High precision searches for baryon number violation via neutron conversions at the European Spallation Source

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ESS European Spallation Source
Lund University
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

ICHEP 2022, International Conference on High Energy Physics, Bologna (Italy)

HighNess

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1. The European Spallation Source and the ESS fundamental physics program
2. The HIBEAM program at the ESS
3. The NNBAR experiment at the ESS

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The European Spallation Source

- The European Spallation Source is a neutron scattering facility under construction in Lund, in southern Sweden

CONSTRUCTION START	COMPLETION STATUS	PERSONNEL	NATIONALITIES	IN-KIND PARTNERS	USER PROGRAMME BEGINS
2014	83%	516	57	40	2027

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- 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€$_{2013}$

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- 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

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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 particle physics research with neutrons

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Precision experiments
Beyond SM
New interactions

High Intensity Baryon Extraction and Measurement (HIBEAM)

Neutron antineutron oscillation beamline (NNBAR)

Cold neutron beamline (ANNI)

UCN
Ultra Cold Neutron beamline

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Search for Dark Matter Baryon asymmetry of the Universe

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The HIBEAM and NNBAR program

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.**

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- The novel experiments presented in this talk will search for **free neutron oscillation processes** that are forbidden in the SM to address both these problems in a unique and innovative way.

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- The novel experiments presented in this talk will search for **free neutron oscillation processes** that are forbidden in the SM to address both these problems in a unique and innovative way.

We will search for:

- neutrons converting to sterile neutrons
- neutrons converting to anti-neutrons via sterile neutrons
- neutrons converting directing to anti-neutrons (NNBAR)

HIBEAM

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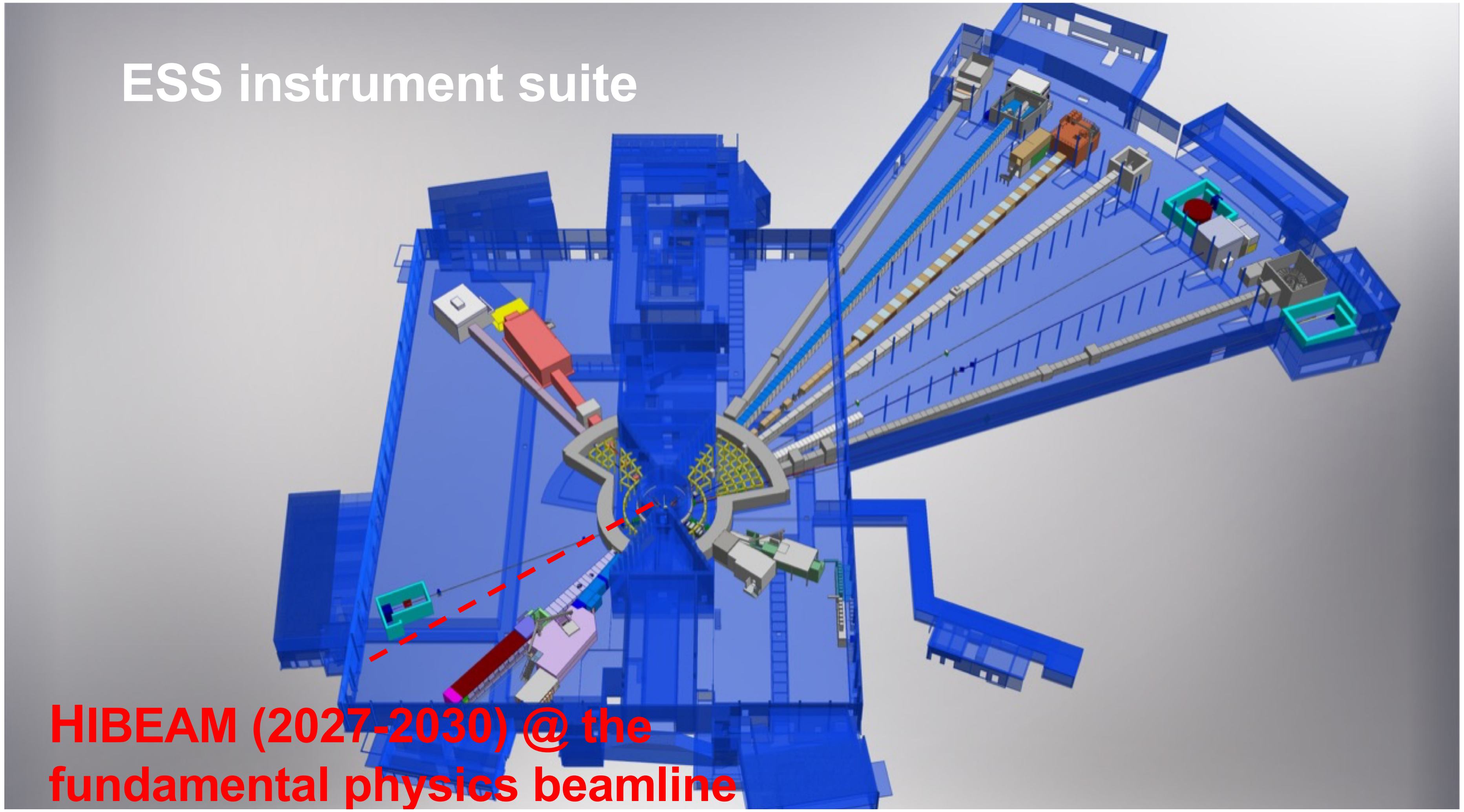
Future Free Neutron Oscillations Searches at the ESS



Two stage program:

- HIBEAM (≳2027): smaller program (with focus on sterile neutron searches)

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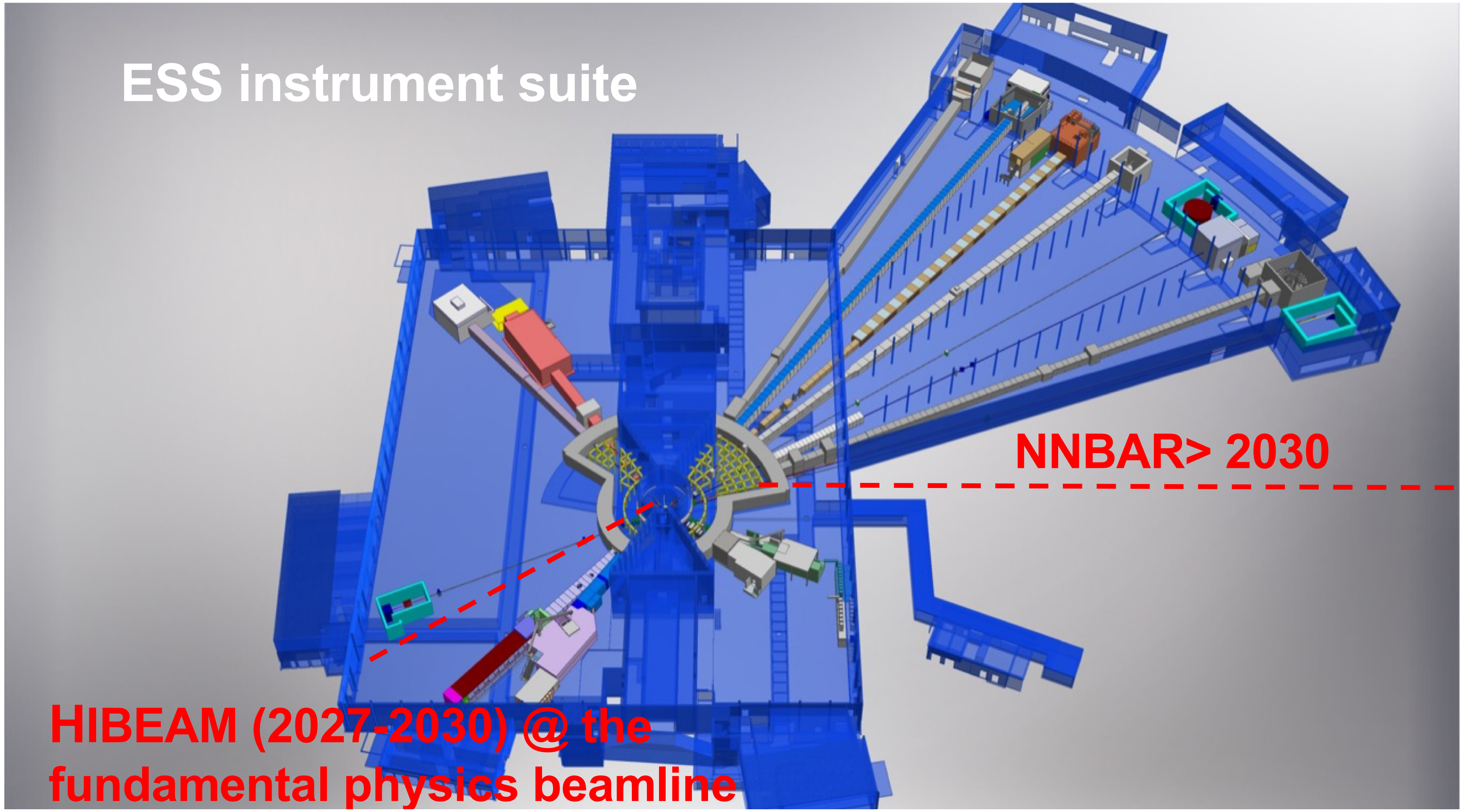

Two stage program:

- HIBEAM (≳2027): smaller program (with 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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Sterile Neutrons (I)

- As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector.

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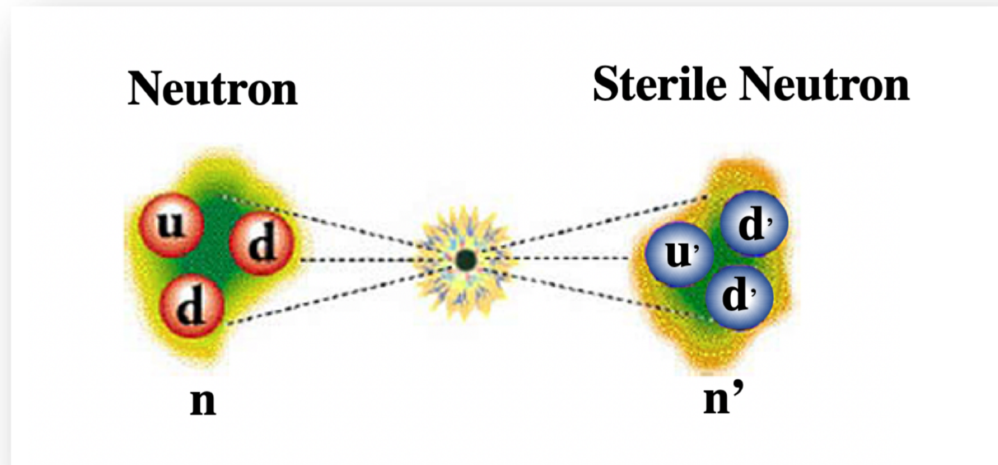
- As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector.

  - 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>**



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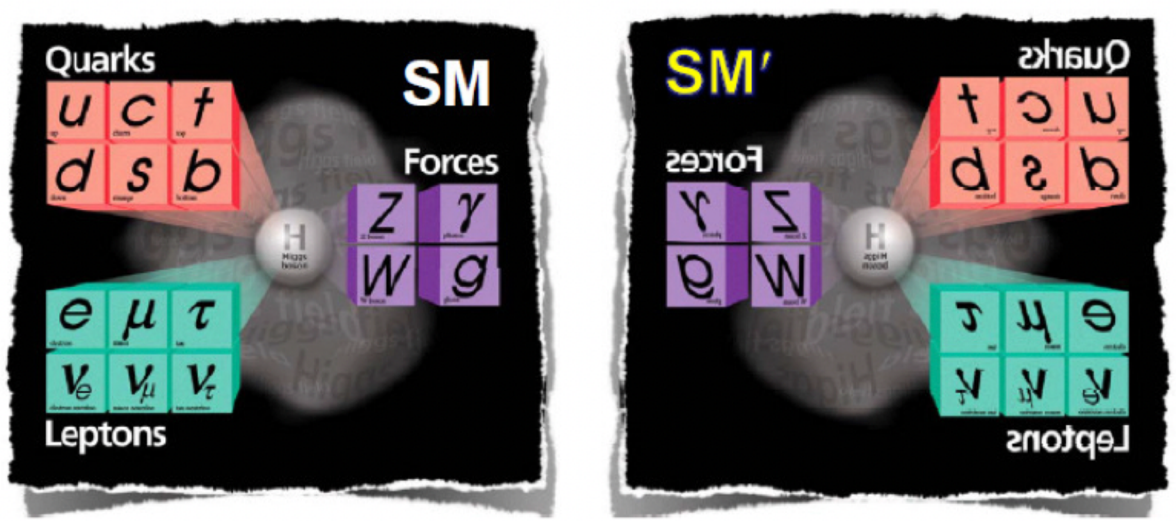
Sterile Neutrons (II)

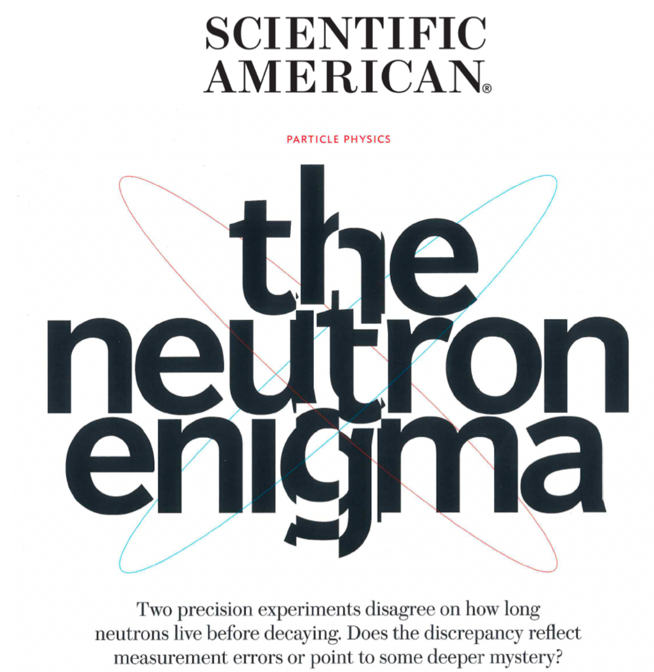
- One of the simplest examples of a hidden sector is the theory of mirror matter, a dark sector represented by a replica of the SM



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

- These transitions can also shed light on the anomaly between neutron lifetime in ”beam” and ”bottle”

F. E. Wietfeldt, “Measurement of Neutron Lifetime,” Atoms 6(4) (2018)



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Search for sterile neutron oscillations at HIBEAM

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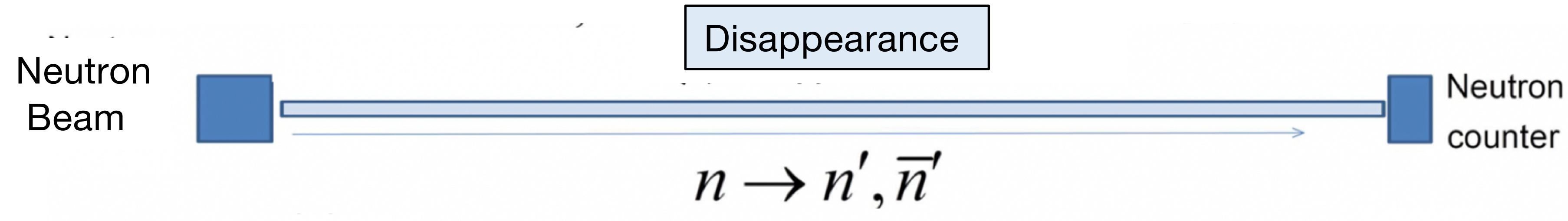

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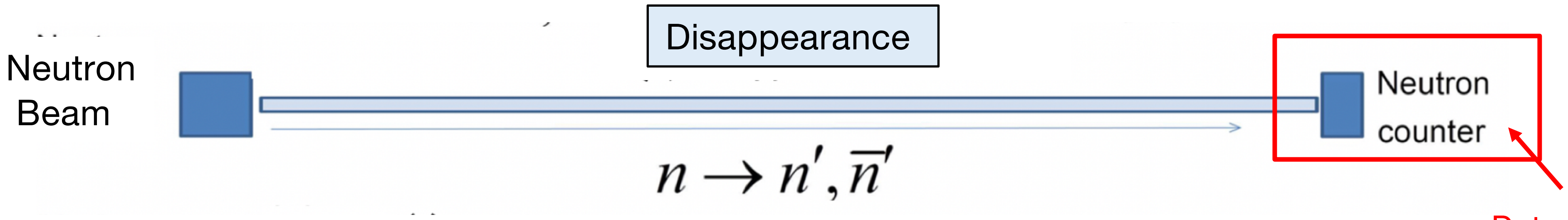

Detector able to reveal a loss of neutrons in an intense source

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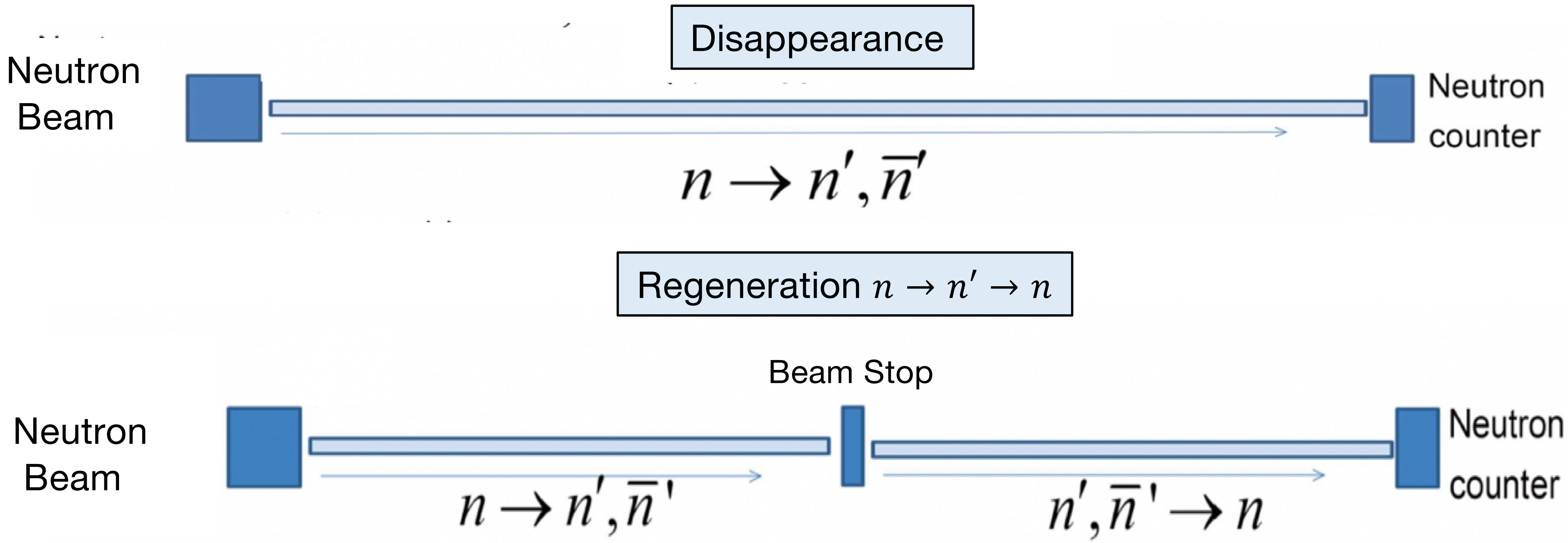

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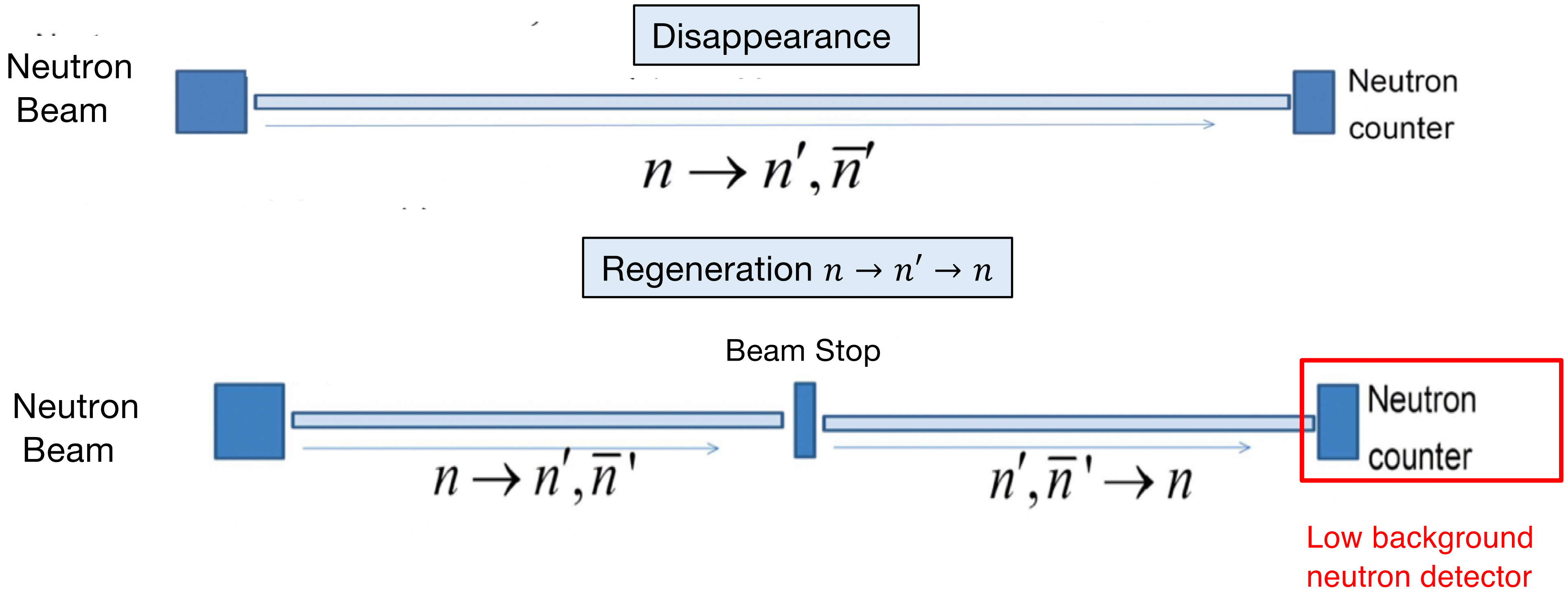

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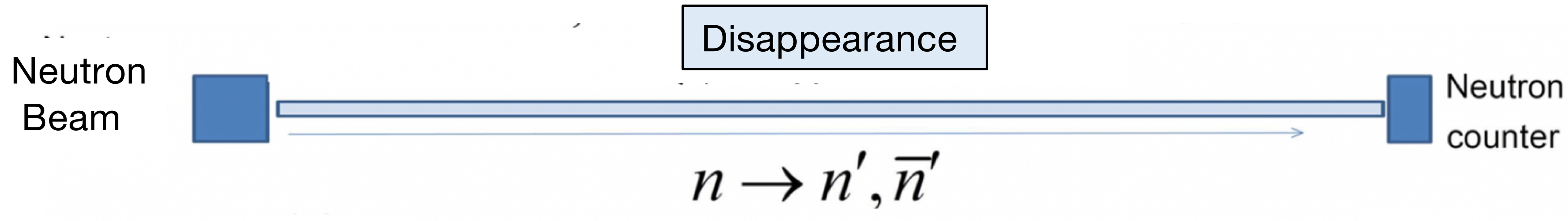

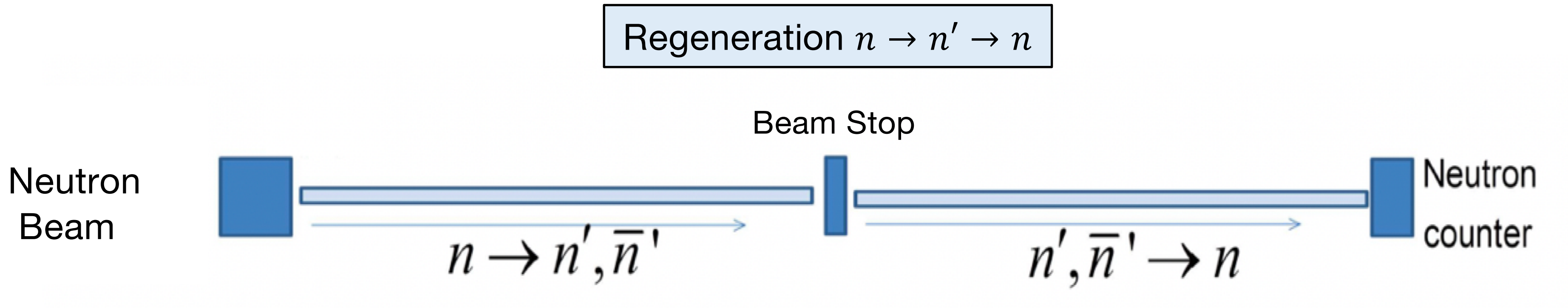

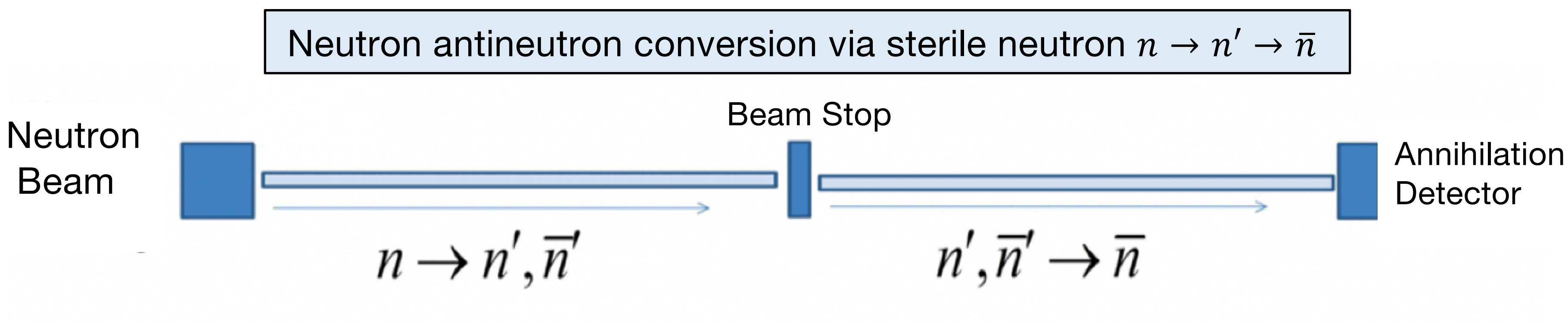

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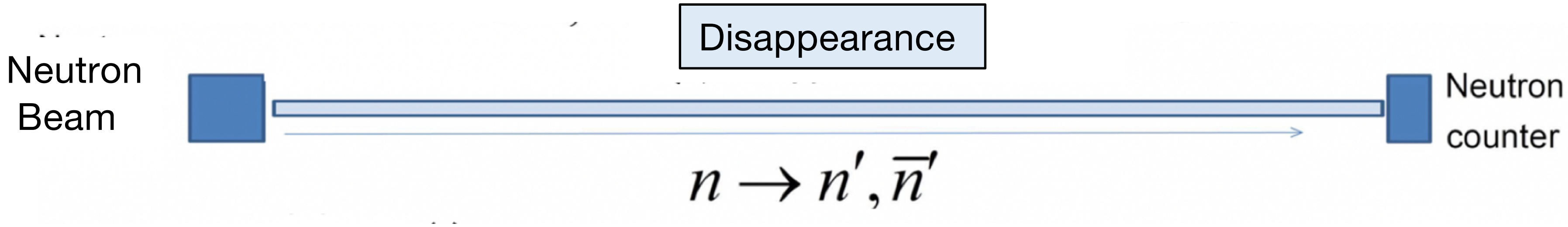
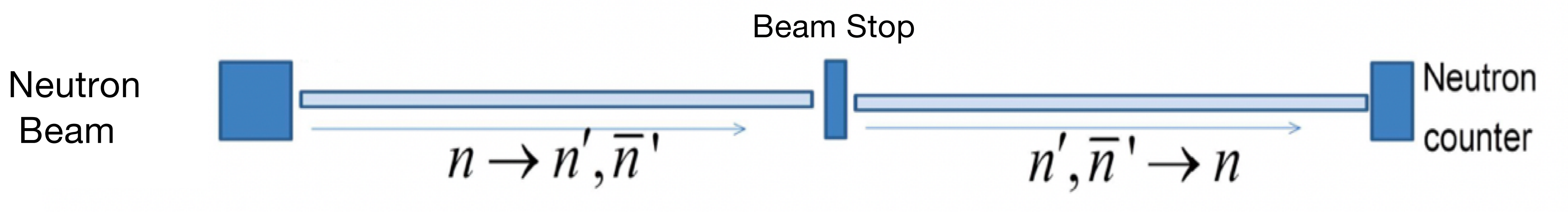
Search for sterile neutron oscillations at HIBEAM

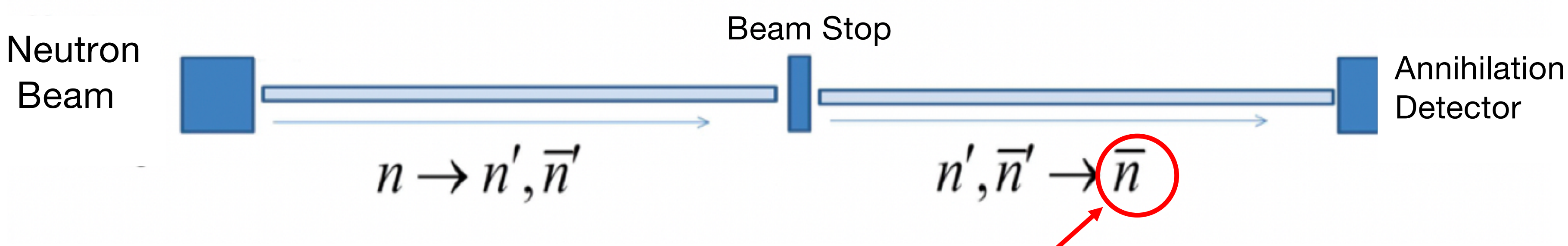
Disappearance



Regeneration $n \to n' \to n$



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



The final state is a anti neutron you need a detector able to reveal the signal due to the annihilation of the antineutron with the matter

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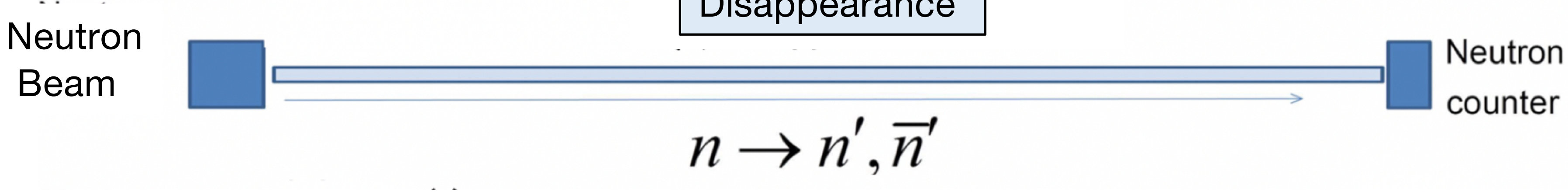
Search for sterile neutron oscillations at HIBEAM

Disappearance



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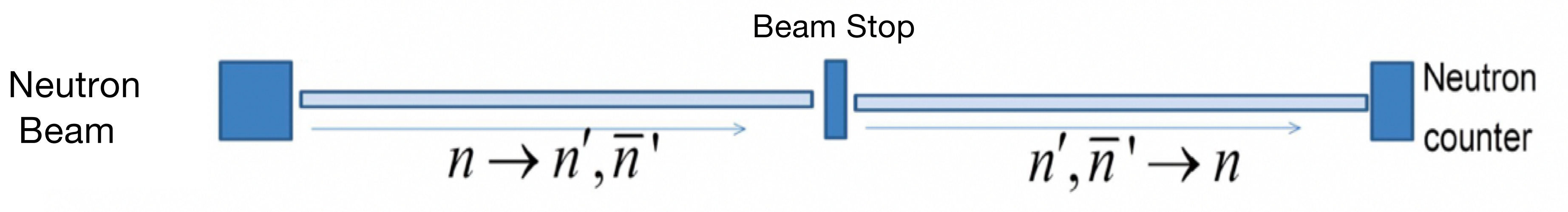

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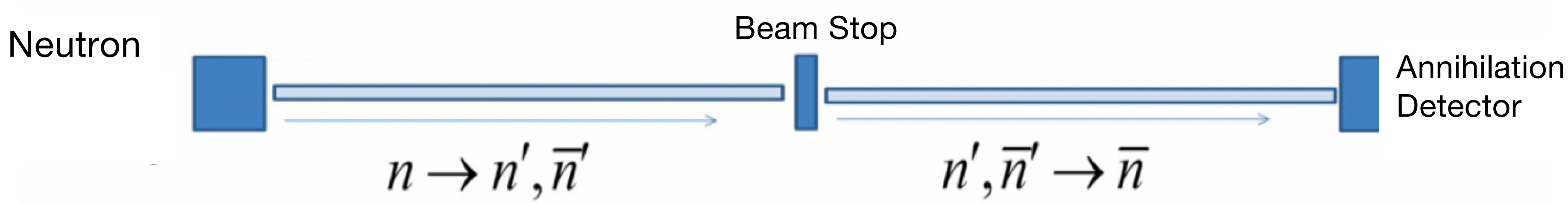

All experiments shown are dependent on the magnetic field. Experiments should scan through the magnetic field range ~ +/- 1 G to massively enhance the sensitivity of these processes

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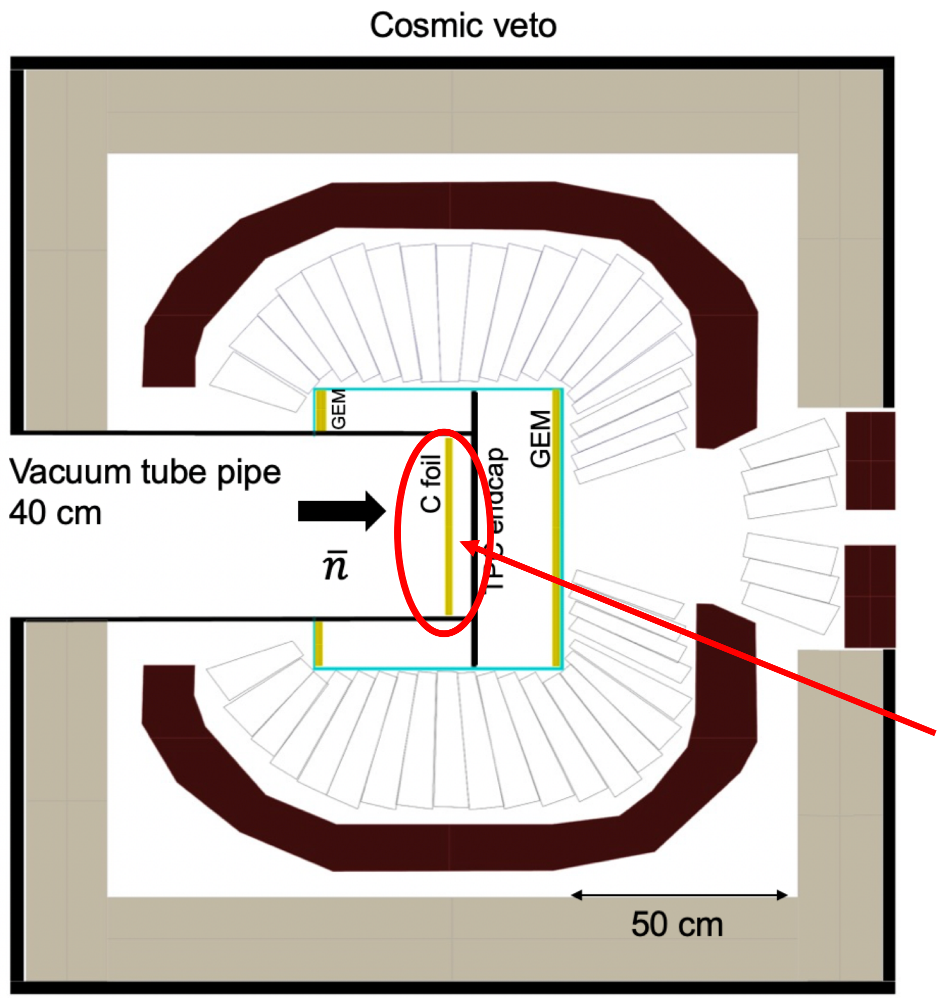
The annihilation detector

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)



Carbon foil were the annihilation takes place

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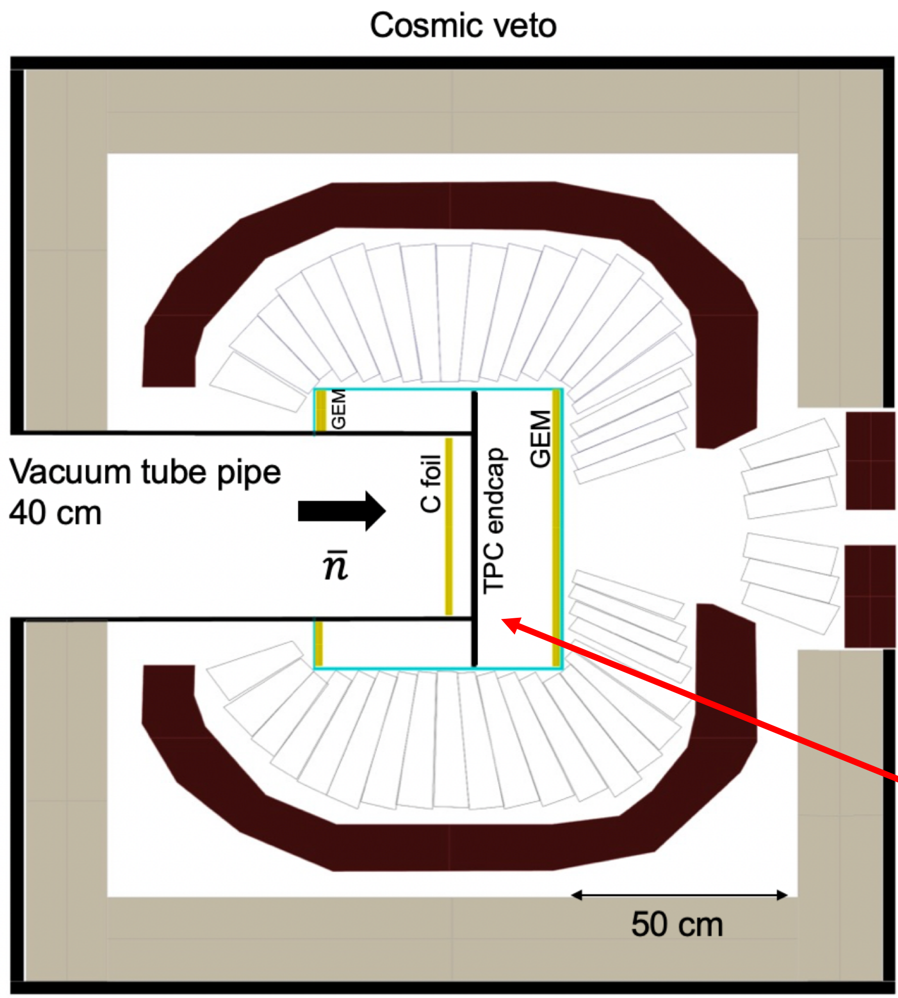

Time Projection Chamber for dE/dx vertexing

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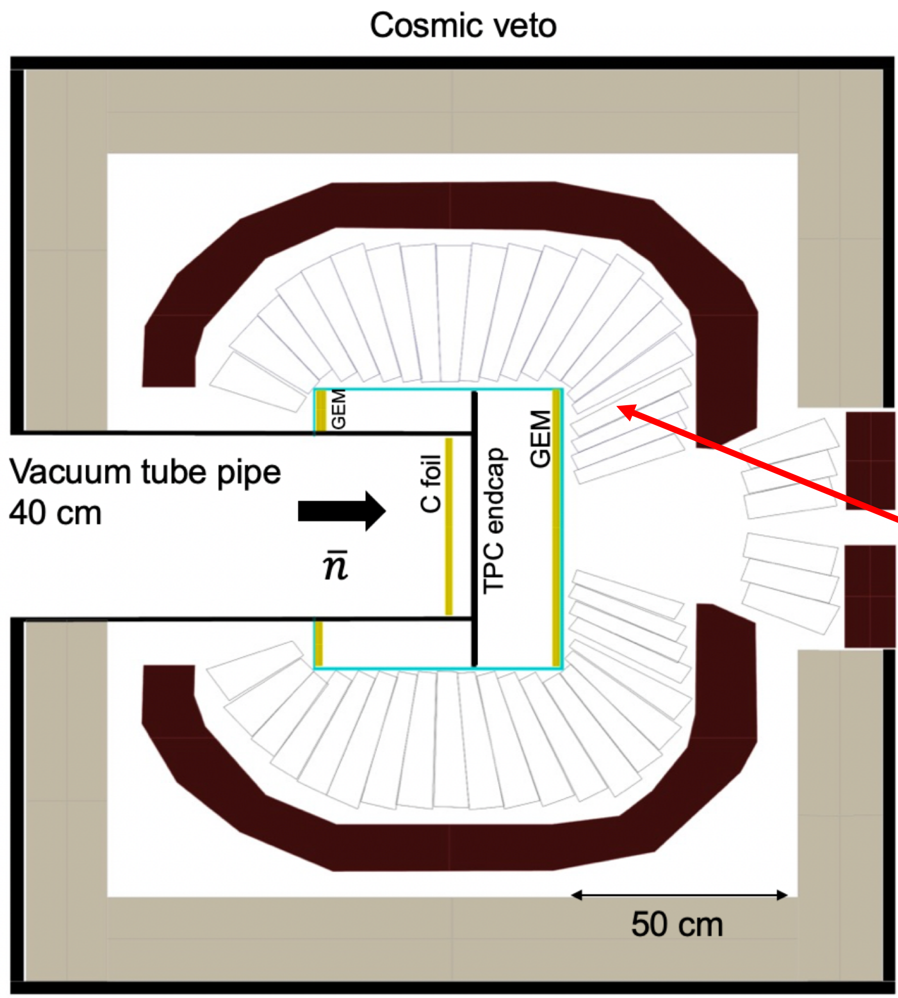

Electromagnetic Calorimeter: for the π^0 reconstruction and to measure the energy of the charged particles it will be also used as trigger of the experiment

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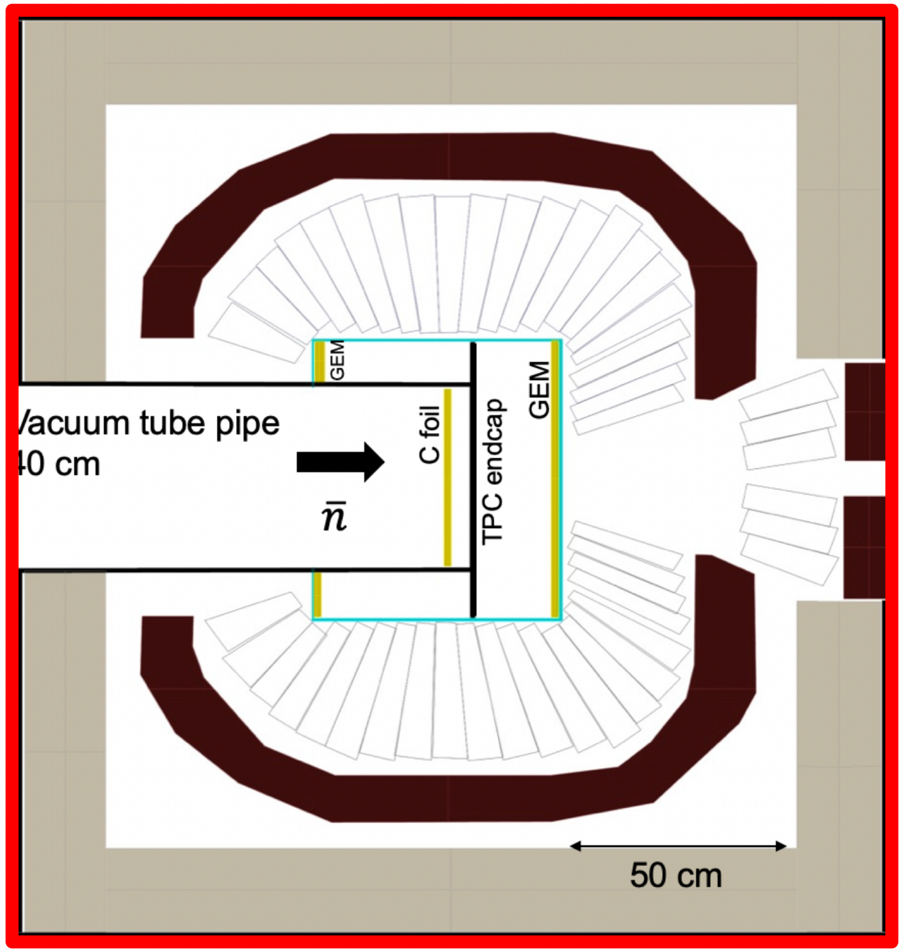
Cosmic veto



Cosmic veto

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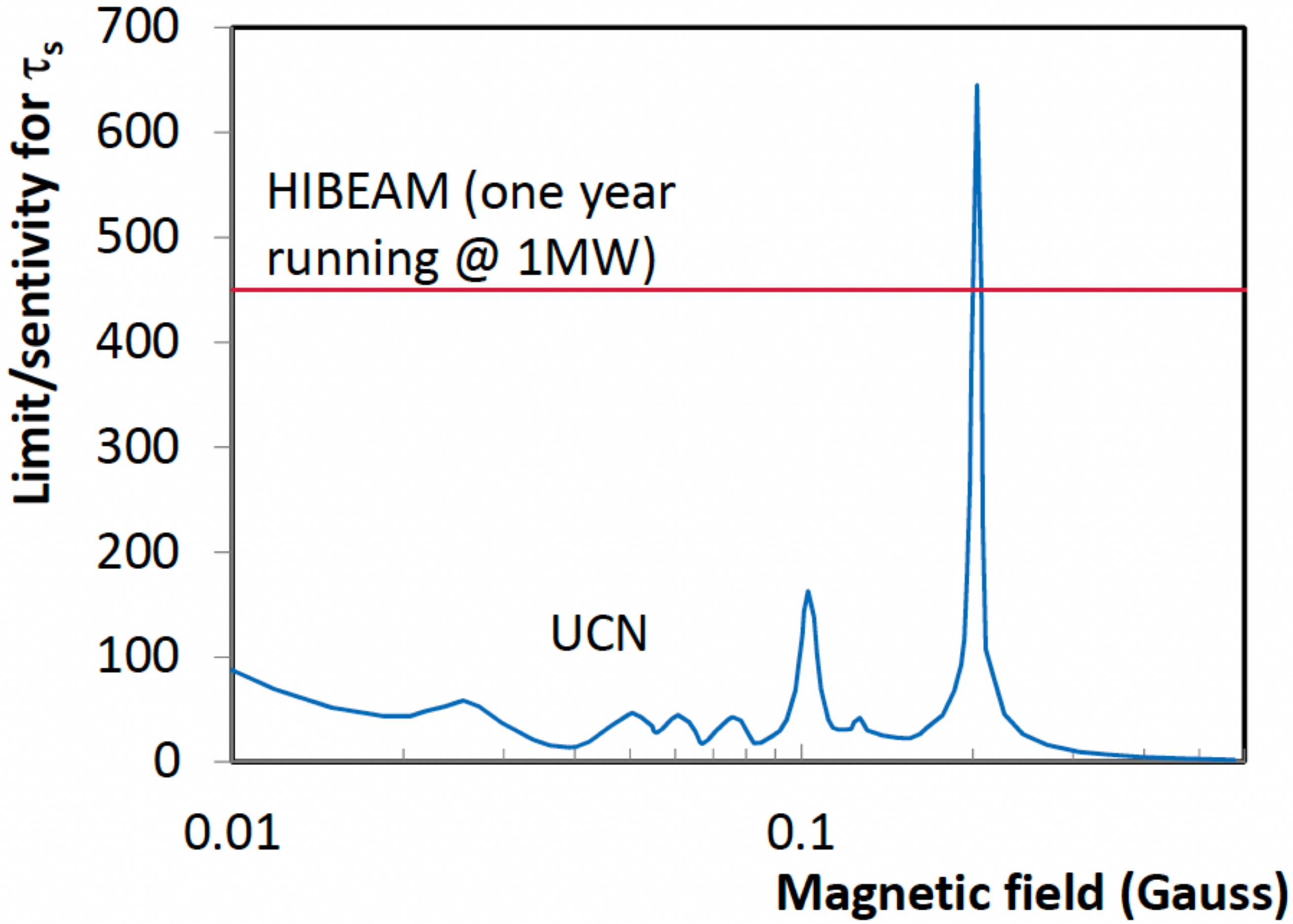
Sensitivity of the HIBEAM experiment



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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 with 1MEURO
- Background and detector studies are ongoing

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NNBar

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The NNBAR experiment @ ESS

- The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology

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- Observing a neutron converting in antineutrons would show that the baryon number is violated by 2 units and provide a clue to how the matter in our universe might have evolved from the B=0 early universe

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- Observing a neutron converting in antineutrons would show that the baryon number is violated by 2 units and provide a clue to how the matter in our universe might have evolved from the B=0 early universe
- NNBAR will have a sensitivity increase of 10^3 compared to previous experiments → **Opportunities for such a leap in sensitivity are rare**

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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Baryogenesis Models

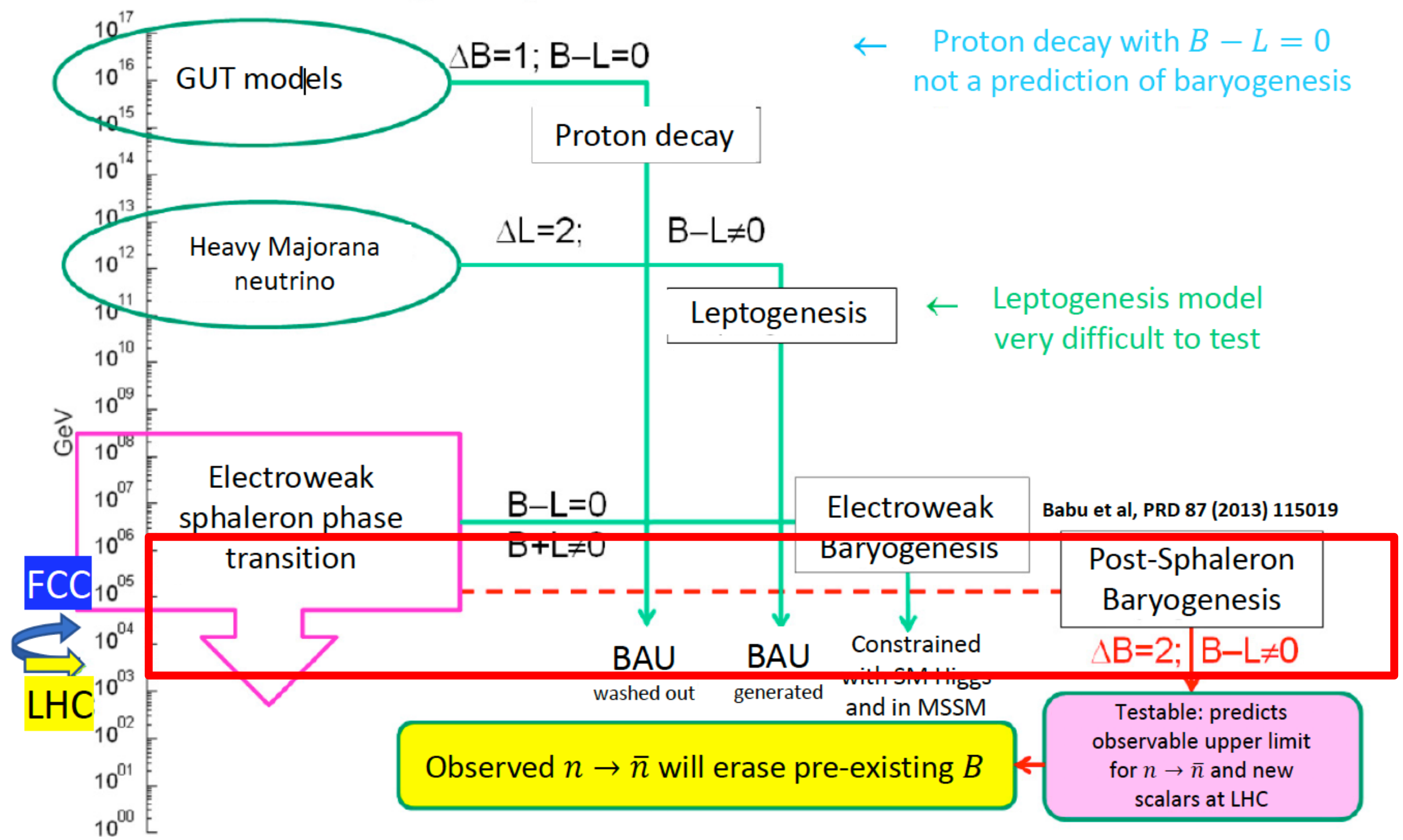
Regimes for baryogenesis

•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

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



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Phenomenology of neutron conversion processes

$$\mathbf{\Psi} = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Mixed $n, \bar{n}$ 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

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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)

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$\Delta E = E_n - E_{\bar{n}}$ and τ_n (mean life time of the free neutron)

Quasi free regime $|\Delta E| t \ll 1$ can be realized in vacuum with very low magnetic shield. Under this condition

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

Figure of merit (background-free): Nt^2
N= number of neutron
t = the neutron flight time

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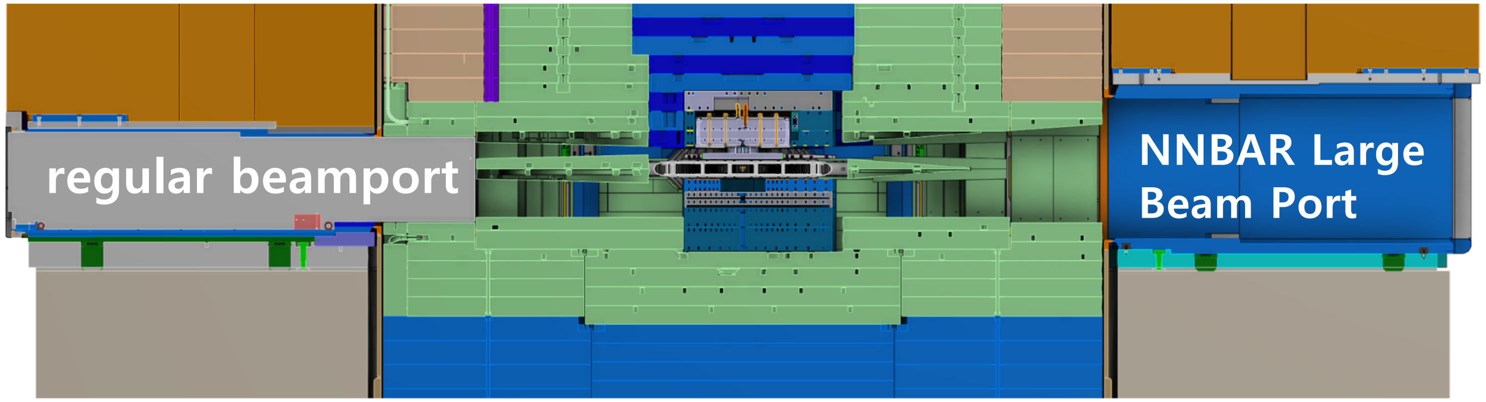
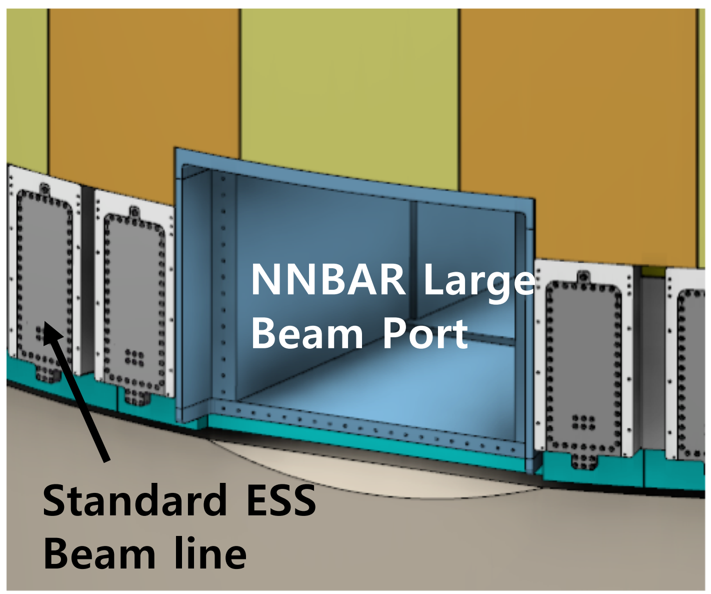
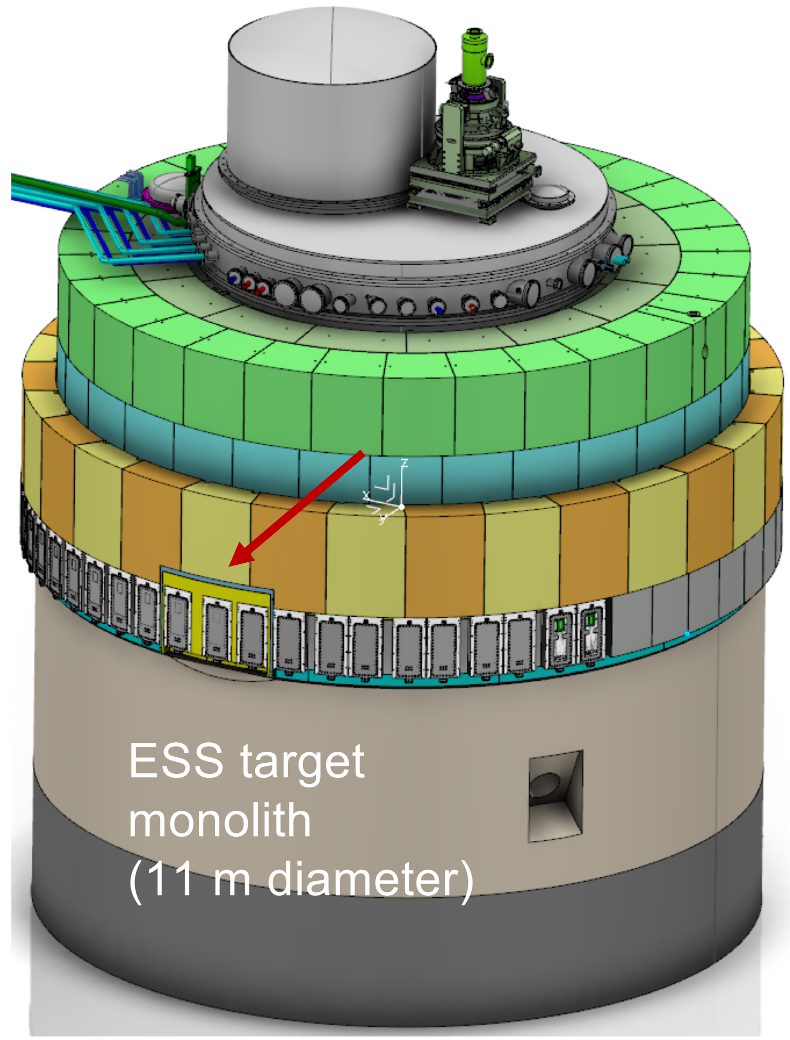
Why NNBAR at ESS?

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







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The Large Beam Port.

- LBP has been constructed and will provide sufficient intensity for $n \rightarrow \bar{n}$ search
- NNBAR figure of merit **Nt^2 (N= number of neutron t is the flight time)**
- Large Beam Port will allow to extract the larges possible number of neutrons (N) available in any facility world wide

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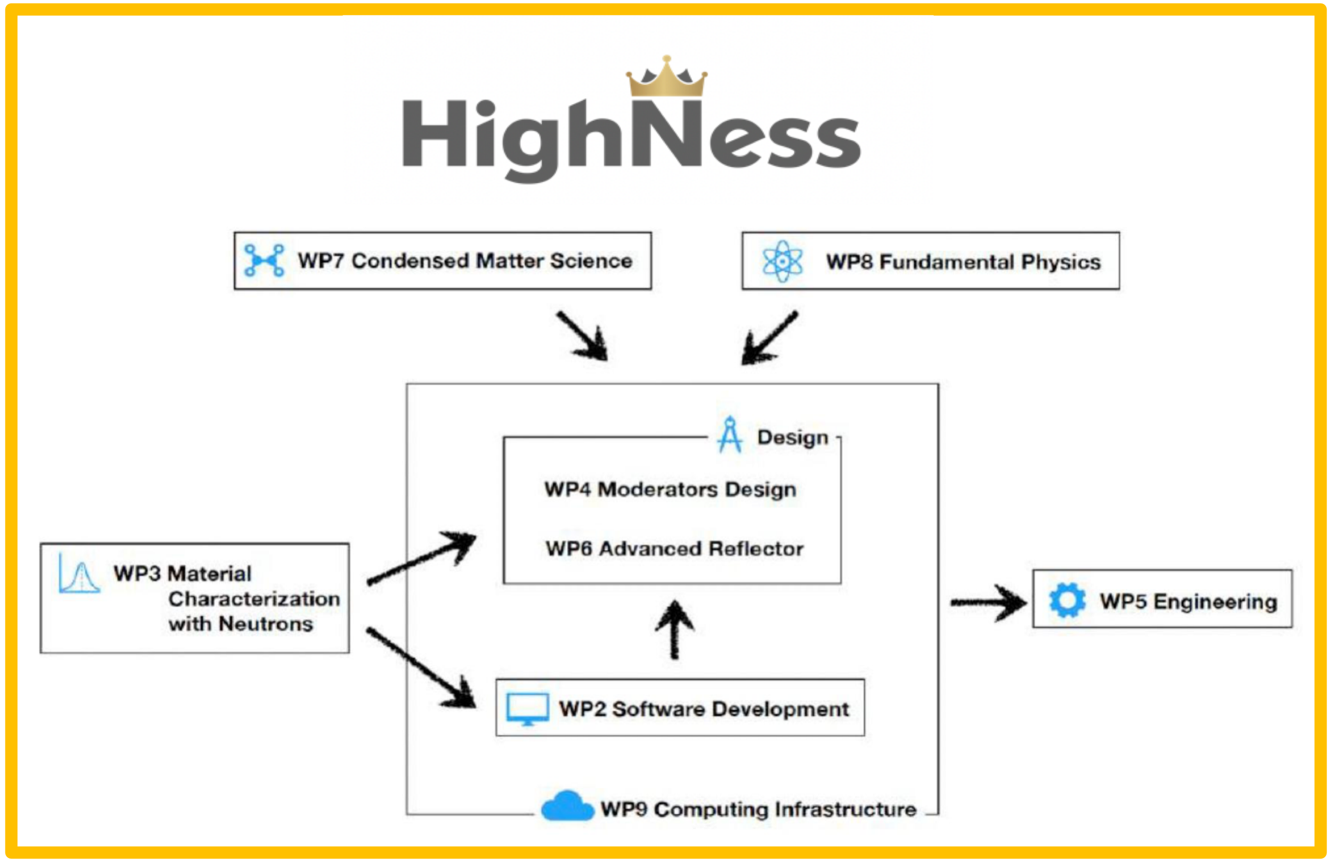
The HighNESS project at ESS

The HighNESS project (3 MEURO funded by the European Commission) which purpose is 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 optmized **<u>for the NNBAR experiment</u>**
In the project we are also developing the future ESS experiments including NNBAR **-> Conceptual Design Report expected by the end of 2023**

8 EU Institutes,
7 countries,
42 people presently involved



V. Santoro et al. "Development of a High Intensity Neutron Source at the European Spallation Source: The HighNESS project" arXiv: 2204.04051 [physics.ins-det] accepted for publication

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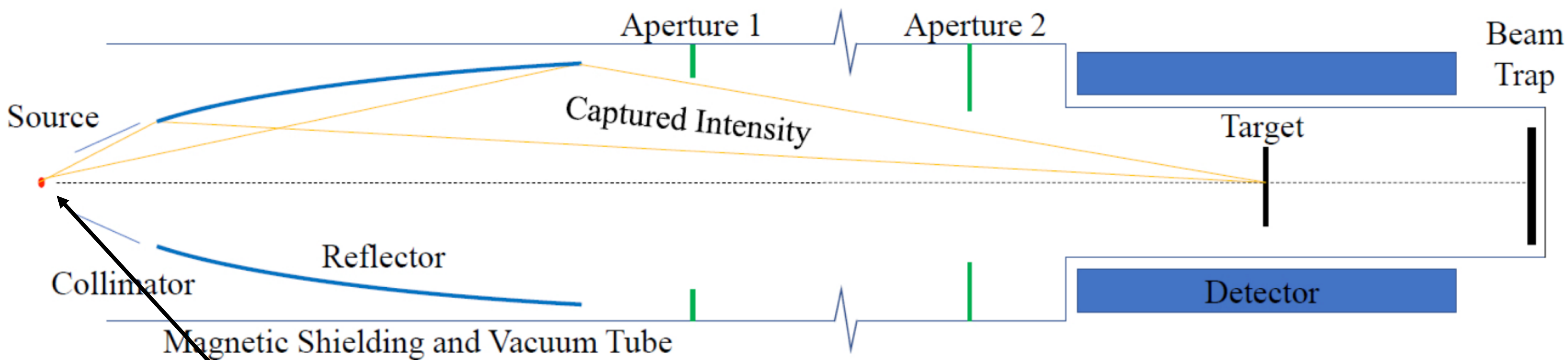
Schematic of the NNBAR experiment

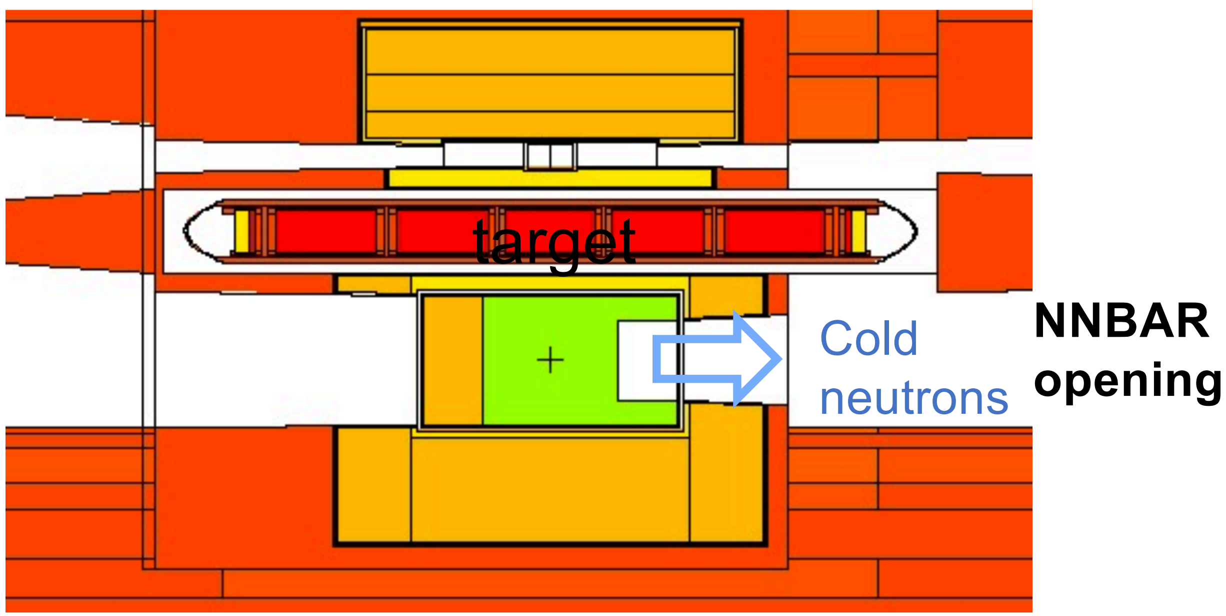


To design the optimal experiment you need to take into account several different aspects:

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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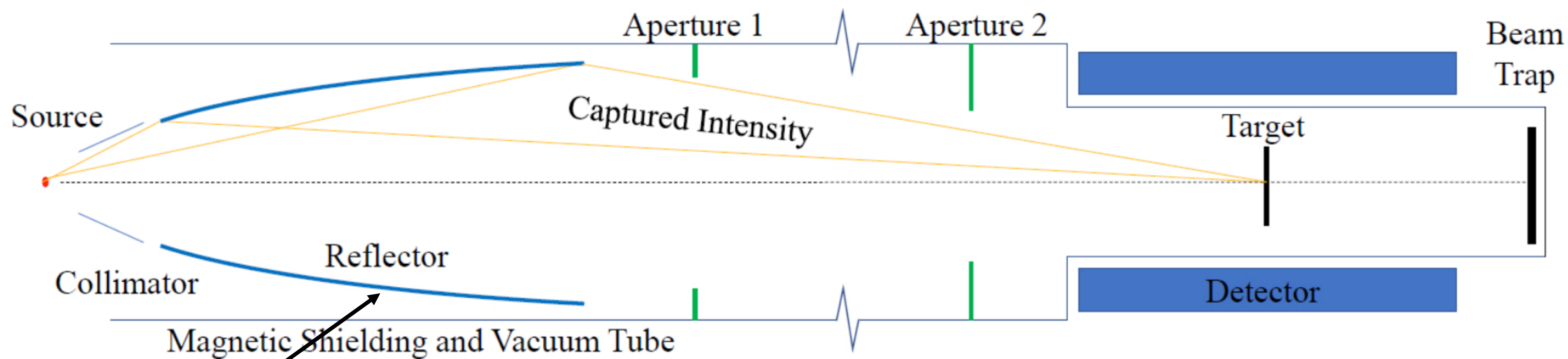
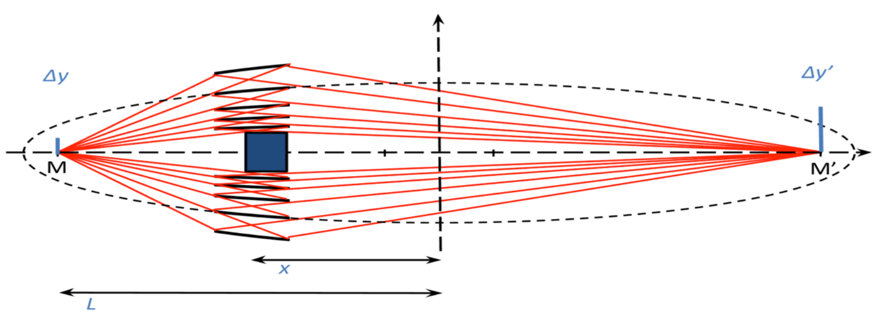


Courtesy of Oliver Zimmer and Richard Wagner (ILL)

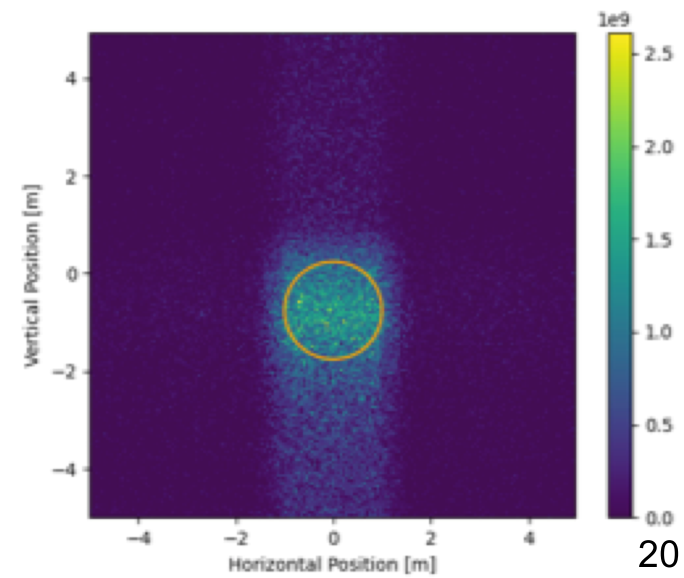
Reflector :

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

Design nested mirror systems to focus the neutron to the detector area



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



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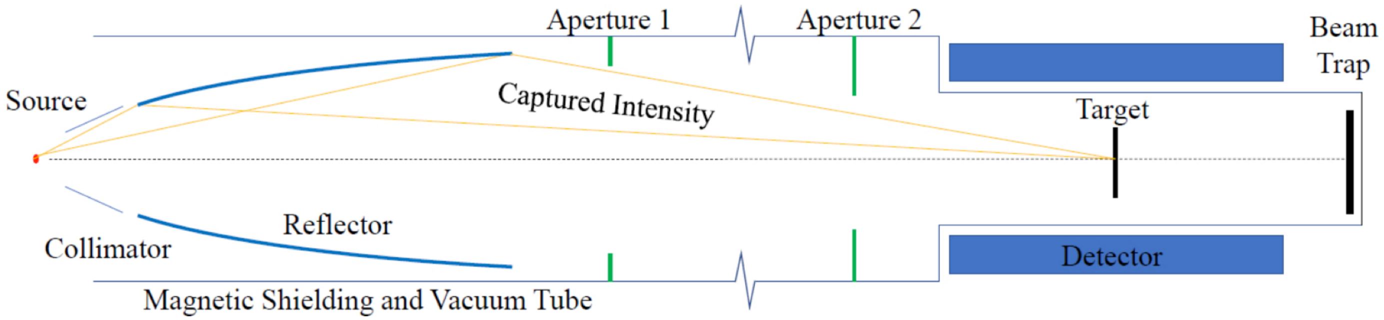
Propagation and annihilation detector



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

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

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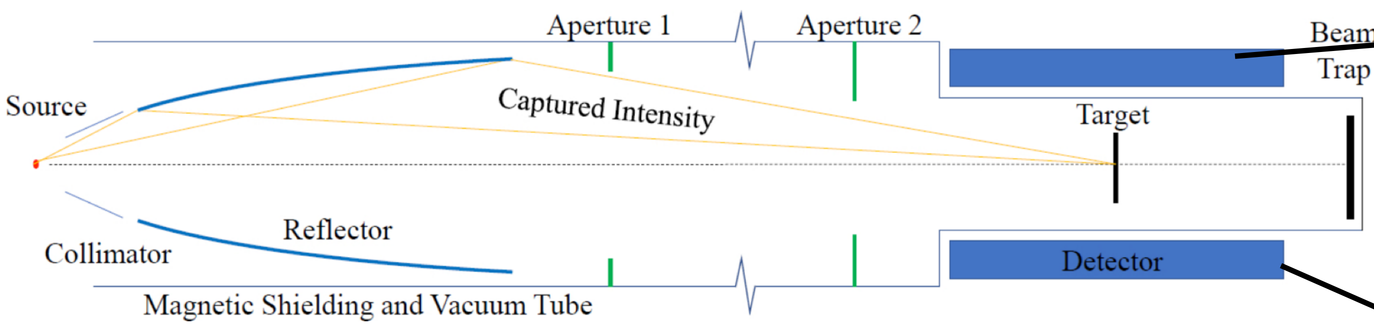

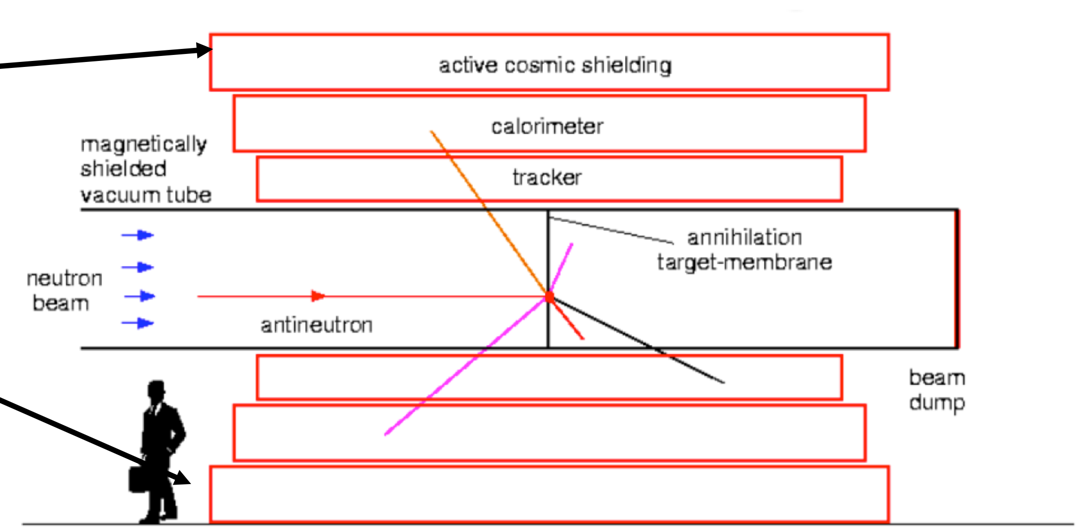

Residual B field <10 nT
Residual vacuum < 10^{-5} P

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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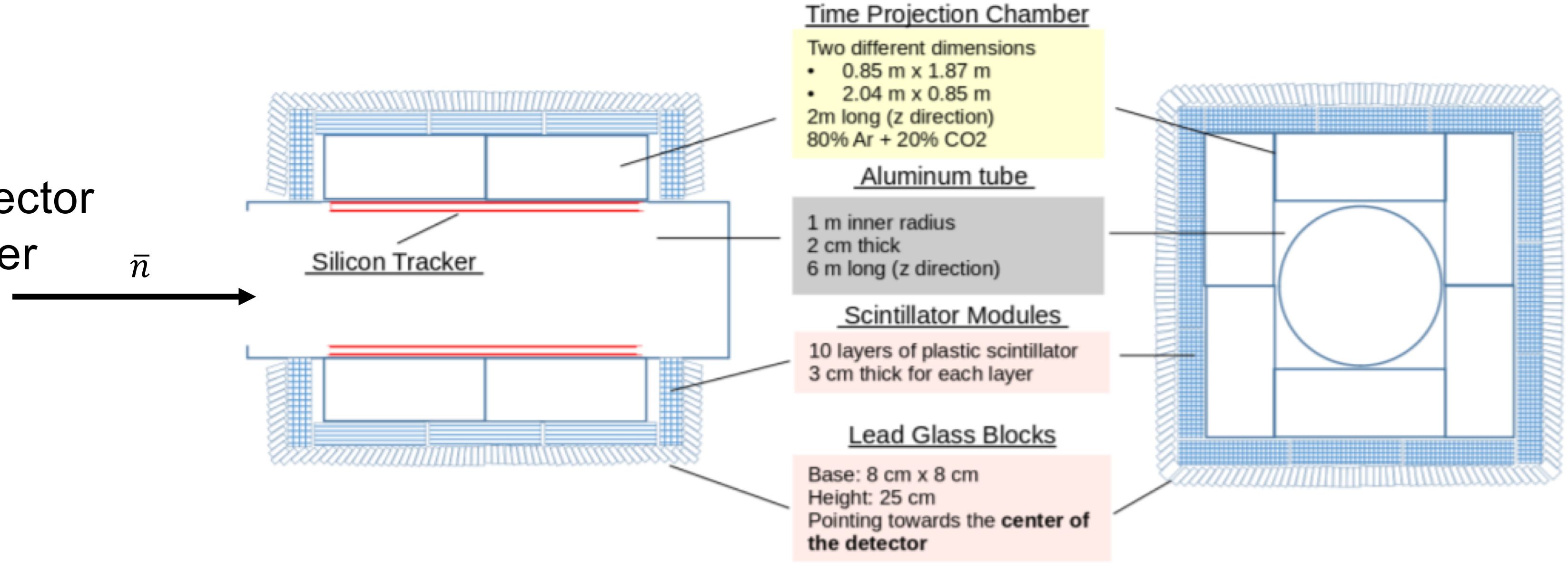
NNBAR Annihilation detector(I)

Design and optimization of the NNBAR detector on going

- Baseline detector
  - Silicon tracker
  - TPC
  - Scintillator range detector
  - Lead-glass calorimeter



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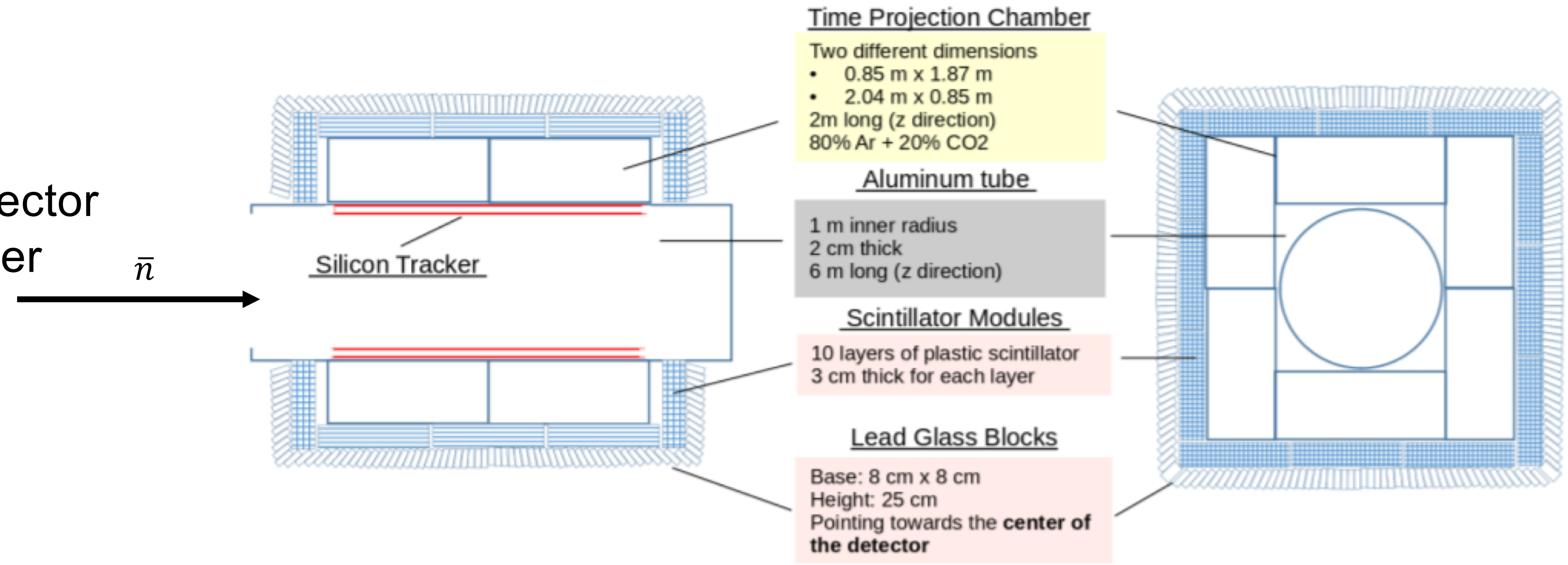
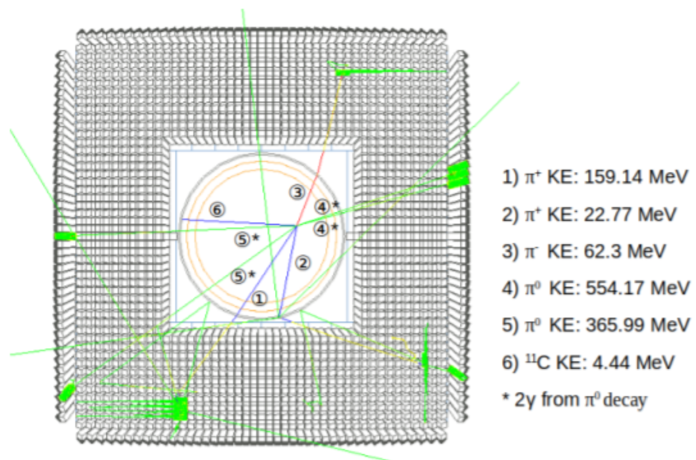
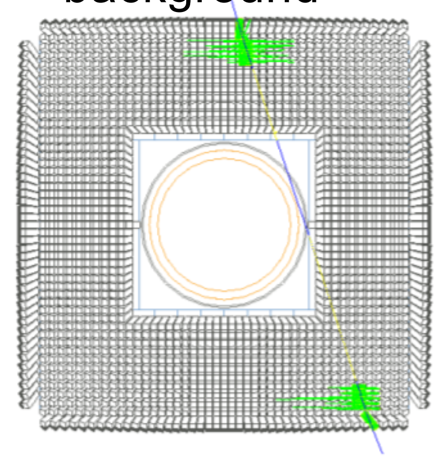


- Requirements
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds

Signal



Cosmic muon background



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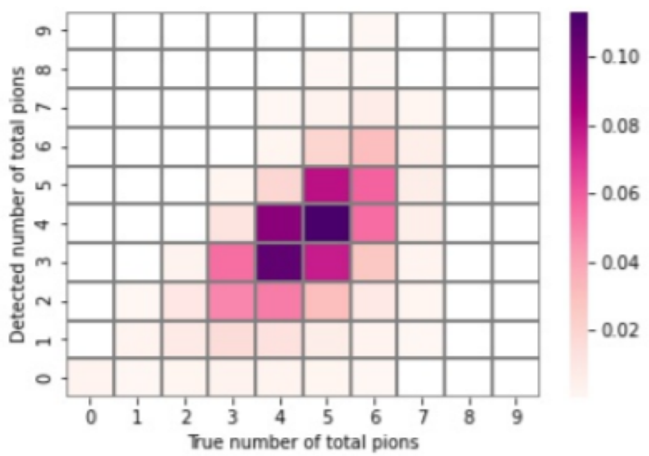
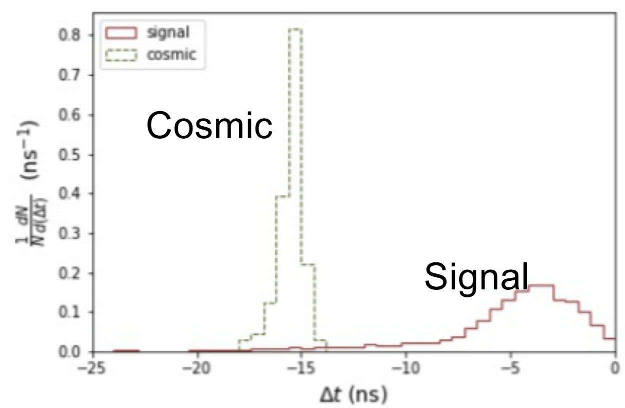
NNBAR Annihilation detector(II)

Detector simulation

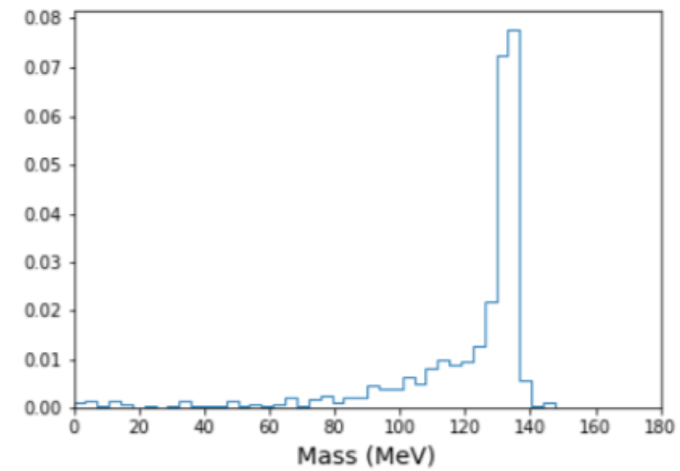
Pion multiplicity

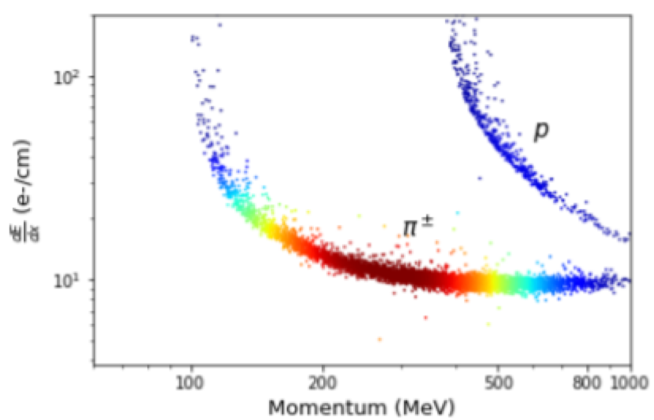


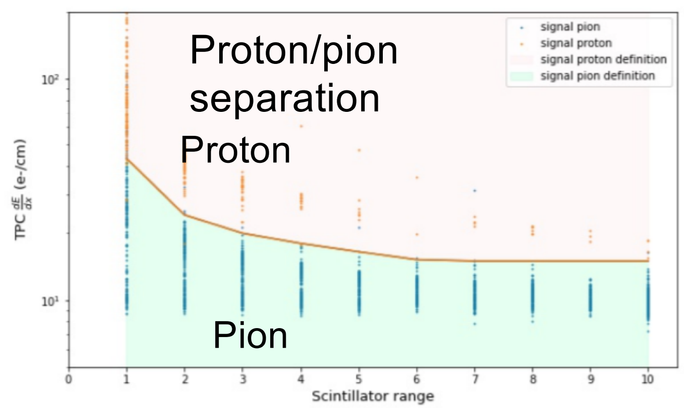
Event timing

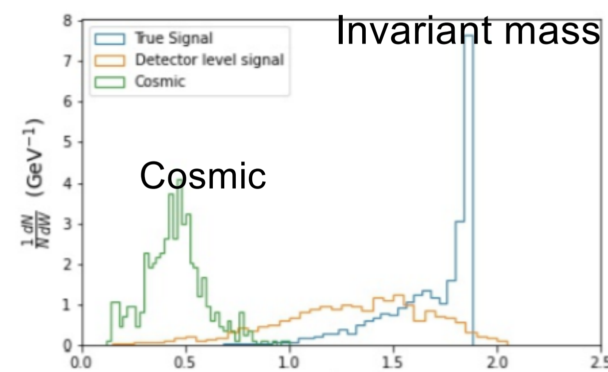


π^0 mass reconstruction









symmetry

Article

Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

Sze-Chun Yiu [1,*], Bernhard Meirose [1,2,*], Joshua Barrow [3,4], Christian Bohm [1], Gustaaf Brooijmans [5], Katherine Dunne [1], Elena S. Golubeva [6], David Milstead [1], André Nepomuceno [7], Anders Oskarsson [2], Valentina Santoro [2,8] and Samuel Silverstein [1]

Geant 4 model designed and reproducing well expected distributions

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

The 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.
- Conceptual design report in 2023
- 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

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

Conclusions

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

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- **CDR of the NNBAR experiment supported by the European Commission**
    - Beamline design (reflector, magnetic shielding and background simulations)
    - Detector development and design optimization
    - Prototype development and construction on-going

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- **HIBEAM > 2027 search for sterile neutron transitions**
- **NNBAR >2030 search for neutron to antineutron oscillations x1000 improvement respect to the previous limit**

References

- 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
- Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source, S-C Yiu et al., *Symmetry* 14 (2022) 1, 76
- Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS, J. Barrow et al., *EPJ Web Conf.* 251 (2021) 02062
- V Santoro et al. "Development of a High Intensity Neutron Source at the European Spallation Source: The HighNESS project" arXiv: 2204.04051 [physics.ins-det] accepted for publication

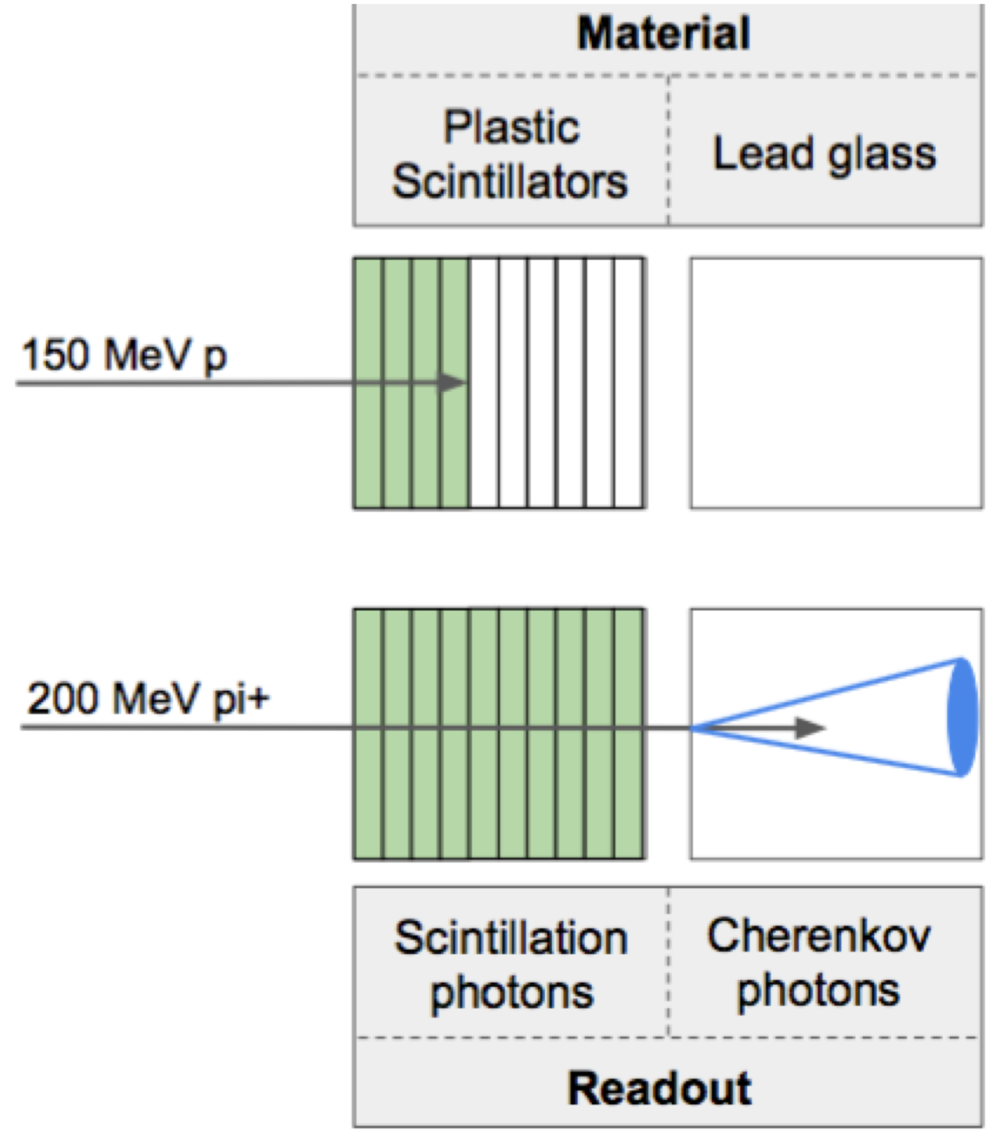
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

BACK-UP SLIDES

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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HighNess

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

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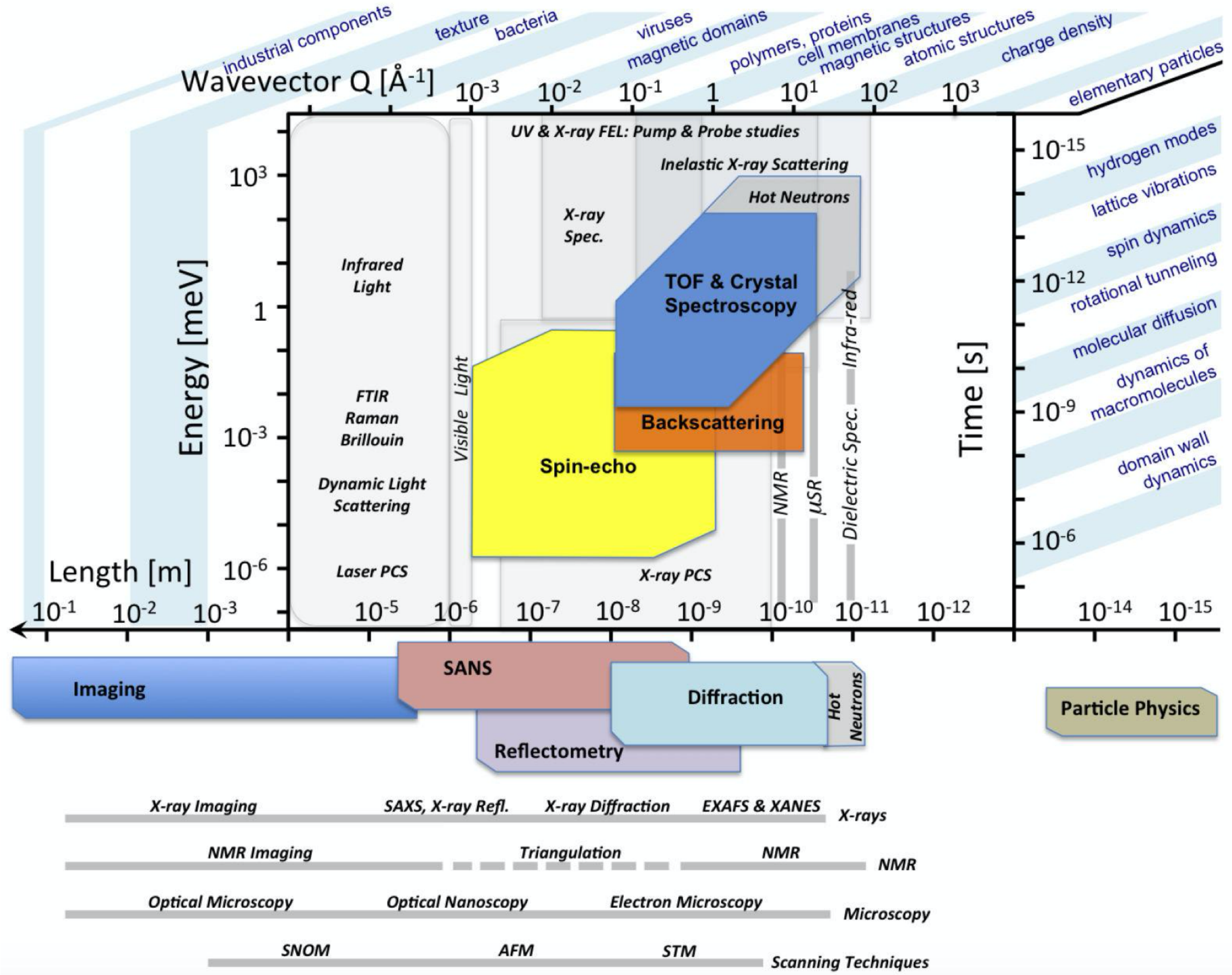
The European Spallation Source (II)



- 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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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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