Co-funded by the European Union

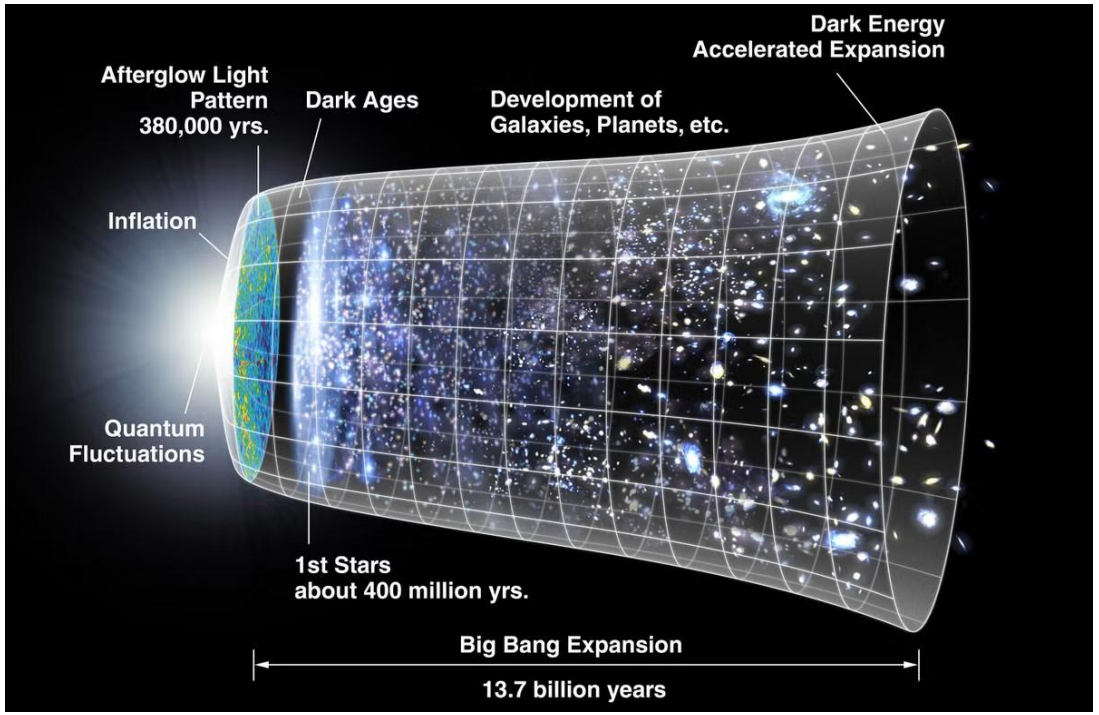
Neutrinos from the European Spallation Source (ESS)

Overview of the physics prospects at ESSnuSB

Sampsa Vihonen (KTH)

on behalf of the ESSnuSB collaboration

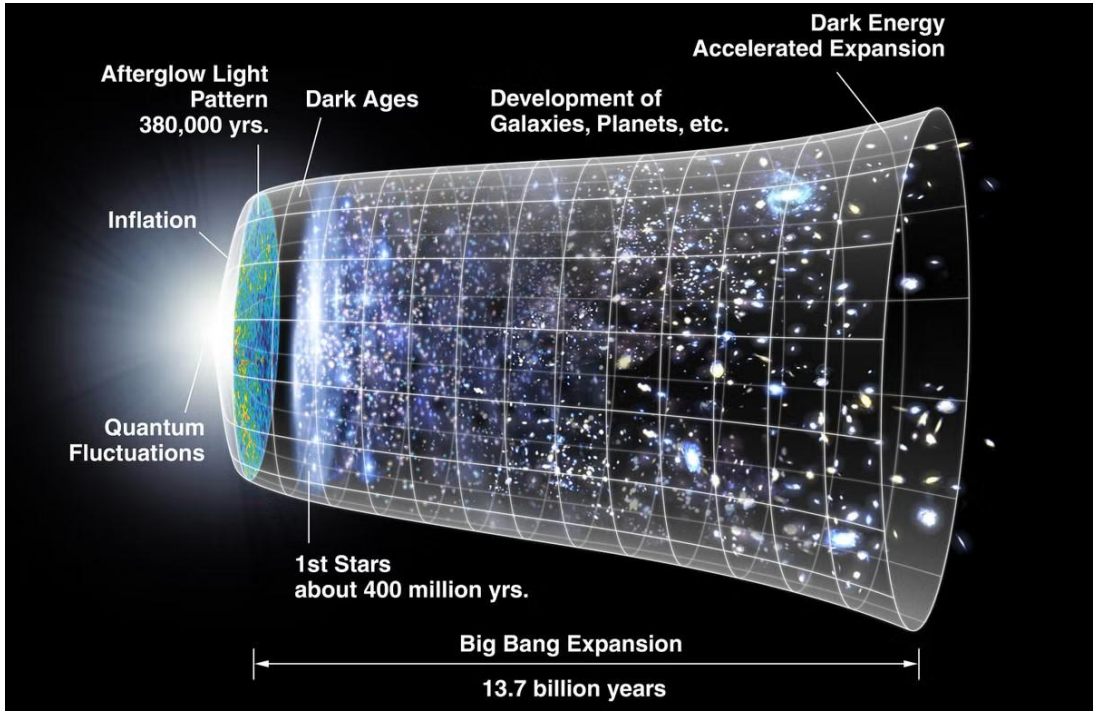
Introduction and motivation



Sakharov's three conditions for successful baryon asymmetry:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Introduction and motivation

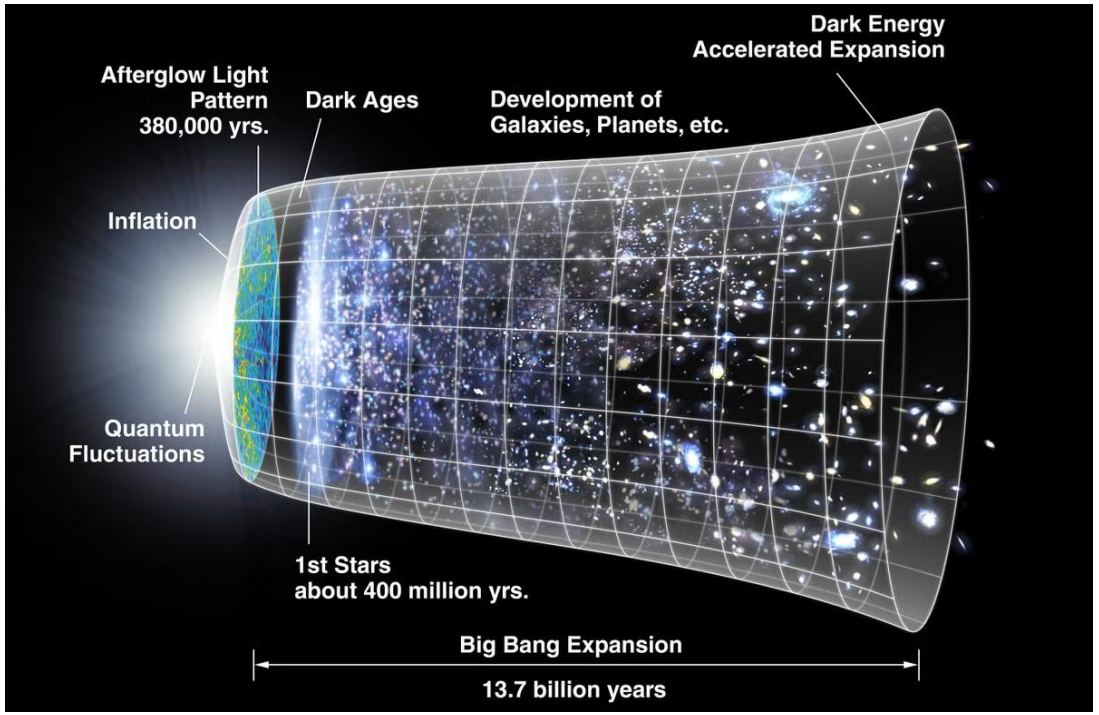


Sakharov's three conditions for successful baryon asymmetry:

1. Baryon number violation
2. **C and CP violation**
3. Departure from thermal equilibrium

1964: CP violation in kaon decays
2025: CP violation in baryon decays

Introduction and motivation



Sakharov's three conditions for successful baryon asymmetry:

1. Baryon number violation
2. **C and CP violation**
3. Departure from thermal equilibrium

ESSnuSB aims to seach CP violation in the leptonic sector!

European Spallation Source

ESS neutrino Super Beam plus

The Europe Spallation Source offers the possibility to elaborate a **high intensity neutrino superbeam in Europe**

LINAC Upgrades

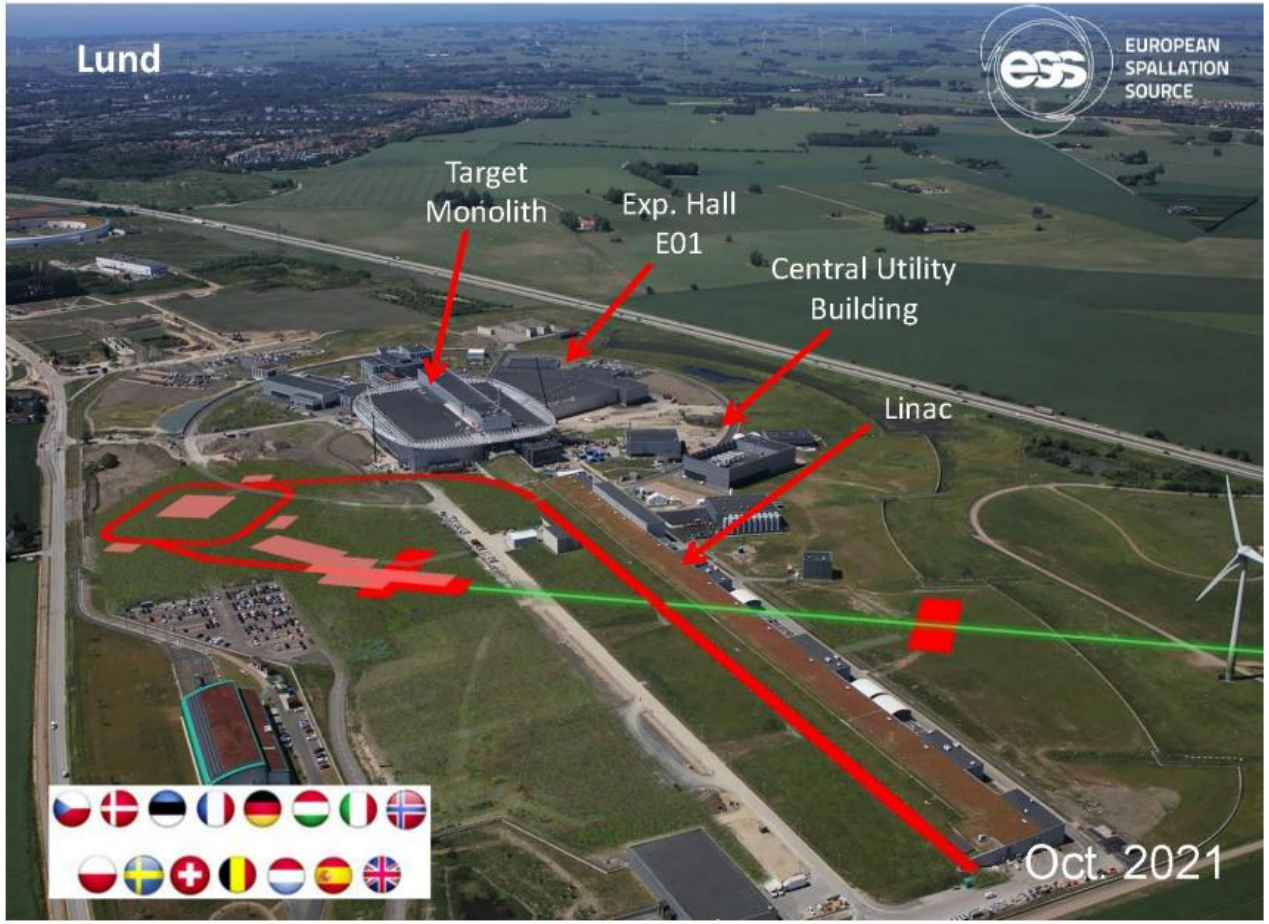
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power => 10 MW
- 125 MW peak power.
- 28 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4% => Duty cycle 8%
- 2.0 GeV kinetic energy protons => 2.5 GeV

Additional Facilities

- Accumulator ring to shorten the pulses to μs order for the horn (Extra H^- source are. needed).
- Target Station to convert the 5 MW proton beam into neutrinos.
- Near and Far detectors.

⇒ ESSnuSB/ESSnuSB+ projects funded by EU and 11 European Governmental research agencies

These facilities has to be in agreement with the regulation rules and environmental constraints in Sweden.



Implementation of the Facility on ESS

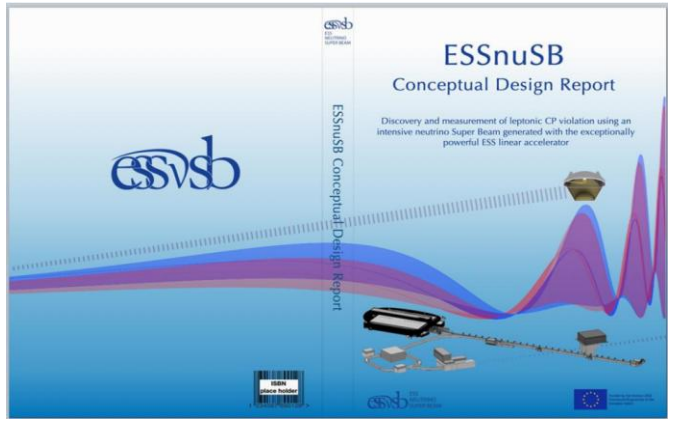
Slide by the courtesy of Tord Ekelöf

About the collaboration

ESS neutrino Super Beam plus

ESSnuSB collaboration

- 92 collaborators
- 20 member institutions
- 11 European countries

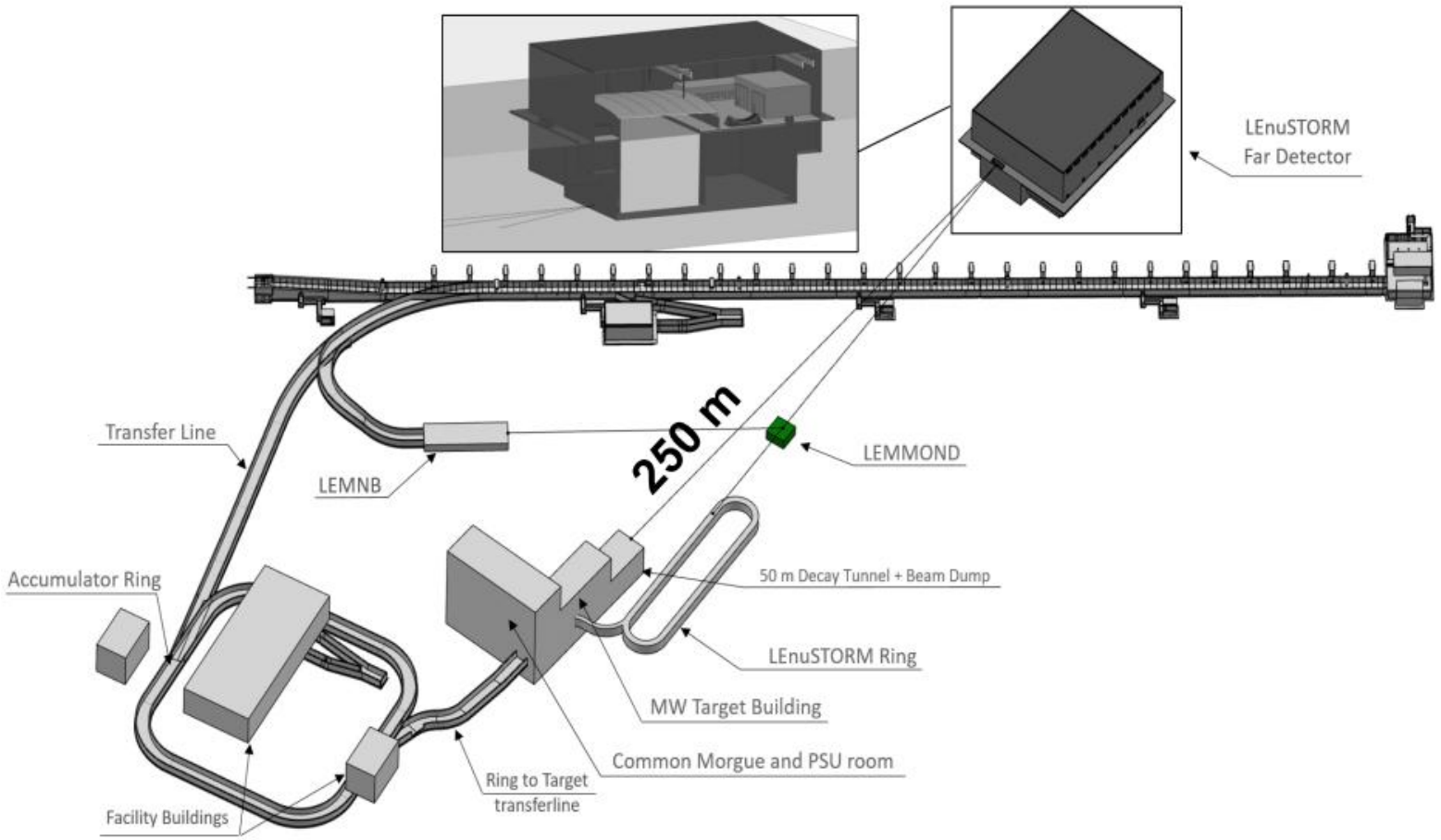


Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Université de Strasbourg	UNISTRA[1]	France
3	Rudjer Boskovic Institute	RBI	Croatia
4	Tokai National Higher Education and Research System, National University Corporation	NU[2]	Japan
5	Uppsala Universitet	UU	Sweden
6	Lunds Universitet	ULUND	Sweden
7	European Spallation Source ERIC	ESS	Sweden
8	Kungliga Tekniska Hoegskolan	KTH	Sweden
9	Universitaet Hamburg	UHH	Germany
10	University of Cukurova	CU	Turkey
11	National Center for Scientific Research "Demokritos"	NCSRD	Greece
12	Aristotelio Panepistimio Thessalonikis	AUTH[1]	Greece
13	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
14	Lulea Tekniska Universitet	LTU	Sweden
15	European Organisation for Nuclear Research	CERN	IEIO[3]
16	Universita degli Studi Roma Tre	UNIROMA3	Italy
17	Universita degli Istudi di Milano-Bicocca	UNIMIB	Italy
18	Istituto Nazionale di Fisica Nucleare	INFN	Italy
19	Universita degli Istudi di Padova	UNIPD[1]	Italy
20	Consorcio para la construccion, equipamiento y explotacion de la sede espanola de la fuente Europea de neutrones por espalacion	ESSB	Spain

[1] Affiliated Partner
[2] Associated Institute
[3] International European Interest Organisation

ESSnuSB Conceptual Design Report
A. Alekou *et al.*, *Eur.Phys.J.ST* 231 (2022) 21, 3779-3955

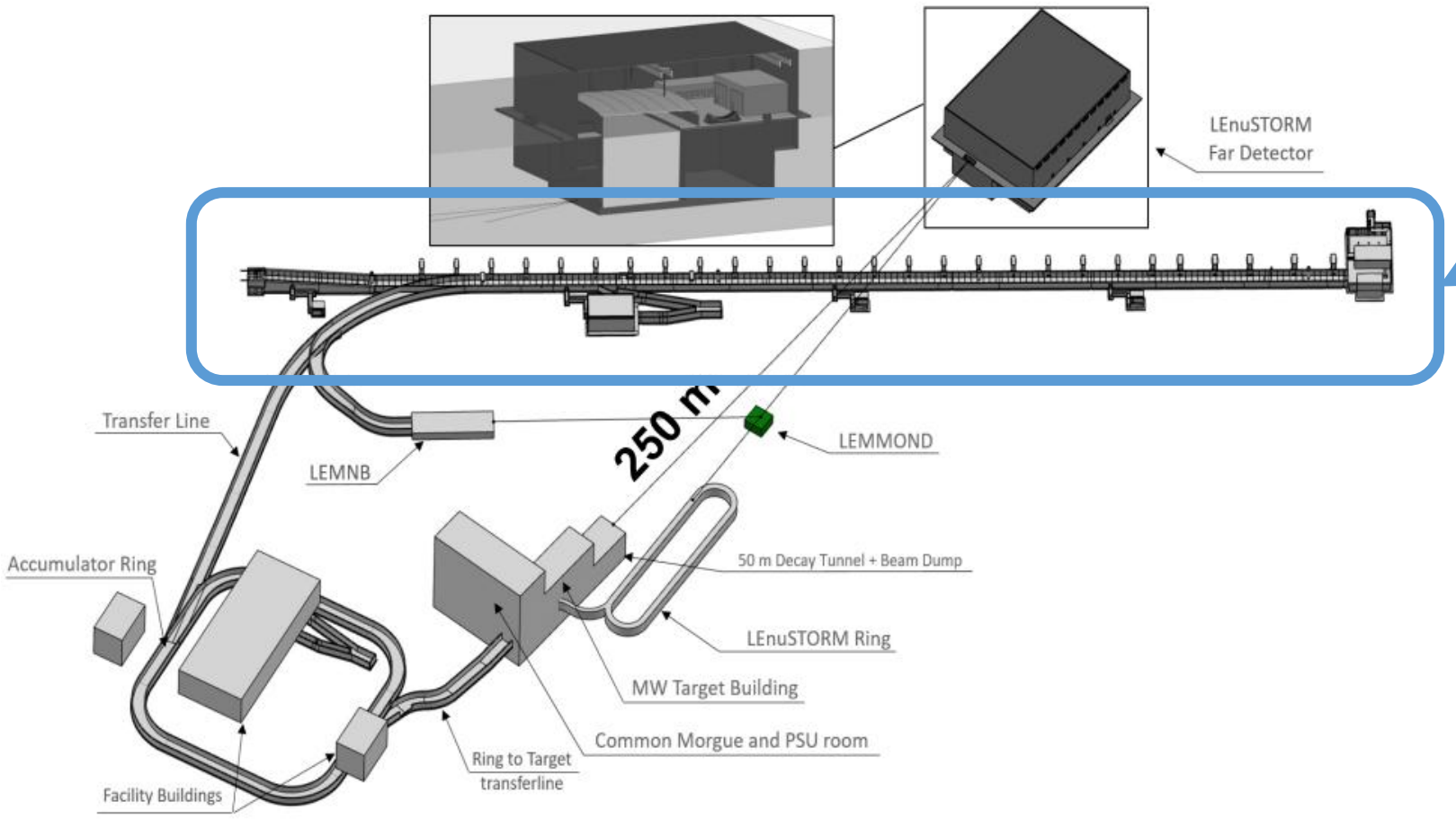
Experimental configuration of ESSnuSB



Major components

1. Main accelerator
2. Accumulator
3. Target station
4. Near detectors

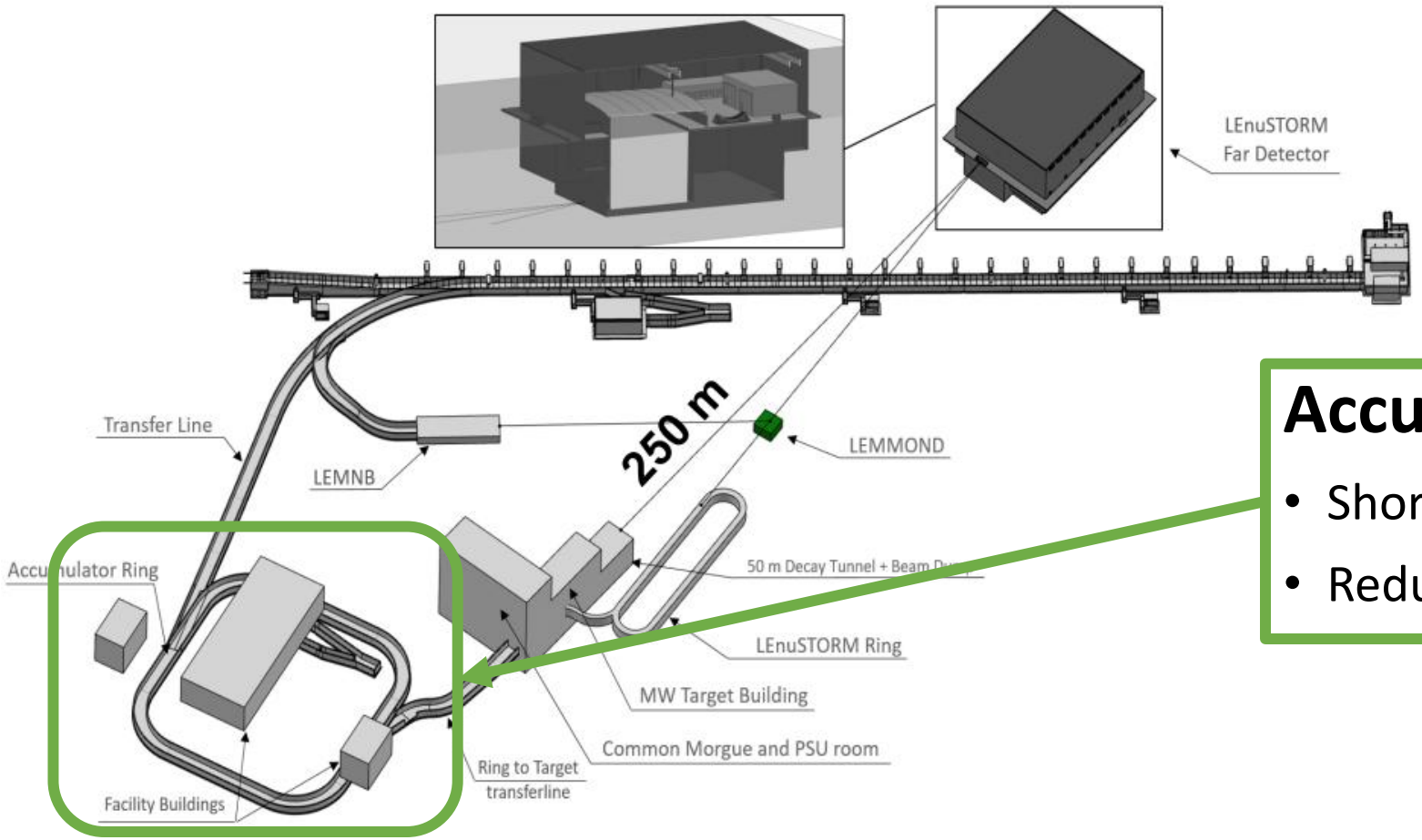
Experimental configuration of ESSnuSB



Main accelerator

- 5 MW proton beam
- 2.5 GeV proton energy
- 2.8 ms beam pulse

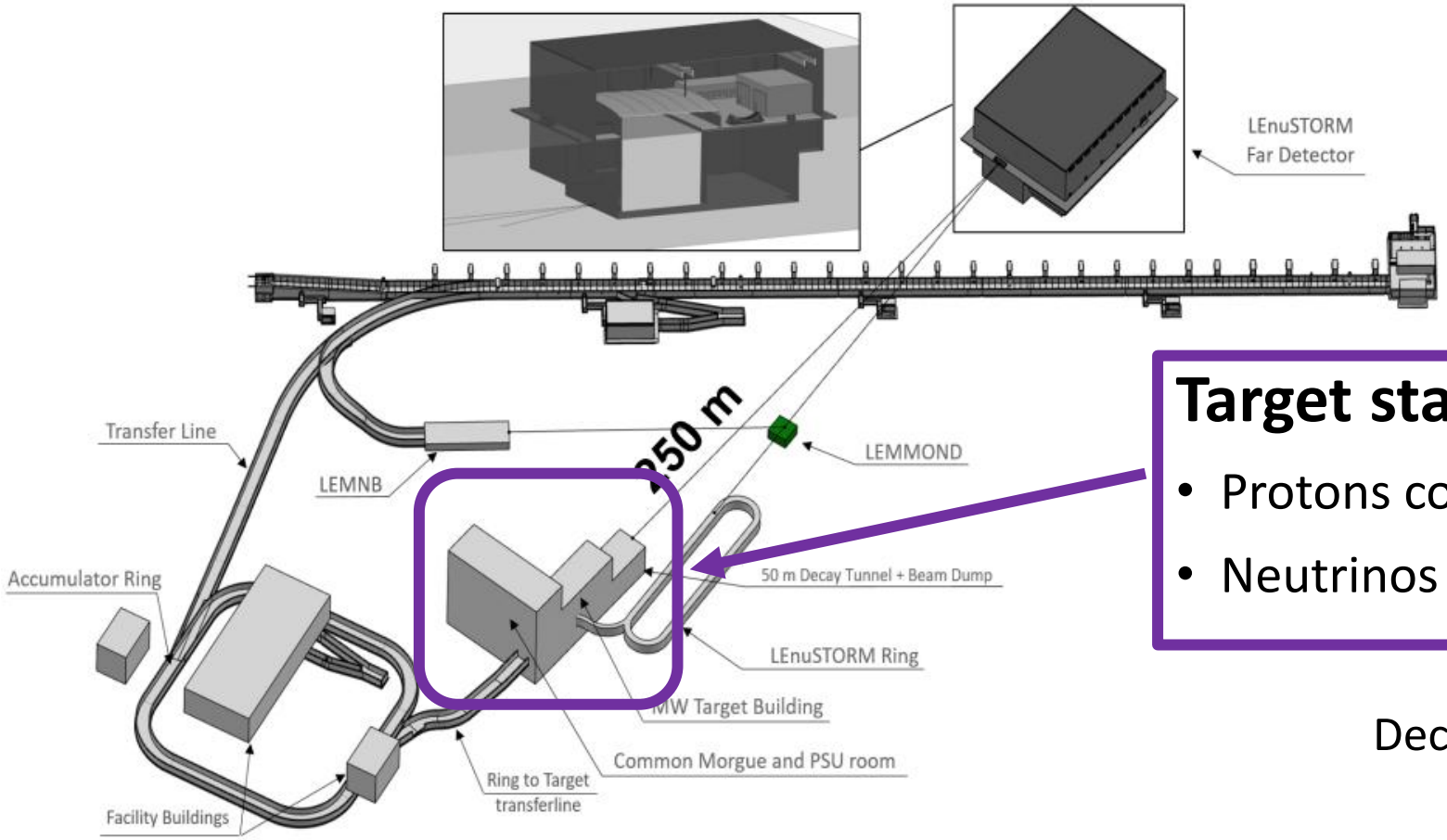
Experimental configuration of ESSnuSB



Accumulator

- Shortens beam pulse to 1.2μs
- Reduces atmospheric background

Experimental configuration of ESSnuSB



Target station

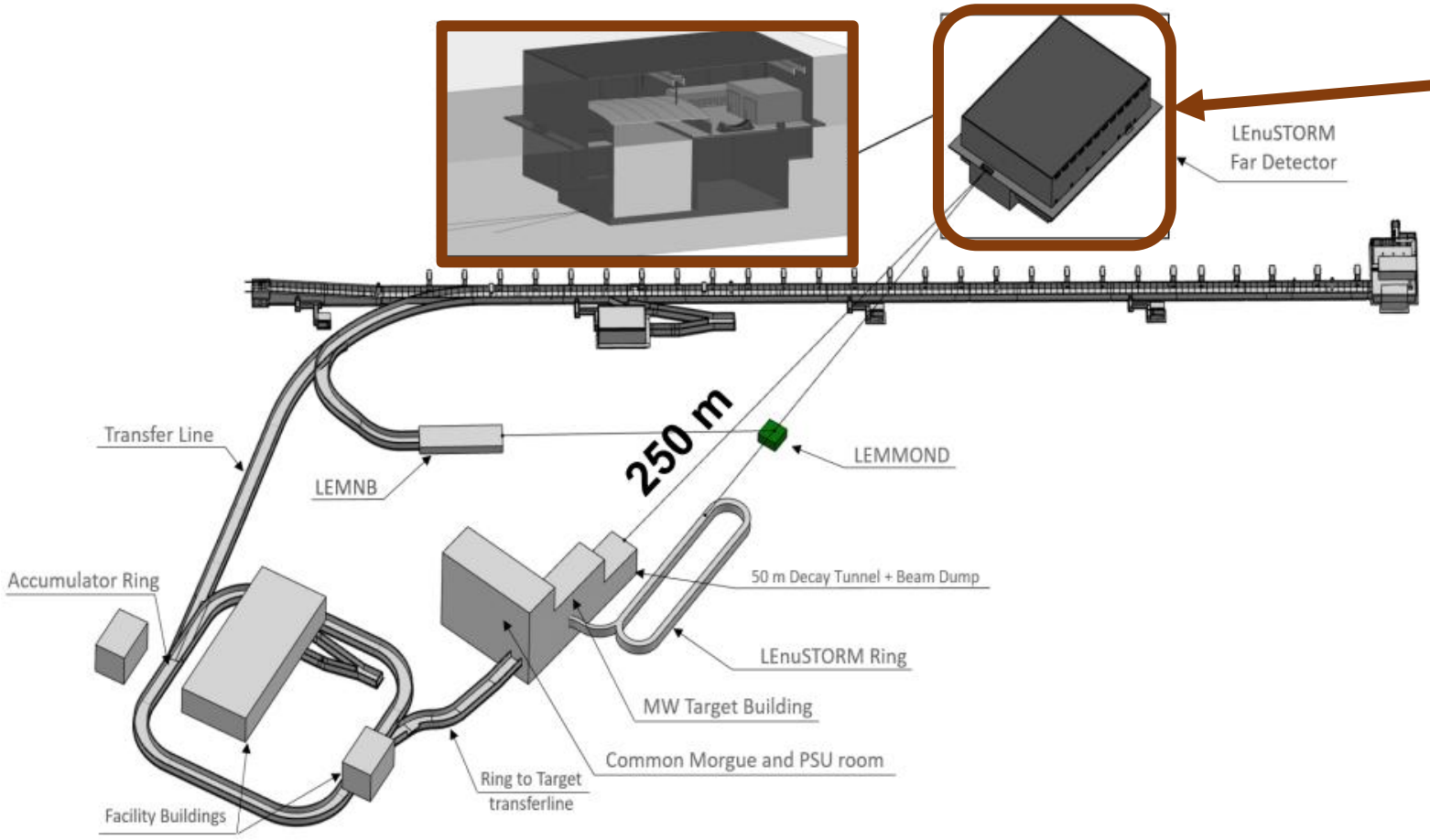
- Protons collide to create charged pions
- Neutrinos are generated in pion decays

Decay channels:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

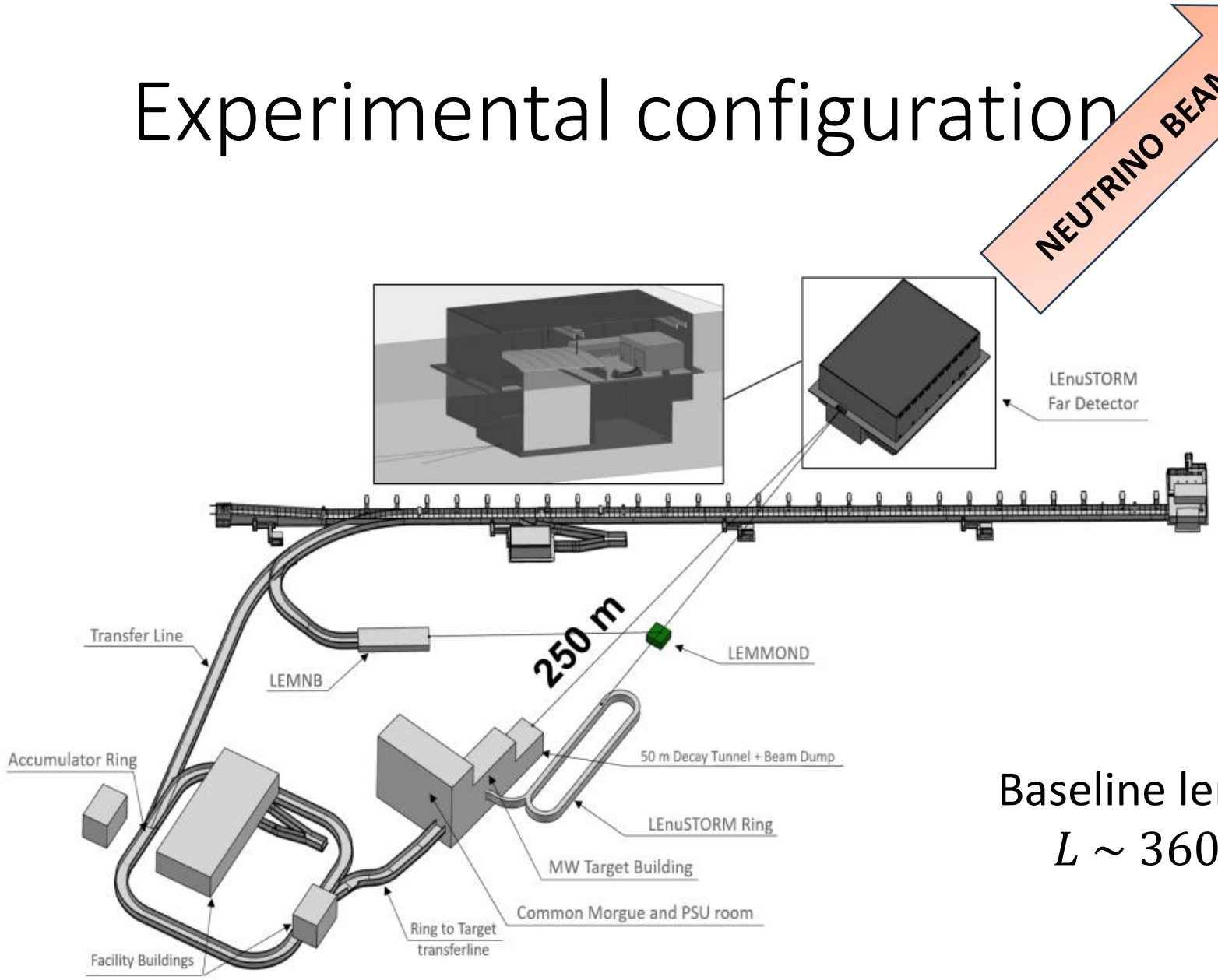
Experimental configuration of ESSnuSB



Near detectors (END)

- Measure neutrino fluxes and neutrino-nucleus cross-sections
- Located 250 m from the target

Experimental configuration ESSnuSB

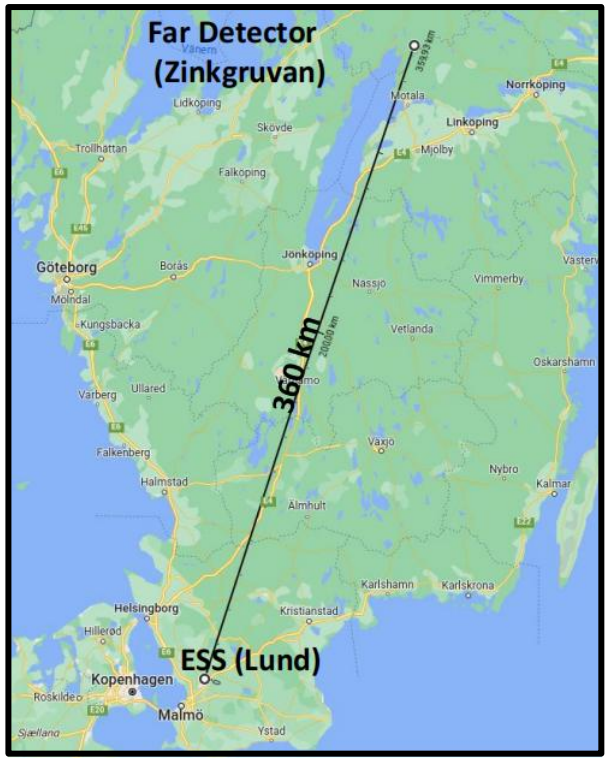


ESSnuSB far detectors

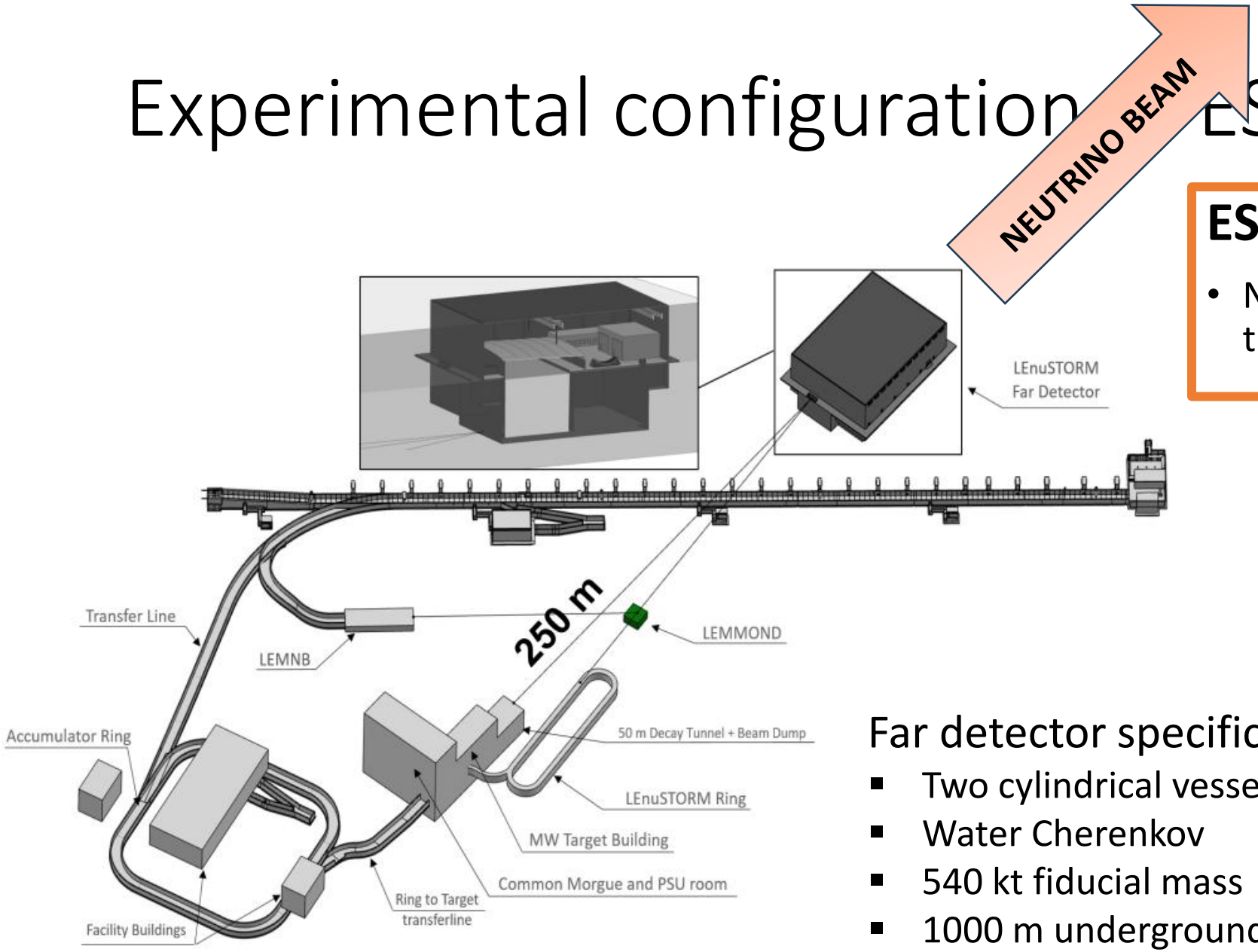
- Neutrino detectors are placed inside the mine in Zinkgruvan

Baseline length:

$L \sim 360$ km

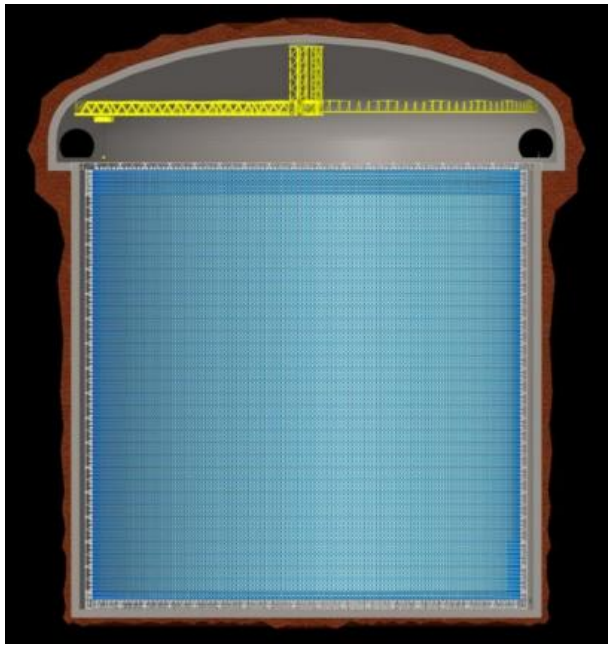


Experimental configuration ESSnuSB



ESSnuSB far detectors

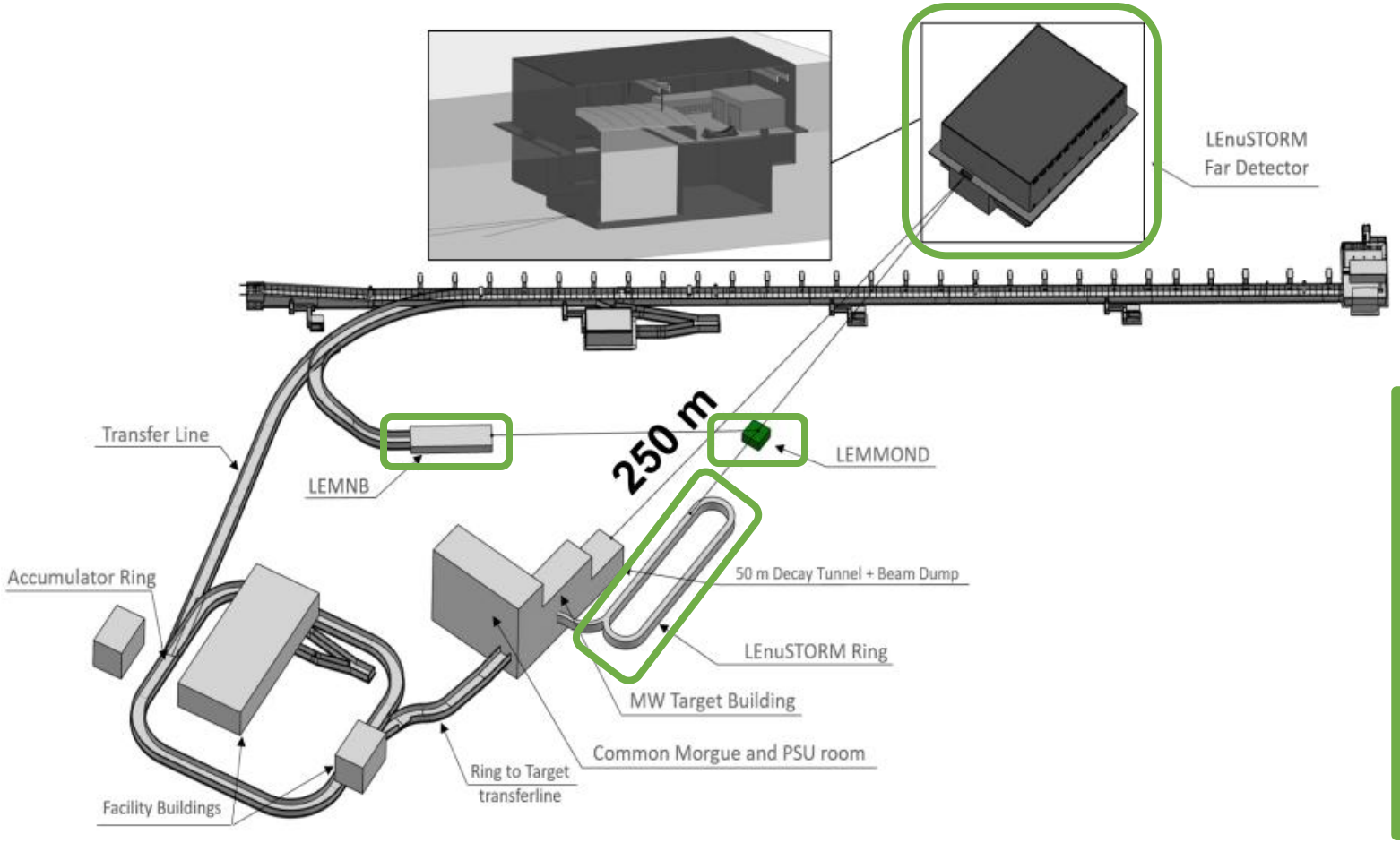
- Neutrino detectors are placed inside the mine in Zinkgruvan



Far detector specifics:

- Two cylindrical vessels
- Water Cherenkov
- 540 kt fiducial mass
- 1000 m underground

Experimental configuration of ESSnuSB



(2023-2026)

ESS neutrino Super Beam plus

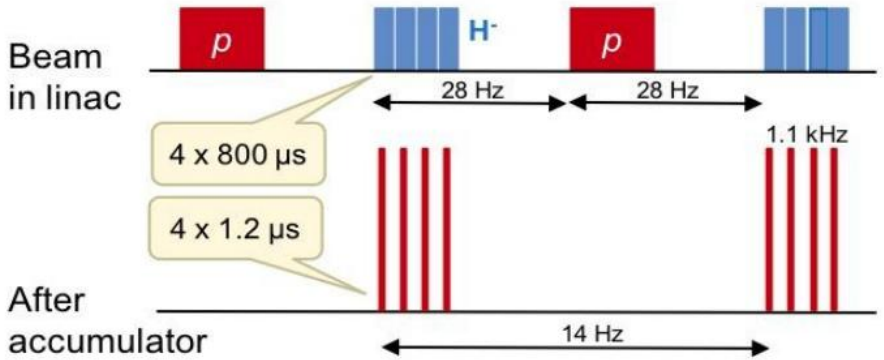
High-precision cross-section measurements

- LEnuSTORM: Low-Energy neutrino from STORed Muons
- LEMNB: Low-Energy Monitored Neutrino Beam

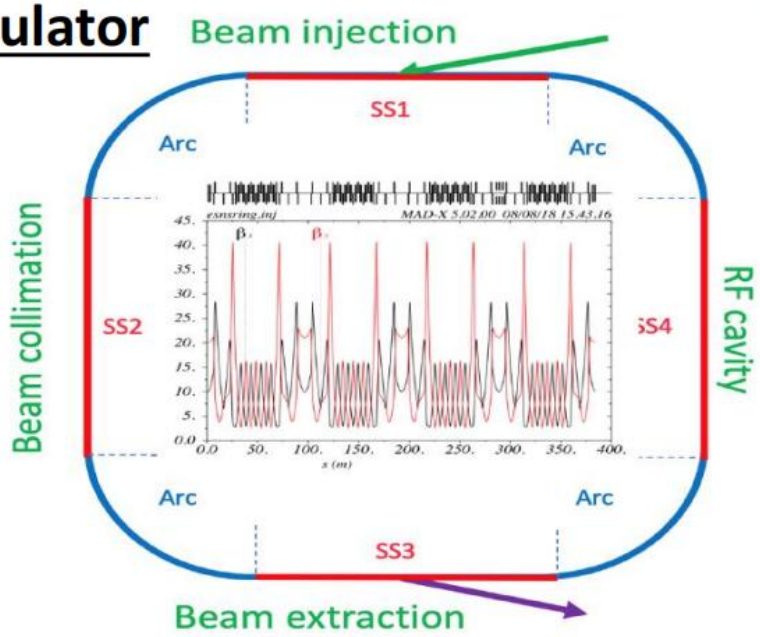
Upgrades to the ESS facilities

ESS neutrino Super Beam plus

Linac Upgrade

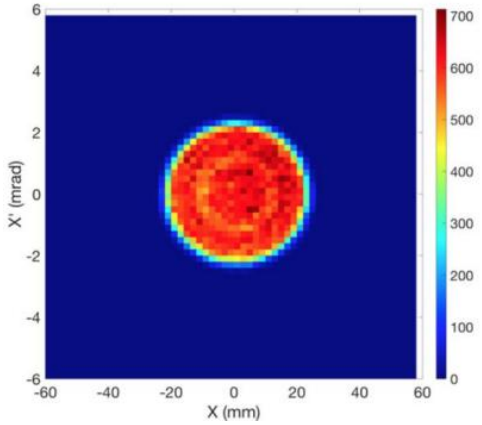


Accumulator

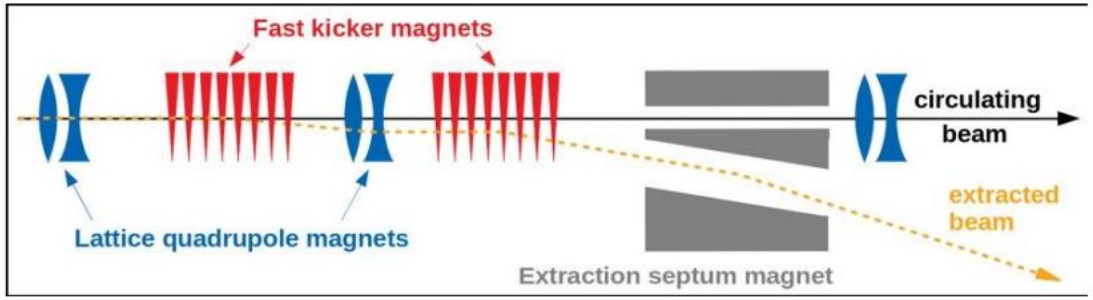


Injection

- **Foil stripping:** a widely used method
- **Laser stripping:** under development at SNS
- **Direct proton injection:** under study at ESS



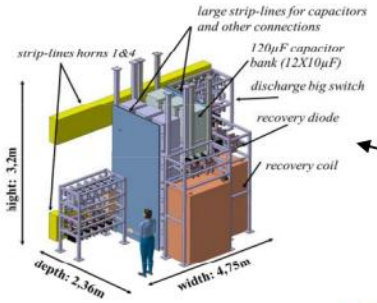
Ring-to-switchyard transfer liner



Target station

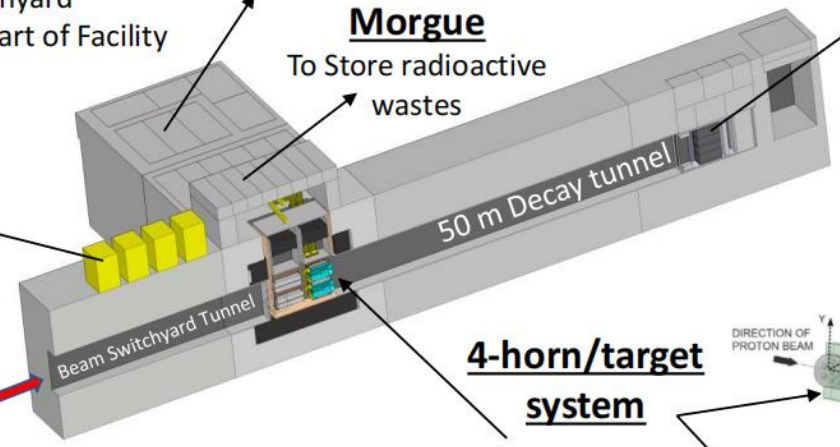
ESS neutrino Super Beam plus

Power Supply Unit
- 16 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

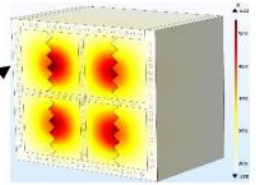


Hot Cell
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

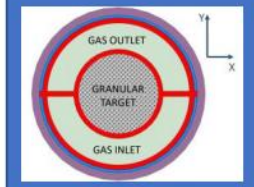
Morgue
To Store radioactive wastes

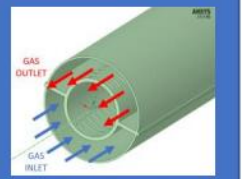


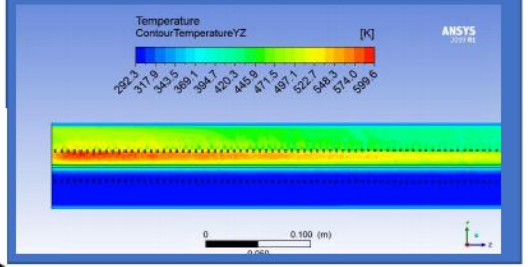
Beam dump



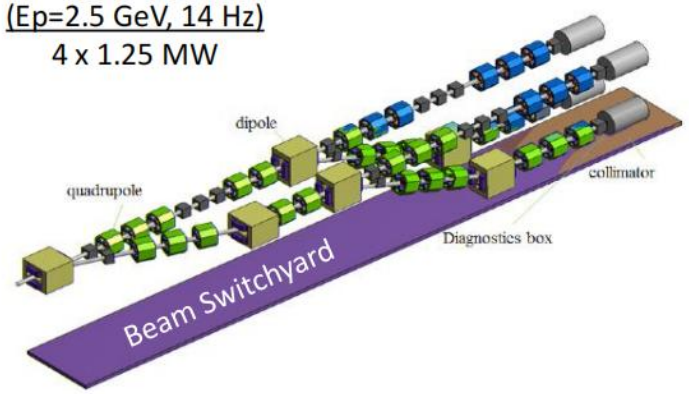
Granular Target Concept
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling



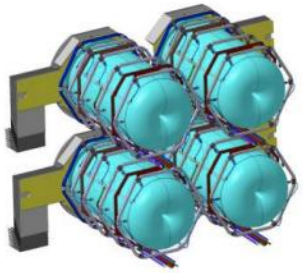




Proton Beam
(Ep=2.5 GeV, 14 Hz)
4 x 1.25 MW

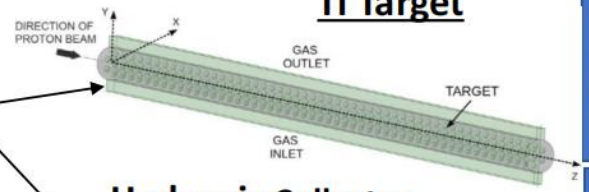


4-horn/target system

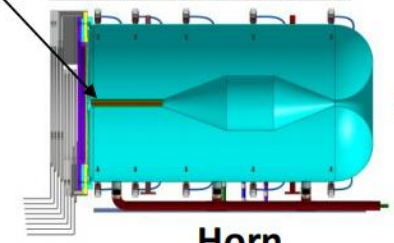


(a) The four-horn system.

Ti Target

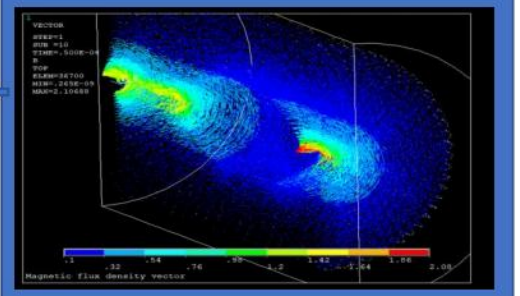


Hadronic Collector

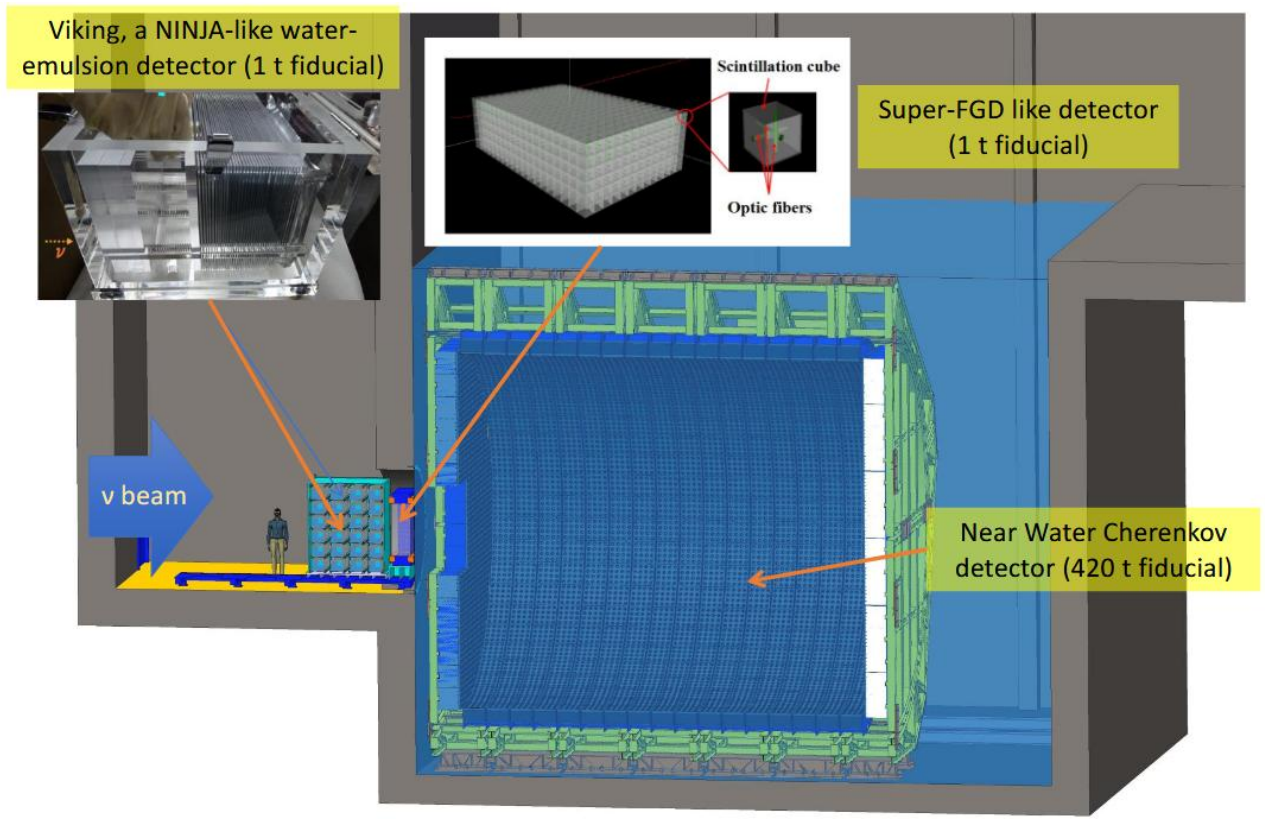


Horn

Magnetic field (350 kA; 1.3 μs pulse)



ESSnuSB near detectors (END)



Composition:

- NINJA-like emulsion detector (Viking) to measure final-state topology and cross-sections
- Magnetized Super Fine-Grained Detector (SFGD) to measure neutrino cross-sections
- Water Cherenkov detector to measure event rates for flux normalization

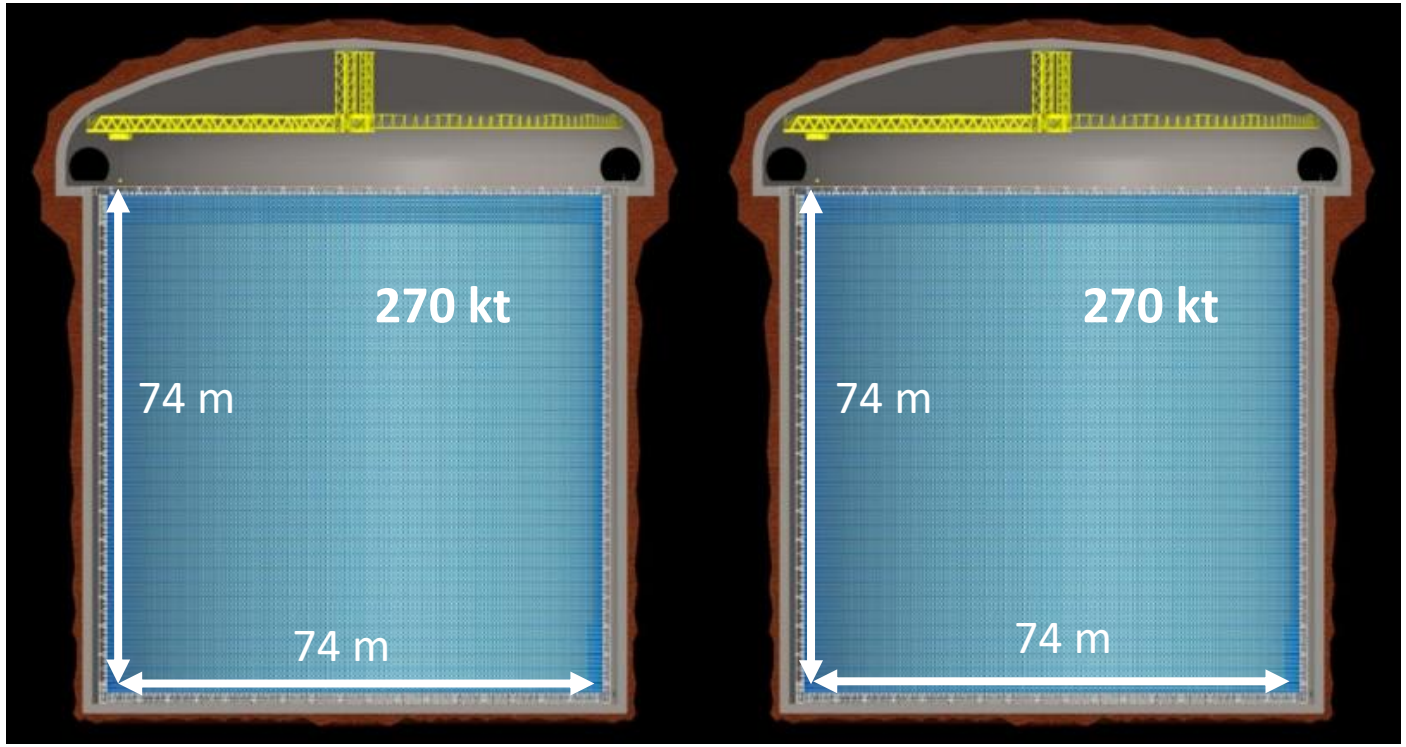
ESSnuSB far detectors (FD)

Detector design:

- Two identical Water Cherenkov detectors with 540kt mass
- Equivalent to 20 x Hyper-K
- Readout: 2 x 38k 20” PMTs, ~30% optical coverage

Performance:

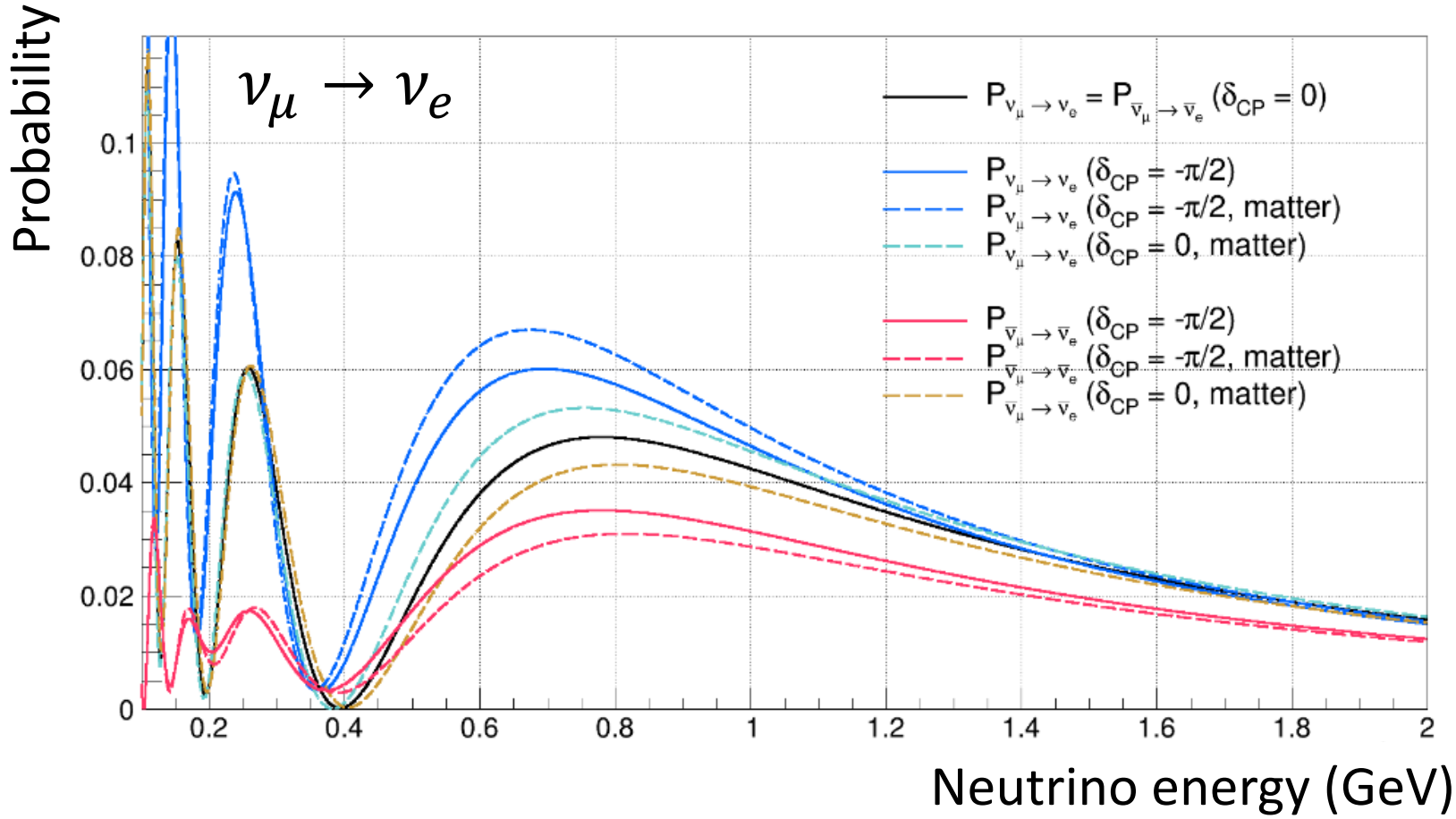
- Detector efficiency > 85%
- Flavor misidentification < 1%



Location: 1000 m of rock overburden

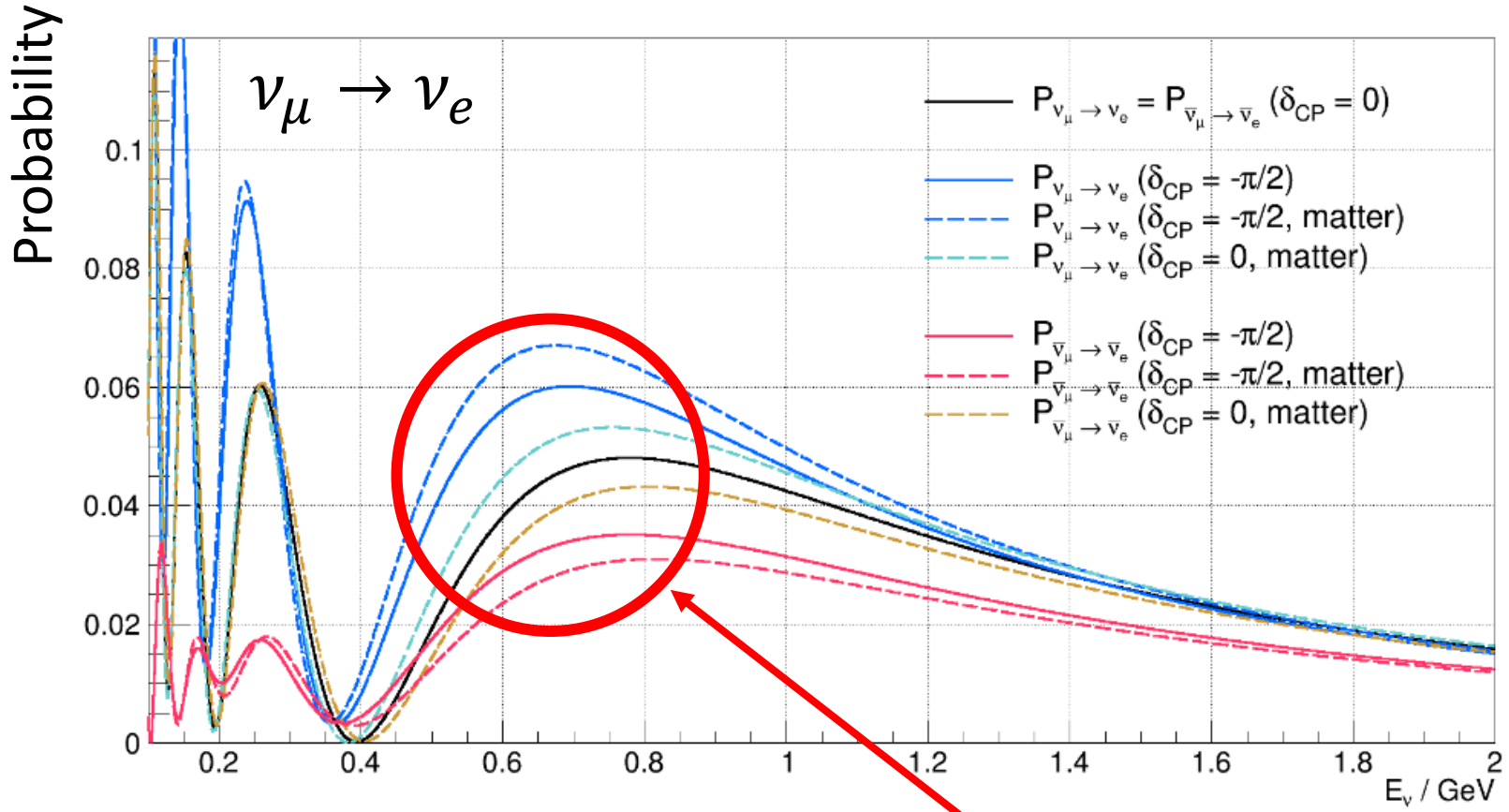
Scientific goals

ESSnuSB aims to measure the leptonic CP phase near the 2nd oscillation maximum



Scientific goals

ESSnuSB aims to measure the leptonic CP phase near the 2nd oscillation maximum

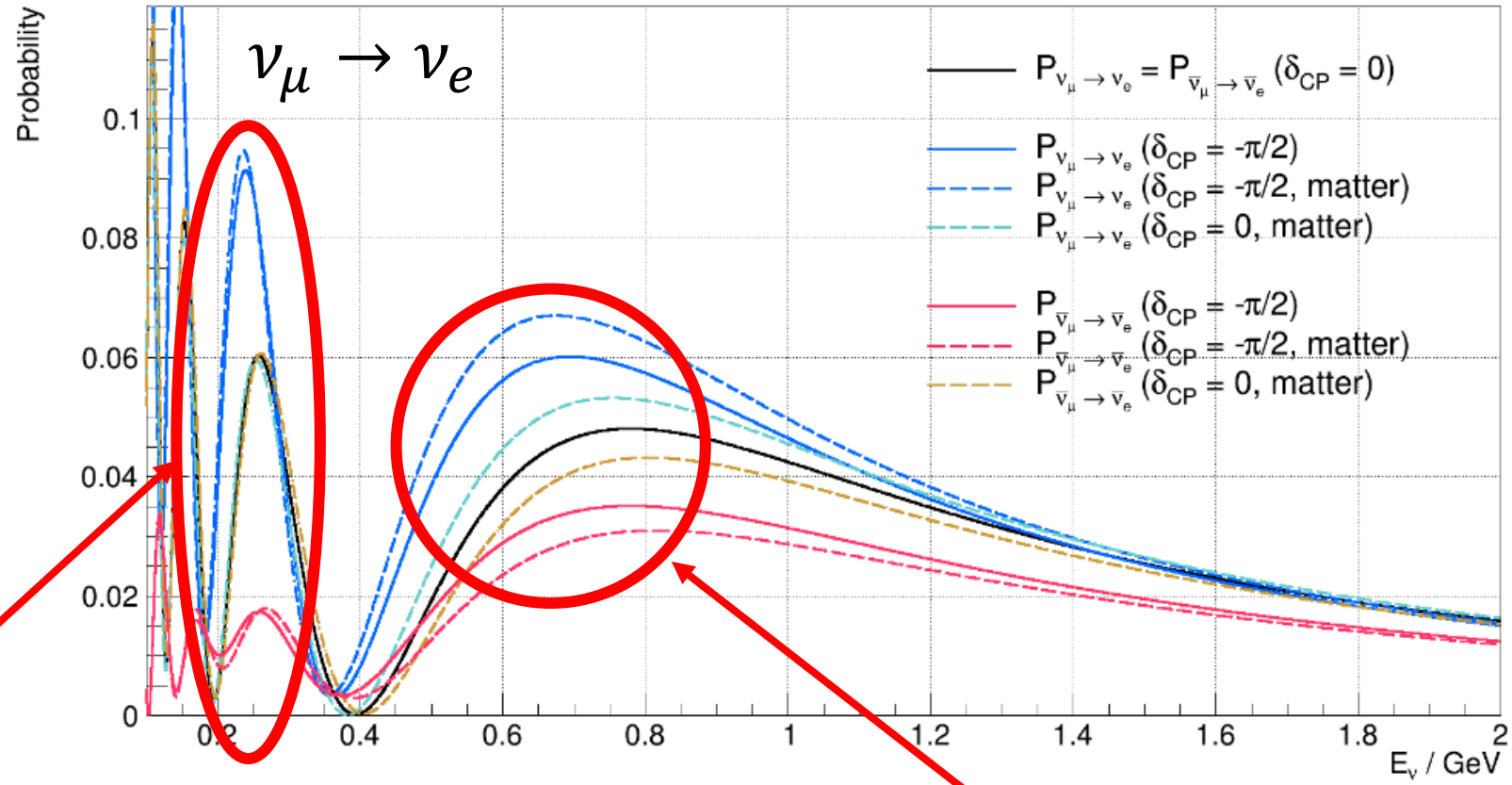


1st oscillation maximum:

- Smaller sensitivity to δ_{CP}
- Matter effects can mimic CP violation

Scientific goals

ESSnuSB aims to measure the leptonic CP phase near the 2nd oscillation maximum



2nd oscillation maximum:
- Larger sensitivity to δ_{CP}
- Matter effects insignificant

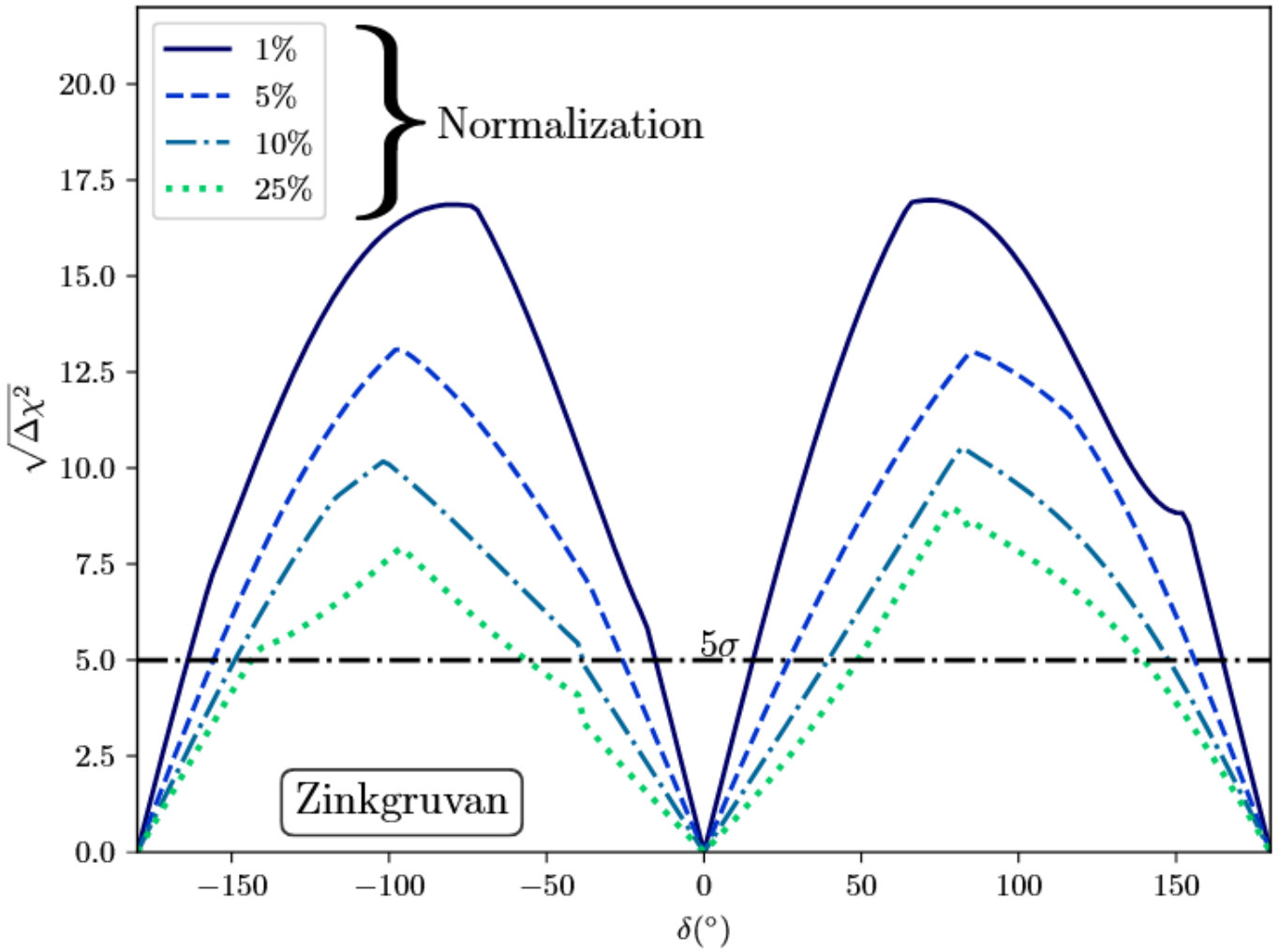
1st oscillation maximum:
- Smaller sensitivity to δ_{CP}
- Matter effects can mimic CP violation

Scientific goals

ESS neutrino Super Beam plus

Sensitivity to CP violation:

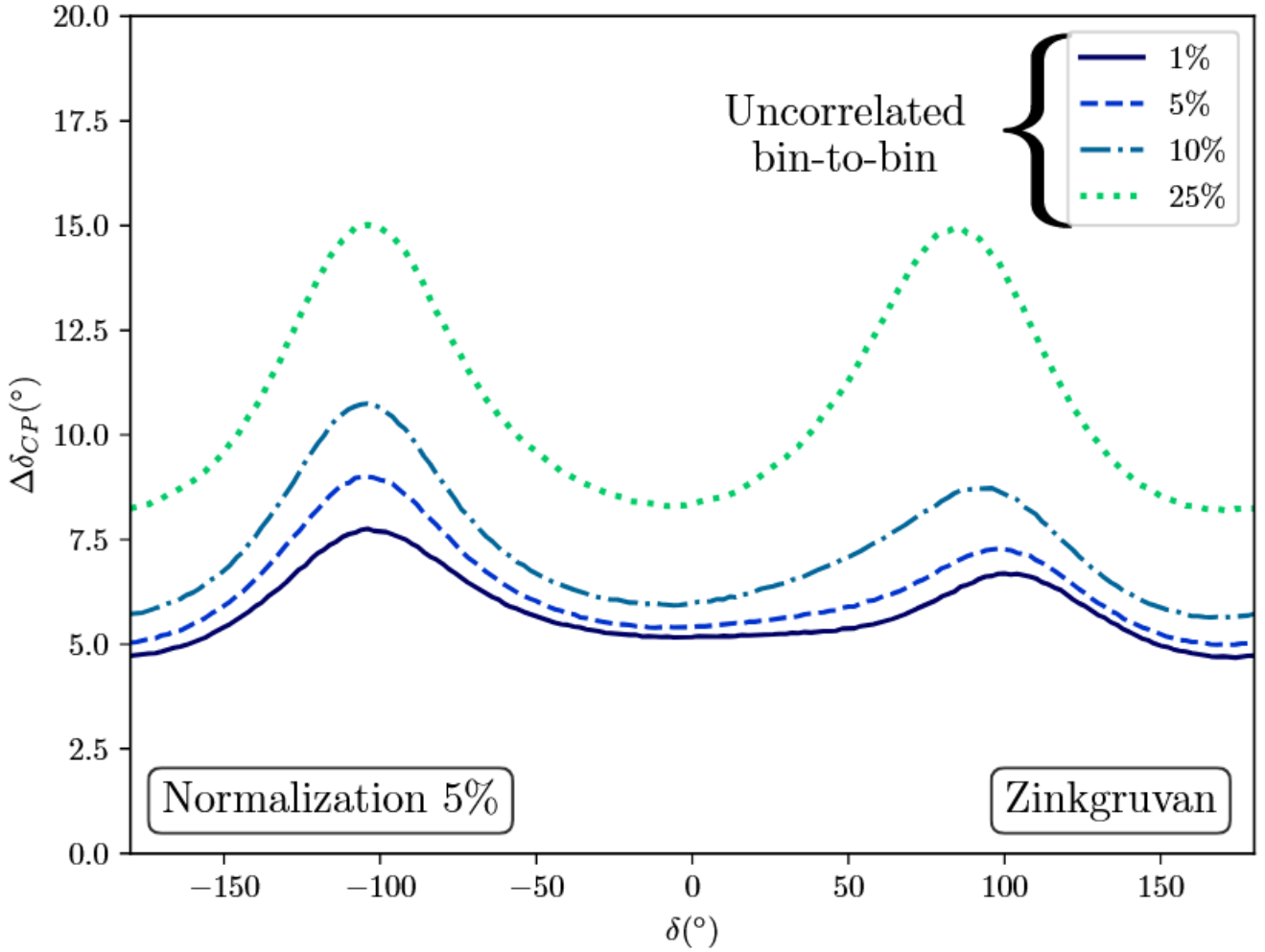
- CP violation can be confirmed for > 70% of δ_{CP} values at 5σ CL
- This is made possible by access to the 2nd oscillation maximum
- The result is unaffected by neutrino mass ordering



Scientific goals

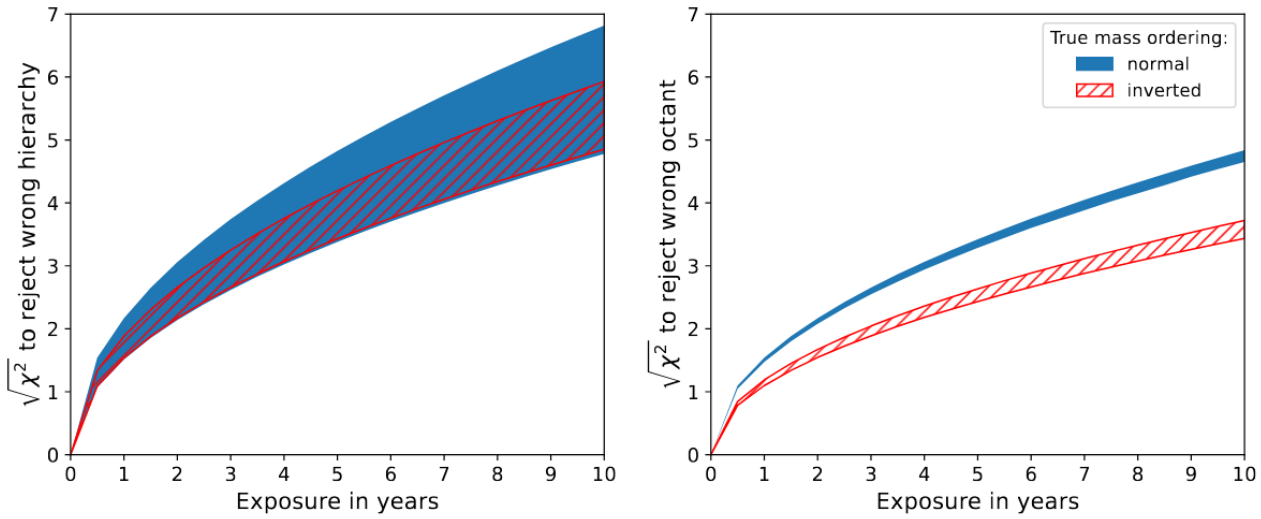
Sensitivity δ_{CP} value:

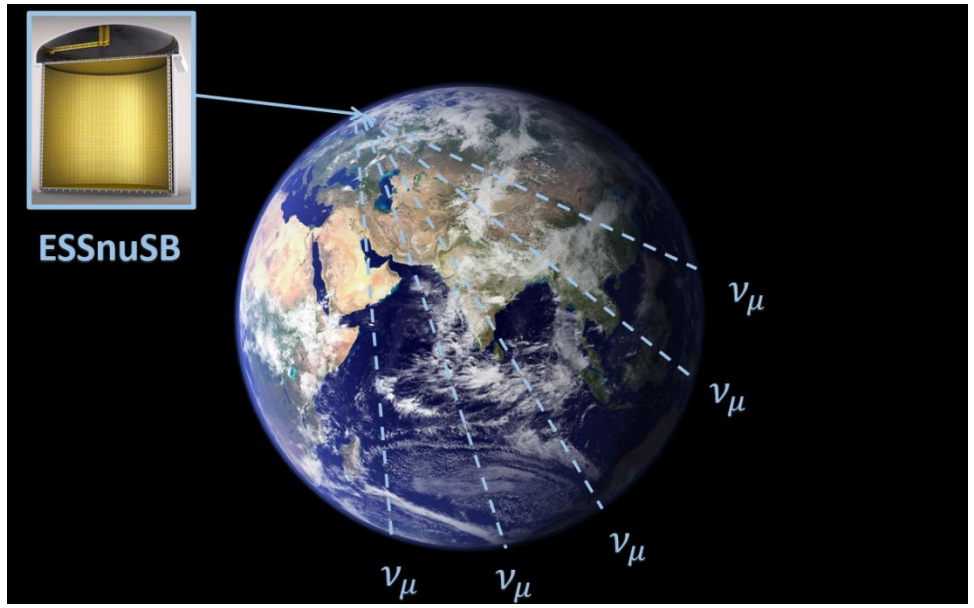
- δ_{CP} can be measured by at least 9° resolution at 1σ CL
- Based on a conservative systematic uncertainty assumption, may be subject to improve
- Complementarity from atmospheric neutrinos



Atmospheric neutrinos

Atmospheric neutrinos are produced in cosmic-ray interactions inside the Earth's atmosphere





Excellent sensitivity to physics that benefit from strong matter effects

A Monte Carlo study has been carried out for ESSnuSB FD:

ESSnuSB collaboration (J. Aguilar *et al.*), JHEP 10 (2024) 187

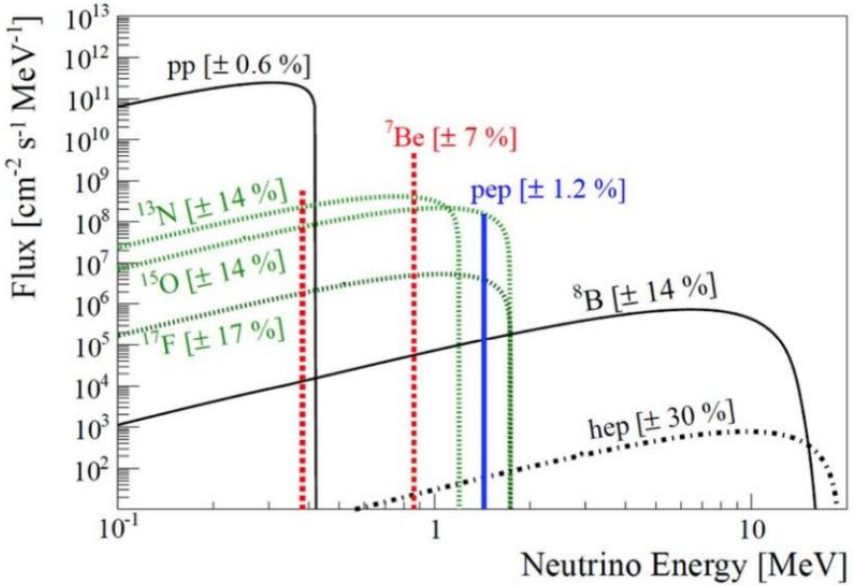
Solar neutrinos

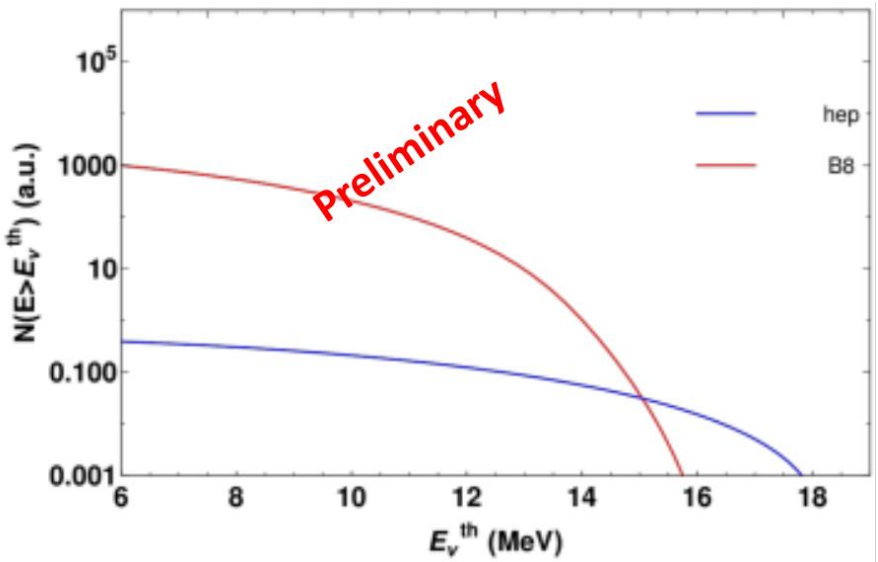
ESSnuSB could help to resolve some of the questions on neutrinos emited by the Sun:

- Observation of hep neutrinos:

$$^3He + p \rightarrow ^4He + e^+ + \nu_e$$

- Discrimination from ^8B background
- Expected events: 370 neutrinos / day





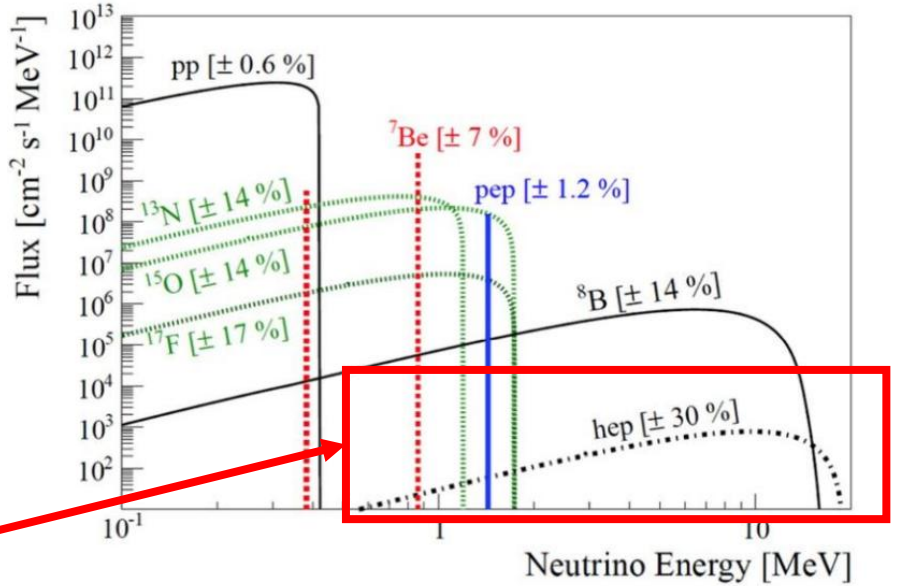
Solar neutrinos

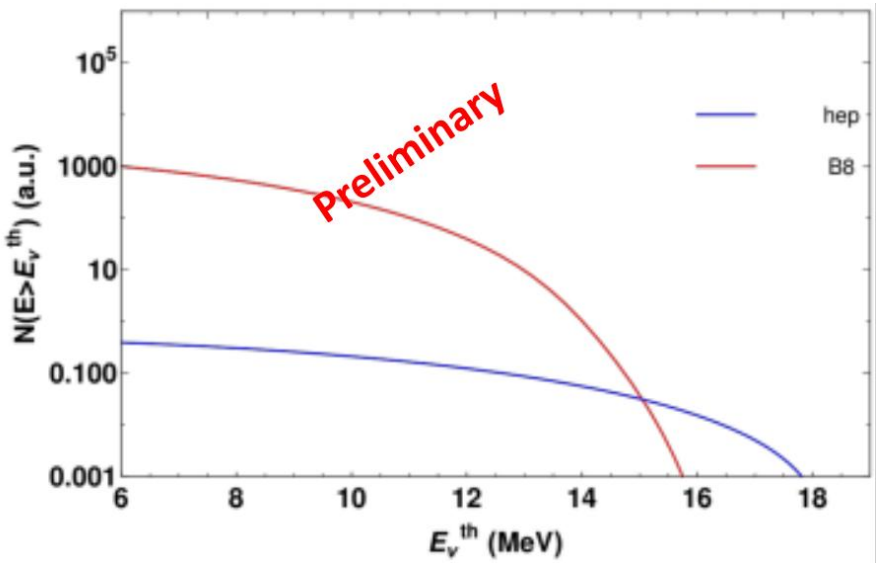
ESSnuSB could help to resolve some of the questions on neutrinos emited by the Sun:

- Observation of hep neutrinos:

$$^{3}He + p \rightarrow ^{4}He + e^{+} + \nu_e$$

- Discrimination from ^{8}B background
- Expected events: 370 neutrinos / day





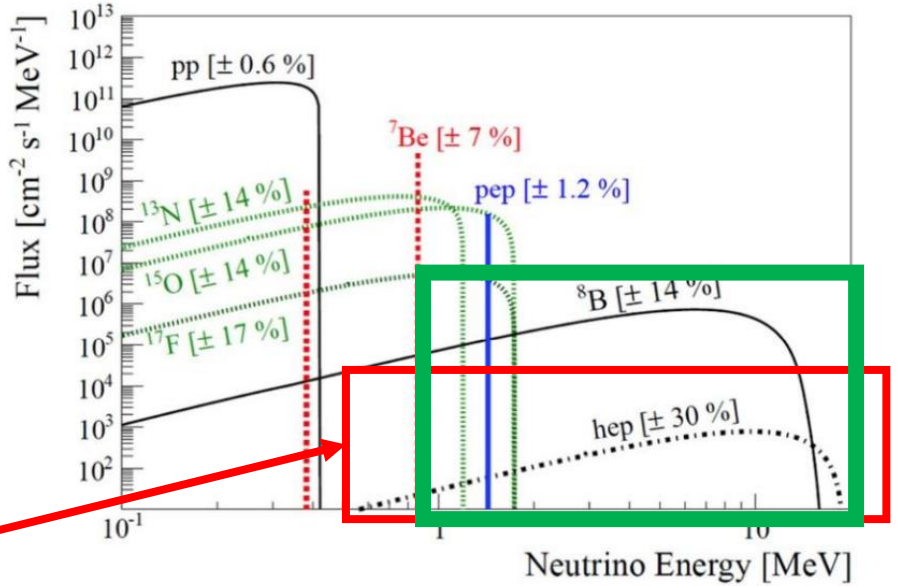
Solar neutrinos

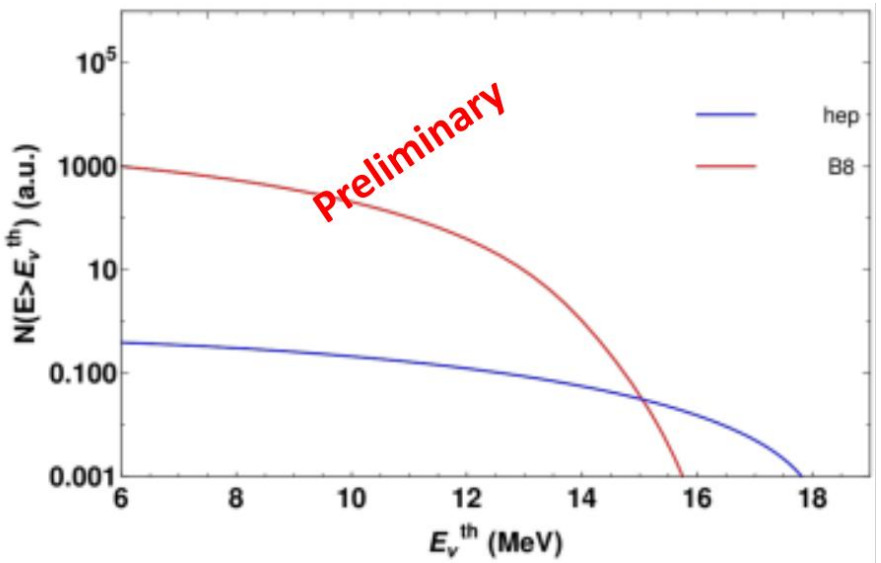
ESSnuSB could help to resolve some of the questions on neutrinos emited by the Sun:

- Observation of hep neutrinos:

$$^{3}He + p \rightarrow ^{4}He + e^{+} + \nu_e$$

- Discrimination from ^{8}B background
- Expected events: 370 neutrinos / day





Supernova neutrinos

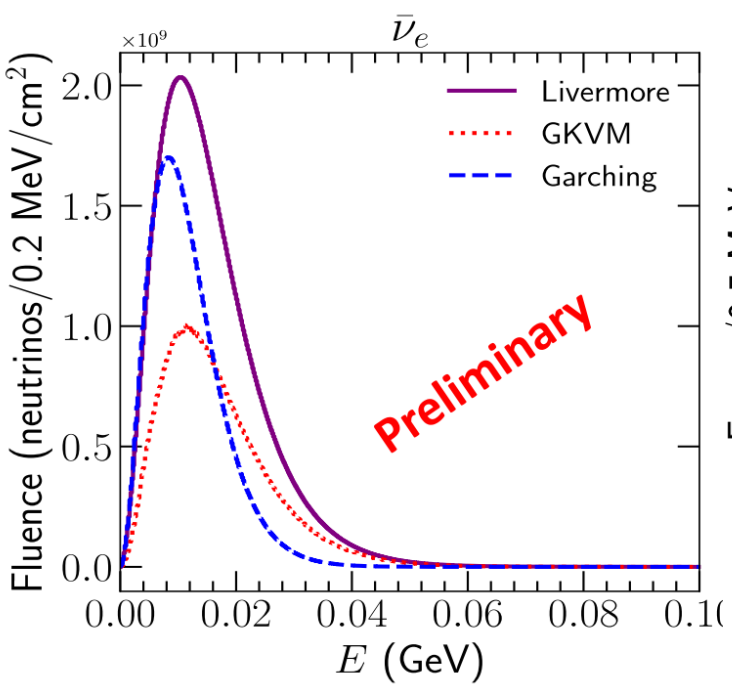
- When a massive star collapses into a supernova, it emits an immensely large number of neutrinos
- With its large fiducial mass, ESSnuSB far detectors could help to determine the correct flux model for supernova neutrinos

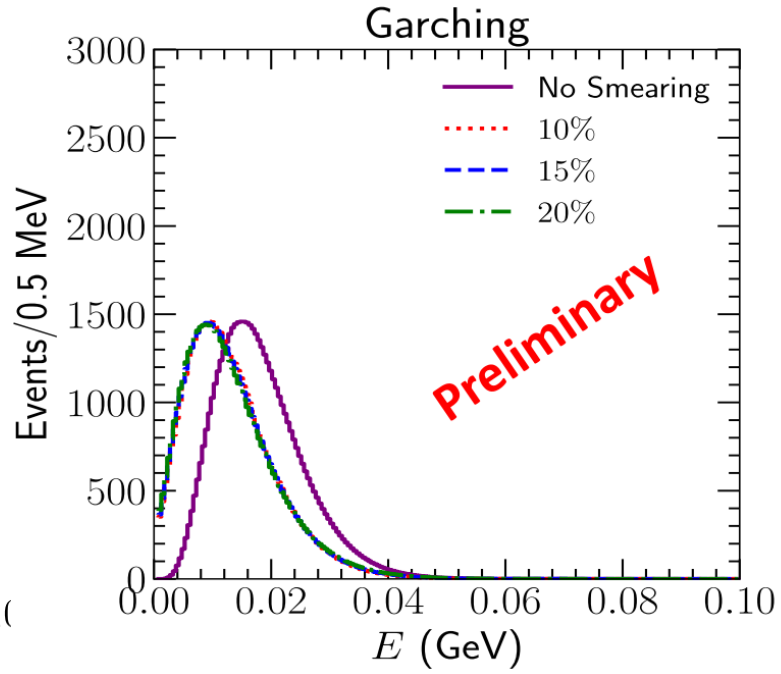
Events per model:

Livermore	GKVM	Garching
148,686	88,528	51,068

Detection channel:

$$\bar{\nu}_e + p \rightarrow n + e^+$$





Next stage 2027-2030: Detailed design study of the Far Detector

Curren call: HORIZON-INFRA-2025-01-DEV-03 Consolidation of the Research Infrastructure landscape – Individual support for evolution, long term sustainability and emerging needs of pan-European research infrastructures

Title of Proposal: Design study of the ESSnuSB Far Detector infrastructure for fundamental neutrino oscillation research with additional benefits of their use for geological exploration and other uses

Acronym of Proposal: ESSnuSB-FD **Submitted to EU-INFRADEV 18 September 2025**

Coordinator: David Saiang, Luleå Technical University, Sweden

Rock Engineering Technology

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Lulea Tekniska Universitet	LTU	Sweden
2	Uppsala Universitet	UU	Sweden
3	University of Oulu	UO	Finland
4	Kungliga Tekniska Hoegskolan	KTH	Sweden
5	Lunds Universitet	ULUND	Sweden
6	European Spallation Source ERIC	ESS	Sweden
7	Cuprum Research & Development Centre	CRD	Poland
8	Universität Hamburg	UHAM	Germany
9	Aachen University	RWTH	Germany
10	Ruder Boskovic Institute	RBI	Croatia
11	Centre National de la Recherche Scientifique	CNRS	France
12	National Center for Scientific Research "Demokritos"	NCSRD	Greece
13	Universita degli Studi Roma Tre	UNIROMA3	Italy
14	Université de Strasbourg	UNISTRA	France
15	Aristotelio Panepistimio Thessalonikis	AUTH	Greece
16	Consorcio Para la Construccion, Equipamiento y Explotacion de la Sede Espanola de la Fuente Europea de Neutrones por Espalacion (ESS Bilbao)	ESSB	Spain
17	University of Oslo	UIO	Norway
18	University of Bergen	UIB	Norway
19	European Organisation for Nuclear Research	CERN	IEIO
20	Hellenic Open University	HOU	Greece
21	Boliden Zinkgruvan	BZ	Sweden

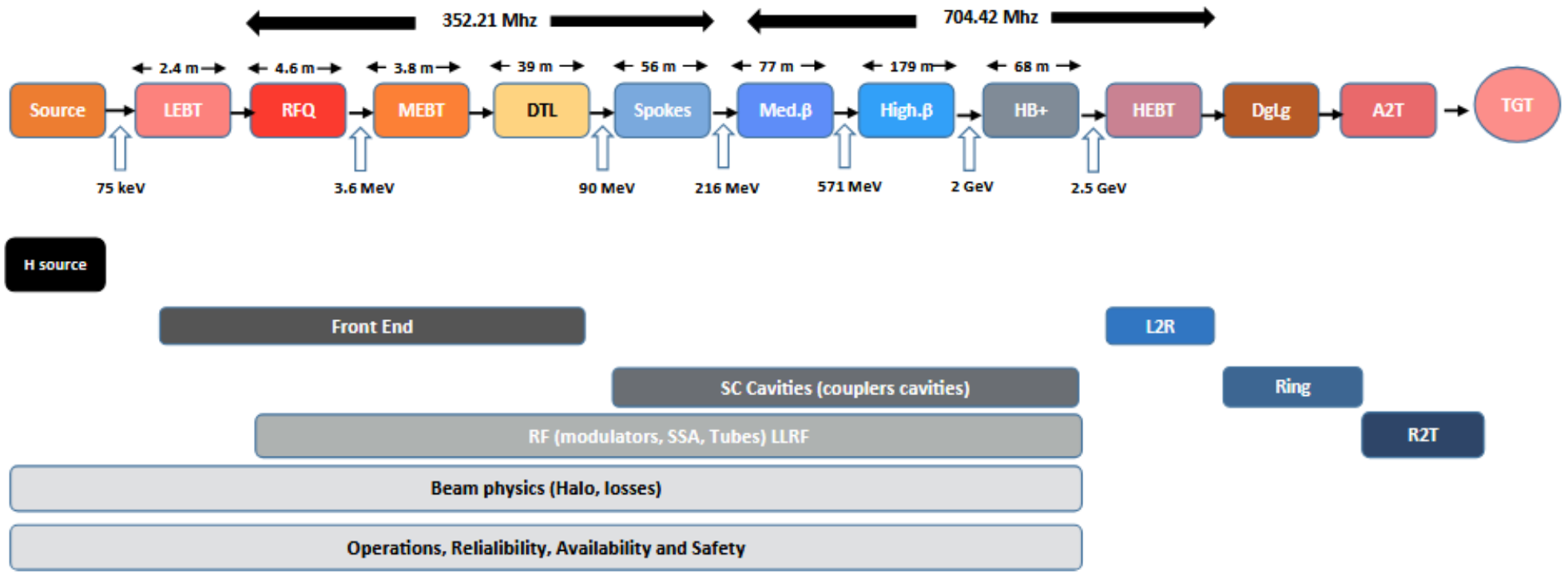
WP #	WP Title	Lead Participant #	Lead Participant Short Name	Person-Months	Start Month	End Month
1	Management	1	LTU	72	1	48
2	ESSnuSB-FD site characterization	1	LTU	91	1	48
3	ESSnuSB-FD civil infrastructure design	7	CRD	79	1	48
4	ESSnuSB Sustainability, decommissioning and post-closure	3	UO	46	1	48
5	The ESSnuSB-FD detector water tanks, photosensors, electronics, data acquisition and computing	15	AUTH	212	1	48
6	Use of the ESSnuSB infrastructure for other applications	6	ESS	46	1	48
	TOTAL			546		

Conclusions

- ESSnuSB aims to measure the leptonic CP phase by observing neutrino oscillations at the 2nd oscillation maximum
- The first phase (3M€ granted) of the ESSnuSB conceptual design study (2018-2022) was successfully concluded with focus on long-baseline neutrino program
- The second phase (3M€ granted) is currently on-going (2023-2026) and focuses on high-precision cross-section measurements
- A third phase (4M€ requested) has been proposed (2027-2030) and it shall focus on the design of the far detector facilities in Zinkgruvan
- ESSnuSB is currently planned to begin construction around 2032 and start data taking around 2040

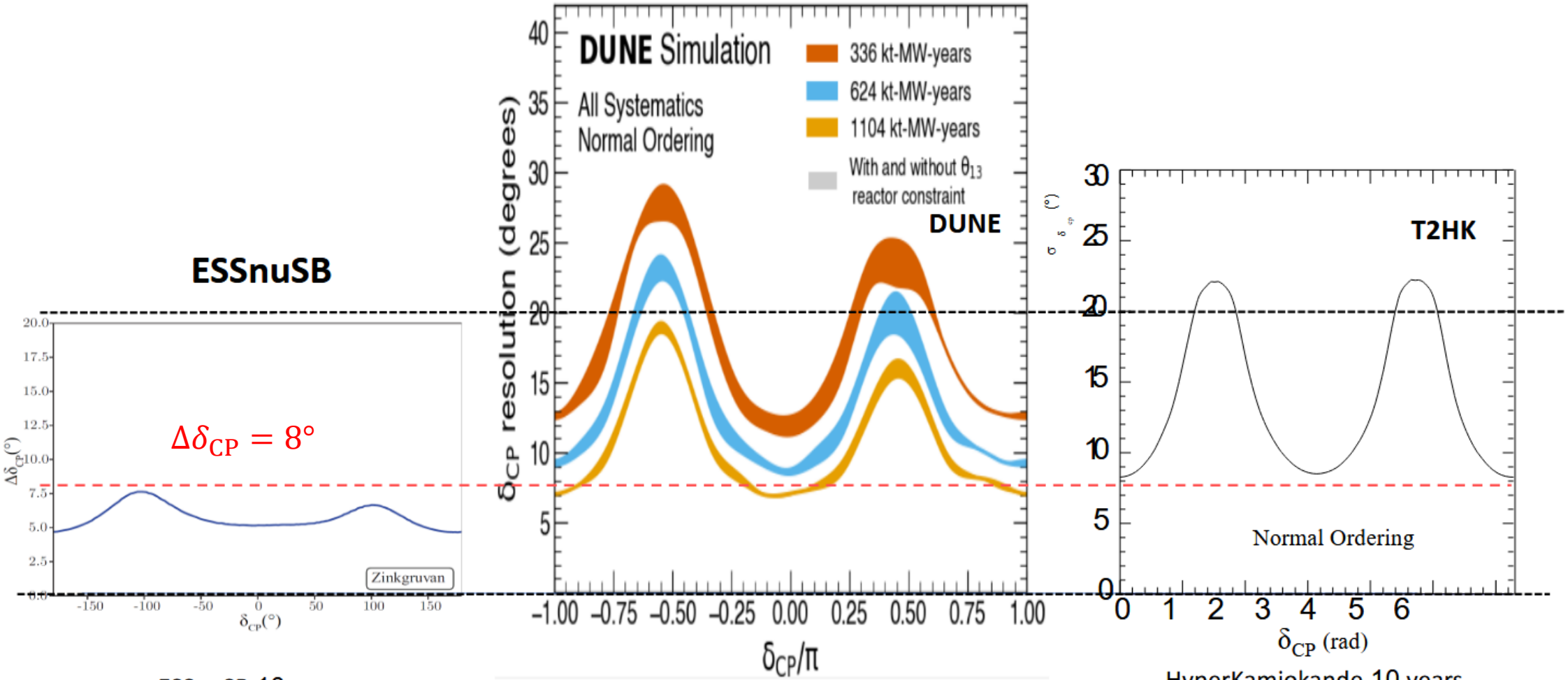

ESS neutrino Super Beam plus
Co-funded by the European Union
ΣΥΝΕΔΡΙΑΚΟ ΚΕΝΤΡΟ
ΓΕΩΡΓΙΟΣ ΗΛΙΟΠΟΥΛΟΣ
Collaboration annual meeting – Milos 2025

Proton driver layout



ESSnuSB in the global context

ESS neutrino Super Beam plus



ESSnuSB 10 years

https://arxiv.org/abs/2206.01208 p. 205

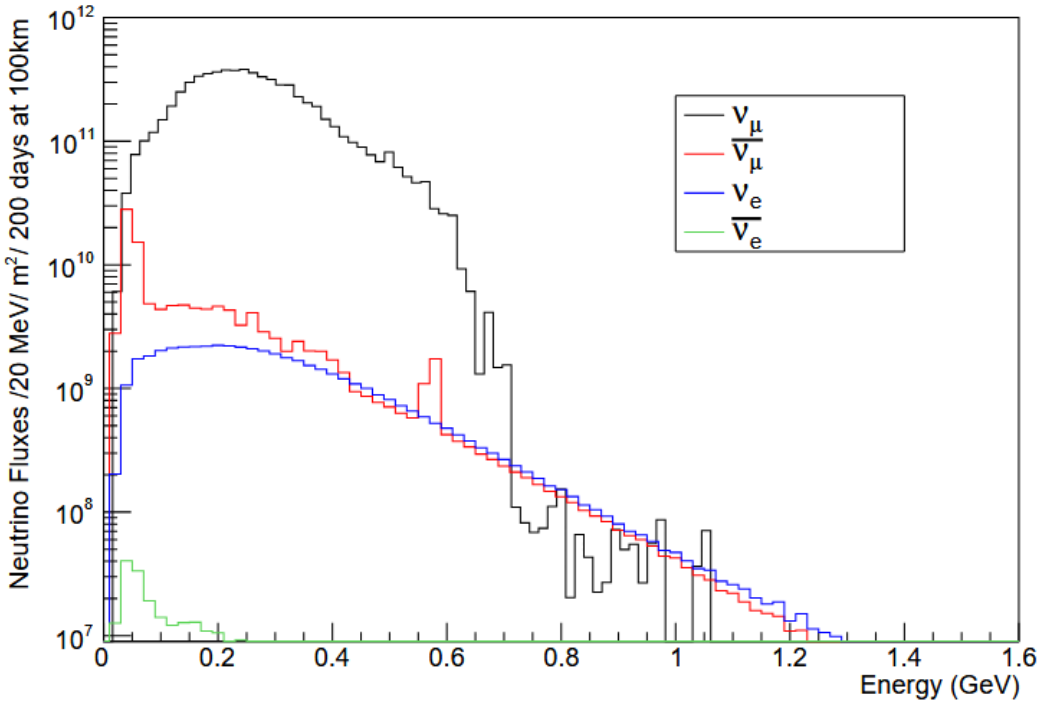
DUNE 10 years, yellow curve

https://arxiv.org/abs/2002.03005 p. 174

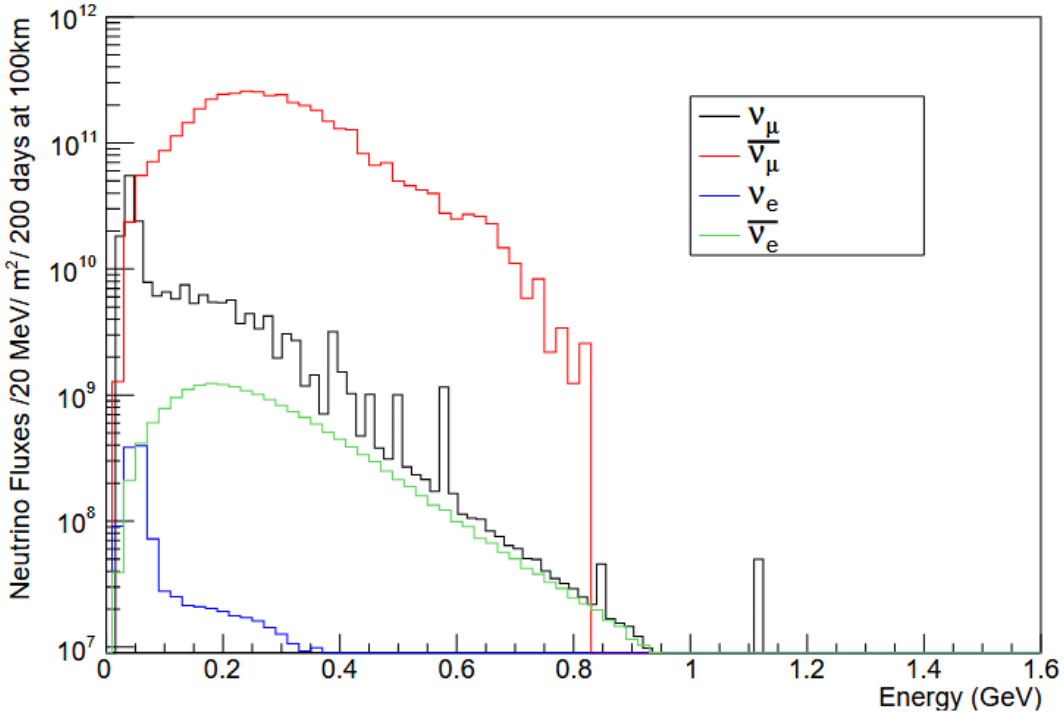
HyperKamiokande 10 years

https://arxiv.org/abs/1611.06118 p. 60

Neutrino fluxes at 100 km distance



Neutrino mode



Antineutrino mode

ESS Linac before and after upgrades

ESS neutrino Super Beam plus

	Nominal Linac	ESSνSB Linac	Units
Species	p	p and H^-	
Energy	2.0	2.5	GeV
Current	62.5	62.5 50 (p) / (H^-)	mA
Average beam power	5	10	MW
Linac length	352.2	~423	m
Macro pulse length	2.86	> 2.86 (p) / 2.9 (H^-)	ms
Protons per pulse	10^{15}	$8.3 \cdot 10^{14}$(p) / $8.9 \cdot 10^{14}$(H^-)	
Sub-pulse length	N/A	~0.65	ms
Repetition rate	14	$28^{\dagger}$	Hz
Beam duty cycle	4	8	%
Total losses	< 1	< 1	W/m

NOMINAL ESS PARAMETERS

ESSnuSB upgrade