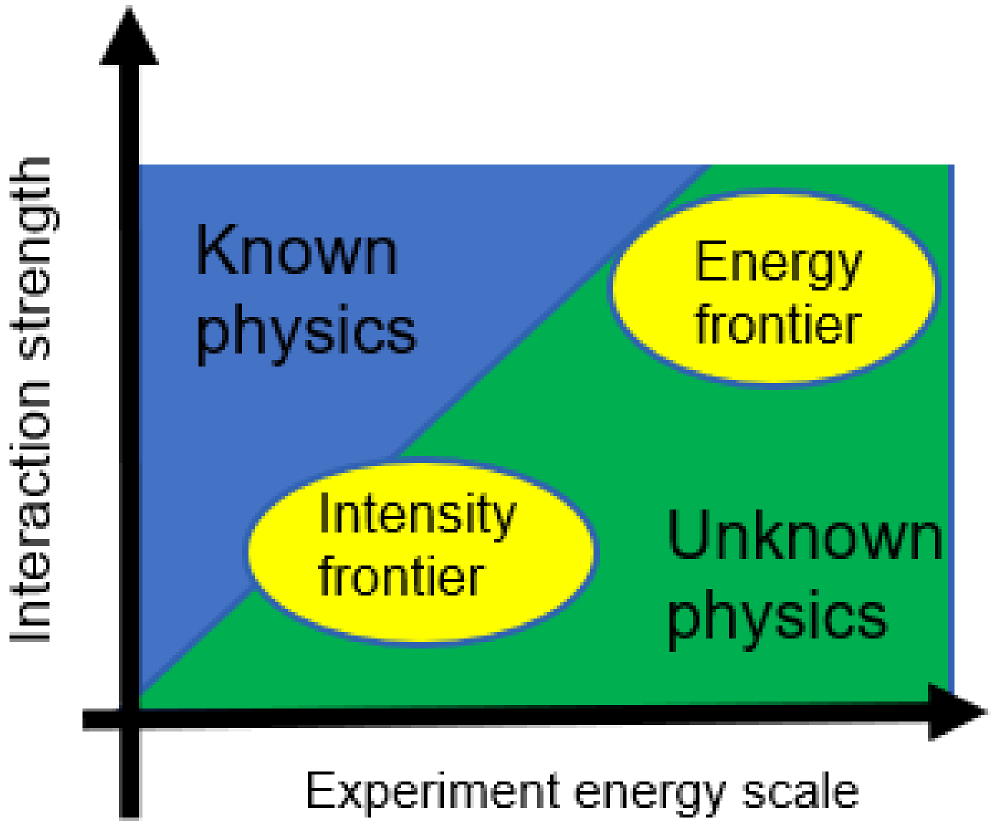
Intensity frontier

Intensity Frontier

- Unique potential with lower energy phenomena in ultra-rare processes requiring highly intense particle beams.
- Overlap with neutrino/astroparticle/cosmo and hadron physics.
  - Activities covered in other talks.
- Activities with institutional commitment
  - **LDMX**
  - **HIBEAM/NNBAR**
  - **ESSnuSB**

  Coherent neutrino-nuclear scattering also included.
- Format
  - **Brief** activity overview
  - Swedish contribution
  - Q4(a)-4(c)

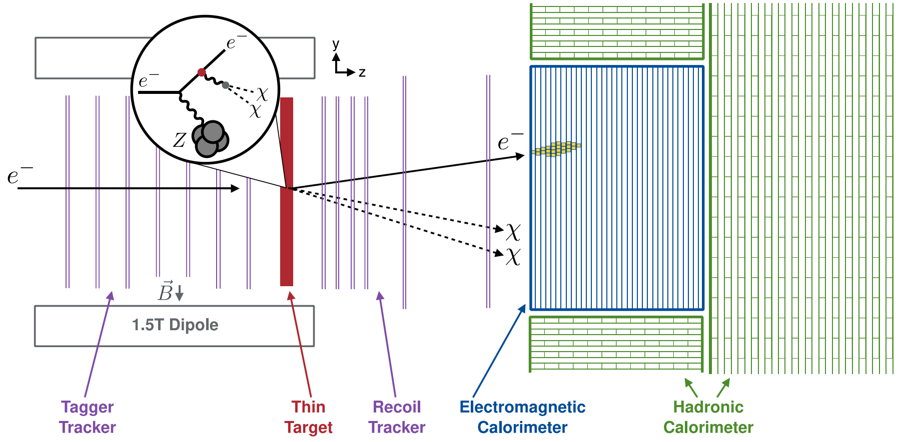


LDMX in a nutshell

Thermal equilibrium in early universe implies accelerator production cross section for MeV – GeV such that generic dark matter thermal-relic scenarios can be conclusively probed with 10^{15} electrons on target.

→ LDMX at SLAC (8 GeV, start data taking ~2029, run <10 years)

Main signal signature: Dark sector particle production in the target
→ *missing energy/momentum* in downstream detectors (Tracker, ECal, HCal)



Direct detection of creation of something massive not charged under QED or QCD

→ Mass estimation possible from recoil-electron p_T spectrum

If measurement compatible with relic abundance, the most logical explanation is that this is DM. (What else should it be? And if it is something else, what happened to this BSM particle in the early Universe?)

World-leading sensitivity beyond relic abundance expectations over much of the MeV-GeV mass range

Broader potential: Search for other low-mass dark-sector signatures (visible and invisible), measurement of electro-nuclear and photo-nuclear reactions in unexplored phase space

Electro-nuclear interesting for neutrino physics (proxy for nu-N reactions)

LDMX commitment in Sweden

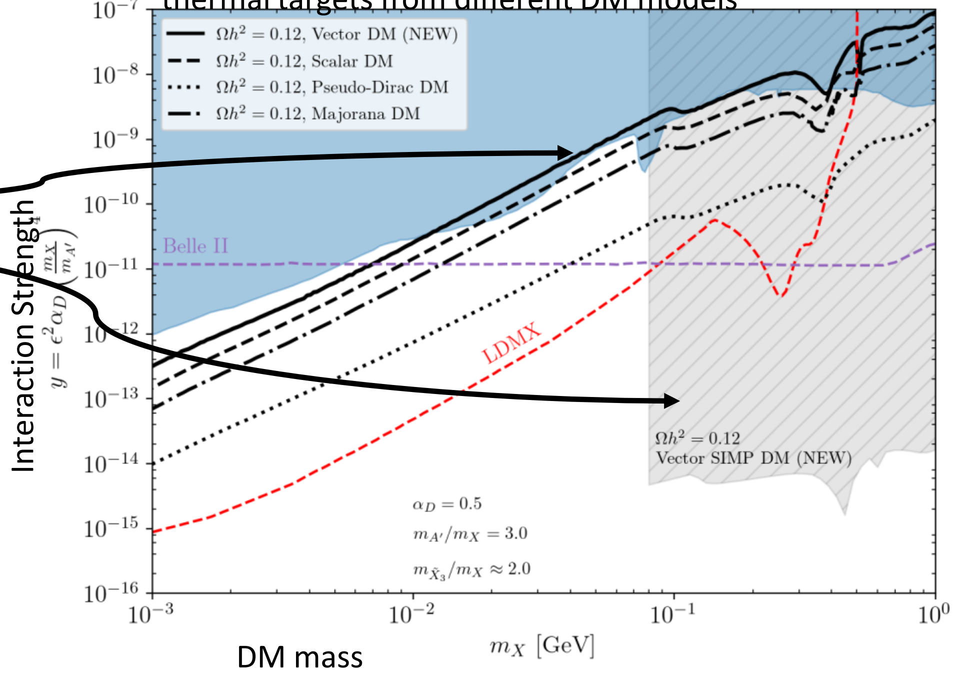
Main: LDMX activity in Lund, part of LDMX collaboration (LU + 9 US institutions)

- Read-out electronics for HCal
- Pile-up handling online and offline, Background and sensitivity studies
- Software development and computing
- Generator comparison, Geant4-PYTHIA integration
- (Climate) Sustainability studies
- 5 seniors, 2 PhD students, several bachelor/master students
- Spokesperson (TÅ), Physics (RP) & SW+Computing (LKB) & Testbeam Coordination (HH)
- Funded by KAW, VR, Crafoord, Fysiografen (~5 MEuro)

In addition, collaboration with Chalmers & SU as part of a [KAW project]

- Model-building
- Statistical analysis, global fits (e.g.[arxiv:2405.17548])
- Implications for direct detection experiments (e.g. [arxiv:2411.10216])

LDMX sensitivity relative to existing bounds and thermal targets from different DM models



Question 4

a) What other areas of physics should be pursued, and with what relative priority?

- Research targeting the big open questions: Dark matter and matter-antimatter-asymmetry

b) What are the most important elements in the response to 4a)?

i) **Physics potential** – Exploring LDM is imperative, LDMX is the best tool

ii) Long-term perspective – Will decisively probe the sub-GeV mass range for thermal DM, where a signal will give indications of what mass range to design for)

iii) **Financial and human resources**: **requirements and effect on other projects**
-- Relatively small scale, inexpensive (20M $, ~50 people)

iv) Timing – window of opportunity at SLAC, conclusive results within the next decade (timeframe of this strategy)

v) Careers and training – Great opportunity for students/postdocs to know all facets of their experiment, high visibility

vi) Sustainability – Relatively small climate footprint

→ In short: Huge scientific potential for relatively small cost, plus some additional benefits

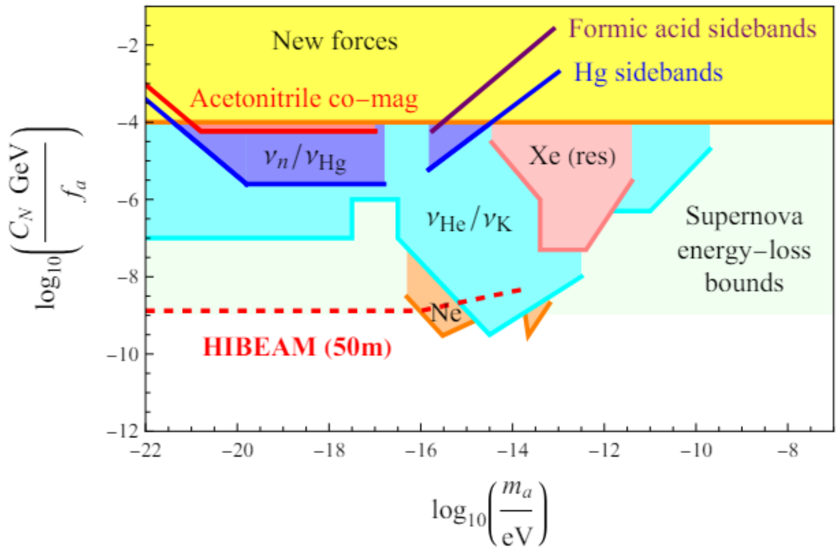
c) To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention? Please use the current level and form of activity as the baseline for comparisons.

CERN supporting a US-based experiment is part of a mutual exchange of access to research infrastructure, via which US researchers have access to CERN w/o paying e.g. for accelerator operations. It would be a wasted opportunity (and wasted money) not to exploit this access.
LDMX would appreciate the opportunity to become a CERN-recognised experiment (once another European institute joins) to benefit from CERN-provided infrastructure, e.g. computing

HIBEAM/NNBAR in nutshell

- The ESS is the world's brightest neutron source
  - ~10^{15} n/s
  - Opens a new intensity frontier in the pp landscape
  - Unique potential to address beyogenesis, dark matter and SM tests

- No fundamental physics program at the ESS
- No instrument under Swedish leadership despite 10BSEK investment
- HIBEAM/NNBAR multi-stage program
  - HIBEAM
    - Fundamental physics beamline
    - Baryon nyumber violation/precision tests of fundamental symmetry/baryogenesis/dark matter
    - Neutron-antineutron, neutron-sterile neutron, axion, neutron charge, neutron EDM
    - CDR/TDR in preparation
    - x10 or above increase in sensitivity
    - Investment by ESS for beam insert
    - Generic but was proposed by HIBEAM
  - NNBAR
    - x 1000 improvement in discovery potential for neutron-antineutron
    - CDR (*J.Neutron Res.* 25 (2024) 3-4, 315-406)



HIBEAM/NNBAR

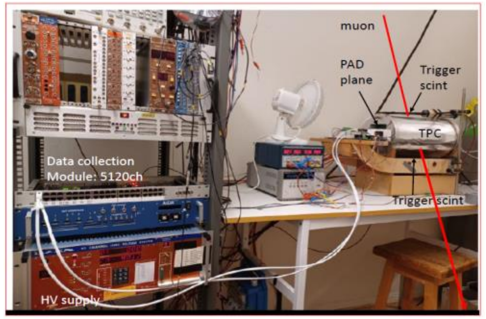
Co-spokespersons: G. Brooijmans (Columbia), D. M. (SU)
Lead scientist: Y. Kamyshkov (Tennesee)
Technical Coordinator : V. S. (ESS, LU)
Prototype coordinator : M. H. (ESS)
Computing and Detector Simulation: B. M. (LU,CTH)

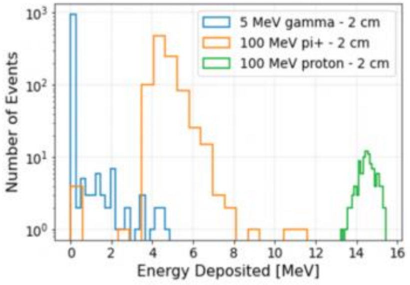
Swedish institutes: SU (DM, Sam S.) , AB) , CTU (BM, AH) ,UU (MW) ,LU (VS, BM, AO)
International – Krakow, Rio, TMU, Tennessee, Columbia…

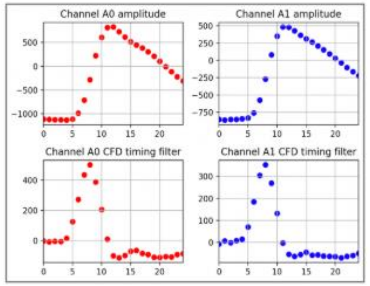
HIBEAM supported by VR and VR RFI (1.4MEuro in past grants, 0.8MEuro in current grant) , the Swedish Foundation for Research Strategy (1.5MEuros), Olle Engkvist Foundation (0.4MEuro), Craaford (~1MEuro) + VR grant for collaborating with Italian institutes

NNBAR was supported as part of a 3MEuro H2020 grant for an upgraded ESS with a new lower moderator.
STINT award for collaboration with Brazilian institutes
Achieved top grade for ERC Synergy application but were on the reserve list.

Current work on annihilation detector prototype, magnetics and beamline and detector simulations







Question 4

a) What other areas of physics should be pursued, and with what relative priority?

- Research targeting the big open questions: Matter-antimatter-asymmetry, dark matter

b) What are the most important elements in the response to 4a)?

i) **Physics potential** – Observables of new physics (e.g. n-nbar, ulm axions) with orders of magnitude more sensitivity than elsewhere.
ii) Long-term perspective – HIBEAM is a general fundamental physics beamline which can run for decades. NNBAR would have a 3-5 year run.

iii) **Financial and human resources**: **requirements and effect on other projects**
-- HIBEAM (14MEuro – funded by ESS and/or externally, ~20 scientists/engineers), NNBAR (~80MEuro, 50-100 scientists)

iv) Timing – window of opportunity wrt exploitation of ESS for new infrastructure.
v) Careers and training – Great opportunity for students/postdocs to know all facets of their experiment, high visibility
vi) Sustainability – Linac operates regardless of HIBEAM's presence. Proposed carbon-neutral NNBAR

c) To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention? Please use the current level and form of activity as the baseline for comparisons.
There is already general ESS/CERN collaboration which should be deepened.

HIBEAM/NNBAR next step to become a CERN-recognised experiment to benefit from e.g. computing.

European Spallation Source neutrino Super Beam ESSnuSB+

Physics Potential

The exact value of the leptonic CP violation phase angle plays a crucial role for the explanation of why there is matter left in the universe after the general matter-antimatter annihilation that followed the Big Bang, something that cannot be explained by the Standard Model. As the neutrino is the only known elementary particle whose observed properties do not agree with the Standard Model's description, it constitutes a central link to physics beyond the Standard Model.
High precision determination of the phase angle of leptonic CP violation.

3 times higher precision than what will be possible with the two other neutrino oscillation experiments, DUNE and Hyper-K

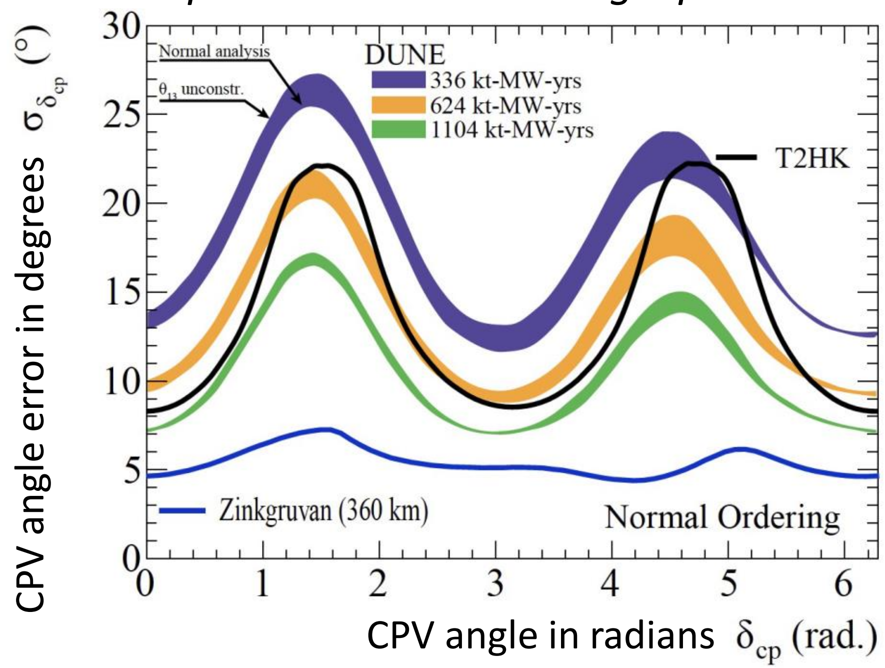
Due to ESS accelerator's very high beam power of 5 MW, with which a world-uniquely intense neutrino beam can be created, enabling measurement at the second neutrino oscillation maximum.

Broad program
Solar, atmospheric and cosmic neutrinos, search for proton decay, measurement of coherent neutrino scattering with greatly reduced background ($x10^{-3}$) due to the 1.2 μs pulse from the accumulator ring.

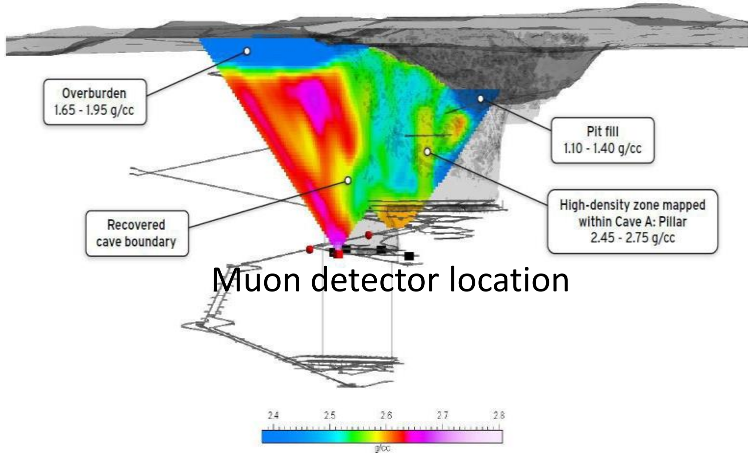
Measurement of fast processes in material physics with spallation-neutron pulses 30 times shorter than the 2.86 ms long pulses produced by the ESS accelerator

Tests for the development of a muon collider, muon tomography for geological investigations and ore prospecting, development of new mining methods for the creation of very large underground chambers and more.

Leptonic CP violation angle precision



Muon tomography precision



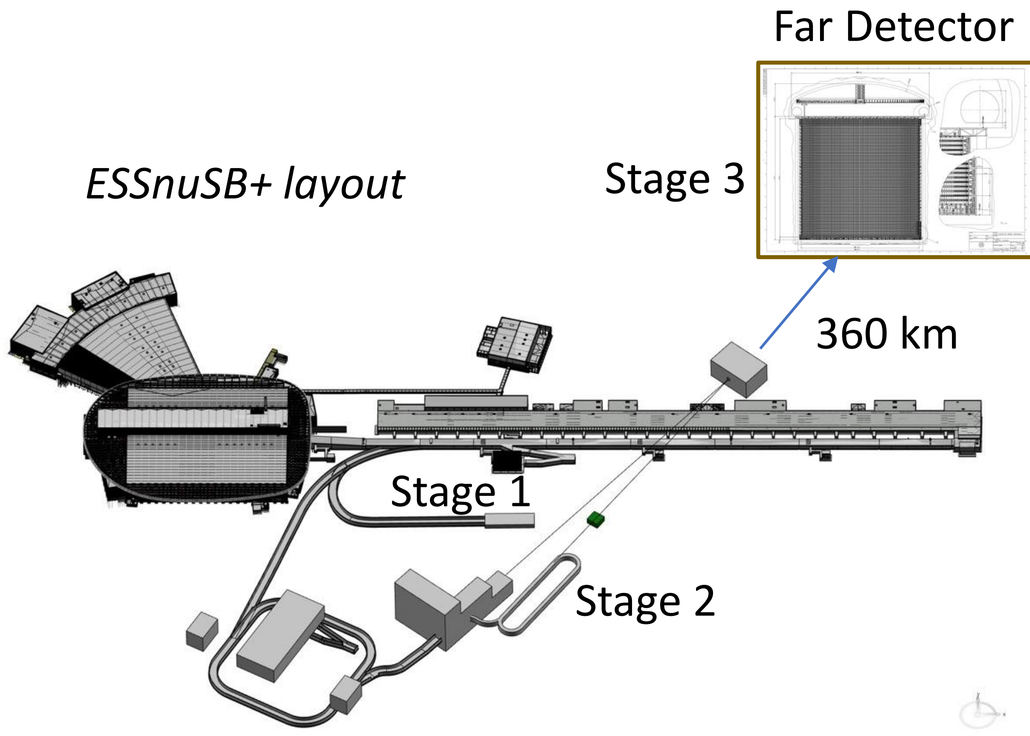
Collaboration and execution

ESSnuSB+ is a project that will be executed in stages
80 researchers at 20 institutions (LU,KTH,UU, LT) and 11 countries

Received 6MEuro from Horizon2020 and Horizon 2020

Swedish leadership:
Scientific leader (TE/UU), Accumulator/nustorm wp leader (MO/UU), Cave consruction (DS,/LTU)

ESSnuSB+ layout



Stage 1 2032 Start operation of the Low Energy Monitored Neutrino Beam LEMNB for ν_μ cross-section measurements

Stage 2 2035 Start of operation of the Low Energy muon Storage Ring LEnuSTORM for ν_e cross-section measurements

Stage 3 2039 Start of operation of ESSnuSB CP-violation Long Base Line operation to continue 10-20 years

ESSnuSB global schedule

Question 4

Financial and human resources, Careers and Training and Sustainability

ESSnuSB Conceptual Design Report, published in 2022 as https://arxiv.org/pdf/2206.01208

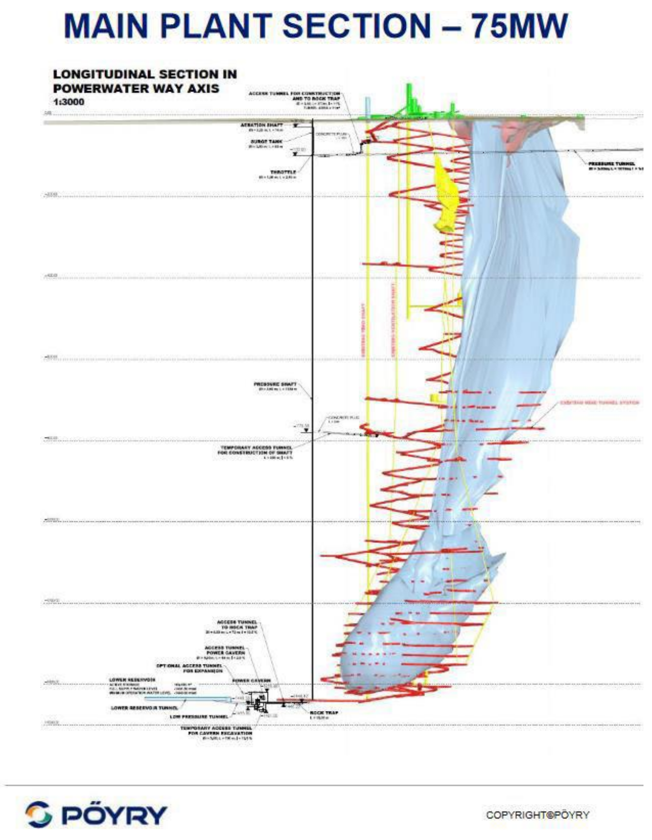
ESSnuSB's investment cost: 1382 M€
Infrastructure costs in the ESS area: €200 million
The total cost will be approximately €1,600 million.

ESSnuSB's European member countries are currently France, Croatia, Sweden, Germany, Greece, Bulgaria, Italy and Spain.
Sweden's share of these countries' combined gross domestic product in 2023 was 4.9%. Sweden's share, 4.9% of €1,600 million, is thus €78 million, which corresponds to approximately SEK 910 million. Under the assumption of a build-up period of about 10 years, this implies an estimated annual cost for Sweden of about SEK 91 million during the build-up period, which is planned to start around 2030.

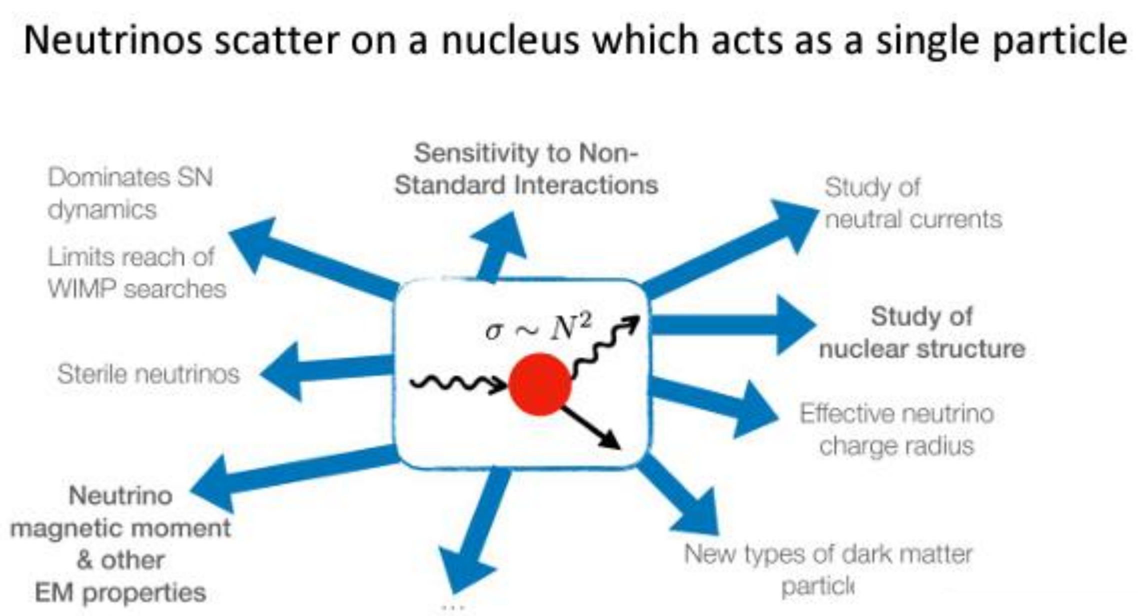
Young researchers working with ESSnuSB will be trained in many challenging tasks typical of experimental particle-physics, developing and operating experimental detectors and accelerators and analysing data. This will constitute an excellent preparation for a continued career in research or, more often, in a professional career in high-tech industry, research education, administration, finance and other branches.

After the decommissioning of ESSnuSB, the 540'000 m^3 cavern volumes will be used for pumped hydro-electricity energy storage, using wind and solar power to pump up to the ground level the water filling the caverns during daytime and letting the water run down to the cavern during nighttime driving electrical generators. Such a project is already underway in the Pyhäsamlmi mine in Finland.

Pumped hydro-electricity energy storage



Coherent neutrino-nucleus scattering

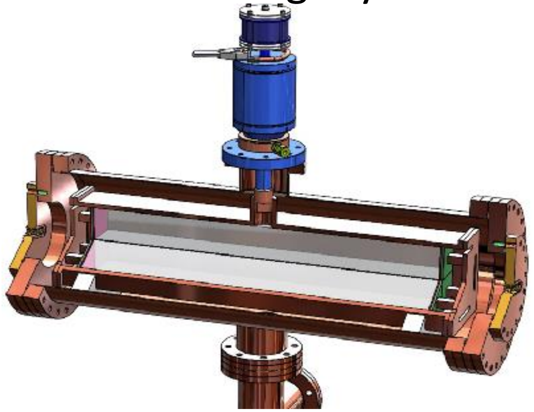


Observed in 2017 (SNS)
Experimental challenge of kEV energy loss
Broad sensitivity increase with ESS.

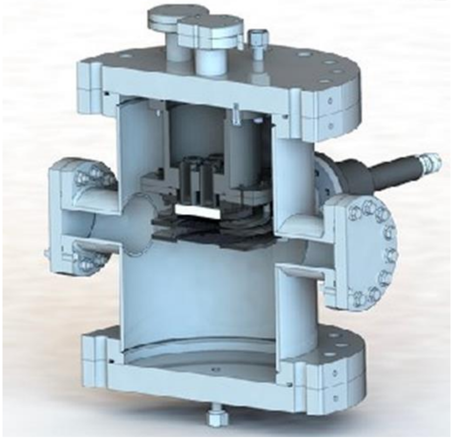
Develop detectors with low threshold sensitivities

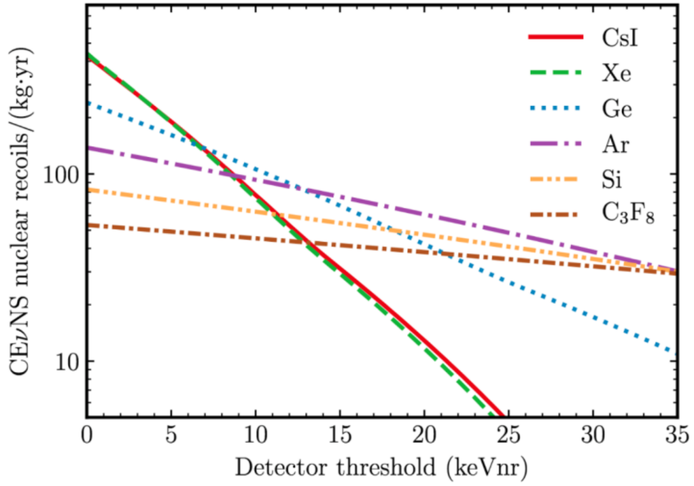
LU – Joakim C., Else L., Johan R.

CsI scintillating crystals



Gaseous detector prototype





Advert: next week: Workshop on Fundamental Particle Physics at ESS featuring all proposed ESS fundamental physics activities

Summary

- Sweden plays leading roles in future intensity frontier experiments.
  - Strategic leadership built up through externally funded and reviewed activities
- A 100km energy frontier collider necessitates that CERN has strong relationships with other laboratories for the intensity frontier to maintain diversity in the field

Cost (MEuro)	Experiment	Search/observable	Earliest Start (years)	Running time (years)	Swedish involvement
15-20	LDMX	Low mass dark matter and dark sector particles, electro-, photo-nuclear	5-6	<10 (HIBEAM: key measurements)	LU + CTU/SU (model building/stats)
	HIBEAM	Neutron-antineutron, sterile neutron, axion, electric charge + others			LU, CTU, UU, SU
80	NNBAR	Neutron-antineutron	> 10	3-5	
1600	ESSnuSB	Leptonic CP violation phase angle, solar, atmospheric and cosmic neutrinos, proton decay	7 years	20-30	LU, KTH, UU, LTU