REPORT TO THE
NUCLEAR SCIENCE ADVISORY COMMITTEE

Neutrinoless Double Beta Decay

Robert D. McKeown

Outline

- Charge and Membership
- Science Overview and Update
- Current and Proposed Projects
- R&D Plans
- Theory
- Summary

Charge Letter

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee (NSAC) Subcommittee on Neutrinoless Double Beta Decay (NLDBD) provide additional guidance to the DOE and NSF regarding an effective strategy for implementing a possible second generation U.S. experiment on neutrino-less double beta decay capable of reaching the sensitivity necessary to determine whether the neutrino is a Majorana or Dirac particle under the inverted-hierarchy mass scenario.

2015 Charge

…the NSAC Subcommittee on Neutrinoless Double Beta Decay is requested, in the context of ongoing and planned US efforts as well as international competitiveness, to consider the following:

- Assess the status of ongoing R&D for NLDBD candidate technology demonstrations for a possible future ton-scale NLDBD experiment.

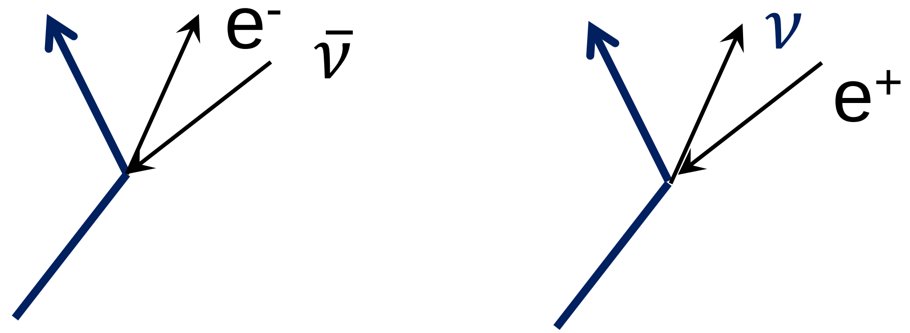
- For each candidate technology demonstration, identify the major remaining R&D tasks needed ONLY to demonstrate downselect criteria, including the sensitivity goals, outlined in the NSAC report of May 2014. R&D needs for candidate technology demonstrations should be sufficiently documented beyond assertion to allow critical examination by the panel and future assessments.

- Identify the time durations needed to accomplish these activities and the corresponding estimated resources, as reported by the candidate technology demonstration groups.

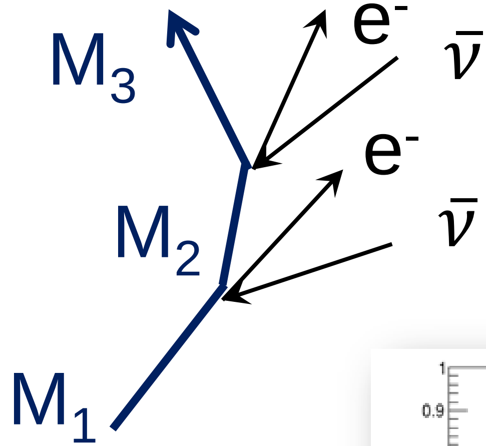
Subcommittee Membership

R. McKeown (Chair)
F. Calaprice
V. Cirigliano
P. Cushman
D. Geesaman (ex-officio)
G. Greene
J. Hardy
D. Hertzog
M. Kamionkowski
K. Langanke
K. Scholberg
H. Sobel
S. Vigdor

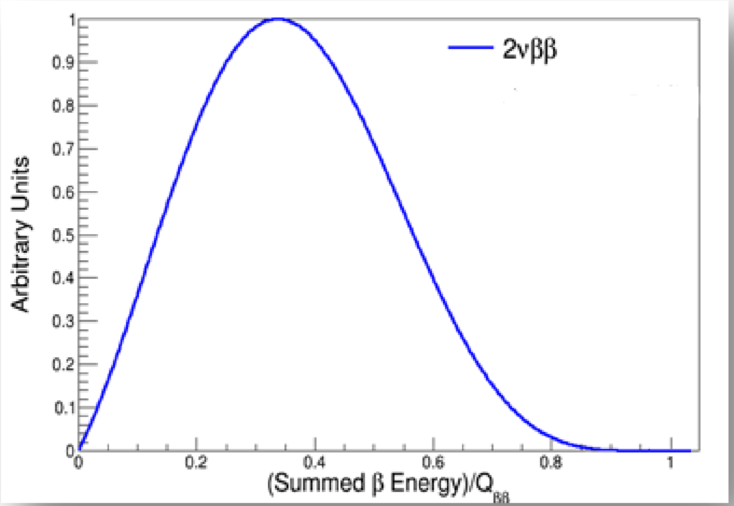
- $\beta^{\pm}$ decay



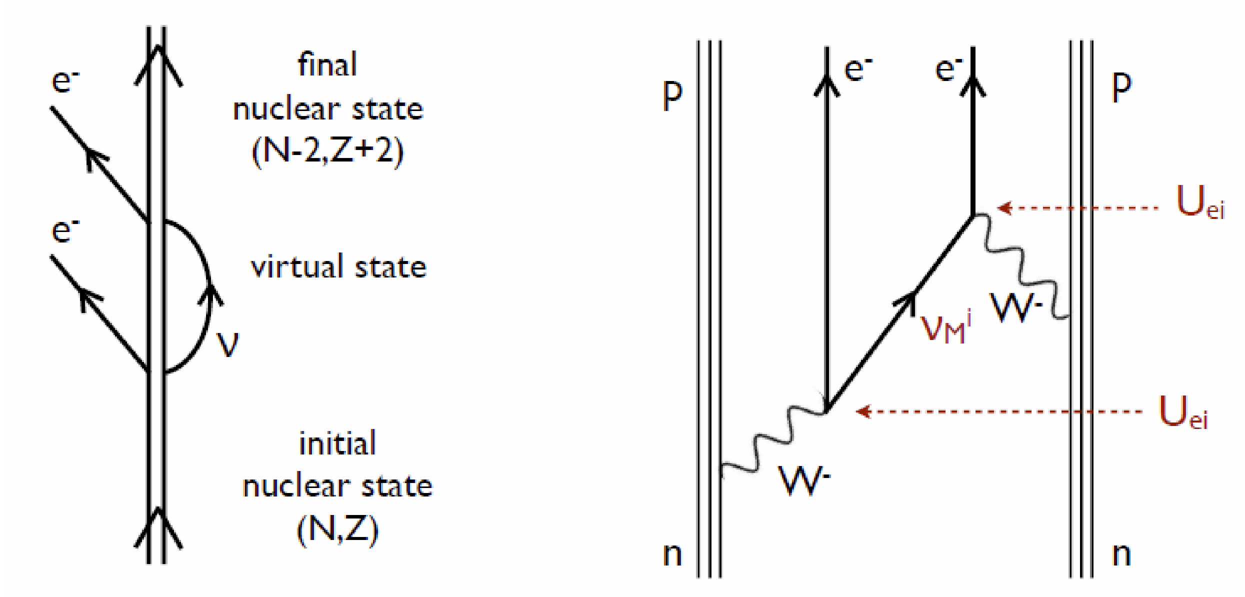
- $2\nu\beta\beta$ decay



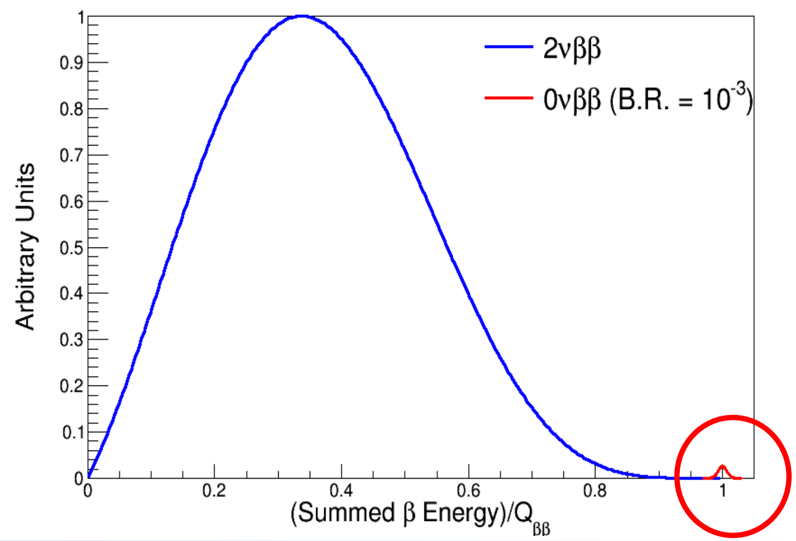
- $M_2 > M_1 > M_3$
- 2^{nd} order weak process



0νββ decay



- Majorana ν
- Flip helicity:
  - RH coupling
  - m ≠ 0

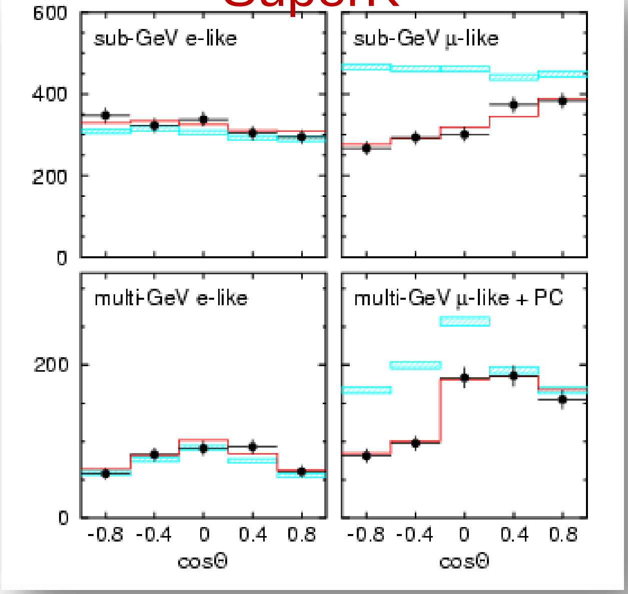


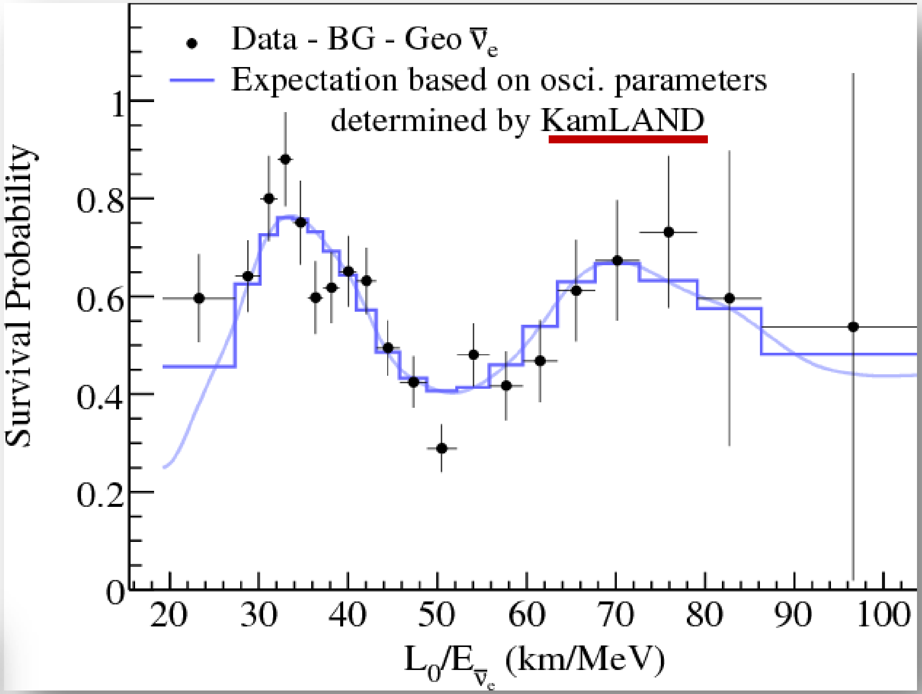
Experimental Issues

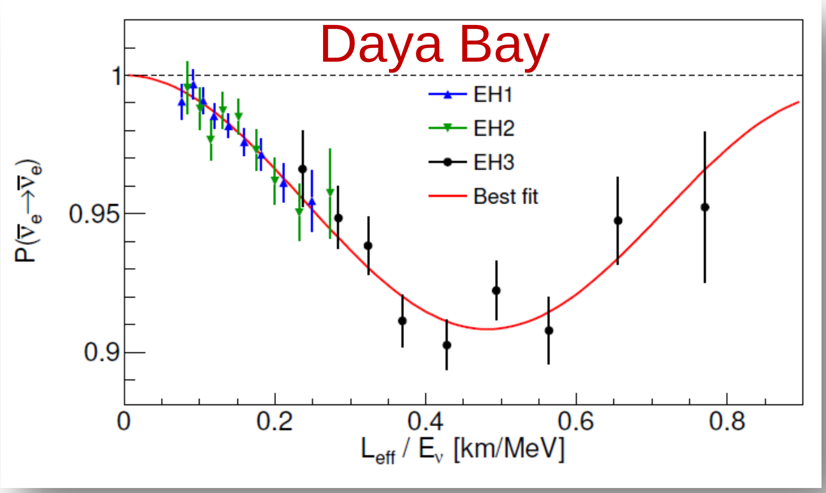
- Good energy resolution
- Low background

Neutrino Oscillations ($m_\nu \neq 0$)

SuperK



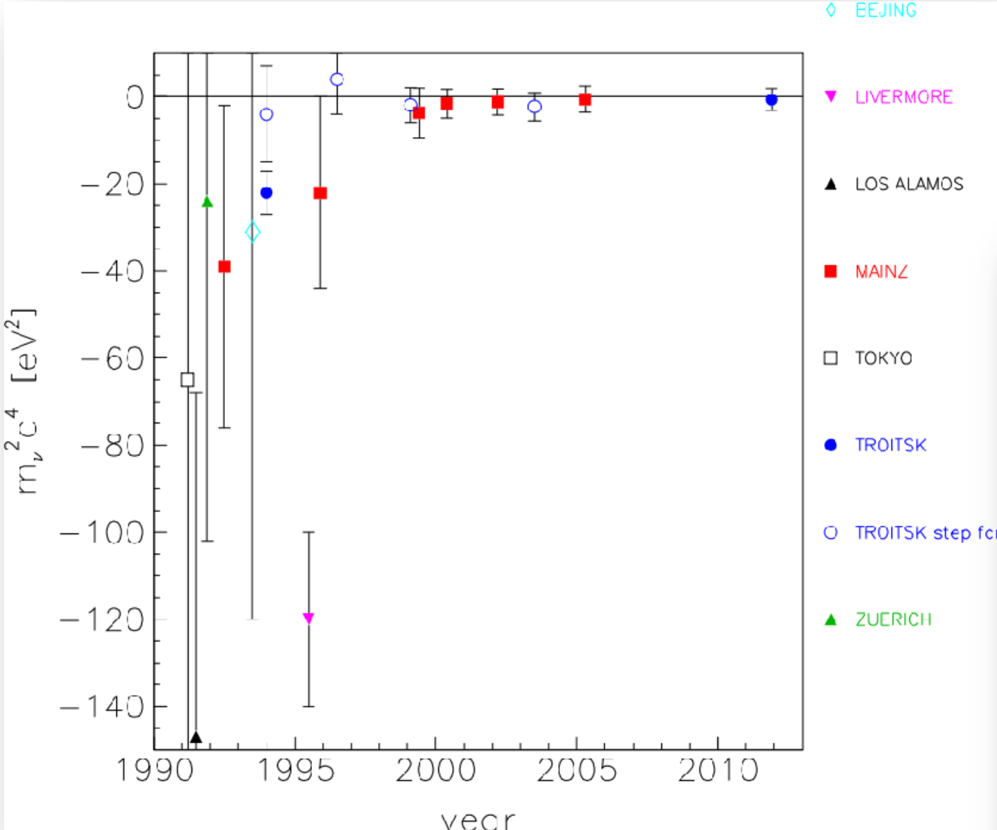


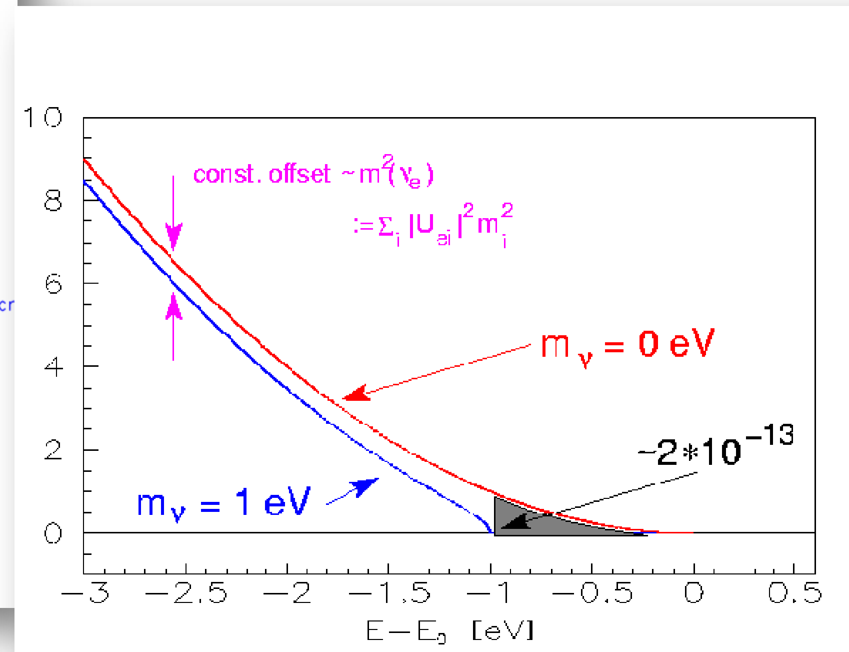


Measure:

- $|\Delta m_{ij}^2|$
- θ_{ij}

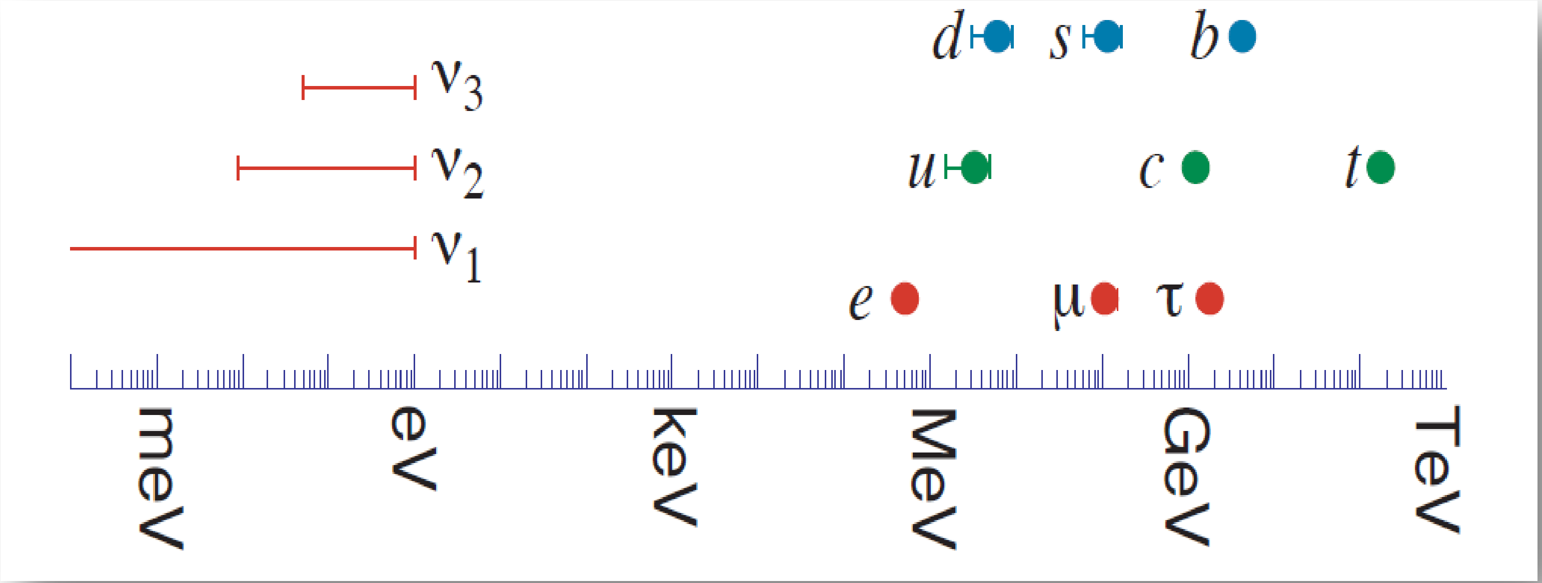
Absolute Neutrino Mass Limits





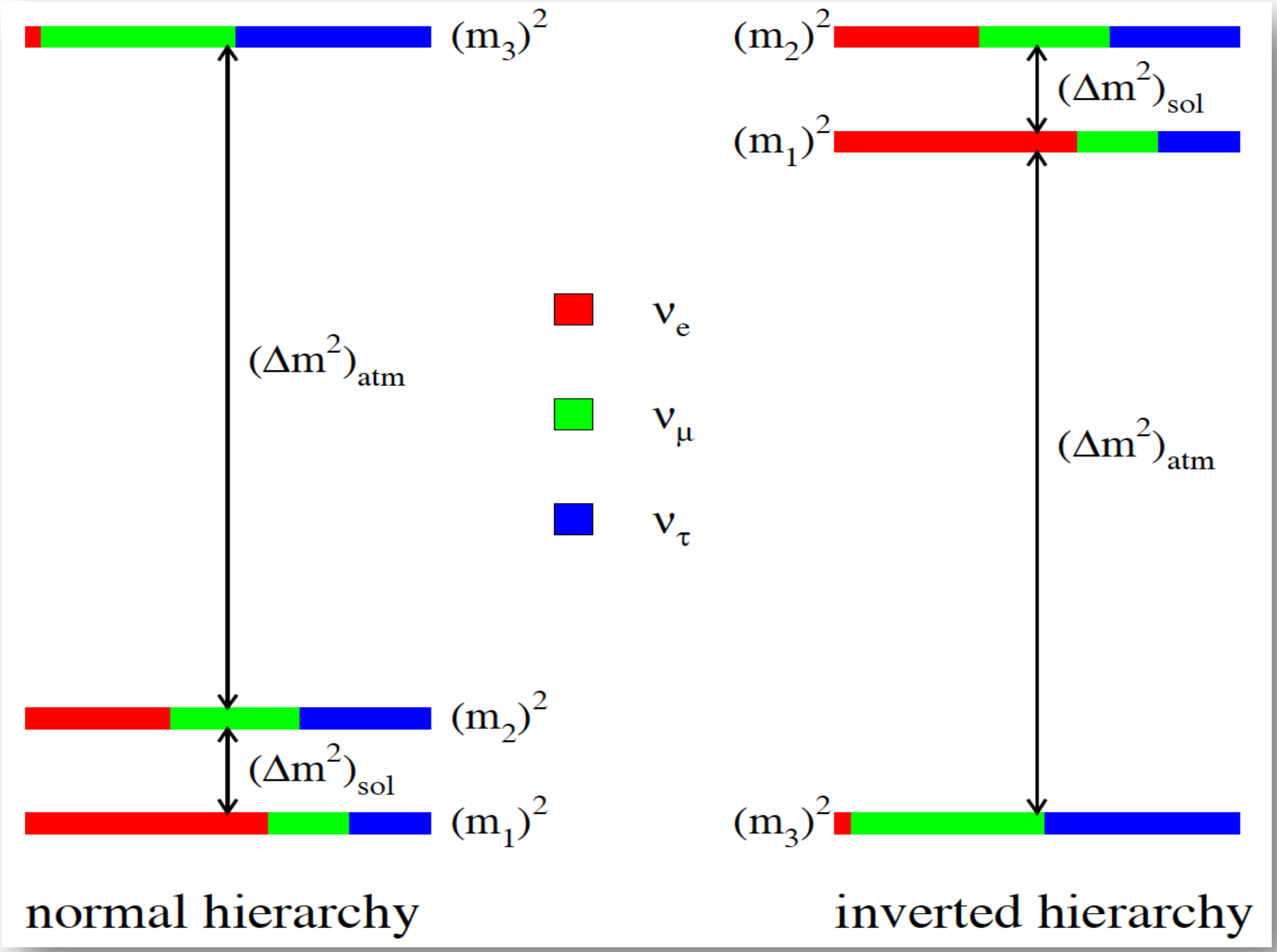
- Present limit from tritium decay: < 2 eV
- Cosmology: $\Sigma\, m_i < 0.23$ eV (95% CL)

Masses of Matter particles



- Higgs mechanism not likely responsible for neutrino masses
- “See-saw” is most common alternative
  → Majorana neutrinos!
  → Leptogenesis

Mass Hierarchy



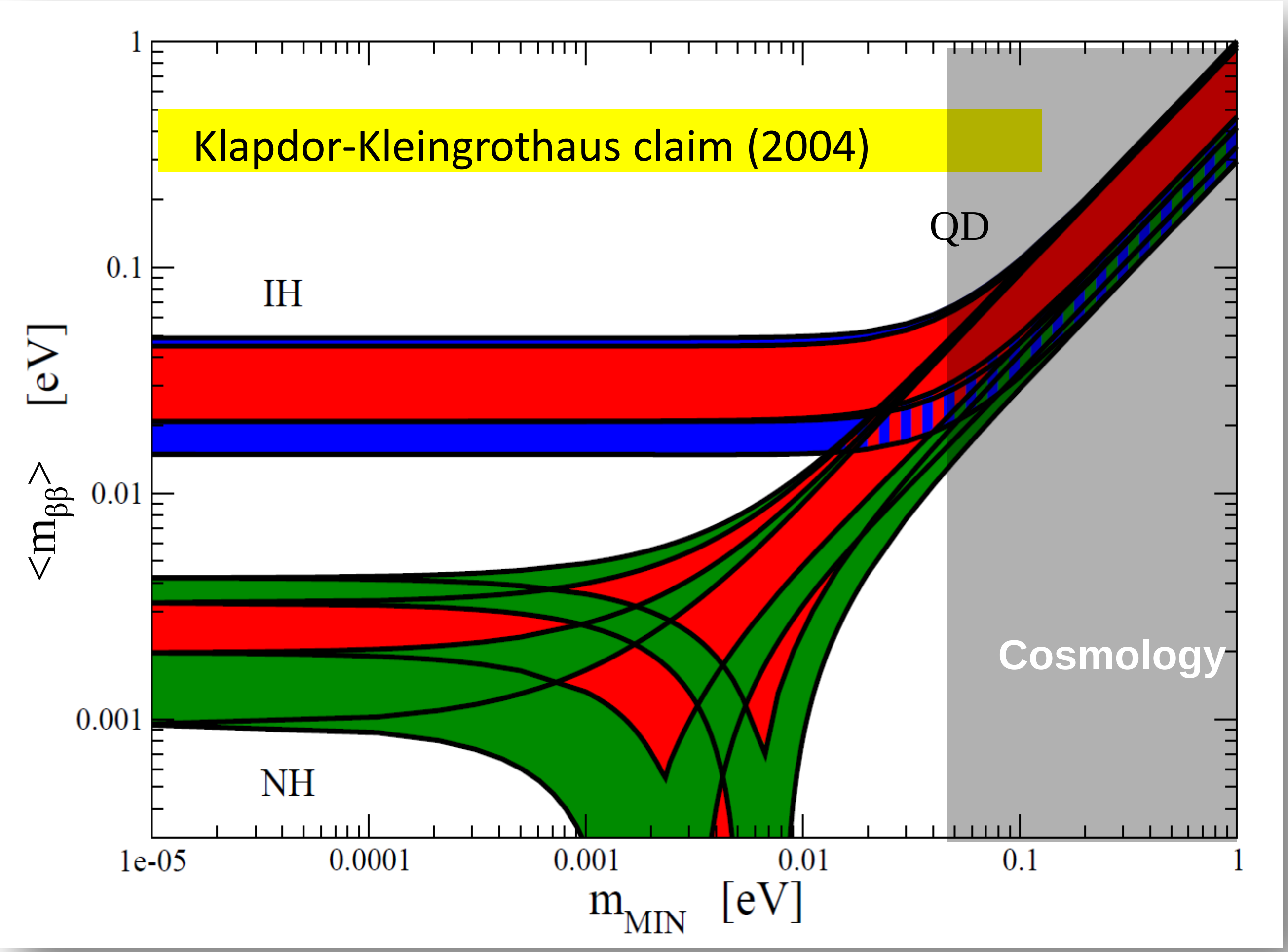
NLDBD and Neutrino Mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space

Nuclear Matrix Element

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U^2_{ei} m_{\nu_i}|^2$$

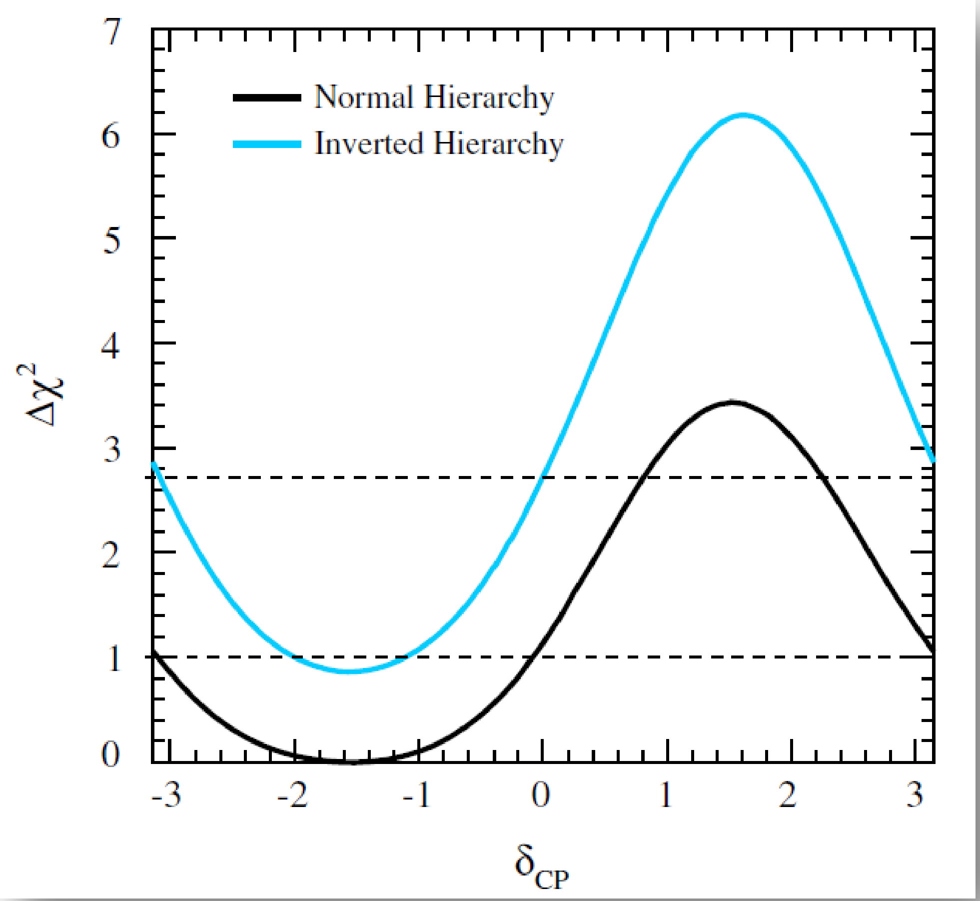


Note: colored bands Indicate allowed variation of U_{ei} due to unknown Majorana phases and uncertainty in mixing angles

- $\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$
- m_{MIN} = lightest $m_{\nu i}$

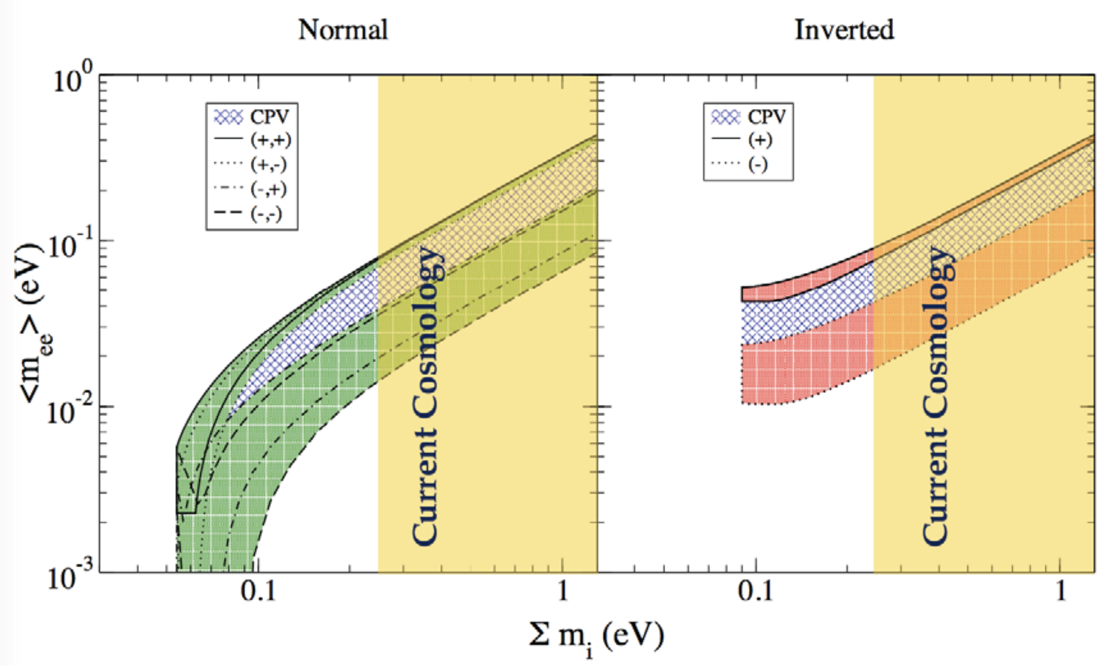
Neutrino Oscillation Experiments

- T2K reports the result shown (combined fit with reactor expts)
  - favors $\delta_{CP} \sim -\pi/2$
  - slightly favors NH
- First results from NovA at Fermilab are consistent
- Both keep running…
- PINGU, JUNO, RENO50 all aim for mass hierarchy within a decade



Phys.Rev. D91 (2015) 7, 072010

Cosmological Limits

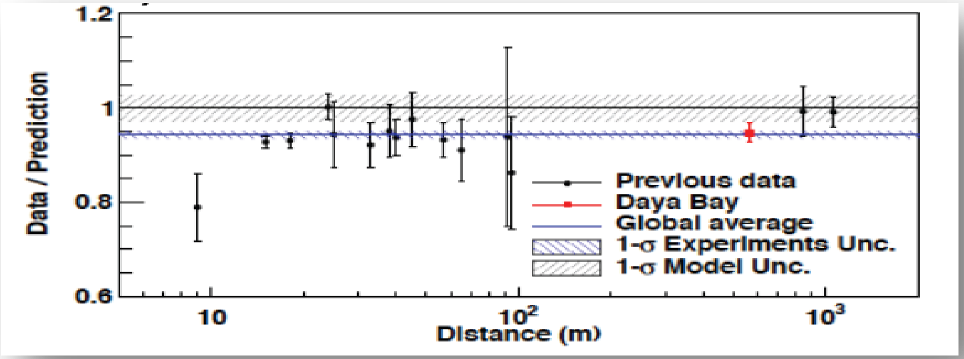


- Within the ΛCDM model, cosmology probes the neutrino freestreaming scale (neutrino hot dark matter component), which depends on $\Sigma \equiv \Sigma_i\, m_i$ and the relic neutrino energy spectra
- Current combined bound: $\Sigma < 230$ meV
- Projected bounds (<10 years): $\Sigma < 100$ meV (could indicate ordering)

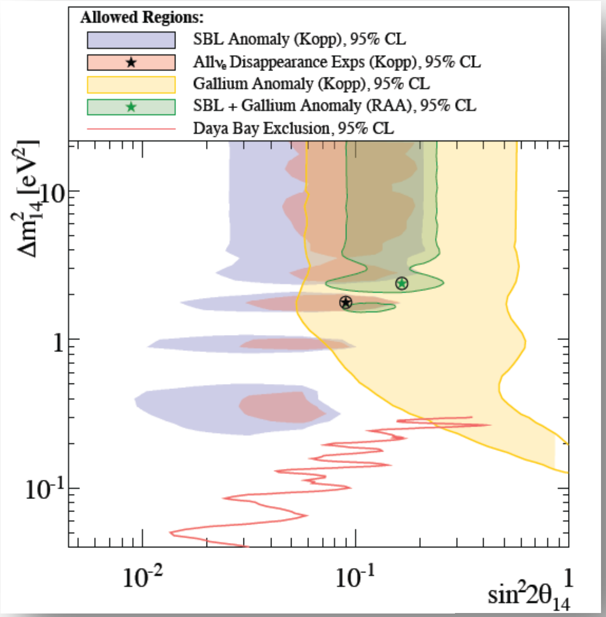
Presentation to Subcommittee by K. Azerbajian (C Irvine)

Sterile Neutrinos

- Reactor Anomaly:



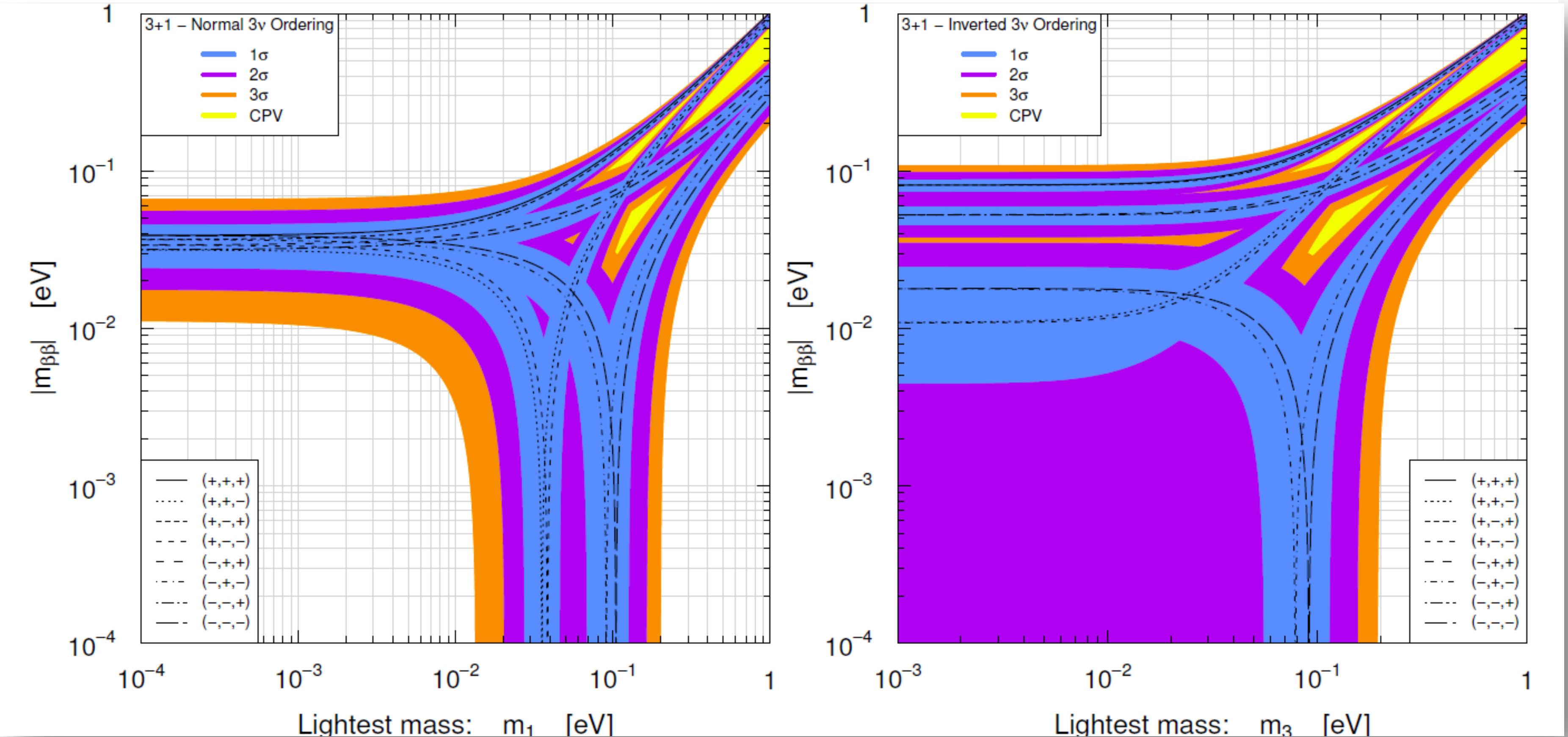
- Fits to sterile ν's:



Many experiments being mounted and proposed to confirm/refute interpretation

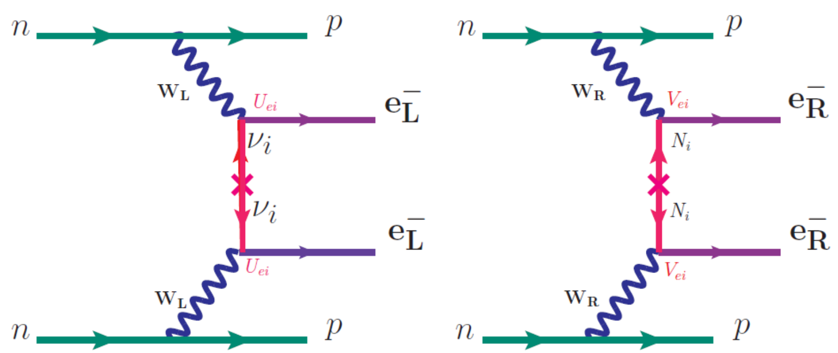
Sterile Neutrinos and NLDBD

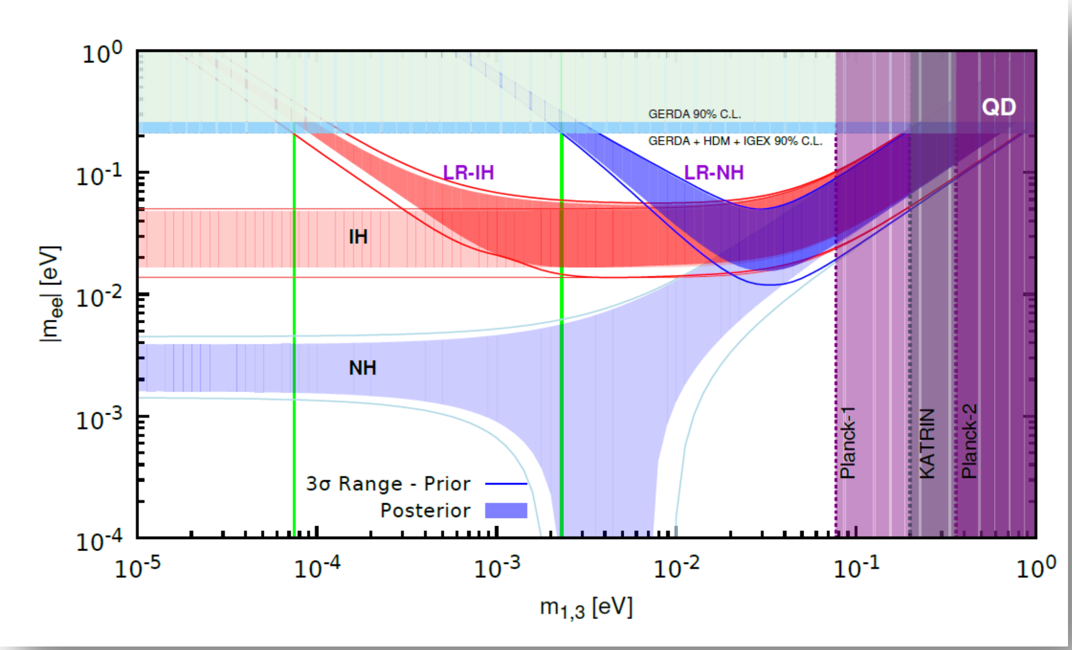
$$|m_{\beta\beta}| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3 + |U_{e4}|^2 e^{i\alpha_4} m_4 \right|$$



arXiv:1507.08204

New Physics and LHC

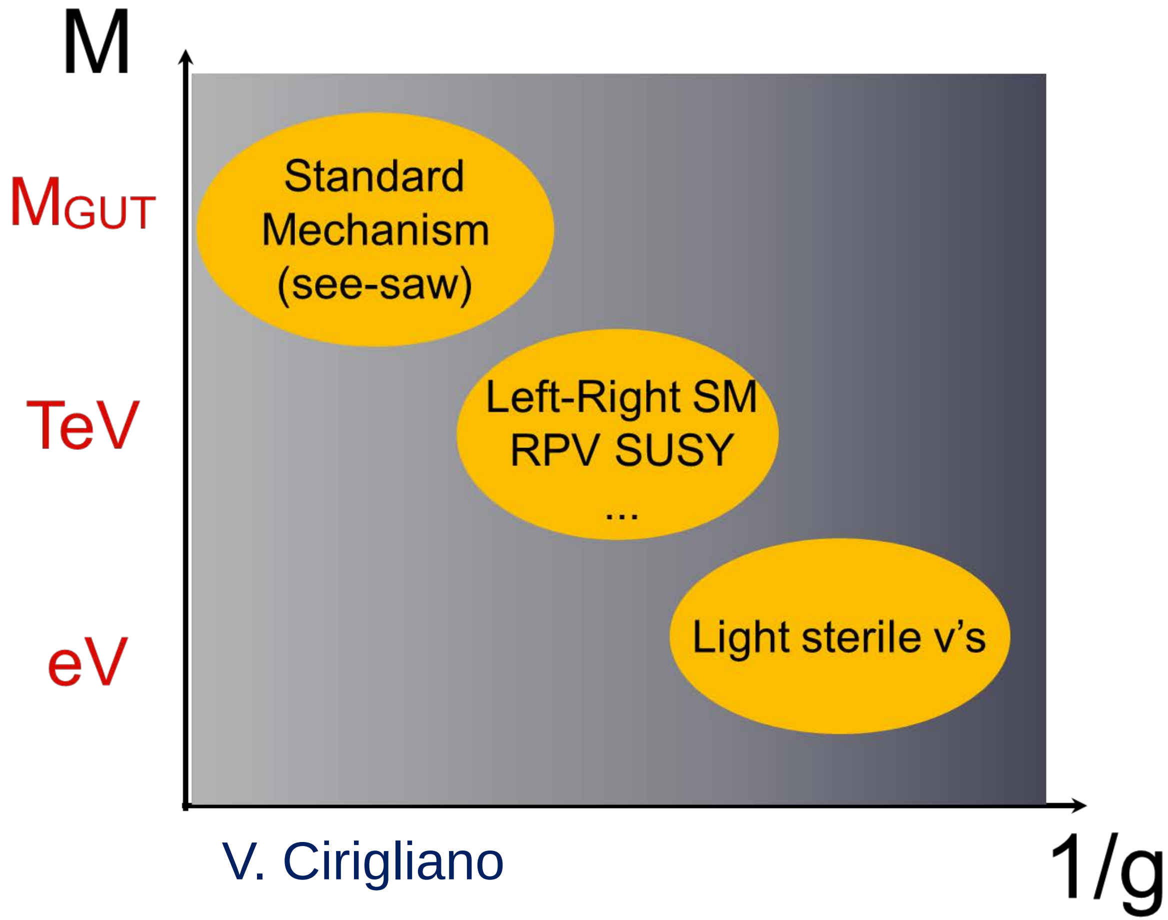




arXiv:1508.07286

Lepton Number Violation and 0νββ

- Ton-scale 0νββ probes LNV from a variety of mechanisms and scales of masses (M) and couplings (g)

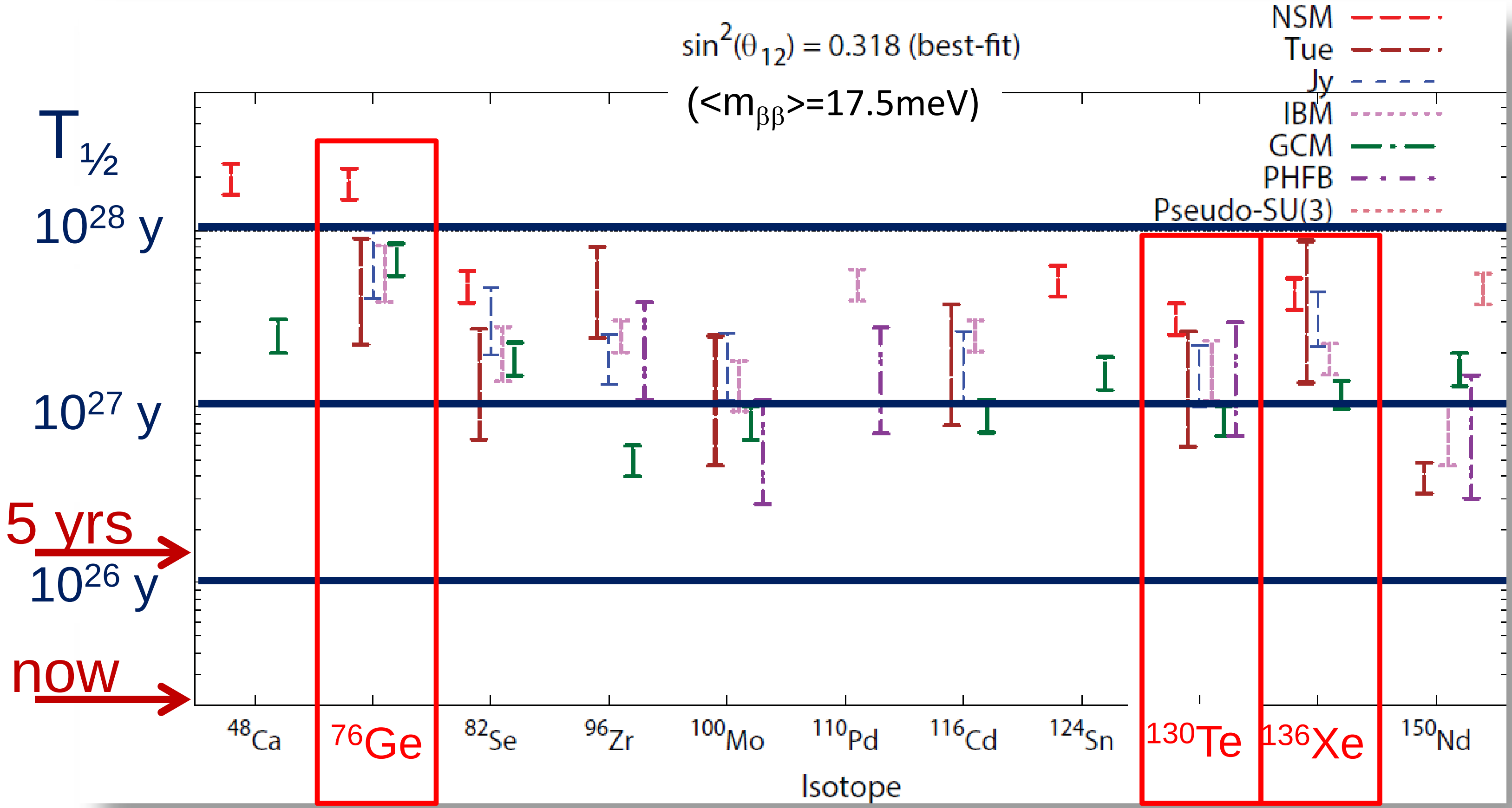


V. Cirigliano

Science Assessment

"…it is important to remember that NLDBD has a unique role in potentially addressing the issue of Dirac vs. Majorana nature of neutrinos. The Subcommittee remains convinced that the scientific case for pursuing NLDBD experiments at the ton-scale is very compelling."

Inverted Hierarchy Coverage



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.

Major Issue: Background

- For "background-free" experiment, lifetime sensitivity goes as $T_{1/2} \sim M \cdot t_{run}$
  (M= isotope mass)
  → factor of 50 in $T_{1/2}$ needs factor of 50 in M (for constant t_{run})

- For experiment with background, as $T_{1/2} \sim (M \cdot t_{run})^{1/2}$
  → factor of 50 in $T_{1/2}$ needs factor of 2500 in M (for constant t_{run})

- Background reduction is the key to a successful program
  - deep underground
  - radiopurity
  - better E resolution
  - better event characterization

→ **R&D will be crucial**

Simple Background Estimate

NLDBD Rate = N x ln(2) / $T_{1/2}$ (assume $T_{1/2} \approx 10^{28}$ yr)

For 1 Tonne, N=10^{6}g x $6\text{x}10^{23}$ / MW
(MW= 67, 130, 136 → use MW≈100)

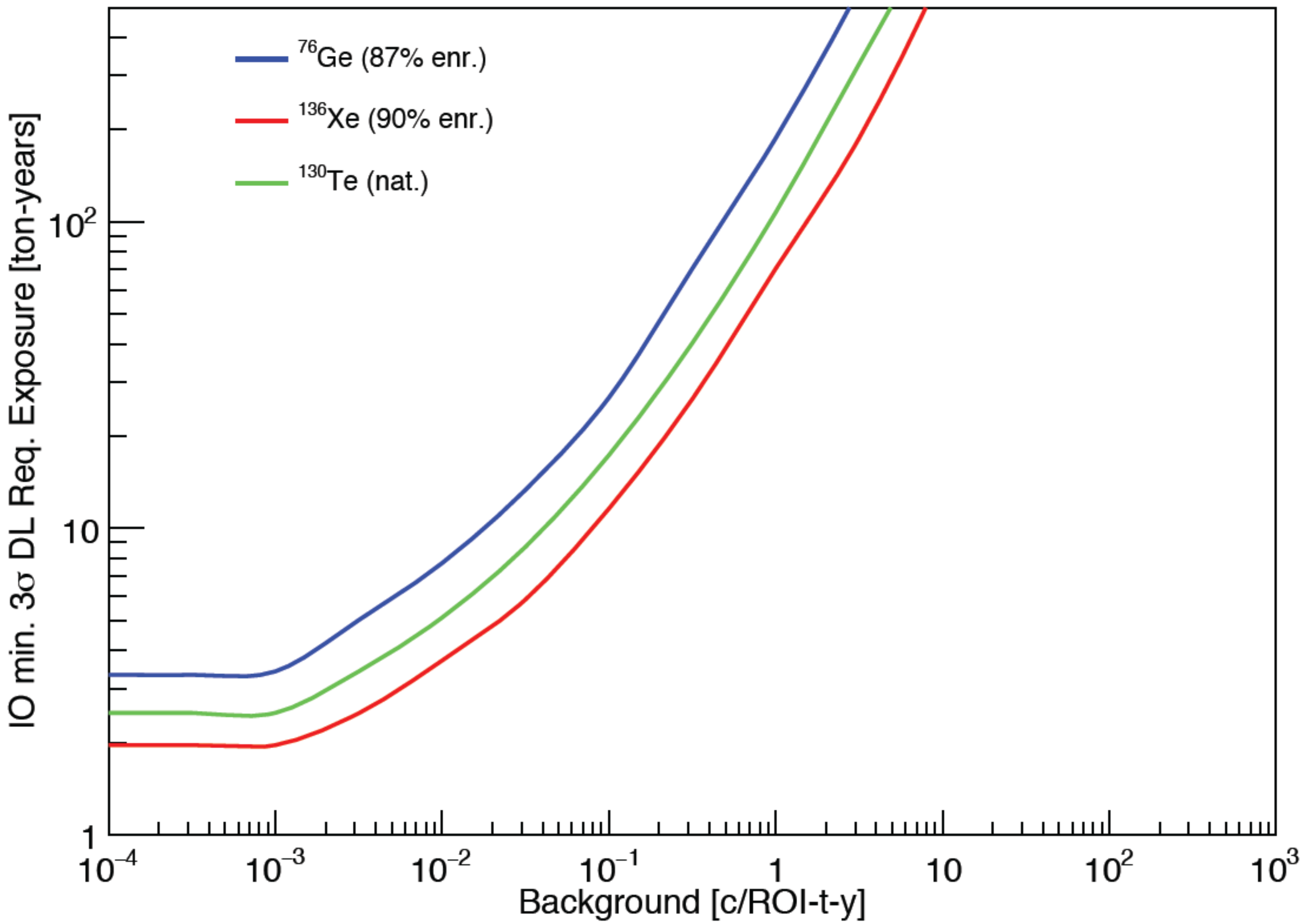
So N≈ $6\text{x}10^{27}$

NLDBD Rate = 0.4 /Tonne/yr

Background free → Background < 0.1/Tonne/yr/ROI

Required 3σ Exposure vs. Background

J. Detwiler



"Required" exposure assuming minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

(IO = Inverted Ordering)

Projects Data Collection

- Requested documentation on
  - Current status and plans
  - R&D required for downselect

- Scheduled 7 presentations for August 17-19 open meeting at SURA HQ in DC

Note: all submissions and slides are
kept private for Subcommittee use

Methods

- ^{136}Xe TPCs (liquid, gas)
- ^{76}Ge Crystals
- Bolometers with particle ID enhancements
- Doped Liquid Scintillators (^{136}Xe, Te)
- Foils with tracking chambers (^{82}Se +)

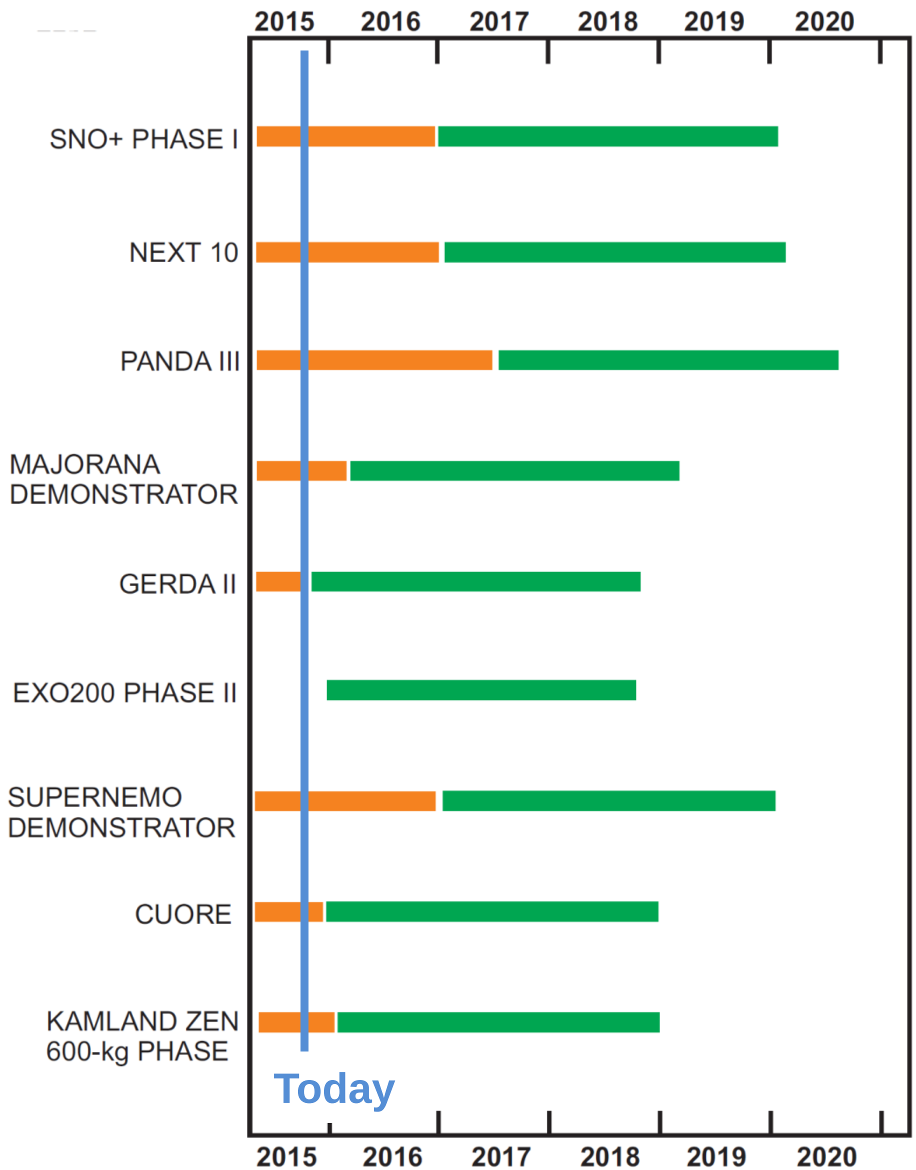
Current Projects

Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	26.9	
GERDA	^{76}Ge	35	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-10	^{136}Xe	10	
SuperNEMO	^{82}Se+	7	>0.001
KamLAND-Zen	^{136}Xe	434	>0.19
SNO+	^{130}Te	160	

Primary goals:

- **Demonstrate background reduction for next generation experiment**
- **Extend sensitivity to $T_{1/2}$~10^{26} years.**

Updated Timeline



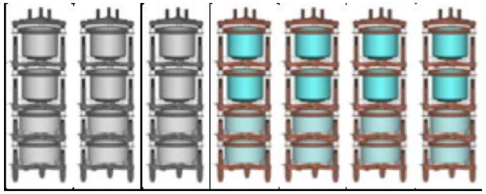
Construction

Operation

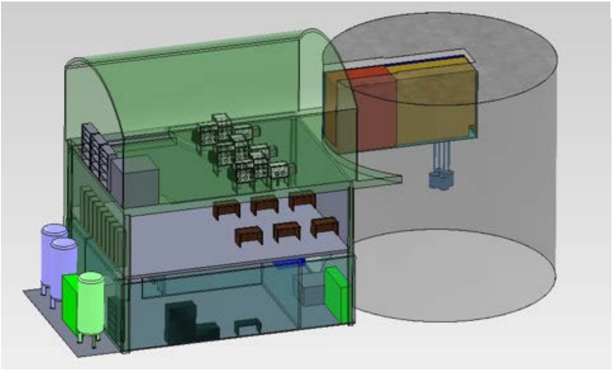
(not time until downselect)

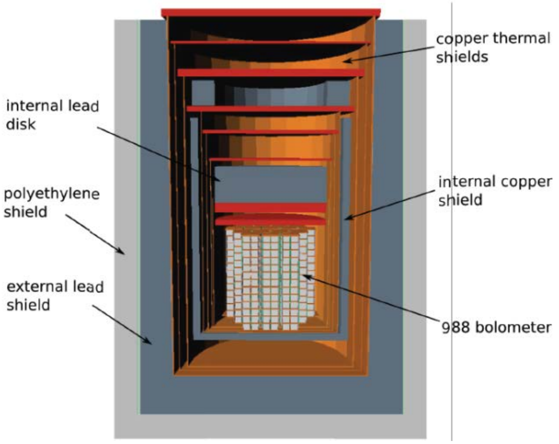
Next Generation Approaches

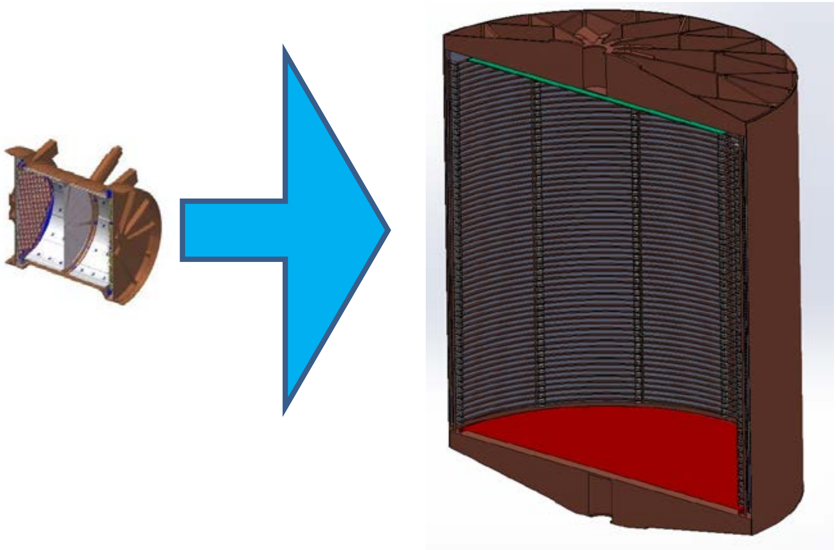
The issue is to scale up to ≥ 1 Tonne with low background.



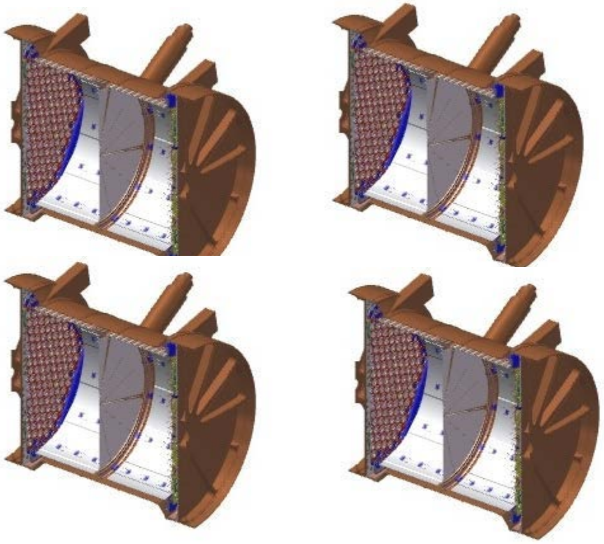
X ~100 →







OR



Technology Assessment

For each project/technique, our report has the structure:

- Status
- Plans for R&D (summary)
- Technical Issue 1
  - Proposed R&D
  - Comments
- Technical Issue 2
  - Proposed R&D
  - Comments
- Other Technical issues (generally beyond downselect)

Note: Sent to collaborations for fact check

Proposed U.S. R&D

Germanium	Higher radiopurity connectors	Radiopure fabrication methods	
CUPID	Particle ID	Component radiopurity	Study Cosmogenics with CUORE
NEXT	Study NEXT10, DEMO, DEMO+	Fluorescence Ba detection	
PANDA X III	HV cage and radiopure pressure vessel	Topmetal readout	
SNO+ Phase II	Run SNO+	Load Te to 3%	Increase Light yield
nEXO	HV @ >50kV	Hi QE radiopure photodetectors (SiPM)	Electronics
SuperNEMO	Foil radiopurity	Scintillator/PMT improvement	Tracker improvement

Total estimated resources ~$11M

Subcommittee Observation

One can see that there is about 1 more year of construction and assembly before all the projects are in an operational phase taking data. Therefore, over the next 2-3 years one can expect to have valuable information based on real data combined with results from additional R&D for these different techniques. At that point, one would expect that an assessment of the relative merits would be more reliable than at the present time.

Overall R&D Assessment

In general, the suite of mid-scale experiments and demonstration projects are making good progress in setting new $0\nu\beta\beta$ limits and in testing out techniques that can be extrapolated to ton-scale installations. During the next 1-2 years many techniques will be acquiring data and producing a body of information that will inform the future plans. However, it is already clear that additional R&D issues must be resolved in preparation for a future downselect decision. **Therefore the subcommittee strongly recommends that R&D efforts aimed at solving specific technical issues relevant to the downselect decision be supported.**

Additional Statement on R&D

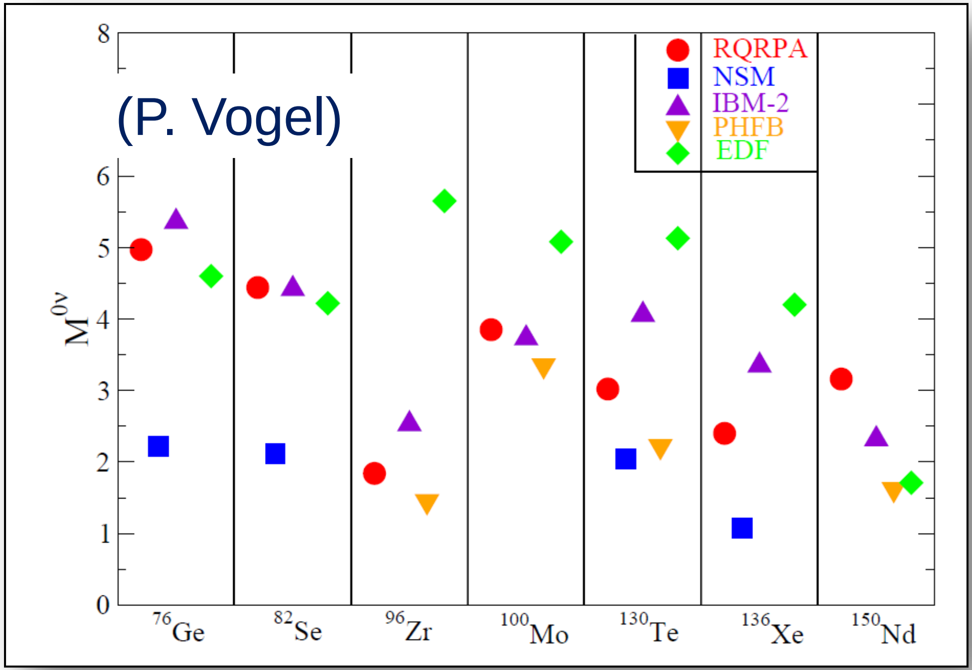
Other technical issues have more open-ended R&D requirements to address. In these cases the allocation of resources will be more difficult to assess. In any case, the longer term future of NLDBD will require continued R&D effort. **The subcommittee strongly urges continuation of longer term R&D necessary for the future development of the subject in addition to the support of shorter term R&D aimed at a near future downselect.**

Common R&D Topics

It was noted by the subcommittee that there are several common R&D topics that would benefit several different techniques. It seems in these cases that a coordinated approach could be a more efficient use of resources. **The subcommittee suggests that the funding agencies consider an approach that would encourage several groups to work together on these common goals.**

Nuclear Theory

- Variety of techniques used for nuclear matrix elements (QRPA, NSM, etc.) give a range of results
  - What is the correct answer?



- There is additional uncertainty regarding possible quenching of g_A in nuclei (role of 2 body currents?)

Nuclear Theory Developments

- Application of modern techniques to $0\nu\beta\beta$ and $2\nu\beta\beta$
  - Ab initio methods
    1.) Light nuclei to test g_A quenching for $0\nu\beta\beta$
    2.) Develop better effective interactions for heavier nuclei
  - Better approximations for heavy nuclei
    1.) Larger model spaces
    2.) Density Functional Theory
    3.) Interacting Boson Model

- Larger and broader group of nuclear theorists interested in working on this problem

Theory Observation

There appears to be a trend towards increasing and broadening the community of nuclear theorists working on this problem and towards employing the most modern theoretical techniques. The subcommittee sees this as a welcome development and hopes that these efforts will lead to a reduction in the uncertainty in the nuclear matrix elements in the near future.

International Aspects

We continue to advocate that the US should plan for a leadership role in (at least) one experiment, while perhaps maintaining options to participate in one or more internationally led projects. This will require timely and astute assessment of both the technological opportunities as well as the inherent strengths of research groups in various countries. At this point, the best one can say is that it is advisable to maintain a nimble posture, with an eye towards a timely decision in the near future (perhaps as short as 2 years).

Acknowledgements

- Thanks to the collaborations for providing valuable material that was essential to the Subcommittee in its work.
- Thanks to SURA for hosting the open meeting in August.
- Thanks to Brenda May (DOE-NP) and Pat Stroop (JLab) for logistical assistance.
- Thanks to Mary Beth Stewart (JLab), and others, for assistance in preparing our report.
- Thanks to Subcommittee members for diligent efforts on a very challenging time frame.