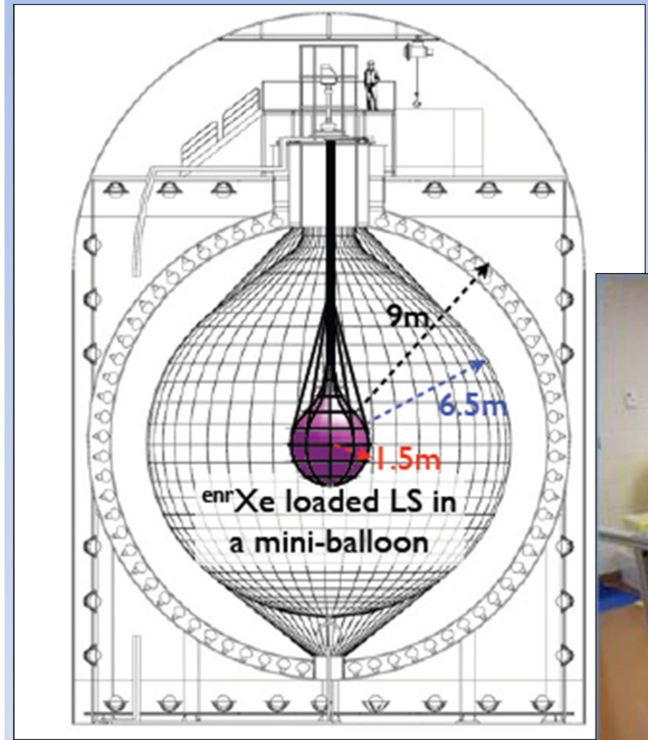
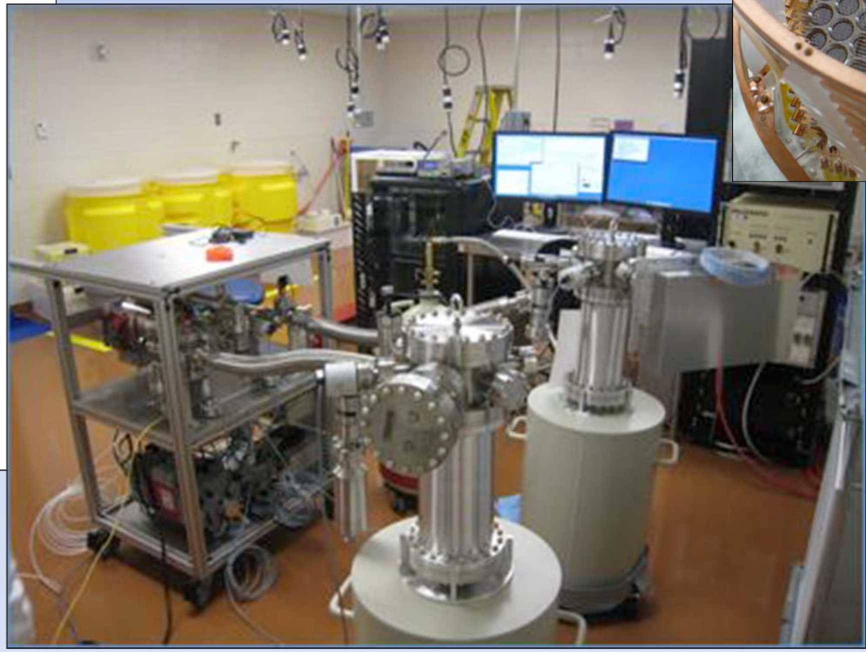
# 0νββ Decay Searches: Current Status and Future Plans

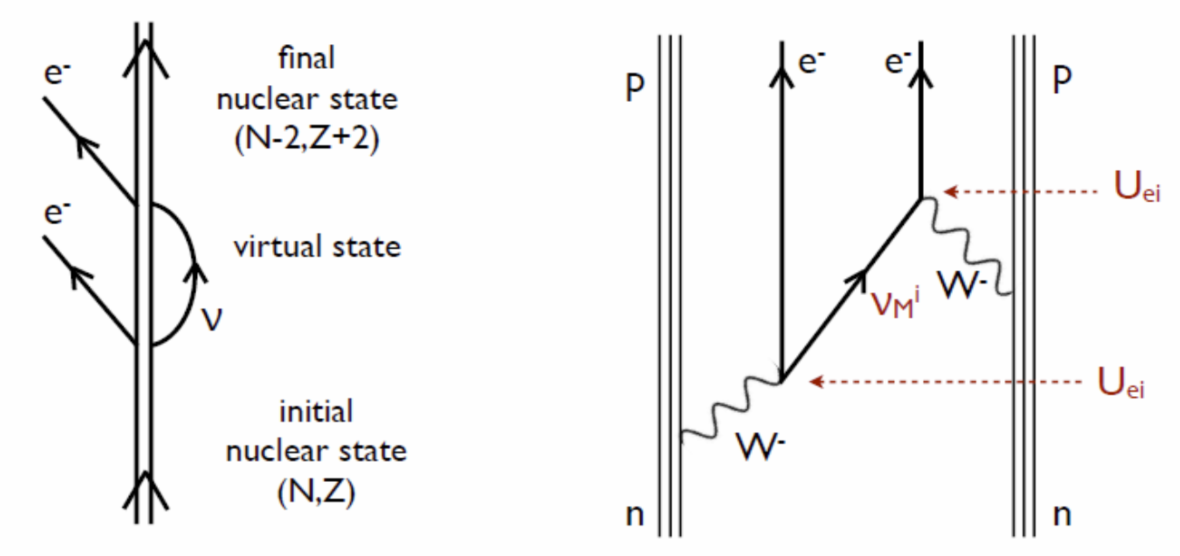


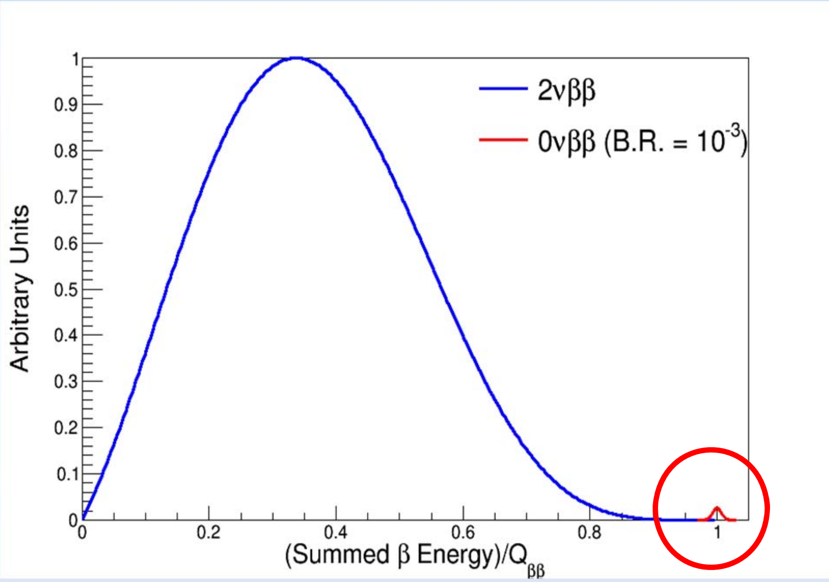
DBD2014
Waikoloa, HI
Oct. 5, 2014


R. D. McKeown
Jefferson Lab
College of William and Mary

# 0νββ decay




- ΔL=2
- Majorana ν
- Flip helicity:
  - RH coupling
  - m ≠ 0




Experimental Issues

- Good energy resolution
- Low background

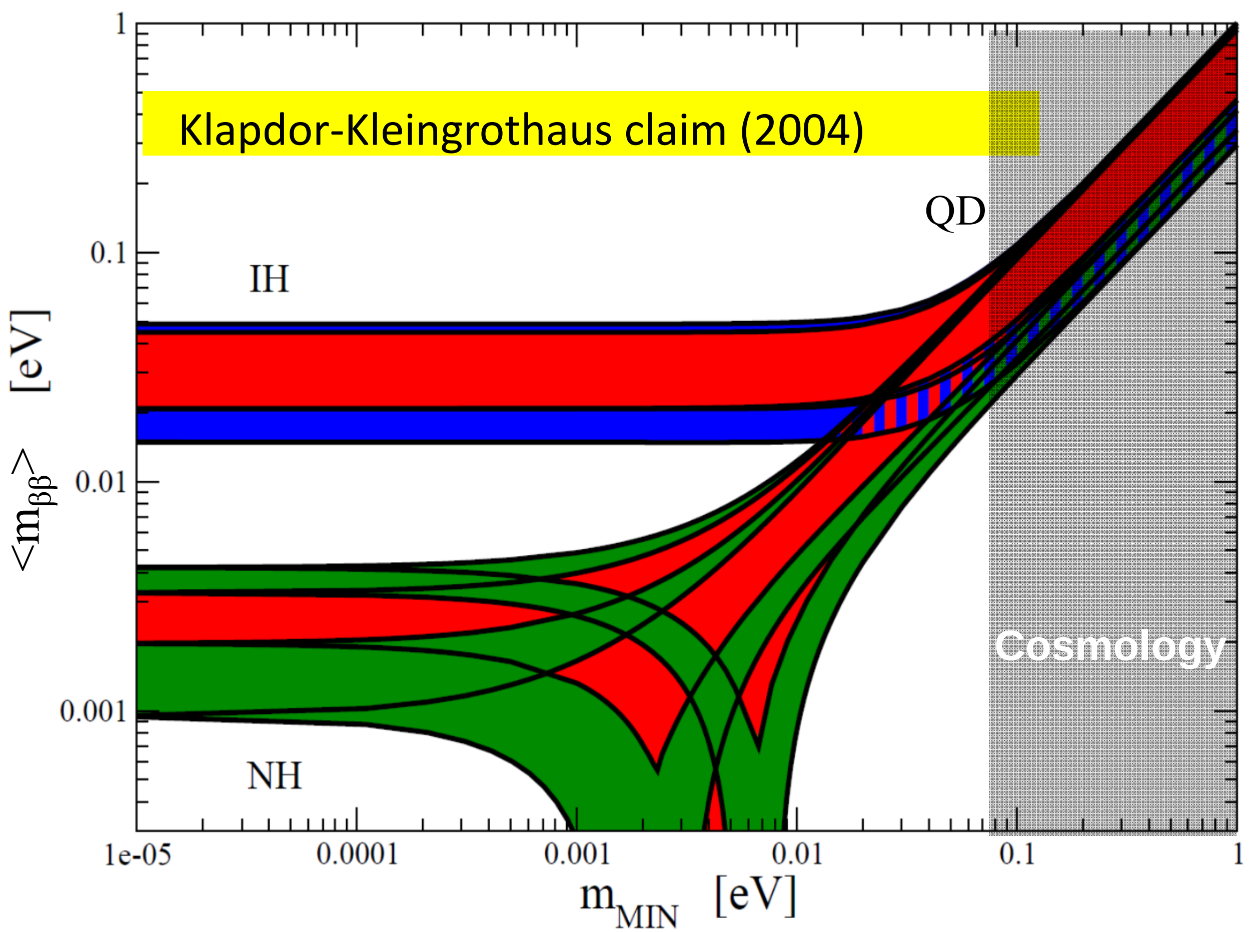
# NLDBD and Neutrino Mass

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

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 $m_{\nu i}$

# NSAC Subcommittee 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.

# Methods

- $^{136}Xe$ TPCs (liquid, gas)
- $^{76}Ge$ Crystals
- $TeO_2$ bolometers (→ 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 | $^{76}Ge$ | 36.8 | |
| 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.

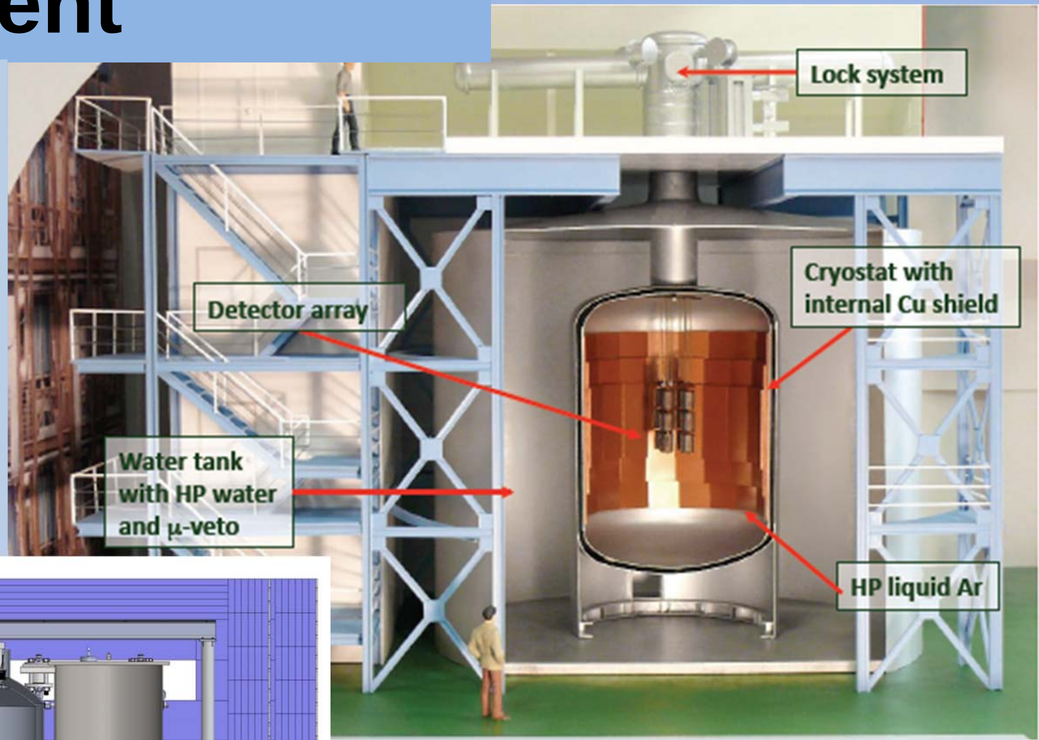
# Subcommittee Report on Projects and Plans

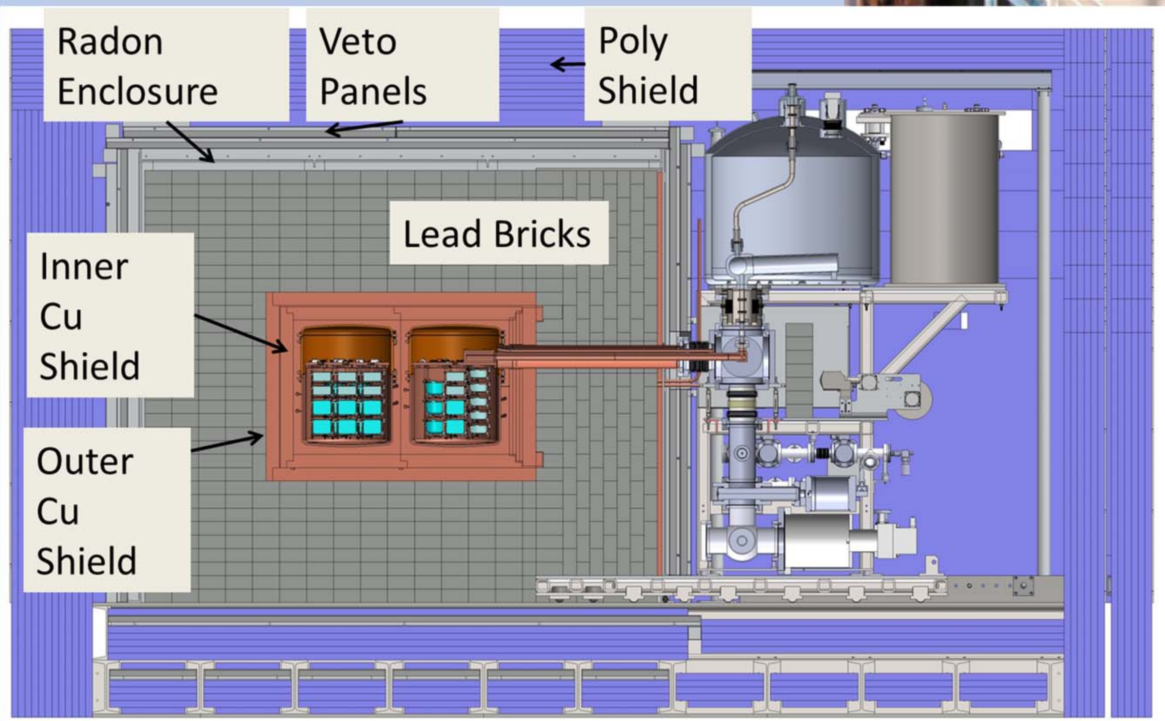
- For each current project, the Subcommittee provided a list of perceived strengths and challenges
- For each envisioned “next generation” project, we provided observations

# $^{76}$Ge Searches: Current

## GERDA @ Gran Sasso:

- GERDA I ⇒ 21.6 kg-yr exposure 2011-13
- Enriched Ge array embedded in LAr shield
- GERDA II upgrade: add new dets., reduce bkgd., active LAr veto; start late 2014

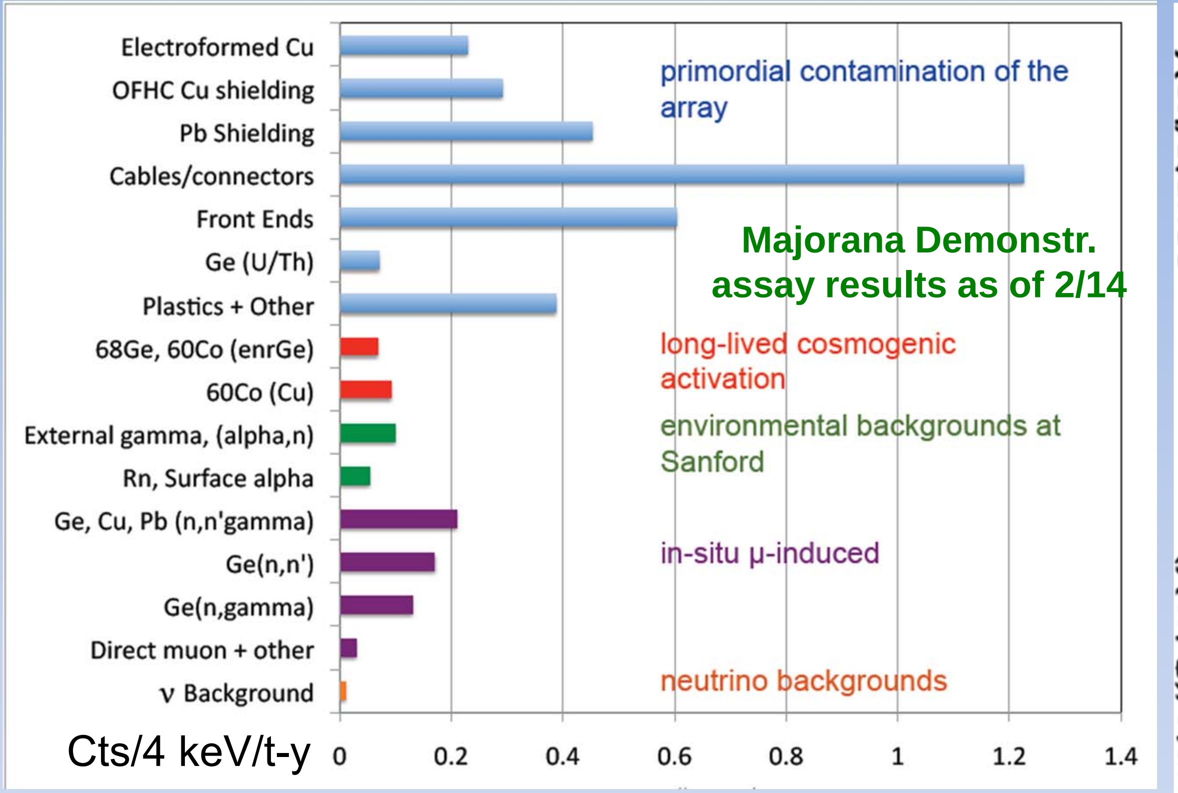


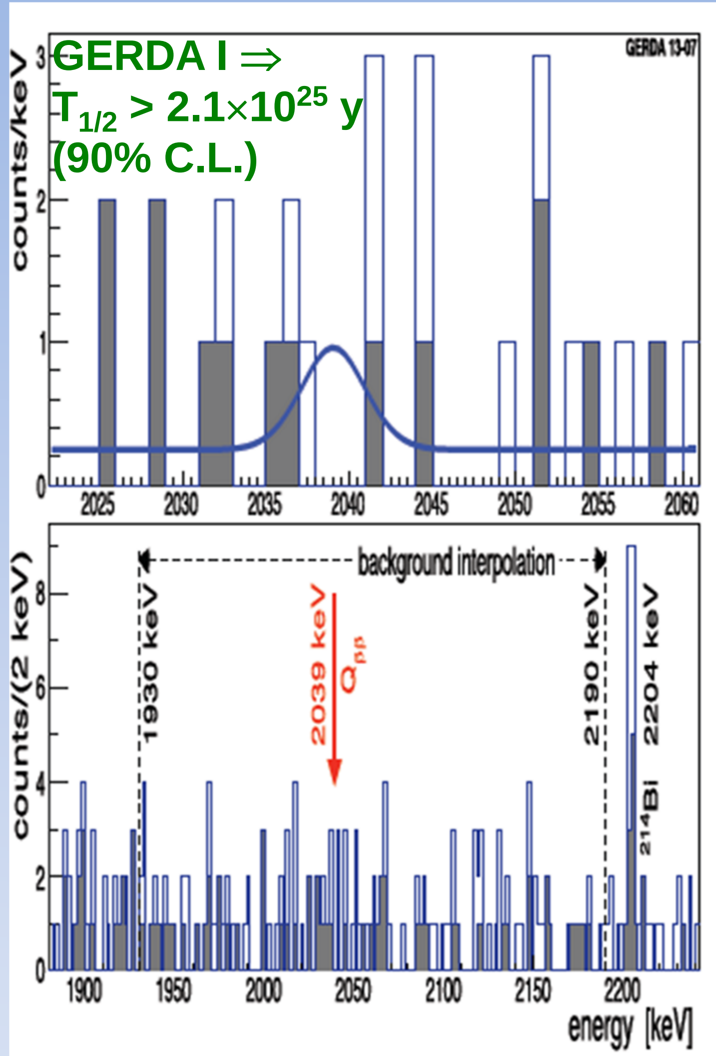




## Majorana Demonstrator:

- Modular instrument housed in 2 ultrapure Cu cryostats @ SURF
- 30 kg enriched + 10 kg nat'l Ge p-type point contact dets. mid-2015 (1st 20 kg Fall 2014)

# $^{76}$Ge Searches: Current




**Strengths:**

- Excellent $E_{\beta\beta}$ resolution ~3 keV FWHM
- ~ flat background near $Q_{\beta\beta}$
- MJD on track to desired 3 cts/ROI/tonne-yr
- Event characteriz'n tools: PSD, hit pattern, …

**Challenges:** **Smaller $^{76}$Ge phase space ⇒ may need sensitivity to higher $T_{1/2}$**

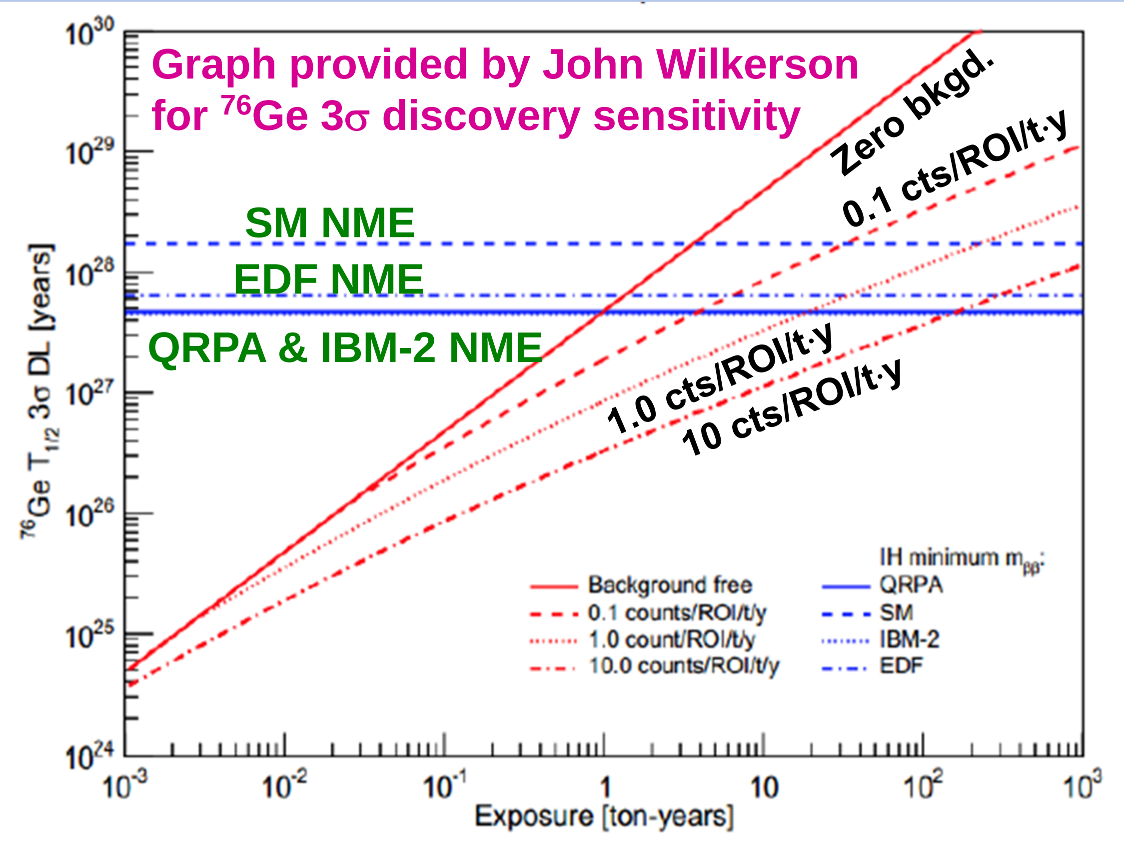
- Some further reductions needed in backgrounds from surrounding materials to achieve needed next-generation sensitivity

# $^{76}$Ge Searches: Next Generation

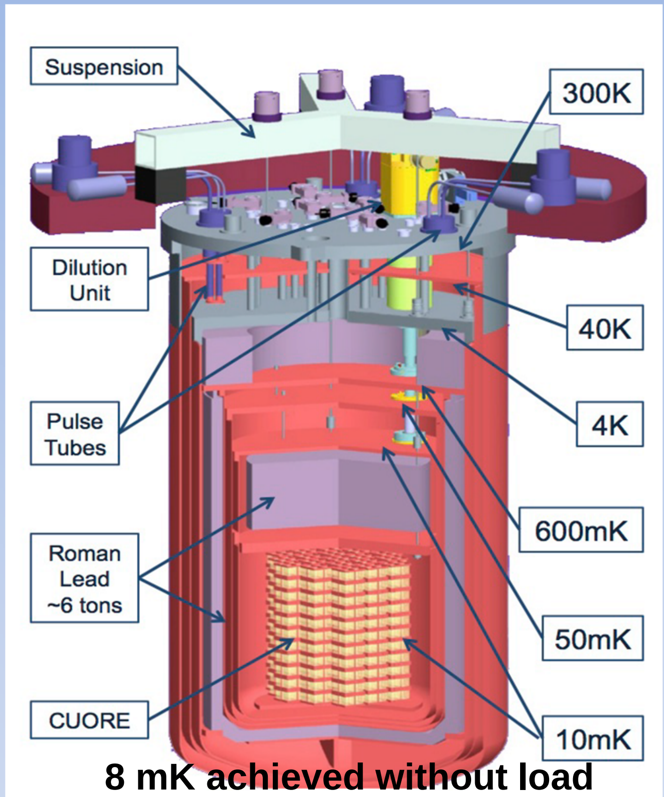
- Majorana & GERDA work toward unified international collaboration
- Down-select best technologies based on demonstrated results from the two exp'ts
- Propose staged approach: 250 → 500 → 1000 kg
- Aim for <1 background count/ROI/tonne-year (self-shielding helps)

**Comments:**

- 2 large experienced groups
- Tech. options will be thoroughly researched
- Projected bkgd ~ flat, but not negligible
- High isotope cost
- Lowest current NME ⇒ need to probe eventually to ~2 × $10^{28}$ years ⇒ need significant further bkgd. reduction

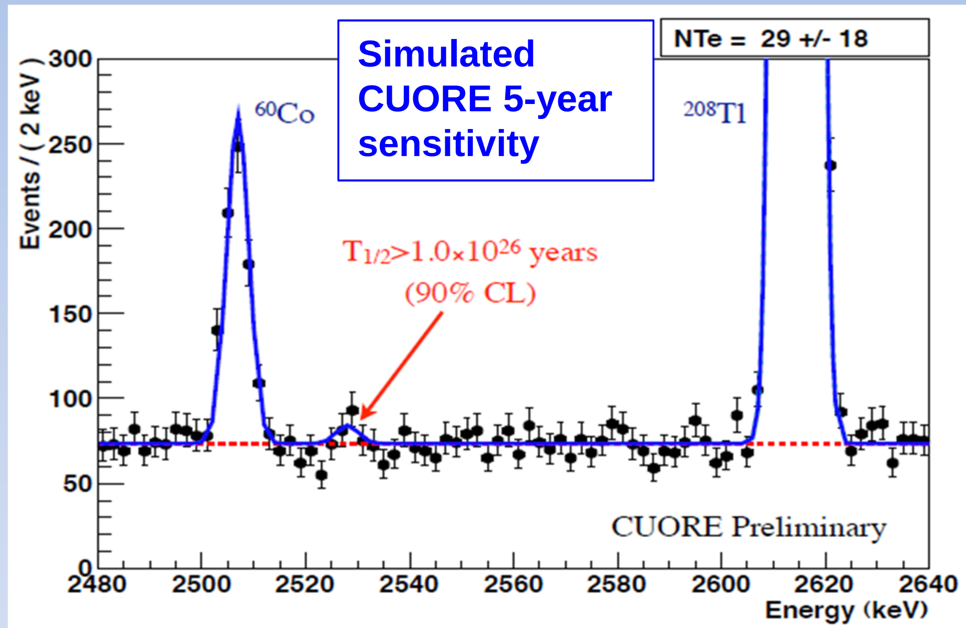


# Bolometer Searches: Current




**CUORE:** ***nat.*** $\boldsymbol{TeO_2}$ ***bolometers @ Gran Sasso***

- 988 crystals ⇒ 206 kg $^{130}$Te by mid-2015
- Operational experience from Cuoricino (⇒ $T_{1/2} > 2.8 \times 10^{24}$ y, 90% C.L.) & CUORE-0 (1 tower = 52 crystals) demonstrate E resol'n and $\alpha$ bkgd. goals for CUORE



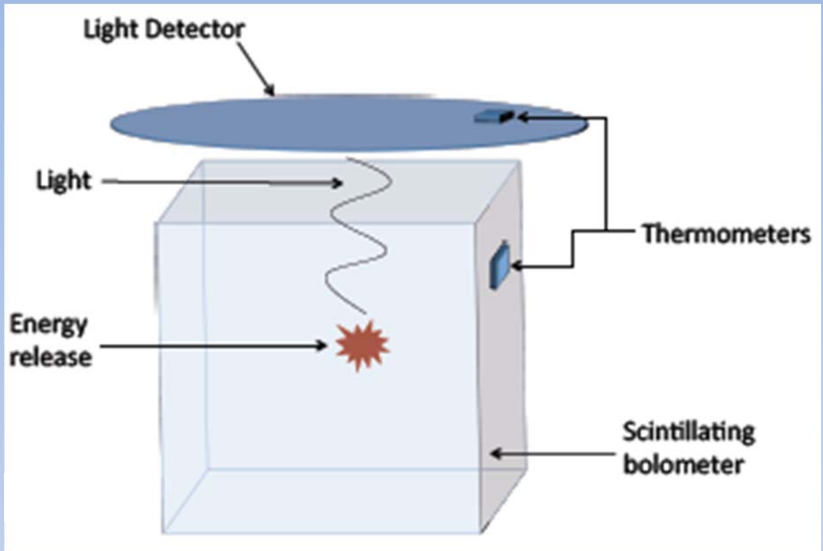

**Advantages:** ***cost-effective nat. Te***

- Very good E resolution ~5 keV
- Multi-site veto capability.
- Scalability, adaptability to different isotopes

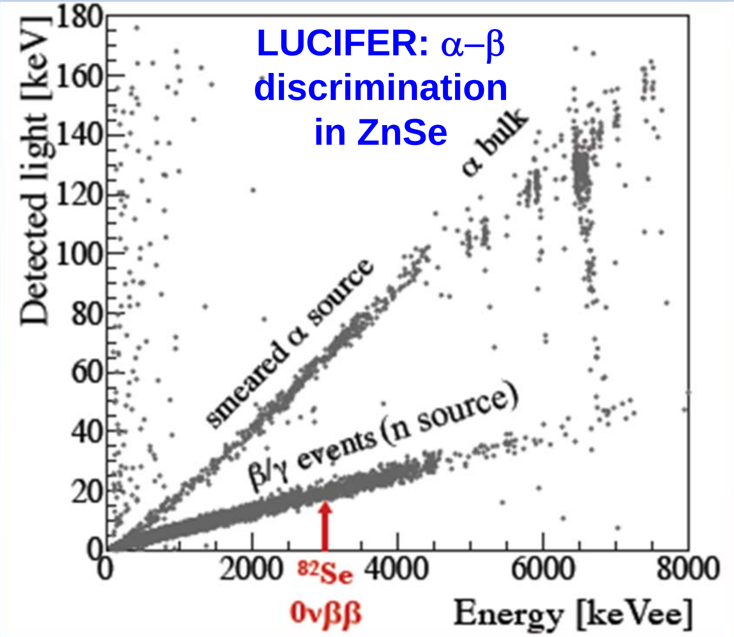
**Challenges:** ***slow response of thermal signal requires low background***

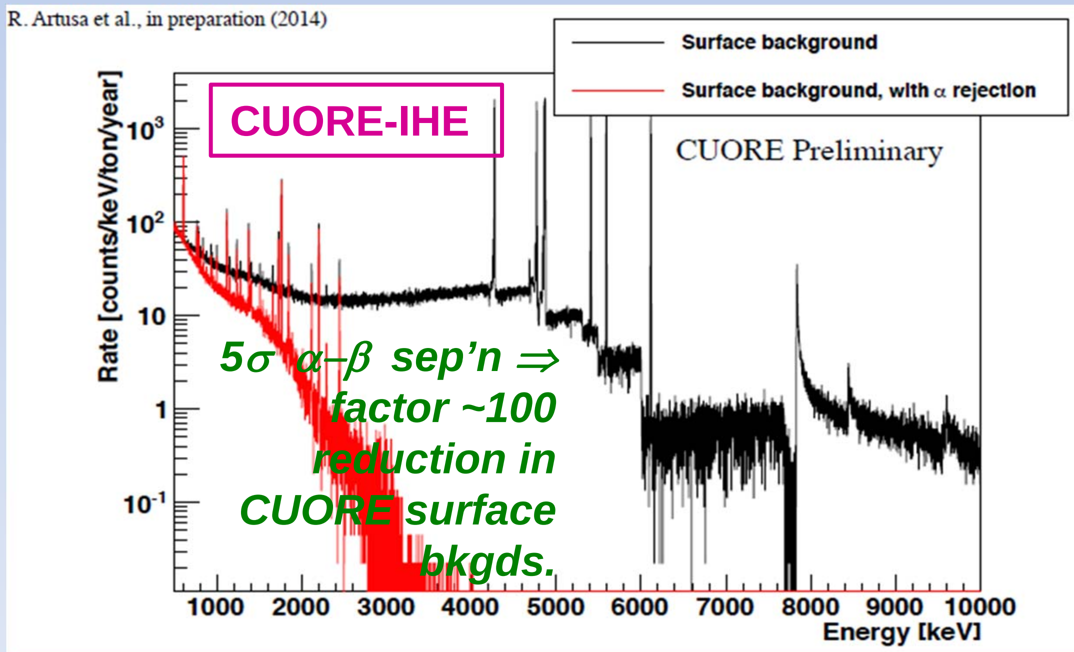
- ~ flat, but sizable bkgd. (~50 cts/ROI/tonne-year, scaled from CUORE-0)
- U- and Th-chain contaminants on crystal and copper surfaces

# Bolometer Searches: Next Generation

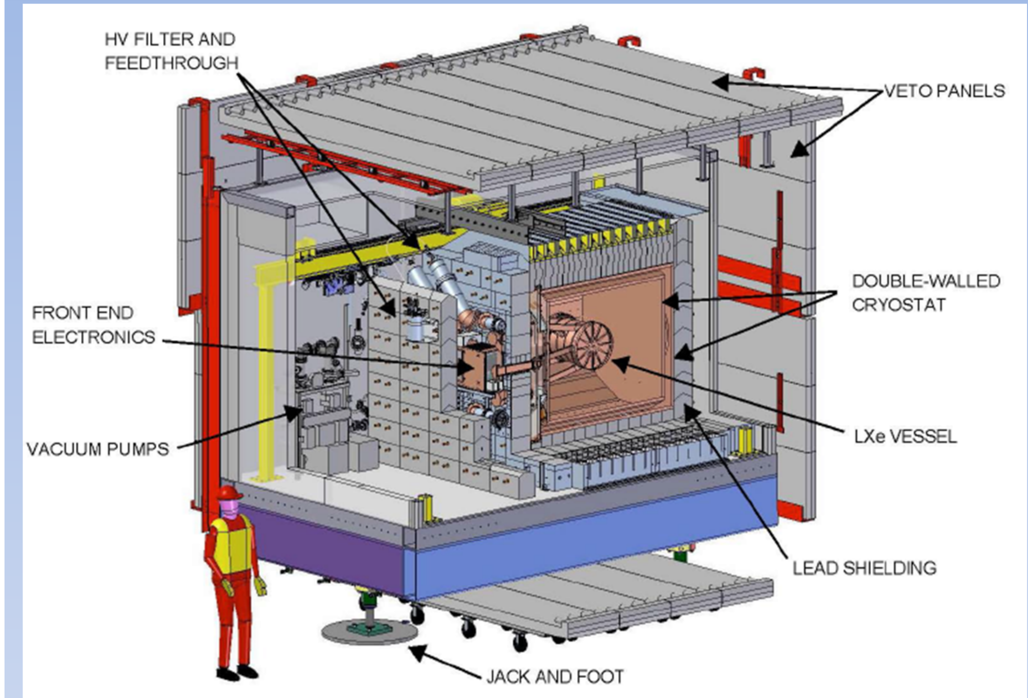



- Similar configuration to CUORE, but with *combined light + heat* readout of bolometers, to provide *$\alpha$ vs. $\beta$ discrim.*
- Scintillating bolometers under development by LUCIFER and others: $Zn^{82}Se$ (8.9kg isotope); $Zn^{100}MoO_4$; $^{116}CdWO_4$
- *$TeO_2$: Čerenkov light only $\Rightarrow$ poorer discrimination; other isotopes cost more*
- *Important R&D effort in progress*



# $^{136}$Xe TPC Searches: Current

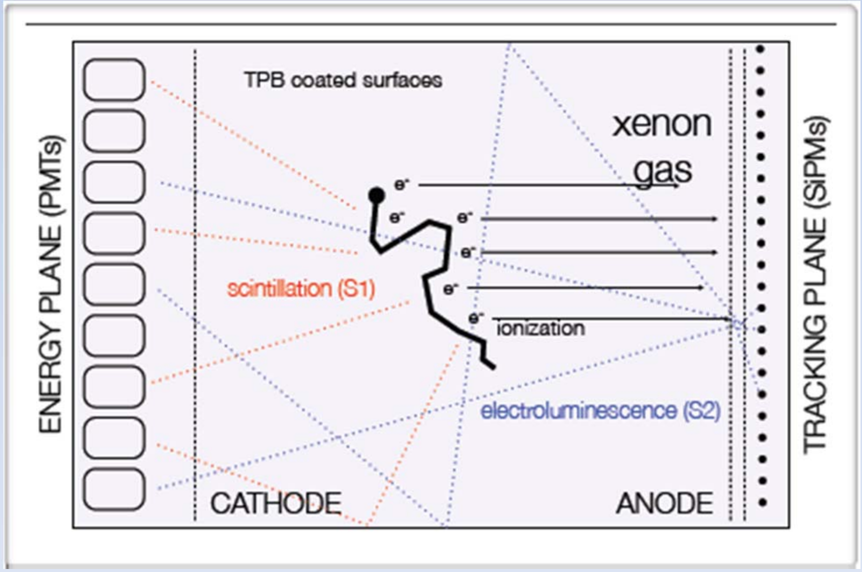



**EXO-200:** *LXe TPC @ WIPP*

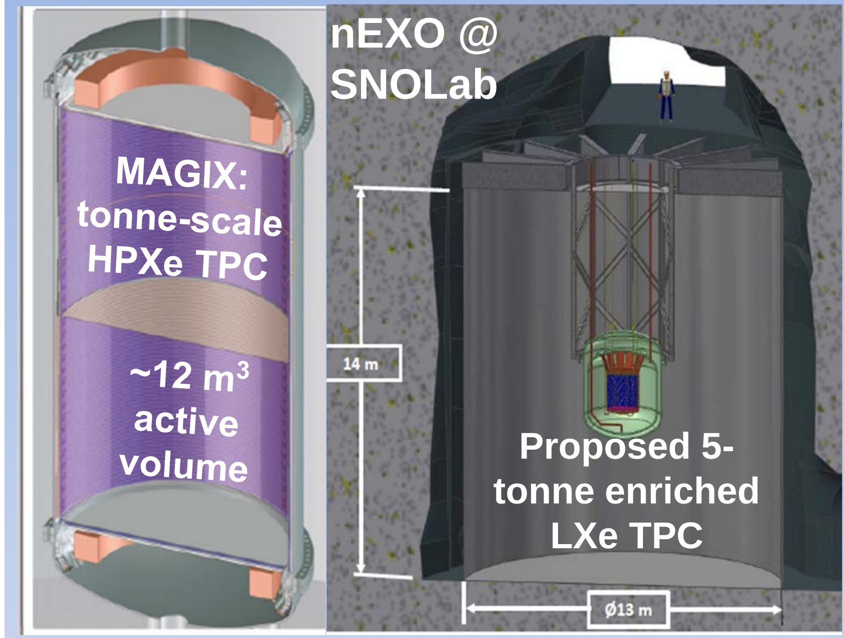
- Simultaneous readout of ionization and scintillation
- 200 kg enriched Xe on hand; 79 kg fiducial $^{136}$Xe
- Moderate E resolution: 88 keV FWHM now→ 58 keV after electronics upgrade
- Taking data since May 2011 ⇒ 2014 result: $T_{1/2} > 1.1 \times 10^{25}$ y (90% CL)

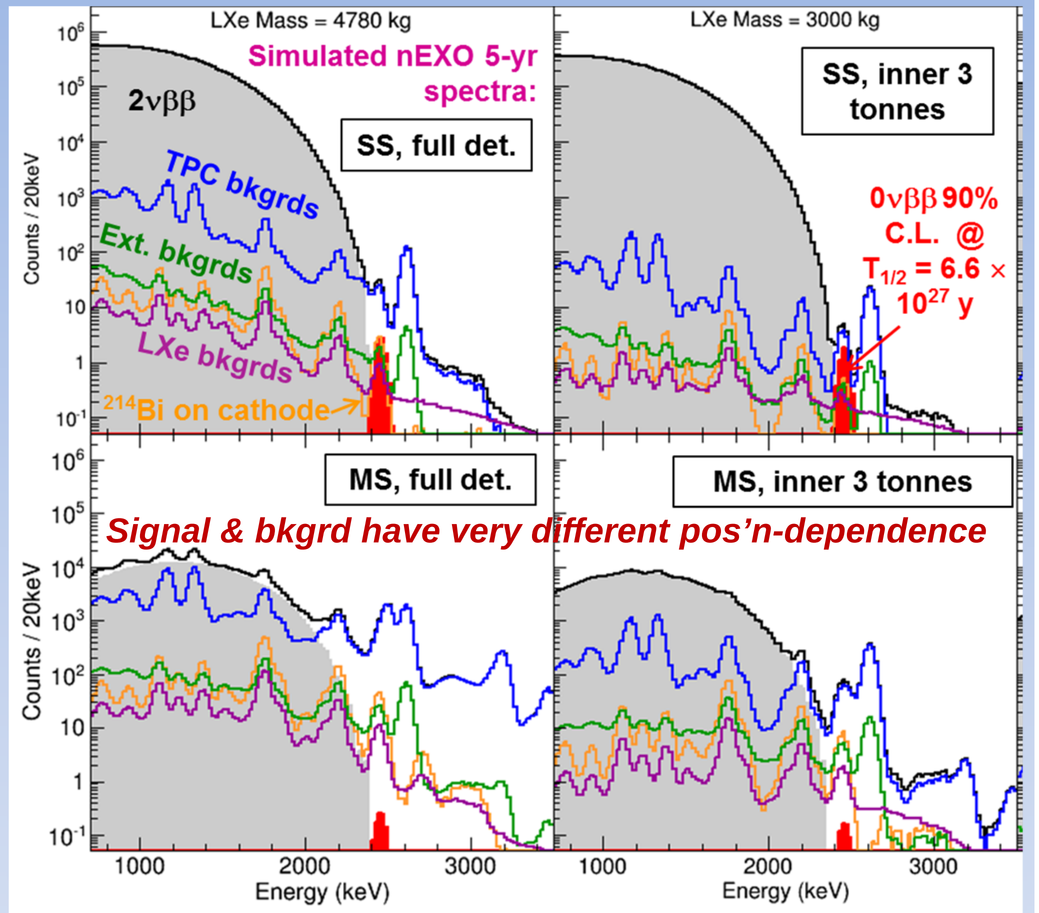
**NEXT-100:** *HPXe (15 bar) gas TPC @ Canfranc (Spain)*

- primary + secondary scint. ⇒ E
- R&D ⇒ ≤ 20 keV FWHM
- SiPM tracking plane looks for characteristic ββ signature
- 10 kg Xe (90%) 2014 → 100 kg (~61 kg fiducial isotope mass) 2016



# $^{136}$Xe TPC Searches: Next Generation

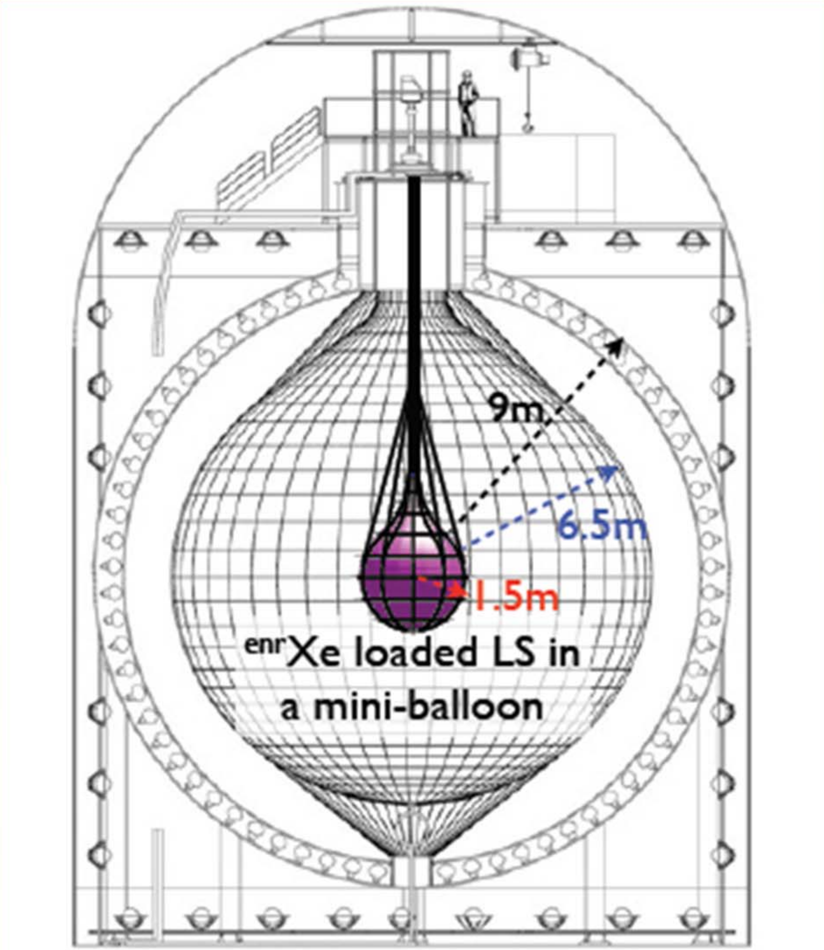



### Comments:

- *Larger TPC ⇒ enhanced self- & Compt suppression*
- *Projected nEXO bkgd. ~ 100× below present EXO performance needs to be demonstrated*
- *Bkgrd ($^{214}$Bi) still strongly structured in ROI, but highly constrained by detailed fits to single- vs. multi-site events as fcn. of pos'n through entire TPC volume*
- *Need non-trivial fraction of worldwide Xe production, but could reconfigure from liquid to high-pressure gas*
- *Important R&D opportunities: daughter Ba tagging; Se-based TPC gas?*

# Loaded Liquid Scintillator Searches: Current

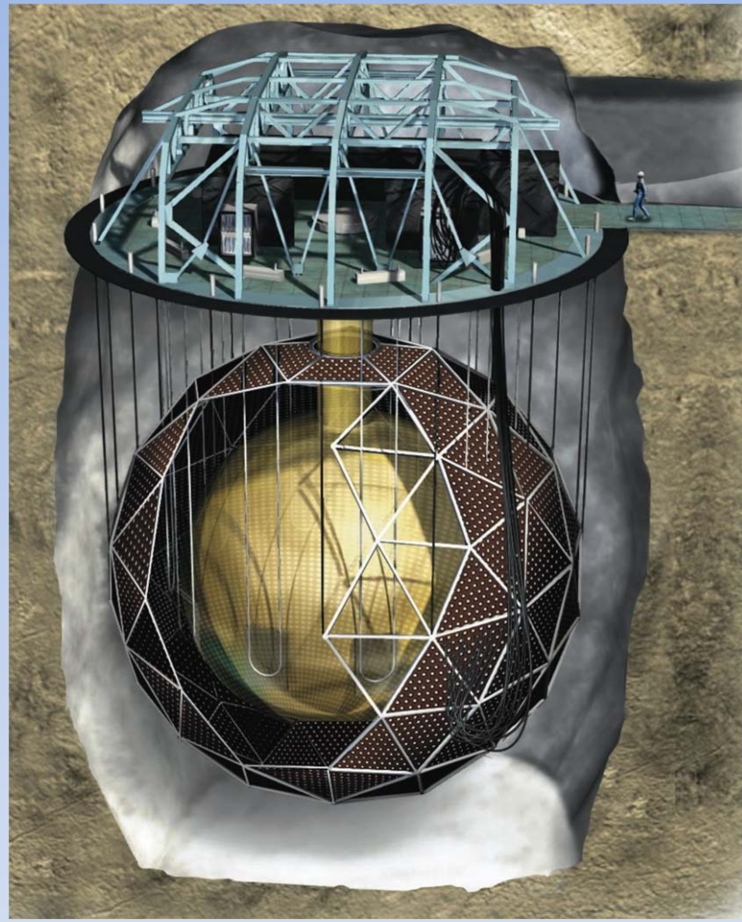



**KamLAND-Zen started 9/2011**

~320kg 90% enriched $^{136}Xe$ installed so far

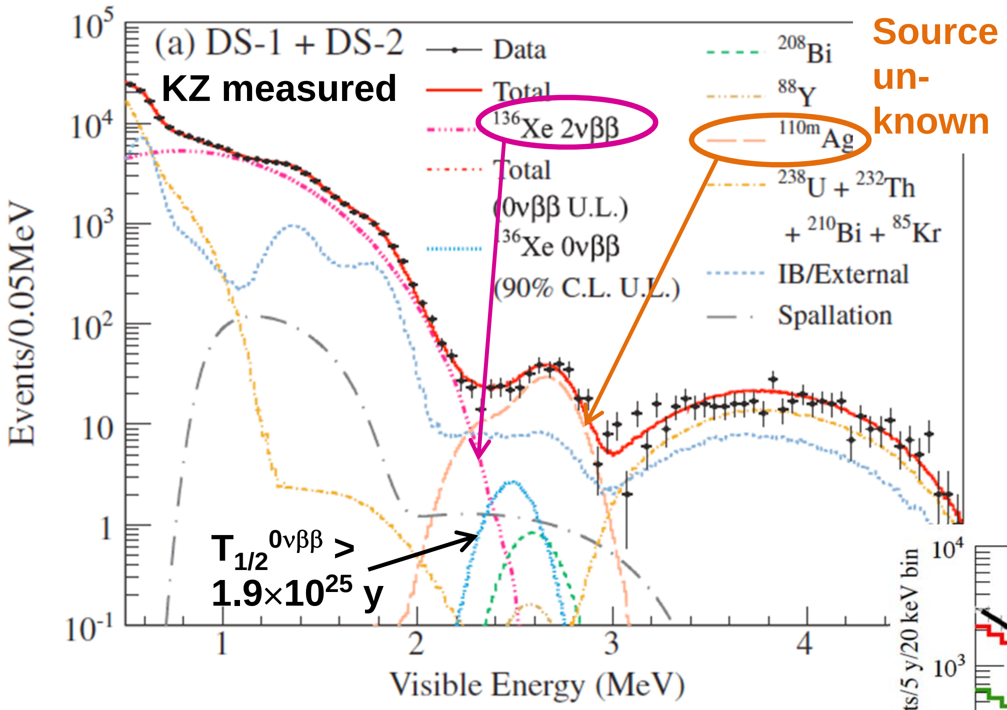
**Add Xe in hand ⇒ 434 kg fiducial isotope mass for 2015 data-taking**

***Loaded LS in existing large under-ground ν detectors ⇒ cost-effective opportunity to study large isotope masses, but with limited energy resolution***



**SNO+: 780 tonnes of LS loaded 0.3% with nat'l Te – start data-taking late 2015 ⇒ fiducial $^{130}Te$ mass ≅ 160 kg**

# Loaded Liquid Scintillator Searches: Current

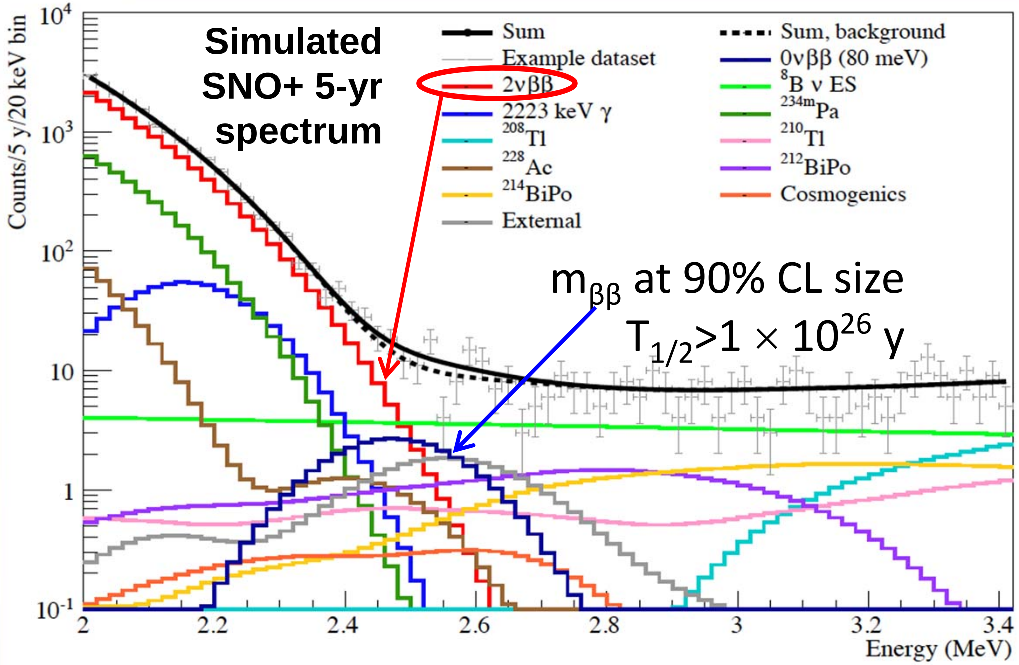



## Advantages:

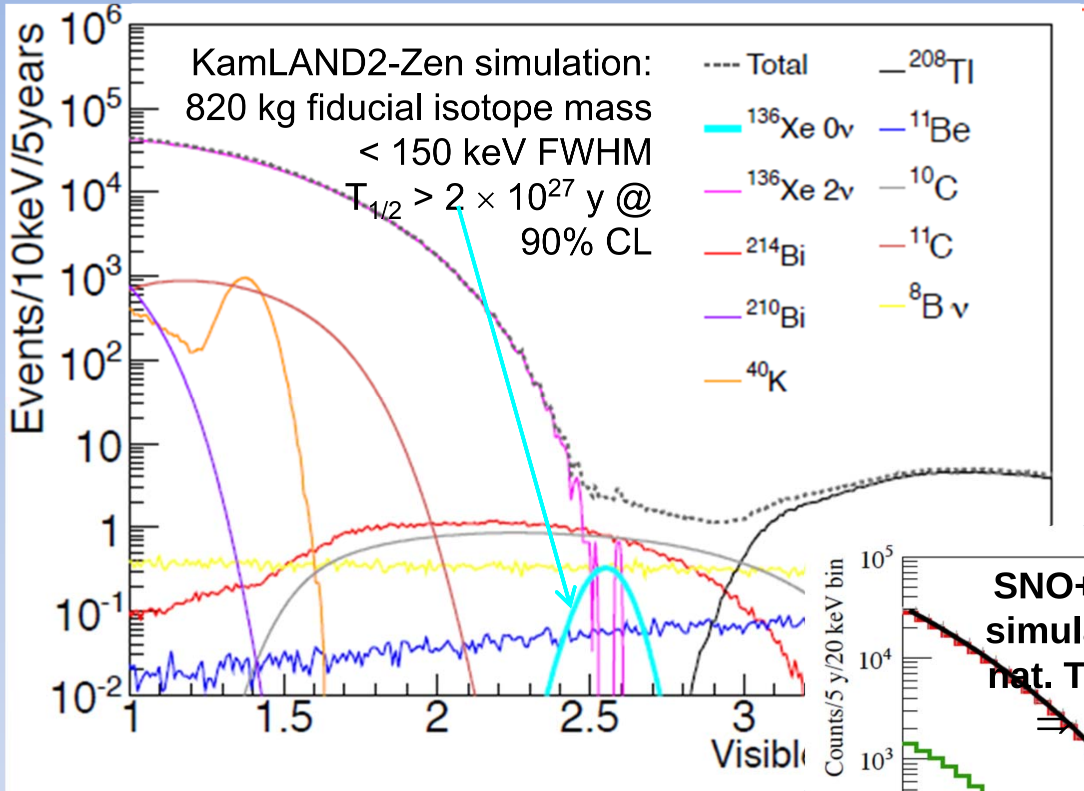
- Cost-effectiveness, scalability to quite large isotope masses
- Ease of repurifying, removing or changing isotope loading
- Shielding of external bkgds. by large LS volume ⇒ low (~5 × $10^{-4}$) bkgd. counts/y/kg/keV
- Adaptability to other isotopes

## Challenges:

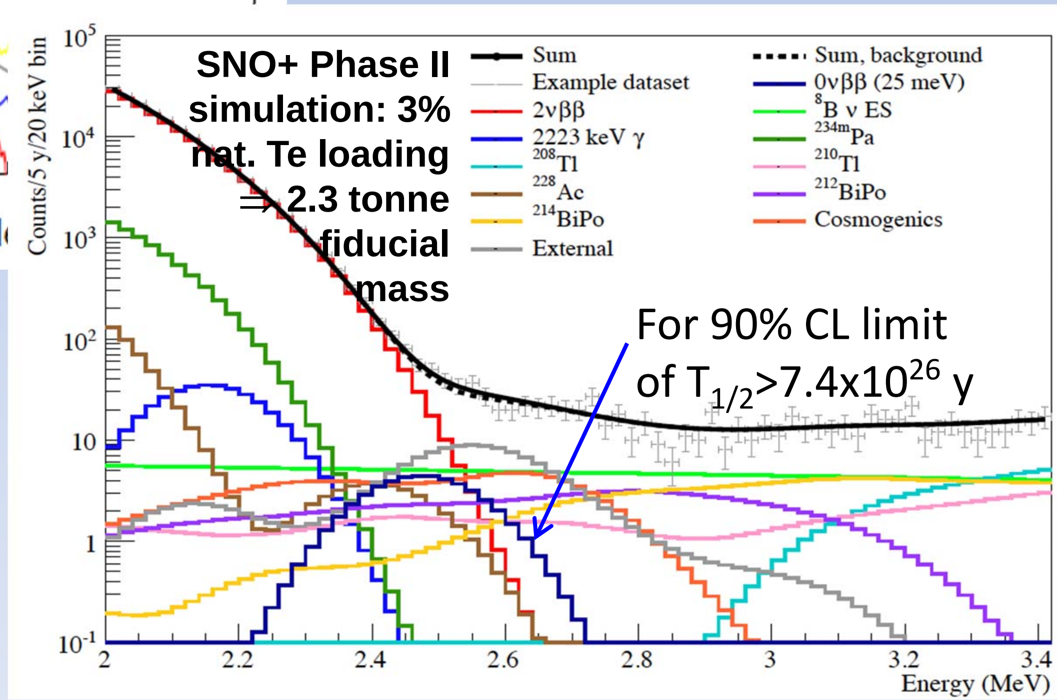
- Limited FWHM E resol'n ~250 keV ⇒ significant 2νββ feed-thru, complex bkgd. shape – ameliorate w/ asymmetric ROI
- Extraction of signal or limits relies on detailed & accurate modeling of detector, optics, bkgd. sources



# Loaded Liquid Scintillator Searches: Next-Gen



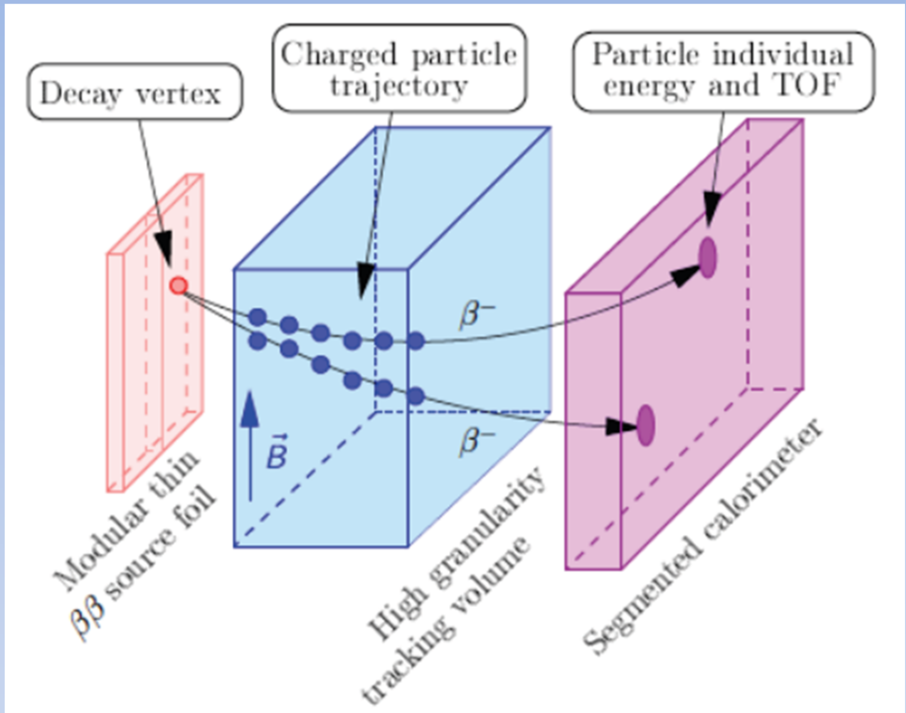

- Replace PMTs, increase light yield for improved resolution (~150 keV KZ, ~200 keV SNO+)
- More mass (for SNO+ via enriched or higher % nat. Te loading -- needs R&D)
- Improved bkgd. rejection




**Comments:**

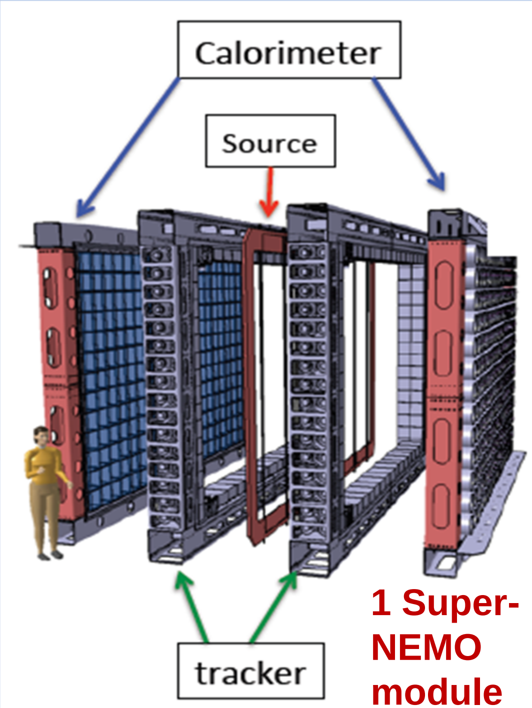
- Large mass capability may ⇒ best near-term lower limits
- Bkgd. R&D options: loading Te (5% achieved), pressurized Xe, scint. mini-balloon film, …
- Limited E resolution limits discovery potential

# Super-NEMO




- Separates thin source foils from tracking + calorimetry detectors to measure full final state kinematics
- Predecessor NEMO3 measured $2\nu\beta\beta$ half-lives for 8 of 11 candidate isotopes

- Demonstrator module with 7 kg enriched isotope ($^{82}$Se and/or $^{150}$Nd) to run at Modane (Fréjus, 4800 mwe) 2015-17
- 20-module 100 kg full SuperNEMO would run 2017-23 if Demonstrator achieves low bkgd.
- Modest E resolution ~ 120 keV FWHM, but potentially very good bkgd. suppression



# Super-NEMO

**Advantages:**

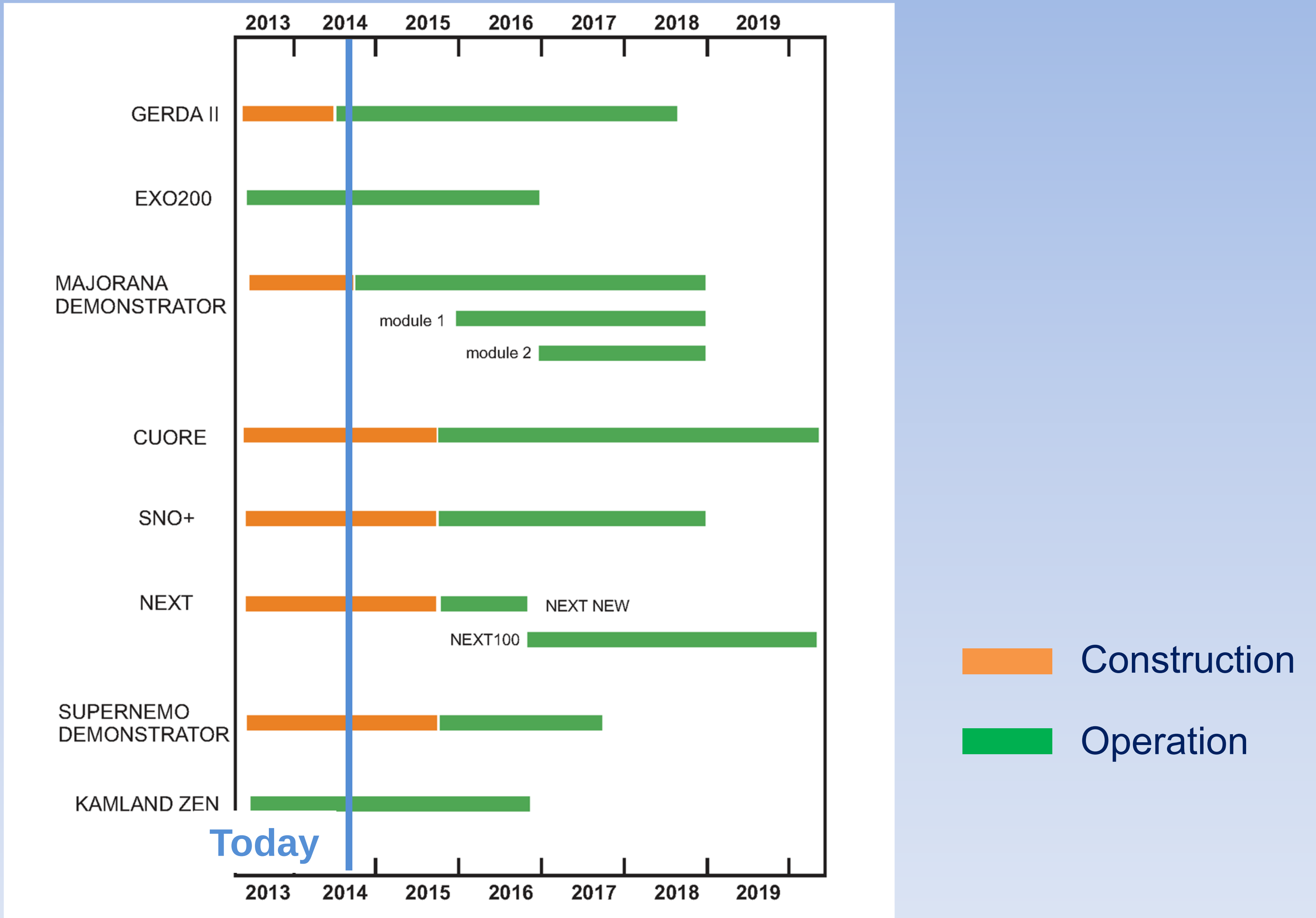
- Reconstruction of full kinematics can suppress bkgd. & measure angular distr. if signal seen
- Allows focus on highest Q-value isotopes, above much of $\gamma$ background
- Can remove/replace enriched isotope to verify any non-null observation

| | Half-life sensitivity, (y) | $<m_\nu>$ sensitivity meV |
|---|---|---|
| **Full SuperNEMO (100kg)** | | |
| $^{82}$Se 90 % (CL) | > $1.10^{26}$ y | < 40 - 110 |
| $^{82}$Se 5$\sigma$ | $2.\ 10^{25}$ Y | 100 - 250 |
| **Demonstrator (7 kg)** | | |
| $^{82}$Se 90 % (CL) | > $6\ 10^{24}$ y | < 160 - 440 |

**Challenges:**

- *Background levels not yet verified. Large surface-to-volume ratio $\Rightarrow$ vulnerability to radon and other external bkgds.*
- *High detector cost per unit isotope mass*
- *Requirement of thin foils to limit electron energy loss and scattering $\Rightarrow$ challenging to scale to tonne-level apparatus*

# Notional Timeline



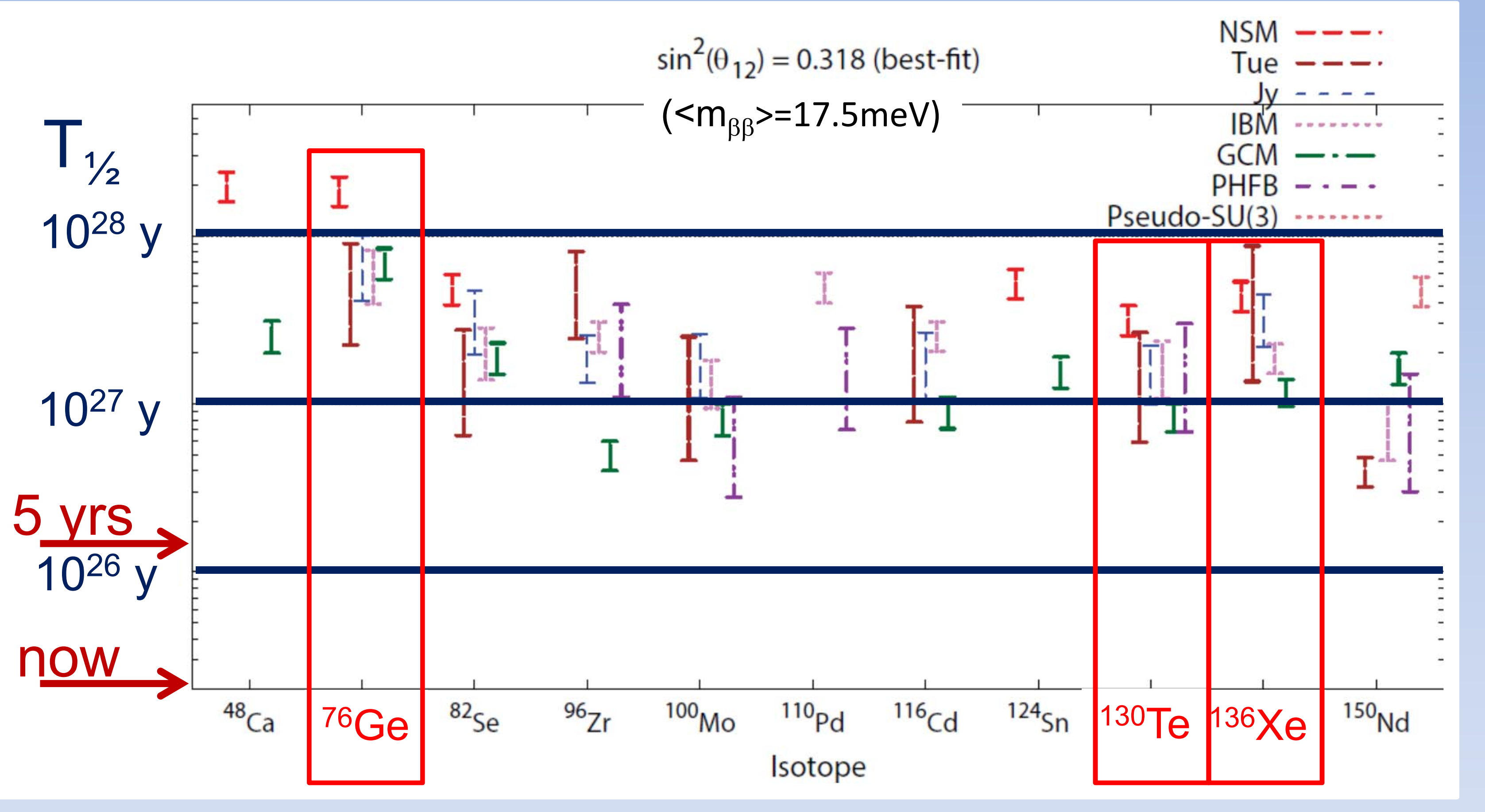
# Subcommittee Observation

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




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

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**

# 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 3$\sigma$ 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)

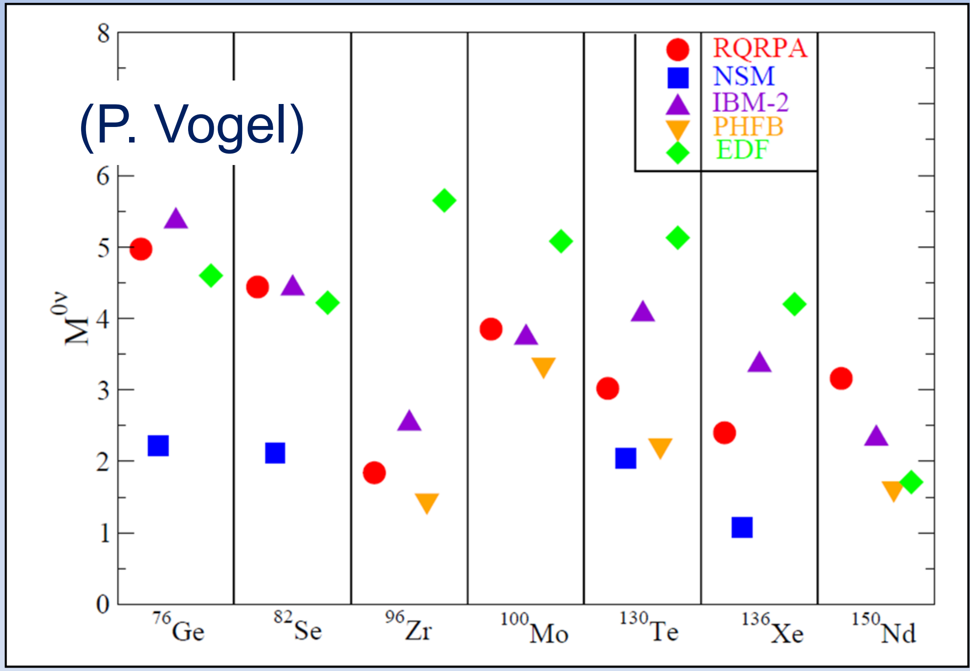
4) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

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.

# Personal Comments

- There is a strong scientific motivation to push NLDBD experiments to fully explore the inverted hierarchy region.
- This will be very challenging – requiring multi-ton experiments with low background.
- The impact of cosmological limits, and potential mass hierarchy determinations, is problematic – need to work on the message.
- The isotope availability issue likely also needs to be addressed.