ESSnuSB+

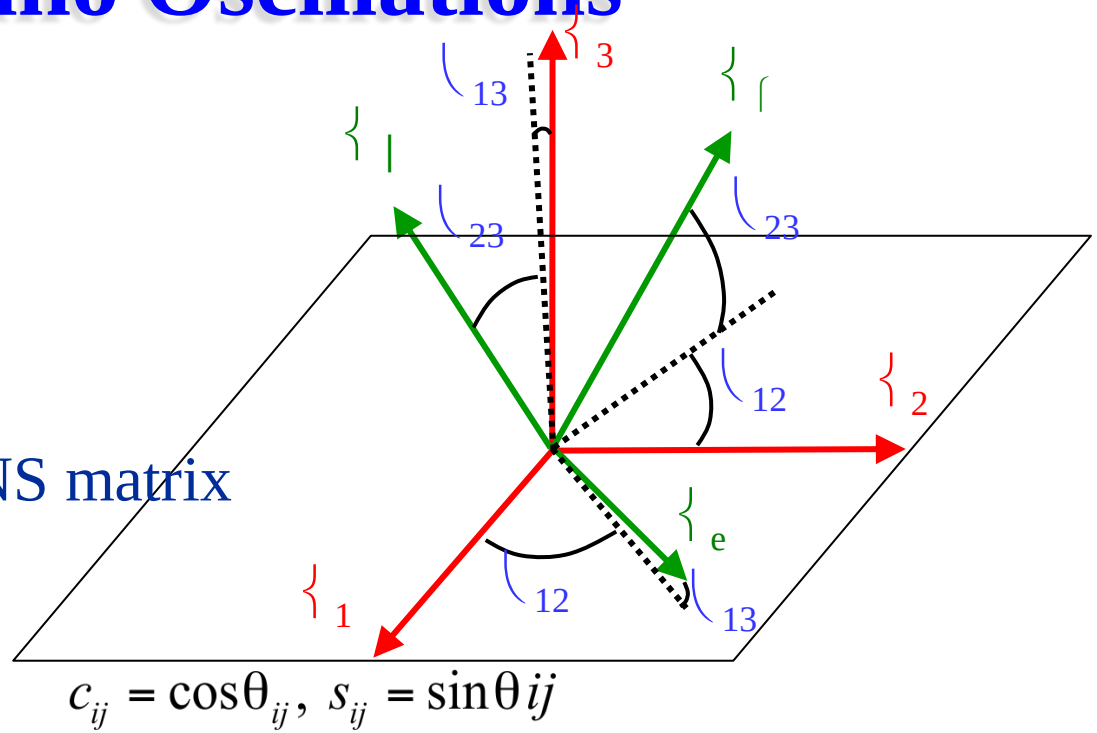
The European Spallation Source Neutrino Super Beam

→ CP violation in the neutrino sector +++

F. Ould-Saada – based on material prepared by others!!

Neutrino Oscillations

3 mixing angles, θ_{12}, θ_{23}, θ_{13}, and one phase, δ_{CP} (+ 2 Δm^2 splittings)



$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta ij$$

Usual parametrisation of PMNS matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

solar, reactors

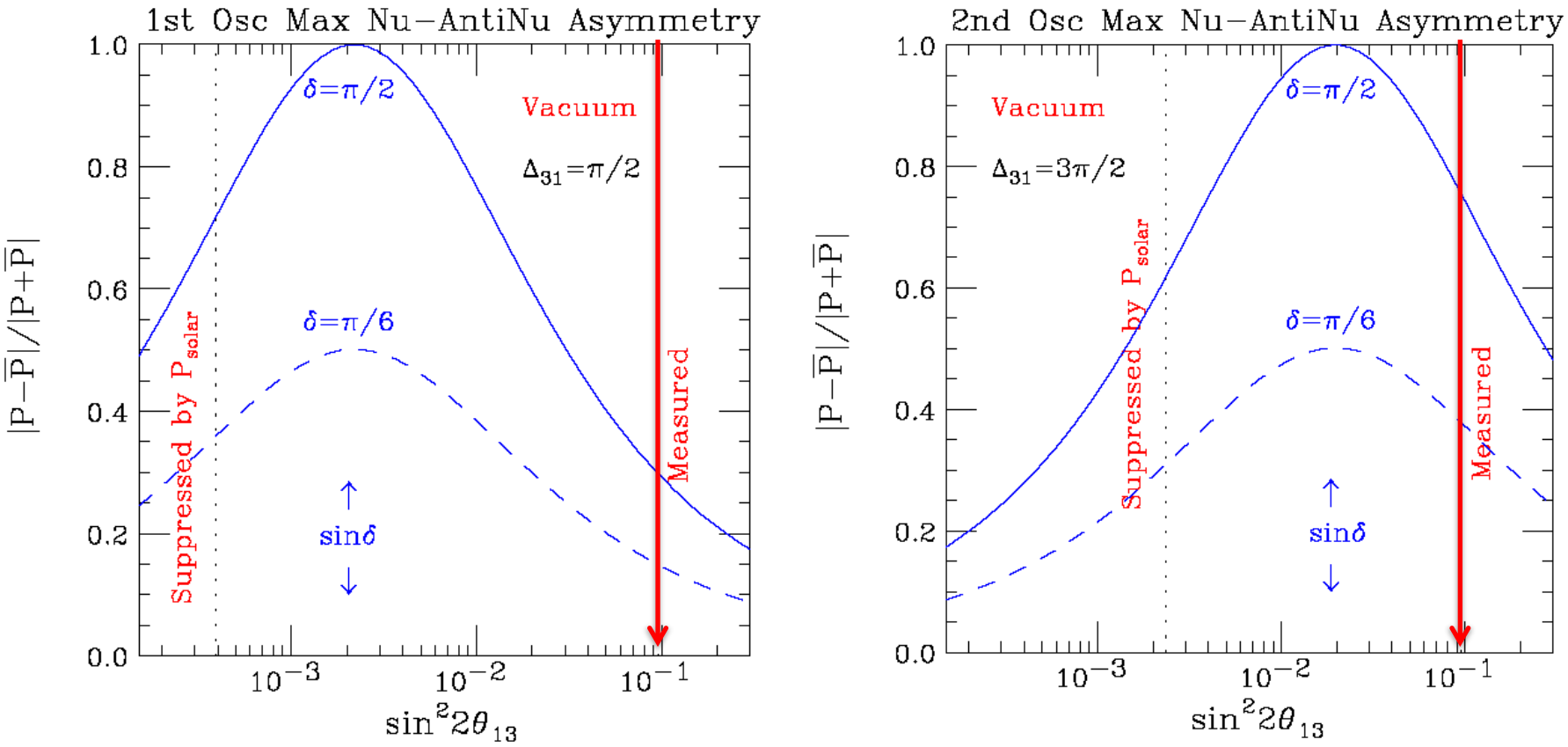
atmospheric, accelerators

reactors, accelerators CP violation

Majorana phases

- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

Neutrino Oscillations with "large" θ_{13}
(more sensitivity at the 2nd oscillation maximum)



- at the 1st oscillation max.: A=**0.3**sinδ_{CP}
- at the 2nd oscillation max.: A=**0.75**sinδ_{CP}

(see arXiv:1310.5992 and arXiv:0710.0554)

2nd oscillation maximum is better

but, more power is needed....

- The ESS proton linac will be soon the most powerful linac in the world, something which cannot be ignored.
- ESS can also become a neutrino facility (ESSνSB) with enough protons to go to the 2nd oscillation maximum and increase significantly the CPV sensitivity and precise measurement of δ_{CP}.
- CPV: 5 σ could be reached over 70% of δ_{CP} range by ESSνSB with large physics potential with less than 8° precision.
- The European Spallation Source will be ready by 2025, upgrade decisions by this moment.

Supporting institutions of ESSvSB

- COST Action EuroNuNet (CA15139): ended March 2020
  - https://euronunet.in2p3.fr
  - video for scientists: https://www.youtube.com/watch?v=PwzNzLQh-Dw

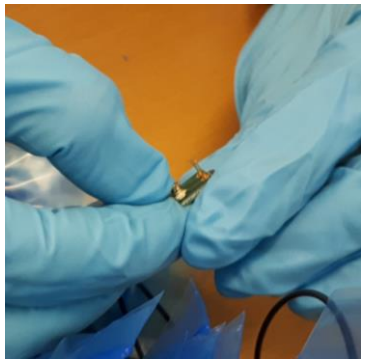
- EU-H2020 Design Study ESSvSB: on going up to March 2021
  - https://essnusb.eu
  - video for general public: https://www.youtube.com/watch?v=qAnvft0nAlg

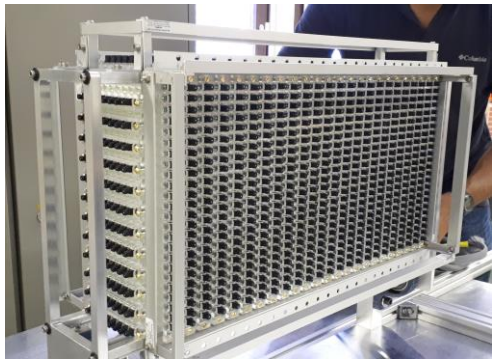
- ESSnuSB+: started January 2023, EU-project 3 MEuros, 4 years

Super Fine Grained Tracking Detector

UiO participation

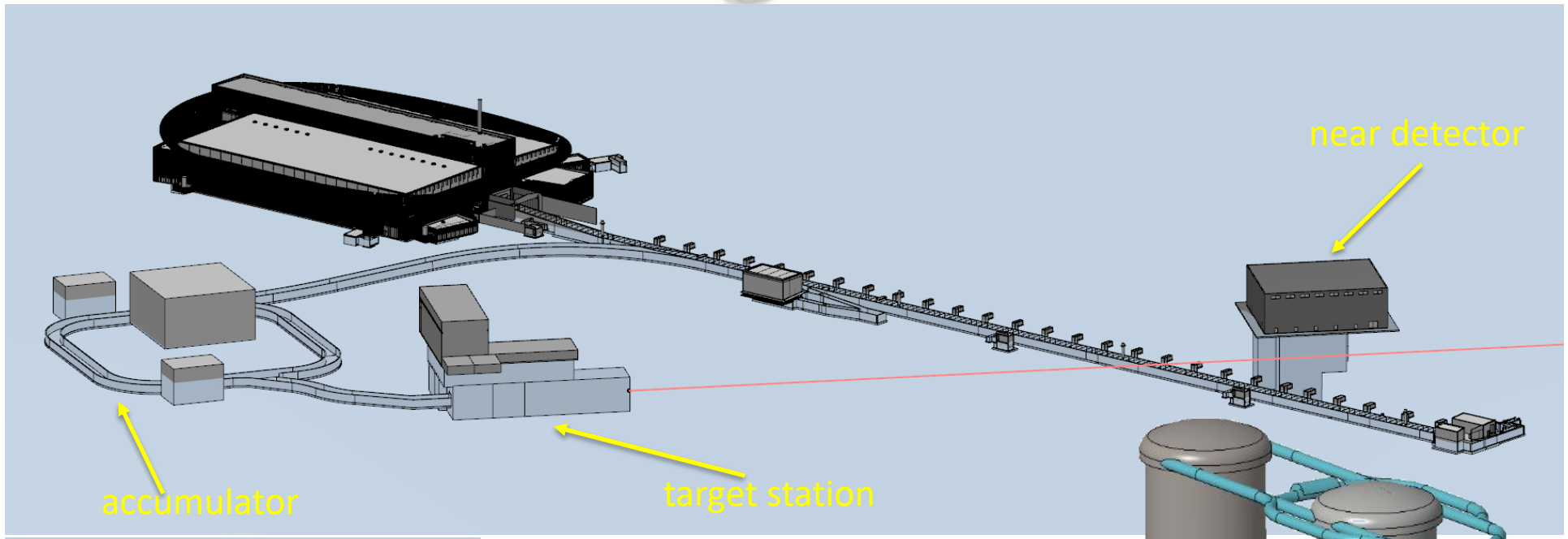
- EuroNuNet "Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery (e-COST)", Ould-Saada, Norwegian representative, member of the management committee
- ESSnuSB – European Spallation Source Neutrino Super Beam – Feasibility study for a long-baseline neutrino experiment; Ould-Saada, Norwegian representative in the Governing Board as observer, 2019-2022.
- E.Gramstad et al. *The SuperFGD Prototype charged particle beam tests*, 2020 JINST 15 P12003, https://dx.doi.org/10.1088/1748-0221/15/12/P12003
- Master thesis, Federico Nardi (Oslo), superv. Ould-Saada, Gramstad, 2020, "Deployment Test and performance of novel Super Fine-Grain scintillation Detectors as active target for future neutrino experiments"

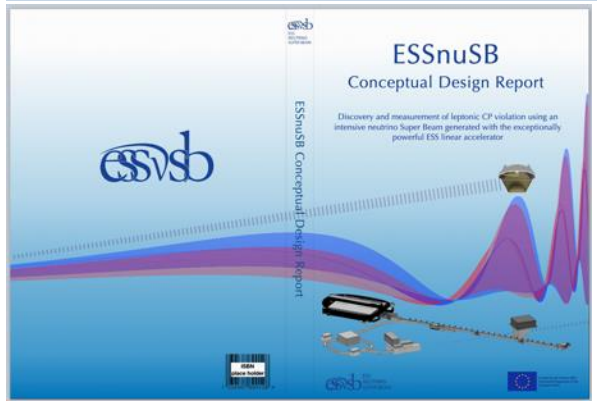




SFGD prototype

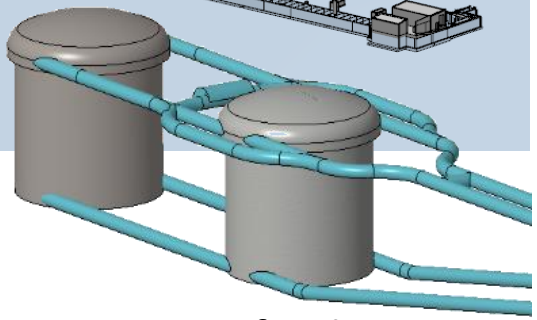
Final ESSvSB facility configuration





Conceptual Design Report

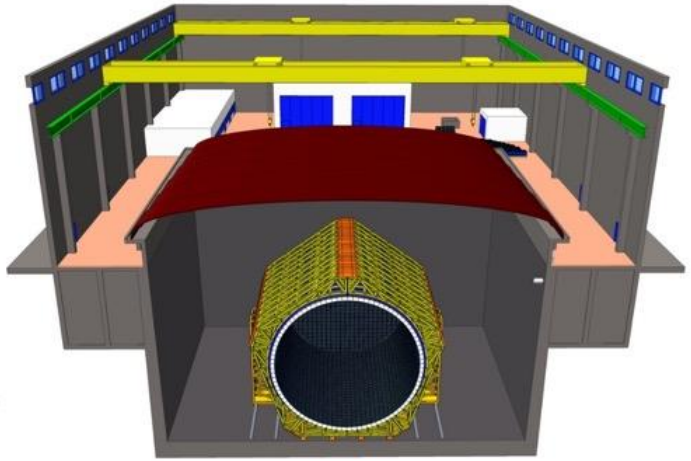
https://arxiv.org/abs/2206.01208



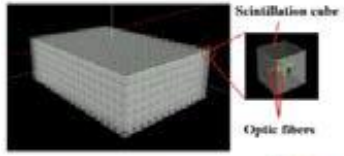
far detector

European Physical Journal Spec. Top. **231**, 3779–3955 (2022).
https://doi.org/10.1140/epjs/s11734-022-00664-w

Detectors

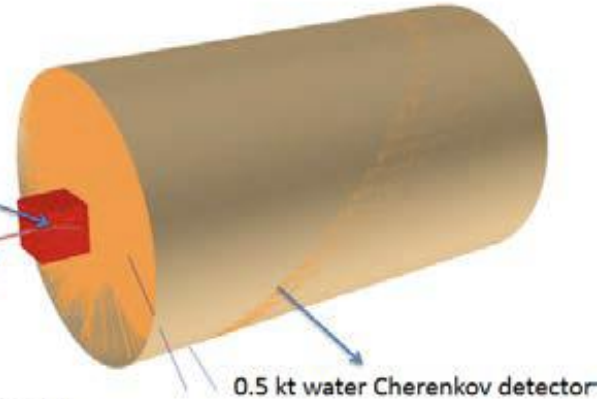


Near detector
(must be able to measure neutrino cross-sections)



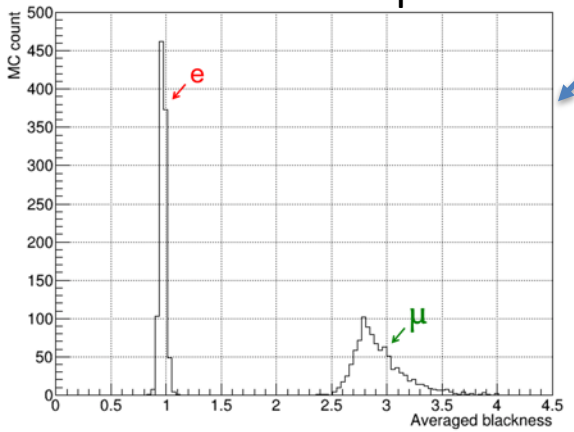
Super-FGD like detector
- 1 – 4 t target mass

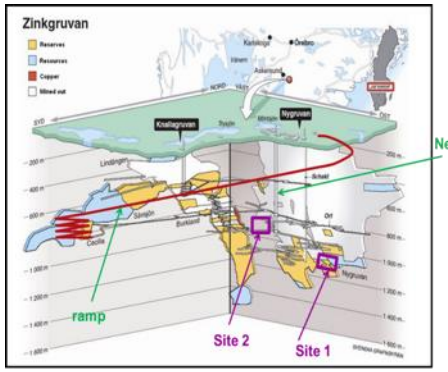
Beam

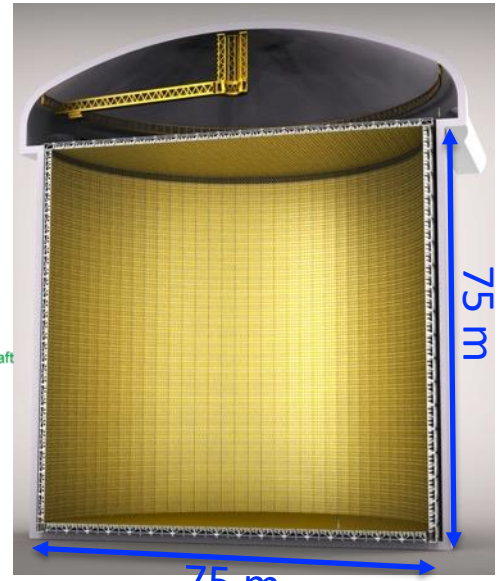


Addition: NINJA-like water-emulsion detector

electron-muon separation





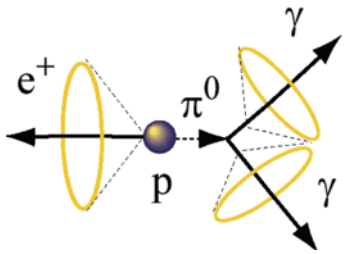


astroparticle physics program with the Far Detector

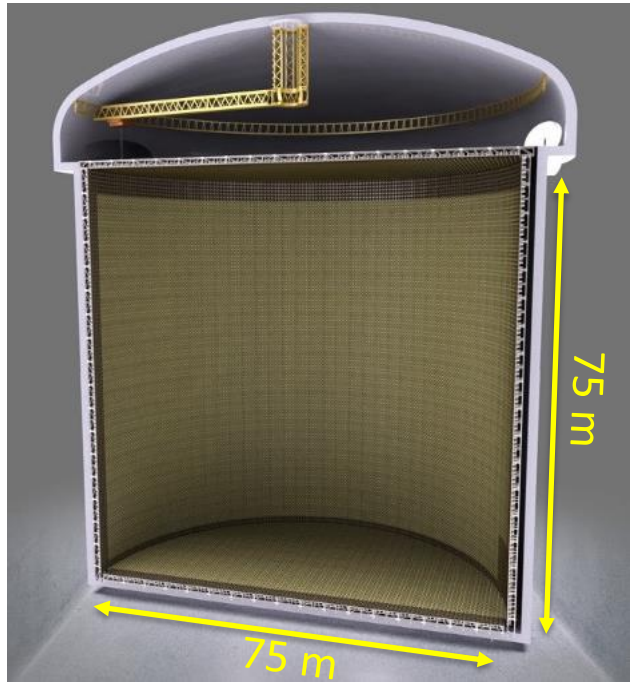
Can we go to the 2nd oscillation maximum using our proton beam?

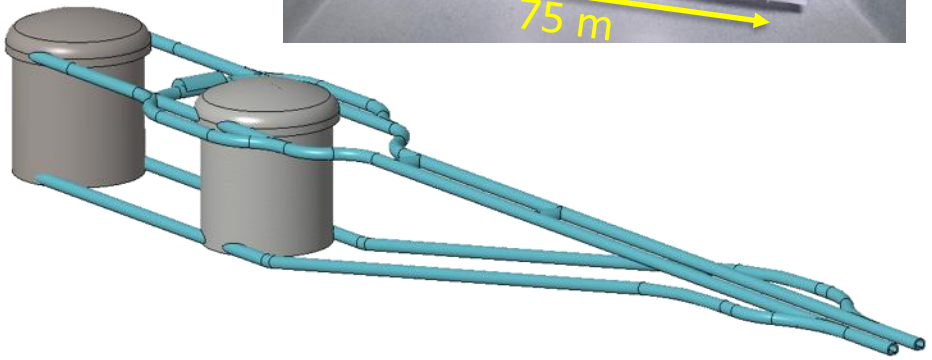
Yes, if we place our far detector at 350- 550 km from the neutrino source.

Megaton Water Cherenkov detector



- **Neutrino Oscillations**
- **Proton decay**
- **Astroparticles**
- Understand the gravitational collapsing: galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

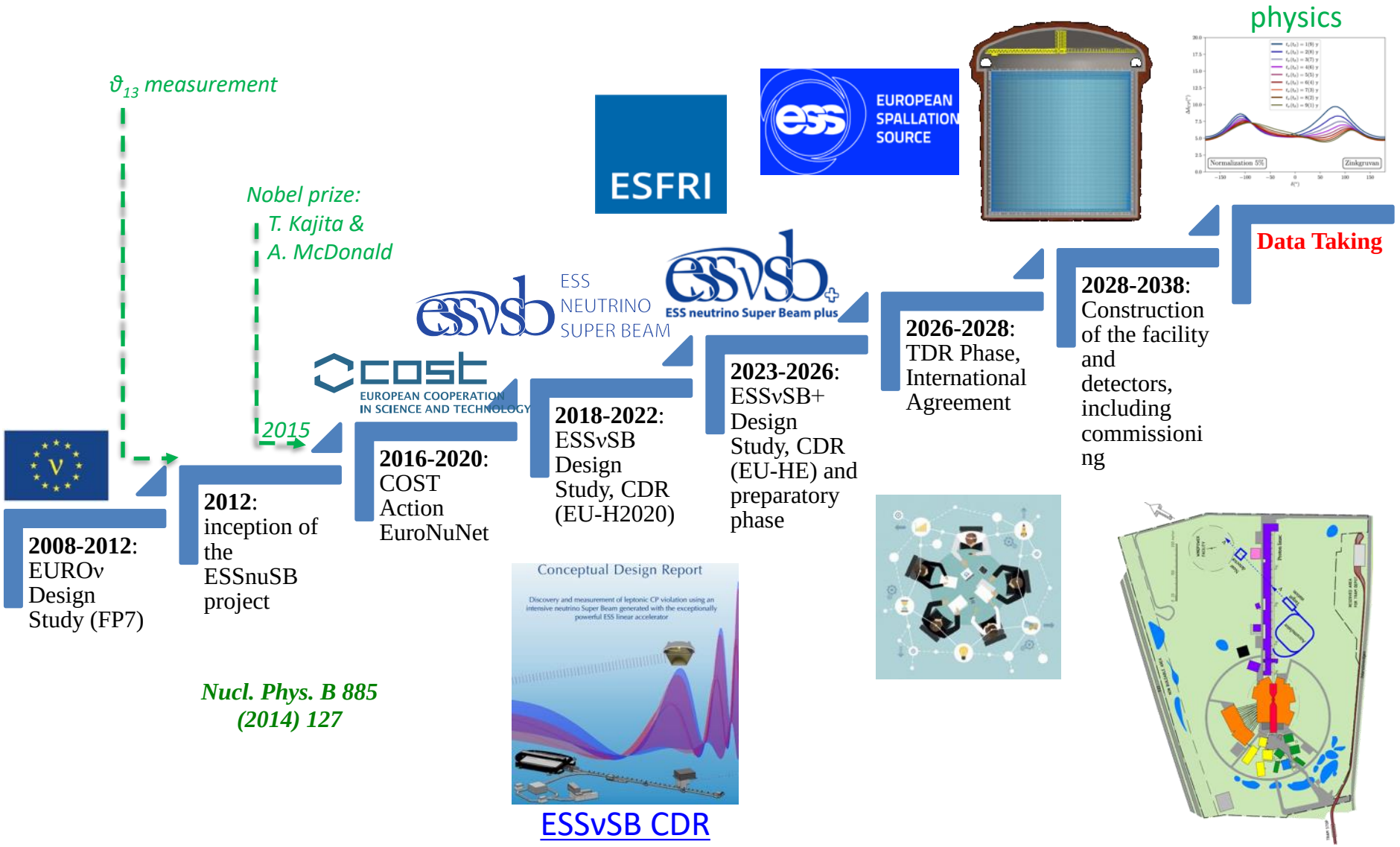




- 500 kt fiducial volume (~20xSuperK)
- Readout: ~20” PMTs
- 30% optical coverage

Possible ESSvSB schedule

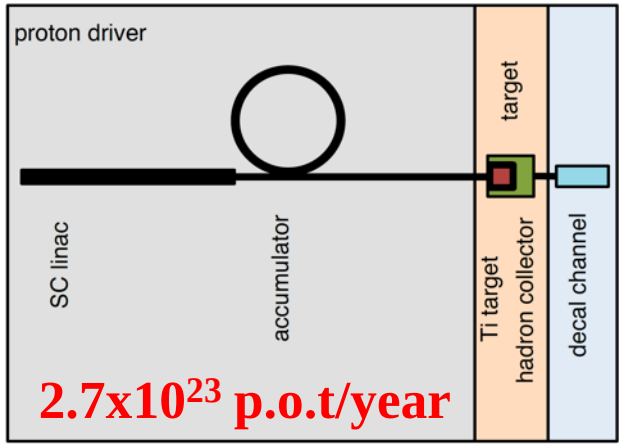
(2nd generation neutrino Super Beam)



ESSνSB and (R&D) synergies

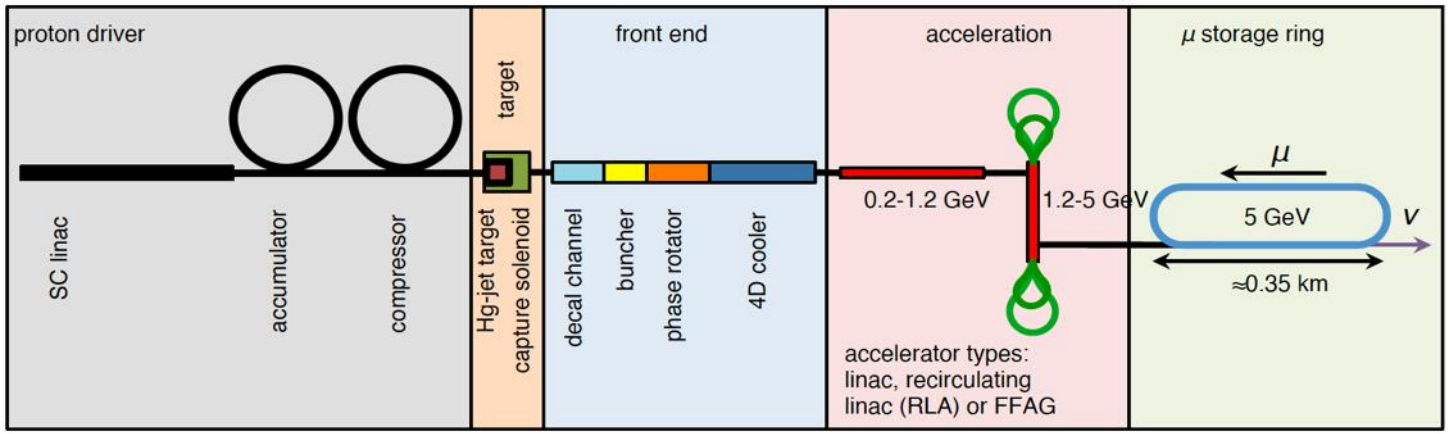
Super Beam

ESSνSB



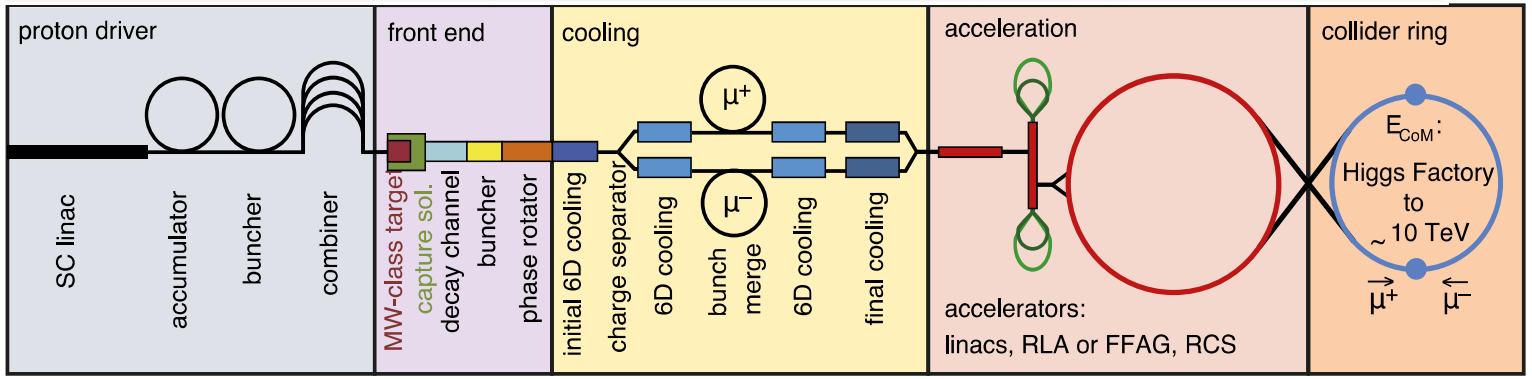
+Decay At Rest and Coherent scat. (with short pulses)

Neutrino Factory



Muon Collider

ESSμSB



A $L \approx 10^{32}$ cm^{-2} s^{-1} $\mu^+\mu^-$ collider ring at the Higgs mass 125 GeV and a $L \approx 10^{34}$ cm^{-2} s^{-1} $\mu^+\mu^-$ collider in the sub-TeV range.