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Ton-Scale Neutrinoless Double Beta Decay Perspectives

NSAC Meeting
November 16, 2021

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Some Information About the DOE NP Portfolio Review

The Ton-Scale Candidates

Each experiment that was proposed is world leading in its isotope of choice. The three experiments under consideration are pretty clearly ahead of other efforts in terms of sensitivity and preparedness.

Each experiment proposed would provide unique benefits and strengths that are unmatched, and all three experiments made a compelling case.

	$T_{1/2}$ (10^{28} years)		$m_{\beta\beta}$ (meV) 3σ Discovery	
	Excl. Sens.	3σ Discovery	Median	Range
CUPID	0.14	0.10	15	12 to 20
LEGEND-1k	1.60	1.30	12	9 to 21
nEXO	1.35	0.74	11	7 to 32

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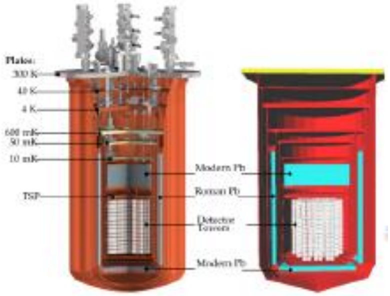
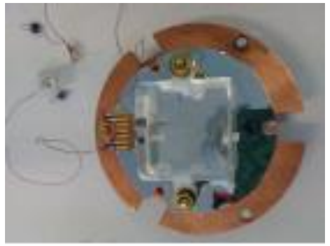
The Ton-Scale Candidates As Proposed

Numbers are in $K

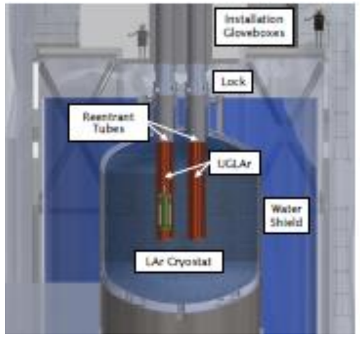
	CUPID	LEGEND-1000	nEXO
Full Project TPC	63,903	442,350	406,169
DOE Only TPC	34,703	257,347	349,531
Non DOE TPC	29,200	185,003	56,638
DOE/Non %	55/45	60/40	85/15
Proj. Complete	2028-2030	2030-2033	2028-2030
Site	LNGS	SNOLab or LNGS	SNOLab

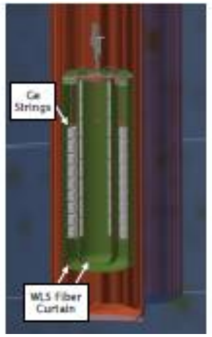
CUPID: Scintillating Crystal Bolometer



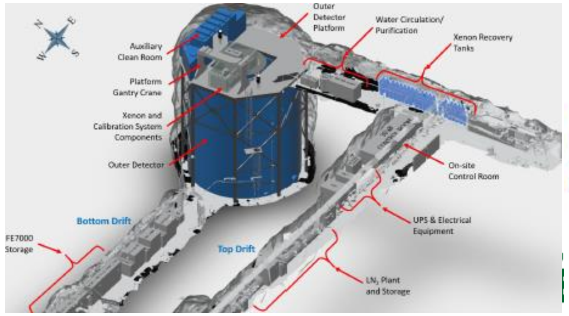


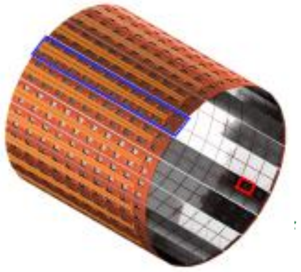
LEGEND: High Purity Ge Crystals





nEXO: Liquid Xe Time Projection Chamber



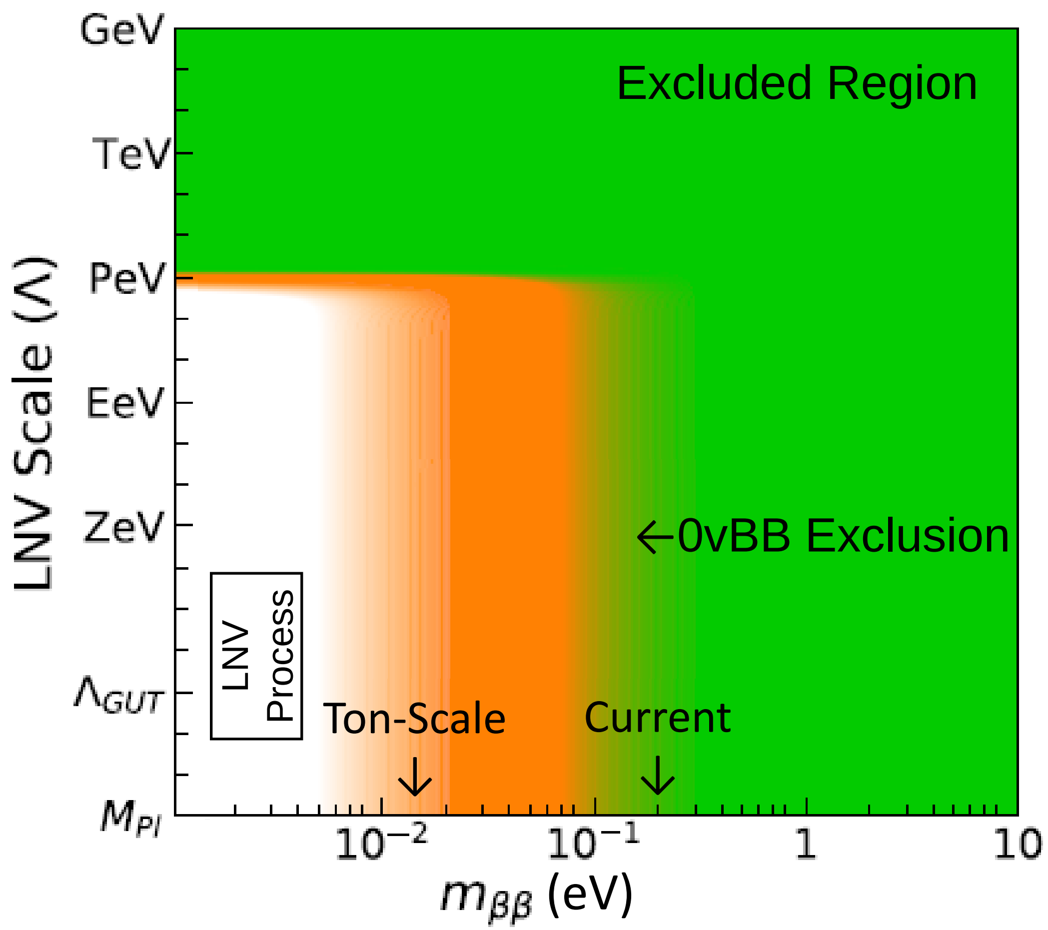


- NEXT was also considered. It is extremely interesting as a potential multi-site option that is truly scalable. If the Ba fluorescence tagging technology is successfully developed, this would be a prime option for a future, near-zero background, multi-ton experiment that could explore phase space deep into the normal hierarchy.

- That said, it was not felt to be as technically mature for the next step ton-scale phase at this time.

Searching for the Origin of the Neutrino Mass

Lepton Number Violation (LNV) is thought to be the origin of the matter/antimatter imbalance in our universe. Neutrinoless Double Beta Decay (0vBB) experiments are sensitive to LNV at any scale.



Observation of 0vBB would at once

- Demonstrate Lepton Number Violation
- Provide a natural explanation for the origin of the matter vs anti-matter asymmetry of our universe (lepto-genesis)
- Confirm Majorana's prediction that neutral fermions can be their own antiparticles
- Explain by what mechanism neutrinos get their mass
- Determine an absolute mass scale for neutrinos

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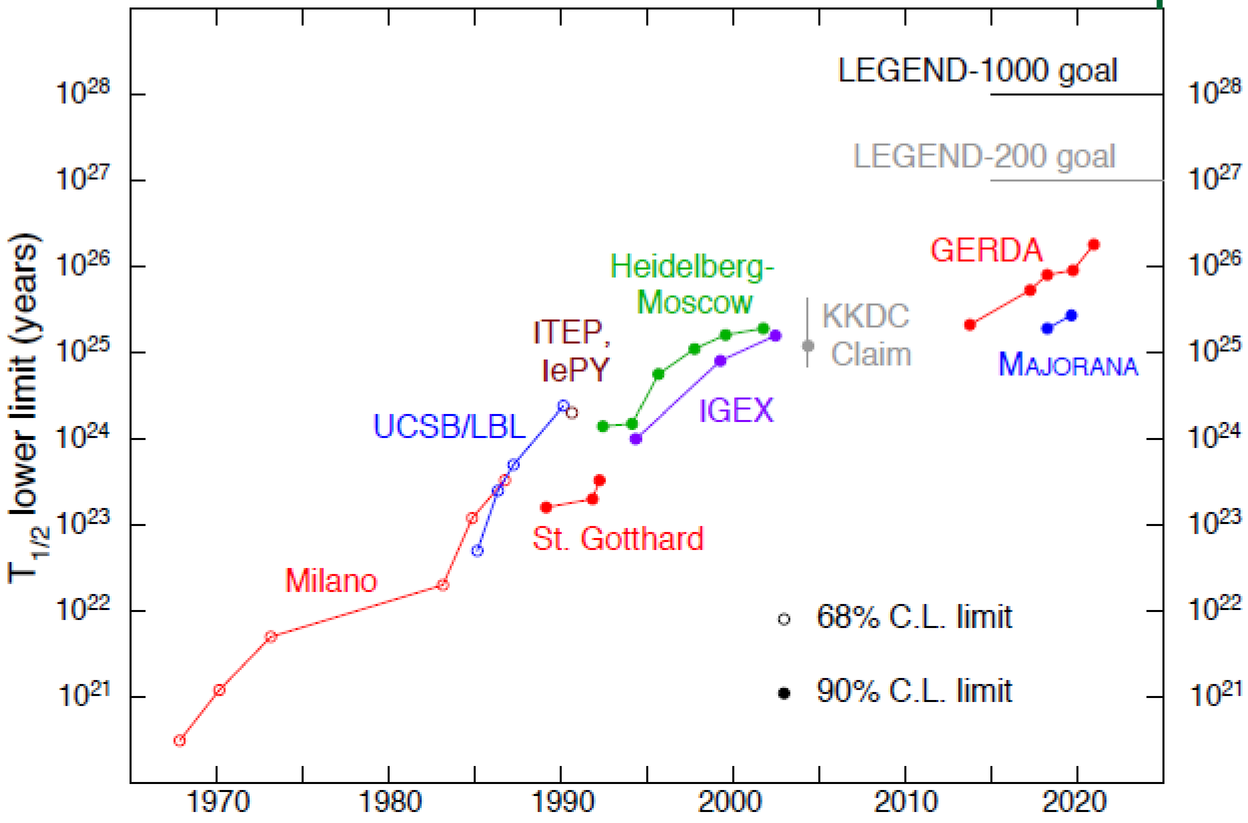
Ambitious goals for the proposed Ton-scale experiments push well beyond past experiments. This example shows progress in high purity Germanium Crystals

normal hierarchy region excluded



Building on Decades of Improvement

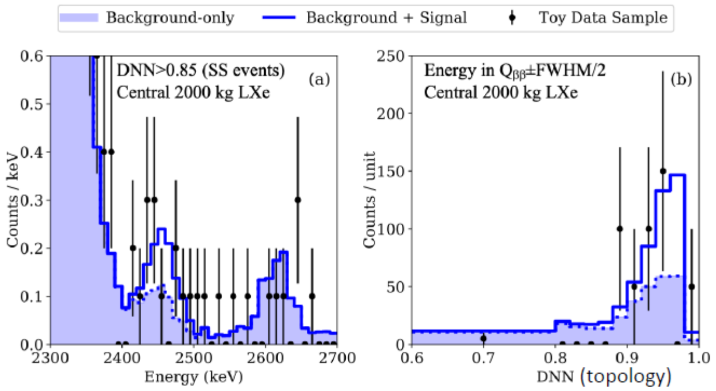
← Ton-scale goal, about 2 orders of magnitude higher than current limit; inverted hierarchy region excluded

← Slowest process ever observed
2×10^{22} years (Xenon-124 double electron capture)

There is an end-point to this line of exploration visible within the technology horzion

Distinct Approaches: limits of sensitivity

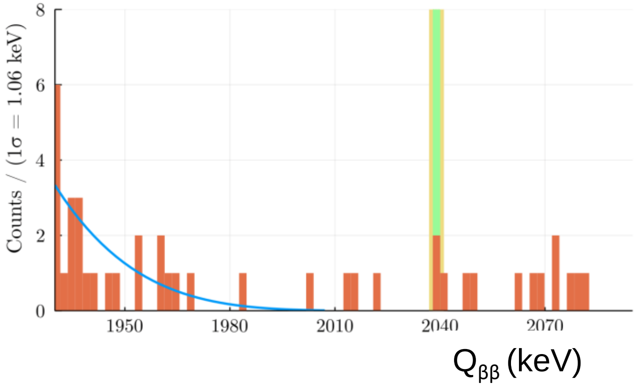
nEXO: Liquid Xe TPC



About 10 counts expected at sensitivity limit

- Monolithic with differential information
- Powerful multiparameter statistical analysis
- Unique control experiment is possible

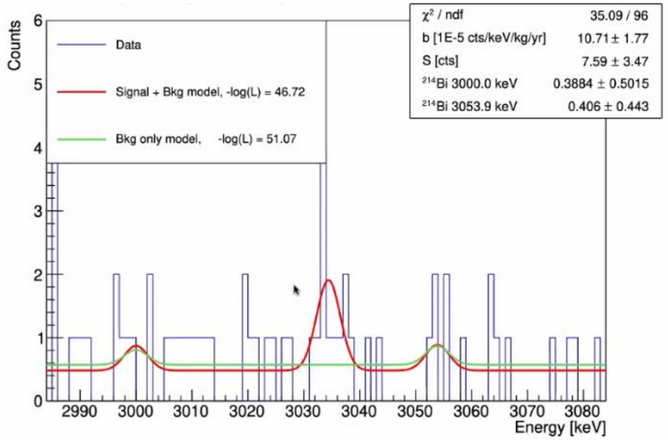
LEGEND-1000: High Purity Ge



Several counts expected at sensitivity limit

- Segmented and scalable
- Excellent energy resolution (narrow ROI)
- Excellent background suppression

CUPID: Scintillating Bolometer



Several counts expected at sensitivity limit

- Advantageous properties of Mo provide boost to sensitivity and room for growth
- Excellent energy resolution
- Upgrade within existing cryostat.

Confirmation likely crucial for such important and challenging measurements

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- Despite all our earnest efforts and total technical success there is a substantial chance after 20 years and ~ $1.0 B in investment that we will only observe background down to the limit of 10^{28} years.

- That puts a big premium on being able to verify any claimed signal at the limit of 10^{28} years

A Cautionary Tale?

Raymond "Ray" Davis Jr. was an American chemist and physicist. He is best known as the leader of the Homestake experiment in the 1960s-1980s, which was the first experiment to detect neutrinos emitted from the Sun; for this he shared the 2002 Nobel Prize in Physics.

- Ray Davis found evidence for neutrino mixing in experiments performed in 1960-1980
- His huge, game-changing discovery was not officially recognized until 40 years later
- **The capability for contemporaneous verification will likely be KEY for a $0\nu\beta\beta$ claim**

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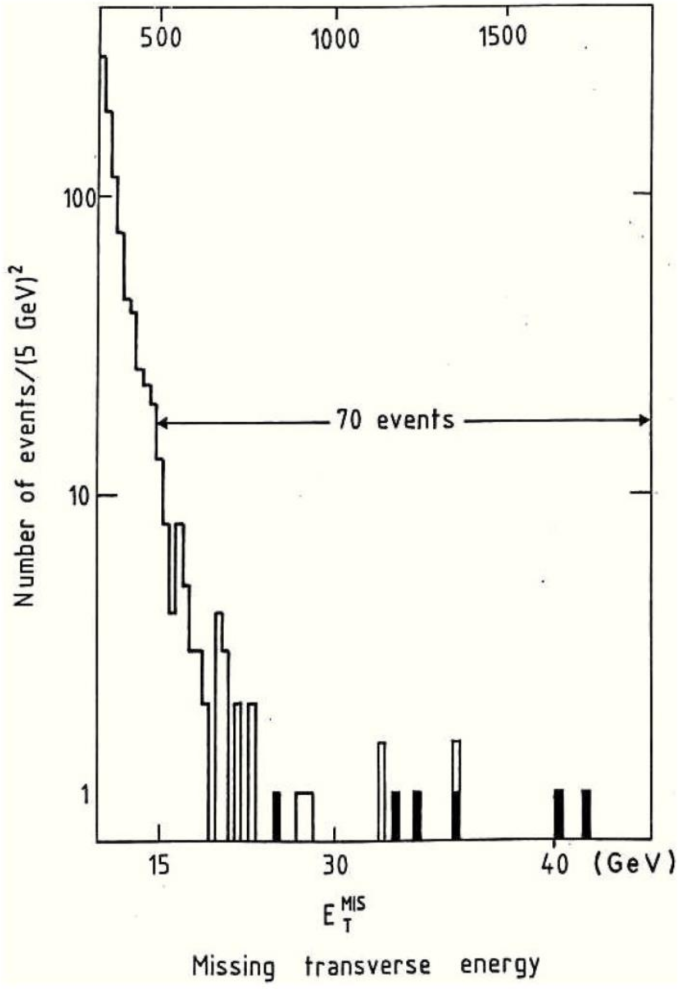
If nature is kind and the signal is strong enough over background -- no issue.

If nature is less kind (usually the case), even if everything goes very well (not usually the case), a single experiment could wind up with a few counts after 10 years of construction and 10 years of running which could be tantalizing but inconclusive. Even a limit that might be set would have significant additional uncertainty without confirmation from a second experiment.

Conclusion: a serious campaign would benefit greatly from having more than one ton-scale experiment and different systematics, especially given the uncertainty in the nuclear matrix elements

Is the possibility of such low statistics after lots of time and money invested a show-stopper for getting to a definitive outcome ?

Not if there is the possibility of contemporaneous confirmation as was done at CERN for the W and the Higgs.



. 10. UA1 distribution of the missing transverse momentum (called E_T^{MIS} in this plot) for
al bins of $(E_T^{MIS})^2$. The events shown as dark areas in this plot contain a high p_T electron.

The raw data used as the basis for UA1 announcement of W discovery

Spectrum is similar in character to the situation expected for $0\nu\beta\beta$

Figure Caption for the Previous Slide

Figure 10 shows the $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$ distribution, as measured by UA1 from the 1982 data.[9] There is a component decreasing approximately as $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|^2$ due to the effect of calorimeter resolution in events without significant $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$, followed by a flat component due to events with genuine $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$. Six events with high $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$ in the distribution of Fig. 10 contain a high-p_{T} electron. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ vector in these events is almost back-to-back with the electron transverse momentum vector, as shown in Fig. 11. These events are interpreted as due to $\mathrm{W} \to e\nu_{\mathrm{e}}$ decay. This result was first announced at a CERN seminar on January 20, 1983. Figure 12 shows the graphics display of one of these events.

The experimental basis for the announcement of discovery of the W in UA1 and UA2.

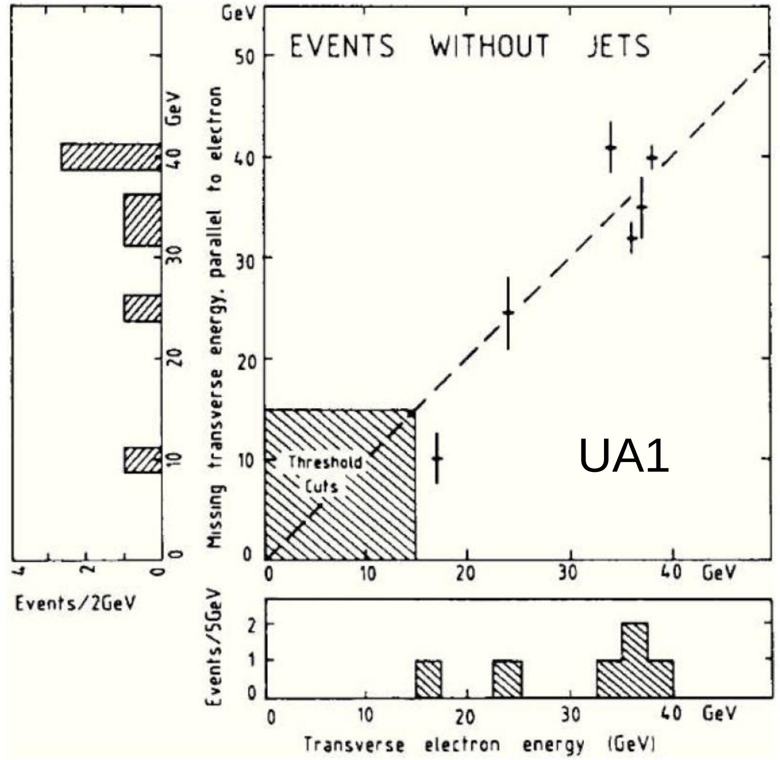


Fig. 11. UA1 scatter plot of all the events from the 1982 data which contain a high-pT electron and large $|\vec{p}_T^{\,miss}|$. The abscissa is the electron $|\vec{p}_T|$ and the ordinate is the $\vec{p}_T^{\,miss}$component antiparallel to the electron $\vec{p}_T$.

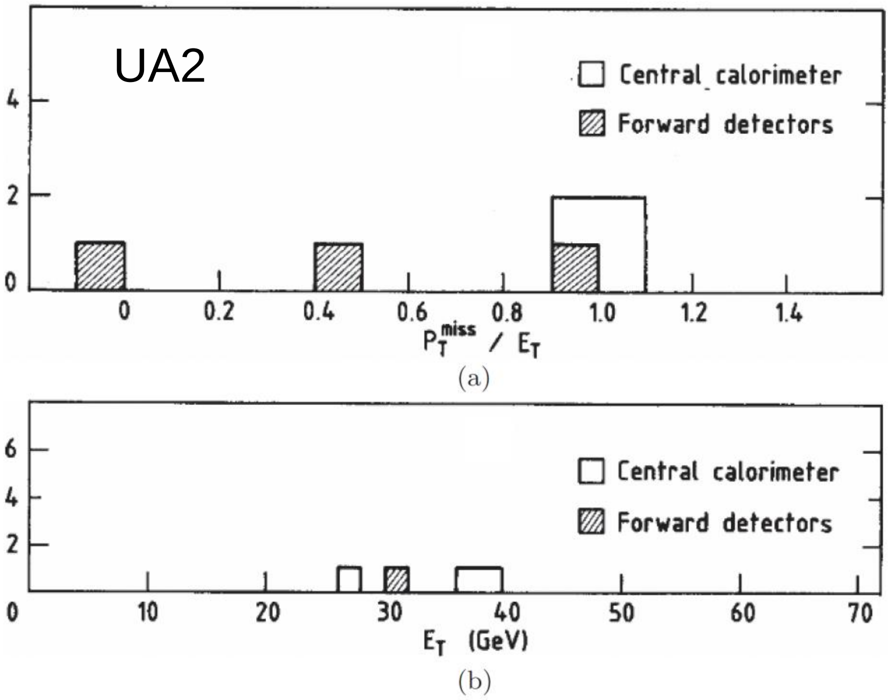


Fig. 13. (a) Display of the ratio between $|\vec{p}_T^{\,miss}|$ and the electron transverse momentum (called E_T in this plot) for six UA2 events containing an electron with $E_T > 15$ GeV; (b) Electron distribution for the four events with the highest $|\vec{p}_T^{\,miss}|/E_T$ ratio.

A handful of counts (6) led to a major discovery in part because there were 2 experiments which both saw a signal

- It is suggested that that the need for contemporaneous verification should be an important (essential ?) part of strategizing about the future path of neutrino-less double beta decay

DOE NP Portfolio Review

- The review produced a numerical ranking.
- All three experiments were highly rated and judged to be worth pursuing.
- To accomplish all three, an international campaign would be required
- That need was the subject of a North American-European DBD Summit, September 29-October 1, 2021.

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Why Consider Supporting Two Ton Scale Efforts

- Multiple experiments greatly increase the chance of a Nobel Prize in our lifetime as opposed to only well-read publications
- Forming a global investment strategy provides significant opportunity to strengthen S&T ties between traditional S&T partners in Europe and North America with possible collateral benefits in other research areas.
- The collegial competition between experiments will dramatically accelerate the pace of progress. It will also create and build out an $0\nu\beta\beta$/neutrino eco-system.
- This strategy could lead to a CERN-like International, Intergovernmental Alliance for Neutrino-less Double Beta Decay research, not only to mount multiple experiments near term, but also to provide stable funding for development efforts key to the next, next multi-ton efforts like NEXT.

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Is this idea possible?

Assertion: the potential discovery of neutrino-less double beta decay would be every bit as much of a game changer as the discovery of super symmetry at CERN, and is as compelling as any accelerator-based research currently underway

The annual investment in accelerator-based research world-wide is of order $2B per year

To mount two ton-scale experiments plus CUPID, would require something of order $1B over 10 years or ~ $100M per year supported collectively by the international stakeholders

Indeed possible, but still non-trivial.

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Readout from the Summit discussion
(As presented by INFN)

The international stakeholders in neutrino-less double beta decay research agree in principle the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade.

The international stakeholders in neutrino-less double beta decay are interested in exploring whether a more formal structure for international collaboration on this research would be beneficial.