Introduction

Valentina Santoro
ESS European Spallation Source
On Behalf of the NNBAR/HIBEAM Collaboration

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

The European Spallation Source

- The European Spallation Source is a neutron scattering facility under construction in Lund, in southern Sweden
- It is an international laboratory with host countries Sweden & Denmark and 11 partner countries with a total construction budget: 1843 M€$_{2013}$
- The facility's unique capabilities will both greatly exceed and complement those of today's leading neutron sources

CONSTRUCTION START	COMPLETION STATUS	PERSONNEL	NATIONALITIES	IN-KIND PARTNERS	USER PROGRAMME BEGINS
2014	79%	516	57	40	2023

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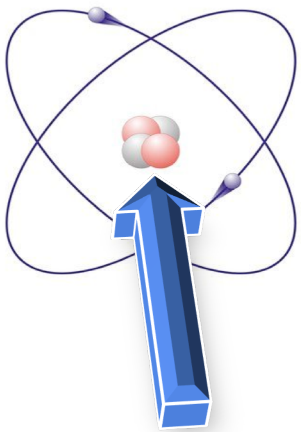
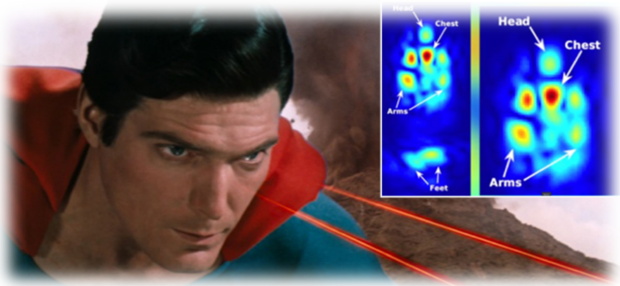
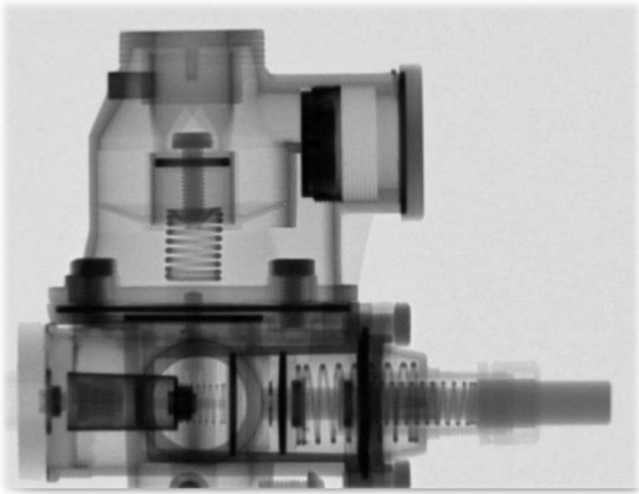
ESS is a microscope where neutrons are used instead of light







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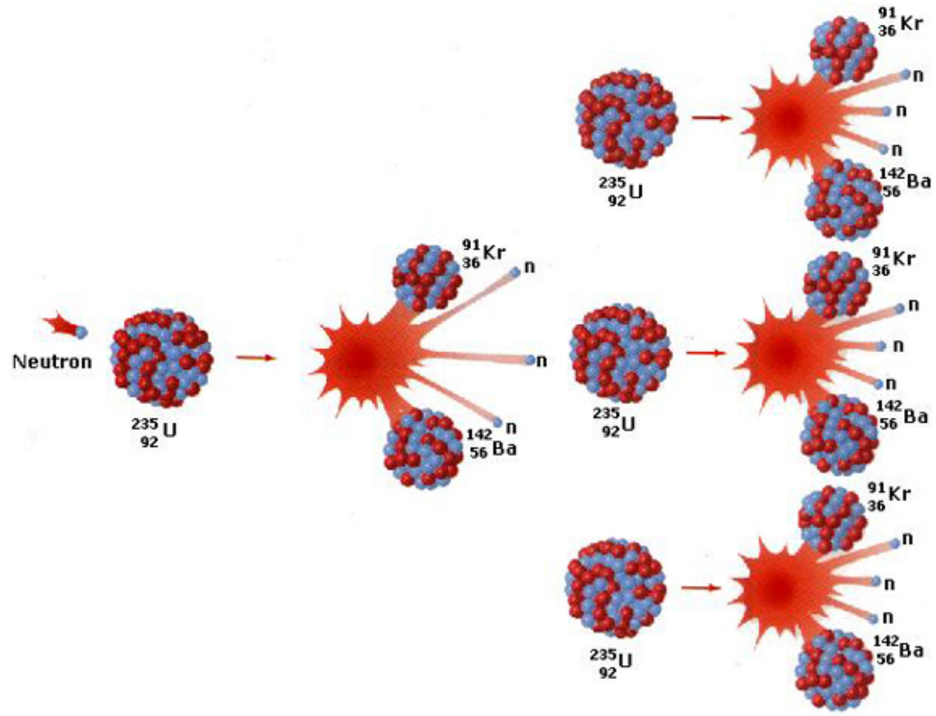
Production of neutrons (I)

Fission of uranium in nuclear reactor



2-3 neutrons per process

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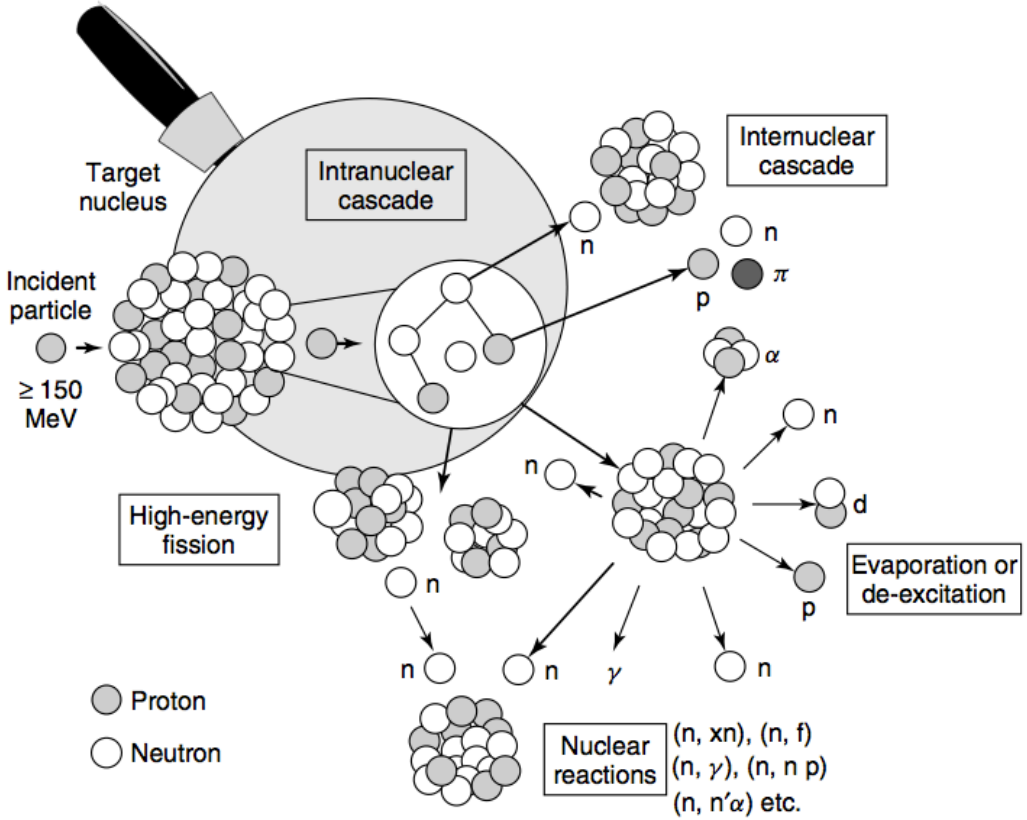
Production of neutrons (II)

Spallation on target using proton accelerator



30 +
neutrons
per process

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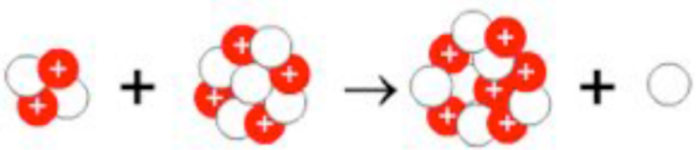
First neutron source James Chadwick 1932

Use Polonium as alpha emitter on Beryllium



$^{4}He + {}^{9}Be \rightarrow {}^{12}C + \text{neutron}$

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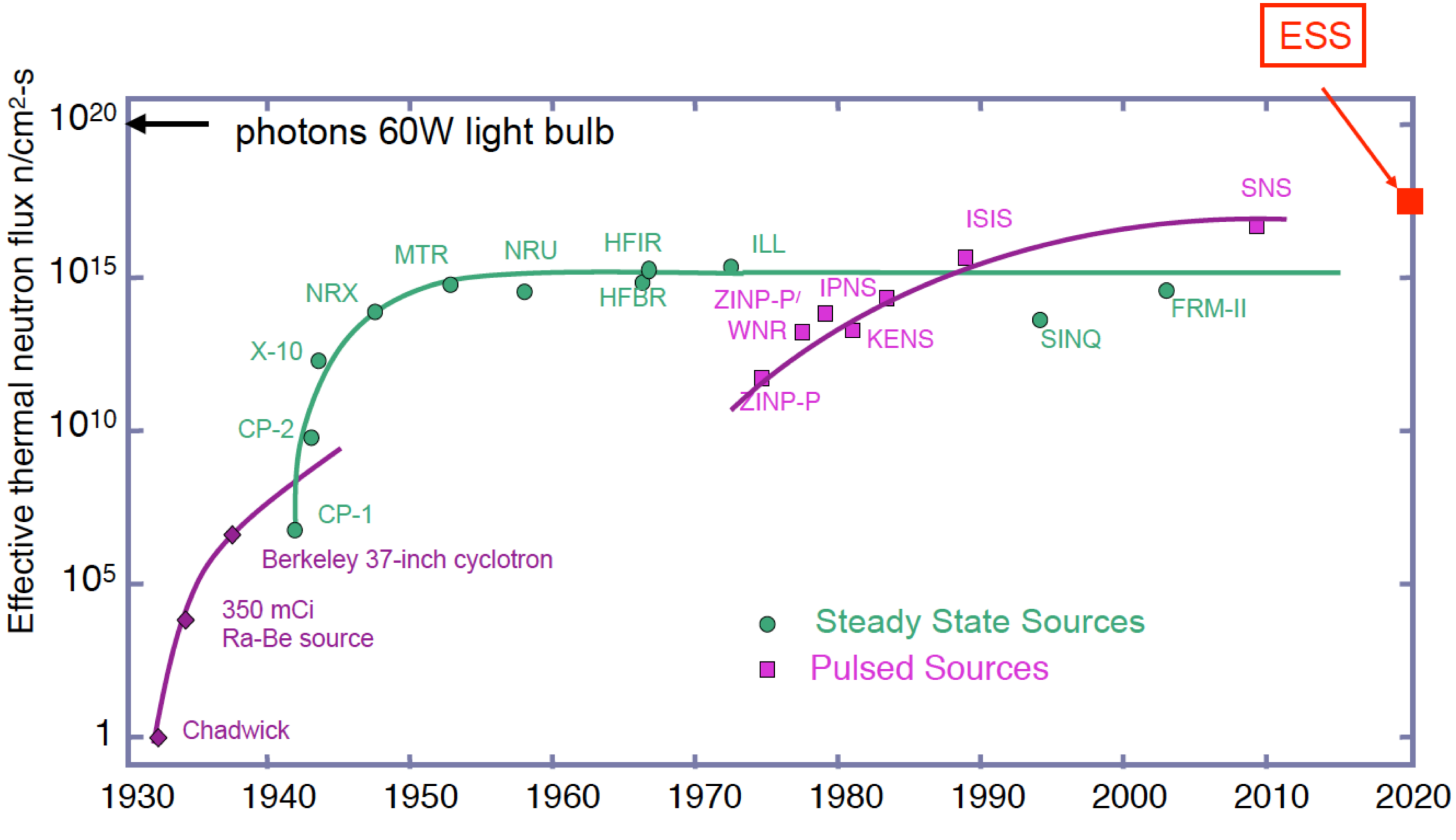
Evolution of neutron sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

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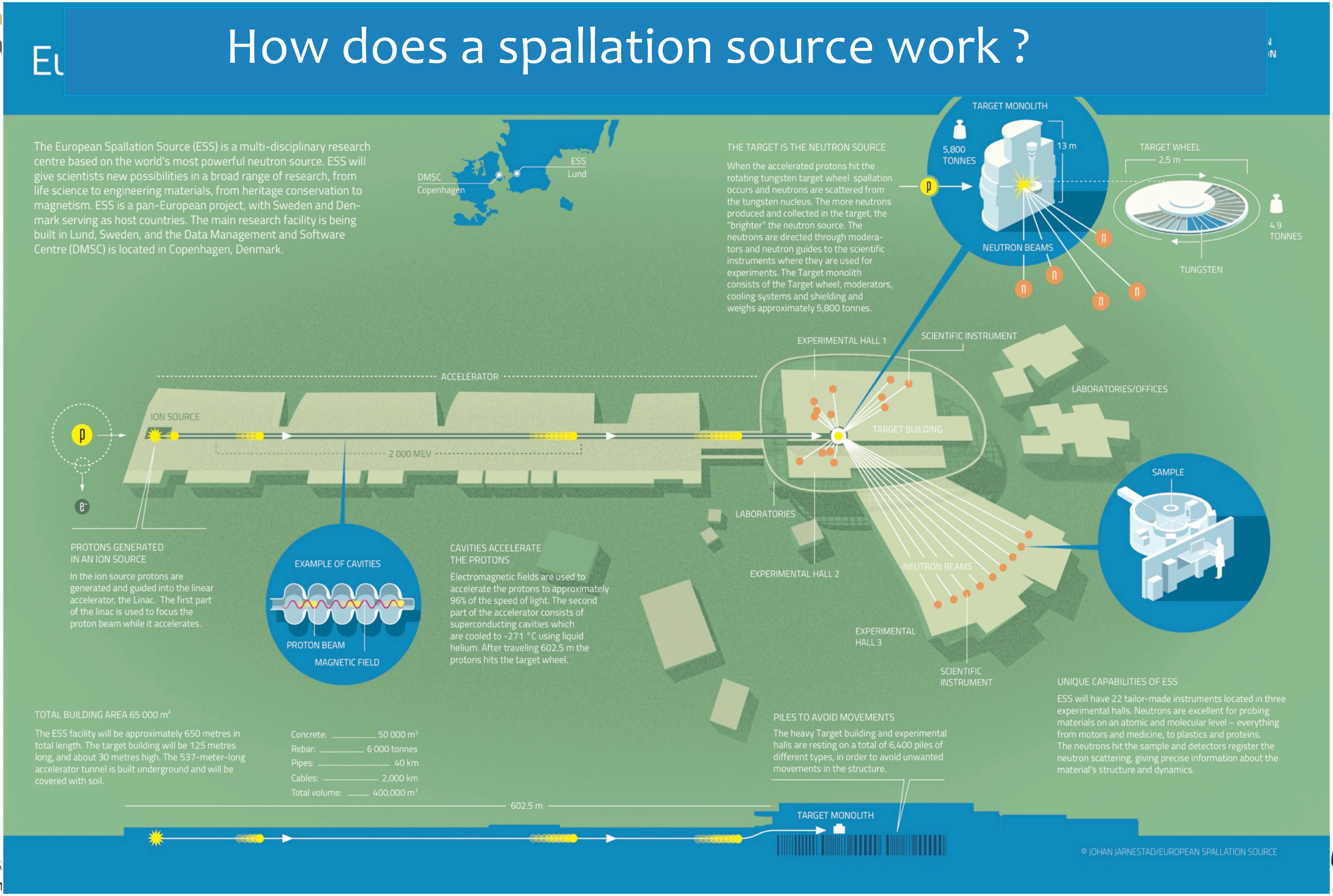
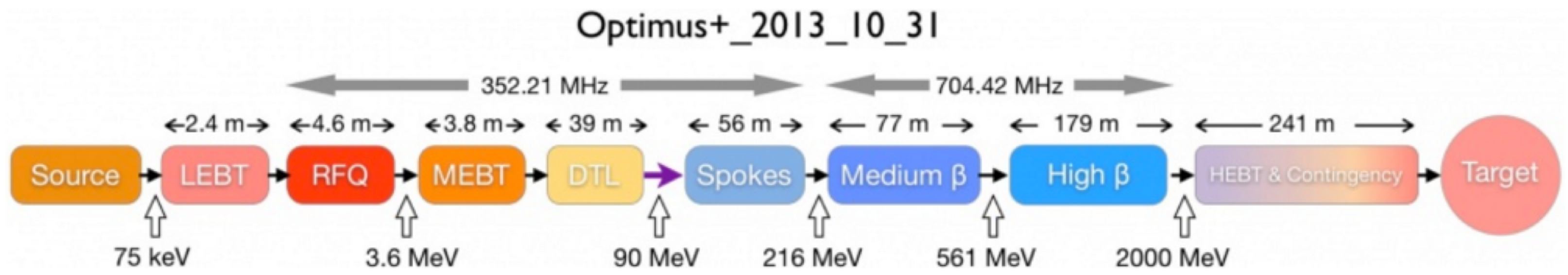
How does a spallation source work ?



ESS Accelerator



- The ion source produces a proton beam that is transported through a Low Energy Beam Transport (LEBT) section to the Radio Frequency Quadrupole (RFQ) where it is bunched and accelerated up to 3.6 MeV.
- In the Medium Energy Beam Transport (MEBT) section the transverse and longitudinal beam characteristics are diagnosed and optimized for further acceleration in the Drift Tube Linac (DTL). The first superconducting section consists of 26 double-spoke cavities (SPK) with a geometric beta value of 0.50.
- The spoke-cavities are followed by 36 Medium Beta Linac (MBL) cavities with $\beta = 0.67$ and 84 High Beta Linac (HBL) elliptical cavities, with $\beta = 0.86$. After acceleration the beam is transported to the target through the High Energy Beam Transport (HEBT) section.

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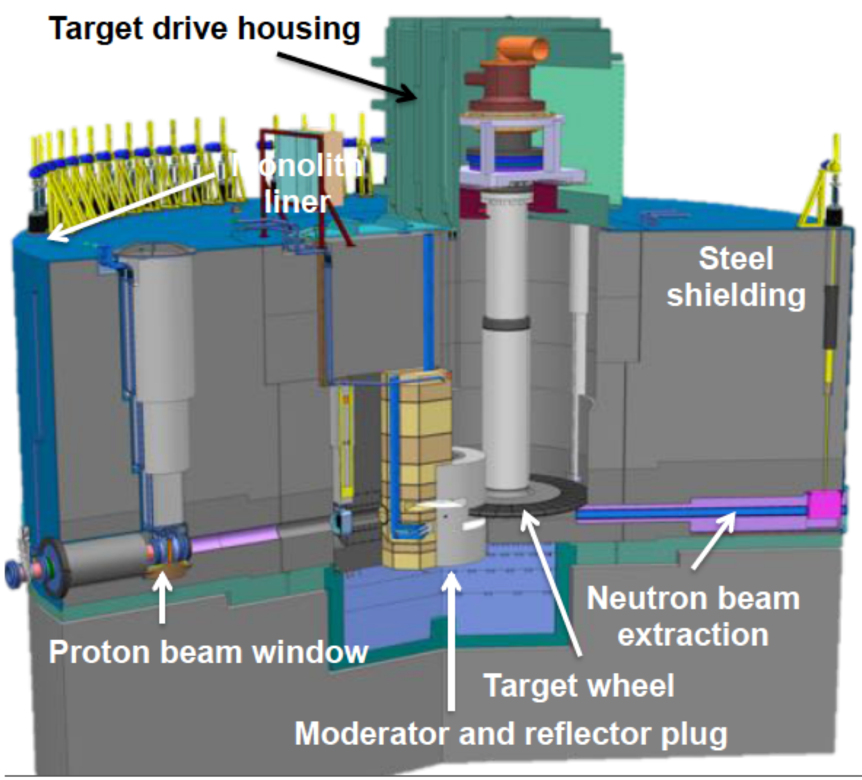
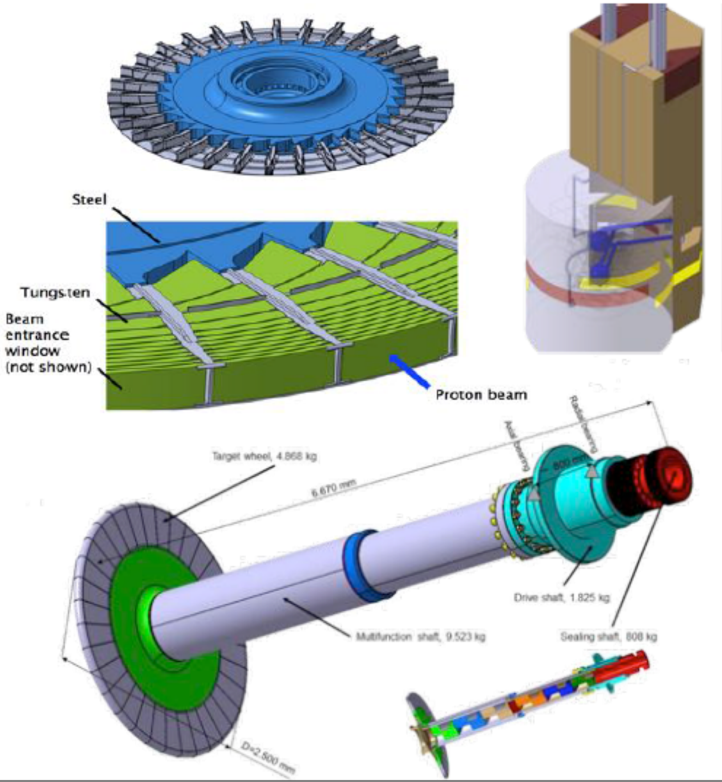
ESS Target:
Helium-cooled rotating tungsten target

Converting protons into neutrons and slowing them down results in …
… peak brightness 30x times leading steady state source





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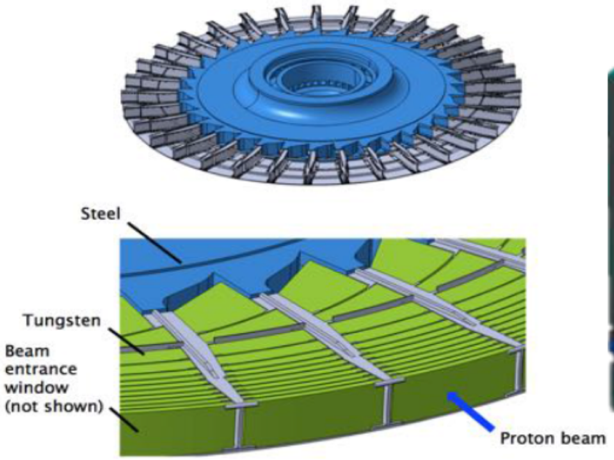
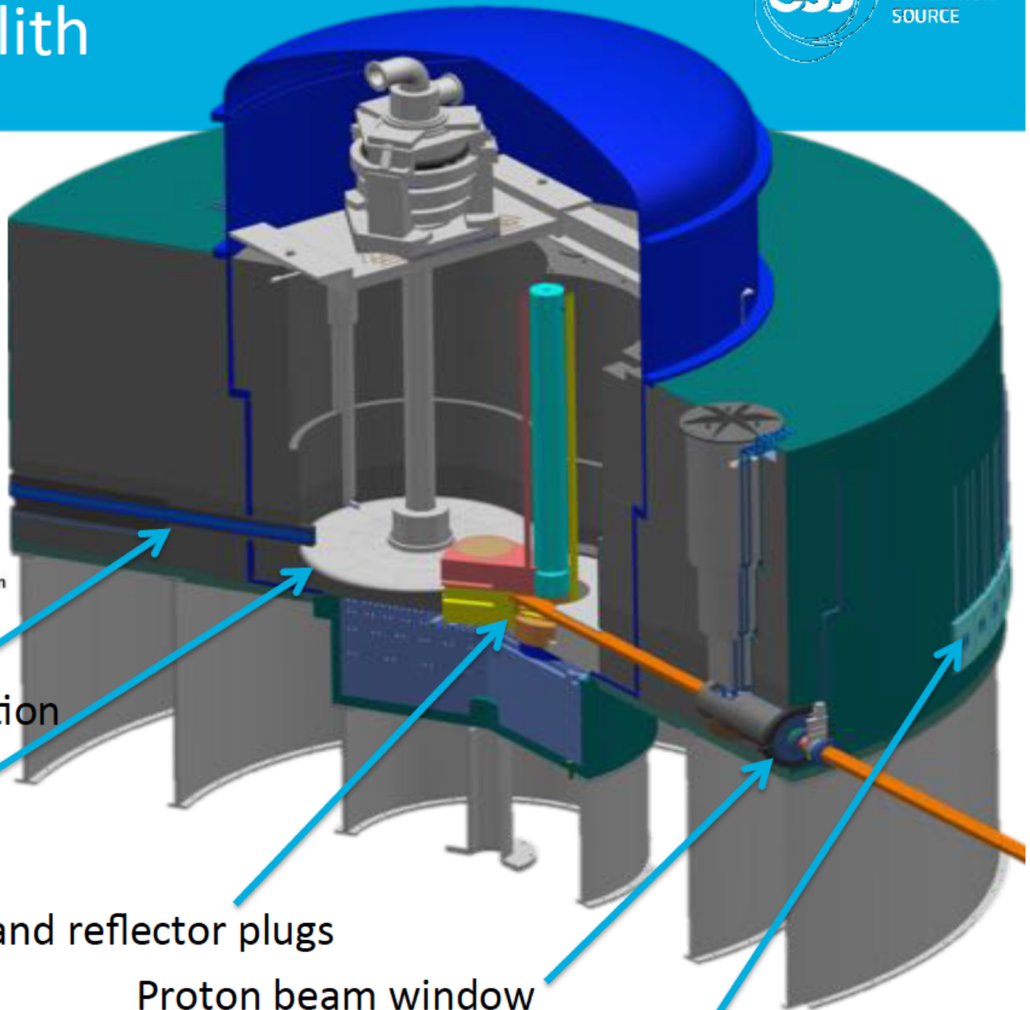
The Target Monolith

EUROPEAN SPALLATION SOURCE





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From MeV to meV

Hydrogen is a very good moderator

1: ~Same mass as the neutron

=> Fewer collisions needed

2: Short mean free path

=> Smaller neutron sources

But: Hydrogen have a fairly high neutron absorption cross section.

Main challenges:

1: Get the neutrons into the bucket.

2: Moderate them.

3: Get the neutrons out of the bucket.

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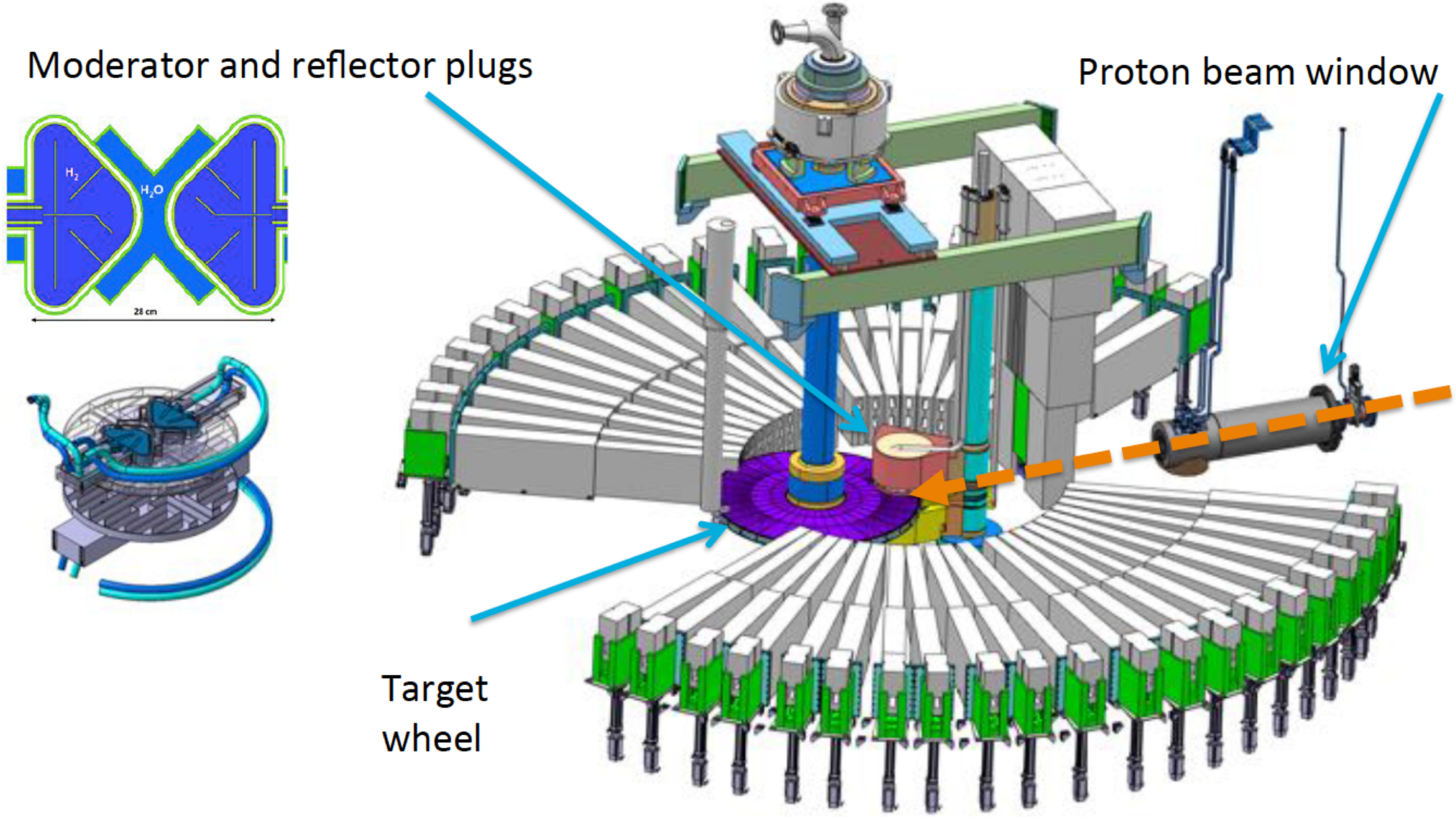
Neutron Beam extraction inside Target Monolith



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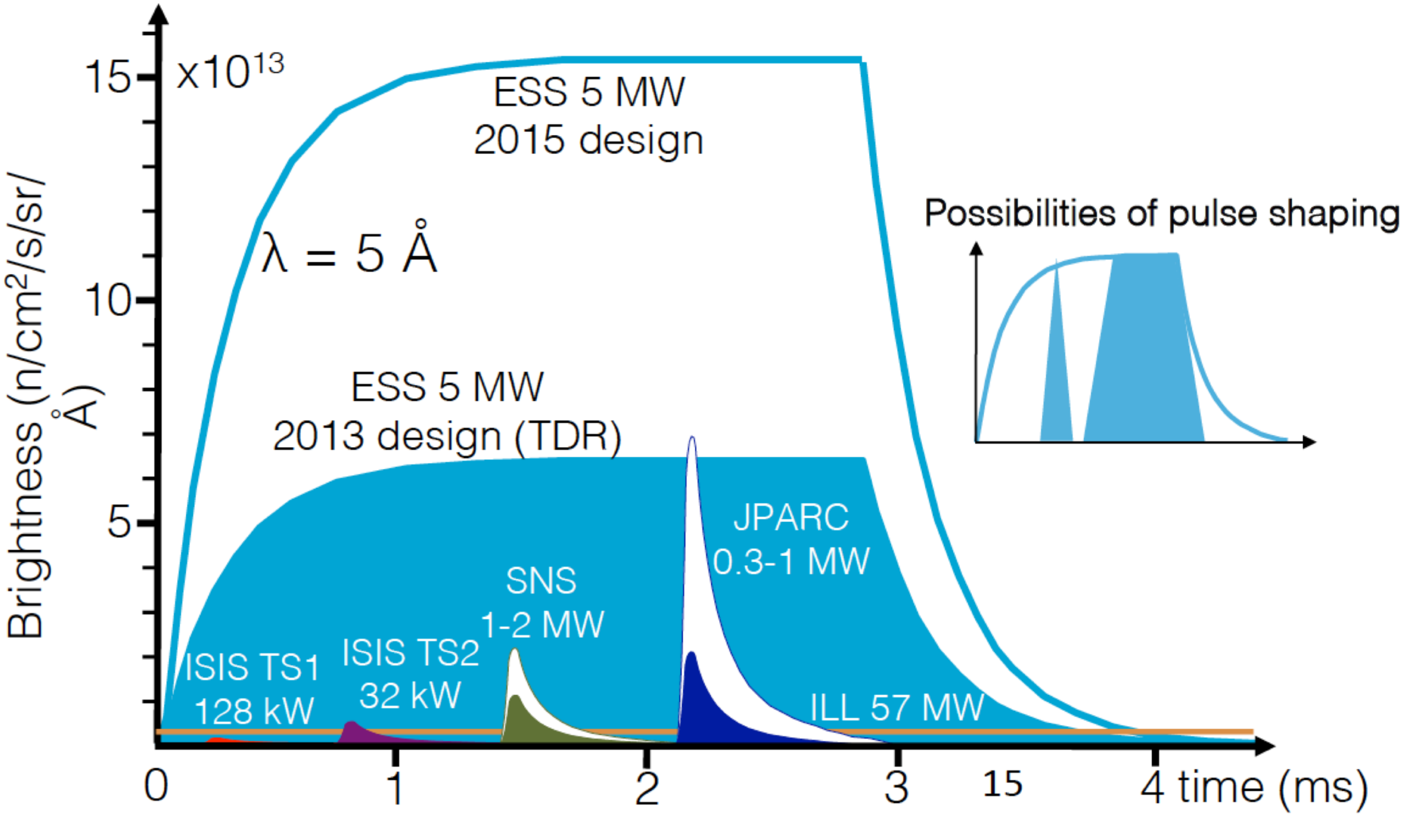
The unique ESS long pulse

ess



more neutrons per second than any steady state source …

… with higher brightness than any other spallation source

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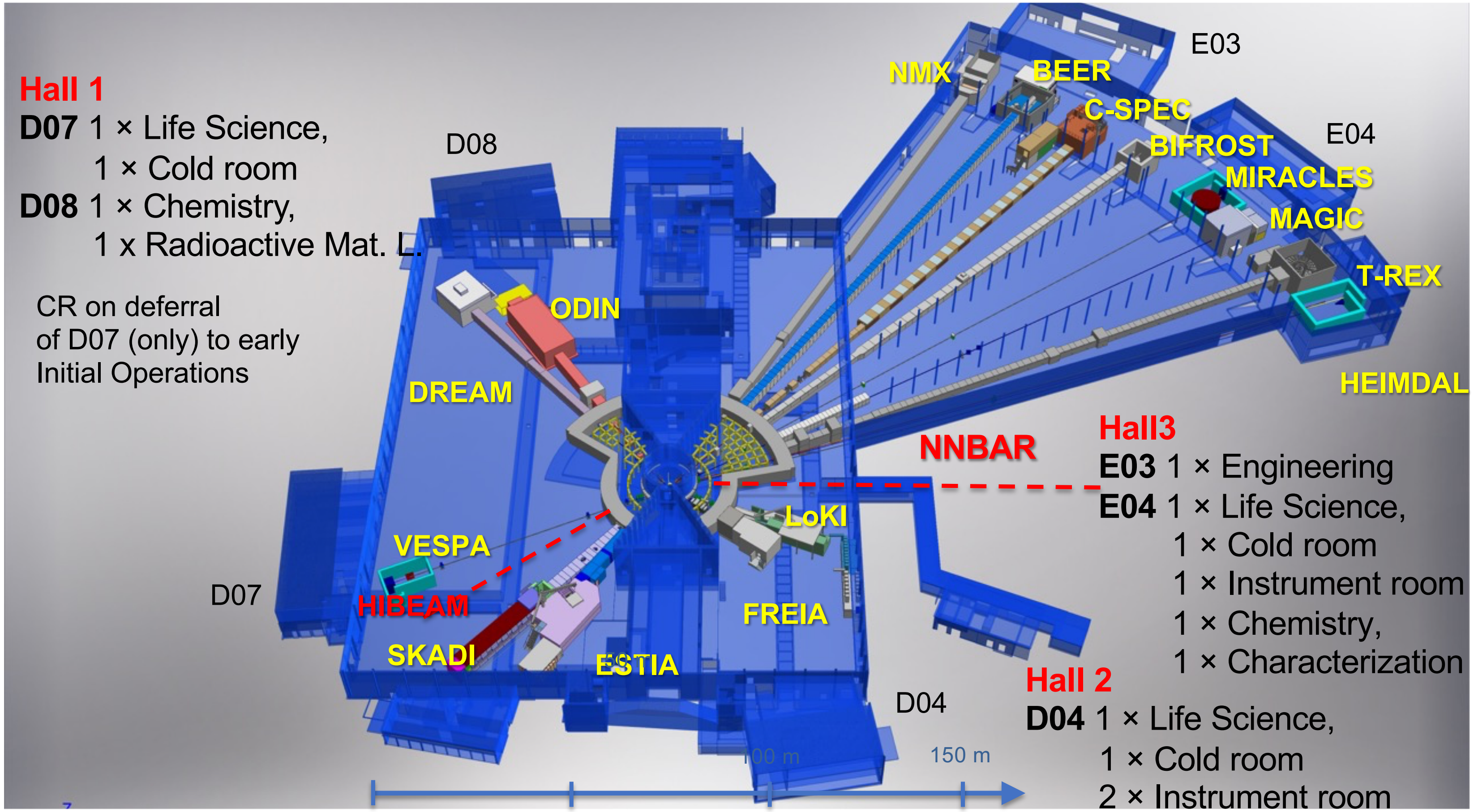
ESS Neutron Instruments 1-15



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Why fundamental physics at ESS?

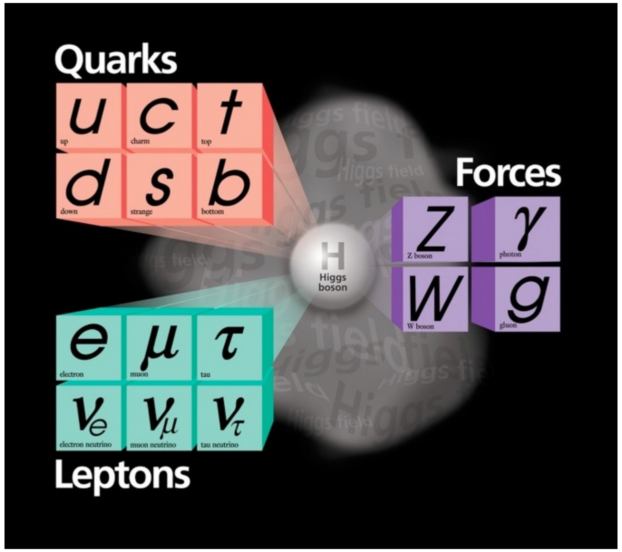
Standard Model Today (I)

Nobel Prize in Physics 2013

- Higgs discovery completes the Standard Model

- Fully consistent, complete, precise description of strong, electromagnetic and weak interactions

- Even generate fermion masses



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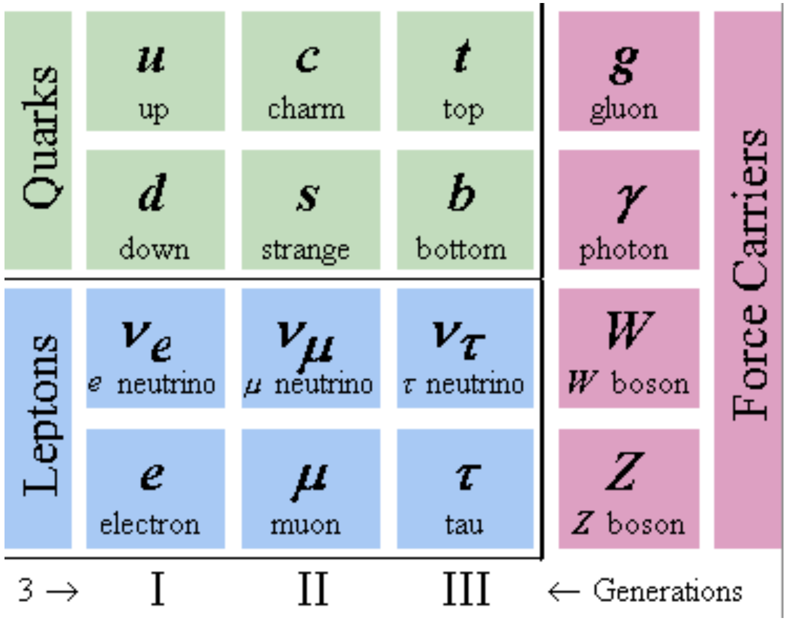
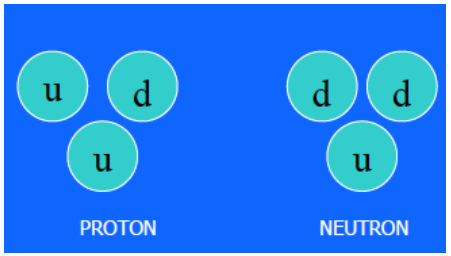
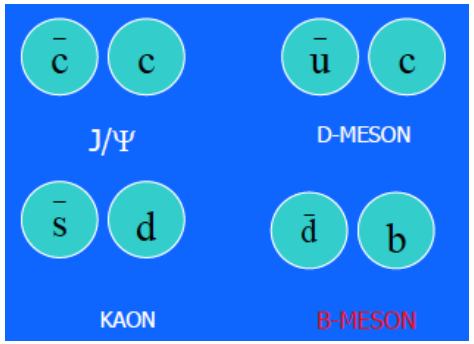
Standard Model Today (II)







- With quarks you can build baryons (qqq) or mesons ($q\bar{q}$)
- You can build stable particles using 1st generation of quarks (neutrons,protons)
- Unstable particles using heavy 2nd and 3rd generation

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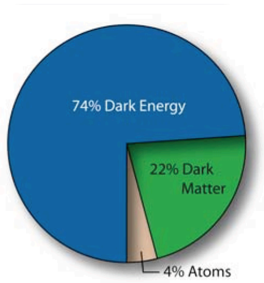
HighNess

5 mysteries that the standard model cannot explain

ess

- Why the neutrinos have mass?
- <u>**What is dark matter?**</u>
- <u>**Why is there so much matter in the universe?**</u>
- Why is the expansion of the universe accelerating?
- Is there a particle associated with the force of gravity?



https://www.symmetrymagazine.org/article/five-mysteries-the-standard-model-cant-explain

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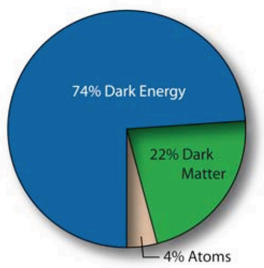

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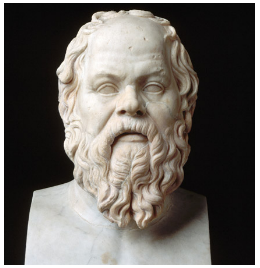

"The only true wisdom is in knowing you know nothing"
Socrates

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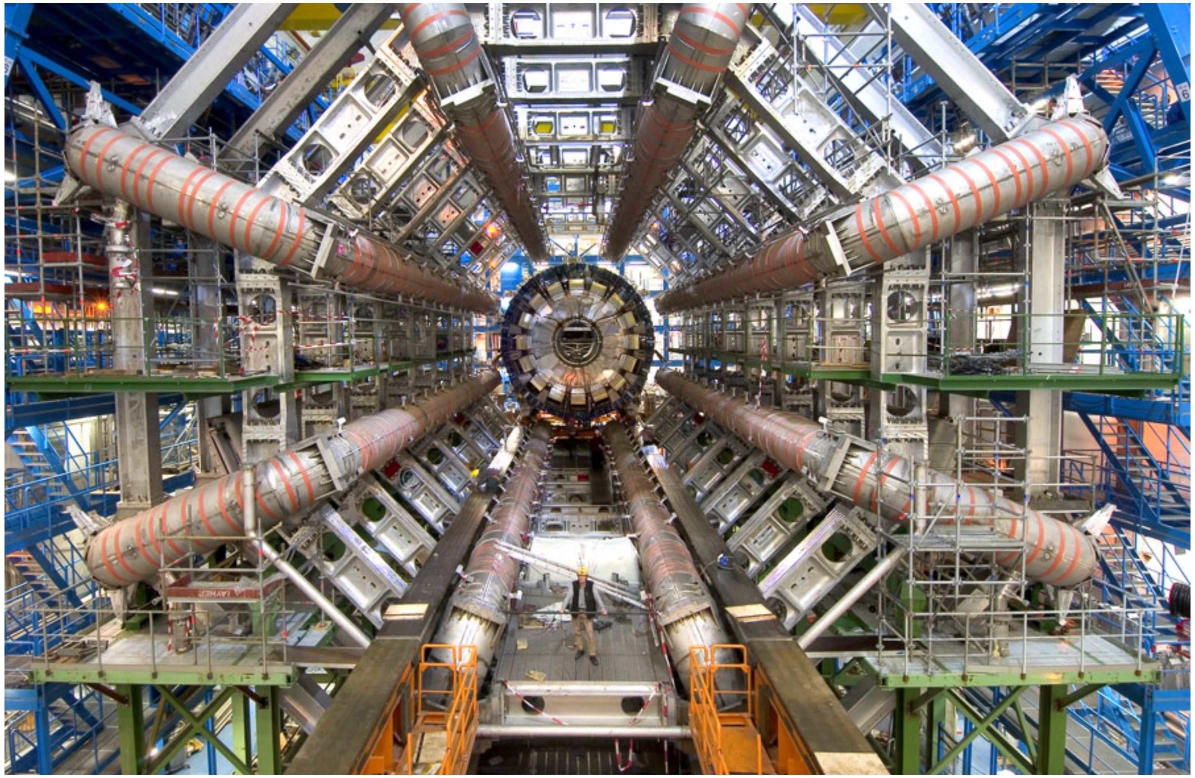
To answer all the present questions people built LHC



- The Higgs is found.
- Lots of questions are still unanswered

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Two important points

- We are living in an interesting time
- ESS fundamental physics measurements can be complementary and competitive with LHC measurements

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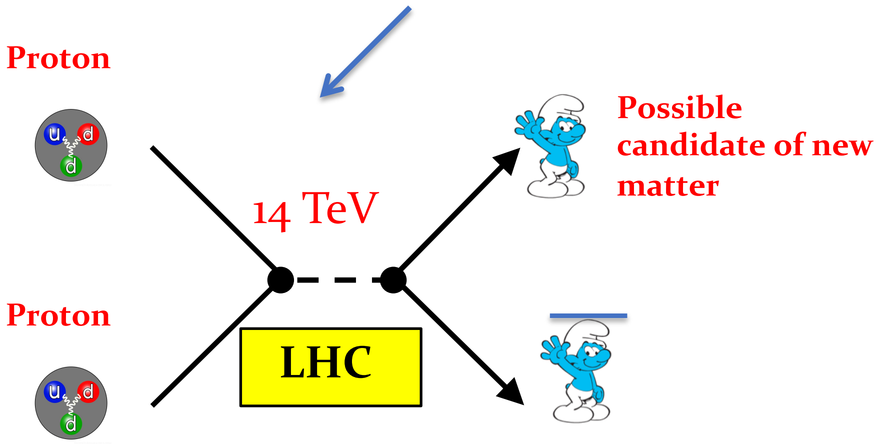
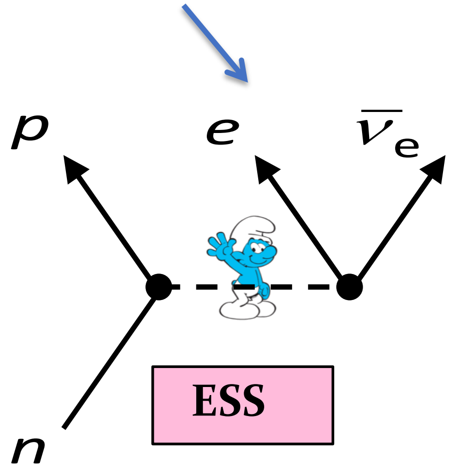
How do we search for new Physics ?

The way to find Beyond the Standard Model physics

Direct Searches
Produce new particles as real particles in pp collisions



Indirect Searches
New particles will appear as virtual particles
in quantum loops



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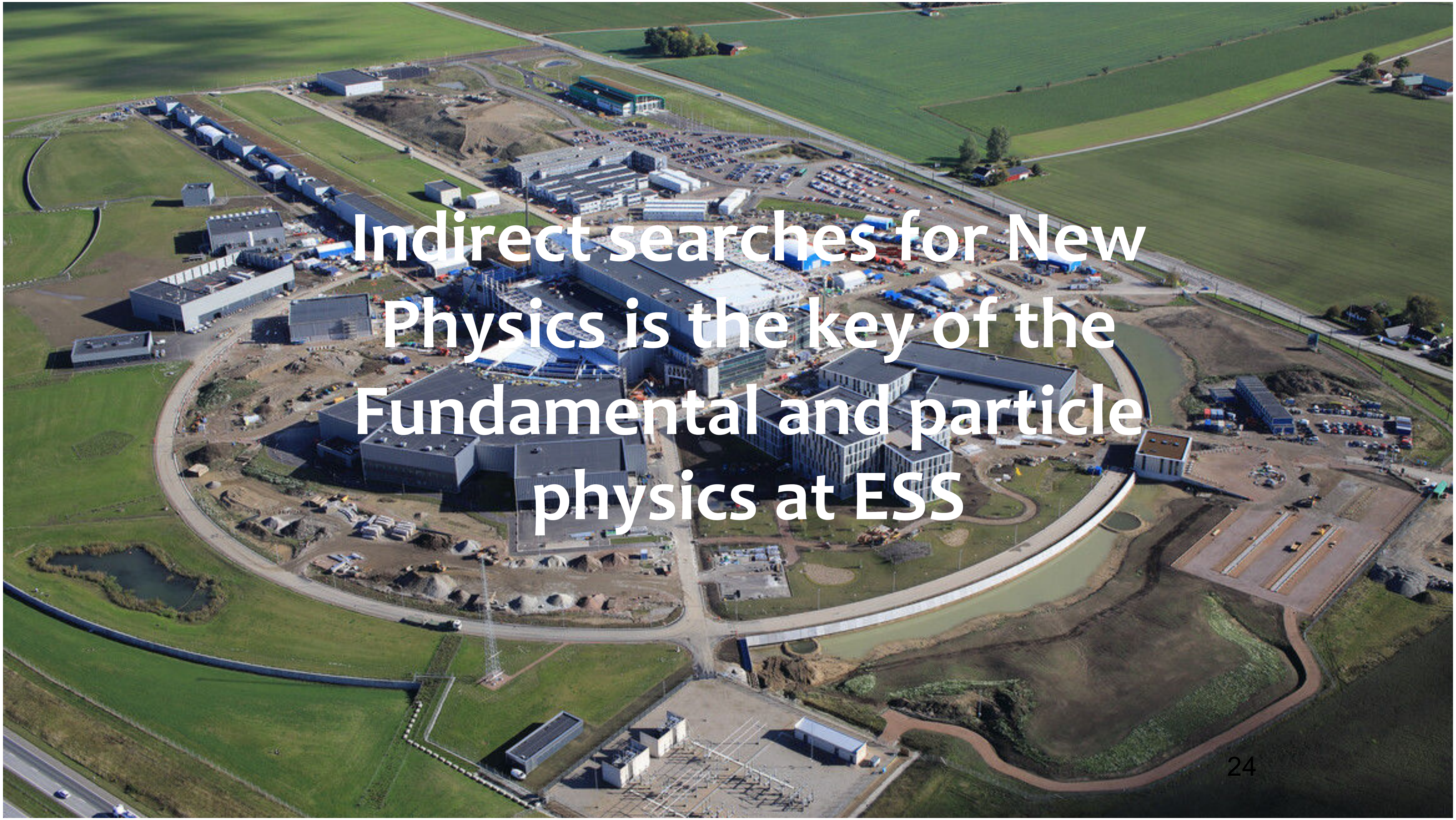

Indirect searches for New Physics is the key of the Fundamental and particle physics at ESS

Fundamental & Particle Physics @ ESS

- In addition to neutron scattering the higher intensity and the pulse structure of ESS provide new possibilities for fundamental physics research with neutrons

Precision experiments
Beyond SM
New interactions

High Intensity Baryon Extraction and Measurement (HIBEAM)

Neutron antineutron oscillation beamline (NNBAR)

Search for Dark Matter
Baryon asymmetry of the Universe

Cold neutron beamline (ANNI)

Neutron beta decay
Hadronic parity violation
Electromagnetic properties of the neutron

UCN
Ultra Cold Neutron beamline

Gravity resonance spectroscopy
Neutron interferometry
Neutron beta decay

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Fundamental & Particle Physics @ ESS

- In addition to neutron scattering the higher intensity and the pulse structure of ESS provide new possibilities for fundamental physics research with neutrons
- The ESS mandate includes a fundamental physics program, and the current lack of an appropriate beamline for fundamental physics has been identified as one of the most important missing capabilities

Precision experiments
Beyond SM
New interactions

High Intensity Baryon Extraction and Measurement (HIBEAM)

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Free Neutron Oscillations Searches at the ESS

(The HIBEM and the NNBAR program)

Valentina Santoro

ESS European Spallation Source

On Behalf of the NNBAR/HIBEAM Collaboration

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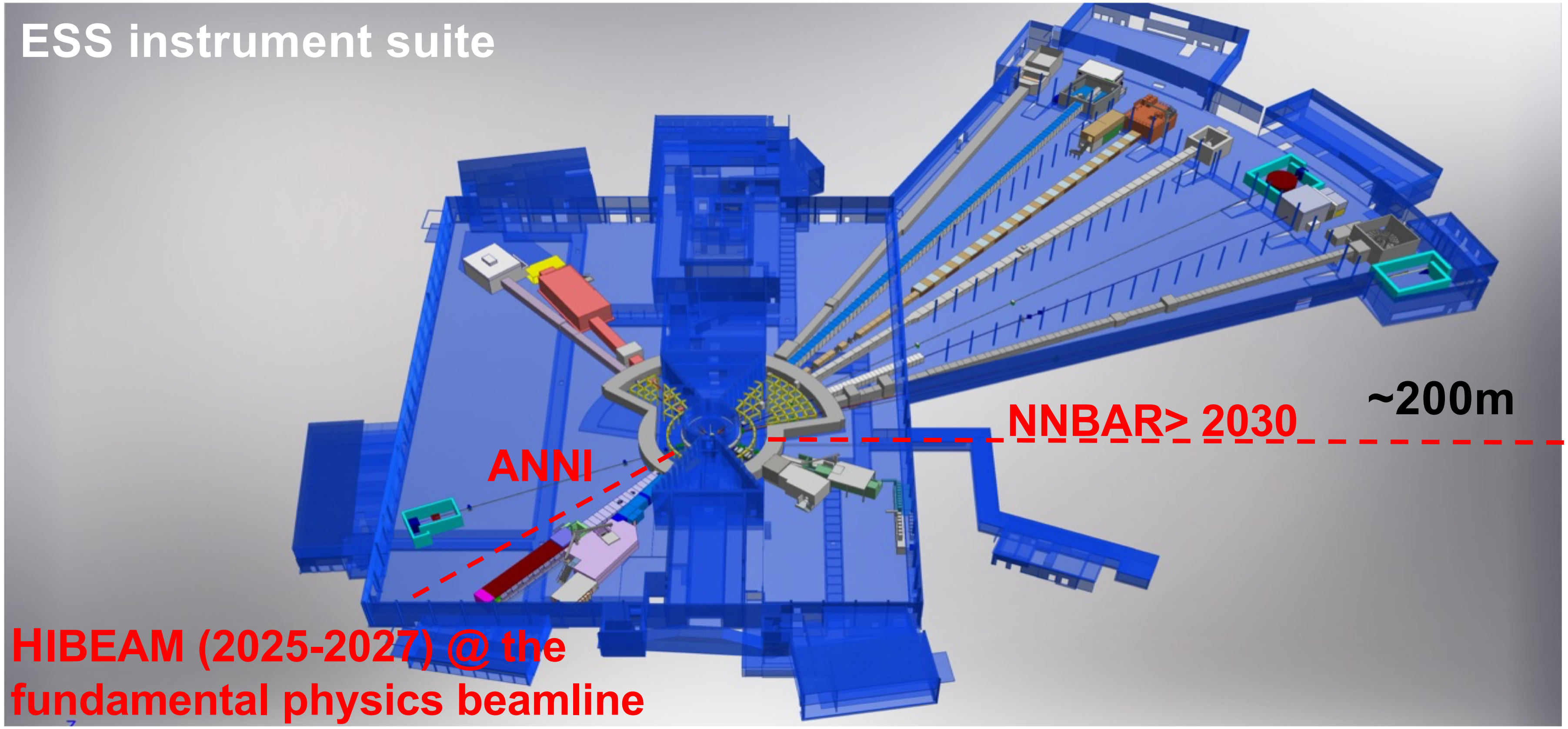
Future Free Neutron Oscillations Searches at the ESS



Two stage program:

- HIBEAM (≳2025): smaller program of complementary experiments (focus on sterile neutron searches)
- NNBAR (>2030): search for $n \rightarrow \bar{n}$ oscillations (sensitivity increase of 10^3 compared to previous experiments)

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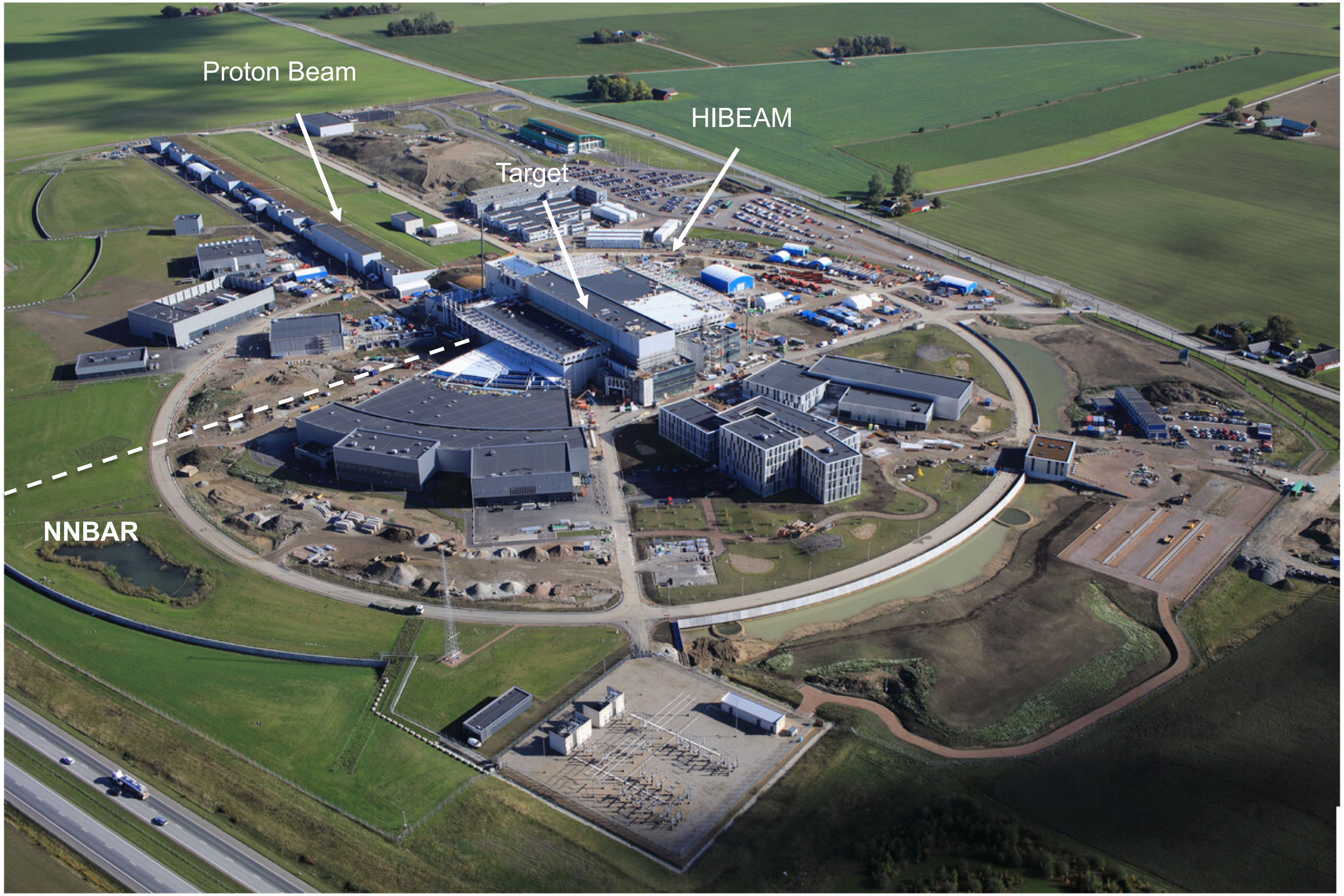
Proton Beam
HIBEAM
Target
NNBAR

Despite its success the standard model it is known to be incomplete …

- There is a number of key questions for which it is unable to provide answers, such as the nature of **dark matter** and the origin of the **matter-antimatter asymmetry or baryogenesis.**

- Free Neutron oscillation searches address both these problems in a unique and innovative way.

- The novel experiments proposed at ESS will search for processes that are forbidden in the SM
  - neutrons converting to sterile neutrons (HIBEAM)
  - neutrons converting to anti-neutrons via sterile neutrons (HIBEAM)
  - neutrons converting directing to anti-neutrons (NNBAR)

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Address the nature of the dark matter problem

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Address the nature of the dark matter problem (first two items)

Baryogenesis (third item)

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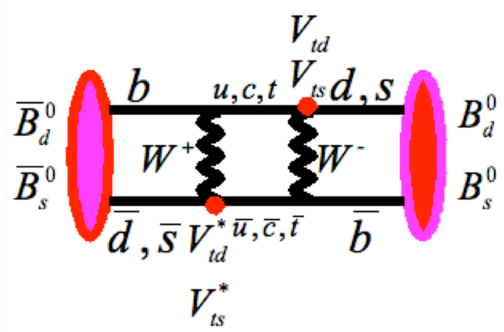
The power of oscillations

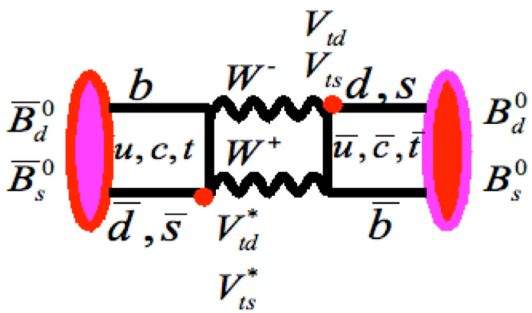
- Neutral particle oscillations have played large role in particle physics

  - K^0-K^0 oscillations (**$\Delta S = 2$**) at the core of our initial understanding of CP-violation

  - B meson oscillations (**ΔBeauty = 2**):
    - Sensitive to CKM elements
    - CP-violation "workhorse"
    - Probe m_t^2/m_W^2
      First indication of large top mass! (1987)



  - Neutrinos oscillations which shows that the neutrinos have mass.



- **Sensitive probes of high mass scales**

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Baryon Number Violation

- *BN* is an "accidental" global symmetry at perturbative level
  - *BNV* in SM non-perturbatively (eg instantons)
  - *B-L* is conserved, not *B, L* separately.

- Baryon number is expected to be violated: Sakharov condition for baryogenesis
- *BNV* generic features of SM extensions (eg SUSY, extra dimensions ...)

- Important to probe possible *BNV* channels

- HIBEAM will search for $n \rightarrow n' \rightarrow \bar{n}$ $(|\Delta B| = 1)$ neutrons to sterile neutron transitions
- NNBAR experiment will search for $n \rightarrow \bar{n}$ $(|\Delta B| = 2)$
  Sensitivity increase of 10^3 compared to previous experiments

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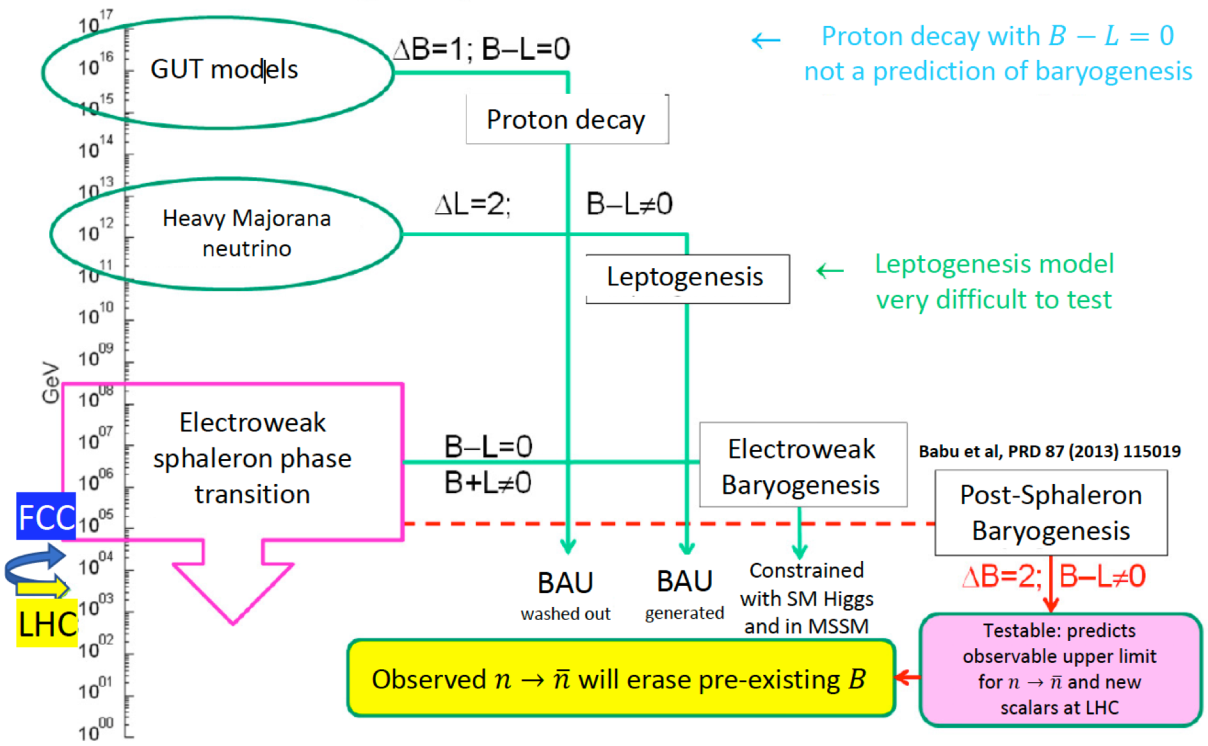
New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501

Baryogenesis Models

Regimes for baryogenesis

- Leptogenesis: Sphalerons convert L into B
- Electroweak baryogenesis: T violation near EW scale creates B without L
- Post-sphaleron baryogenesis: New BNV process below EW phase transition
- $n \rightarrow \bar{n}$ targets accessible energy scales . Null result will restrict phase space of PSB models



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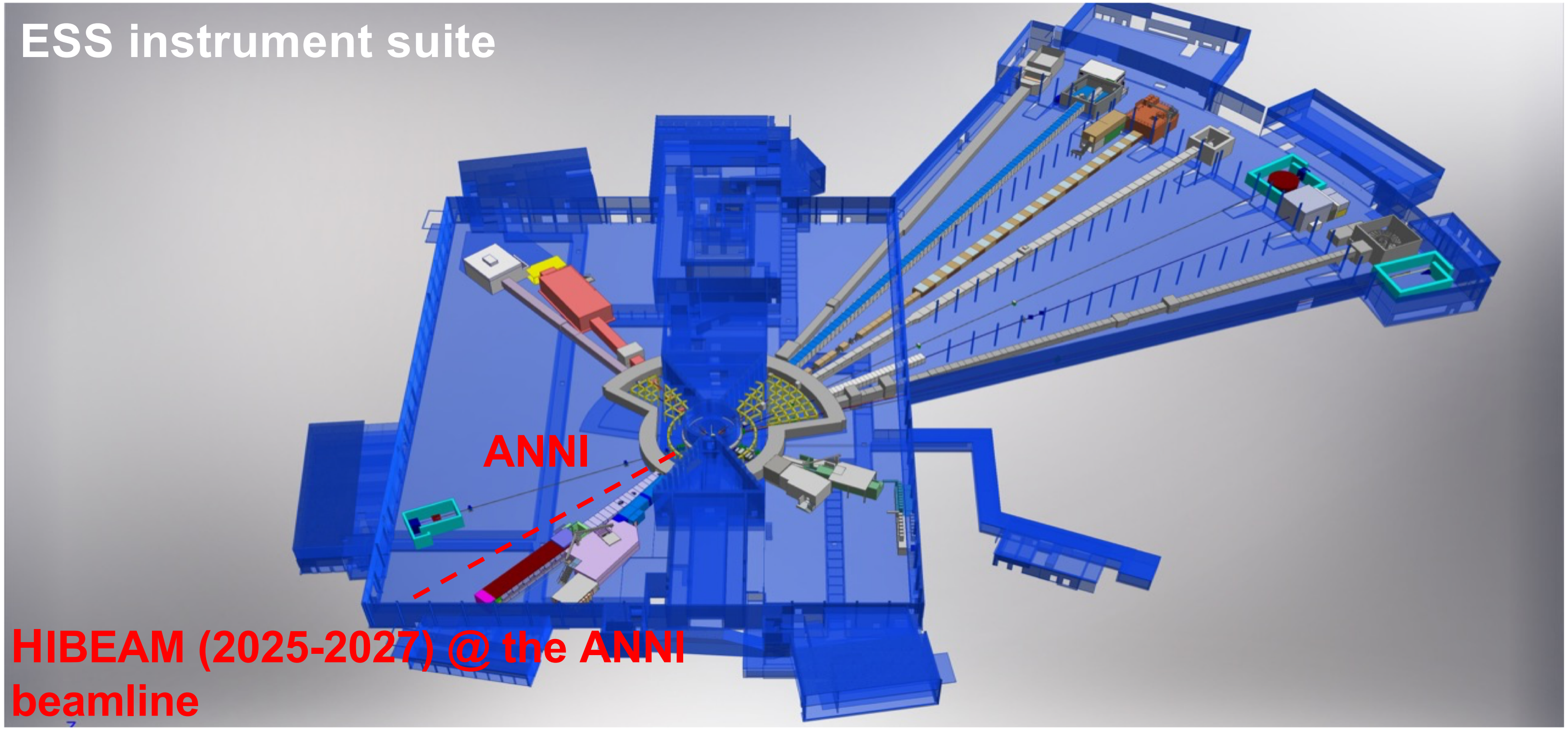
The HIBEAM PROGRAM



HIBEAM (≳2025): Search for Sterile Neutron transitions
HIBEAM will make use of the ANNI beamline

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DARK Matter

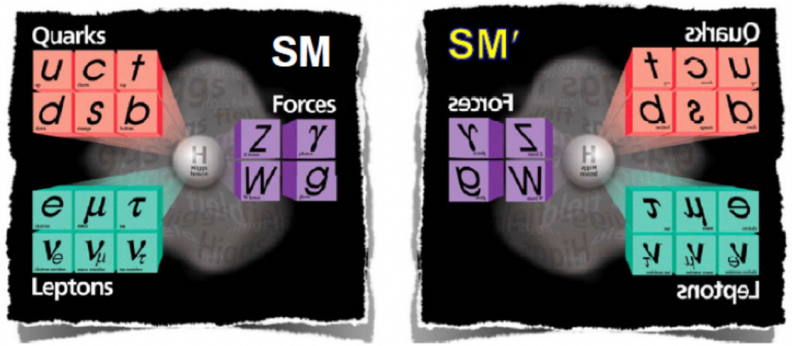
- What is the nature of dark matter?
- The fact that our astronomical observations are not sufficiently well described by the SM is unquestioned.
- The existence of a dark sector, interacting primarily gravitationally with our familiar visible sector, has long been postulated to explain astronomical data
- Such dark sector is assumed to have particles having interactions similar to our own SM interactions, sterile neutrinos and sterile baryons
- In principle, observable portals onto such a sector can occur ia mixing phenomena between any stable or meta-stable electrically neutral particles, allowing for conversion into a dark partner particle.

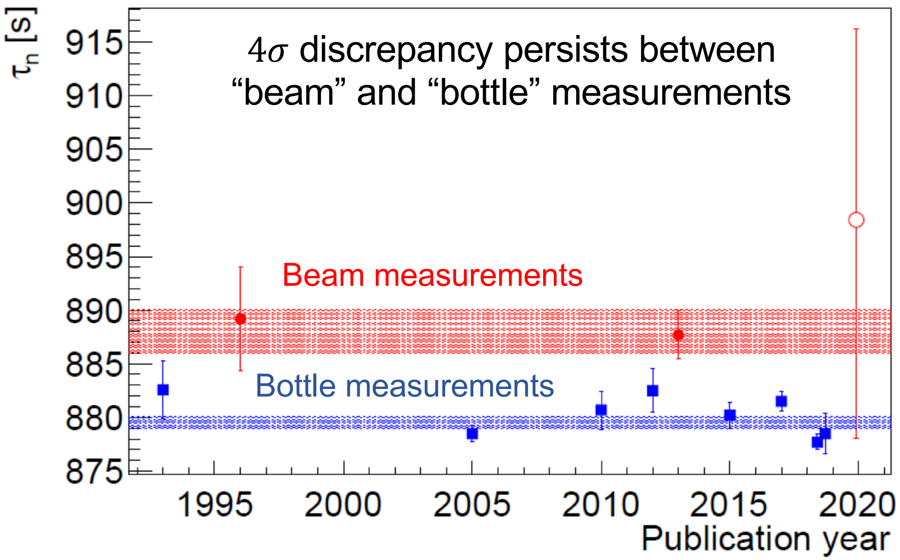
Neutron to sterile neutrons conversions

- As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector. (e.g. mirror matter and generic dark sectors)

- Z. Berezhiani, Phys. Rev. Lett. 96 (2006) 081801
- Z. Berezhiani, arXiv:hep-ph/0508233 (2005)
- R. Foot, Int. J. Mod. Phys. A29 (2014) 1430013
- Z. Berezhiani, Int. J. Mod. Phys. A29 (2014) 3775-3806

- n mixing with dark sector n': relatively unexplored experimentally
- These transitions can also shed light on the anomaly between neutron lifetime in "beam" and "bottle" [EPJC **79**, 484 (2019)]





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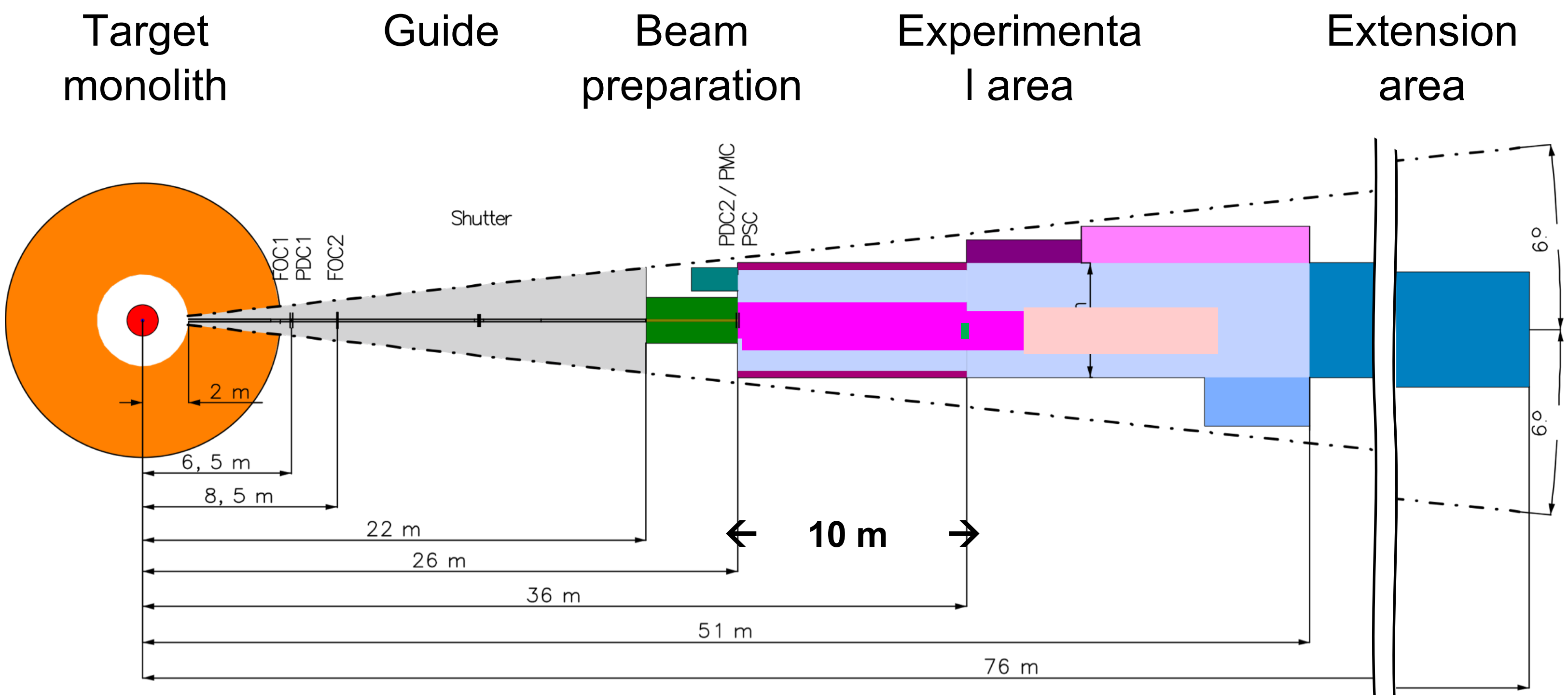
The ESS Fundamental Physics Beam Line: ANNI



Apart from HIBEAM there are several other experiments planned at the ANNI beamline (EDM searches, neutron beta decay correlation coefficients, hadronic weak interaction ecc..)

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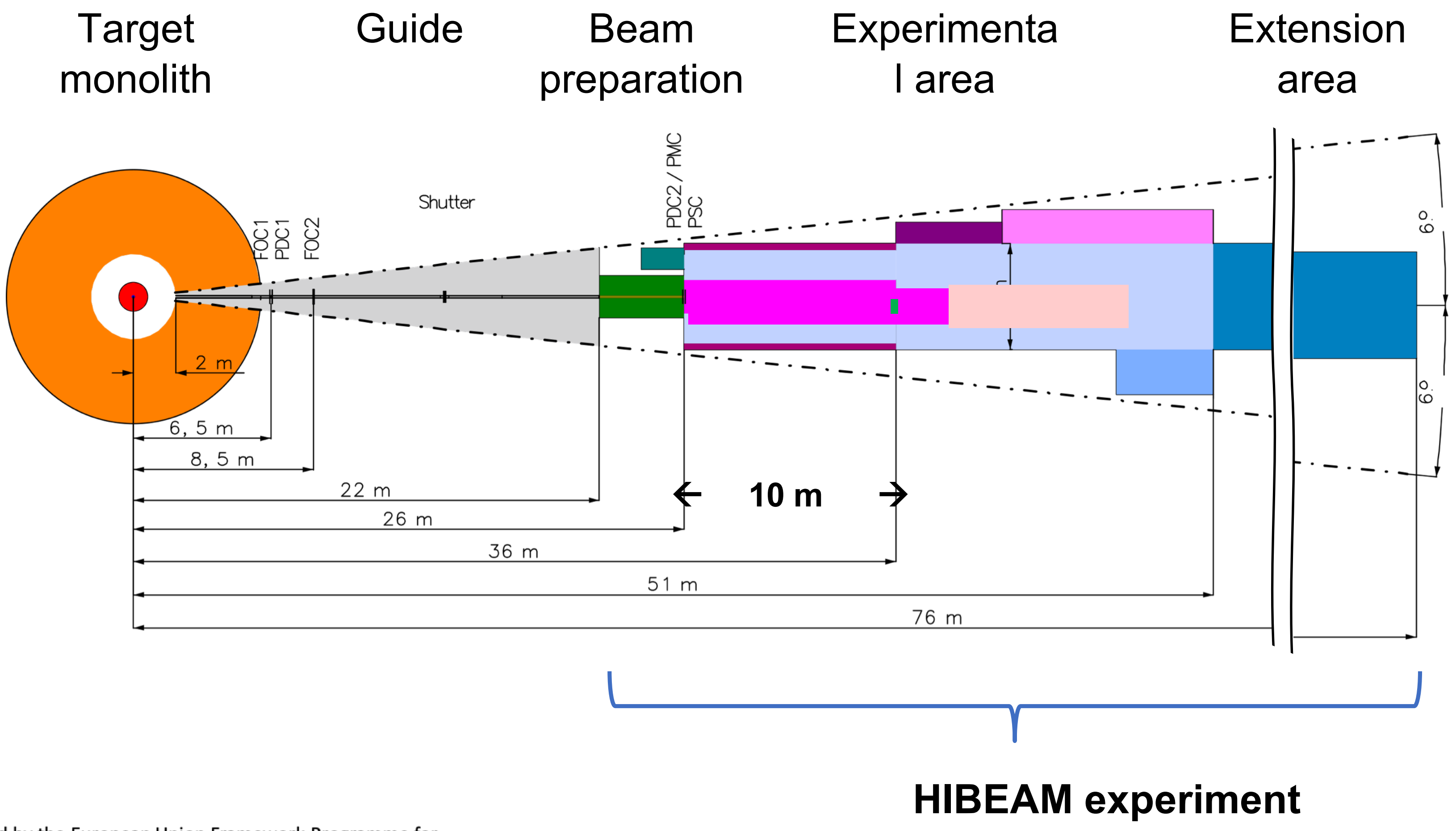
The ESS Fundamental Physics Beam Line: ANNI



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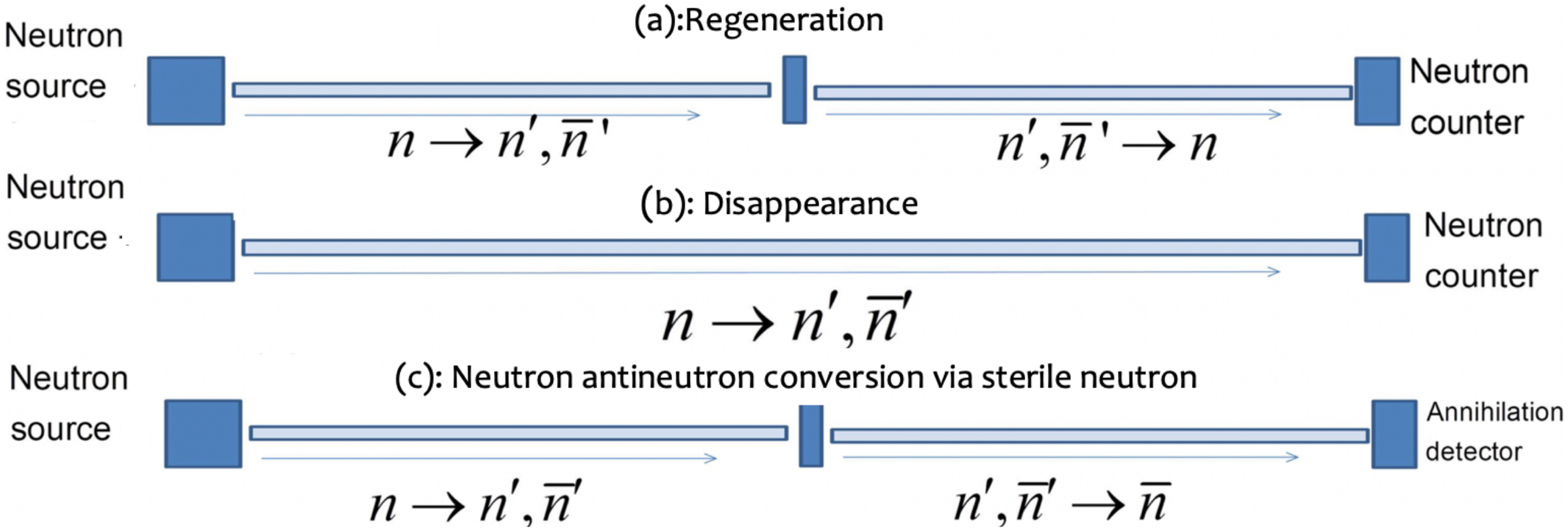
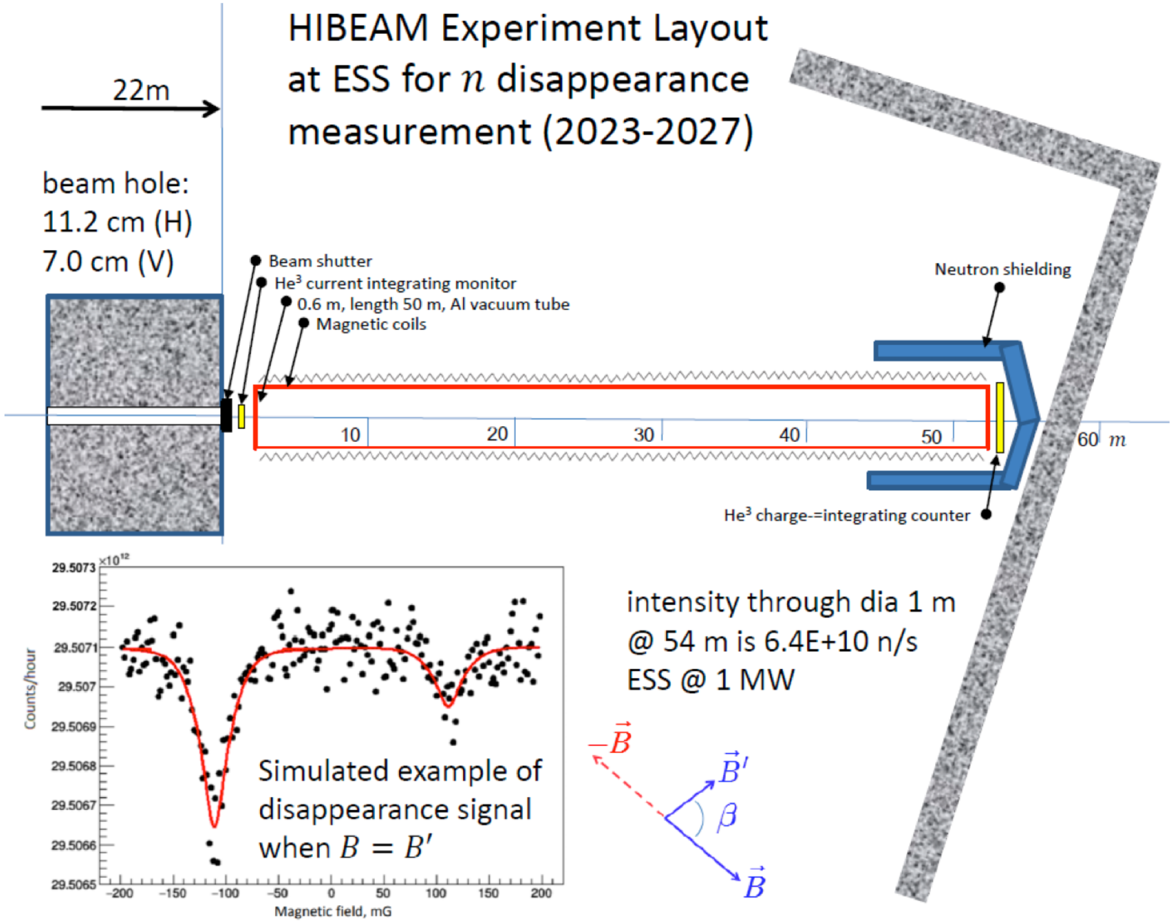
The HIBEAM program: search for neutron to sterile neutron conversion (I)

- HIBEAM will look for ***n*** regeneration, ***n*** disappearence and ***n*** to antineutron conversion via sterile neutron
- All experiments shown are dependent on the magnetic field. Experiments (a), (b), and (c) should scan through the magnetic field range ~ +/- 1 G to coincide in resonance with the unknown value of the "mirror magnetic field" in magnitude and in direction. For the flight path of these experiments, full 3D control of the magnetic field will be needed.



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 *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501**

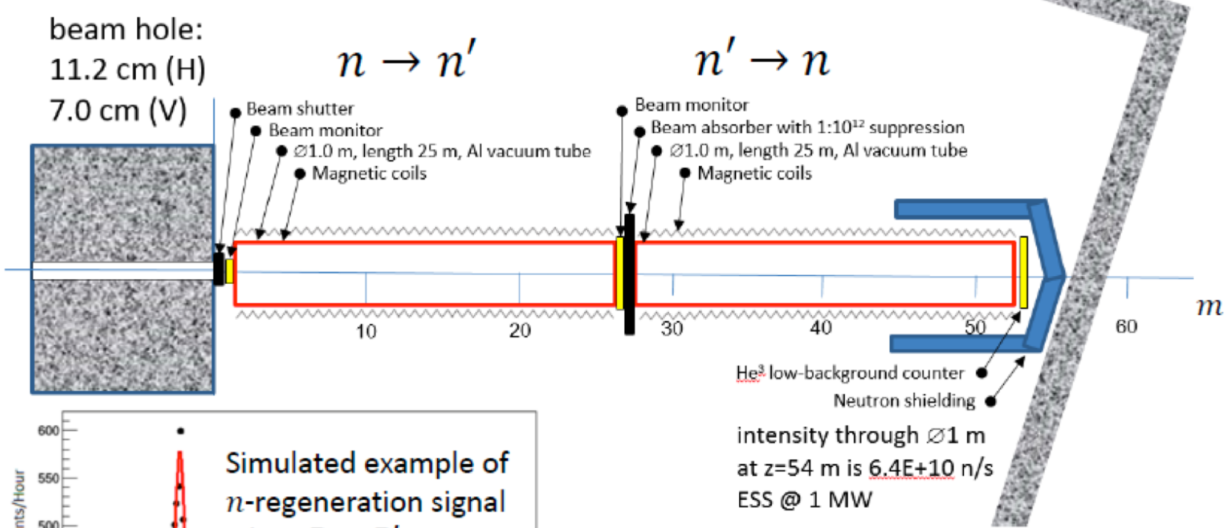
HIBEAM Experiment Layout at ESS for *n* disappearance measurement

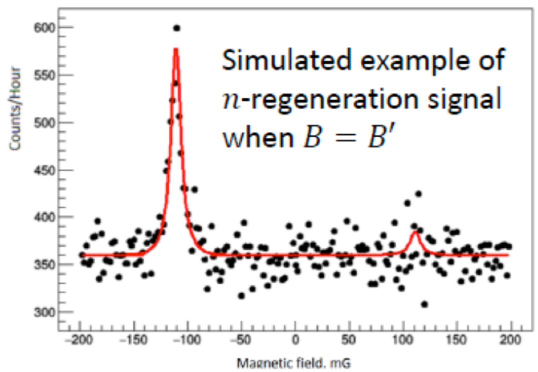


HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

HIBEAM Experiment Layout at ESS for *n*-regeneration measurement

HIBEAM Experiment Layout at ESS for n-regeneration measurement 2023-2027

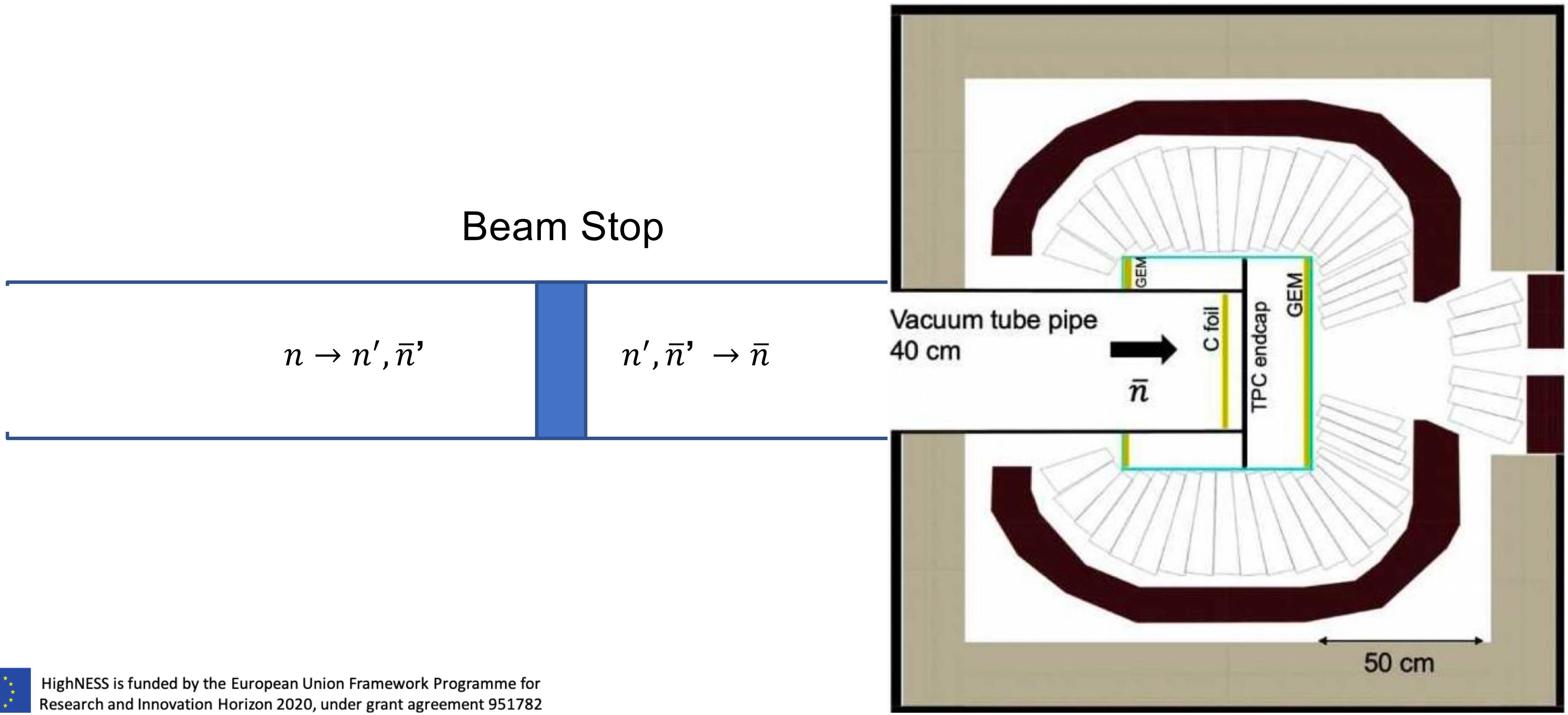




Detection of resonance via variation of magnetic field B will also demonstrate the existence of mirror photons field γ'

HighNESS is funded
Research and Innova

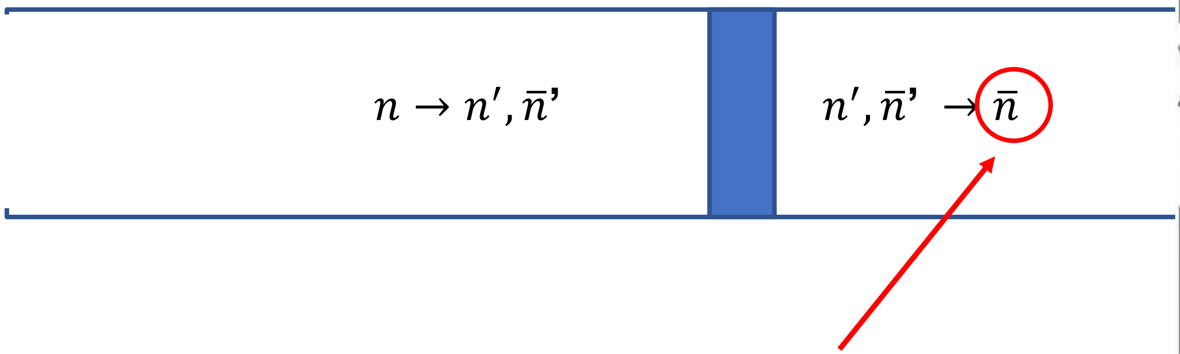
HIBEAM Experiment Layout at ESS for neutron antineutron conversion via sterile neutron

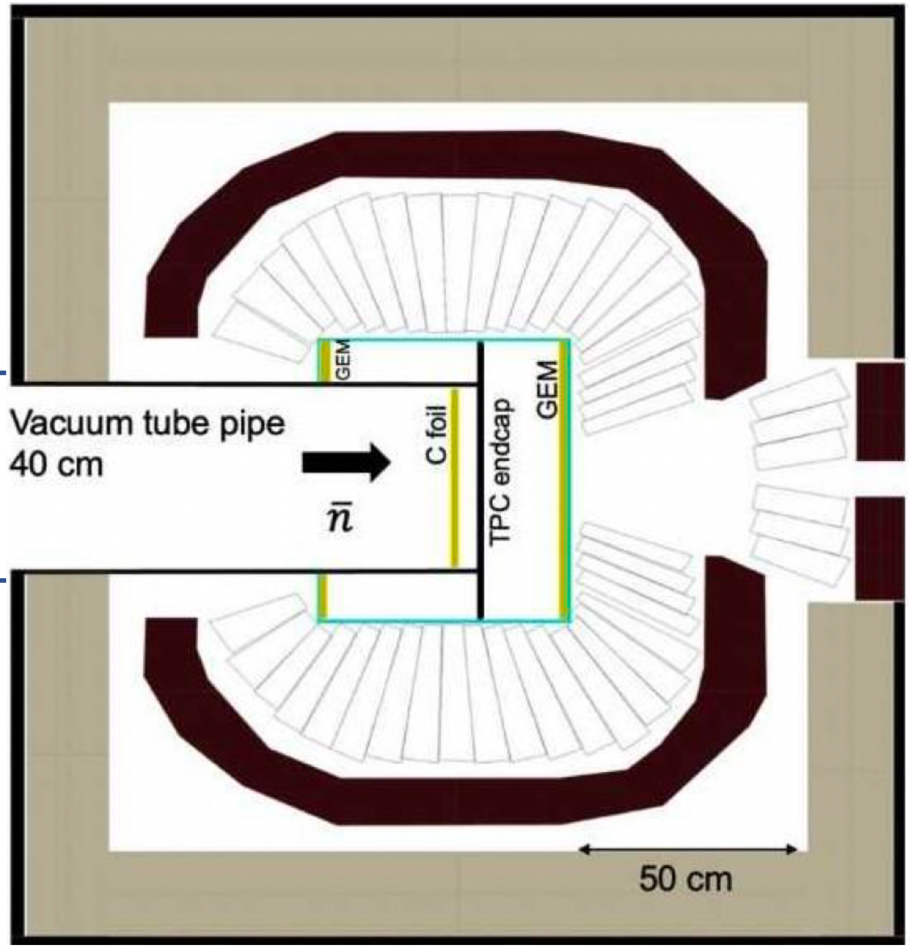


HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

HIBEAM Experiment Layout at ESS for neutron antineutron conversion via sterile neutron

Beam Stop





You need to have an annihilation detector in order to detect the annihilation of the antineutron with a target material

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Recent News

- The HIBEAM/NNBAR collaboration has been recently awarded with 10MSEK for the project “ Pre-studies for a HIBEAM Instrument at the ESS” by Vetenskapsrådet
- D. Milstead (SU) is the project leader
- Lund University, ESS, Chalmer, Uppsala, ILL and Tennesse University are involved in the project
- Scope of the project is to deliver the TDR of the HIBEAM experiment

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Why is there so much matter in the universe?

- The Big Bang should have created equal amounts of matter and antimatter in the early universe. But today, everything we see is made almost entirely of matter.
- There is not much antimatter to be found.

- Something must have happened to tip the balance.

Sakharov conditions (1967) for Baryogenesis

- Baryon number violation
- *C* and *CP* violation
- Departure from thermodynamic equilibrium (non-stationary

The NNBAR experiment @ ESS

Abstract

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. Observing the $n-\bar{n}$ transition would show that baryon number (B) is violated by two units and that matter containing neutrons is unstable. It would provide a clue to how the matter in our universe might have evolved from the $B=0$ early universe. If seen at rates observable in foreseeable next-generation experiments, it might well help us understand the observed baryon asymmetry of the universe. A demonstration of the violation of $B-L$ by 2 units would have a profound impact on our understanding of phenomena beyond the Standard Model of particle physics.

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Phenomenology of neutron conversion processes

$\mathbf{\Psi} = \binom{n}{\bar{n}'}$

Mixed n, $\bar{n}, n'$ QM state

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

ε is the mixing mass term that depends on the scale of the new physics
the mass mixing term ε is different for $n \to \bar{n}$ and $n \to n'$

$m_n = m_{\bar{n}}$ by CPT invariance, E_n and $E_{\bar{n}}$ are **not** generically equal due to enviromental effects (i.e. matter medium or magnetic fields)

Probability to find an antineutron at time t is given by

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

ΔE= E_n- $E_{\bar{n}}$ and τ_n (mean life time of the free neutron)
-> the probability of conversion is suppressed when the energy degeneracy between neutron and antineutron is broken.
Quasi free regime $|\Delta E| t \ll 1$ can be realized in vacuum with very low magnetic shield. Under this

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

Figure of merit (background-free): Nt^2

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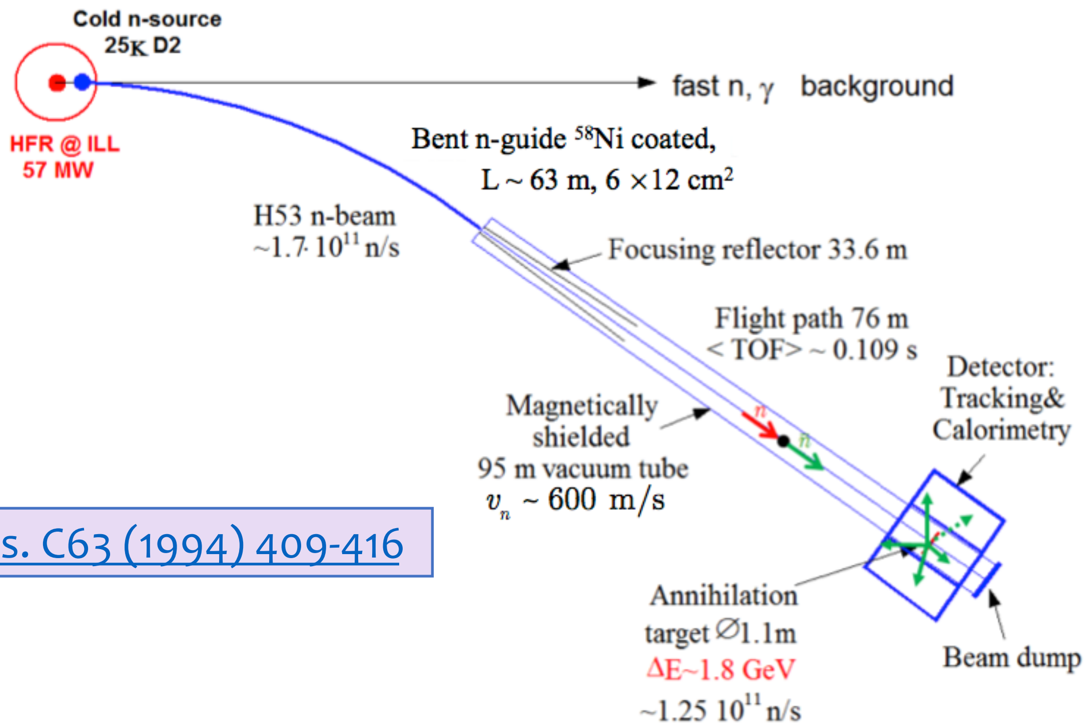
Previous searches: Neutron antineutron oscillation @ ILL in 1994



Baldo-Ceolin et al, [Z.Phys. C63 (1994) 409-416]

$Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau_{n \to \bar{n}} > 0.86\ 10^8$s

(***N*** is the free neutron flux reaching the annihilation target and ***t*** is the neutron observation time).

Many subtle optimizations to minimize losses and backgrounds

Experiment was background-free

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Sensitivity of the NNBAR experiment at ESS

- **Increase number of neutrons**
  - Flux
  - Moderator brightness and area
  - Angular acceptance
  - Longer run
- **Increase time-of-flight**
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
- **Better B_{Earth} suppression**

Factor	Gain wrt ILL
Source Intensity	≥ 2
Neutron Reflector	40
Length	5
Run time	3
Total gain	≥ 1000

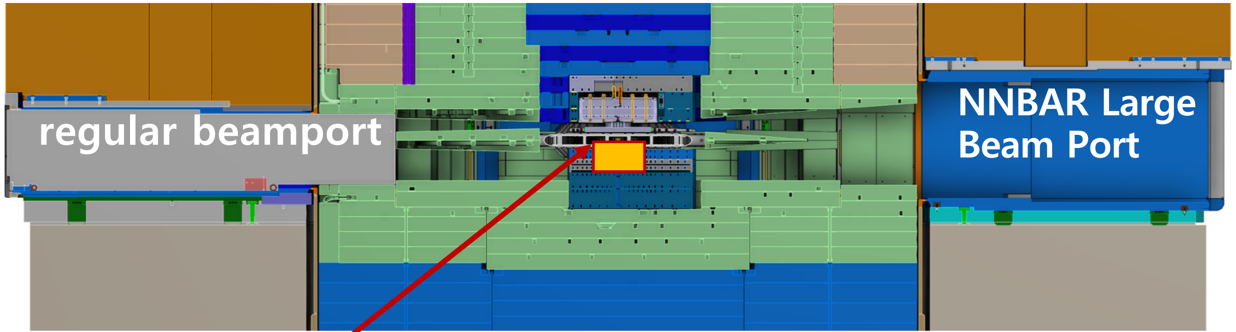
All these factors are being currently studied and optimized in the HighNESS Project (see next two slides)

NNBAR final design aim
to improve by 10^3 the ILL limit

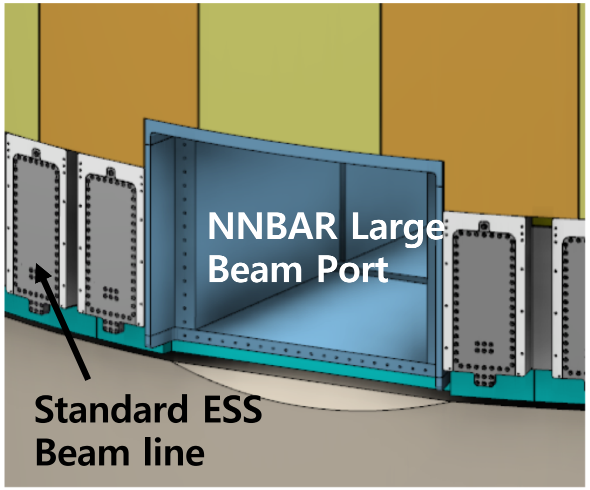
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

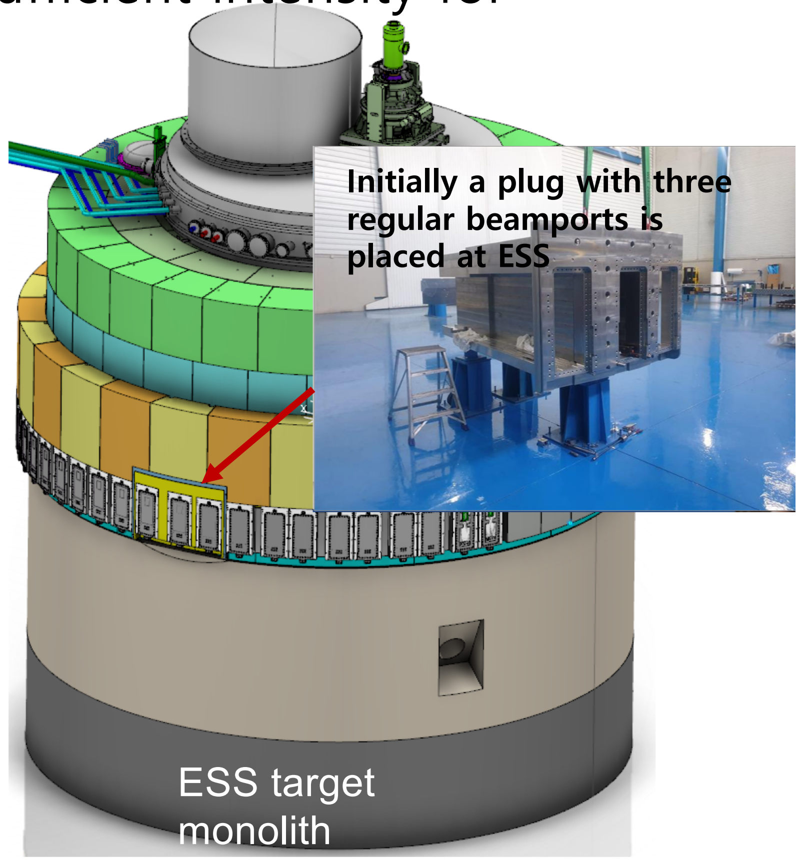
Why NNBAR at ESS?

A large beam port has been built at ESS specifically for NNBAR to allow for extraction of a high intensity beam to provide sufficient intensity for neutron to antineutron search



Location of lower moderator



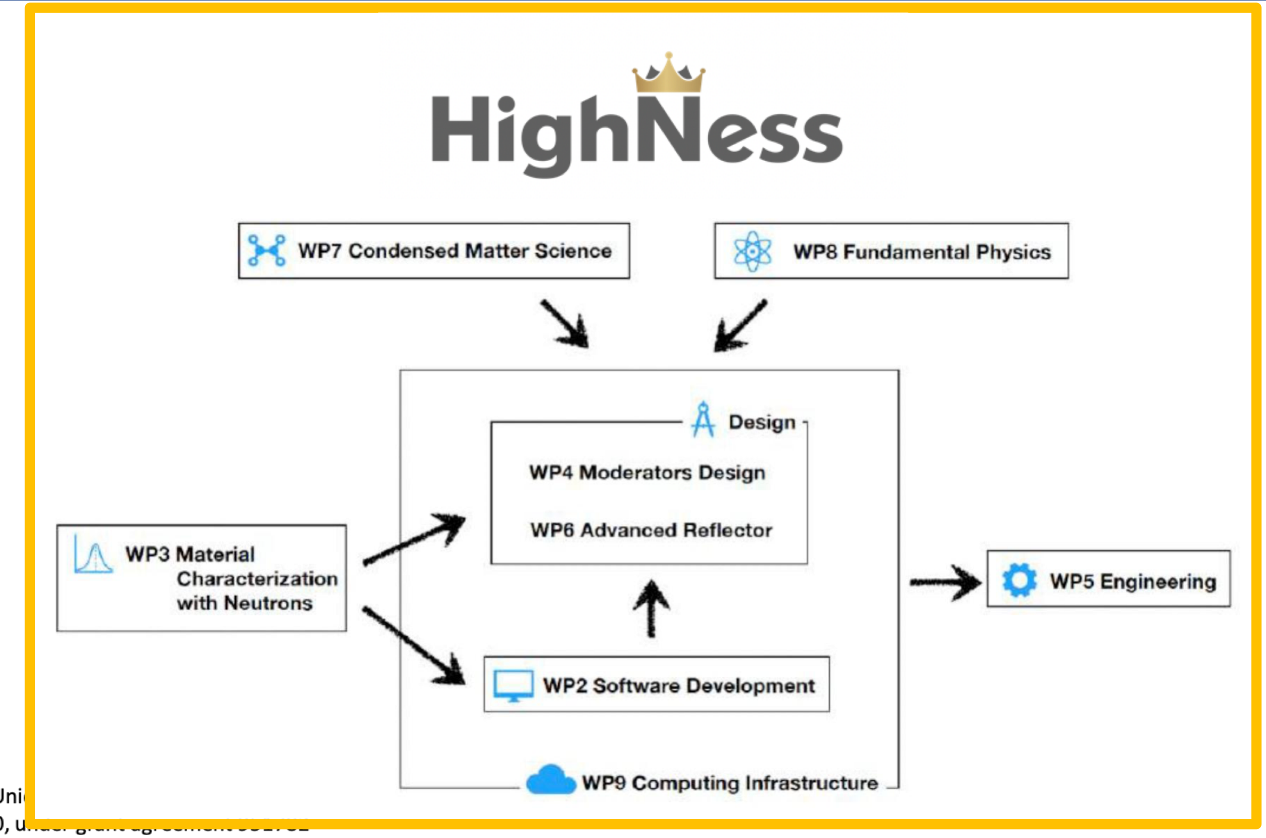


HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

The HighNESS project at ESS

The HighNESS project (3 MEURO funded by the European Commission) has as purpose the development of the new source that will be installed at ESS >2030
The new source will be composed by Liquid deuterium moderator that will serve a UCN moderator and a VCN source using advanced reflectors. **<u>The new source will be designed to be optimal for NNBAR</u>**
In the project will be also developed the associated experiments including NNBAR **-> Conceptual Design Report expected by the end of 2023**

8 EU Institutes,
7 countries,
34 people presently involved



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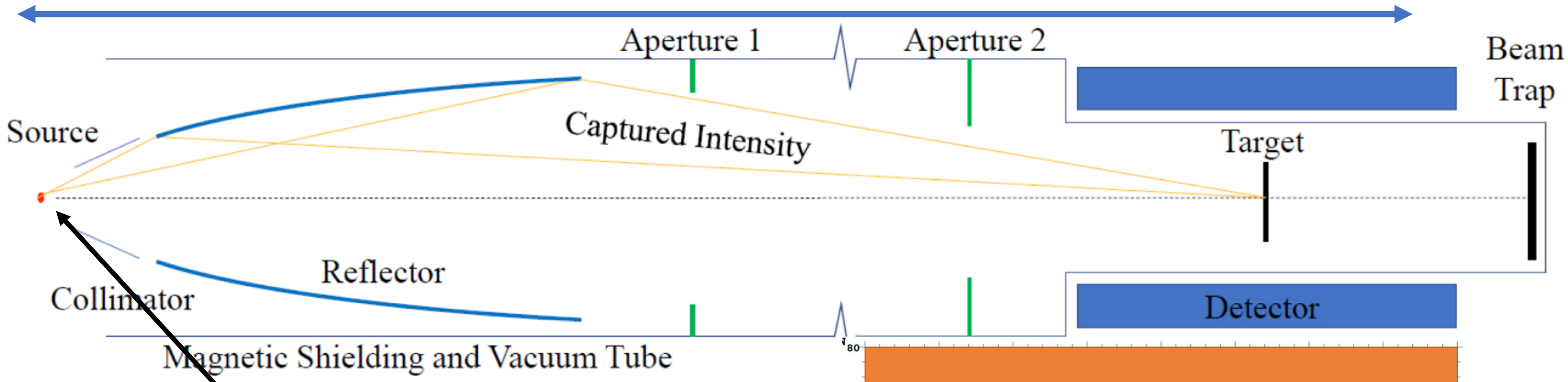
Research and Innovation Horizon 2020, u...

Schematic of the NNBAR experiment

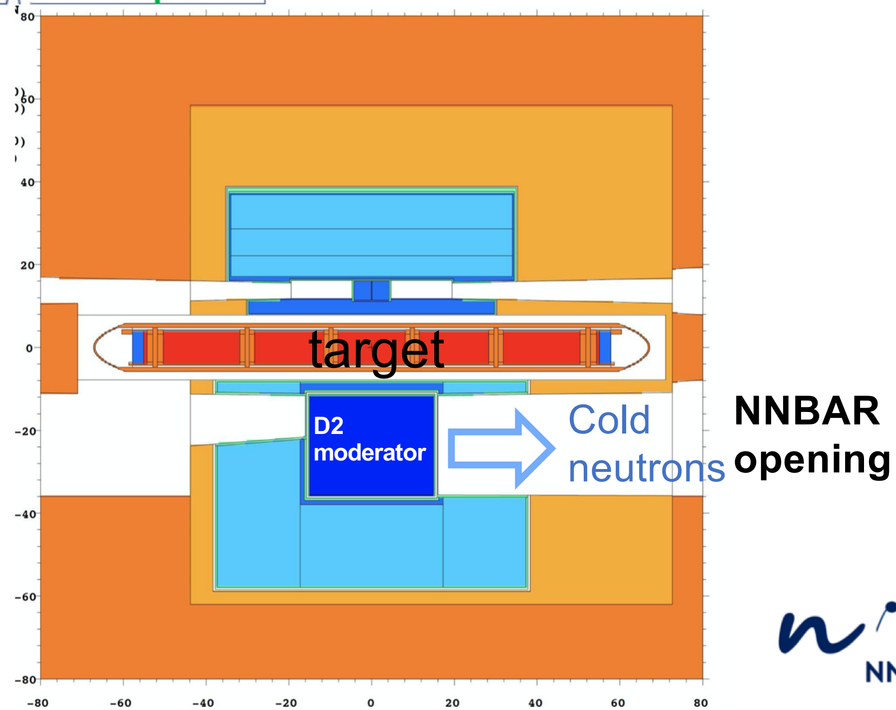


To design the optimal experiment you need to take into account several different aspects:

Source (Moderator):

It determines the number of cold neutrons emitted by the source

Work-on going at ESS+ collaborators to design the ideal source for NNBAR



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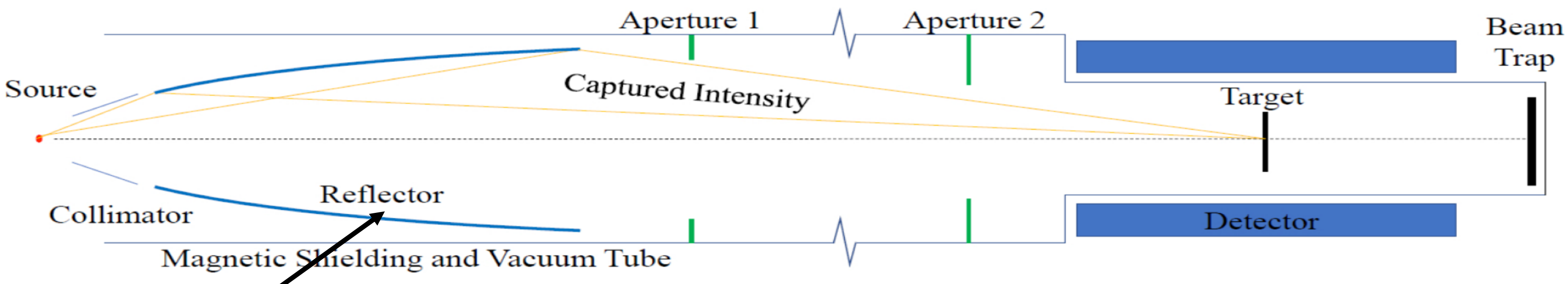
The NNBAR experiment (schematic)

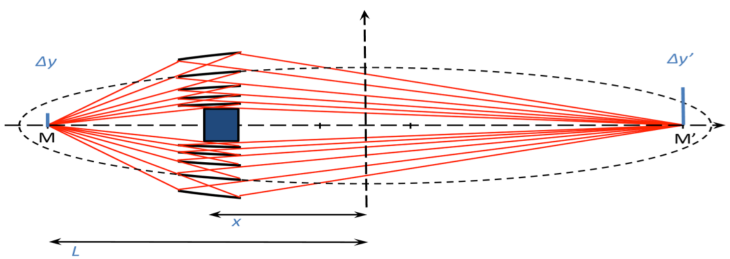


Reflector :

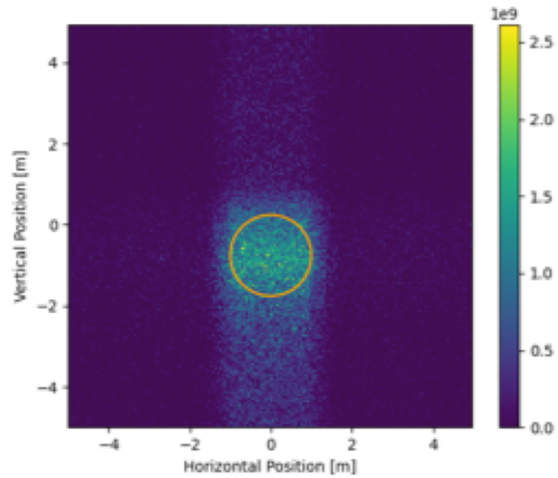
How many neutrons you collect, transport and focus in the experiment

Courtesy of Oliver Zimmer and Richard Wagner (ILL)

Design nested mirror systems of a single set of elliptic/short mirrors and of Wolter-optic types.



Optimization studies on-going at ILL +collaborators Circle of radius 1m at maximum (⇒ detector placed at optimal position)



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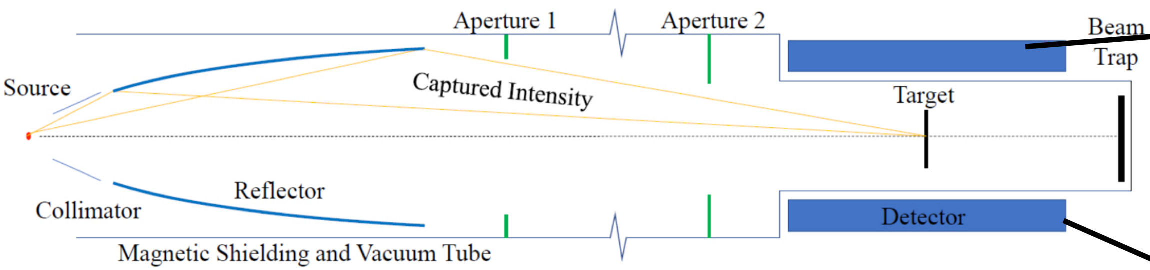
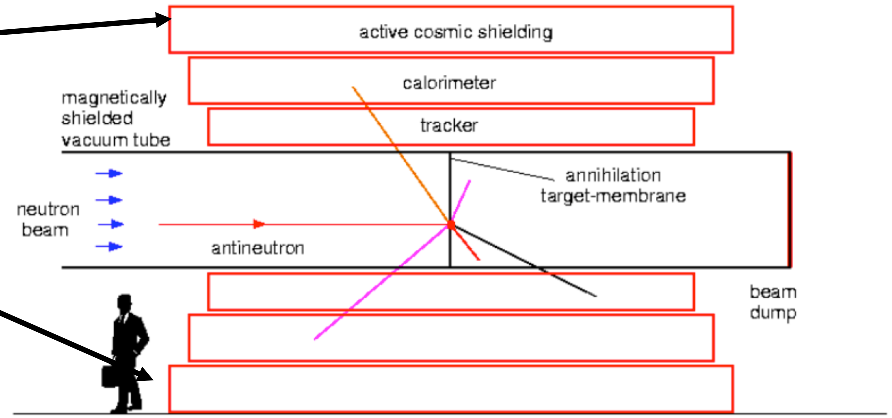
Propagation and annihilation detector





Residual B field <10 nT
Residual vacuum < 10^{-5} P

Work on-going to design the magnetic shielding system and the vacuum pipe

Detector :

- At the end of the beamline the neutron beam will hit a thin carbon foil target
- If the neutron has converted to antineutron it will annihilate in the carbon foil
- The carbon has large $\bar{n}$ annihilation cross section
  ~5 pions produced in annihilation
- Detector design on-going (TPC for tracker, scintillator+lead-glass for calorimeter +cosmic shield)

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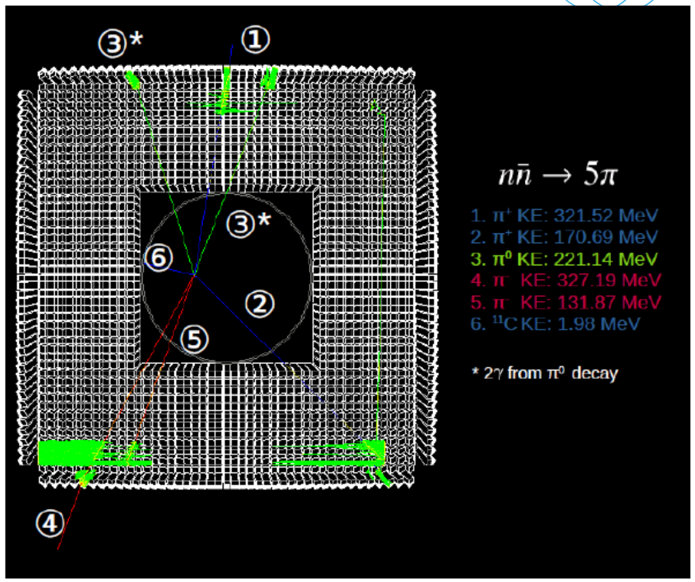
NNBAR Annihilation detector

Design and optimization of the NNBAR detector on going



y direction

Time Projection Chamber

80% Ar + 20% CO_2
Two different dimensions (x-y)
- 0.85 m x 1.87 m
- 2.04 m x 0.85 m

2m long (z direction)

Scintillator Modules

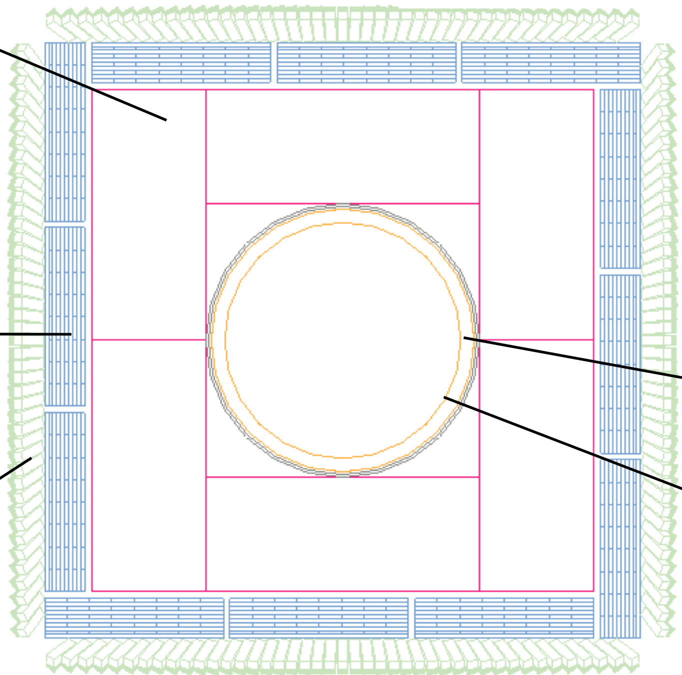
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

Consecutive layers are perpendicular

Lead Glass Blocks

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



Silicon Trackers

Layer 1:	Layer 2:
Inner radius = 87.97 cm	Inner radius = 97.97 cm
Thickness = 0.03 cm	Thickness = 0.03 cm
Length = 6 m	Length = 6 m

Vacuum tube

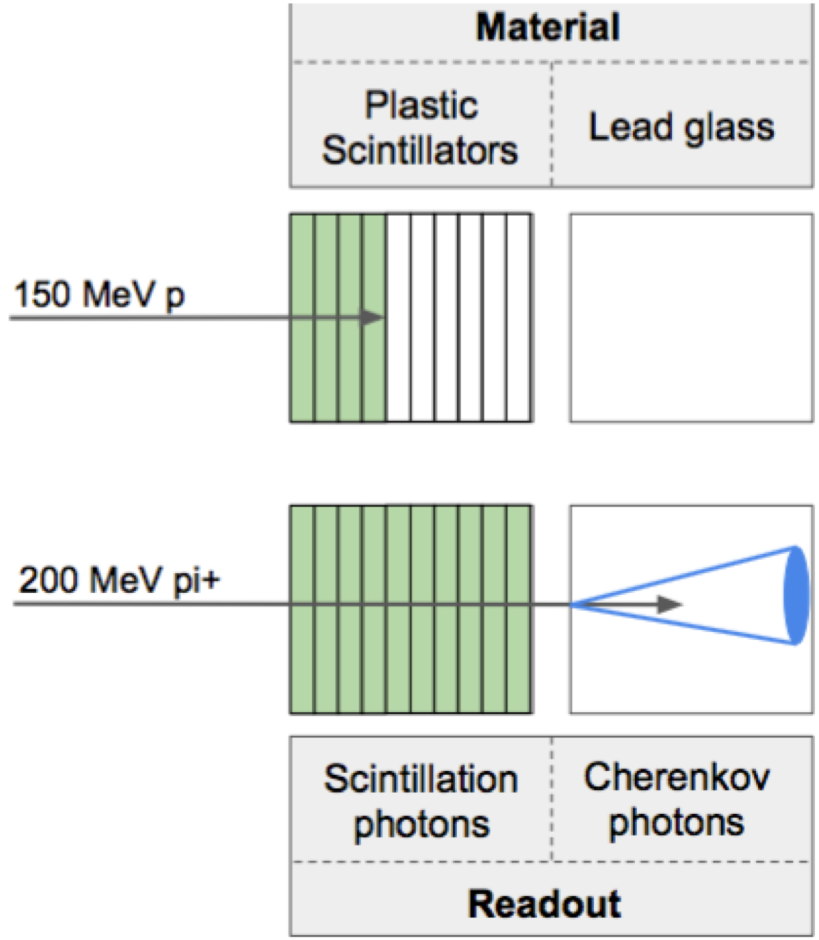
1 m inner radius
2 cm thick
6 m long (z direction)

A computing and Detector Simulations framework for the HIBEAM/NNBAR Experimental program at the ESS EPJ Web of Conferences 251, 02062 (2021)

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

NNBAR prototype Calorimeter

- Work on-going at Stockholm University + collaborators
- Hybrid hadronic range detector + EM calo
- Binary readout (hit/not hit) of staves+ Cherenkov light from lead glass
- Measurement inform simulations of full detector
- Next year Low energy hadrons/electrons
  - PSI : protons 74--230 MeV
  - INFN : electrons 25--500 MeV
- Ultimately to be deployed at ESS test beam to validate in situ background



The HIBEAM/NNBAR Calorimeter prototype arxiv 2107.02147

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Summary of neutrons oscillations searches at HIBEAM and NNBAR

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

$$\mathcal{H} = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}} \end{pmatrix}, \quad \mathcal{H} = \begin{pmatrix} E_n & \alpha_{nn'} \\ \alpha_{nn'} & E_{n'} \end{pmatrix}, \quad \ldots\ldots \quad + \text{nTMM terms}$$

Channel		Mixing terms	Experimental conditions
$n \to \bar{n}$	"Classic" nnbar	$\varepsilon_{n\bar{n}}$	Field-free
$n \to [\bar{n}', n'] \to \bar{n}$	Nnbar via sterile neutrons	$\alpha_{nn'} \alpha_{n\bar{n}'}$	Scan *B*-field
$n \to \bar{n}', n'$	Disappearance	$\alpha_{nn'} \alpha_{n\bar{n}'}$	Scan *B*-field
$n \to n', \bar{n}' \to n$	Regeneration	$\alpha_{nn'} \alpha_{nn'} + \alpha_{n\bar{n}'} \alpha_{n\bar{n}'}$	Scan *B*-field

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 *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501**

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Improve by 10^3

- Baryon Number Violation at the core of our existence

  Physics of Baryon Number Violation of utmost importance

- Standard Model tells us about interactions

  But *nothing* about nature of quarks and leptons

  Our existence, Grand Unification our best hints

- Baryon Number Violation excellent probe

  We *know* it exists

- **Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare**

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Conclusions

- Lots of activities are going on right now in the HIBEAM/NNBAR collaboration

- HighNESS project started in 2020:
  - **<u>Design of the optimal moderator for NNBAR</u>**
  - **<u>CDR of the NNBAR experiment</u>**

- Prototype development and construction on-going

- VR Grant recently awared towards the HIBEAM TDR

- **HIBEAM > 2025 search for sterile neutron transitions**
- **NNBAR ~2030 search for neutron to antineutron oscillations x1000 improvement respect to the previous limit**

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HIBEAM/NNBAR collaboration

- Broad international base and supporters
  ~ 100 authors from 50 institutes in 8 countries
- Combines experts in neutronics, magnetics, nuclear and particle physics
- Leah Broussard, and Y. Kamyshkov Co-pi of ORNL mirror neutron program
- NNBAR Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (Stockholm Uni.) Lead scientist: Y. Kamyshkov (Tennessee Uni.) Technical coordinator: V. Santoro (ESS)
- White paper: A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501
- CDR in 2023 as part of HighNESS program
- **Collaborators are welcome !!**

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 *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501

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BACK-UP SLIDES

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www.highness.eu
https://cordis.europa.eu/project/id/951782

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NNBar

Fundamental & Particle Physics @ ESS

There are also interesting neutrino searches in program
but I will not discuss today during the presentation

Standard Model of particle physics (SM)

Precision experiments

Beyond SM
New interactions

ESSnuSB
Discover and measure neutrino CPV

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

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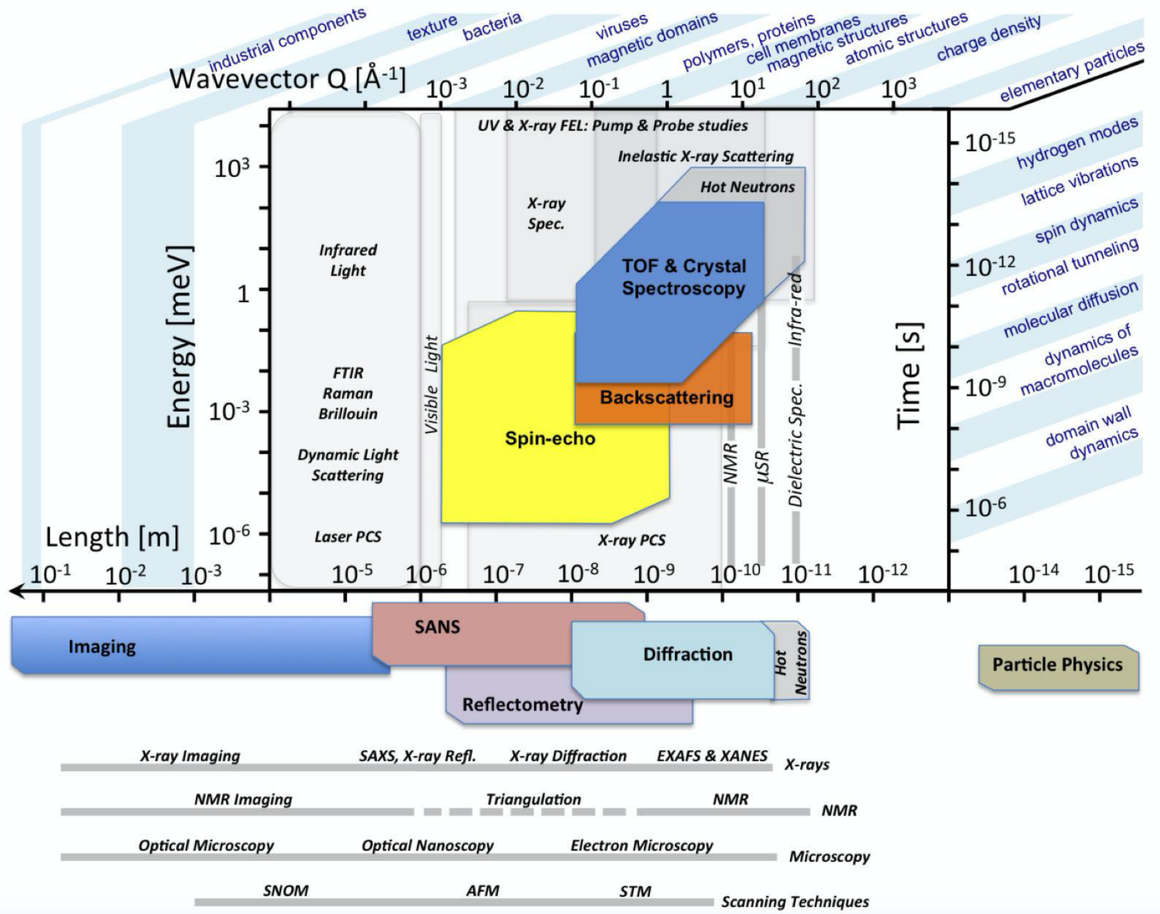
The European Spallation Source (II)



- Neutron scattering can be applied to a range of scientific questions, spanning the realms of physics, chemistry, geology, biology and medicine.
- In neutron scattering the neutron is used as a probe for revealing the structure and function of matter from the microscopic down to the atomic scale.

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Baryogenesis Models

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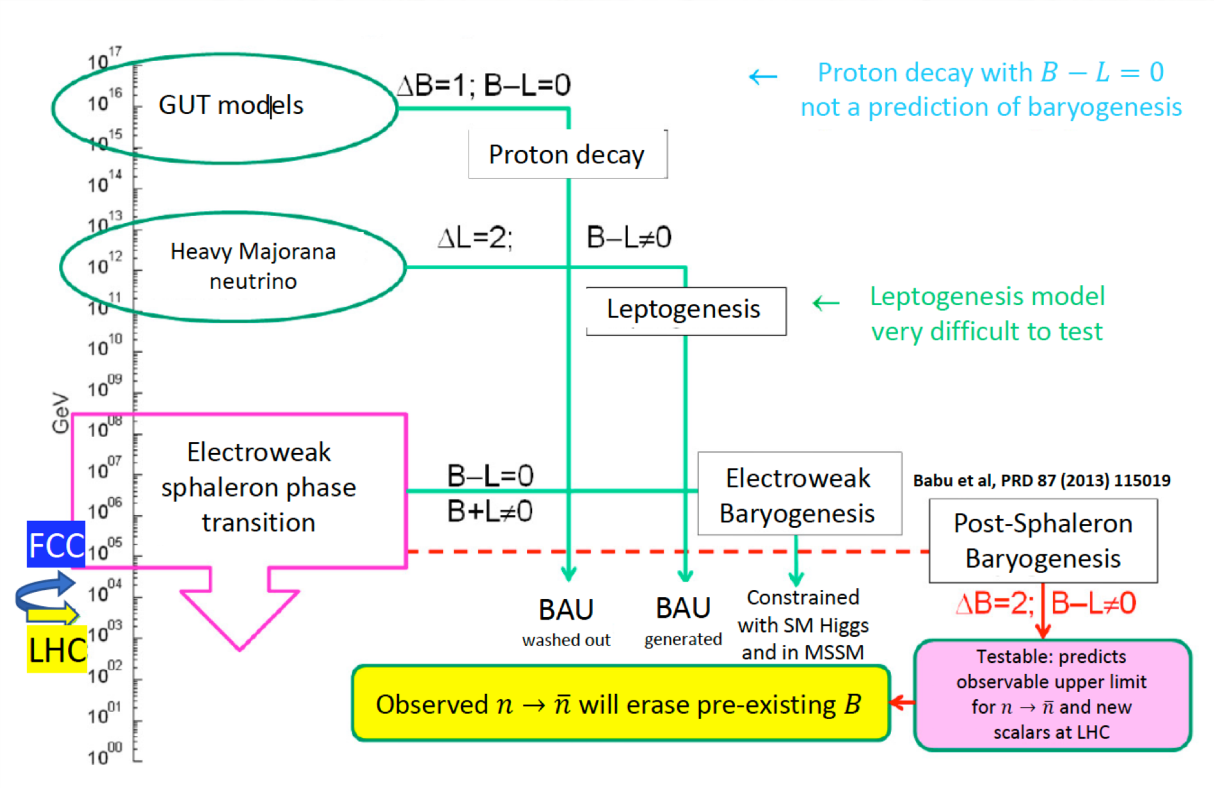
Regimes for baryogenesis

•Leptogenesis: Sphalerons convert L into B

•Electroweak baryogenesis:
T violation near EW scale creates B without L

•Post-sphaleron baryogenesis: New BNV process below EW phase transition

• $n \rightarrow \bar{n}$ targets accessible energy scales . Null result will restrict phase space of PSB models



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The Capability Gap Analysis

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- The scope of ESS, as defined in the ESS statutes, is to build and operate 22 world-leading instruments in an open user program. Of these, the first 15 will be brought on-line by the end of 2025.

- Regarding instruments 16-22 a document from ESS (The ESS Instrument Suite – A Capability Gap Analysis (https://europeanspallationsource.se/instruments/capability-gap-analysis) has analysed the capability gaps

- Result of this analysis has shown that one of the community that is not catered is the particle physics community. **Therefore filling this capability gap is given the highest priority.**

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DARK Matter

- What is the nature of dark matter?
- The fact that our astronomical observations are not sufficiently well described by the SM is unquestioned.
- The existence of a dark sector, interacting primarily gravitationally with our familiar visible sector, has long been postulated to explain astronomical data
- Such dark sector is assumed to have particles having interactions similar to our own SM interactions, sterile neutrinos and sterile baryons
- In principle, observable portals onto such a sector can occur ia mixing phenomena between any stable or meta-stable electrically neutral particles, allowing for conversion into a dark partner particle.

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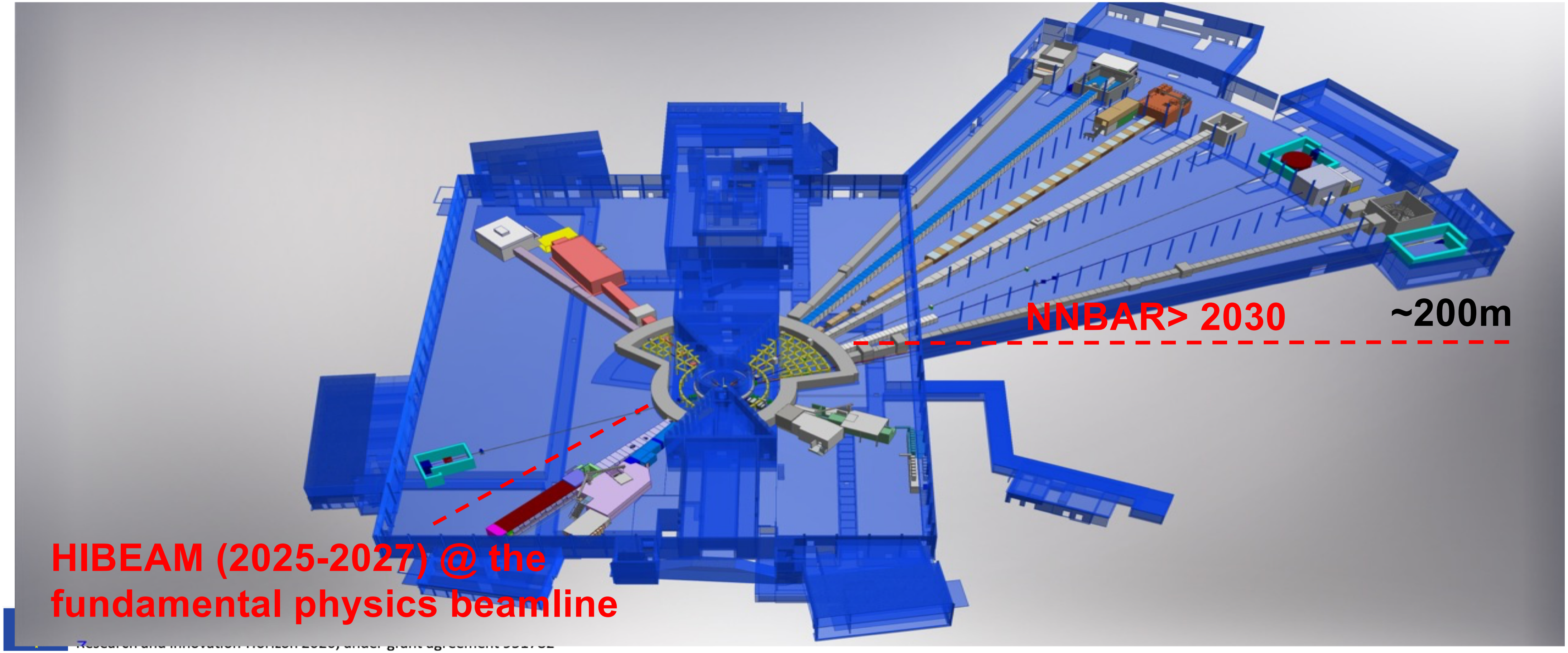
ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations

- HIBEAM: smaller program of complementary experiments (with focus on sterile neutron searches) ≳2025
- NNBAR: Beamline earliest available ≥ 2030



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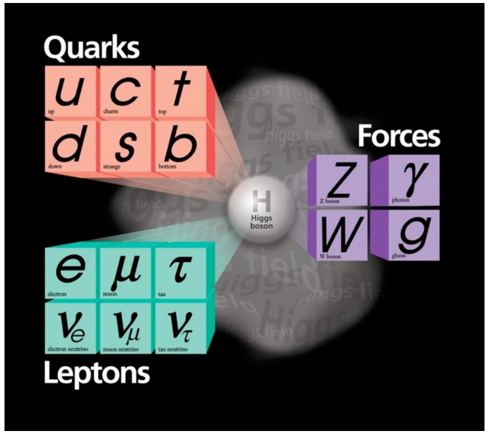
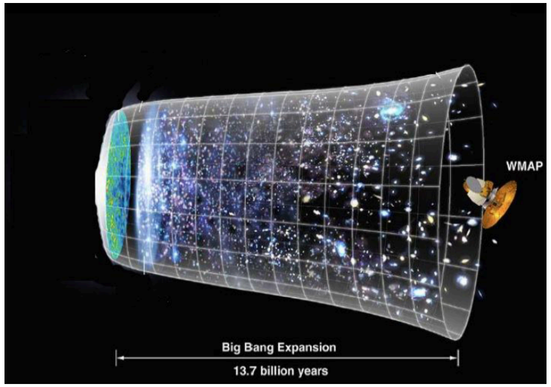
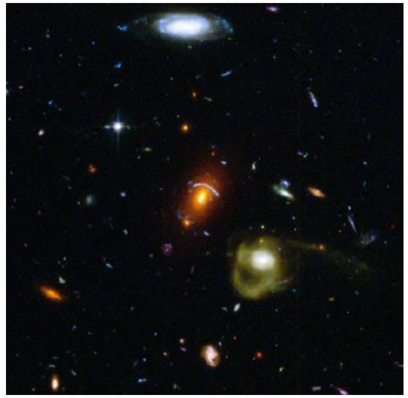
Standard Model + General Relativity = Universe ???







We are able only to account for 5% of the energy content of the universe

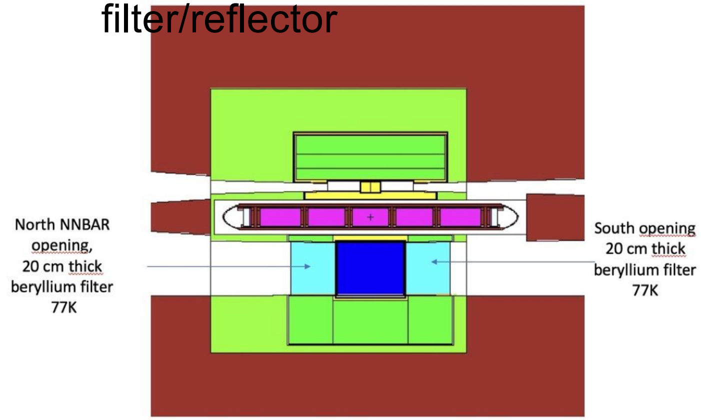
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Liquid deuterium moderator design on-going

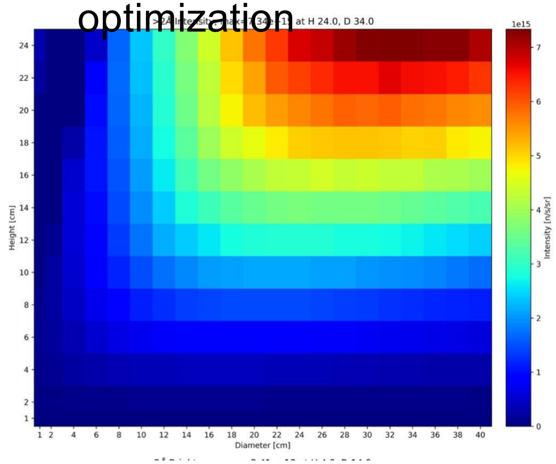
- Neutronic study of large D_2 moderator ongoing
  - Intensity variation with dimensions, number of beamlines, use of Be filter /reflector
- Additional works:
  - Design of nanodiamond reflector for cold and very cold neutrons (advanced reflector)
  - Design of UCN source
  - Prototype experiment will be performed at Budapest reactor

opening optimization

Use of Be filter/reflector



size optimization



Luca Zanini
Alan Takibayev and many others

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HighNess

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- Two stage experiment
- HIBEAM (>2025)
  - High precision (x10 improvement): $n \rightarrow \bar{n}', n'$ (disappearence) ; $n \rightarrow [\bar{n}', n'] \rightarrow n$ (regeneration) ; $n \rightarrow [\bar{n}', n'] \rightarrow \bar{n}$ (nnbar via sterile neutrons)
  - Possibility to match earlier sensitivity from 1990's ILL experiment: $n \rightarrow \bar{n}$ and perform new search $n \rightarrow [\bar{n}', n'] \rightarrow \bar{n}$
  - ANNI cold neutron beamline
- NNBAR (>2030)
  - $\sim 10^3$ improvement in sensitivity: $n \rightarrow \bar{n}$
  - Large Beam Port

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

NNBar

Theoretical motivation

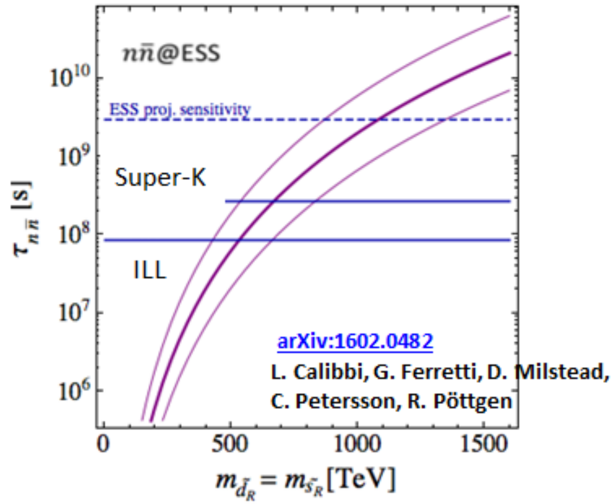
- Baryon number is expected to be violated: Sakharov condition for baryogenesis
- Accidental symmetry in the SM

$n \rightarrow \bar{n}$

- Baryogenesis (eg post-sphaleron baryogenesis)
- RPV-SUSY, LR symmetric models, Extra dimensions …

$n \rightarrow \bar{n}', n'$

- Co-genesis (baryogenesis and dark matter)
- Generic dark sector
- Mirror matter
- Can potentially solve ”beam” vs ”bottle” neutron lifetime anomaly
- Much theoretical work (Z. Berezhiani : INFN, Uni. of L'aquila)



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