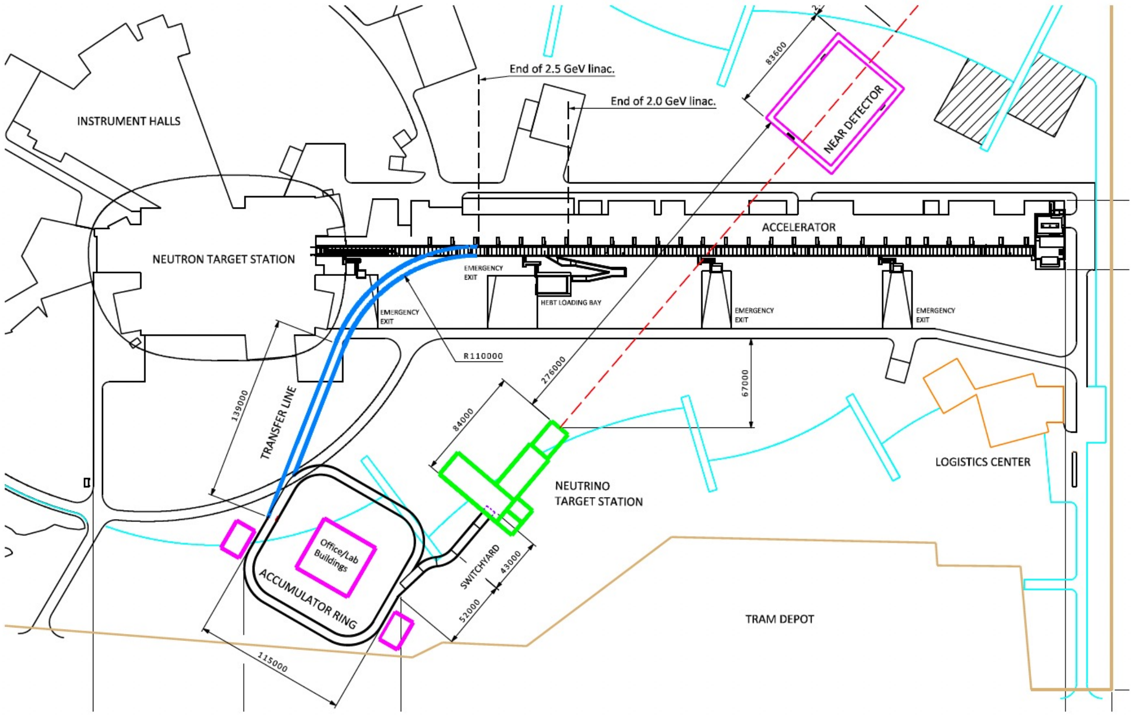
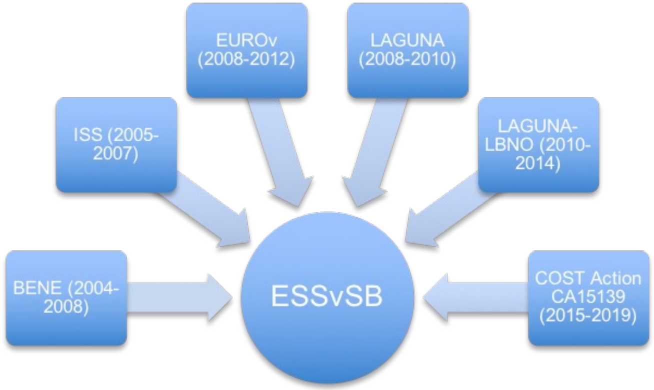
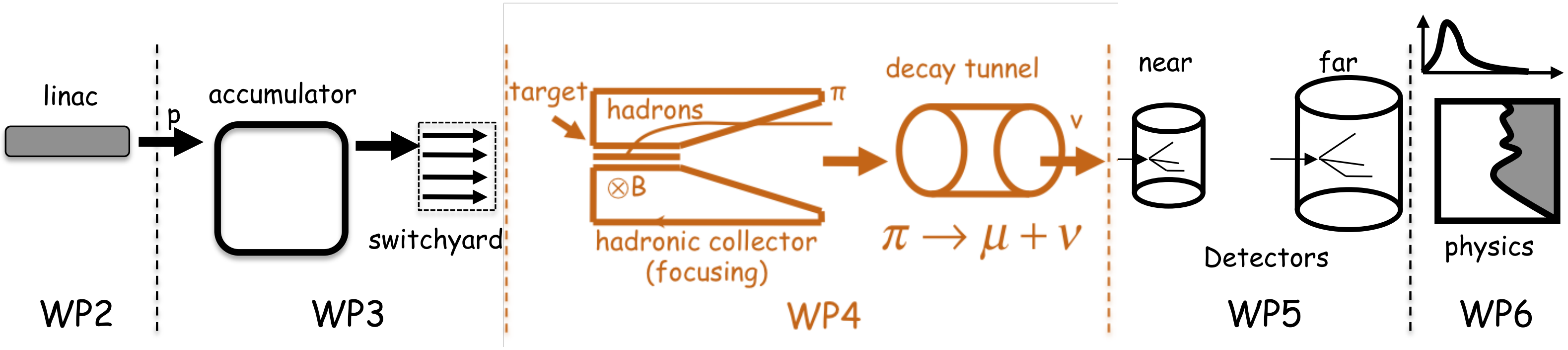
- An accumulator ring will be built to shorten the ESS pulse to 1.2μs
- A neutrino production target station composed of four identical target will be built
  - There will be a near detector to monitor the neutron beam
  - The far detector will be located at the Zinkgruvan mine 360 km from ESS or at the Garpenberg mine at 540 km from ESS



ESSnSB design study from 2018-2022 supported by the European Commission

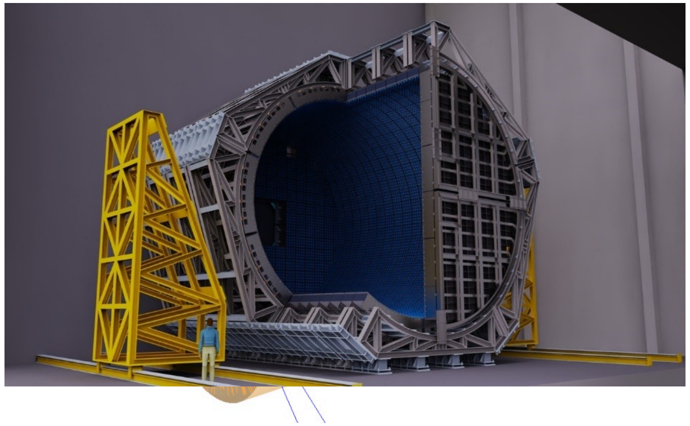
- **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
- **Duration: 4 years**
- **Total cost: 4.7 M€**
- **Requested budget: 3 M€**
- 15 participating institutes from
  11 European countries including CERN and ESS
- 6 Work Packages

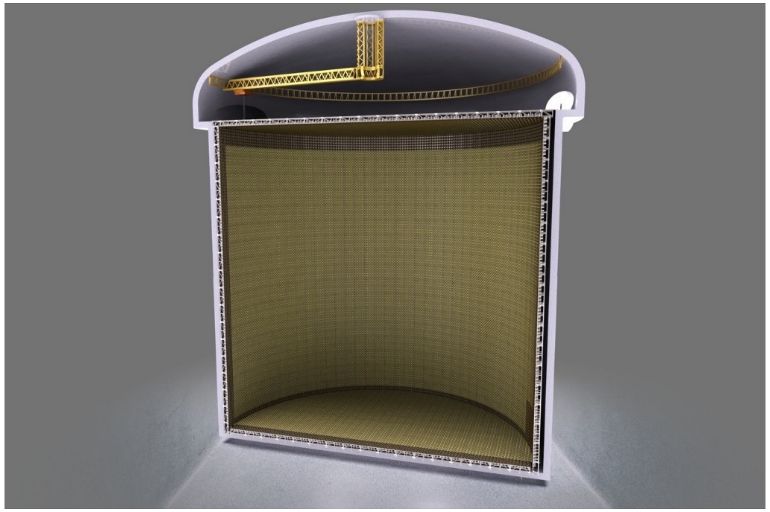




They will submit soon a new applitcation to the call HORIZON-INFRA-2022-DEV01
Developing European Research Infrastructures to maintain global leadership Deadline: **20 April 2022**

Near and Far Dectors





Near Water Cherenkov Detector

Located 250 m from the target

11 m lenth, 4.72 m radius, 770 m^3 voume

In front of it there a Plastic Cube Tracker (sFGD)

$1.4 \times 1.4 \times 0.5$ m^3 with 1 cm^3 cubes

Two Far Water Cherenkov Detector

Located 370 km from the target

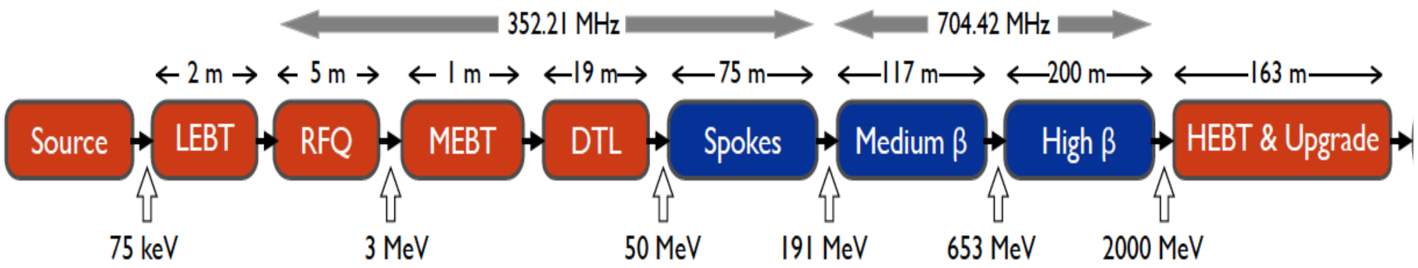
Each detector 74 m height, 74 m diameter, 270 m^3 volume

Total fiducial volume: 540 m3

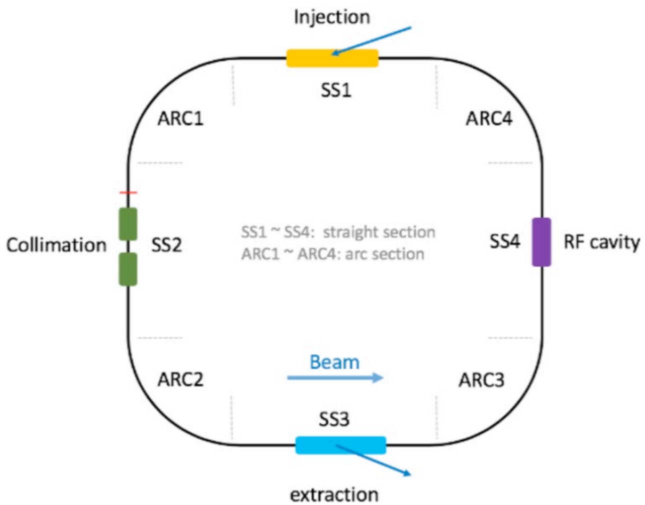
Order 100’000 20 inch photomultiplies

40% coverage

Accelerator upgrade and accumulator ring



Upgrade of energy to 2.5 GeV and power to 10 MW with extra H- pulses
- requires additional H- source and increase of linca duty cycle from 4% to 8%



Compression of the 2.86 ms linac pulses to 1.3 μs by multi-turn injection and Single-turn ejection – requires H- pulses to be injected and stripped at injection

BACK UP SLIDES

Moderator cooling block location number 2

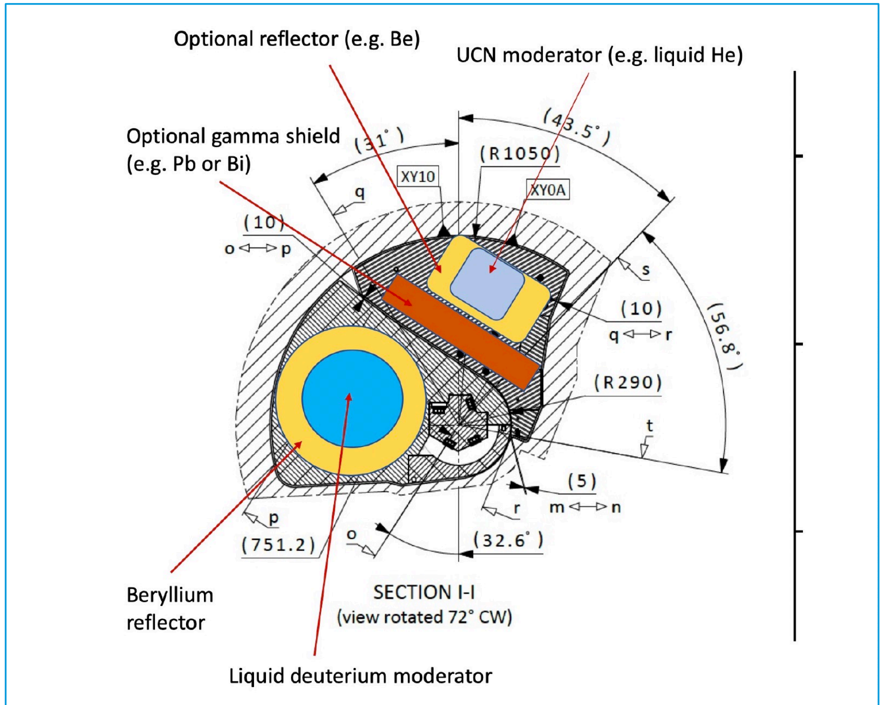
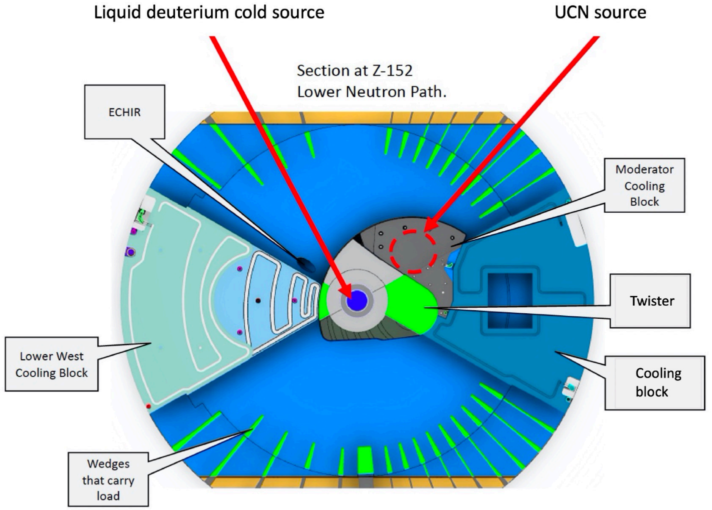
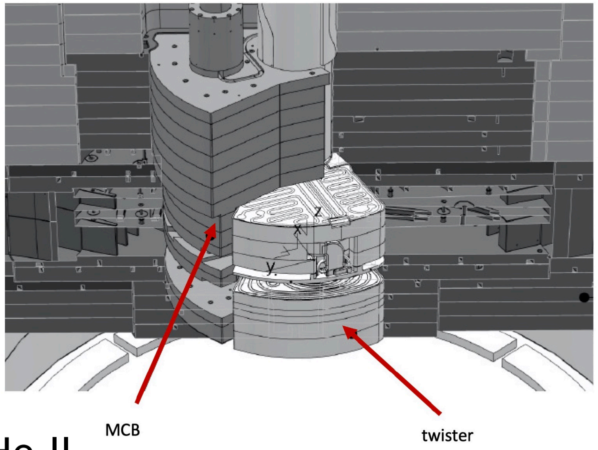


Figure 17: Possible location of an in-pile UCN source in the moderator cooling block.

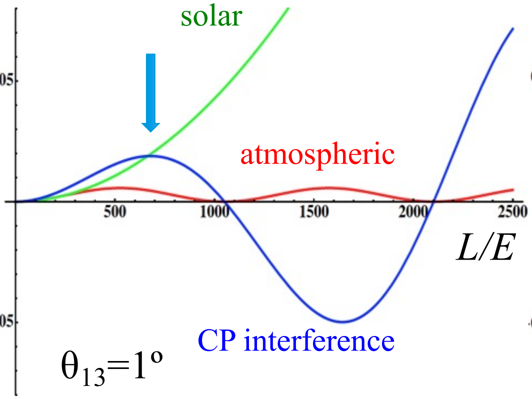


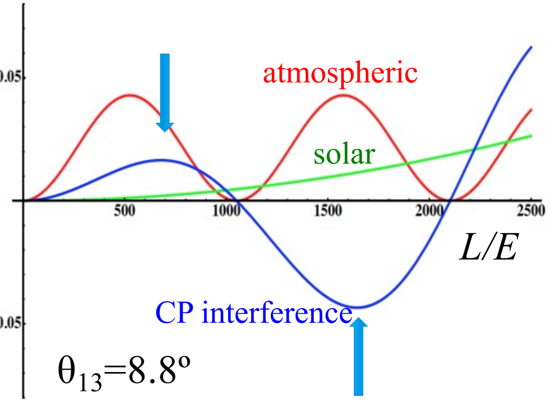


MCNP model under development -> could be challenging for cooling of He-II in 2012 it was discovered that the neutrino ν_1 and ν_3 mass eigenstates mixing angle $\theta_{13} = 8.8^o$, a value which was much larger than assumed before 2012 when HyoperK and DUNE were designed

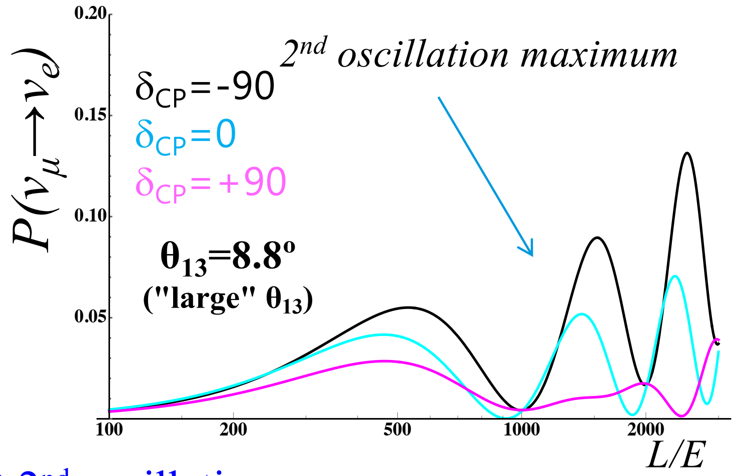
for small θ_{13} 1st oscillation maximum is better

(arXiv:1110.4583)





for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term



- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

(see arXiv:1310.5992 and arXiv:0710.0554)

→ more sensitivity at 2nd oscillation max.

Conclusions

- The discovery of a large - in comparison with assumptions made before 2012 - value of θ_{13} implies that the influence of irreducible systematic errors in the search for, and measurements of, leptonic CP violation is close to three times lower at the second neutrino oscillation maximum as compared to the first. As it is the systematic errors that currently limit the accuracy in the measurement of the CP violation using neutrino long-baseline experiments, measuring at the second oscillation maximum represents a crucial advantage. However, making measurements at the times more distant second maximum requires a significantly more intense neutrino beam to keep the statistical errors comparable to the systematic errors, implying the need for an exceptionally powerful proton driver.

- The ESSνSB project proposes to use the world-uniquely powerful 5MW ESS proton LINAC to produce a very intense neutrino beam, and place the far detector at a distance corresponding to the second oscillation maximum. With the use of a 540 kt fiducial mass Cherenkov detector, it has been demonstrated that ESSνSB will reach, after 10 years of data taking, 70% δCP discovery coverage with a significance larger than 5 σ. After discovery of leptonic CP violation, ESSνSB will measure δCP with a a standard error smaller than 8◦ for all values of δCP.

-The compression of the 3.84 ms linac pulse required for the neutrino Super beam will profit also neutron material science, Coherent Neutrino Scattering (CEνNS) and Decay at Rest (DAR) (as I explained earlier today).

- Moreover, ESSνSB has a high potential for future upgrades by using the muons produced at the same time as the neutrinos for the realisation of a future low energy nuSTROM and, in a longer term perspective, a Muon Collider.

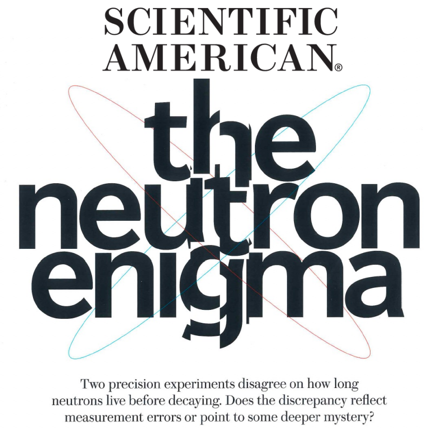
The HIBEAM and the NNBAR program

Two stage program:

- **HIBEAM (≳2028): focus is to search for sterile neutron transitions**
- **NNBAR direct transitions for $n \rightarrow \bar{n}$ oscillations (sensitivity increase of 10^3 compared to previous experiments)**

The HIBEAM program search for neutron to sterile neutron conversion (II)

- Sterile neutron oscillations also violate the baryon number, a key Sakharov condition for the understanding of the matter-antimatter asymmetry of the universe



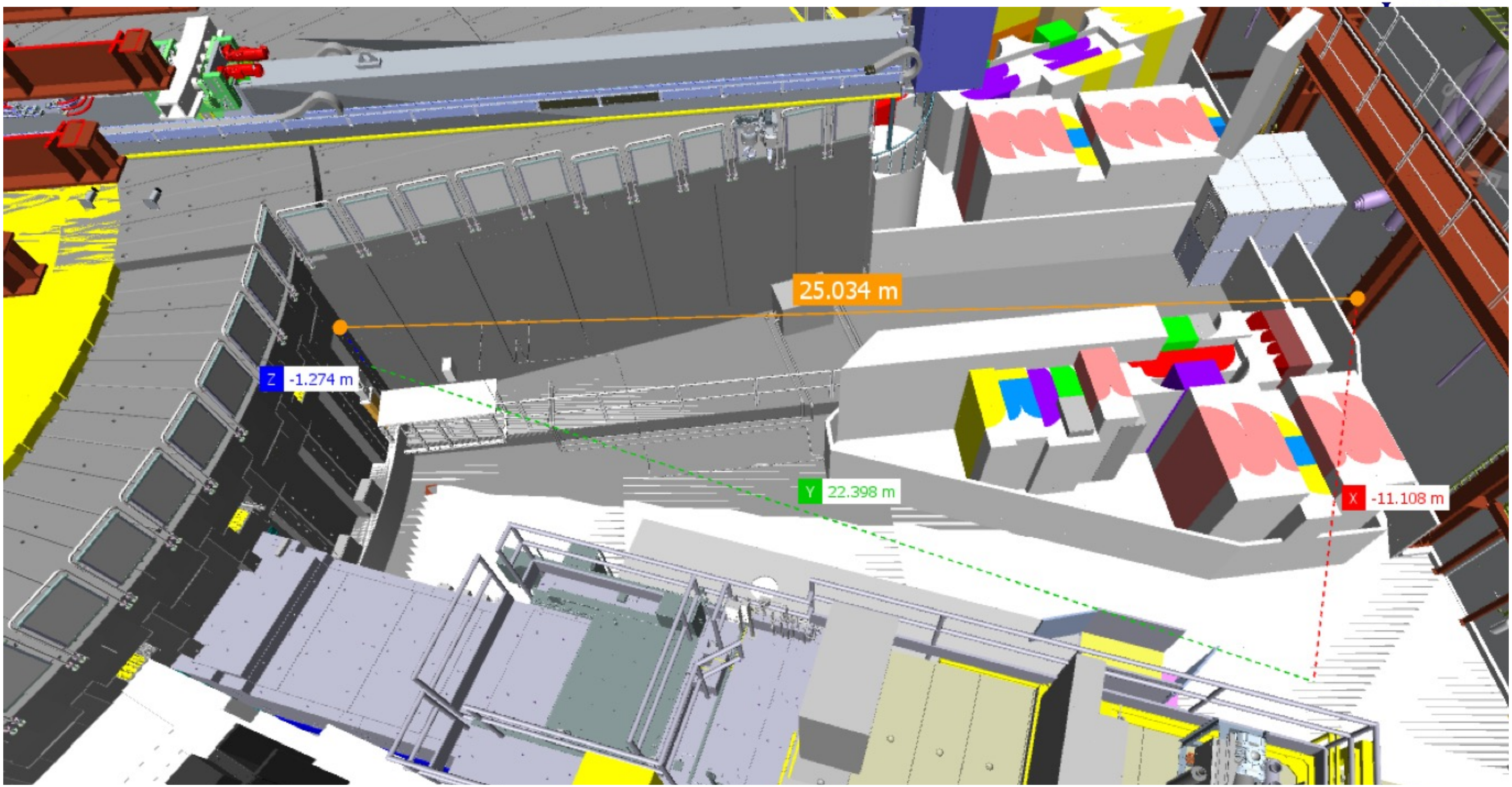
- Sterile neutrons can also address a long-standing anomaly of the neutron lifetime

- 2020 European Particle Physics Strategy Update ”**searches for dark sector and feebly interacting particles are essential activity”**

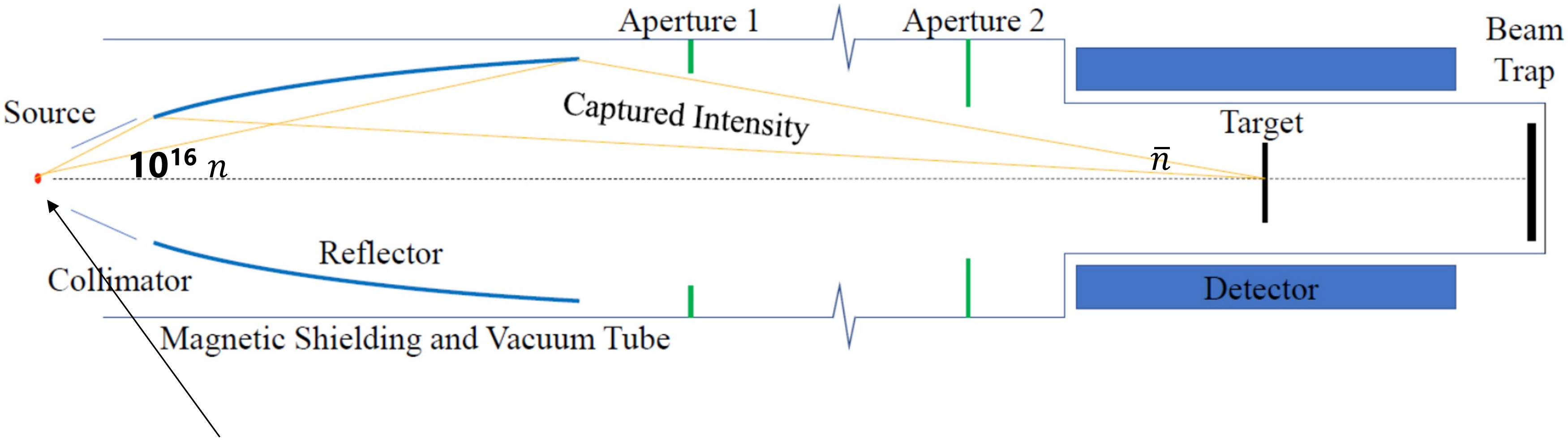
Summary of HIBEAM

- HIBEAM will search for neutron to sterile neutron transition with neutron flight
- These measurements have never been done before
- TDR by the end of 2023 funded by the Swedish Research Council
- Background and detector studies are ongoing
- Many possibilities for collaborations (simulations, detector prototype, data analysis)

The ESS test beamline (II)



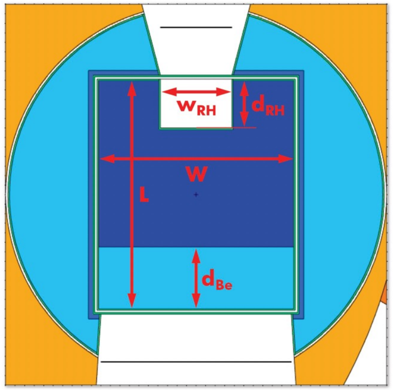
Towards the CDR of the NNBAR experiment

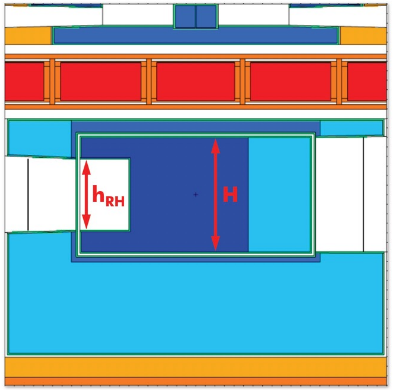


To design the NNBAR experiment you need to take into account several different aspects:

Source (Moderator): It determines the number of cold neutrons emitted by the source

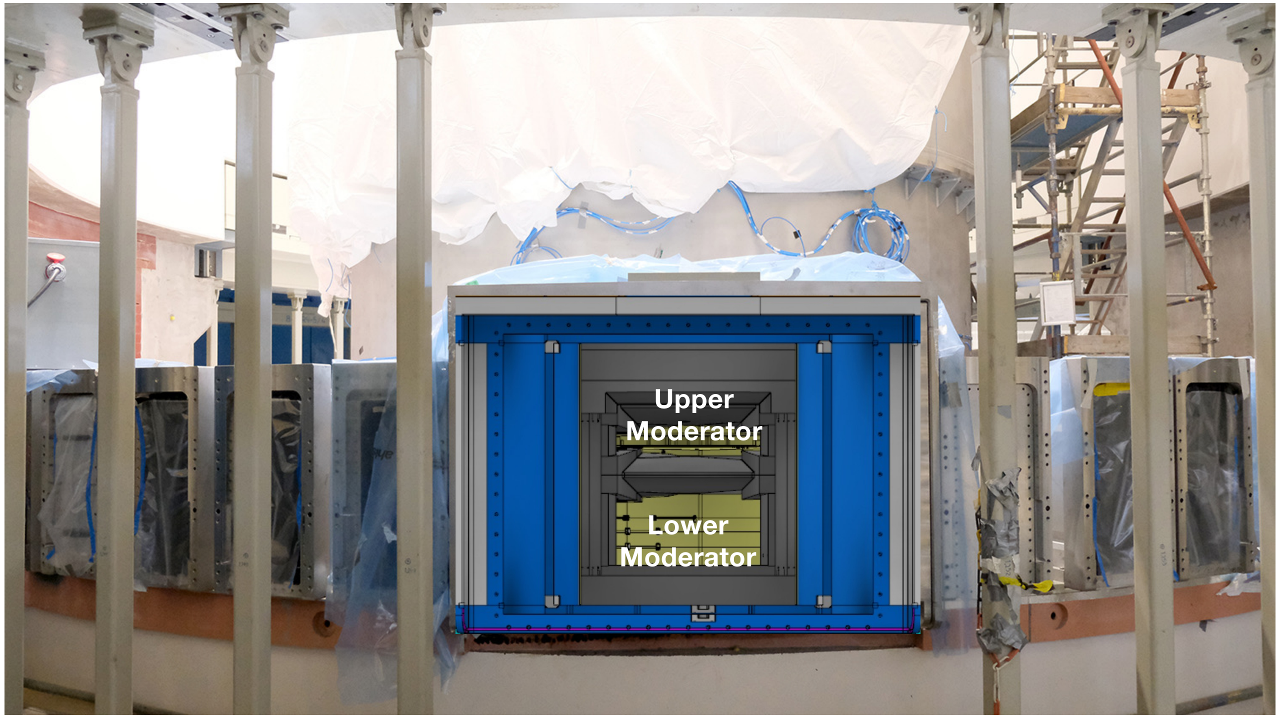
NNBAR needs an internse source of neutrons





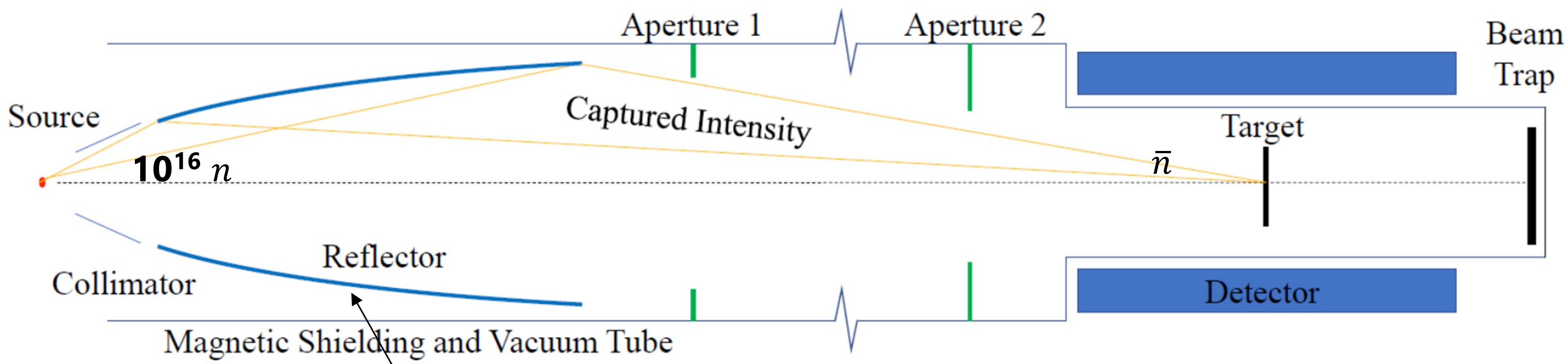
Superpower number 2

ESS is equipped with a 1m x 1m neutron beam port



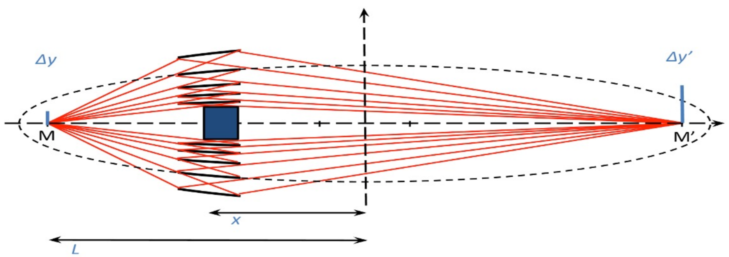
- NNBAR Large Beam Port has been constructed to provide sufficient intensity for $n \rightarrow \bar{n}$ search

Towards the CDR of the NNBAR experiment



Reflector :

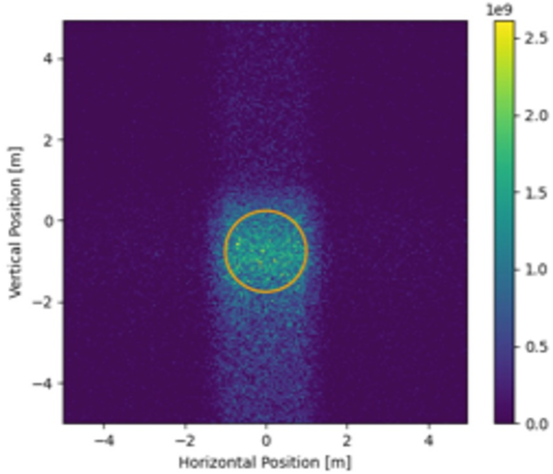
How many neutrons you collect, transport and focus in the experiment



Optimization studies on-going at ILL +collaborators

NEUTRONS FOR SOCIETY

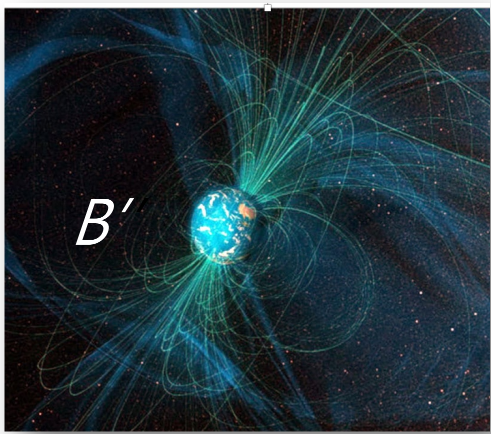
Neutron reaching the Annihilation Target



Scanning the magnetic field (I)

- The measurements proposed in this project should be performed scanning the magnetic fields (±500 mG)

- A neutron in a sterile sector may in fact be affected by **a sterile magnetic field B′** generated by ionization and flow of gravitationally captured dark material in and around the Earth



- The presence of the sterile magnetic field **B′** and the laboratory magnetic field **B** suppress the oscillations unless **B∼B′**

Current Status

- The ESS will be the brightest neutron source in the world enabling new opportunities for researchers across the spectrum of scientific discovery, including materials and life sciences, energy, environmental technology, cultural heritage and fundamental physics

- The ESS will have the unprecedented capability to access and unlock some of the greatest challenges of the universe

- We are developing a broad fundamental physics program, that will be evaluated in few years, with a time span of at least two decades

- This includes mainly
  - Physics with neutrons
  - Physics with neutrinos