LAGUNA-LBNO: design of an underground neutrino observatory coupled to long baseline neutrino beams from CERN

André Rubbia
ETH Zurich, 101 Rämistrasse, CH-8092 Zurich, Switzerland
E-mail: `andre.rubbia@cern.ch`

Abstract. A new design study called LAGUNA-LBNO has been recently funded by the European Commission to further develop the design of a deep underground neutrino observatory for the study of neutrino oscillations at long baselines, the investigation of the Grand Unification of elementary forces and for the detection of known and unknown astrophysical sources of neutrinos. Building on the successful format and on the findings of the LAGUNA design study, LAGUNA-LBNO is wider in scope but also more focused, and is specifically considering Long Baseline Neutrino Oscillations (LBNO) with beams from CERN. Two far sites, Fréjus and Pyhäsalmi, will be considered with main priority.

1. Main physics goals and motivation

Multi-purpose underground neutrino detectors, like for instance SuperKamiokande [1], have been very successful in particle and astroparticle physics (see e.g. [2, 3] for recent updates), finding first evidence of physics beyond the Standard Model (SM). The feasibility in Europe of an underground neutrino observatory of even larger scale, able to significantly extend present bounds and explore presently inaccessible domains, has been thoroughly studied since several years in a design study called LAGUNA [4] (Large Apparatus studying Grand Unification and Neutrino Astrophysics). LAGUNA is presently one of the top priorities of the ASPERA European astroparticle roadmap [5].

If built, the LAGUNA observatory will provide a very rich physics program, bringing new scientific opportunities and discoveries, in particular:

(i) Coupled to long baseline neutrino beams, it will explore neutrino flavor oscillations with unprecedented sensitivities, complete the understanding of the mixing matrix, determine the neutrino mass hierarchy and explore the existence of CP violation in the leptonic sector *"to help solve the puzzle of the observed matter-antimatter asymmetry in the Universe"*.

(ii) It will test Grand Unification with the search for proton decay and n-$\bar{n}$ oscillations, pursuing one of the key ideas towards a more fundamental understanding of elementary particles. Grand Unified Theories (GUTs) [6] attempt to answer questions like "*what is the origin of the three forces between the known elementary particles described by the SM*" or "*are they unified at high energies, i.e. can they be derived from a single unified force*"? GUTs are supported by the quantized values of the electric charges of the SM particles, by the automatic cancellation of gauge anomalies, and by the running of the gauge couplings, which apparently cross at high energy, but experimental evidence for proton decay has not been observed.

(iii) Taking advantage of the low background environment, it will detect rare events *induced by known and unknown "neutrino messengers" from astrophysical objects to give information on processes happening in the Universe*, which cannot be studied otherwise. In particular, it would sense a large number of neutrinos emitted by exploding galactic and extragalactic type-II supernovae, allowing an accurate study of the mechanisms driving the explosion. It will also enable precision studies of other astrophysical or terrestrial sources of neutrinos like solar and atmospheric ones, and search for new sources of astrophysical neutrinos, like for example the diffuse neutrino background from relic supernovae or those produced in Dark Matter (WIMP) annihilation in the centre of the Sun or the Earth.

2. An underground observatory optimized for large liquid-target detectors

LAGUNA was organized as a 3-year long project funded by the European Commission (EC) to carry out underground sites investigations and develop a concept for a facility able to host the new underground neutrino observatory. It was primarily motivated by the fact that, although Europe currently has four national underground laboratories (at Boulby (UK), Canfranc (Spain), Gran Sasso (Italy), and Modane (France)), none of them is large enough to host a next-generation observatory. LAGUNA selected seven potential underground sites (Boulby (UK), Canfranc (Spain), Fréjus (France), Pyhäsalmi (Finland), Sieroczowice (Poland), Slanic (Romania), Umbria (Italy)) to study, and compared them in order to identify the scientifically and technically most appropriate and cost-effective strategy towards a large scale European neutrino observatory. Three detector options, following the concepts of GLACIER [7, 8], LENA [9], and MEMPHYS [10], were considered at each site. They are based on large surface-instrumented volume of liquids, respectively liquid argon (LAr), liquid scintillator (LSc) and water (WCD).

One of the key conclusion of LAGUNA is that all of the seven considered underground sites are in principle technically feasible, and able to host the desired types of detectors. The rock engineering work was performed by industrial partners with years of experience in various excavation projects completed in geological conditions nearly identical to those of the considered sites. The present engineering know-how combined with the possibilities offered by the modern technology allows to construct the required caverns in each of the chosen locations. While there are site- and detector specific differences in the excavation time and price, the cavern construction is not the dominant cost of the project. It will be only approximately 10–30% of the final price tag. An important conclusion in favor of all sites is that seismology is not an obstacle for the construction of large underground caverns and tanks. The support of the local governments is equally enthusiastic at all LAGUNA sites and also the accessibility is quite comparable. No environmental show-stoppers were found. With the reduced impact of all the other factors, site selection should be based on the physics arguments.

3. The new LAGUNA-LBNO design study

A new design study called LAGUNA-LBNO [11] has been recently funded by the EC. It is based on the successful concept and format of LAGUNA. It will further evaluate the findings of LAGUNA, and in particular, it will assess the underground construction of the large detectors, their commissioning, and the long-term operation of the facility. LAGUNA-LBNO will in addition specifically consider long baseline beams from CERN [12]. The scope of LAGUNA-LBNO is hence wider than the one of LAGUNA, and more funds have been allocated. In addition, the size of the consortium has also nearly doubled.

At the same time, LAGUNA-LBNO is more focused since two sites (instead of the seven of

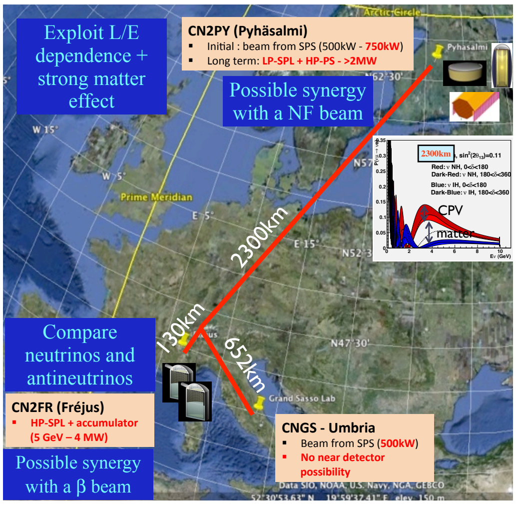

Figure 1. Thee two options considered as main focus in the LAGUNA-LBNO design studies: (1) the "shortest" CERN-Fréjus CN2FR baseline (2) the "longest" CERN-Pyhäsalmi CN2PY baseline. The CNGS baseline with a new "off-axis" site in Umbria is presently disfavored.

LAGUNA) will be developed[1]. From the seven pre-selected LAGUNA sites, the two deepest, Fréjus (4800 m.w.e.) and Pyhäsalmi (4000 m.w.e.), were found particularly attractive and deserved further attention. The study of long baseline neutrino oscillations is one of the main scientific goals, and LAGUNA-LBNO will develop an incremental path towards neutrino mass ordering determination and CP-violation discovery. As can be seen in Figure 1, the far sites provide two complementary baselines from CERN and the following scenarios are being considered:

(i) the CERN-Fréjus (CN2FR) baseline of 130 km with a large WCD detector coupled to a high-power low-energy superbeam from a 4 MW, 5 GeV HP-SPL proton driver;

(ii) the CERN-Pyhäsalmi (CN2PY) baseline of 2300 km, with a large LAr detector coupled to a high-energy conventional beam from protons accelerated with the SPS accelerator upgraded for LHC high luminosity and possibly eventually from a high-power 2 MW, 50 GeV HP-PS proton driver [12].

Both far locations offer excellent opportunities to include a large LSc detector, to enhance the physics program at the lowest energy range, in particular for solar, geo-neutrinos detection and short baseline oscillometry studies with artificial low energy neutrino sources.

4. Focusing on neutrino mass hierarchy and CP-violation at long baselines

From the broad particle and astroparticle physics program, neutrino oscillations at long baseline play a very important role, further exploring the flavor content of the SM. Especially attractive is the ultimate question of a new source of CP violation from the leptonic sector. Linear upgrades of existing long baseline oscillation facilities can find evidence for CP violation only in a limited part of the parameter space [14]. Therefore, new facilities like LAGUNA-LBNO are essential for a definitive exploration of CP violation and the determination of the neutrino mass hierarchy.

A first phase with a conventional neutrino beam is regarded as a mandatory step, especially to establish the far detector site. At conventional neutrino beams, searches for CP-violating effects are based on the electron appearance channels $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. Including higher order terms and matter effects, the $\nu_\mu \to \nu_e$ (resp. $(\bar{\nu}_\mu \to \bar{\nu}_e)$) probabilities can be written

[1] All LAGUNA sites remain in principle available regardless of the LAGUNA-LBNO prioritization. In particular, a third solution is the continuation of CNGS (CNGS+) with a new "off-axis" site in an Italian region [13]. However, this option is disfavored because of the difficulties in locating a near detector and of the intrinsic power limitation of the facility.

as [15]: $P(\nu_\mu \to \nu_e)(\text{resp.} P(\bar{\nu}_\mu \to \bar{\nu}_e))) = P_0 \mp P_{\sin\delta} + P_{\cos\delta} + P_3$ where

$$
\begin{aligned}
P_0 &= \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\hat{\Delta}_{31}) \\
P_{\sin\delta} &= \alpha\,\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31}) \\
P_{\cos\delta} &= \alpha\,\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31}) \\
P_3 &= \alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\hat{\Delta}_{31})
\end{aligned}
$$

with $\Delta m^2_{21} = \alpha \Delta m^2_{31}$ and $\hat{A} = \pm A/\Delta m^2_{31} = \pm 2VE_\nu/\Delta m^2_{31}$. The phenomenology of CP is quite complex given its dependence of the oscillation probability on all oscillation parameters including solar and atmospheric sectors. Two main modes of investigations of CP-violation emerge when considering a conventional neutrino beam:

(i) to measure the CP asymmetry by comparing the appearance rates of neutrinos and antineutrinos; it requires both beam polarities with similar statistics which is more challenging for antineutrinos due to lower fluxes and cross-sections; it can be performed in a narrow band beam and experimentally requires a good control of systematic errors between neutrino and antineutrino runs;

(ii) to look for $\nu_e(\bar{\nu}_e)$ appearance and to measure its energy spectrum shape in a wide-band beam (WBB) at a given baseline L. Experimentally this measurement requires good energy resolution and low background systematics. The fit of the CP-phase is basically determined by the peak positions and height of the 1st and 2nd maximum and minimum. This method is sensitive to all values of δ_{CP} and allows determining the value of δ_{CP} using neutrinos only. However, degeneracies require the neutrino mass hierarchy to be determined beforehand. In a wide band beam and at very large distance where matter effects are significant, the hierarchy is determined unambiguously with an essentially equal sharing of neutrino and antineutrino running modes with much less statistics than needed to explore CP, so this can be achieved as an initial phase of the experiment.

Both methods are complementary for CP-determination, although the second provides a richer phenomenology.

In the LAGUNA context, the CN2FR option would allow the study of CP-violation with a precise comparison of neutrino and antineutrino oscillation rates. The CN2PY option would exploit the L/E dependence of the neutrino and antineutrino oscillations and would benefit from strong matter effect to rapidly determine the neutrino mass hierarchy.

It is important to note that the required size of the detector and integrated beam power, that are needed to discover CP-violation in the leptonic sector, are to first order independent of θ_{13} for large values of θ_{13}, but strongly depend on the true value of δ_{CP}. The physics reach of this kind of setup can be advantageously expressed as a function of the "exposure", which scales like the total active mass of the far detector and the integrated power (=number of protons times proton energy) on target. If Nature has chosen δ_{CP} close to 90° or 270°, there is a chance that significant evidence could be found with setups which are smaller in size than the ultimate detectors considered in LAGUNA. Therefore, the option to increase the scope of the project as a function of progressive findings on CP – the *incremental approach* – was strongly advocated in Ref. [16]. The LAGUNA-LBNO study will consider the physics reach achievable with "exposures" reachable in 5 to 10 years with existing accelerators at CERN as well as significantly larger "exposures" reachable with new accelerators such as the CERN HP-SPL [17] or HP-PS [12]. Conventional beams will eventually become limited by systematic uncertainties, assumed at present to be at the level of 5% or so. If the CP effect is small, e.g. if $\delta_{CP} < 15^{\circ}$, evidence for CP violation could be beyond the reach of conventional beams.

In this case, the chosen LAGUNA-LBNO baselines are already optimal for upgrades towards the beta-beam [18] for the CN2FR and the neutrino factory [19] for the CN2PY, and upgrades towards one of these facilities could be envisaged. New ways to further explore CP violating effects and with higher precision would be potentially possible. The "megaton-scale" Water Cerenkov detector at Fréjus would already be adequate for the beta beam. In the case of a neutrino factory from CERN to Pyhäsalmi, magnetization of the far detector or a hybrid solution, expanding the fine grained and the magnetized muon detector, should be further considered.

5. Beam flux optimization and expected event rates

High-intensity neutrino fluxes as required for LAGUNA-LBNO require high-power proton sources. Prospects for such sources at CERN and their relevance for high intensity neutrino beams were discussed in Ref. [12]. The existing 400 GeV SPS accelerator, profiting from the LHC luminosity upgrades (LIU project), might be able to deliver up to 600–700 kW in a near future. Reaching megawatt beam power at the SPS would likely require significant replacement of its injector chains and a big stretch of its performance. A more appropriate solution which was advocated in Ref. [12] is to consider a new ring accelerator (HP-PS), with a proton energy in the range 30 to 50 GeV, designed for high power with, for instance, an intensity of 2.5×10^{14} ppp and a fast cycle of 1.2 seconds, yielding an average proton beam power of 1.6 MW. A conceptual design is presently being developed within LAGUNA-LBNO.

In LAGUNA, conventional beams to each of the seven considered far sites were analyzed, spanning baselines from 130 km up to 2300 km. In order to optimize the physics sensitivity of long baseline oscillations, the energy spectrum of the neutrino beams must be optimized for each distance to cover well the first and second maximum of the oscillation. For all possible LAGUNA baselines, this implies neutrinos in an energy range $0 \div 7$ GeV. The actual optimization depends on the chosen site and preliminary work was performed based on a full simulation of the neutrino beam line [20]. To produce the beam to shortest distance (130 km), the 4 MW, 5 GeV HP-SPL proton driver was assumed. For the other baselines, the 1.6 MW, 50 GeV HP-PS was considered. If we adopt a 200 days per calendar year, the HP-SPL delivers 56×10^{21} pot and the HP-PS yields integrated 3×10^{21} pot per year. See Table 1. The resulting fluxes are shown in Figure 2. The energies of the oscillation maximum for each baseline are indicated with vertical lines having the same color as the corresponding spectrum for $\Delta m^2_{31} = 2.45 \times 10^{-3}\,\text{eV}^2$. The expected charged current event rates are listed in Table 1. They are normalized to a detector mass of 100 kton and a running time of one year. We note that contrary to naive expectation the event rates for ν_μ CC do not scale like $1/L^2$ since the neutrino focusing increases with the boost and the cross-section increases linearly with energy. The number of tau charged current events increases as well with distance, in particular for the 2300 km baseline the first oscillation maximum is above the tau production threshold.

6. Opportunities with the CERN-Pyhäsalmi (CN2PY) baseline

The Pyhäsalmi mine offers a unique infrastructure for underground access in an excellent condition, and could be readily transformed into a dedicated science facility once the mine closes, currently foreseen towards the end of this decade. The CN2PY baseline offers a very compelling long baseline physics program which can be implemented in a truly *incremental approach* as was shown in Ref. [16]. The initial phase is focused at determining the neutrino mass hierarchy and testing the maximal CP scenario. Owing to the very strong matter effects, the mass hierarchy can be determined with 100% certainty of the unknown δ_{CP} value. The

Table 1. Charged current event rates with optics optimized for the seven LAGUNA far sites (see text). Figures are normalized to a detector mass of 100 kton and a running time of one year corresponding to 3×10^{21} p.o.t. for the 50 GeV LP-SPL+HP-PS proton driver [12] and 56×10^{21} p.o.t. for the 4.5 GeV option.

baseline	neutrino polarity			antineutrino polarity		
km	ν_μ(no osc.)	ν_e(no osc.)	$\nu_\mu \to \nu_\tau$	$\bar{\nu}_\mu$(no osc.)	$\bar{\nu}_e$(no osc.)	$\bar{\nu}_\mu \to \bar{\nu}_\tau$
130	41316	174	–	5915	15	–
630	36844	486	28	13652	157	11
665	38815	516	28	14287	158	11
950	37844	349	40	14700	107	15
1050	51787	314	148	21728	88	65
1570	26785	174	170	11184	47	73
2300	17257	110	377	7577	32	172

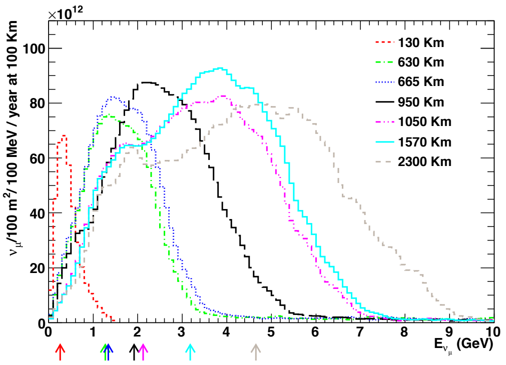

Figure 2. Neutrino fluxes at 100 km for the optimized setups. The energies of the oscillation maximum for each baseline are indicated with vertical lines having the same color as the corresponding spectrum. From Ref. [20].

CP violation parameter space will subsequently be further explored with increased "exposures", which could achieved by expanding the far detector mass and/or increasing the beam power.

Table 2 shows the assumed accelerator parameters, starting with the present SPS configuration, the expected SPS performance after the LIU upgrade, a kind of ultimate SPS++ performance, and finally the figures to be achieved with the HP-PS accelerator.

Table 2. Assumed parameters for different machine scenarios.

	SPS now	SPS+LIU	SPS++	LP-SPL+HP-PS [12]
Proton energy (GeV)	400	400	400	50
ppp	4.00×10^{13}	6.00×10^{13}	7.00×10^{13}	2.50×10^{14}
Tc (s)	6	6	6	1.2
Peak beam power (MW)	0.43	0.64	0.75	1.67
Global eff	0.85	0.85	0.85	0.85
Beam sharing	0.85	0.85	0.85	1
Running (d/year)	200	200	200	200
Npot/year	8.32×10^{19}	1.25×10^{20}	1.46×10^{20}	3.00×10^{21}
Npot equiv at 50 GeV	7.00×10^{20}	1.00×10^{21}	1.20×10^{21}	3.00×10^{21}

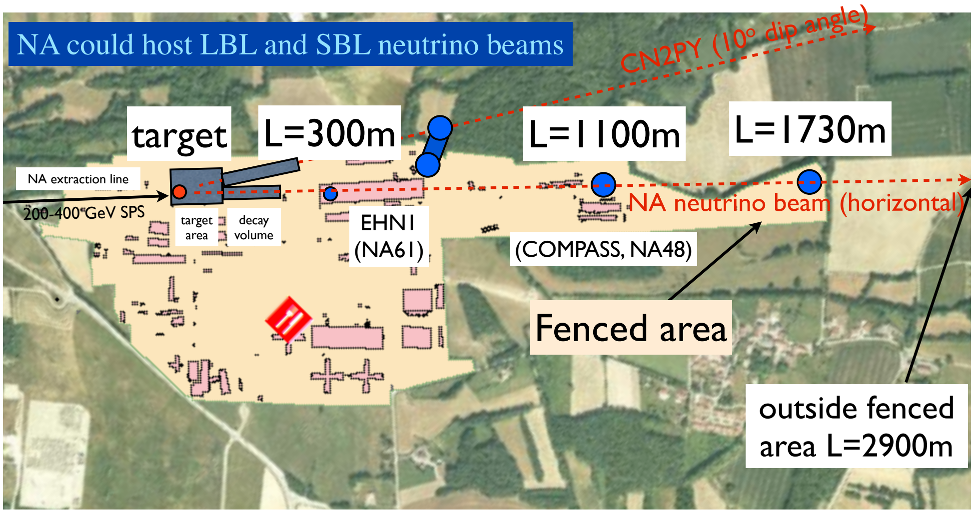

Figure 3. Neutrinos in the CERN North Area: the area could in principle host a facility with both long and short baseline beams.

7. An extension of the CERN North Area for neutrinos ?

Preliminary considerations show that the CERN North area could be the optimal location to host the CN2PY neutrino beam line facility. Protons with an energy of 400 GeV are presently slow extracted from the SPS to the North Area to drive the fixed target program. The proton beam can be extracted from the existing extraction line and horizontally bent north and downward by 10° in order to produce the beam directed at Pyhäsalmi. A preliminary layout foresees an underground near detector accessible from the North Area. See Figure 3. This configuration opens the possibility to have a synergy with a short baseline neutrino beam. The short baseline beam would require a dedicated target and an horizontal decay tunnel. Several detector locations can be identified at 300 m, 1100 m, 1730 m and possibly 2900 m (outside the CERN domain), as shown in the Figure. Further investigations are in progress.

8. Conclusions and outlook

The indications for $\sin^2 2\theta_{13} > 0.01$ have given new impulse to the design of next generation experiments with appropriate baselines and powerful conventional beams. In Europe, the LAGUNA-LBNO design study, a continuation of the LAGUNA project but with a wider scope and more focus than before, has started. The consortium has been enlarged and is aiming at proposing a "realistic plan" for a medium- and long-term European long baseline program, with large discovery potentials at each phase. The first goal is to determine the neutrino mass hierarchy (with the 2300 km baseline). Then, *incrementally* exploring the phase space, leading to CP-violation discovery. In parallel, ultimate searches for proton decay and interesting neutrino astrophysics measurements will also be possible. An expression of interest to the European Strategy Roadmap is foreseen. A graph illustrating a possible timescale for the different steps to develop the LAGUNA-LBNO CERN-Pyhäsalmi programme is shown in Figure 4.

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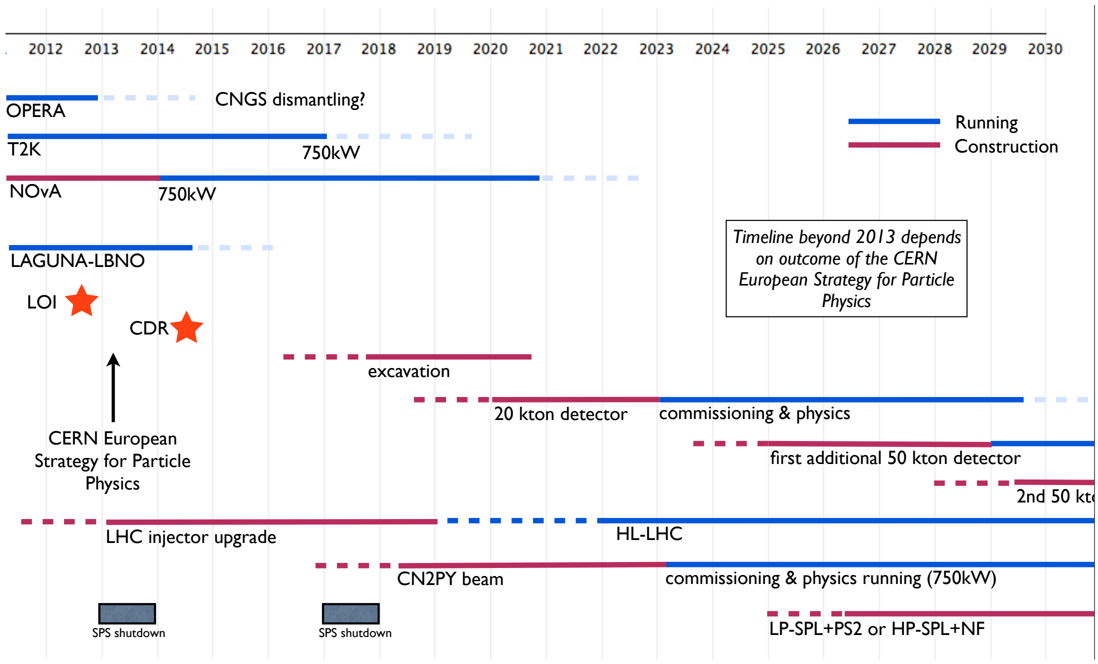

Figure 4. Timeline illustrating the milestones and phases to develop the complete LAGUNA-LBNO CERN-Pyhäsalmi programme.

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