Summary of the outcomes of the neutrinoless double beta APPEC procedure

As part of the implementation of the APPEC Roadmap 2017-2026, a panel, led by S. Pascoli and composed by A. Giuliani, J. J. Gomez Cadenas, S. Pascoli, E. Previtali, R. Saakyan, K. Schaeffner, S. Schoenert, had mandate from the APPEC SAC to produce a document on the roadmap for the necessary future steps on neutrinoless double beta (0nubb) decay, containing the status of the art, the European context and its relationship with the international one, a SWOT analysis of major experimental efforts, the theoretical view and containing recommendations. The SAC received the document on Jun 17, 2019 and feedback from the SAC was received on July 4 and integrated in the document during the period that followed. At the beginning of October the document was released in the archive in view of a Workshop in London held on Oct. 31, 2019, organized by S. Pascoli and R. Saakyan. The meeting had the scope to receive comments from the community. In view of the meeting APPEC released the news describing the process set up by APPEC and the panel recommendations, approved by the SAC. Additionally *the SAC recommended endorsement of at least 2 large experimental programmes in Europe*, an update on the programs in less than 3 yrs, and also endorsed R&D. GA endorsed SAC recommendations and gave *mandate to explore the international situation*.
The document in the archive incorporates the comments of the community received in the London meeting, it was approved by SAC and then by GA on December 3. GA gave mandate to its Chair to further explore synergy and alignment of European funding agencies with US ones. Here, we report on the status of this process, which follows the recommendations of the panel, which are here remembered.

Recommendation 1: *The search for neutrinoless double beta decay is a top priority in particle and astroparticle physics.*
Despite the possibility that next generation of experiments may not be able to reach a positive result in the event of normal ordering (NO), the coming generation of experiment has the potential to reach 15 meV and cover the inverted ordering region (IO). There is consensus between community and agencies in Europe and US that this is a *milestone that needs to be achieved*. Additionally, positive indications from cosmology may drive future searches.

Recommendation 2: *A sustained and enhanced support of the European experimental programme is required to maintain the leadership in the field, exploiting the broad range of expertise and infrastructure and fostering existing and future international collaborations.*
Three lines of research in Europe have this potential, with different schedules for readiness and advantages and risks. Two programs, foreseeing different level of funding, are at the level of CDR, while the NEXT program with gaseous Xe still foresees focused R&D, and will be covered below. Support should be found in Europe to maintain the leadership role in these programs, which have indicated appropriate scheduling and possibilities of milestone verification, while staging to the scale able to probe neutrinoless double beta decay at IO, and with potential to grow further beyond.
The LEGEND program, using enriched ^{76}Ge, has successfully proposed a design, which exploits maximally the synergy between the US driven program Majorana and the EU led GERDA by combining an active LAr shield and high purity Ge detectors. This program achieves unbeaten energy resolution of ~0.15% FWHM at $Q_{\beta\beta}$ of 2039 keV (proved by GERDA) and a very aggressive schedule.
A complementary approach is offered by bolometers using a variety of isotopes with higher Q value than ^{76}Ge. This is quite an advantage since potentially it can achieve lower costs for comparable performance. The need for measurements with various isotopes is highlighted by the ***Recommendation 3****. A multi-isotope program exploiting different technologies at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.*

The findings, supported by the community and funding agencies, are that Europe should suppot *two ready projects to reach the scale necessary to probe IO*. It is also important that the agencies in APPEC align between themselves and with the US agencies, given that all projects have important US participation.
Data taking of LEGEND200 is foreseen 2021 and fully funded. 2025/26 the start of data taking for LEGEND1000 is foreseen if fundings will become available timely. The milestones on background index (BI) reduction are well defined and the strategy towards a factor of 10 reduction in LEGEND1000 from LEGEND200 is realistic and based on a reliable background model. This program requires underground LAr for the shield – in synergy with DarkSide, massive enriched isotope production and good control of α background. With modifications, the Borexino infrastructure, or alternatively the location of the current LVD experiment could be used at LNGS, which also hosted the precursor GERDA and will host LEGEND200.
The LEGEND1000 cost (order of 150 M€) requires strong international cooperation and also cooperation with the DM experiments using LAr. Additionally, such program requires appropriate availability of space at LNGS. The advantage is that LEGEND can be staged, but clearly achivieng the critical mass of 1 ton is the scope to address the IO region. The mass and time of detection are in an inverse linear relation in a null background regime. Being the collaboration composed by 15 Institutes in US, it requires strong support from US and understanding the outcome of their down-selection process, in which LEGEND is involved. The Nuclear Division of DOE is now proceeding towards a down-selection of the site, which sees SNO Lab in pole position. DOE foresees to finance a program with strong US participaton in this site and another across the border also with strong US participation. Between the projects involved in the downselection there are LEGEND and nEXO, while the level of funding of 40 M€ makes CUPID most probably not subject to this process. While LEGEND is European co-led, nEXO is US driven and it has also strong Canadian support, but it did not succeed to extend to collaborators capable for becoming national driven programs in Europe. In order to have LEGEND remain based in Europe, a clear sign of leading support from Germany and Italy is very relevant, as well as the growth of the community in UK with initiatives at national funding level. Other countries involved in the project that have potential to grow are in Belgium, Czech Republic, Poland, Slovakia, Switzerland and Russia. Large scale enriched isotope production is currently carried out only in Russia. The sole non-Russian producer of stable isotopes is Urenco in the Netherlands which plans to scale up production in the future. Hence, it is important to understand the reliability of mass production on enriched germanium in Russia and participation of Russian groups (JINR, NRCKI, ITEP, INR, MEPHI), not only to LEGEND, but also to CUPID. The forefront universities in China and Taiwan are also involved in LEGEND and also a Canadian Institute.
The CUPID experiment plans to use the cryostat of CUORE, hence there is no uncertainty on its location at LNGS. It aims at a ton-scale bolometric detector, after having gained numerous enlightening results through the experience of CUORE using TeO_2,NEMO-3 using ^{100}Mo and ^{82}Se, and also thanks to the relevant results from CUPID-0 with $Zn^{82}Se$. CUPID targets scintillating bolometers with $Li_2{}^{100}MoO_4$ which reduce α backgrounds thanks to PID achieved with light detection in scintillator bolometers and reduction of gamma background due to the high Q-value. Enrichment can achieve 95%. They offer good energy resolution (~0.2% at at $Q_{\beta\beta}$ of 3034 keV of ^{100}Mo proved by CUPID-Mo). The background model is reasonably understood in the existing cryostat. CUPID will start deploying 250 kg of ^{100}Mo in the CUORE cryostat, an important step and a milestone will be the full crystal production procedure (ensuring possible multiple producers) and achievement of BI two orders magnitude better than CUPID-Mo[1] and CUORE reaching 10^{-4} counts keV^{-1} kg^{-1} yr^{-1}. The CUPID CDR is ready.

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[1] In the CUORE infrastructure the background can be improved by two orders of magnitude compared to the background of CUPID-Mo, known to be < 2 x 10^{-2} ckky (90% c.l.). This is known from the CUORE background model joined with information on crystal purity and alpha rejection capability coming from CUPID-Mo and CUPID-0. The upper limit of CUPID-Mo is affected by insufficient statistics, so that value at current stage no counts are present in the ROI and by contaminant elements contained in the Eidelweiss cryostat where crystals were run.

CUPID includes about 50% of US partners in the collaboration and their contribution could cover an important fraction of the full costs. A strong commitment is expected from INFN and Italian institutes in CUORE in a timely fashion. It is relevant that France, where a numerous community working in CUPID with about 40 of the collaborators from CSNSM, IJCLab, IP2I, CEA are present, takes actions at funding agency level to exploit the important inheritance from NEMO and SuperNEMO, which see in CUPID a timely opportunity. As already stated, also for CUPID cooperation with Institutes in Russia and Ukraine (ITEP, NIIC, INR NASU) are important for isotope and crystal procurements. Other countries involved are Spain and then China, which is interested to develop bolometric technologies also for the future. It is difficult to think to a convergence with AMoRE in South Korea, though communication should continue.

The SAC and GA also endorsed R&D towards new technologies to reach the normal hierarchy and for new physics searches in line with ***Recommendation 4.*** *A programme of R&D should be devised on the path towards the meV scale for the effective Majorana mass parameter*. The program using gas and liquid xenon is promising. The international situation is somewhat more complex, and it requires interfacing further with the international community and in particular with the US. There is also a possible convergence of dark matter programs with liquid noble gases, which can reach good background rejection in the region of interest, that will be further explored also by the SAC panel on direct detection of DM. Experiments in DM, which aim at detecting nuclear recoil in the eV-keV range, can extend their reach for electrons in the MeV range (as shown by K. Schäffner and Marc Shumann at the London meeting). Recently XENON published the measurement of rare nuclear decays from ^{136}Xe and electron capture from ^{124}Xe and XENON-1t energy resolution of 0.8% at $Q_{\beta\beta}$ ~2435-2481 keV is promising. Backgrounds, dominated by ^{137}Xe and external material background, need careful studies, which already started. Overall synergy between the 0nbb decay and DM community are biderectionally beneficial.

The NEXT program opens the unique opportunity of Ba tagging, enabling the reconstruction of the 2 electrons in the decay, potentially leading to a dramatic reduction of backgrounds. Extrapolated values from ^{83}Kr at 45 keV indicate energy resolution of ~0.5% FWHM at $Q_{\beta\beta,}$ though energy resolution has a dependence on Z. Additionally, NEXT-WHITE achieved 0.91 ± 0.12% FWHM at 2615 keV with 3.3 kg of fiducial mass (arXiv:1905.13110). The reconstruction of the 2 electrons has been achieved independently from Ba tagging, so it enables the possibility to reconstruct the Ba position (arXiv:1905.13141). About 40 days data of NEXT-WHITE where used to develop the background model (arXiv: 1905.13625). Subsequently, in about a year this model will be validated with NEXT-100. Another milestone will be the measurement of the 2 neutrino-double beta decay. NEXT-100 has 2 R&D lines: NEXT-HD is based on exploiting energy resolution, 2 electron separation and radiopurity; NEXT-BOLD is focusing on Ba tagging.

Finally, both the neutrinoless double beta decay, and now also the draft of the SAC panel working on direct detection of DM expressed important recommendations on networking of underground experiments:
Recommendation 5. *The European underground laboratories should provide the required space and infrastructure for next generation double beta decay experiments. A strong level of coordination is required among European laboratories for radiopurity material assays and low background instrumentation development in order to ensure that the challenging sensitivities of the next generation experiments can be achieved on competitive timescales.*
This recommendation was discussed in London and it was recommended that LNGS, being the largest of underground labs in Europe, takes the leadership towards ensuring coordination

between laboratories. APPEC should accompany this process and reconsider possibility to establish a network of underground laboratories.

It is strongly felt in Europe that a diverse isotope program is necessary to improve in understanding of the nuclear matrix elements (NME), to which the inverse of the half-life is quadratically dependent. Theories can advance by a diverse program on various isotopes including measurements on double beta decay with neutrinos and strong synergy with nuclear physics measurements. Neutrinoless double beta decay experiments and theory represent an important point of synergy with the NuPPEC community. For instance, the possibility to issue an EoI to the APPEC-ECFA-NuPPEC communities for increasing synergy in grid calculations in QCD and cosmology was considered in the meeting in London. The importance of support to theory emerged in ***Recommendation 6.*** *The theoretical assessment of the particle physics implications of a positive observation and of the broader physics reach of these experiments should be continued. A dedicated theoretical and experimental effort, in collaboration with the nuclear physics community, is needed to achieve a more accurate determination of the Nuclear Matrix Elements (NME).*

APPEC is ready to update the situation on the neutrinoless double beta decay projects in the mid-term review process which should be finalized in 2021.
Additionally, we nominated as APPEC representative for the Snowmass 2021 process, Berrie Giebels (IN2P3), who is also an APIF representative. We expect discussions in the Neutrino Frontier panel on 0nubb decay with US agencies.