Review on the scientific merit of the envisaged Paarl Africa Underground Laboratory (PAUL)

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Introduction

This brief review aims to comment on the PAUL initiative based on information collected from arXiv:2306.12083v1 by R. Adams et al. and the *Basic Engineering Design Guidelines* provided to the author.

In the following Fig. 1 the excavated volume of existing and planned underground laboratories (ULs) is shown, including PAUL.

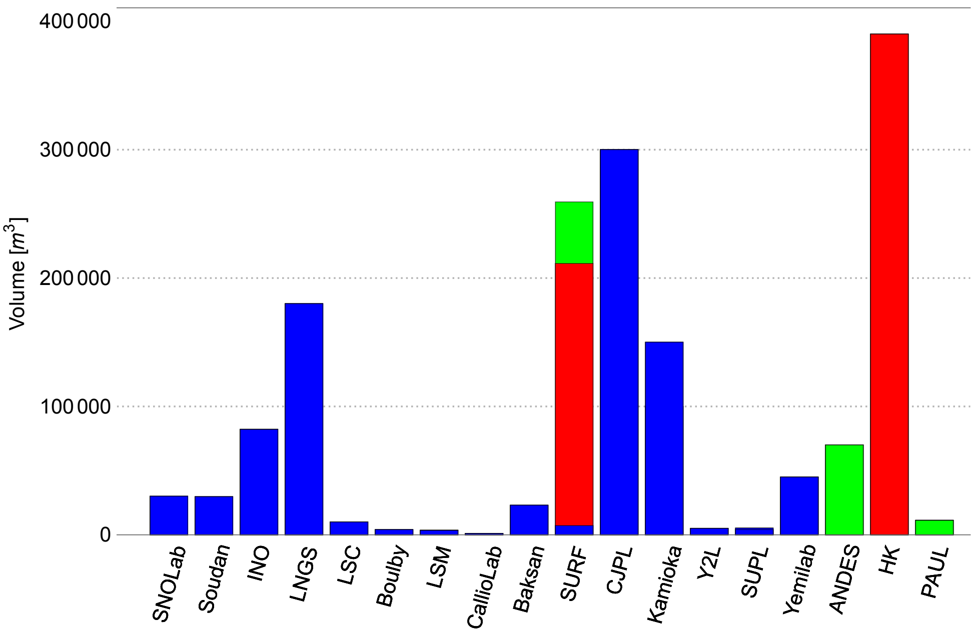

Fig. 1. Excavated volume in existing and planned ULs. Blue: in operation. Red: being excavated. Green: planned.

From this Fig. 1 it is clear that PAUL will be a small-size facility similar to LSM and LSC. In common with LSC and LSM, PAUL will have an easy access through the existing Huguenot tunnel.
In Fig. 2 the cosmic muons flux in ULs is shown in km of water equivalent. For comparison the flux under a flat surface (solid line) is shown. Some ULs are located under a mountain. The mountain profile affects significantly the overall flux with a strong angular dependence. This will also be the case for PAUL.

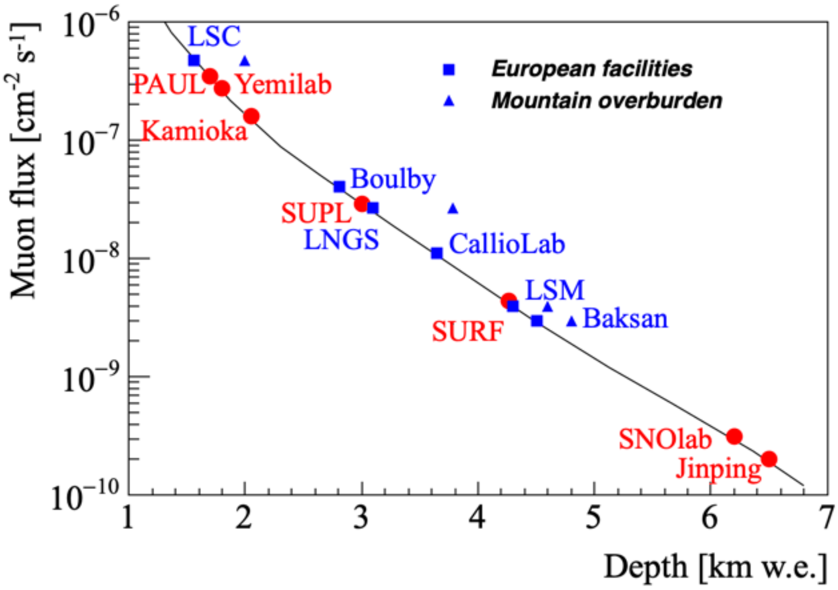

Fig. 2 Cosmic muons flux in ULs. The solid line shows the flux under a flat surface. The approximate position of PAUL in this line is shown. For ULs under a mountain the maximum overburden is also reported (this will also be the case for PAUL – here not shown).

Fig. 1 and 2 helps us to better classify PAUL's proposal in the context of ULs worldwide.

At present, science in ULs is mainly focused to the direct search for dark matter (DM), the observation of neutrinoless double-beta decay (0νDBD), and neutrino physics (precision measurement of neutrino oscillation parameters). Apart from these main activities, ULs are also offering opportunities to investigate low energy cross-sections for nuclear astrophysics, biology in extreme and low radiation environments, new techniques for rare events observations, and technology to support quantum computing.

Currently there is a consensus that next-generation experiments for DM and 0νDBD will require a strong collaboration effort between ULs and work load sharing. This need is not only a funding issue but also a technical one. Therefore, an effort is ongoing to build a network among ULs to meet the challenges of the coming projects. For any new UL this is an important parameter to be taken into consideration.

Finally, it should be noted that all ULs but SUPL are located in the Northern hemisphere. PAUL will be located in the Southern hemisphere and this point is valuable.

Comments on the characteristics of the proposal

<u>Location</u> PAUL is proposed to be built along the Huguenot tunnel connecting the town of Paarl and Worcester in South Africa. PAUL's location is about 60 km from Cape Town and about 70 km from the Koeberg Nuclear Power Station. PAUL can serve as

Research Infrastructure for nearby Universities (Stellenbosch, Western Cape and Cape Town). Therefore, the location is excellent.
Incidentally, the distance from the Koeberg Nuclear Power Station is especially interesting because it is the optimal distance for nuclear reactor antineutrino studies. However, considering the upcoming JUNO experiment in China and the proposed dimensions of PAUL, this could be a second order science option for PAUL.

Overburden The expected overburden is about 800 m under a mountain profile. Around the Huguenot tunnel the rock is solid and this ensures long-term stability of the structure. The underground cosmic muons flux is expected to have a significant angular dependence, similarly to the LSC case, due to the mountain profile. Therefore, a mapping of the flux around a few hundred meters from the deepest location it should be performed before selecting the final position. At LSC, as an example, there are two underground laboratories, LAB2400 and LAB2500. LAB2400 is at the deepest location with respect to the mountain profile. LAB2500 is a few hundred meters away but it shows a cosmic muons flux with a less angular dependence. In any case the PAUL's overburden is in the low side of present operating ULs. This will impact on science possibilities when, as an example, a low background from neutrons induced by cosmic muons is crucial for the physics case under consideration. In addition, it should be taken into account that at the depth of PAUL any experimental activity on DM and 0νDBD has to be equipped with a muon veto detector. Similar strategy is adopted at LSC, Y2L, Yemilab, and SUPL. In general, when specific experimental activities are discussed, one can envisage an active veto for muon-induced background.

Radiopurity In the present proposal low radioactivity shotcrete coating is foreseen. In case of high Radon emanation from the rocks an internal surface coating with a specific resin to reduce emanation is foreseen. These are crucial assets for PAUL. Preliminary Radon concentration levels of order 45-65 Bq/m^3 have been reported without a specific ventilation system, which can further improve the situation. No results on U and Th concentration from gamma-rays spectroscopy are reported although measurements have been performed. It would be nice to compare the results with those from other ULs. It is recommended that all materials being used in making PAUL will be selected through radio-purity assay.

Underground laboratory design Two options are under consideration: A with a single Hall; B with three Halls. The overall excavated volume and available surface are the same. Option B allows to better separate different experimental activities, including safety. However, it limits the possibilities PAUL could face. Therefore, considering also the case of LSM and LSC, I would recommend option A, which is the preferred one.

Ventilation The requirement for PAUL is a ventilation system which ensures ISO8 cleanliness level. The possibility to make the entire laboratory a clean room with better cleanliness level is under consideration. I recommend a dedicated ventilation system for PAUL for safety reasons mainly but also for high standard cleanliness performance. Considering the size and depth, with a clean room standard infrastructure at ISO6 PAUL could offer a more valuable opportunity for future science activities. A few examples follow: LSM is a small size laboratory with a high air exchange rate through a dedicated ventilation system, which reduces significantly the Radon concentration; BOULBY is a ISO7 clean room with a sub-section at ISO6; SNOlab is a large underground clean room. The rate exchange in PAUL of order of one total volume per hour should meet the requirement for an ambitious low Radon concentration <15 Bq/m^3. This item is of utmost importance.

Accessibility PAUL will have an easy access which is a valuable feature. The accessibility is similar to that of LSM which has been in operation for many years. A loading and unloading equipment procedure is foreseen.

General Services Based on the documentation provided these Services (water and electricity supply, external communication connections, waterproofing, sewer system, air conditioning, illumination, parking area, surveillance, energy and wiring network, sanitation) are well suited for PAUL. Bridge cranes (central 40 ton) and lifting systems are included. I think one service is missing and could be included. A monitoring system of the underground excavated Hall with fibers or fixed points for periodic precision distance measurements.

External services External support facilities must be included in the overall program. Any ULs need an external surface area with offices, computing center, workshop, storehouse and a minimum dedicated scientific and technical staff. An external service facility is envisaged on the Paarl side.

Environment PAUL is meant to be designed to have negligible impact on the environment. This aspect is not detailed. However, this aspect is of utmost importance for a long-term operation of PAUL, based on the experience from other ULs.

Future expansion No future expansion for PAUL is under consideration. This is an important evaluation parameter. In fact, due to the present proposed size, this parameter should be considered to make PAUL a facility with unique characteristics for its long-term use. One characteristic is, as an example, a clean room infrastructure with low Radon level. A second one is its location in the Southern hemisphere.

General comments on the proposal

Taking into account the above considerations, I think PAUL offers several opportunities:

1. a new ULs in the Southern hemisphere (with respect to SUPL in Australia, PAUL should have some new and specific feature to make it a valuable alternative for a Southern hemisphere UL);
2. the opportunity for Universities in South Africa to actively participate in international efforts on DM, 0νDBD, and other rare events searches;
3. the opportunity to install in the laboratory small/medium-size experiments on DM and 0νDBD supporting the international effort;
4. the opportunity to install in the laboratory specific facilities to support the search for rare events;
5. the opportunity to expand the research activities in ULs on biology and quantum computing.

To be successful this program requires:

1. PAUL to be a unique facility with a clean room standard infrastructure;
2. to reduce the Radon level (<15 Bq/m^3) (from data available this milestone seems feasible);
3. to be equipped with a radiopurity assay facility underground and a service area on surface (regardless any future experiment, this is an important initial investment to be planned with the excavation).

With respect to the international ULs framework, it should be understood that in its present configuration PAUL will not host large next-generation experiments but can give a crucial contribution to expand the physics case of small/medium-size experiments which can benefit of multiple locations; it can give crucial contribution to design and test new detectors; it is a unique opportunity for the community in South Africa to be engaged in an active way in a global effort in science projects carried out in ULs. Clearly, PAUL's staff and associate representatives will need to be proactive in the international community of ULs.

In conclusion, my recommendation on the present proposal for PAUL is very positive provided the above points I have underlined.

Date: August 21, 2023

To: Prof. Richard Newman
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Review of the Proposed Paarl Africa Underground Laboratory

This review considers the technical and scientific value of the proposed Paarl Africa Underground Laboratory listed in the arXiv
document 2306.12083v1 titled "Paarl Africa Underground Laboratory" and the document titled "Paarl Africa Underground Laboratory: Basic Engineering Design Guidelines."

I was told to:

- Review the PAUL concept paper (this gives background to PAUL and a broad description of science we envisage being pursued there),
- Review a document detailing the basic engineering guidelines (in particular the proposed cavern dimensions and scope this gives to pursue research in the fields related to Dark Matter search, ultra-low gamma-ray spectroscopy, neutrino (or anti-neutrino – PAUL will be located about 70 km from the Koeberg PWR) physics and radiation biology)
- Comment on the foreseen value/impact (especially internationally) of scientific outputs from the PAUL, keeping in mind its location and envisaged scope of research.
- Submit his/her report by 21 August 2023.

REVIEW SUMMARY

The proposed Paarl Africa Underground Laboratory (PAUL) would be a valuable addition to the African and global research enterprise. PAUL would enable detailed studies of fundamental and applied science while training a workforce on cutting-edge technology. The scientific goals include neutrino properties, the nature of dark matter, the impacts of low radiation environments on biological systems, underground biology, environmental monitoring, underground facilities and technology, geothermal energy, and geology. The broader goals of hosting international experiments is viable, and investments in the local South African research community, as well as local partner countries, would help maximize the return on an investment in PAUL.

PAUL WITHIN THE INTERNATIONAL CONTEXT

PAUL would be the only underground laboratory in Africa and only the second underground laboratory in the Southern Hemisphere; a facility opened in Australia in 2022. Facilities that are like the proposed PAUL are more numerous in the Northern Hemisphere with labs in North America, Europe, and Asia. The proposed PAUL will not be the deepest laboratory in the world, but its depth will reduce the cosmic radiation to a level acceptable for the envisioned science programs. The size of the PAUL is like the Stawell Underground Physics Laboratory in Australia, so PAUL will be a significant addition to the underground experimental space in the Southern Hemisphere. The size of the laboratory will allow for a single large experiment, such as the mentioned reactor neutrino experiment, along with a suite of smaller experiments, such as the low-mass dark matter, biology, and other experiments.

The personnel envisioned for PAUL are not discussed. Some underground laboratories have minimum staffing and require experimenters to supply all the labor required to stage and operated experimental infrastructure. Some laboratories have more optimized staffing and can accomplish engineering, construction, scientific, and operational tasks for experiments. Having a clear plan for the staff will allow researchers considering experiments to fully plan the staff and operations funding will be needed for future experiments.

There was not a discussion of the research community that is interested in this infrastructure in the two documents. The international community has been growing at an accelerated rate since the neutrino research in the 1990s and impacts over 1000 academic publications a year. Concept papers for large international projects can list hundreds of authors[i]. The underground scientific fields are driven by friendly competition and large collaborations. A robust and local research community that can incorporate into this larger international community will be an important part of developing a successful PAUL.

Having a local and African research community eager and able to exploit new infrastructure in South Africa is an important and natural part of developing such research infrastructure. Investing in workshops and local researchers should be done in parallel with the engineering and construction of PAUL to maximize the scientific and technological returns from the investment in the infrastructure. There are 26 institutions in the author list of the PAUL concept paper, and 13 of them are African, so there appears to be sufficient interest to seed a fulsome research community. 13 of the institutions on the author list were from outside of Africa, so the envisioned international engagement and collaboration appears to be viable as well and should be encouraged to incorporate a nascent African underground research community into the broader international community.

In summary, PAUL would be a valuable addition to a growing international scientific endeavor. The underground infrastructure around the world is still being developed, so there are scientific niches that have not been exploited in many of the areas listed in the PAUL concept paper. An investment in PAUL should be in parallel with developing the scientific community and projects that would use the infrastructure.

SCIENTIFIC VALUE OF THE PAUL CONCEPT

The PAUL concept paper lists a variety of potential scientific topics for the PAUL facility. These include fundamental particle physics including neutrino and dark matter studies, underground biology, underground farming, age-dating to study climate, and geothermal research. These scientific fields can be enabled by the PAUL. Underground laboratories have much lower radiation levels, and this allows most of this science. Some studies on underground biology and engineering do not require low radiation levels but are still enabled by the easy research access to the underground environment.

The PAUL concept paper identifies low-mass dark matter as an opportunity within the larger dark matter field. Numerous concepts for low-mass dark matter searches have recently been published in the literature, so a laboratory to host these projects would be valuable in the southern hemisphere. There are many unknown backgrounds at low energies, but the hypothesized dark matter scattering rates are higher. Thus, modulations in the rates to remove backgrounds is compelling and having experiments in both the Northern and Southern Hemispheres will allow critical systematic checks on modulation experiments. Without Southern Hemisphere experiments, modulation experiments are less valuable to the field.

In addition to allowing for systematic checks on low-mass dark matter experiments, the PAUL concept paper identifies an academic area where the South African community could make new intellectual contributions, specifically around merging the underground experiments with the astronomical measurements being done by the South African community in the Square Kilometer Array, the Hydrogen Epoch Reionization Array, and the Cosmic Microwave Background Stage-4 survey. There are scientific opportunities in combining the most sensitive underground searches with the most detailed astronomical surveys to narrow down the possibilities for dark matter, and to gain the most insights into any discoveries regarding the dark matter problem. If these communities could be brought together in South Africa, then that represents an opportunity for thought leadership.

There isn't significant discussion of the proposed anti-neutrino experiments utilizing the local Koeberg power reactors. This is described as an opportunity in the abstract of the PAUL concept paper and as a detector in the basic engineering design document. This is an opportunity to create connections between the nuclear power industry and the academic community, which can be beneficial in creating new technologies and innovations as well as creating paths to educate and train the highly qualified personnel required by the nuclear industries as well as improving the assay capability to monitor performance and containment of the reactors.

The unparalleled ability to assay for low-levels of radioactivity in underground environments can be used to monitor the environment for radioactive releases by industry, but also allows careful monitoring of the materials that go in low-background experiments to ensure no radioactive materials are used in construction. Additionally, the capability to assay for low levels of isotopes enables environmental studies. The PAUL concept paper identifies ice cores from the poles as an opportunity to contribute detailed data on the history of ice growth over the timescale of centuries, an important timescale to study the impact of the industrial revolution on the climate.

There are sufficient research opportunities that PAUL would make valuable scientific contributions to several fields. The multi-disciplinary approached offered by the strong investments in astronomy in South Africa could allow for scientific leadership in the area of dark matter. Furthermore, the industrial ties to underground research are nascent, so the developing PAUL scientific goals could incorporate national goals, e.g. around nuclear energy or underground infrastructure, producing highly trained and qualified personnel aligned with those goals.

BASIC ENGINEERING DESIGN CONSIDERATIONS

The basic engineering considerations for PAUL appear to be appropriate for a laboratory with this scientific vision and size. The ambition to make the inner laboratory a monolithic cleanroom is like SNOLAB, which has proved advantageous for deploying small-to-medium-sized experiments such as the low-mass dark matter experiments envisioned for PAUL.

The electrical requirement to deliver two megawatts of power will require a commensurate rejection of the heat from using this amount of power in the underground space. The engineering document does not make it clear if the heat would be removed through the water service or the ventilation, or some combination. The requirement to remove heat can be the dominant requirement for the chilled water and/or ventilation.

Even though no future expansion is planned at this moment, it may be prudent to add that consideration to the initial engineering design. Sometimes it is possible to make inexpensive design adjustments that can save significant resources if the desire to expand does appear in the future.

The communications infrastructure is important and can be critical for operational excellence in these highly technical experiments. Most experiments designed for underground laboratories are designed for highly remote operations. Having robust internet connectivity can be important for equipment safety. Additionally, some of the world leading experiments collect large quantities of data, so ensuring the internet connection has upgrade capabilities beyond 10 Gb/s may be important to allow future experiment concepts.

All the engineering considerations appear to be appropriate for a world-class underground research facility. The engineering considerations are a good basis to consider developing a preliminary engineering design for cost and feasibility.

CONCLUSION

The proposed PAUL would be a valuable addition to the international research infrastructure at a time when the technique of utilizing underground environments for research is just entering maturity. This laboratory would enable important experiments as only the second such infrastructure in the Southern Hemisphere. It will be important to invest in the researchers and the research plans for the laboratory to maximize the return on any investment in PAUL.

Sincerely,

Jeter Hall

Jeter Hall
Director of Research

[i] The recent white paper on the XLZD dark matter project had over 500 authors. https://arxiv.org/abs/2203.02309

Review of the scientific merit of the envisaged PAUL

The South African Underground Laboratory (SAUL) and now the Paarl Africa Underground Laboratory (PAUL) initiative has long been discussed in the wider South African physics community.

Without repeating the details contained in the science case paper https://doi.org/10.48550/arXiv.2306.12083 (Robert Adam et. al., 2023), I would like to emphasize that an Underground Laboratory (UL) facility in South Africa will unleash the county's untapped resources and capability in science and technology. Tapping into the UL space will open new avenues of innovation which will spin off into sectors such as archaeology, health, agriculture, mining, and future underground infrastructure.

An UL facility's research activities will complement and enhance the country's flagship projects such as the SKA science, SA-CERN science, and those mentioned in the science case paper. A network of such facilities in SA will be able to answer some of the unanswered science questions and questions about our origin here on earth and in the universe.

The science case paper has already articulated why an UL facility offers unique ways of research that can only, or best, be studied in such facilities. The Huguenot tunnel is identified as an ideal UL facility for reasons explained in the science case paper.

The Paarl facility is envisaged to bring in the international community to join future projects to be planned at the UL facility. This is key to the sustainability of such big project. This will surely put SA's research and innovation on the global competitive edge.

Due to its envisaged multidisciplinary and interdisciplinary nature of future projects the UL facility will train many students and produce knew knowledge to be published in high impact journals and various media platforms - locally and internationally.

While this is a great initiative by the local and international physics community and related fields, there are certain points I would like to recommend for the authors of the concept.

1. **The original idea(s) of a South African Underground Laboratory be kept as collective dream to be realized through a system or network of Underground Research facilities just like in other counties, or just like the GW detectors or an array of ground and space bound telescopes. Such a network will complement the ground facilities and the future underwater facilities.**

2. **The Paarl facility should be the first of the facilities of the network. Its performance will determine the future of SA UL network.**
3. **There should be consultation with communities that could be affected by the presence of the facility in Paarl. An independent environmental assessment should be done once the full plan has been presented, including the engineering aspects.**
4. **There should be consultation with the NSI stakeholders before a final product is presented, e.g. consultation with the humanities to see how they could contribute in a transdisciplinary collaboration in some of the projects.**
5. **From its inception the project(s) should be driven by a diverse team – in particular young and early career researchers should grow within the conceptualisation leading to initial stages. There should be a plan for sustainable HR pipeline.**
6. **The paper on science case should be turned into a document for DSI, the one on arXiv is fine for peers.**
7. **A roadmap might have to be drafted. The roadmap should follow a clear strategy. Please refer to the DSI White Paper and the DSI Decadal Plan**
8. **The Basic Engineering Design Guidelines document should be detailed to specifics. So far the list is fine but I can't comment on the document until it is at a stage of detailed specifics. This will depend on the user community requirements. At some point this type of document should be written by both scientists and engineers.**
9. **The principle of diversity and inclusion should be embraced intentionally at the conceptualisation level. I did not see a single author from a Historically Black/Disadvantaged University on the list of the authors of the science case paper. I can't comment on female authors on the list since I can't tell who is who in terms of gender balance. If you do not start on a clean and clear principles you will end up rushing to tick the boxes when policy makers start to demand transformation.**

In conclusion the PAUL initiative should be supported due its positive impact for South Africa and the international community. A properly written concept document for DSI (the arXiv paper is fine for me as a peer) will assist the decision makers.

28/08/2023

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