

# Large underground, liquid based detectors for astro-particle physics in Europe: scientific case and prospects

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**ABSTRACT:**

This document reports on a series of experimental and theoretical studies conducted to assess the astro-particle physics potential of three future large-scale particle detectors proposed in Europe as next generation underground observatories.

**KEYWORDS:** Keyword1; Keyword2; Keyword3.

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## Contents

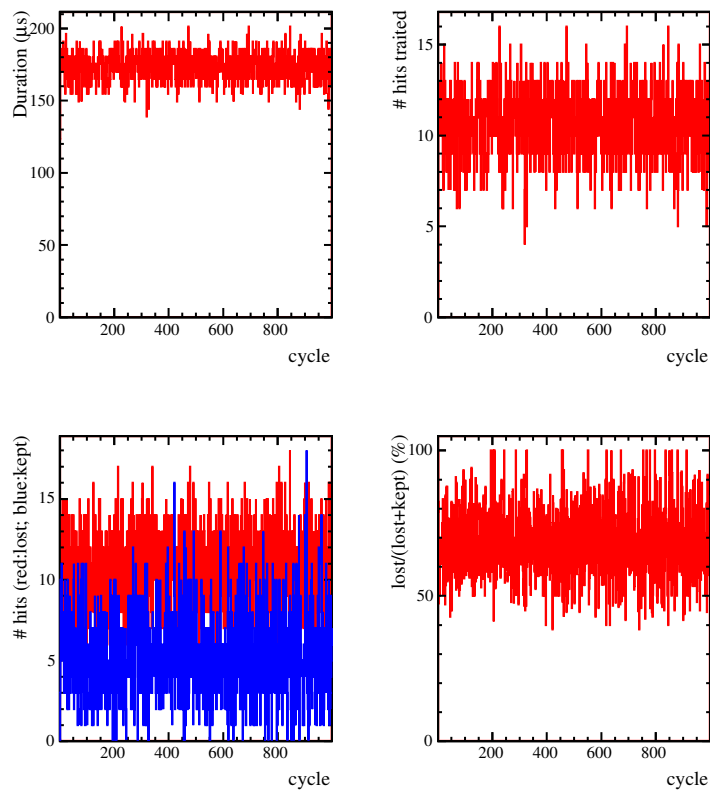
### 1. Physics motivation

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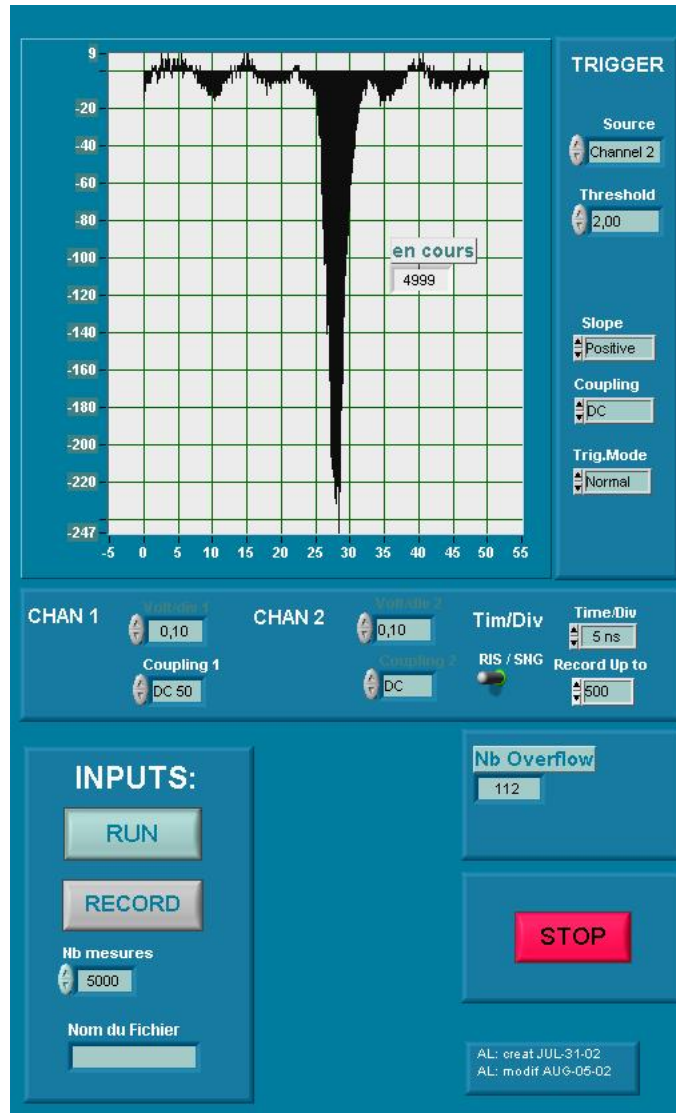
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### 1. Physics motivation

Several outstanding physics goals could be achieved by the next generation of large underground observatories in the domain of astro-particle and particle physics, neutrino astronomy and cosmology. Proton decay [1], in particular, is one of the most exciting prediction of Grand Unified Theories (for a review see [2]) aiming at the unification of fundamental forces in Nature. It remains today one of the most relevant open questions of particle physics. Its discovery would certainly represent a fundamental milestone, contributing to clarifying our understanding of the past and future evolution of the Universe.



**Figure 1.** Example of figure PDF



**Figure 2.** Example figure JPEG

Several experiments have been built and conducted to search for proton decay but they only yielded lower limits to the proton lifetime. The window between the predicted proton lifetime (in the simplest models typically below  $10^{37}$  years) and that excluded by experiments [3] ( $O(10^{33})$  years, depending on the channel) is within reach, and the demand to fill the gap grows with the progress in other domains of particle physics, astro-particle physics and cosmology. To some extent, also a negative result from next generation high-sensitivity experiments would be relevant to rule-out some of the theoretical models based on SU(5) and SO(10) gauge symmetry or to further constrain the range of allowed parameters. Identifying unambiguously proton decay and measuring its lifetime would set a firm scale for any Unified Theory, narrowing the phase space for possible models and their parameters. This will be a mandatory step to go forward beyond the Standard Model of elementary particles and interactions.

Another important physics subject is the physics of astrophysical neutrinos, as those from supernovae, from the Sun and from the interaction of primary cosmic-rays with the Earth's atmosphere. Neutrinos are above all important messengers from stars. Neutrino astronomy has a glorious although recent history, from the detection of solar neutrinos [4, 5, 6, 7, 8, 9, 10] to the observation of neutrinos from supernova explosion, [11, 12, 13], acknowledged by the Nobel Prizes awarded to M. Koshiba and R. Davis. These observations have given valuable information for a better understanding of the functioning of stars and of the properties of neutrinos. However, much more information could be obtained if the energy spectra of stellar neutrinos were known with higher accuracy. Specific neutrino observations could give detailed information on the conditions of the production zone, whether in the Sun or in a supernova. A supernova explosion in our galaxy would be extremely important as the evolution mechanism of the collapsed star is still a puzzle for astrophysics. An even more fascinating challenge would be observing neutrinos from extragalactic supernovae, either from identified sources or from a diffuse flux due to unidentified past supernova explosions.

Observing neutrinos produced in the atmosphere as cosmic-ray secondaries [14, 15, 16, 17, 18, 19, 20] gave the first compelling evidence for neutrino oscillation [21, 22], a process that unambiguously points to the existence of new physics. While today the puzzle of missing atmospheric neutrinos can be considered solved, there remain challenges related to the sub-dominant oscillation phenomena. In particular, precise measurements of atmospheric neutrinos with high statistics and small systematic errors [23] would help in resolving ambiguities and degeneracies that hamper the interpretation of other experiments, as those planned for future long baseline neutrino oscillation measurements.

Another example of outstanding open questions is that of the knowledge of the interior of the Earth. It may look hard to believe, but we know much better what happens inside the Sun than inside our own planet. There are very few messengers that can provide information, while a mere theory is not sufficient for building a credible model for the Earth. However, there is a new unexploited window to the Earth's interior, by observing neutrinos produced in the radioactive decays of heavy elements in the matter. Until now, only the KamLAND experiment [24] has been able to study these so-called geo-neutrinos opening the way to a completely new field of research. The small event rate, however, does not allow to draw significant conclusions.

The fascinating physics phenomena outlined above, in addition to other important subjects that we will address in the following, could be investigated by a new generation of multipurpose experiments based on improved detection techniques. The envisioned detectors must necessarily be very massive (and consequently large) due to the smallness of the cross-sections and to the low rate of signal events, and able to provide very low experimental background. The required signal to noise ratio can only be achieved in underground laboratories suitably shielded against cosmic-rays and environmental radioactivity. We can identify three different and, to large extent, complementary technologies capable to meet the challenge, based on large scale use of liquids for building large-size, volume-instrumented detectors

- Water Cherenkov. As the cheapest available (active) target material, water is the only liquid that is realistic for extremely large detectors, up to several hundreds or thousands of ktons; detectors have sufficiently good resolution in energy, position and angle. The technology is

well proven, as previously used for the IMB, Kamiokande and Super-Kamiokande experiments.

- Liquid scintillator. Experiments using a liquid scintillator as active target provide high-energy resolution and offer low-energy threshold. They are particularly attractive for low energy particle detection, as for example solar neutrinos and geo-neutrinos. Also liquid scintillator detectors feature a well established technology, already successfully applied at relatively large scale to the Borexino [25] and KamLAND [26] experiments.
- Liquid Argon Time Projection Chambers (LAr TPC). This detection technology has among the three the best performance in identifying the topology of interactions and decays of particles, thanks to the bubble-chamber-like imaging performance. Liquid Argon TPCs are very versatile and work well with a wide particle energy range. Experience on such detectors has been gained within the ICARUS project [27, 28].

Three experiments are proposed to employ the above detection techniques: MEMPHYS [29] for WC, LENA [30, 31] for liquid scintillator and GLACIER [32, 33, 34, 35, 36] for Liquid Argon. In this paper we report on the study of the physics potential of the experiments and identify features of complementarity amongst the three techniques.

Needless to say, the availability of future neutrino beams from particle accelerators would provide an additional bonus to the above experiments. Measuring oscillations with artificial neutrinos (of well known kinematical features) with a sufficiently long baseline would allow to accurately determine the oscillation parameters (in particular the mixing angle  $\theta_{13}$  and the possible CP violating phase in the mixing matrix). The envisaged detectors may then be used for observing neutrinos from the future Beta Beams and Super Beams in the optimal energy range for each experiment. A common example is a Beta Beam from CERN to MEMPHYS at Frejus, 130 km away [37]. High energy beams have been suggested [38], favoring longer baselines of up to  $O(2000)$  km). An exhaustive review on the different Beta Beam scenario can be found in the reference [39]. The ultimate Neutrino Factory facility will require a magnetized detector to fully exploit the simultaneous availability of neutrinos and antineutrinos. This subject is however beyond the scope of the present study.

Finally, there is a possibility of (and the hope for) unexpected discoveries. The history of physics has shown that several experiments have made their glory with discoveries in research fields that were outside the original goals of the experiments. Just to quote an example, we can mention the Kamiokande detector, mainly designed to search for proton decay and actually contributing to the observation of atmospheric neutrino oscillations, to the clarification of the solar neutrino puzzle and to the first observation of supernova neutrinos [11, 40, 5, 15, 21]. All the three proposed experiments, thanks to their outstanding boost in mass and performance, will certainly provide a significant potential for surprises and unexpected discoveries.

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