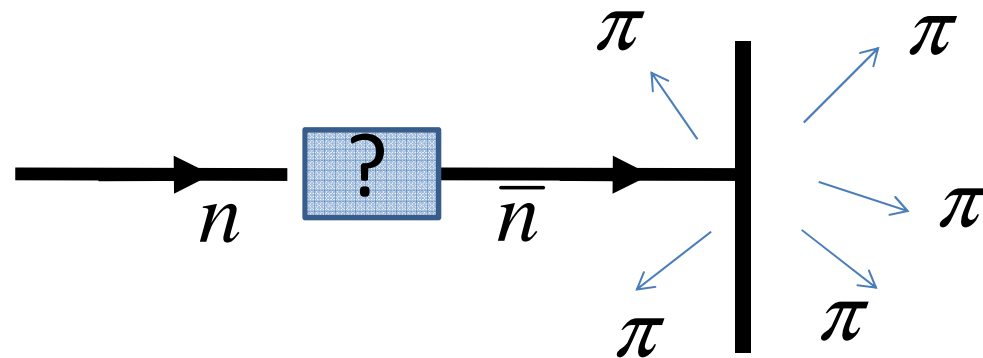


A search for free  $n \rightarrow \bar{n}$  oscillations at the ESS



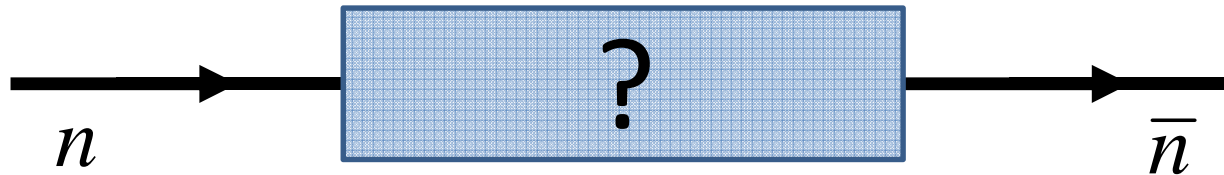
D. Milstead  
Stockholm University

# Motivation for a search for $n\bar{n}$

- Why baryon number violation ?
  - Baryon number is not a “sacred” quantum number
  - “Accidental” symmetry in the SM
  - $BNV$  in SM by non-perturbative processes (instantons)
  - Generic  $BNV$  in BSM theories
- Why  $n\bar{n}$  ?
  - Baryogenesis:  $n\bar{n}$  is  $BNV$  and  $CP$ -violating (Sakharov conditions)
  - Synergy between  $n\bar{n}$  ( $\Delta B=2$ ) and double neutrinoless  $\beta$ -decay ( $\Delta L=2$ ) via  $B-L$
  - Scan for  $BNV$  beyond LHC energies up to  $\sim$ GUT scale.
  - Set limit on stability of matter
  - Few pure  $BNV$  searches
    - Nucleon decay searches largely require  $BNV$  and  $LNV$
    - $n\bar{n}$  and dinucleon decays sensitive to  $BNV$  -only

See arXiv:1410.1100 for more details

# $n \rightarrow \bar{n}$ mixing formalism



$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

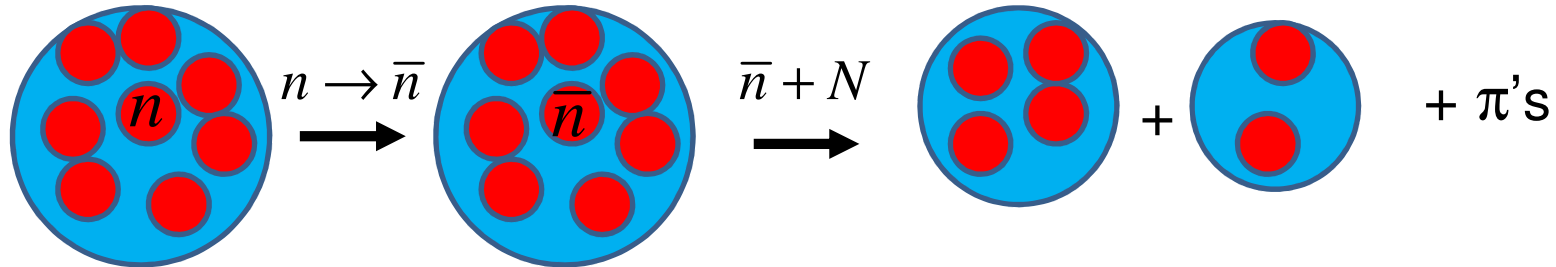
$$\delta m = \langle \bar{n} | H_{eff} | n \rangle < 10^{-29} \text{ MeV} = n\bar{n} \text{ mixing physics}$$

$$P_{n \rightarrow \bar{n}} = \left( \frac{\delta m}{\Delta E} \right)^2 \sin^2 (\Delta E \times t)$$

$\Delta E$  = energy difference of  $n$  and  $\bar{n}$

# Search strategies and limits

## Nuclear disintegration after neutron oscillation



$$P_{n \rightarrow \bar{n}} = \left( \frac{\delta m}{\Delta E} \right)^2 \sin^2(\Delta E \times t), \quad \Delta E \sim 100 \text{ MeV} . \text{ Suppression: } \left( \frac{\delta m}{\Delta E} \right)^2 < 10^{-60}$$

Best current limits (SuperKamiokande)  $\Rightarrow \tau_{free} > 2.7 \times 10^8 \text{ s}$

## Free neutron oscillation

$$\Delta E \times t \ll 1 \Rightarrow P_{n \rightarrow \bar{n}} \sim (\delta m \times t)^2 = \left( \frac{t}{\tau_{free}} \right)^2$$

Best current limit (ILL)  $\tau_{free} > 0.87 \times 10^8 \text{ s}$

## Free neutron oscillation at ESS

$\sim 10^3$  increase in  $P_{n \rightarrow \bar{n}}$  sensitivity:  $\tau_{free} > 3 \times 10^9 \text{ s}$

Stability of matter sensitivity up to  $\sim 10^{34}$  years.

# The European Spallation Source

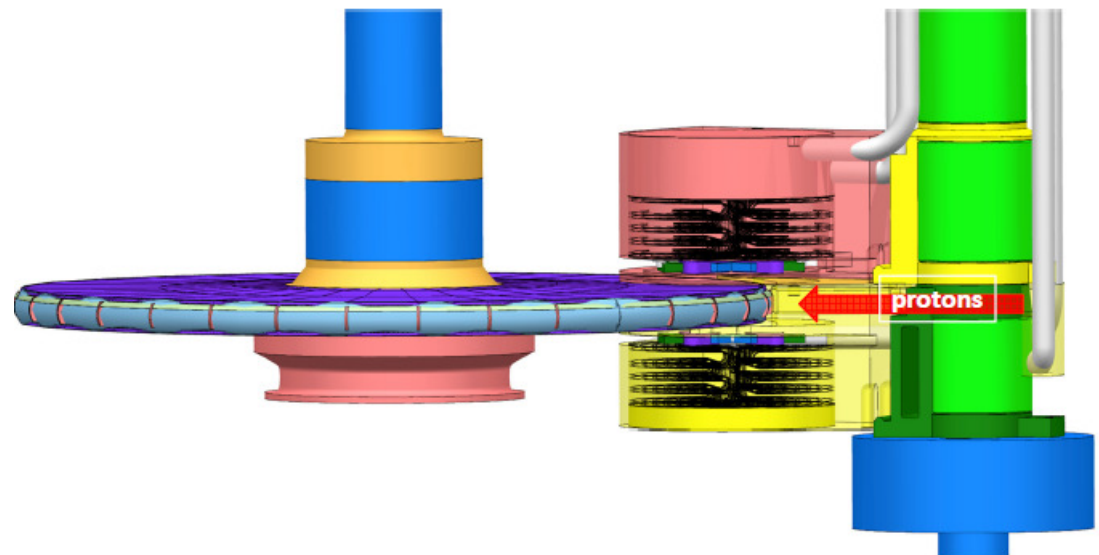
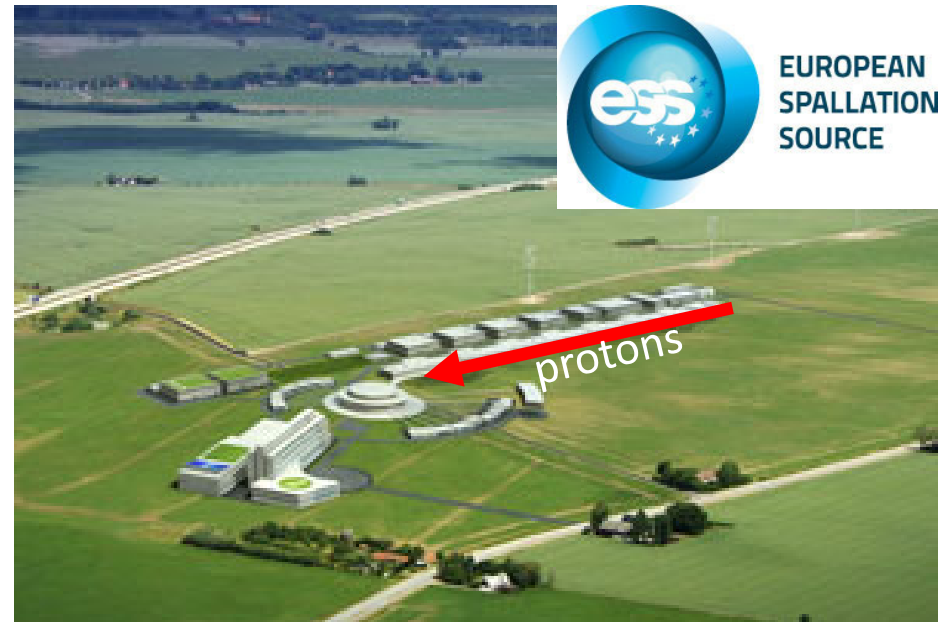
High intensity spallation  
neutron source

Multidisciplinary research centre  
with 17 European nations  
participating.

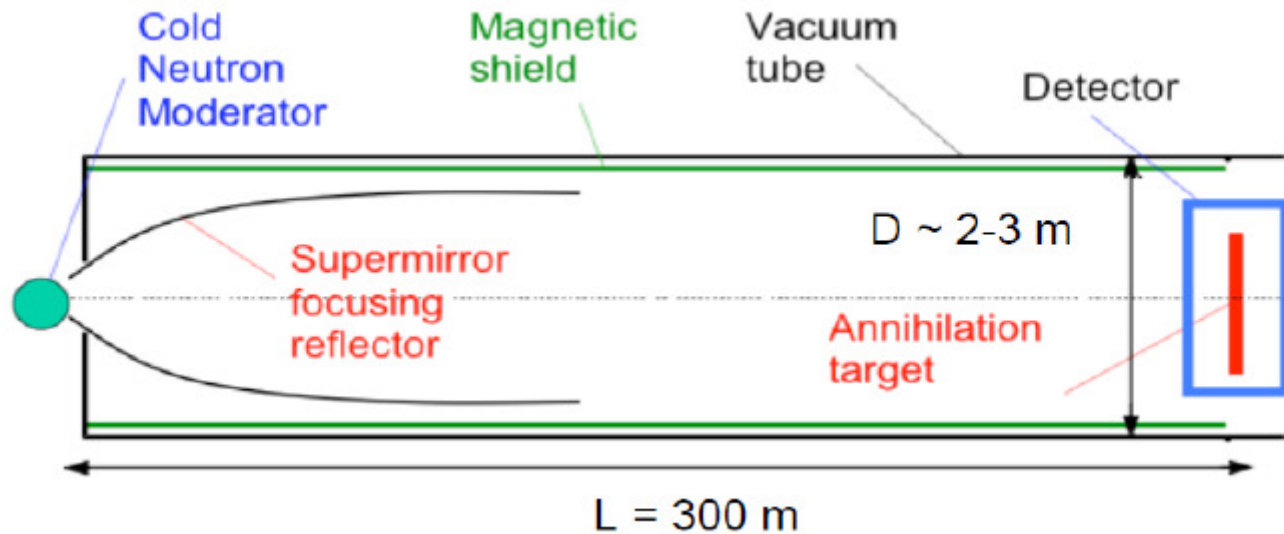
Lund, Sweden.  
Start operations in 2019.

2 GeV protons (3ms long pulse,  
14 Hz) hit rotating tungsten  
target.

Cold neutrons after interaction  
with moderators.



# Overview of the Experiment



Optimise sensitivity =  $N_n t^2$

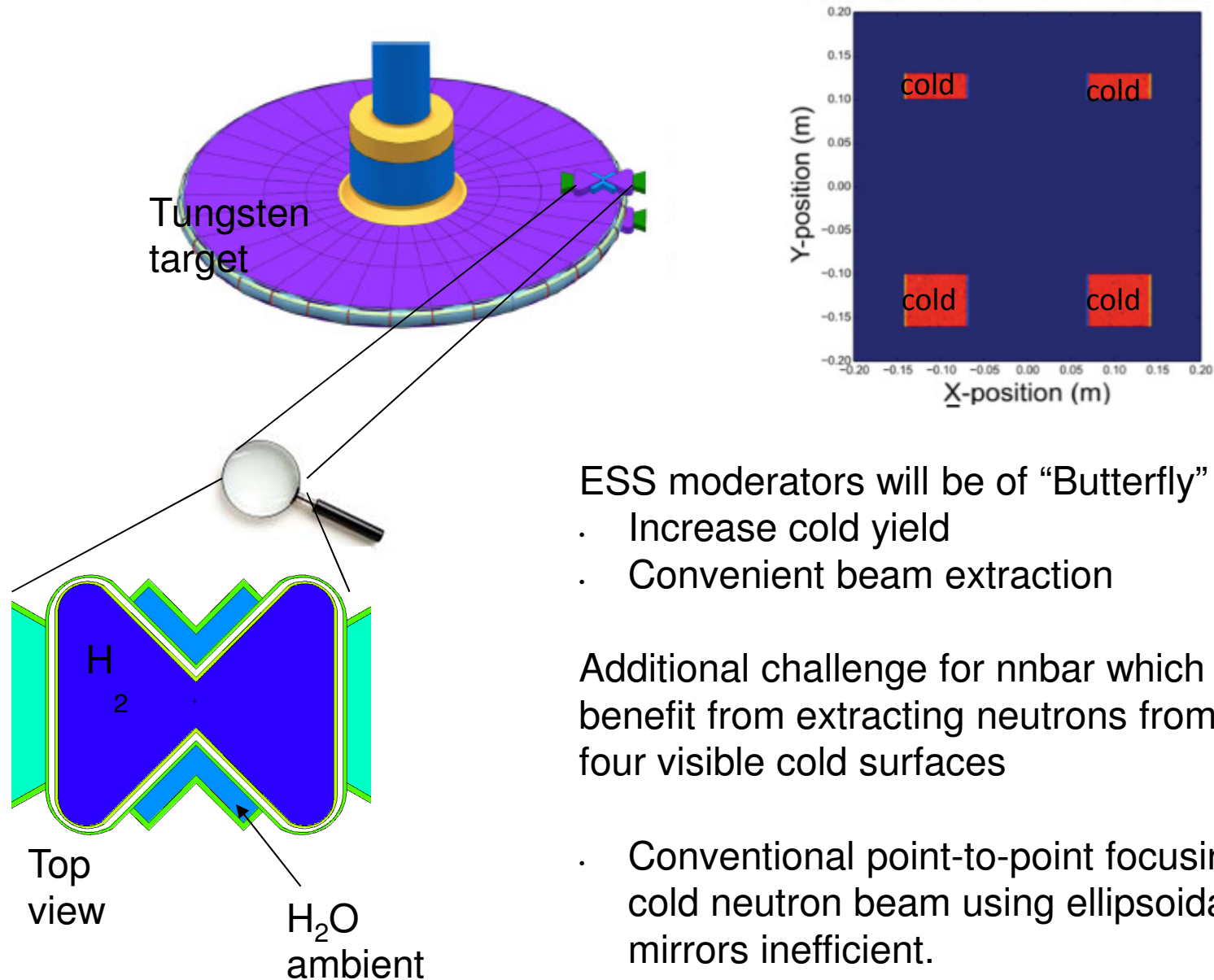
$N_n$  = free neutron flux at target;  $t$  = transit time

- Cold neutrons ( $E < 5 \text{ meV}$ ,  $v < 1000 \text{ ms}^{-1}$ )
- Low neutron emission temperature (50-60 K)
  - Supermirror transmission and transit time
- Large beam port option, large solid angle to cold moderator.

Increase in sensitivity for  $P_{n\bar{n}} \sim 10^3$  compared to previous experiment (ILL)

- Neutron guiding, larger opening angle, higher flux, particle ID technologies, running time.

# Neutronics



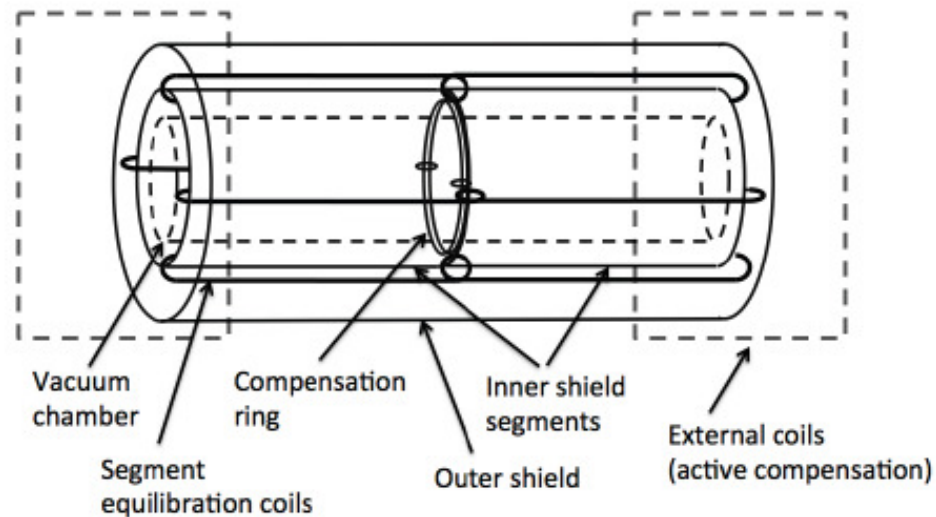
ESS moderators will be of “Butterfly” design

- Increase cold yield
- Convenient beam extraction

Additional challenge for nbar which could benefit from extracting neutrons from all four visible cold surfaces

- Conventional point-to-point focusing of a cold neutron beam using ellipsoidal mirrors inefficient.
- Ongoing studies on neutron optics

# Shielding



Energy difference of  $n, \bar{n}$  in B-field:  $\Delta E = -2\vec{\mu} \cdot \vec{B}$

⇒ Magnetic shielding for flight volume

- $B < 5\text{nT}$ ,  $P \sim 10^{-5}\text{mbar}$
- Aluminium vacuum chamber
- Passive magnetic shield from magnetizable alloy
- External coils for active compensation
- Background studied by turning on/off  $\vec{B}$ -field.

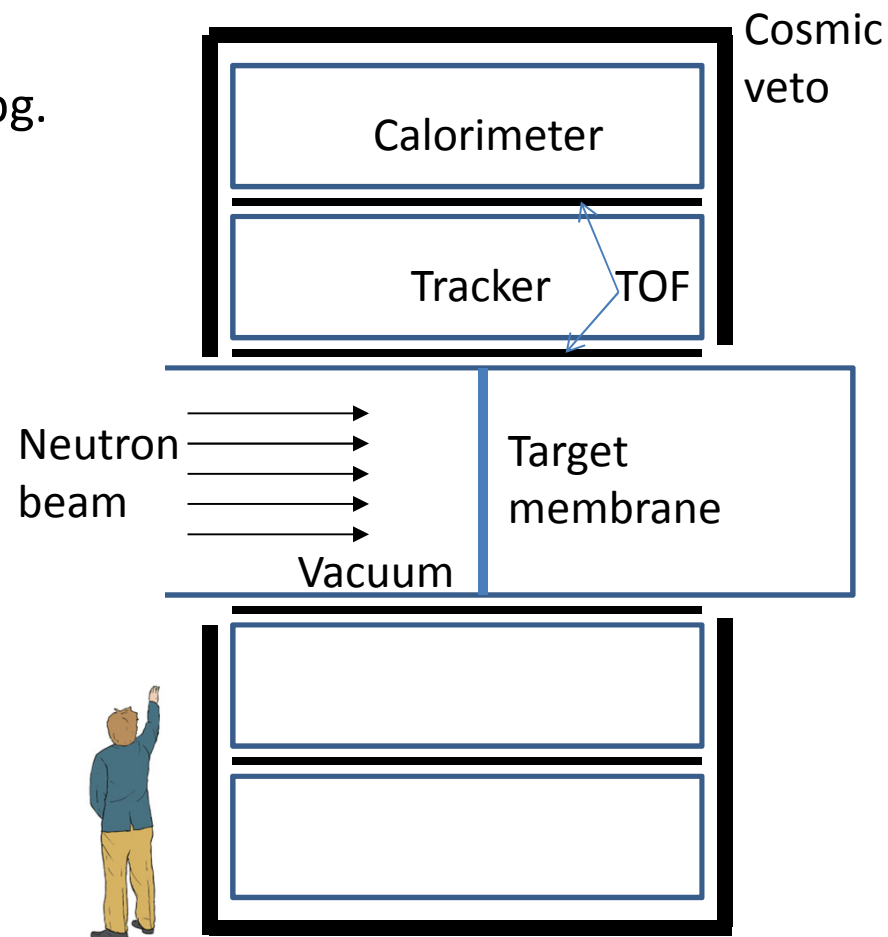


# Detector

Expect  $n + \bar{n} \rightarrow \sim 5\pi$  at  $\sqrt{s} \sim 2$  GeV.

Detector design for high efficiency and low bg.

- Annihilation target - carbon sheet
- Tracker - vertex reconstruction
- Time-of-flight system
  - scintillators around tracker.
- Calorimeter
  - lead + scintillating and clear fibre.
- Cosmic veto - plastic scintillator pads
- Trigger - Track and cluster algorithms



# Collaboration and approximate timescales

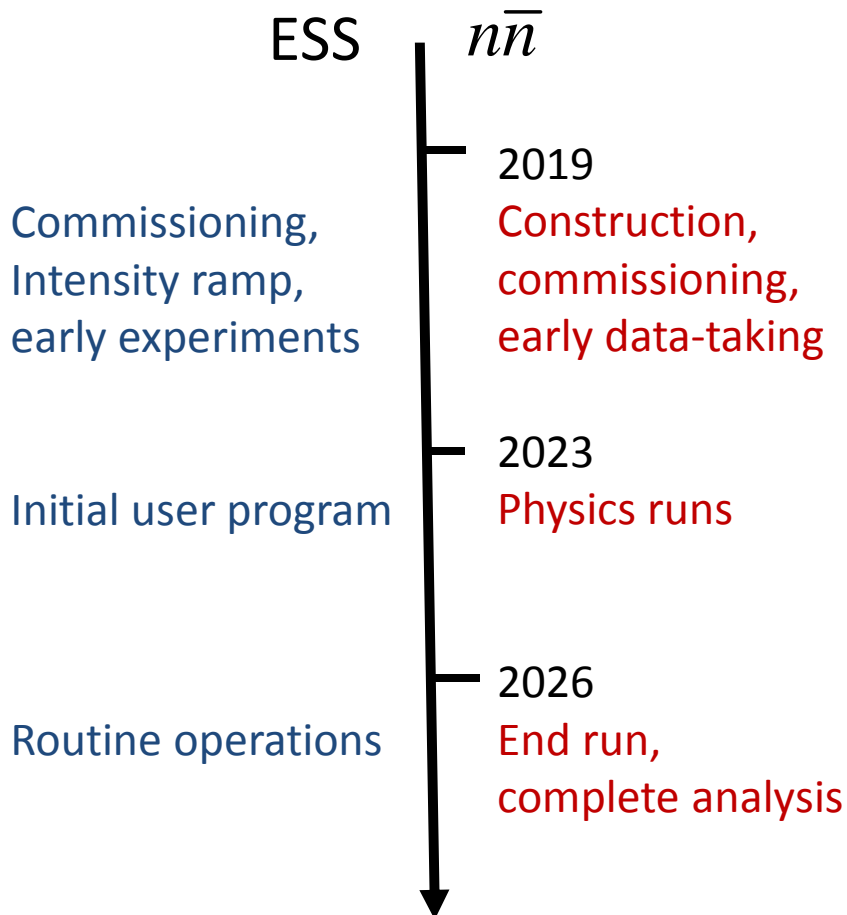
Several workshops (CERN, Lund)

Collaboration formed – interim spokesperson G. Brooijmans

Expression of Interest submitted to ESS.

Signatories from 26 institutes , 8 countries.

**More collaborators are welcome!**



The poster features a blue header with the title 'Neutron-Anti-Neutron Oscillations at ESS' and the dates 'Lund, Feb 18-19, 2015'. Below the header is a photograph of the ESS facility in Lund, Sweden. The main body of the poster contains text about the scientific importance of neutron oscillations and the details of the workshop. At the bottom, there are logos for ESS and CERN, and a registration box.

**Neutron-Anti-Neutron Oscillations at ESS**  
Lund, Feb 18-19, 2015

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. Kaon oscillations provided us with our first insight into CP-violation, fast B<sub>s</sub> oscillations provided the first indication that the top quark is extremely heavy, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation. The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with at least three orders of magnitude improvement in sensitivity to the neutron oscillation probability.

At this workshop the physics case for such an experiment will be discussed, together with the main experimental challenges and possible solutions. We hope the workshop will conclude with the first steps towards the formation of a collaboration to build and perform the experiment.

**Organising committee:**

- G. Brooijmans (Columbia University)
- S. Chakraborty (Cockcroft Institute)
- R. Holt-Wilson (European Spallation Source)
- V. Kuznetsov (University of Tennessee)
- E. Hübner (Technical University of Denmark and European Spallation Source)
- M. Lindner (European Spallation Source and Lund University)
- L. Mepel (ESS)
- M. Mezzetto (INFN Padova)
- H. M. Sorenson (Plymouth University)
- W. M. Snow (Indiana University)
- T. Seldner (Institute Laue-Langevin)
- C. Thomaas (European Spallation Source)

**Register before 19 May on**  
[www.nbar-at-ess.org](http://www.nbar-at-ess.org)

ESS EUROPEAN SPALLATION SOURCE CERN

# Summary and outlook

- The search for neutron-antineutron oscillations addresses open questions in modern physics.
- An experiment at the ESS offers a new opportunity to extend sensitivity to neutron oscillation probability by several orders of magnitude and set a new limit on the stability of matter.
- Collaboration formed and EOI submitted
- Provisional schedule made
- **New collaborators welcome!**
  - **Next workshop 27th-28th August in Gothenburg**
  - **Open to collaboration members and those who are interested in potentially joining.**
  - **<https://indico.esss.lu.se/indico/event/349/>**