Fundamental Physics with HIBEAM at the ESS

Alexander Burgman (Stockholm Univ.)
for the HIBEAM/NNBAR Collaboration

Outstanding questions

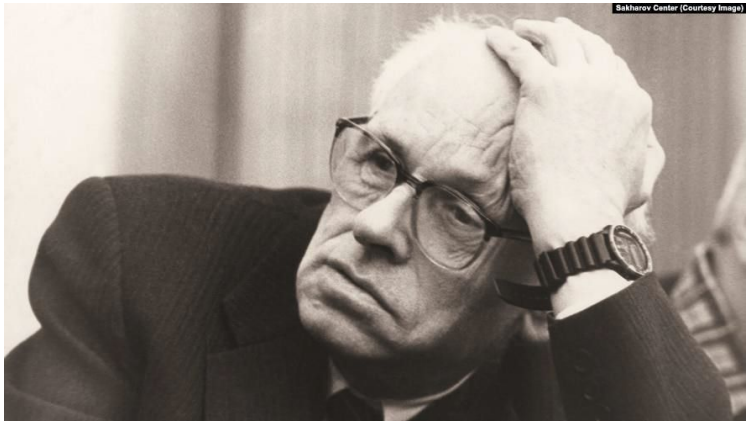
Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry
- Dark matter
- Dark energy
- Grand unification (strong+electroweak)
- Gravity

Matter/antimatter asymmetry

Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry ⇐ Sakharov conditions
  - Baryon number *B* violation
  - *C*- and *CP*-symmetry violation
  - Interactions out of thermal equilibrium



Baryon number violation

Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry ⇐ Sakharov conditions
  - Baryon number *B* violation (and lepton *L*)

Sphaleron processes,

Unification models

Supersymmetry

Hidden sector

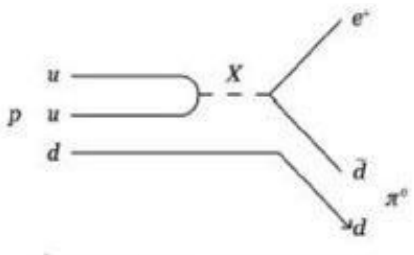
[…]

Baryon number violation

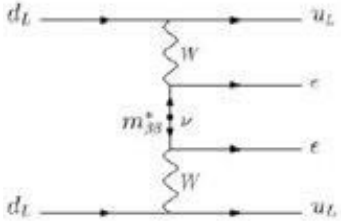
Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry ⇐ Sakharov conditions
  - Baryon number *B* violation (and lepton *L*)

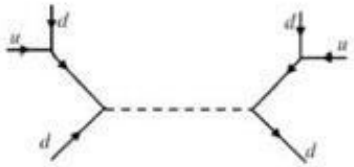
$p \to e^+ + \pi^0$
$\Delta B \neq 0, \Delta L \neq 0$



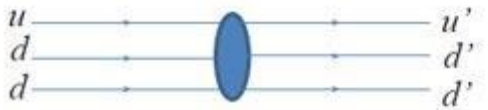
$0\nu 2\beta$
$\Delta B = 0, \Delta L \neq 0$



$n \to \bar{n}$
$\Delta B = 2, \Delta L = 0$



$n \to n'$ (mirror)
$\Delta B = 1, \Delta L = 0$



Baryon number violation

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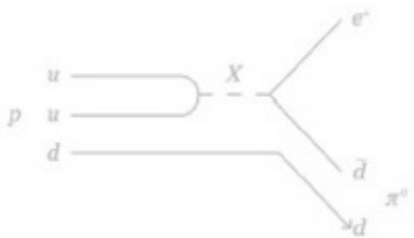

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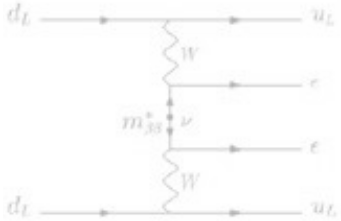

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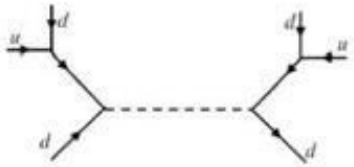

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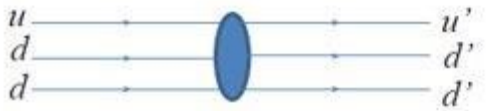
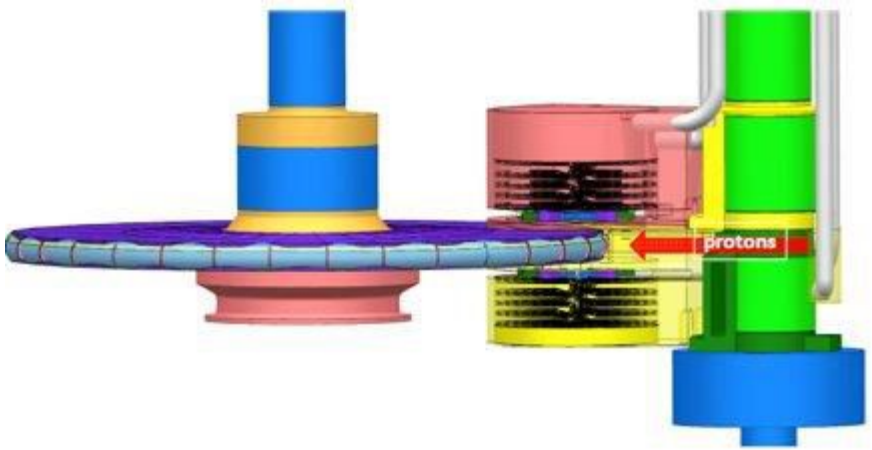


The European Spallation Source (ESS)

World's highest intensity neutron source

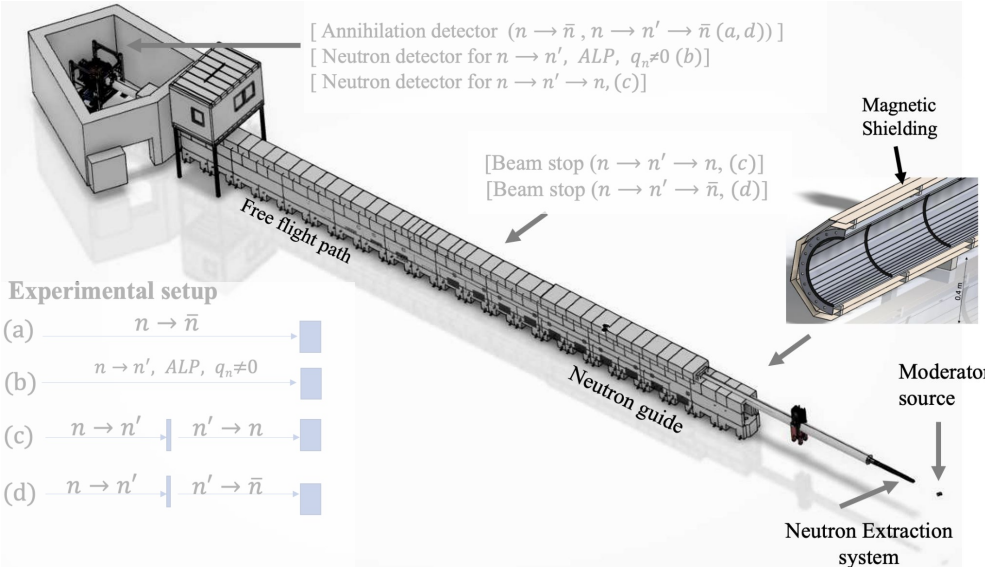
- Lund, Sweden
- Operations from 2027/2028
- Neutron imaging material, lifescience

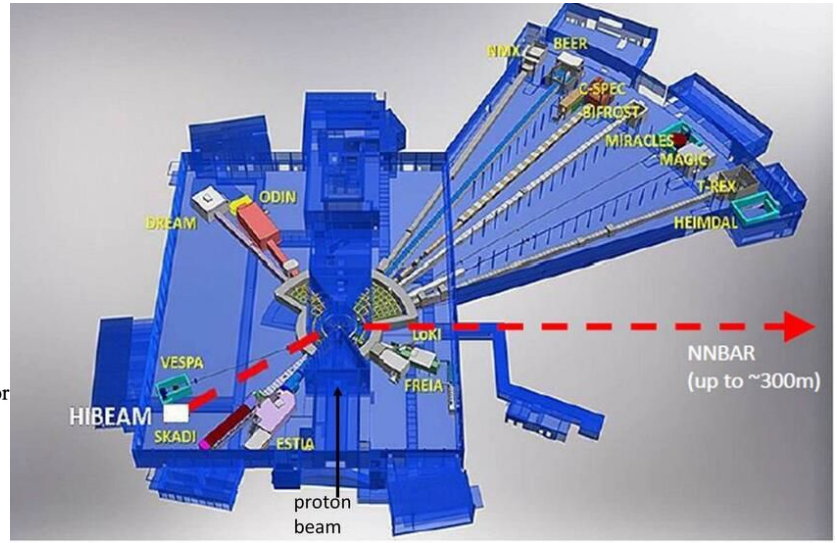


- Nominally 2 GeV protons,
  3 ms pulse, 14 Hz, (2;5) MW
- Rotating tungsten target
- Neutrons cold after moderators
- 15 beamlines/instruments (+ 22?)

The HIBEAM Beamline

arXiv:2311.08326





Magnetically shielded 50 m beamline

WASA (CsI) crystal calorimeter + TPC

$n \to \bar{n}$

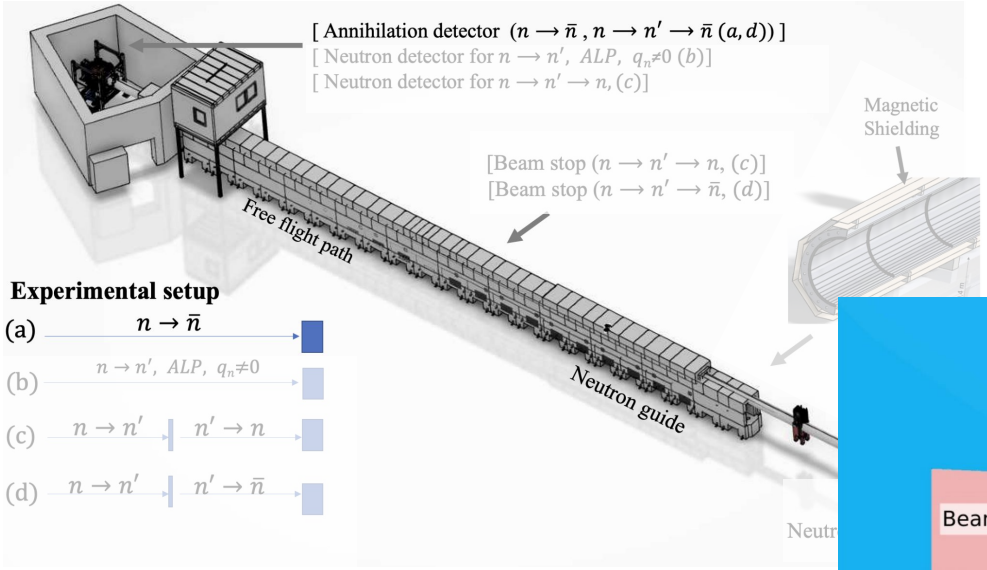
$n \to n'$

q_n

axions

nEDM

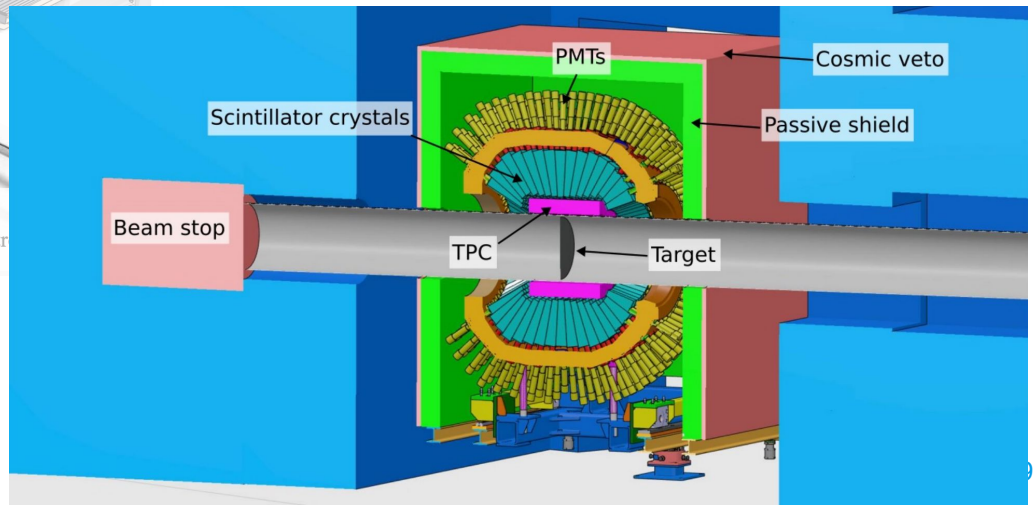
Antineutrons $n \to \bar{n}$



Neutron beam oscillating to antineutrons, incident on annihilation detector

Most recent search 1994 (ILL)

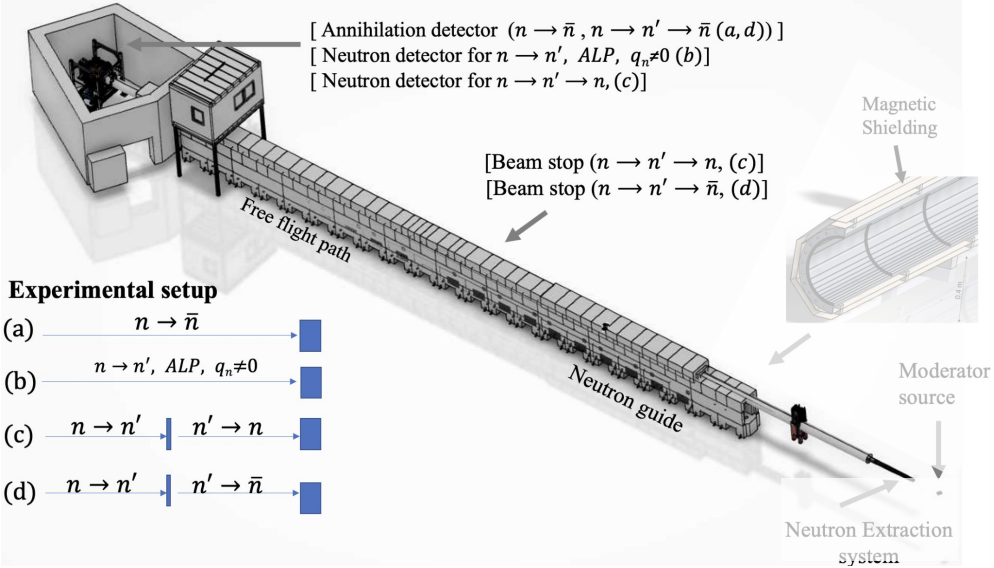
→ neutron lifetime $\tau_{n \to \bar{n}} > 8.6 \times 10^7$ s



10^{12} n/s, runtime 3–4 yr

Sensitivity improvement × 10

Sterile neutrons $n \rightarrow n'$



Magnetic field scan ± 2 G (200 μT) to find degeneracy with sterile sector

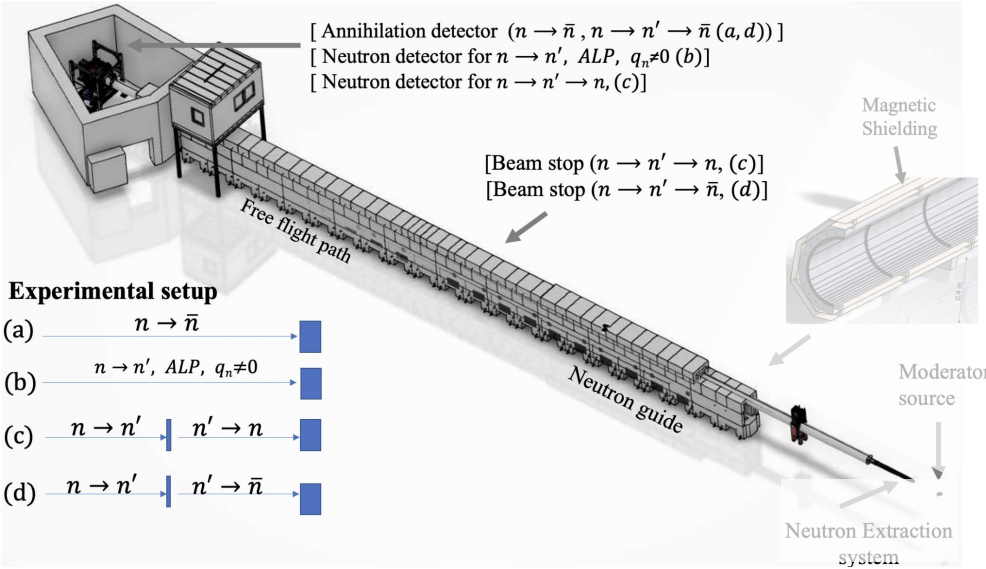
Possible beam stop to allow regeneration search

disappearance $n \rightarrow n'$

regeneration $n \rightarrow n' \rightarrow n$

anti-regen. $n \rightarrow n' \rightarrow \bar{n}$

Sterile neutrons $n \to n'$



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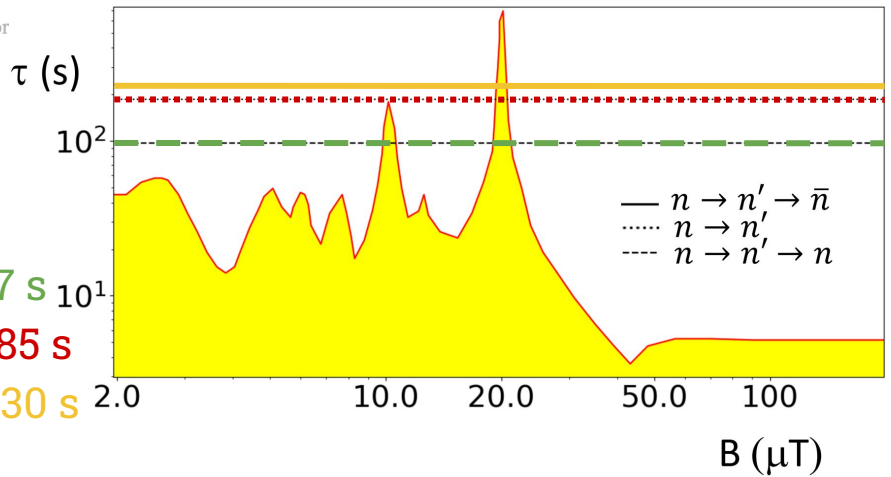


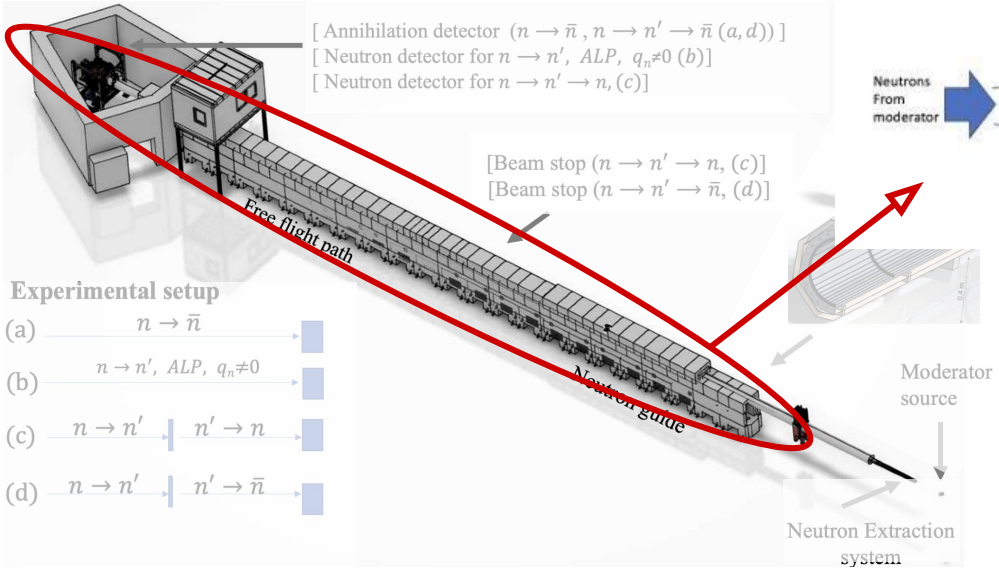
disappearance $n \to n'$ $\tau_{n \to n'} \sim 97$ s

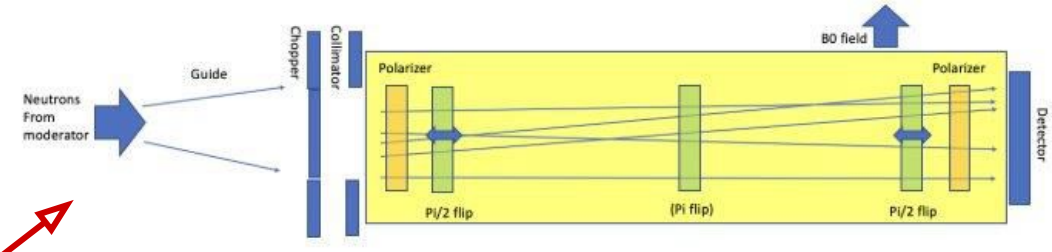
regeneration $n \to n' \to n$ $\tau_{n \to n'} \sim 185$ s

anti-regen. $n \to n' \to \bar{n}$ $\sqrt{(\tau_{n \to n'} \tau_{\bar{n} \to n'})} \sim 230$ s

Axions

arXiv:2404.1552





Ambient axions as pseudomagnetic field

Changes the Larmor frequency (magnetic moment precession)

Detected through Ramsey interferometry

Axions

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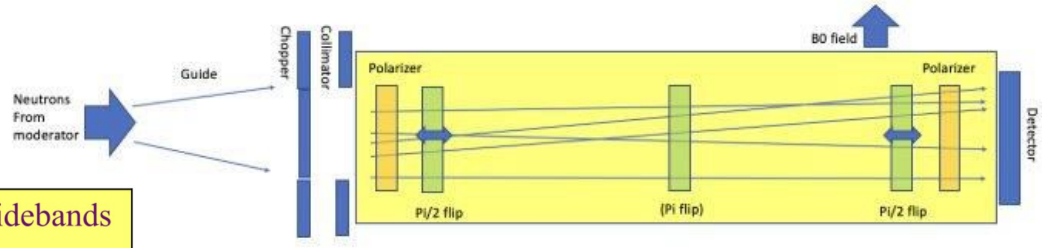
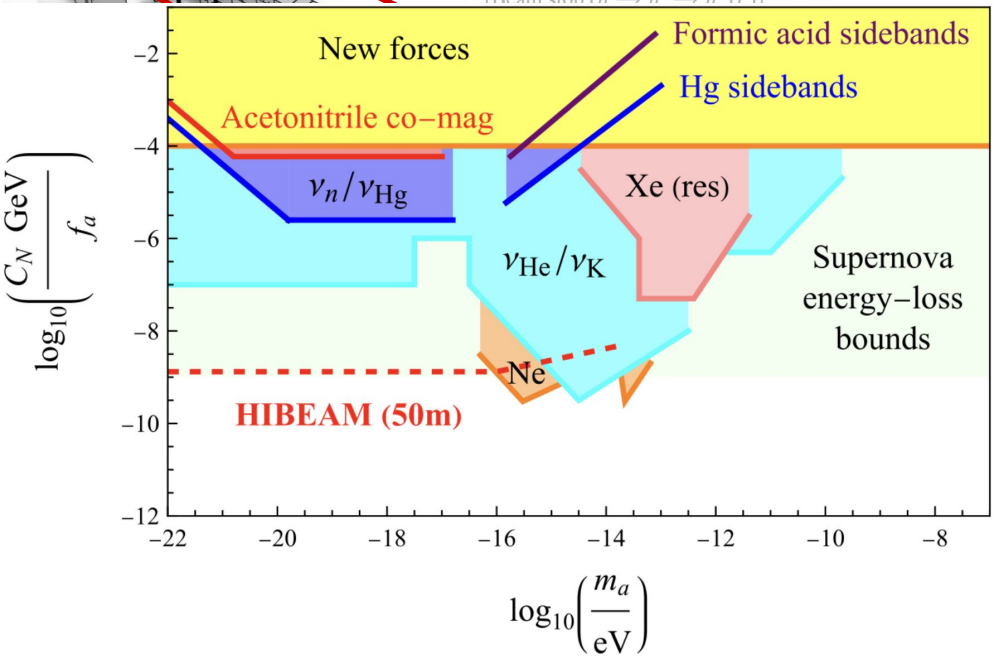




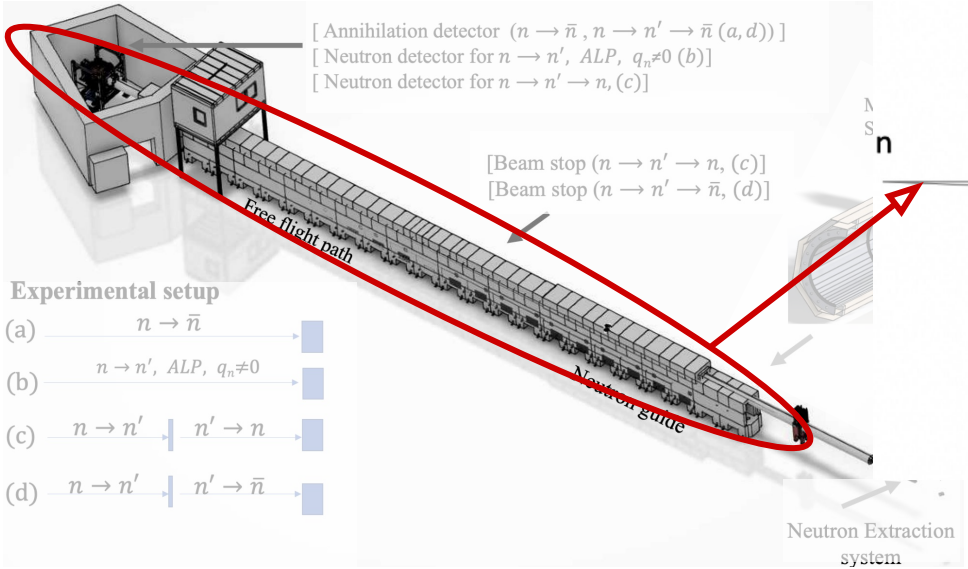
Ambient axions as pseudomagnetic field

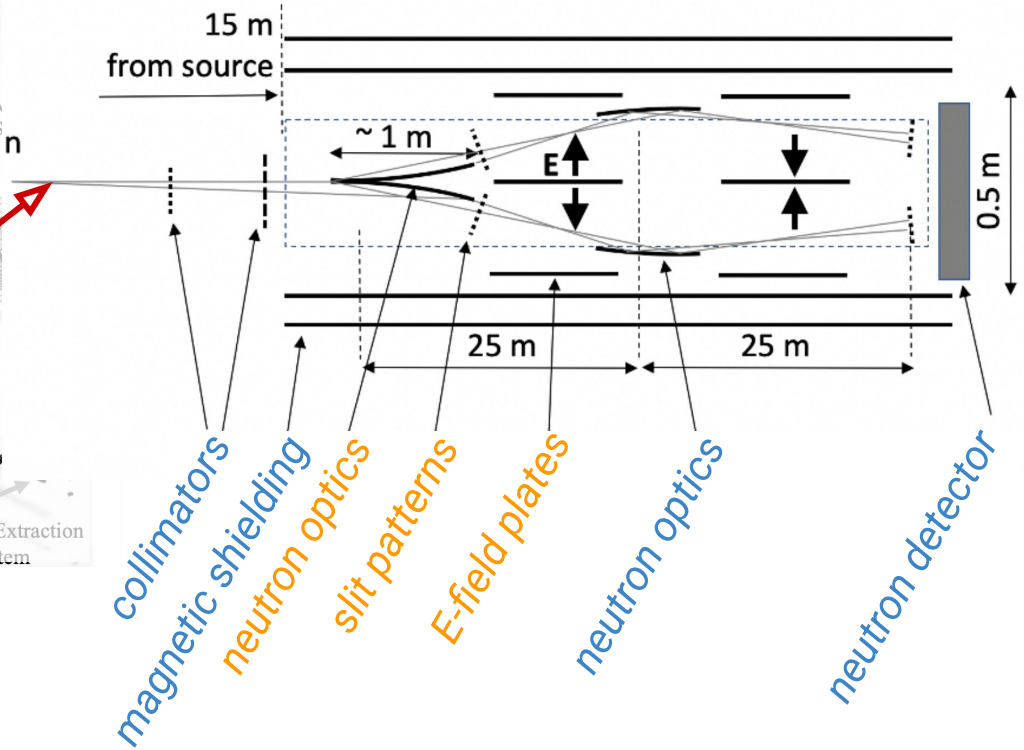
Changes the Larmor frequency (magnetic moment precession)

Detected through Ramsey interferometry

Sensitivity improvement × 10^2–10^3 for 10^{-22} eV < m_a < 10^{-16} eV

Neutron electric charge q_n



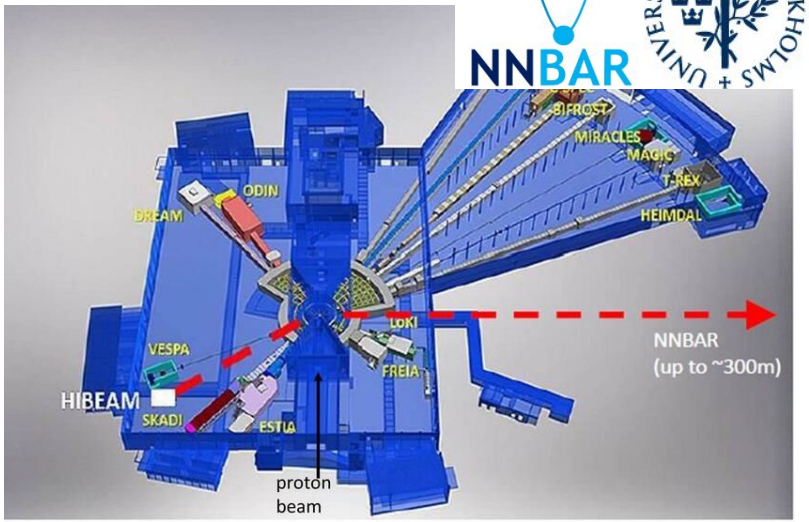


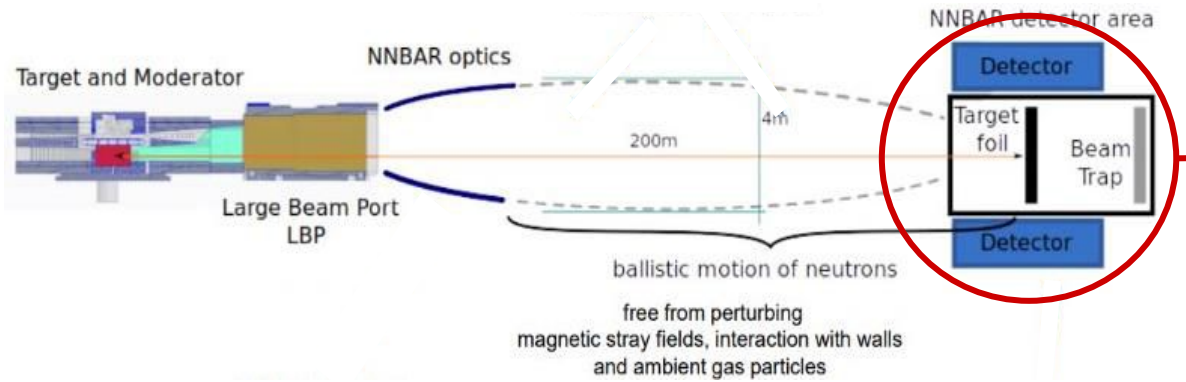
beam deflection ~ 0.1 nm per 10 m
(with $q_n \sim 10^{-21}\ e$)

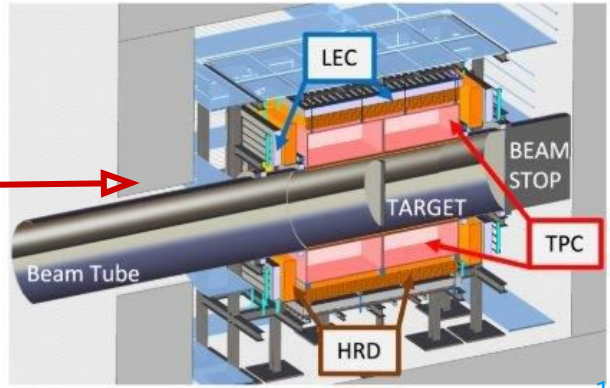
Sensitivity improvement × 700

NNBAR

×4 larger beamport, 4 m diameter, 200 m beampipe
improved neutron optics,
magnetic beampipe shielding
TPC, plastic scintillator, lead-glass calorimeter







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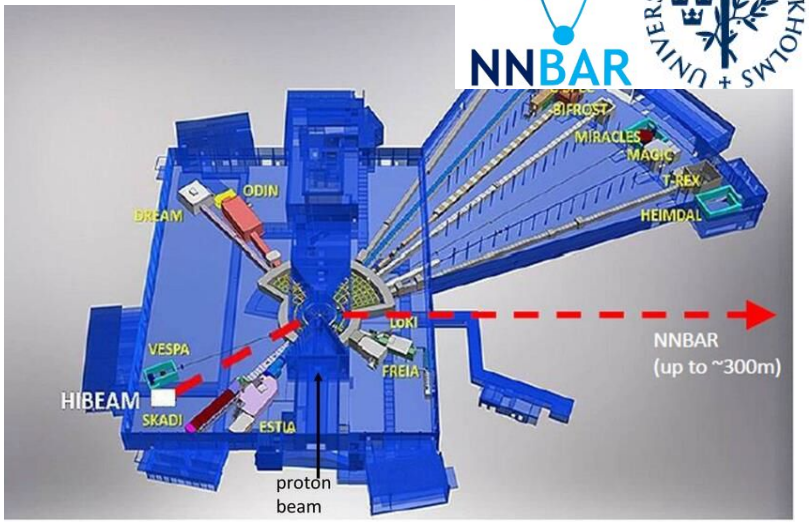
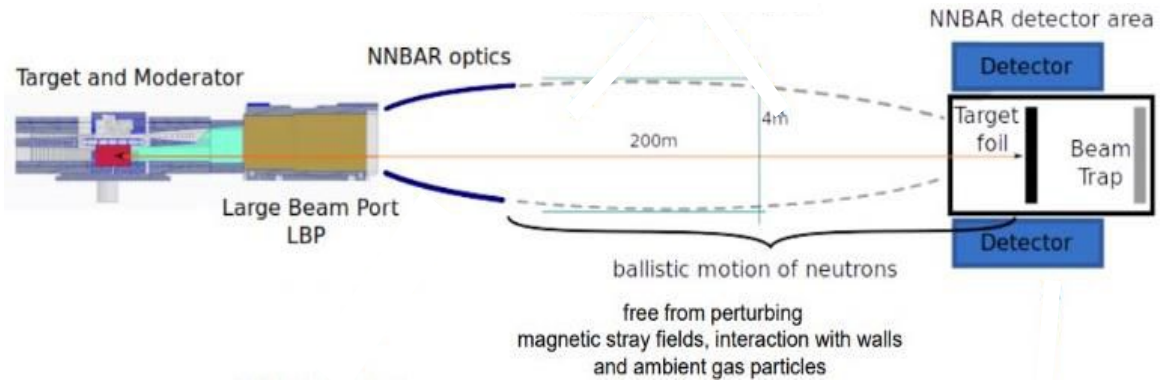




$(n \to \bar{n})$ $\tau_{n\to\bar{n}}$
sensitivity improvement × 10^3
over ILL results

Conclusions

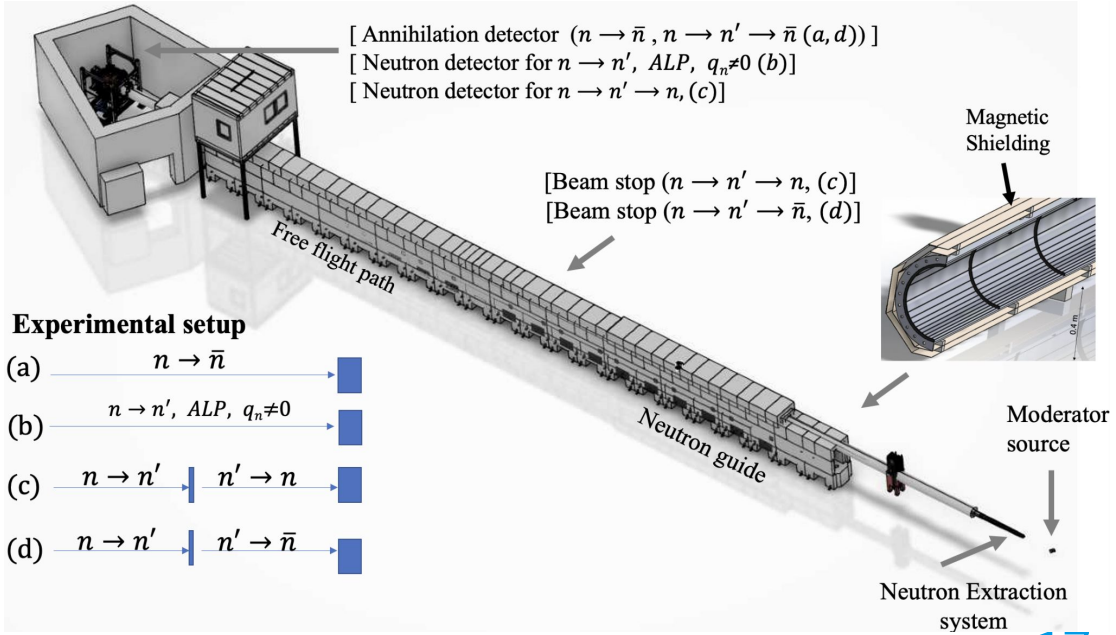
Enormous neutron flux at ESS
⇒ fundamental physics

HIBEAM

- $n \to \bar{n}$ sens. × 10
- $n \to n'$ $\tau \sim 230$ s
- axions sens. × 10^2–10^3
- q_n sens. × 700

NNBAR

- $n \to \bar{n}$ sens. × 10^3



Thank you

Abstract

One of the great open questions in modern physics is the origin of the matter-antimatter asymmetry. This requires baryon-number violation, which has never been experimentally observed. Baryon-number violation may arise in the neutron sector as the direct conversion between neutrons and antineutrons, or with a sterile/mirror neutron.

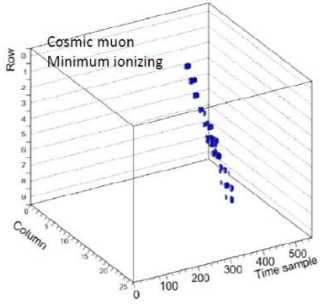
This process will be probed with the proposed HIBEAM/NNBAR program, a two-stage experiment at the European Spallation Source. The initial stage of the program, HIBEAM, will present opportunities to search for baryon-number violation in neutron conversion to antineutrons, or to sterile neutrons (as a disappearance search) or to sterile neutrons and into neutrons/antineutrons, with discovery potential reaching a factor of ten higher than previous experiments. HIBEAM also presents unprecedented sensitivity for direct searches for low mass axions as a dark matter candidate, surpassing previous results by two-to-three orders of magnitude for axion masses between 10^-22 eV to 10^-16 eV. Additionally, HIBEAM presents opportunities to search for a nonzero neutron electric charge as well as an electric dipole moment of the neutron with world-leading sensitivity.

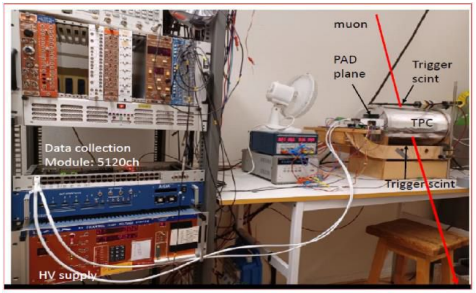
In this talk we present the fundamental physics opportunities of HIBEAM at the European Spallation Source.

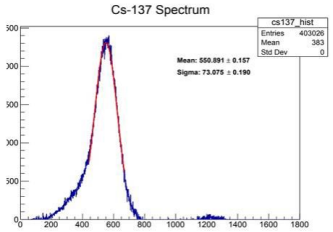
HIBEAM prototype

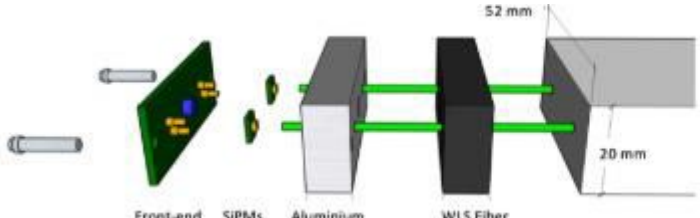
Swedish Research Council infrastructure grant to Stockholm U, Lund U, Chalmers TU, ESS

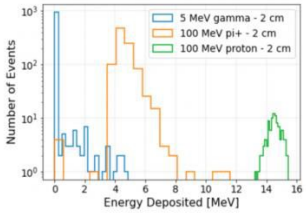
- Prototype development
  - Time projection chamber
  - WASA crystal calorimeter
  - Scintillator/lead-glass calorimeter
- Annihilation detector
- Neutron detector
- Beamline design

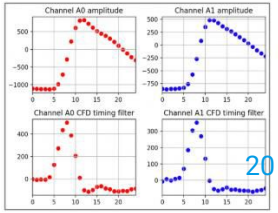












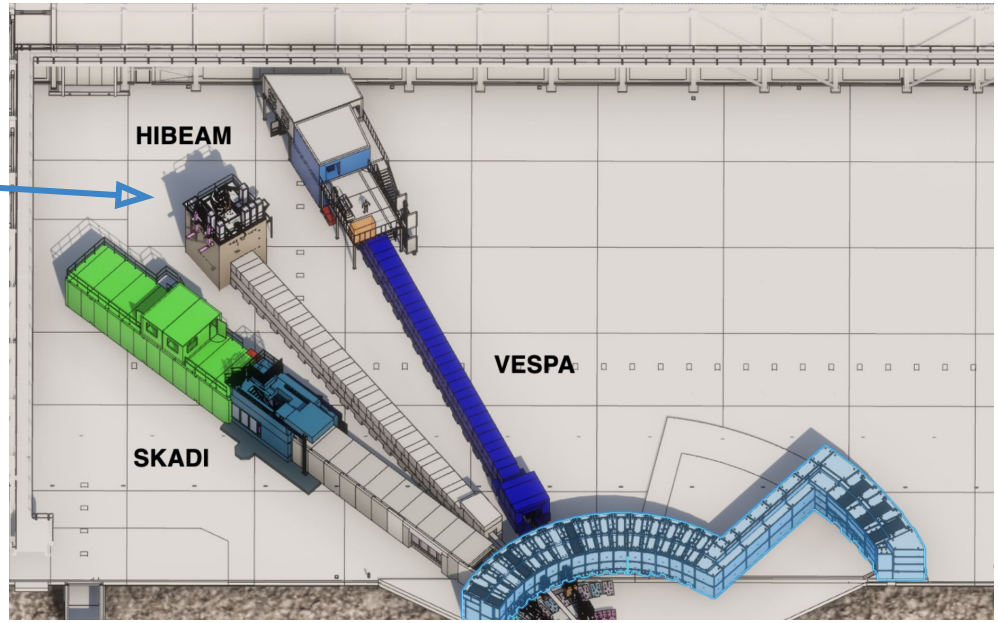
Electric dipole moment *nEDM*

Priority for neutron community

nEDM@SNS cancelled

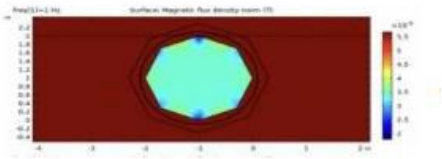
→ possible at the ESS?

Investigations ongoing to reach the 10^{-29} *e* cm sensitivity!

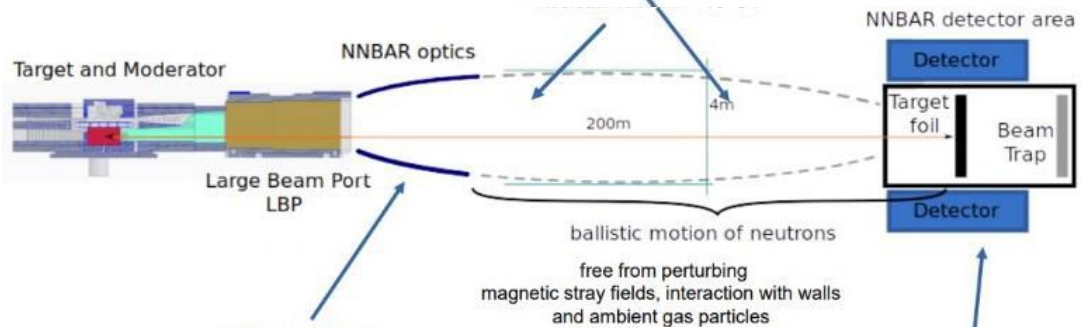


NNBAR

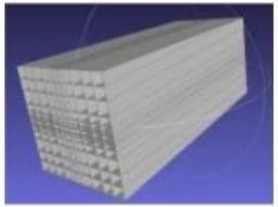
Outer and inner octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.



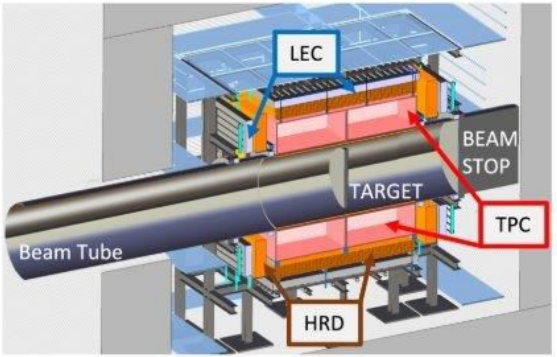
Residual B field <10 nT
Residual vacuum < 10 -5 P



Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area



Eg double planar reflector



NNBAR

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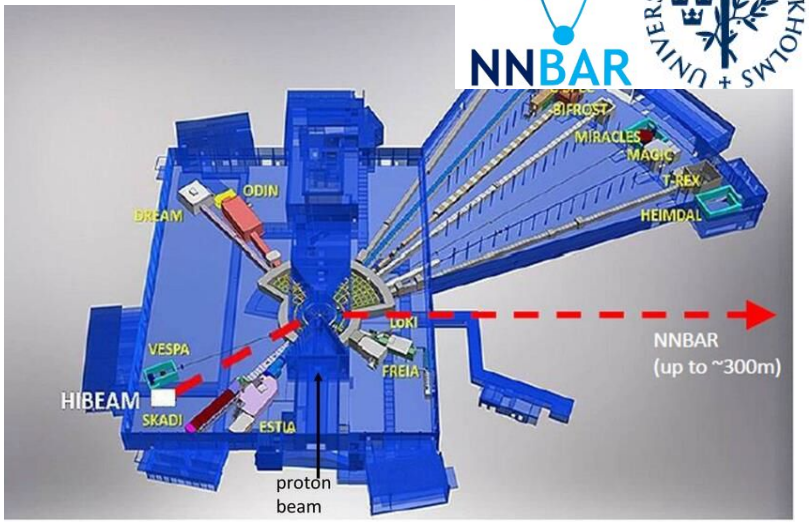

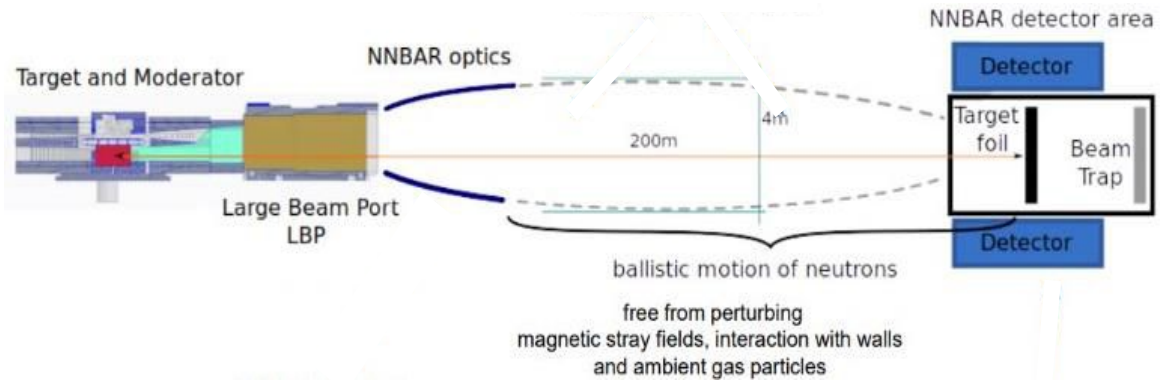

Neutron exotic decays

$$n \rightarrow X + e/\nu \rightarrow [\mathrm{SM}]$$

NNBAR sensitive,
discovery potential in 3 yr

Studies underway!
arXiv:2506.08701

Conclusions

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- axions sens. × 10^2–10^3
- q_n sens. × 700
- nEDM underway!

NNBAR

- $n \to \bar{n}$ sens. × 10^3
- *exotic decays* underway!