



# Plans and developments for fundamental and particle physics at the European Spallation Source

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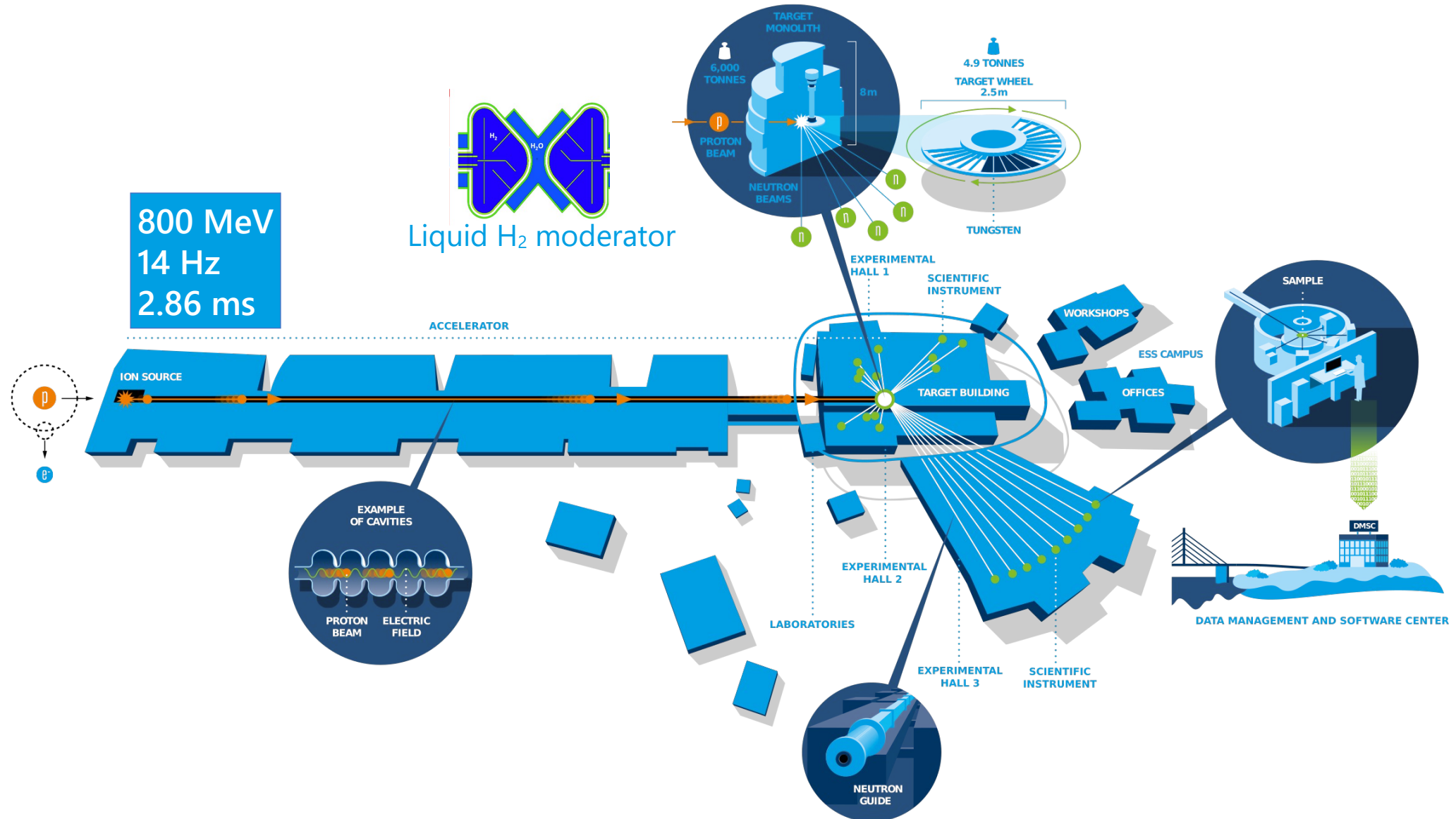
# The European Spallation Source

- Currently under construction in Lund, Sweden
- Upon completion the world's brightest spallation neutron source
- Beam on target 2025, user operations 2027
- Broad range of research:
  - Chemistry
  - Material Sciences
  - Life Sciences
  - Fundamental and Particle Physics
- Currently no beamline for particle physics
  - Has been identified as a capability gap of the highest priority<sup>1</sup>



<sup>1</sup> <https://europeanspallationsource.se/instruments/capability-gap-analysis>

# Beam Production at ESS



# Fundamental and Particle Physics Experiments at ESS

## Neutrino Experiments

**CevNS**

- Nuclear structure
- Neutrino magnetic moment
- Dark matter searches

**ESSvSB**

- Search for charge parity violation

## Neutron Experiments

**HIBEAM**

- Search for neutron oscillations
- Dark matter searches
- nEDM

**NNBAR**

- Search for neutron oscillations
- Baryon number violation

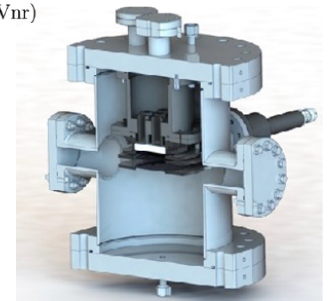
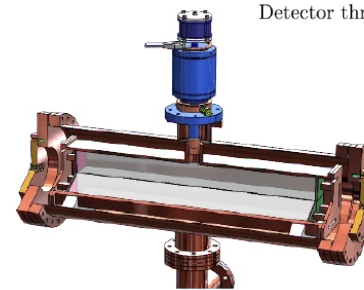
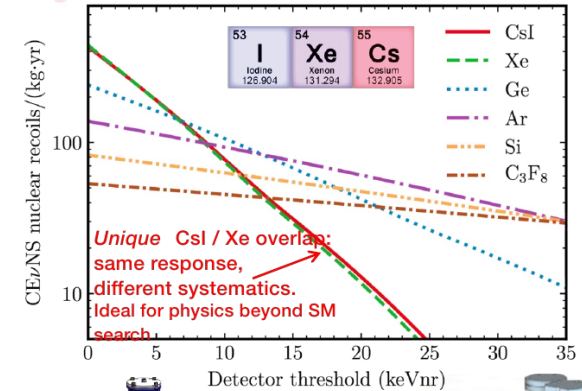
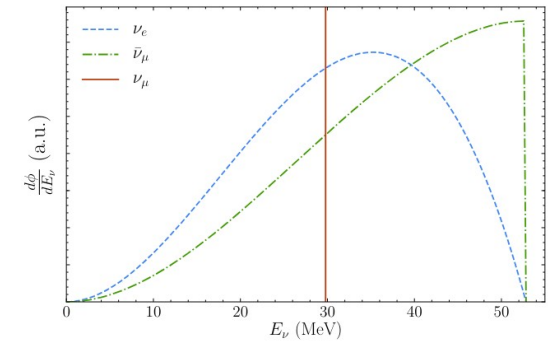
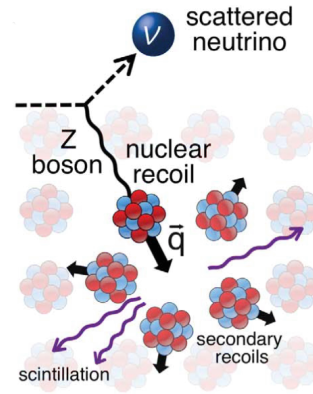
**Ultracold Neutrons**

- nEDM
- Gravity resonance spectroscopy
- Neutron beta decay

# Neutrino Experiments at ESS

## Coherent elastic neutrino-nucleus scattering (CEvNS)

- Low-energy  $\nu$  scatters off nucleus as a whole
  - Coherent contribution from all nucleons
  - Enhancement of the cross-section ( $\sim N^2$ )
  - Nuclear recoil (<few keV) only observable
- Relevant for studies of
  - Properties of neutrinos and neutrino interactions
  - Nuclear structure and astrophysics
  - Dark matter searches
- ESS: Complementary technologies to minimize systematic effects
  - Cryogenic CsI
  - TPC (Ar, Xe and Kr)
- Project funded, space at ESS required

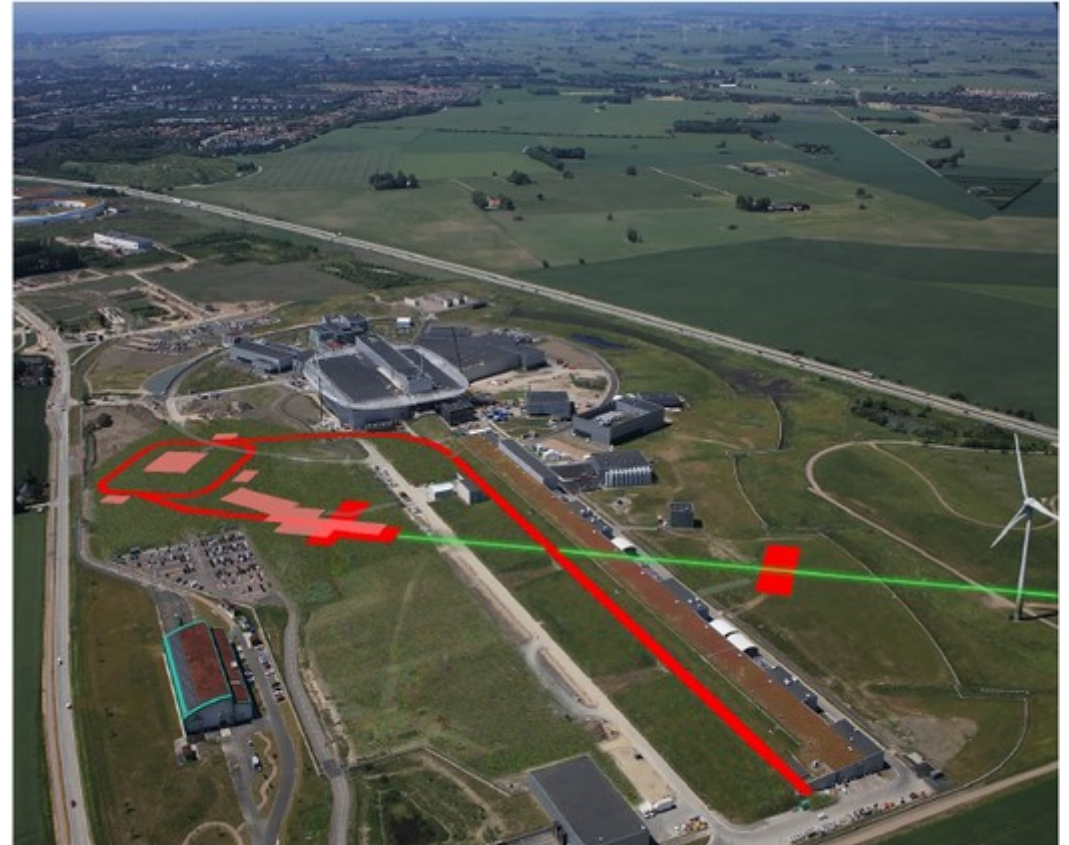




# Neutrino Experiments at ESS

## ESS Neutrino Super Beam (ESSvSB)

- Proposed accelerator long baseline neutrino experiment at ESS
- Search for CP violation in the leptonic sector with high precision
- Significant addition to ESS facility
  - Requires upgrade of ESS accelerator
  - Neutrino production target station needs to be built
  - Near detector close to the target station
  - Far detector in the north of Sweden
- Supported by 2 European INFRADEV grants
- CDR published, TDR to be completed by 2028

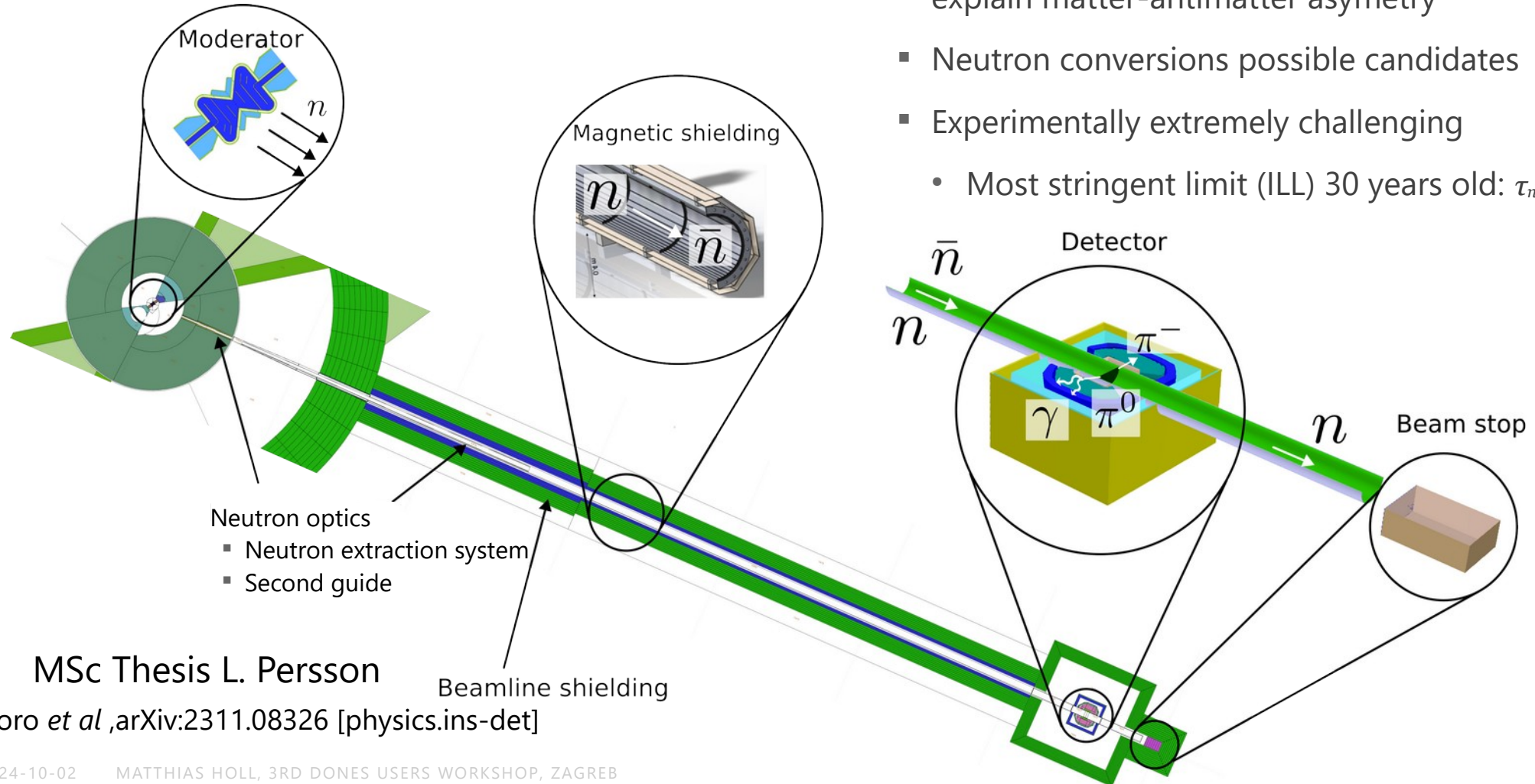


Eur. Phys. J. Spec. Top .(3955-3779 :231 (2022))  
<https://doi.org/10.1140/epjs/s11734-022-00664-w>  
<https://arxiv.org/abs/2206.01208>

# The HIBEAM Beamline

## Search for neutron-antineutron conversions

- Baryon number violating processes necessary to explain matter-antimatter asymmetry
- Neutron conversions possible candidates
- Experimentally extremely challenging
  - Most stringent limit (ILL) 30 years old:  $\tau_{n\bar{n}}=8.6 \cdot 10^7 \text{ s}$



MSc Thesis L. Persson

Santoro *et al*, arXiv:2311.08326 [physics.ins-det]

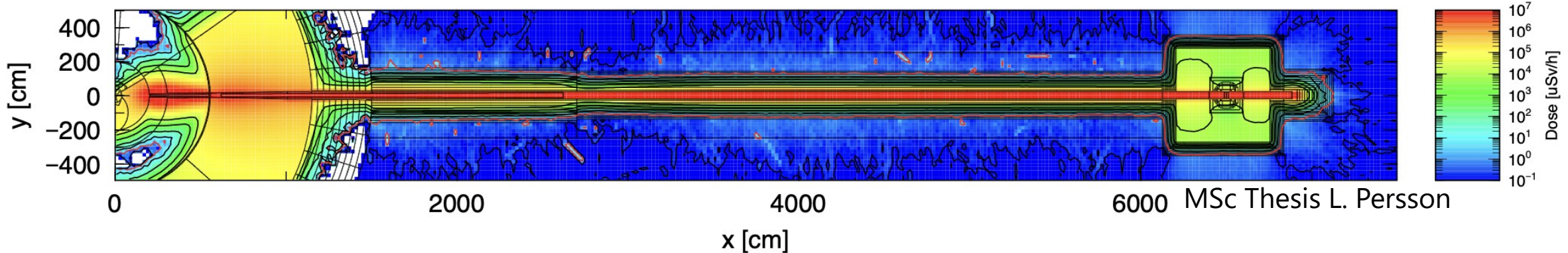
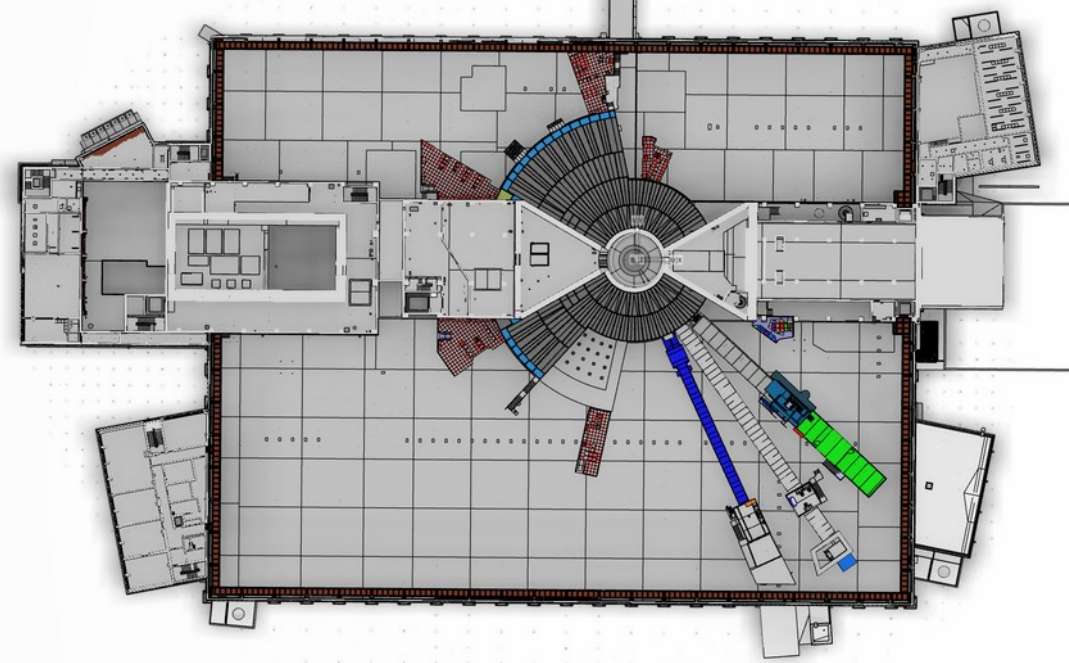


# The HIBEAM Beamline

## Status

- Located in east sector of ESS experimental hall
- Construction of neutron extraction system has started
- Full design of radiation shielding
- Possible start of measurement: 2029
- Expected sensitivity from McStas simulations
  - $10^{12}$  neutrons,  $\langle E \rangle = 5.7$  meV ( $\sim 1000$  m/s)
  - $t^2 \sim 2.5 \times$  current limit/year

Santoro *et al*, arXiv:2311.08326 [physics.ins-det]



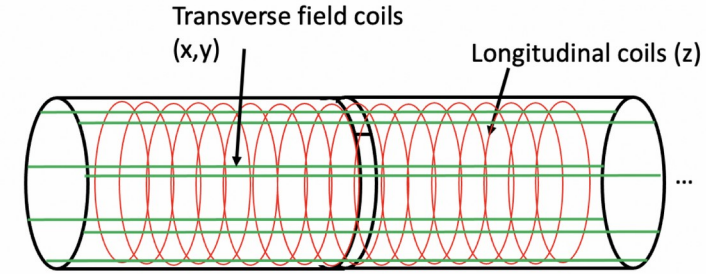
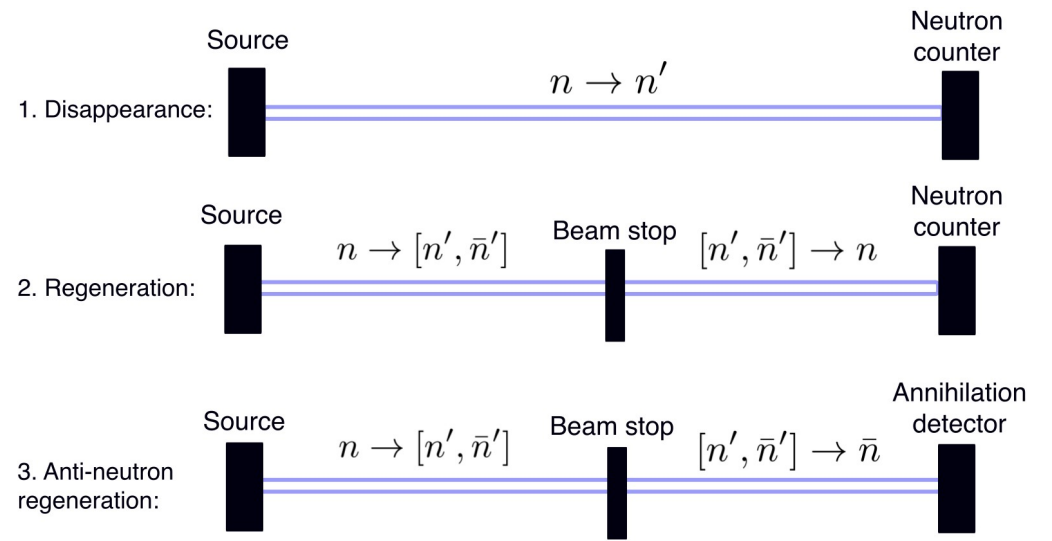
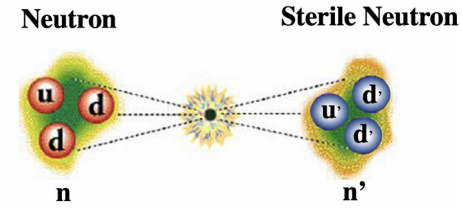


# Sterile Neutron Searches @ HIBEAM



## Induced instead of free oscillations

- Neutron is one of the few possible portals to a hidden/dark sector ("sterile" neutron)
- If  $n'$  exists, it can be produced by neutron to sterile neutron oscillations
  - Possible explanation for neutron lifetime anomaly ("beam" vs. "bottle")
- A sterile neutron may be affected by a sterile magnetic field  $B'$ 
  - Presence of  $B'$  and  $B_{lab}$  will suppress conversions unless  $B' \approx B_{lab}$
- Magnetically controlled beamline required
  - $-1 \text{ G} < B_{lab} < 1 \text{ G}$
  - 2 mG accuracy

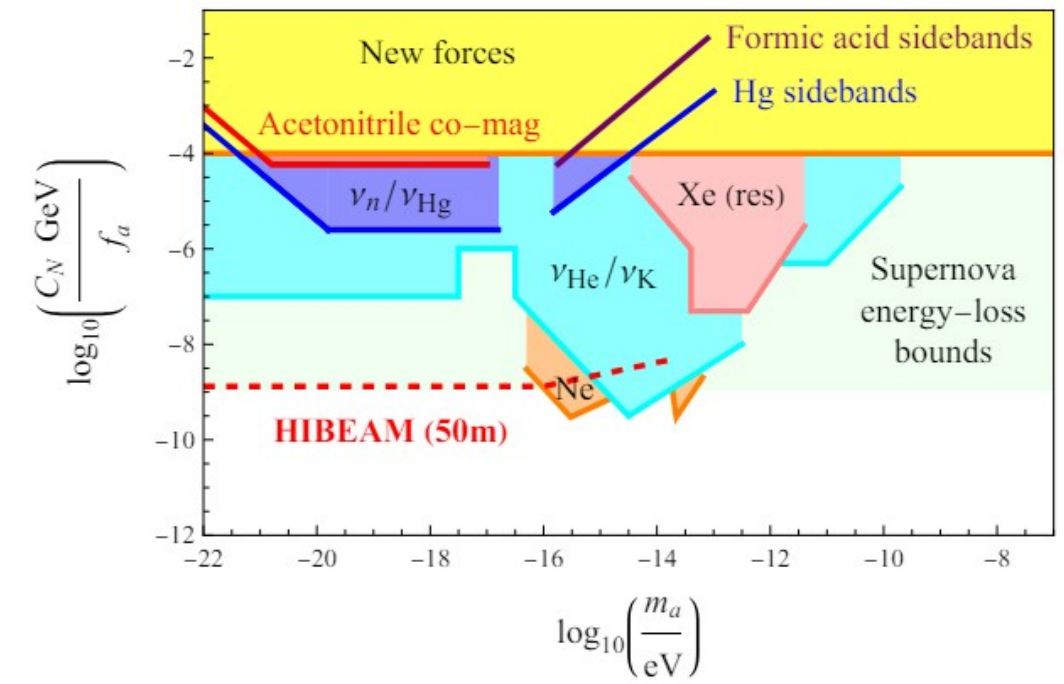
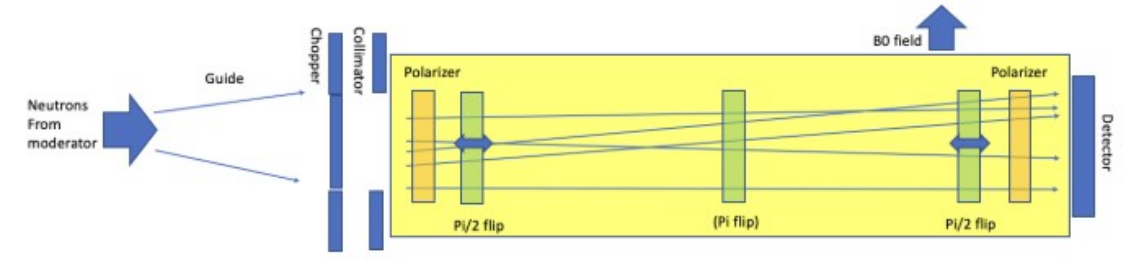


# Search for Axion-like Particles @ HIBEAM



## Coupling of axions to nucleons

- Axion: Low-mass dark matter candidate
- Ramsey experiment
  - Axions act as a pseudomagnetic field
  - Change in Larmor frequency due to axions
- Direct search sensitivity improvement by 2-3 orders of magnitude
  - Indirect searches have model dependence
- Could be first ESS particle physics experiment
  - Most of the equipment already available

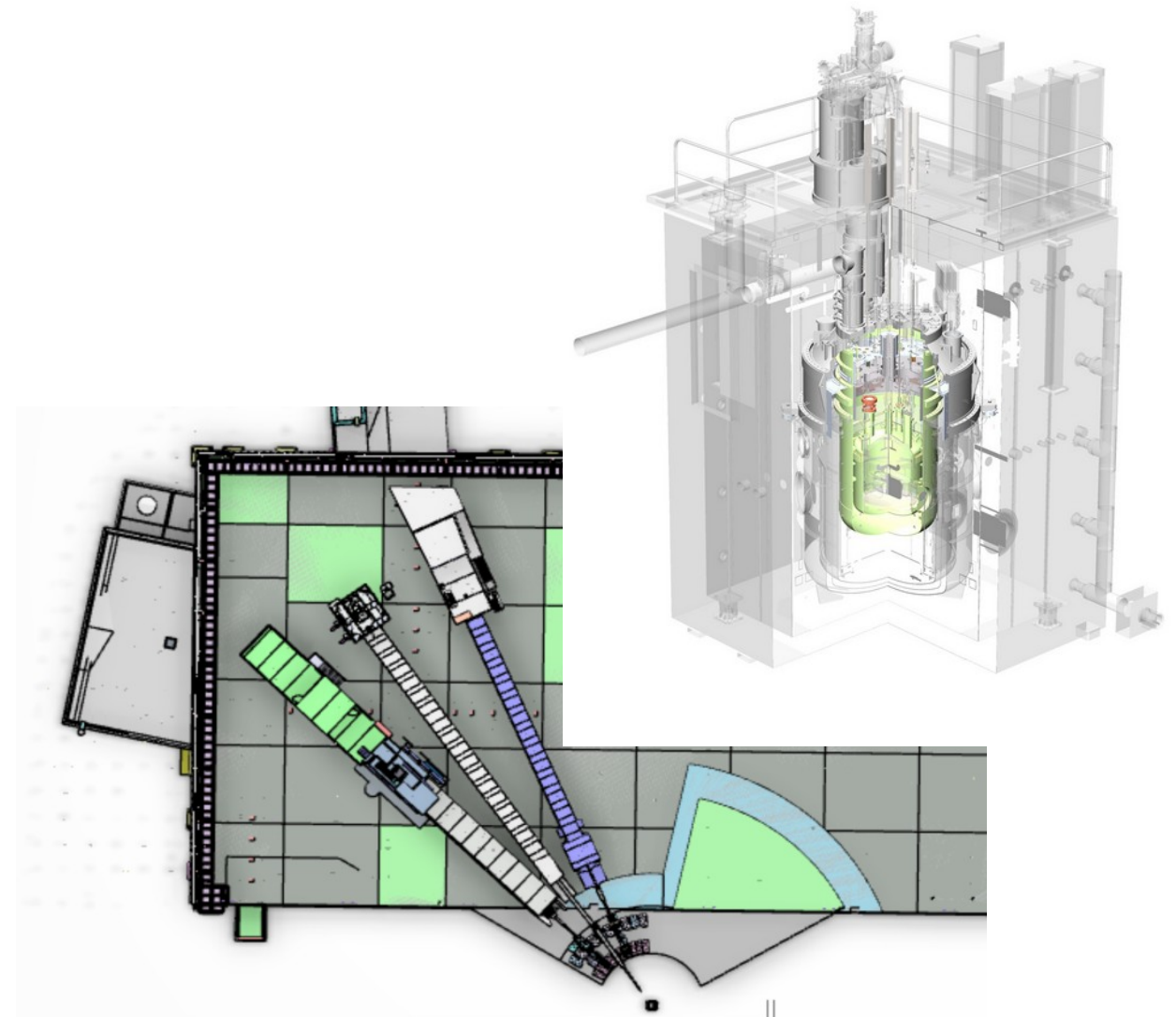


Stadnik *et al*, arXiv:2404.15521 [hep-ph] (accepted to PRL)

# Cryogenic Neutron EDM

## U.S./European Initiative

- UCNs produced in situ in superfluid  $^4\text{He}$ 
  - high UCN density in measurement cell
  - $^4\text{He}$  also used as scintillator
  - $^3\text{He}$  injected as polarizer and spin analyzer
  - Sensitivity below  $3 \cdot 10^{-28}$  e-cm
- Mostly developed by US DOE and NSF
  - funding terminated in 2023 with construction underway
- Planning a sequence of preparatory demonstration measurements at ILL
- Could run as part of general purpose particle physics beamline at ESS
  - e.g. after HIBEAM

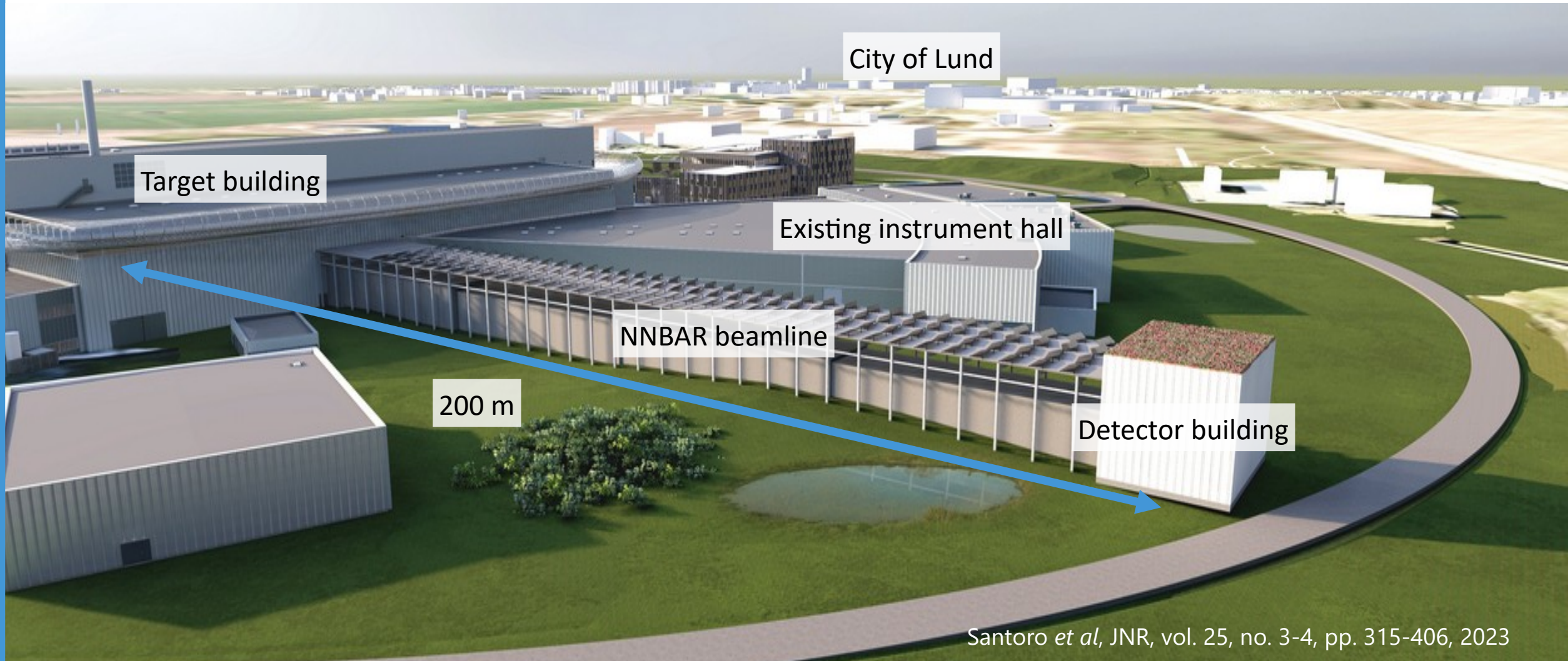






# The NNbar Experiment

2035+



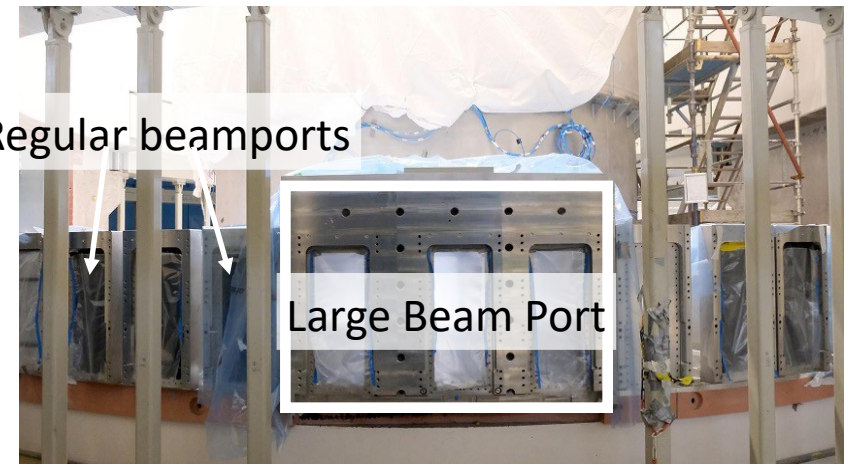
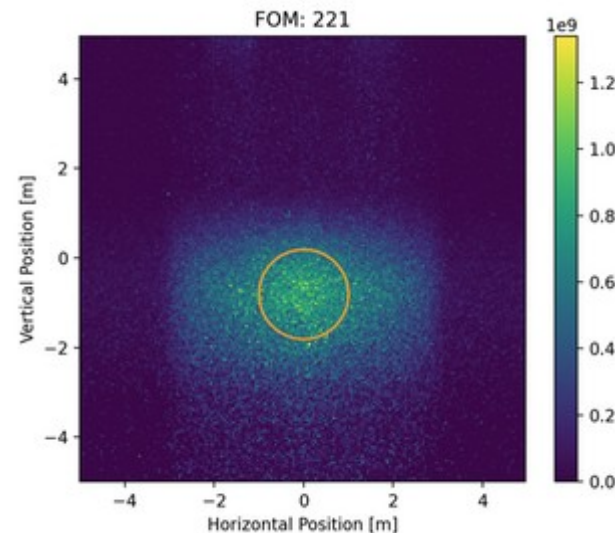
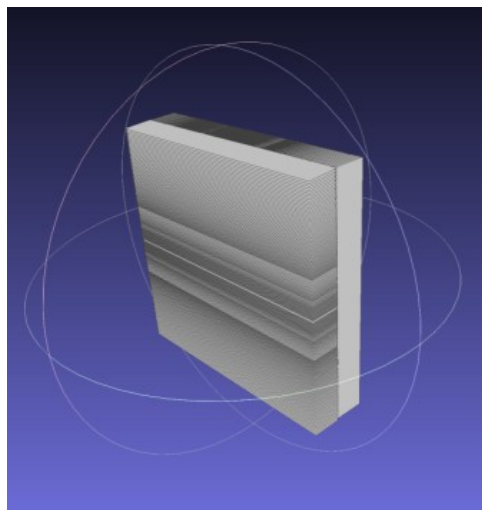
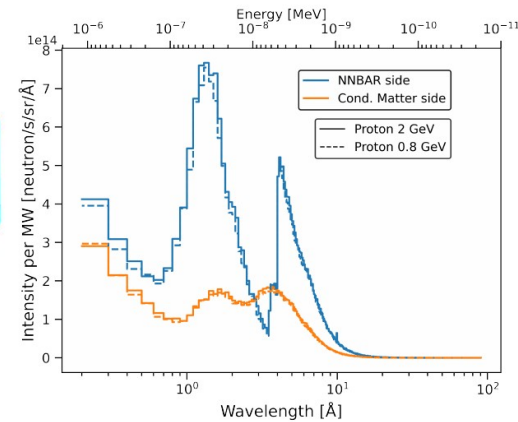
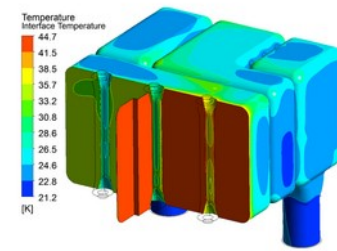
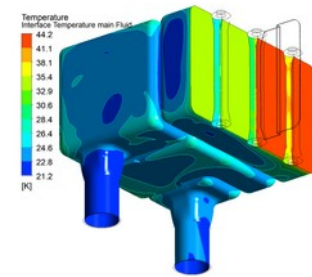
Santoro *et al*, JNR, vol. 25, no. 3-4, pp. 315-406, 2023



# NNbar Sensitivity

Aim: Increase current sensitivity limit by 1000

- Concept of a liquid D<sub>2</sub> moderator developed
  - high intensity of slow neutrons
- Large angular acceptance: The Large Beam Port (LBP) at ESS is a worldwide unique facility and accepts neutrons with an emission angle  $\pm 5^\circ$
- Reflector system: Large-scale nested neutron mirrors



Santoro *et al*, JNR, vol. 25, no. 3-4, pp. 315-406, 2023



# Summary

- Upon completion the world's brightest spallation neutron source
- Proposed fundamental science program consists of neutrino and neutron experiments
- Exciting possibilities for fundamental physics at ESS
  - Short term: CevNS, HIBEAM
  - Long term: NNBAR, nEDM @ HIBEAM, ESSvSB
- New ideas and collaborators welcome!



**Thank you for your attention!**

2024-10-02