Report to the Nuclear Science Advisory Committee

Neutrinoless Double Beta Decay

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Outline

- Charge and Membership
- Science Overview
- Current and Proposed Projects
- Goals and Criteria
- Theory
- Summary

Charge Letter

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee (NSAC) form a Subcommittee to provide 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 (NLDBD) capable of reaching the sensitivity necessary to determine whether the nature of the neutrino is Majorana or Dirac. While the Office of Nuclear Physics is the Office of Science steward for NLDBD, this scientific question is of broad interest to both the Nuclear Science and High Energy Physics communities, and NSAC should solicit input from the High Energy Physics Advisory Panel (HEPAP) as well as the nuclear science community in formulating the membership of this Subcommittee.

Subcommittee Membership

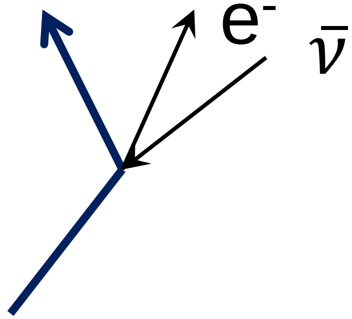
R. McKeown (Chair)
F. Calaprice
V. Cirigliano
P. Fisher
D. Geesaman (ex-officio)
G. Greene
J. Hardy
W. Haxton
D. Hertzog
K. Langanke
Z.-T. Lu
K. Scholberg
T. Shutt
H. Sobel
S. Vigdor

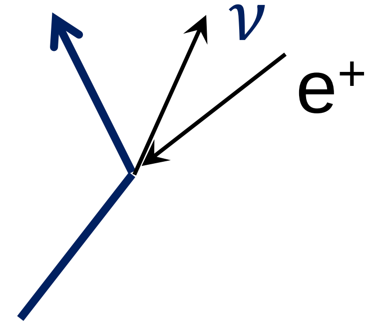
Charge

The NSAC Subcommittee is requested, in the context of ongoing and planned U.S. efforts as well as international competitiveness, to assess:

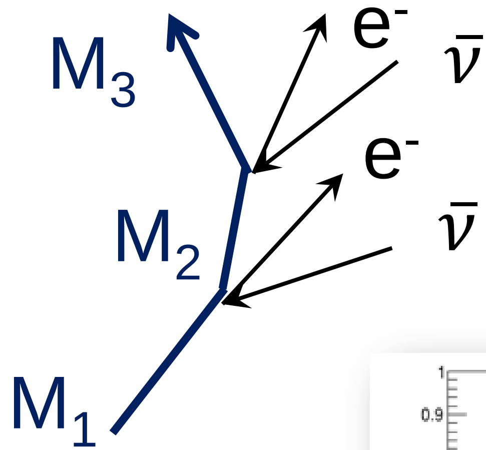
- The scientific merit of pursuing a second-generation NLDBD experiment;
- The status of ongoing and planned first phase NLDBD experiments toward achieving their goals, including major remaining challenges;
- The science-driven down-select criteria for arriving at the most promising approach to a second generation experiment, including a sensitivity goal that, at a high level of confidence, based on present understanding, would be expected to answer the question of the Majorana vs. Dirac nature of neutrinos for the inverted mass hierarchy scenario when combined with the results from other experiments that aim at establishing the hierarchy and masses of the three known neutrino flavors.
- Status and expected progress in theoretical calculations that are needed to determine the sensitivity limits that can ultimately be reached in NLDBD experiments.

- $\beta^{\pm}$ decay

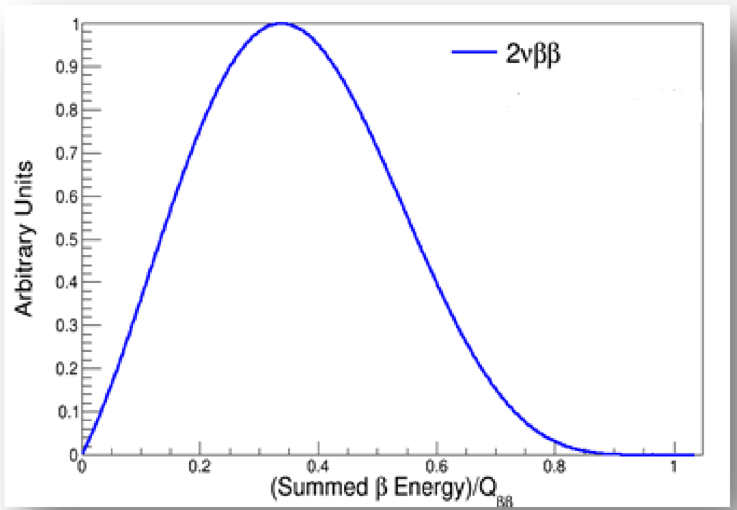




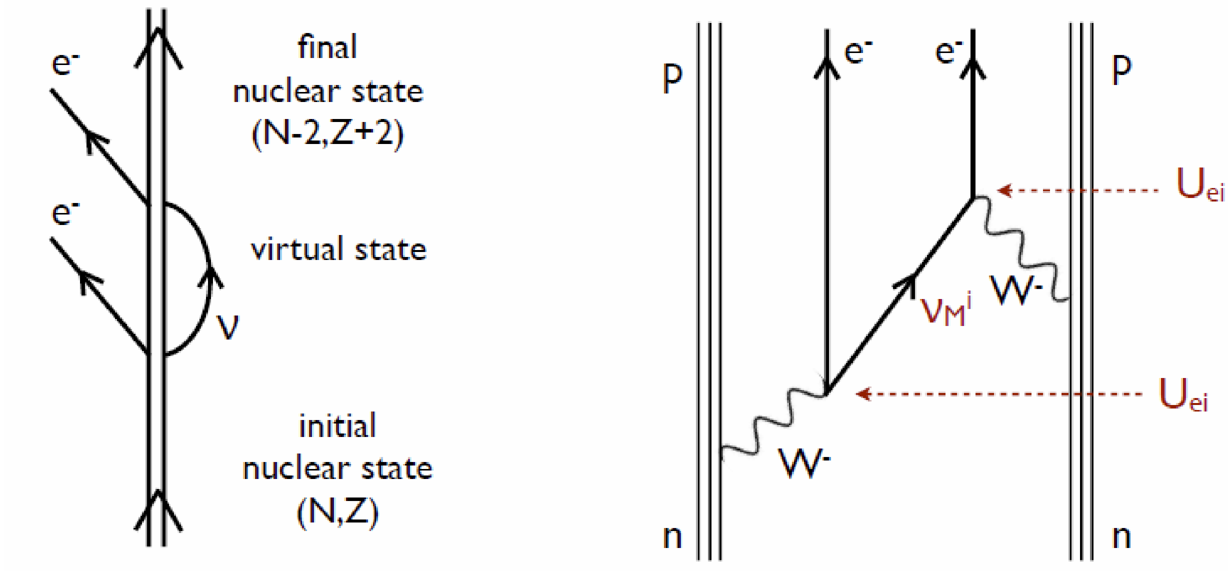
- $2\nu\beta\beta$ decay



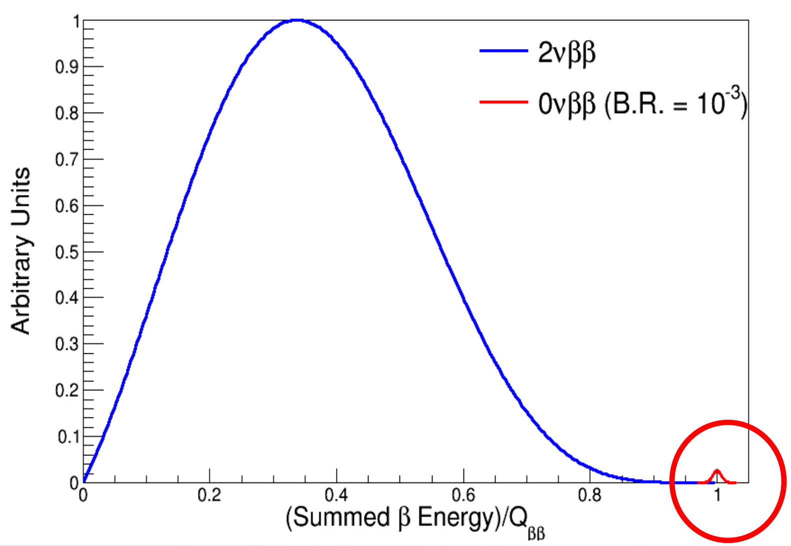
- $M_2 > M_1 > M_3$
- 2nd order weak process



0νββ decay



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

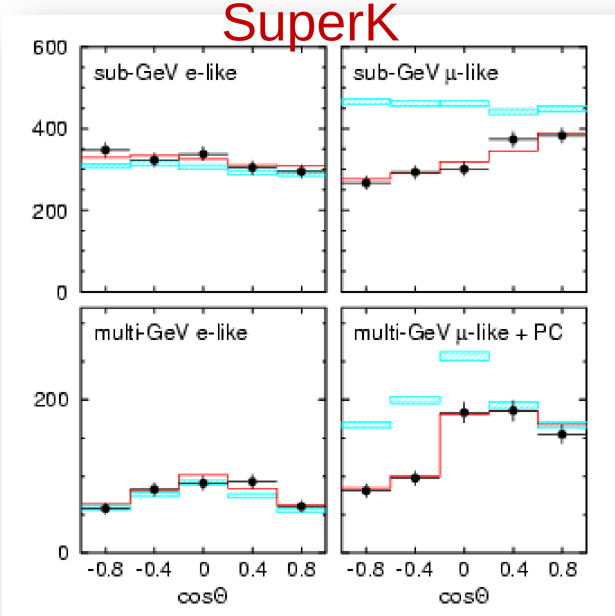


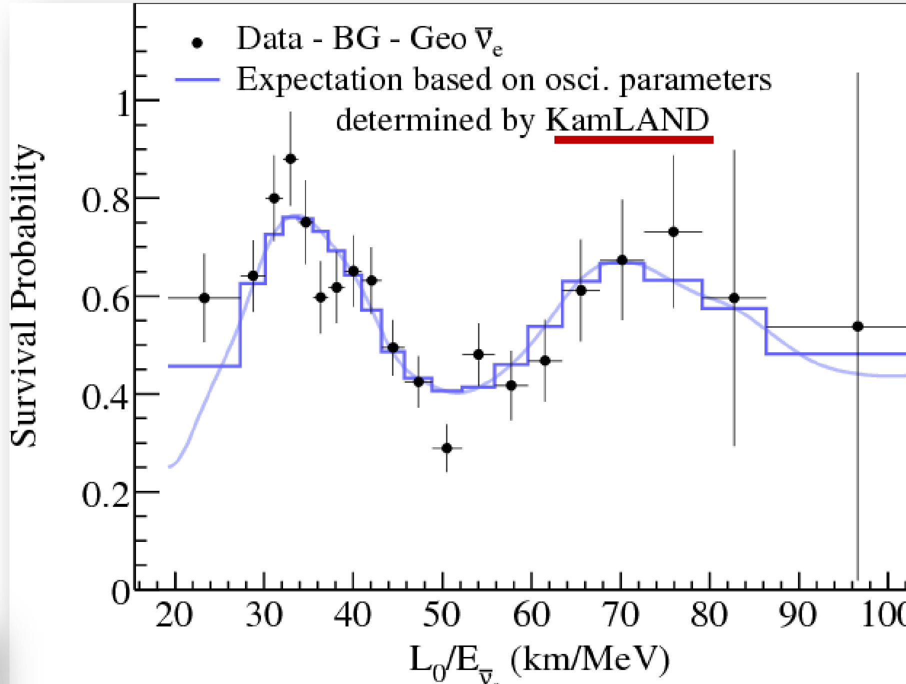
Experimental Issues

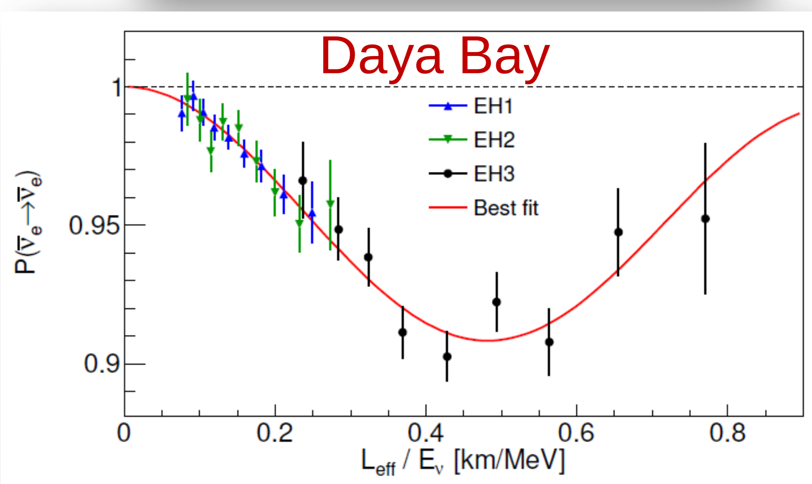
- Good energy resolution
- Low background

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

SuperK



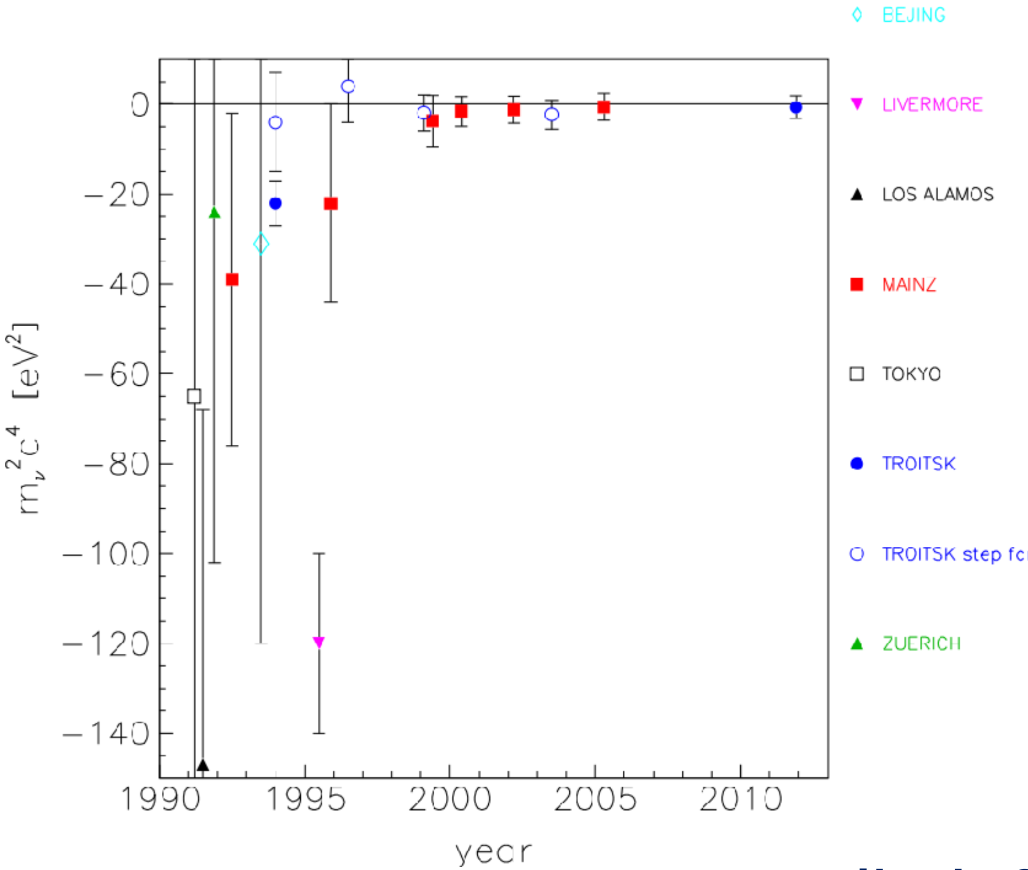


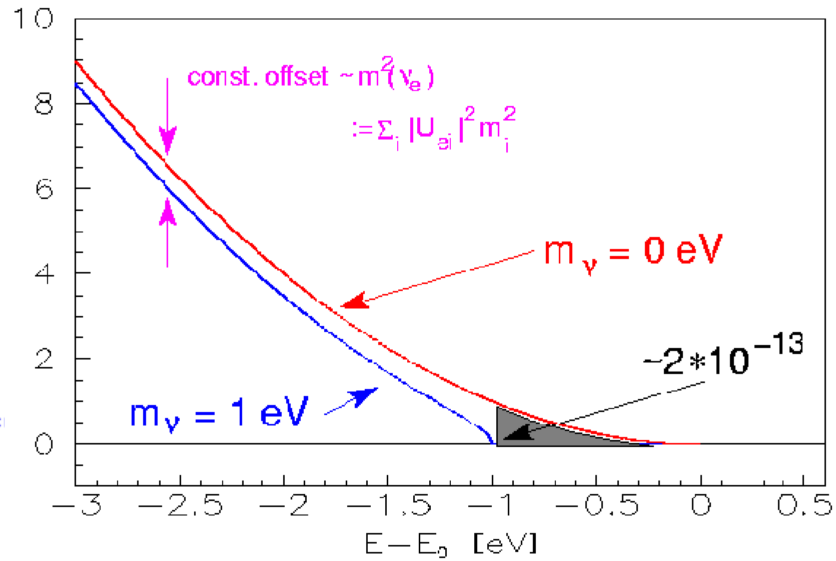


Measure:

- $|\Delta m_{ij}^2|$
- θ_{ij}

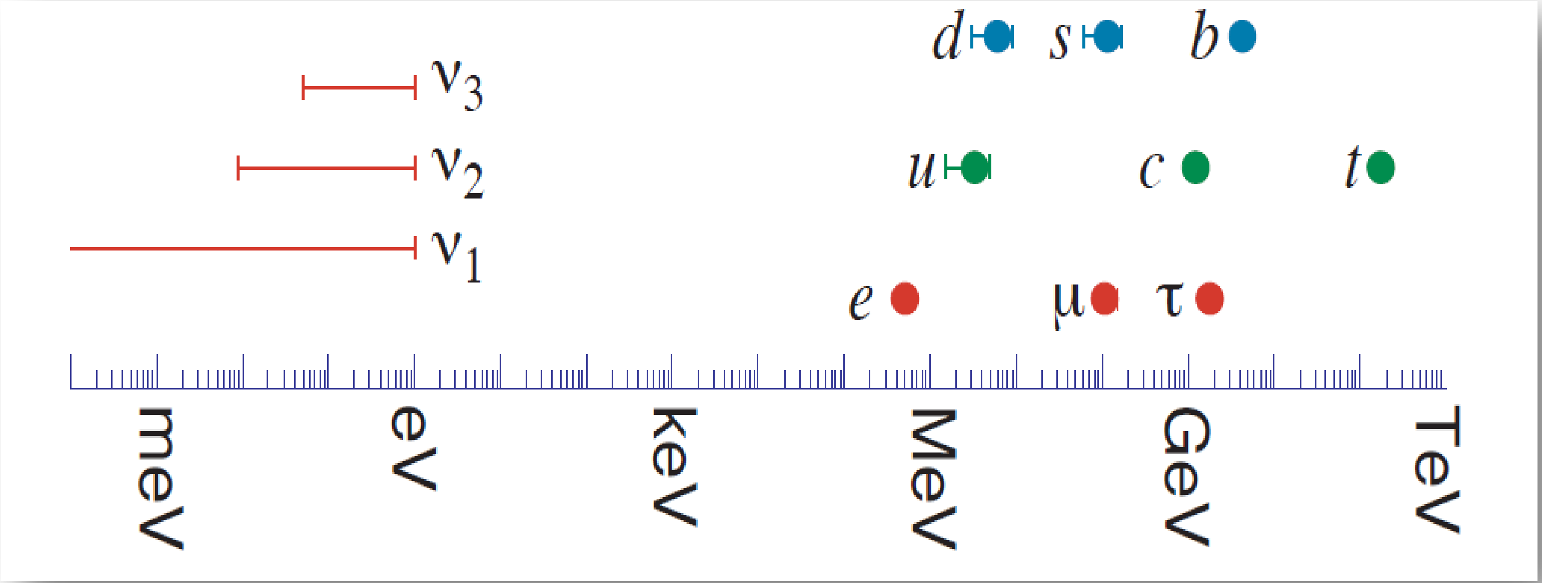
Absolute Neutrino Mass Limits





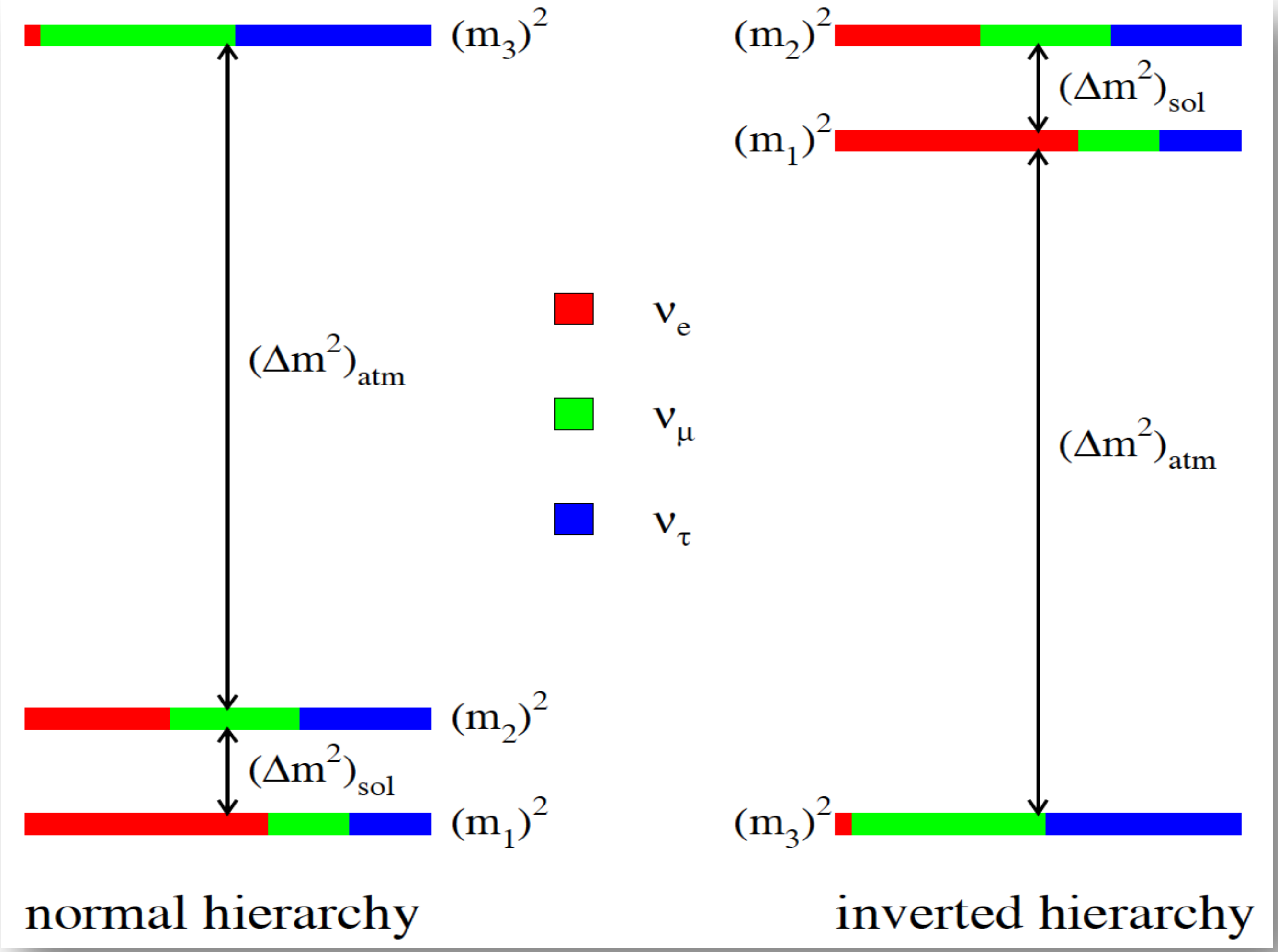
- Present limit from tritium decay: < 2 eV
- Cosmology: Σ m_i < 0.23 eV (95% CL)

Masses of Matter particles



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

Mass Hierarchy



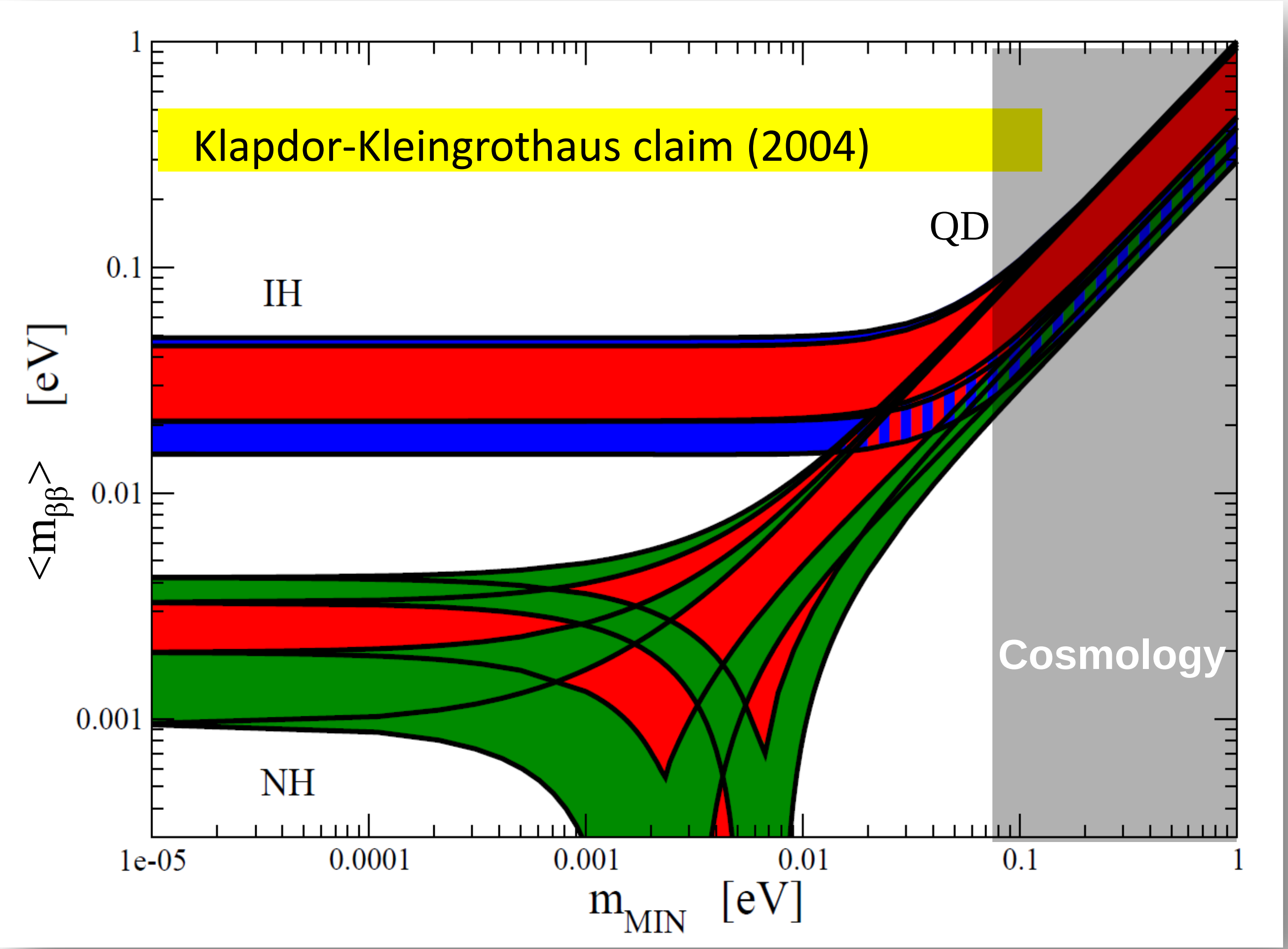
NLDBD and Neutrino Mass

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

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 $m_{\nu i}$

Science Assessment

It is the assessment of this Subcommittee that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery. Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in this next phase of discovery-caliber research.

Projects Data Collection

- Provided template to 11 collaborations
  - "current" project
  - future "next generation" project

- Scheduled 9 presentations for February 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
- TeO_2 bolometers ($\rightarrow$ 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	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	100	
SuperNEMO	^{82}Se+	7	>0.001
KamLAND-Zen	^{136}Xe	434	>0.19
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

Primary goals:

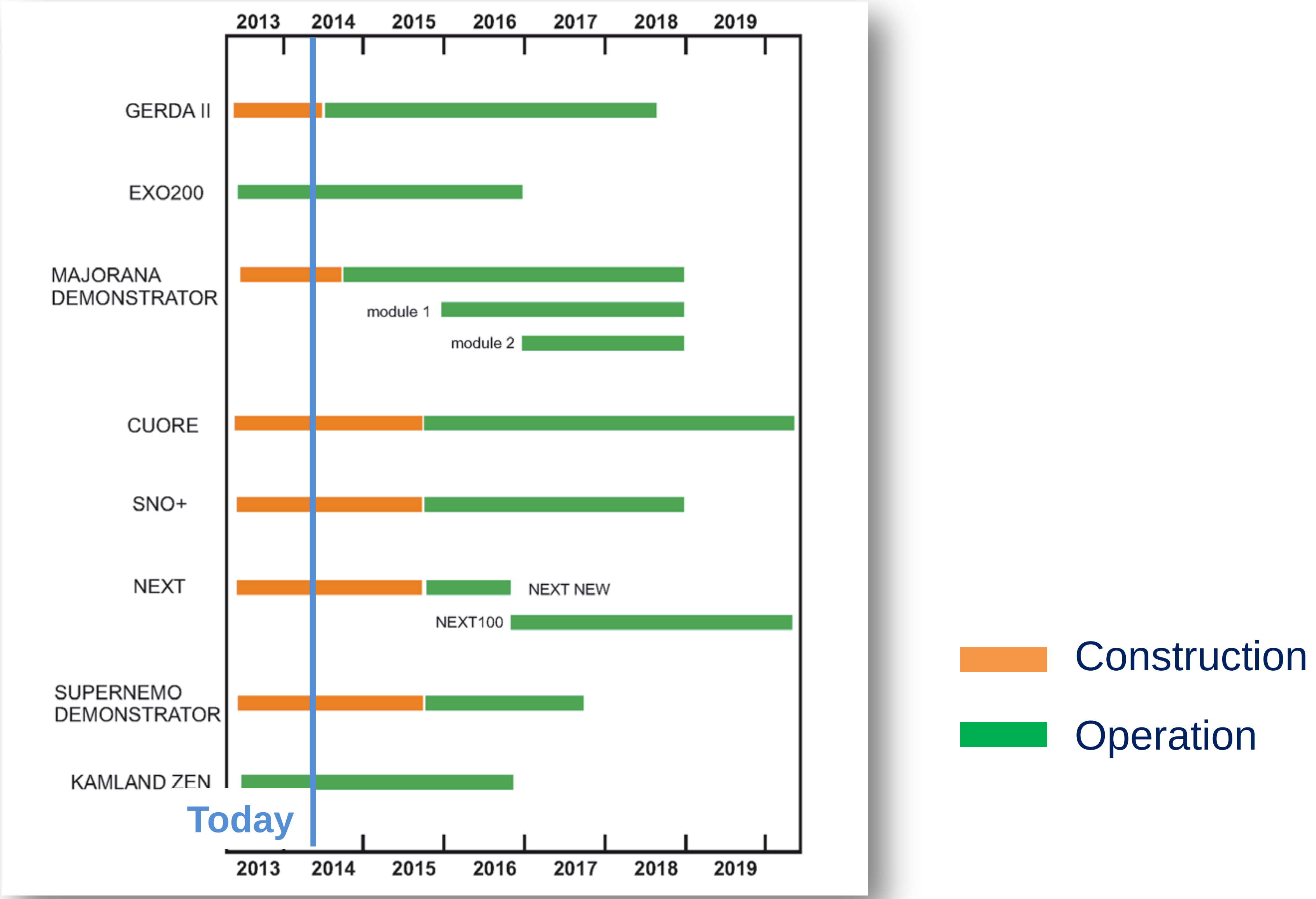
- **Demonstrate background reduction for next generation experiment**
- **Extend sensitivity to $T_{1/2}$~10^{26} years.**

Report on Projects and Plans

- For each current project, the Subcommittee provided a list of perceived strengths and challenges

- For each envisioned “next generation” project, we provide observations

Notional Timeline



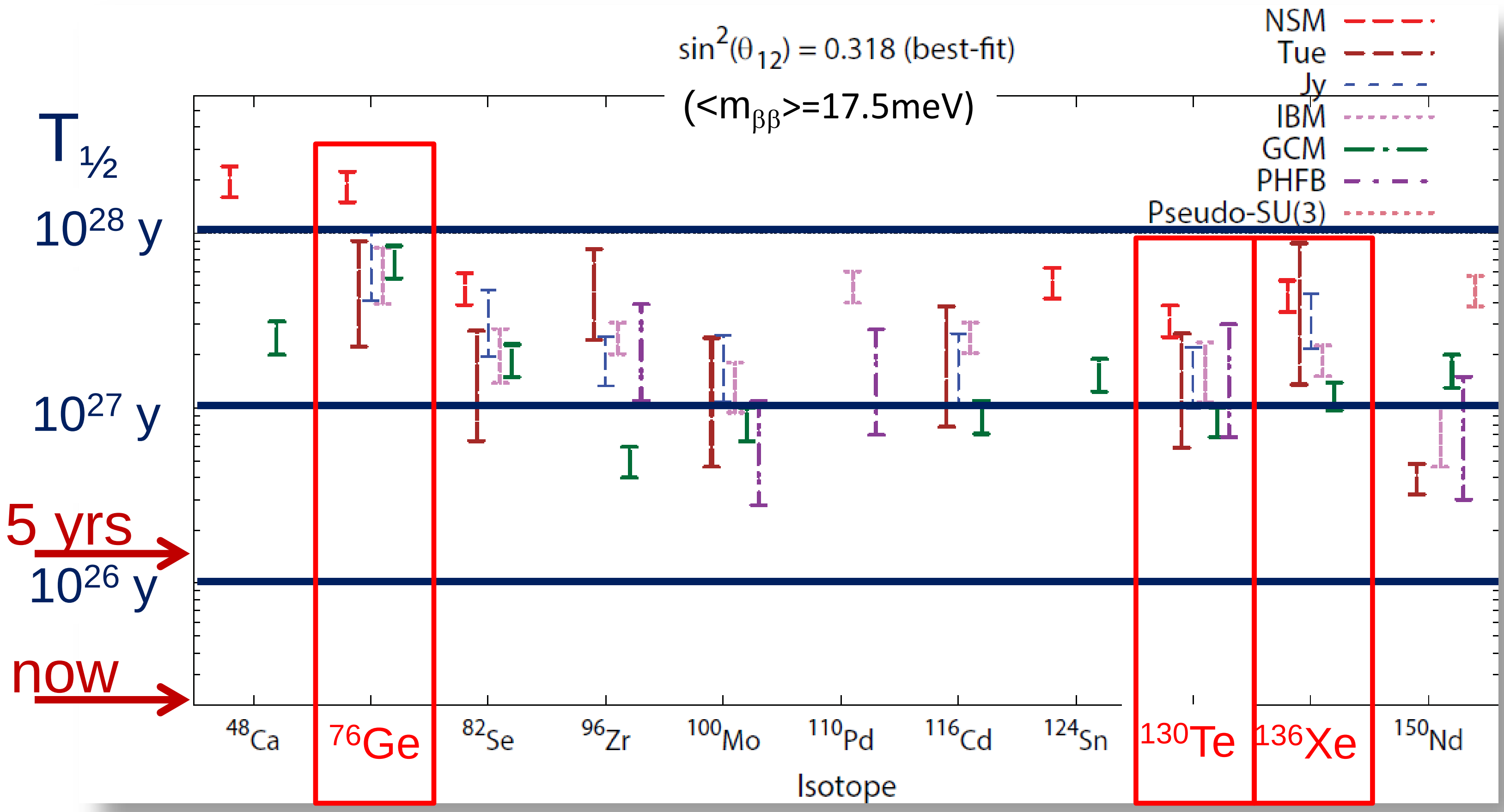
Subcommittee Observation

Based on the information provided to us, we judge that in a period of 2-3 years there will be much more information available from the results of these experiments. At that point one could assess the future prospects with much higher reliability than today.

Current Projects Assessment

The Subcommittee recommends that the "current generation" experiments continue to be supported and that the collaborations continue to work to resolve remaining R&D issues in preparation for consideration of a future "second generation" experiment. New techniques that offer promise for dramatic reductions in background levels should also be supported.

Inverted Hierarchy Coverage



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

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**

Guidelines for the Future

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1) **Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.**

2) **Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.**

3) **Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.**

Guidelines for the Future (cont'd)

4) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

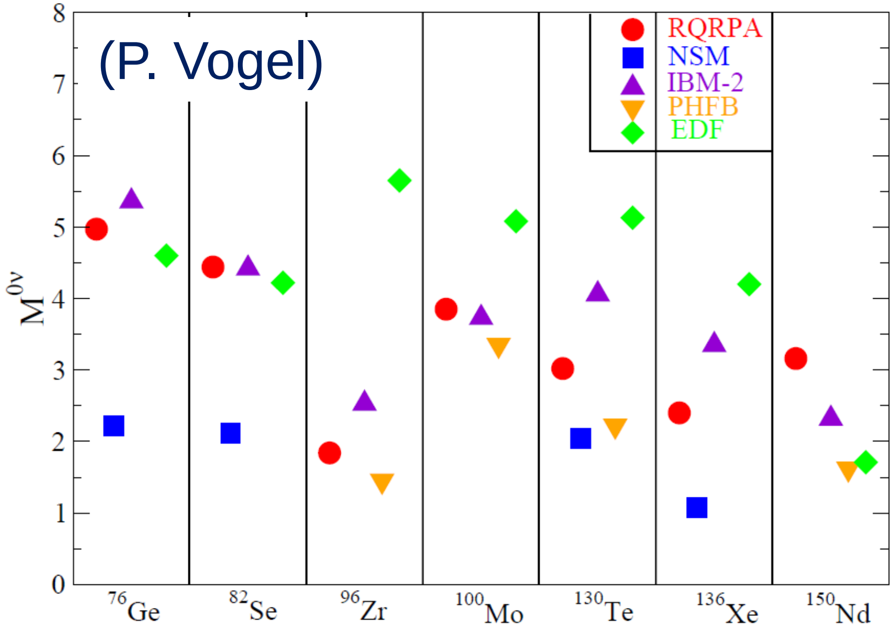
5) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.

6) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

Theoretical Issues

- Other mechanisms are possible besides the light Majorana neutrino

- 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?)

Theory Recommendation

There is generally significant variation among different calculations of the nuclear matrix elements for a given isotope. For consideration of future experiments and their projected sensitivity it would be very desirable to reduce the uncertainty in these nuclear matrix elements.

The subcommittee recommends establishing a theory task force that aims at:

1.) **developing criteria to establish and rank the quality of existing and future calculations,**
2.) **identifying methods to constrain the less tested assumptions in existing approaches.**

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 Feb.
- 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.