The Experimental Search for Neutrinoless Double Beta Decay

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Town Meeting on Fundamental Symmetries, Neutrinos, Neutrons and Astrophysics
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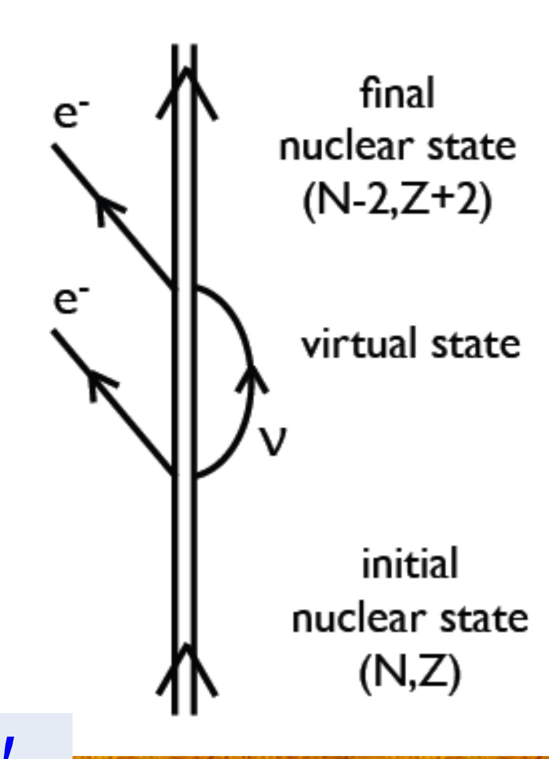
I. Why me?
II. Scientific Motivation, very briefly
III. Experimental Features and Goals
IV. Advantages/Challenges for Current Generation Searches
V. The Leap to the Next Generation
VI. NSAC Subcommittee Recommendations
VII. Conclusion & Suggested LRP Target



Thanks to all the NLDBD proponents for extensive input!

Why Me for This Talk?

Organizers wanted "non-aligned, but not diffident," rapporteur.
(WWII billboards: "Switzerland: neutral but not cowardly")

From Wendell Castle's 10 Adopted Rules of Thumb:

1) If you are in love with an idea you are no judge of its beauty or value.
   -- I'm not in love, but want to see NLDBD experiments succeed for the good of physics and NP, in particular.

2) It is difficult to see the whole picture when you are inside the frame.
   -- Seeing the picture from well outside the frame, barely in the same room.

3) After learning the tricks of the trade, don't think you know the trade.
   -- What I know of the tricks comes mostly from service on NSAC subcommittee on NLDBD. Don't think I know the trade, but I do have experience in what it takes to get large NP projects funded, and helped to develop strategic advice for both the funding agencies and the proponents.

NB: *not all opinions expressed represent NSAC Subcommittee!*

Must-Do Science

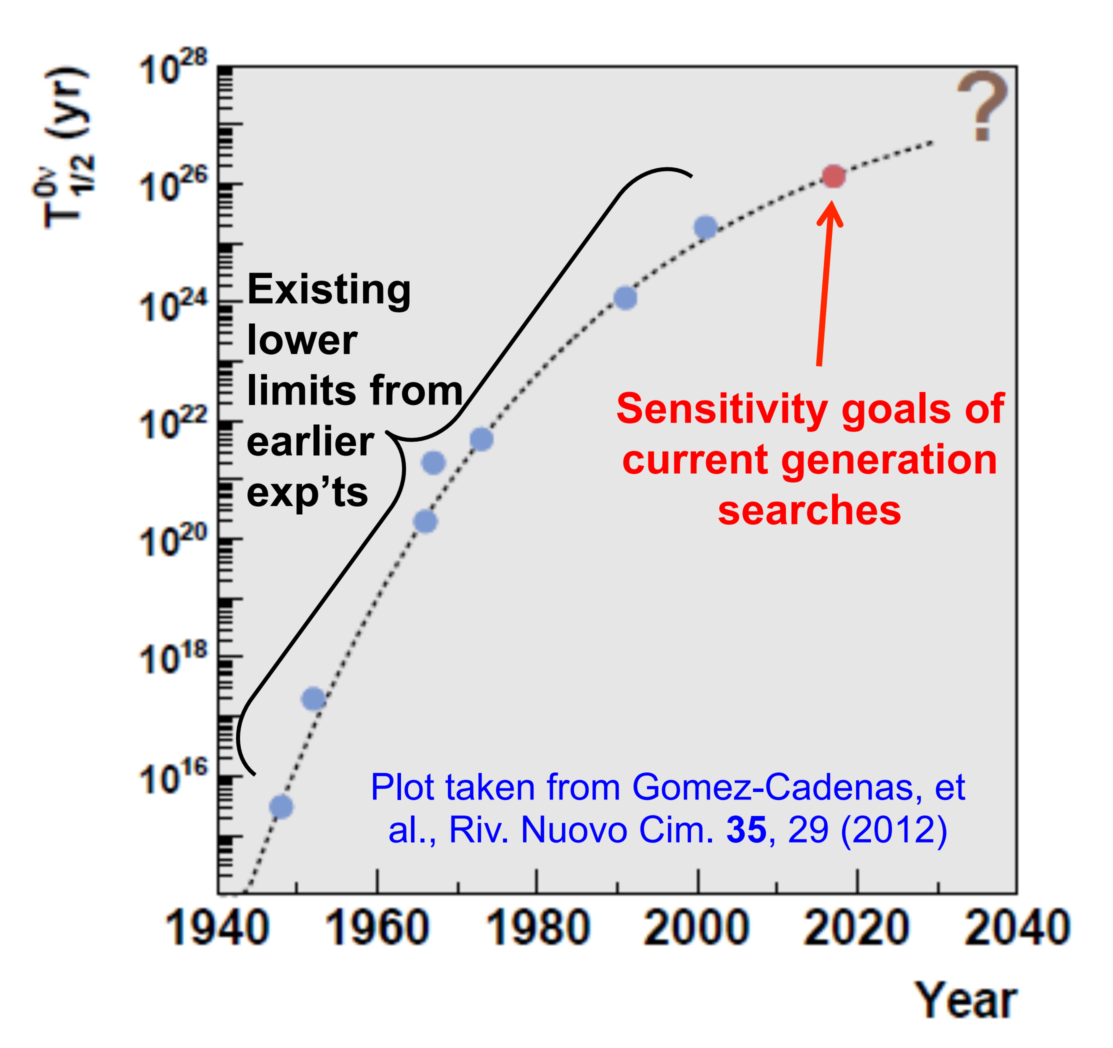
A definitive observation of 0νββ decay would achieve:

1) *Clear discovery of lepton number non-conservation ⇒ beyond Standard Model physics*
2) *Clear demonstration of Majorana mass term contributions for neutrinos*
3) *Added plausibility for the seesaw mechanism to account for the ultra-light neutrino masses*
4) *Added plausibility for leptogenesis mechanisms to account for the universe's matter-antimatter asymmetry*
5) *Possible sensitivity to physics near the GUT scale*

⇒ NSAC Subcommittee assessment of the science:

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.

Where Are We Now?

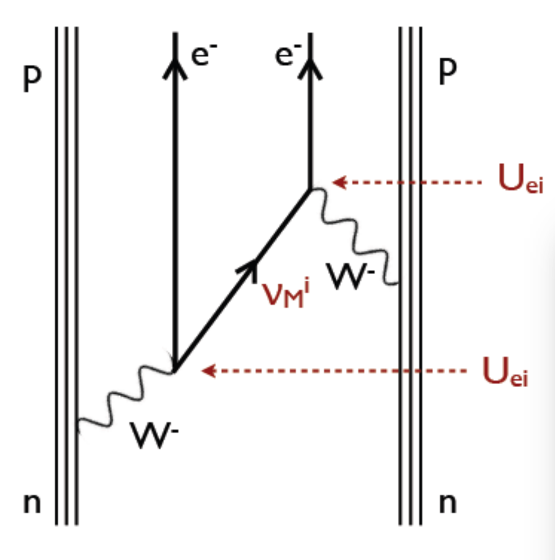


~70-year history of searches, exploiting extraordinary opportunity offered by the nuclear pairing force to search for such rare processes, bypassing normal β-decay

Earlier report (Klapdor-Kleingrothaus, et al.) of a positive signal in ^{76}Ge is now effectively ruled out by more recent results

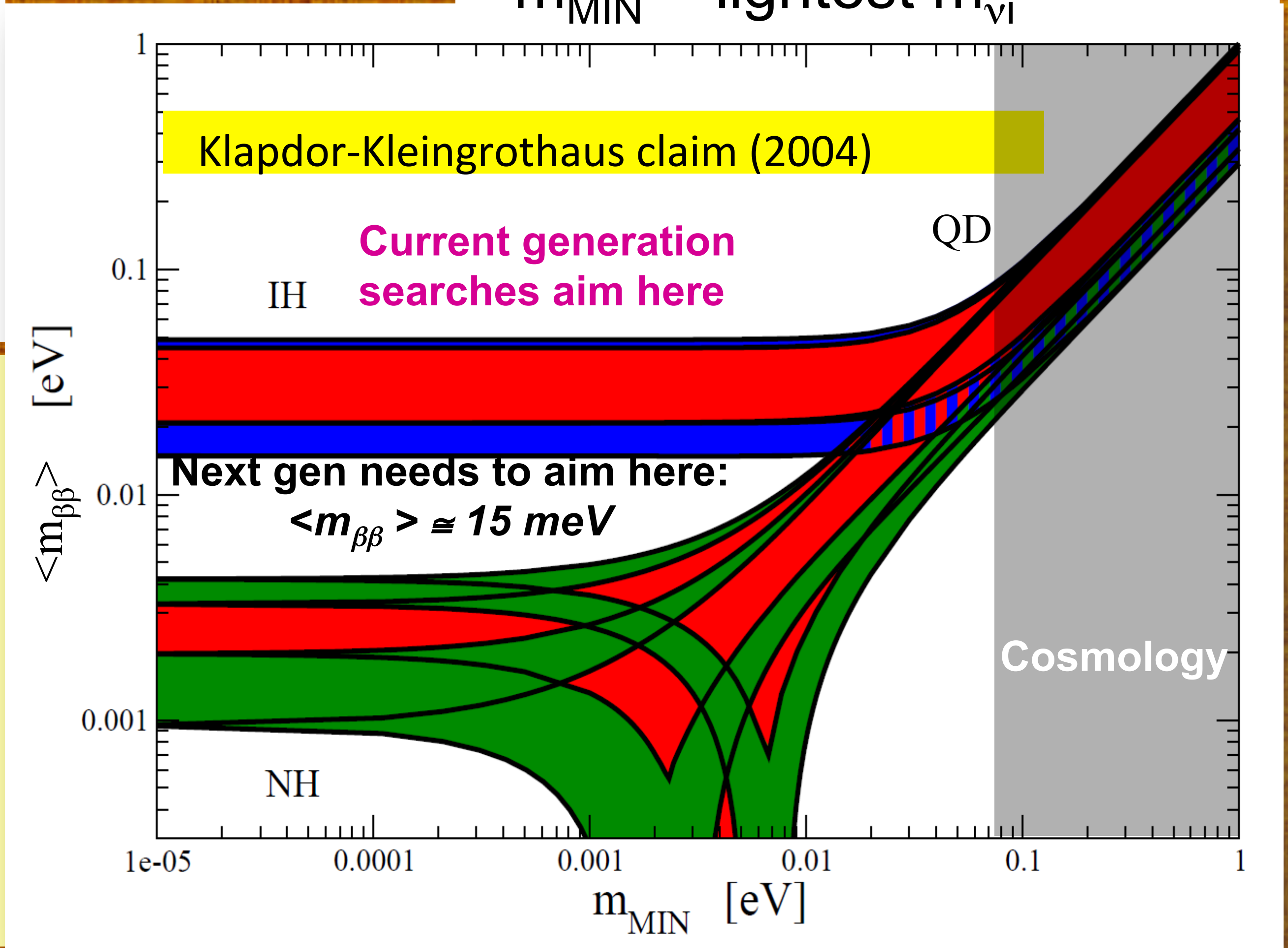
The likely cost of next-generation searches ~n\$100M ⇒ imperative to convince Office of Science and OMB of high discovery potential, not just measuring zero better! Also will require down-selection!

Where Do We Need to Get?



Light Majorana ν exchange mechanism ⇒ sensitivity to:

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



- ***Uncertain mass hierarchy, CPV Majorana phases & ν mixing θ ⇒ complex picture***
- ***Next generation should address crisply posed question:***

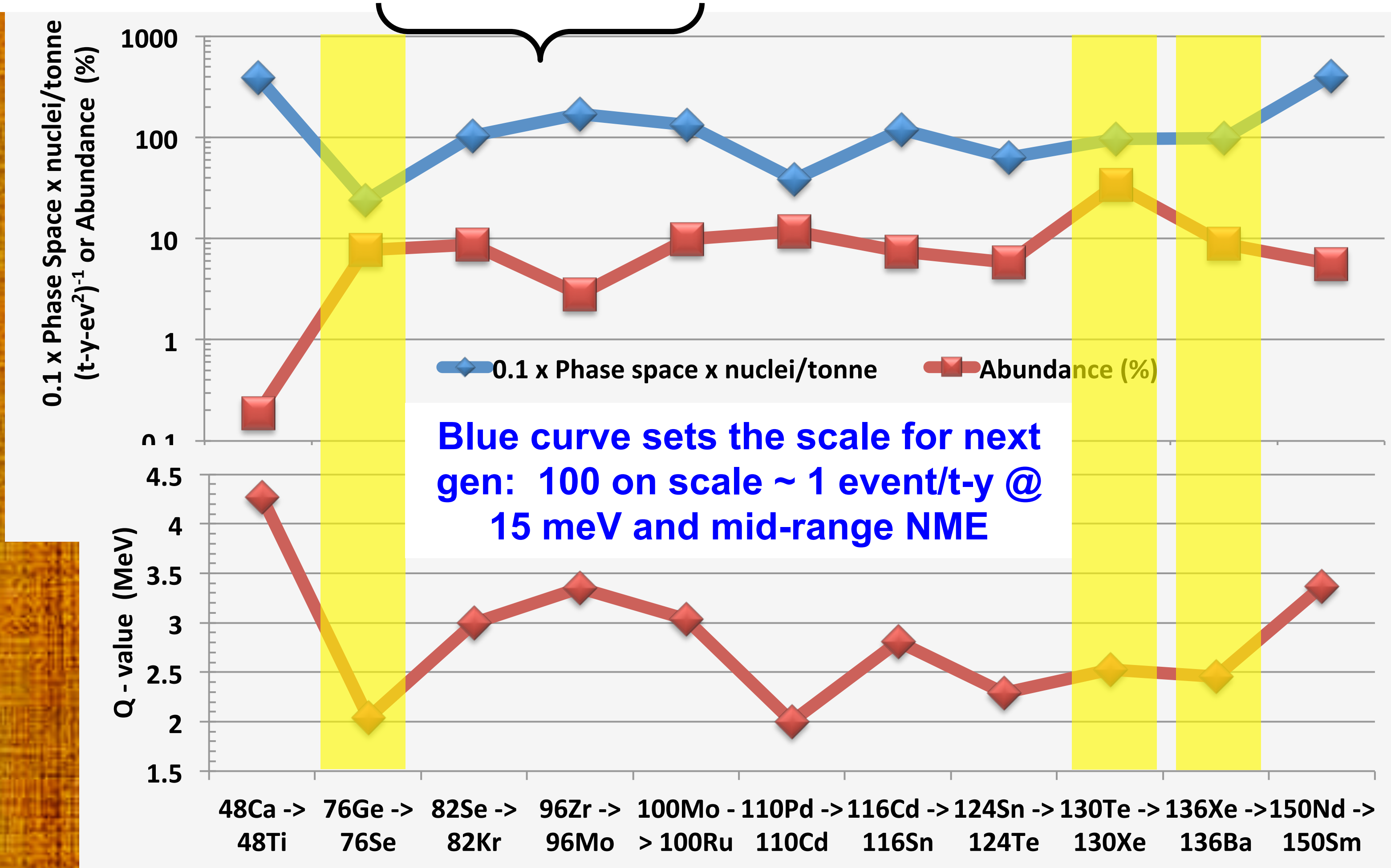
Is L# violated at level consistent with IH Majorana ν's?

Candidate Isotopes with Q > 2 MeV

Phase space factor → $G^{0\nu}$; **Nuclear matrix element (NME)** → $\mathcal{M}^{0\nu}$

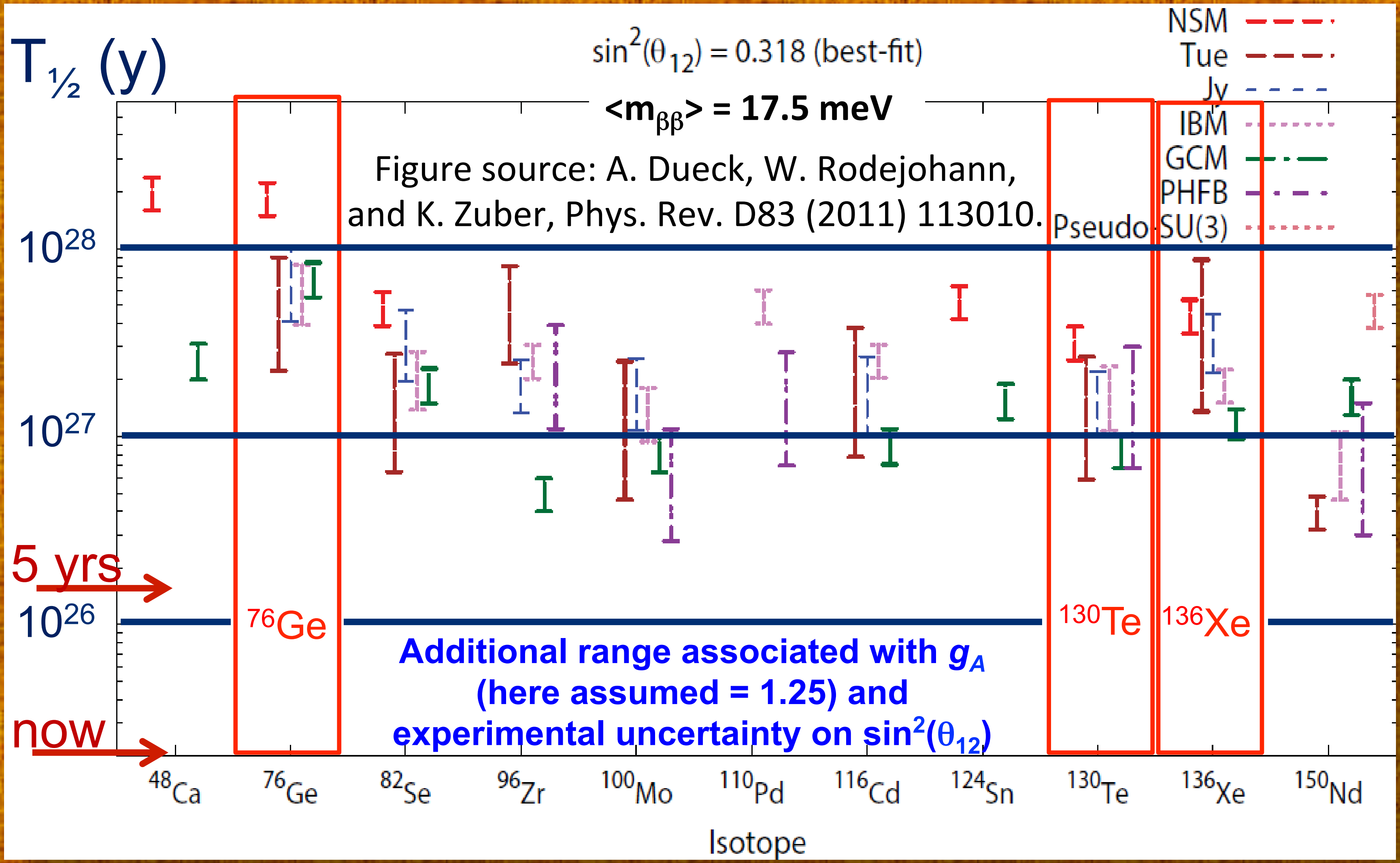
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\cdot\left|\mathcal{M}^{0\nu}\right|^2\cdot\left\langle m_{\beta\beta}\right\rangle^2$$

$$\Rightarrow \text{signal rate} = \ln(2)\cdot\frac{\#\,\text{nuclei}}{\text{tonne}}\cdot G^{0\nu}\cdot\left|\mathcal{M}^{0\nu}\right|^2\cdot\left\langle m_{\beta\beta}\right\rangle^2\cdot\varepsilon\cdot M_{fiducial}^{isotope}(\text{tonnes})$$



Blue curve sets the scale for next gen: 100 on scale ~ 1 event/t-y @ 15 meV and mid-range NME

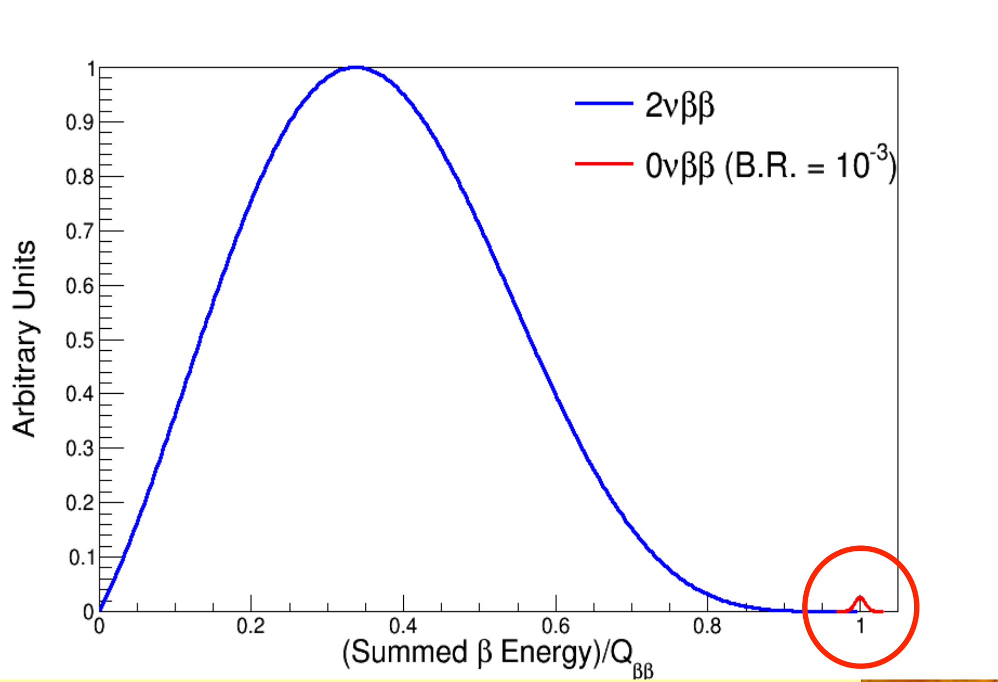
Needed Half-Life Sensitivity



- *Factor ~2-3 range in NME (see next talk) ⇒ factor ~4-9 in $T_{1/2}$ sensitivity*
- *Must design next gen. for at least ~ few x 10^{27} years, probably with staging*
- *To maximize discovery potential, want eventual reach for lowest viable NME*

"Ideal" Next-Gen Search / "As Good As It Gets"

- **Low, flat background*** in ROI *vs.* signal size at half-life sensitivity goal;
- **Good $E_{\beta\beta}$ resolution** & calibration, to enhance signal / backgrounds and minimize 2νββ tail;
- **Scalability** to larger masses at realizable cost, as needed to cover full IH region;
- **Tracking capability** to ID 0νββ decay event topology;
- **Favorable 0νββ Q-value** to enhance phase space and ⇒ ROI above many radio-impurity γ lines;
- **Ability to remove or replace enriched isotope** w/o affecting detector performance, to verify possible non-null signal.



** If background non-negligible and scales with isotope mass, would need ~10^3 x current mass to achieve needed factor >~30 improvement in $T_{1/2}$ sensitivity!*

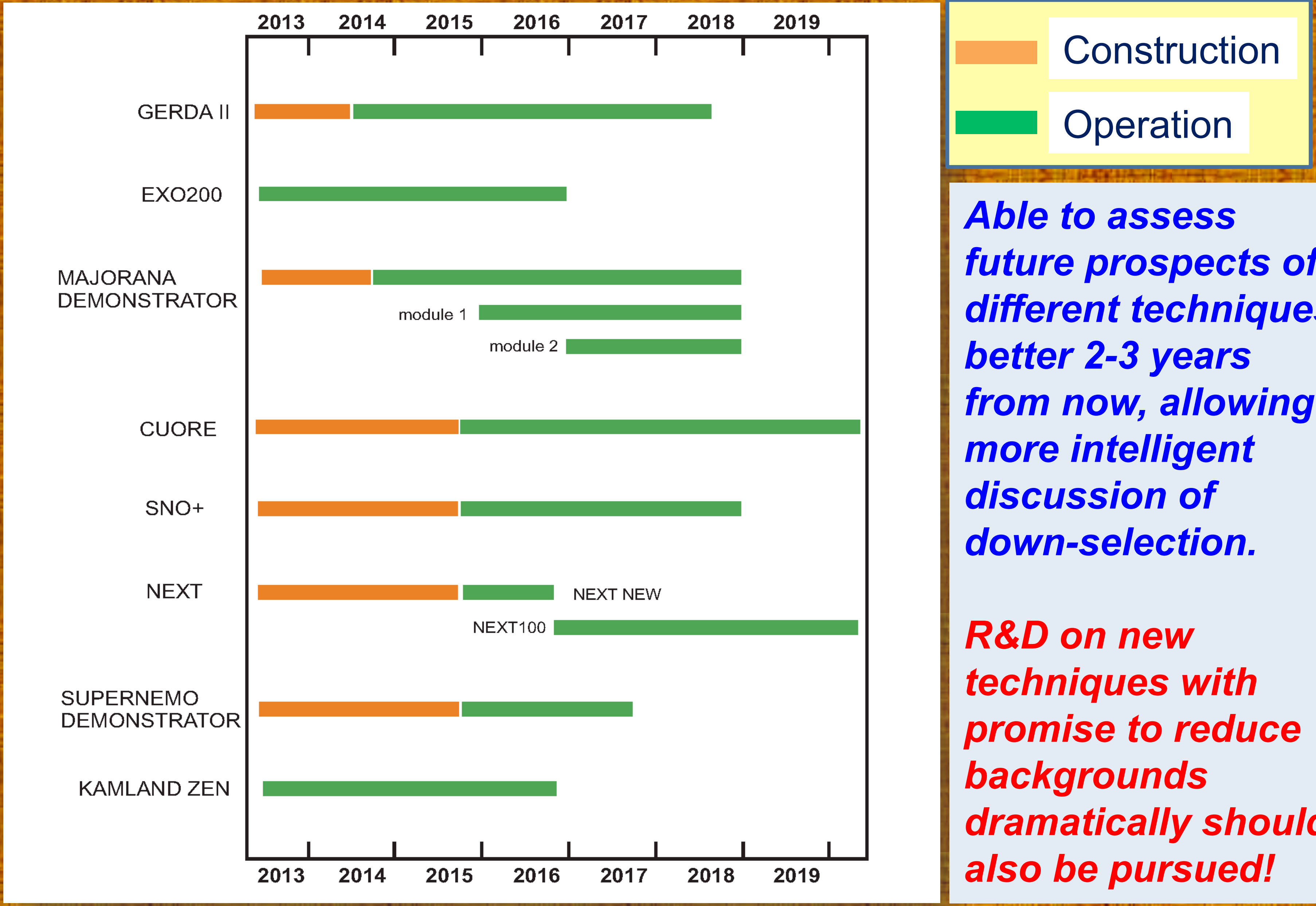
What Experimental Searches Do Exist?

Current Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved Lower Limit (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	61	
SuperNEMO	^{82}Se+	7	>0.001
KamLAND-Zen	^{136}Xe	434	>0.19
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

Primary goals of current projects:

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

Notional Timeline of Current Projects



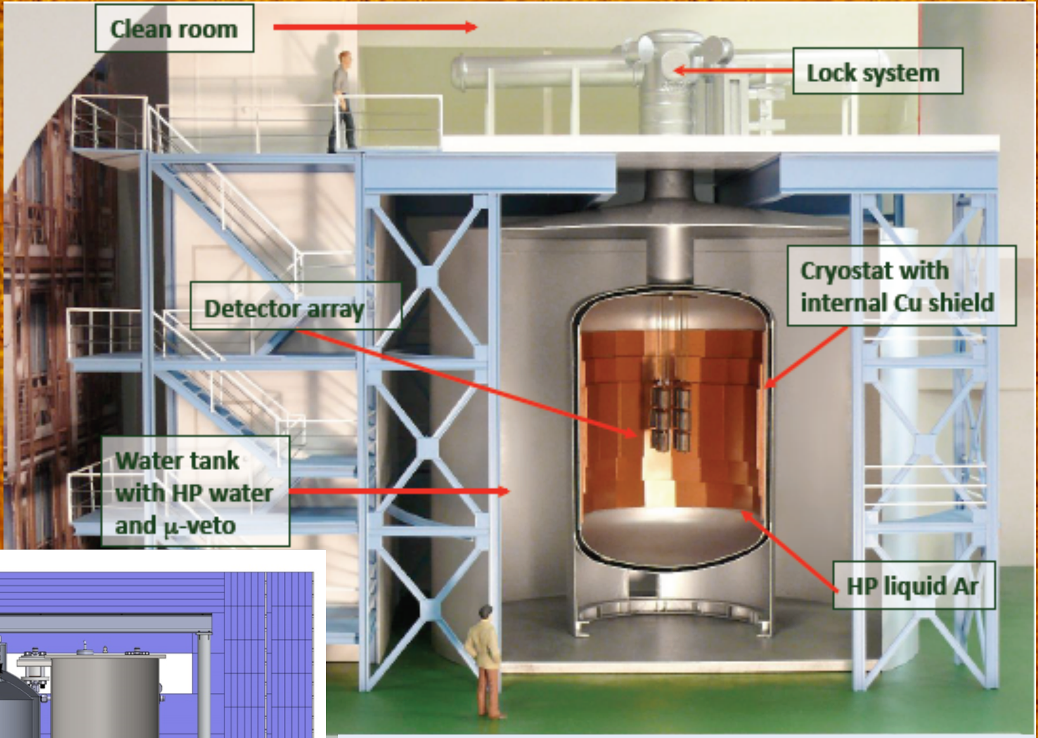
Able to assess future prospects of different techniques better 2-3 years from now, allowing more intelligent discussion of down-selection.

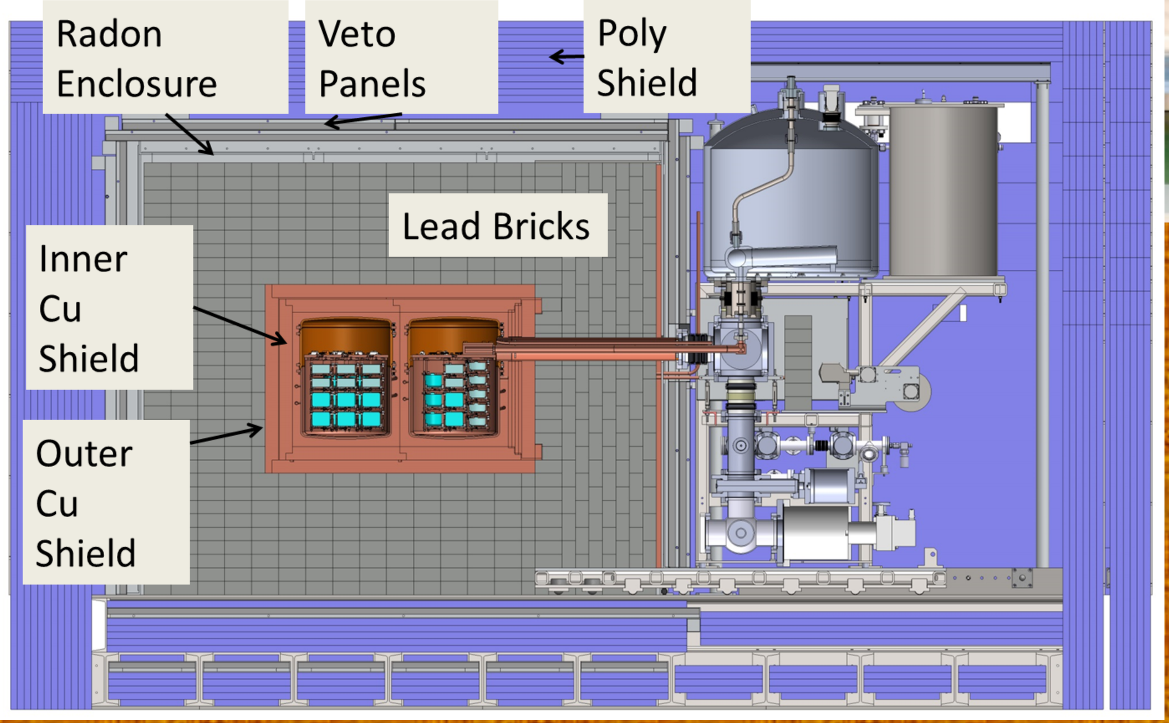
R&D on new techniques with promise to reduce backgrounds dramatically should also be pursued!

^{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*

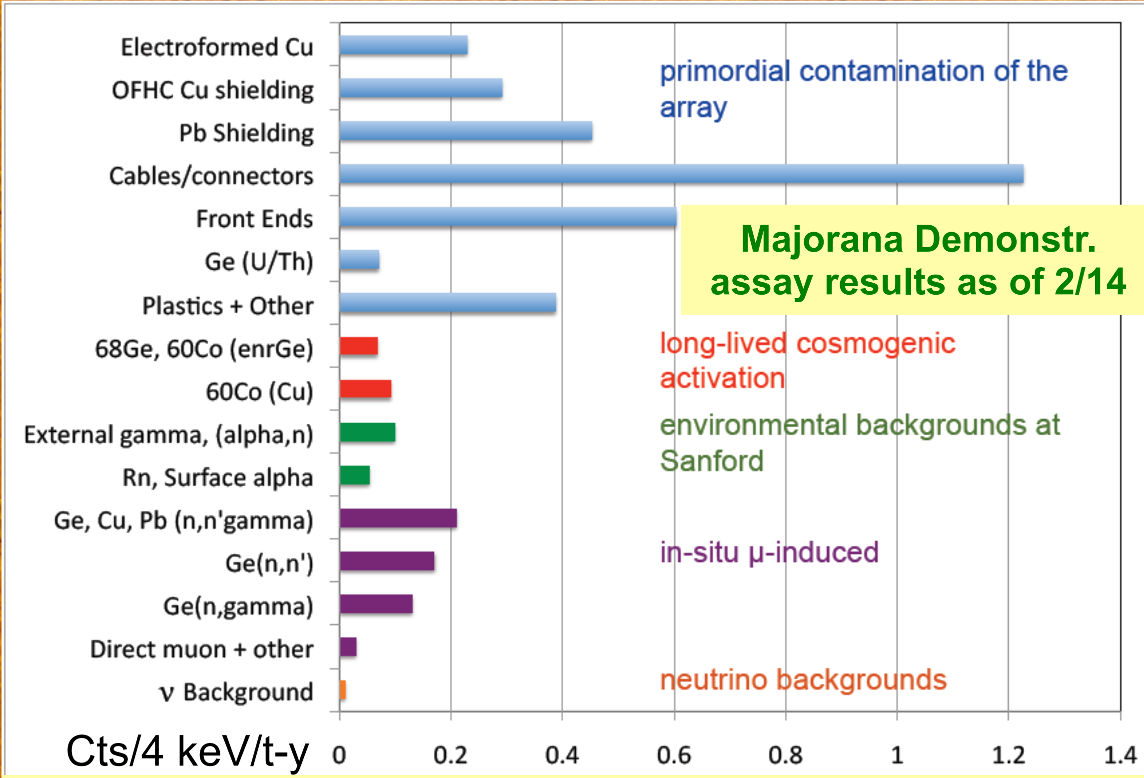


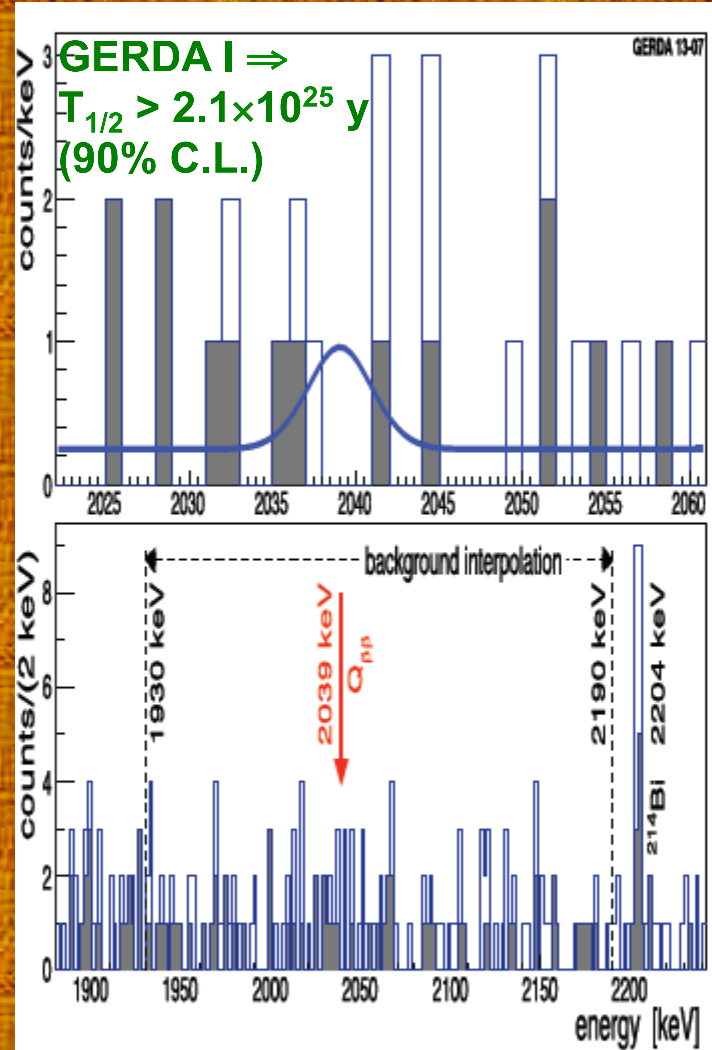


Majorana Demonstrator:

- *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





Advantages:

- **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 $T_{1/2}$**

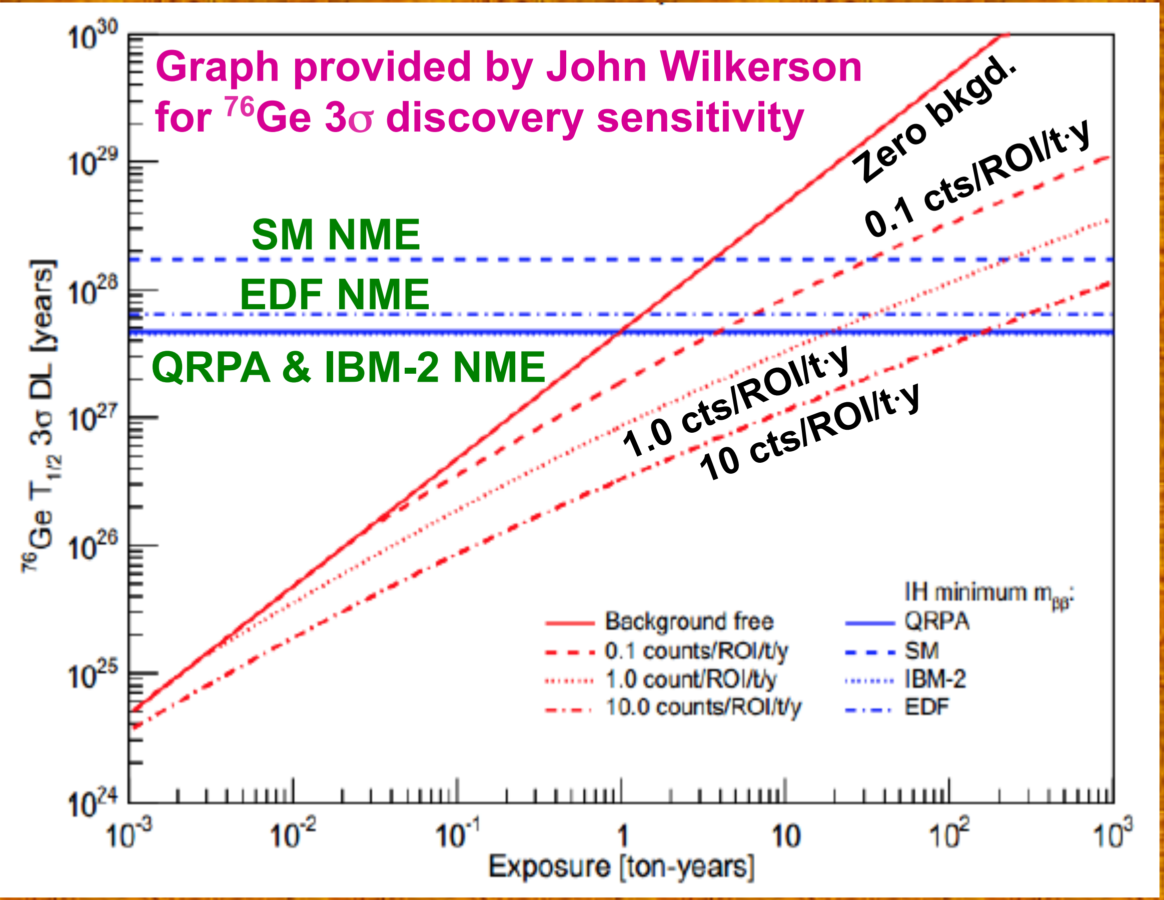
- **Some further reductions needed in backgrounds from surrounding materials to achieve needed next-generation sensitivity**

^{76}Ge Searches: Next Generation

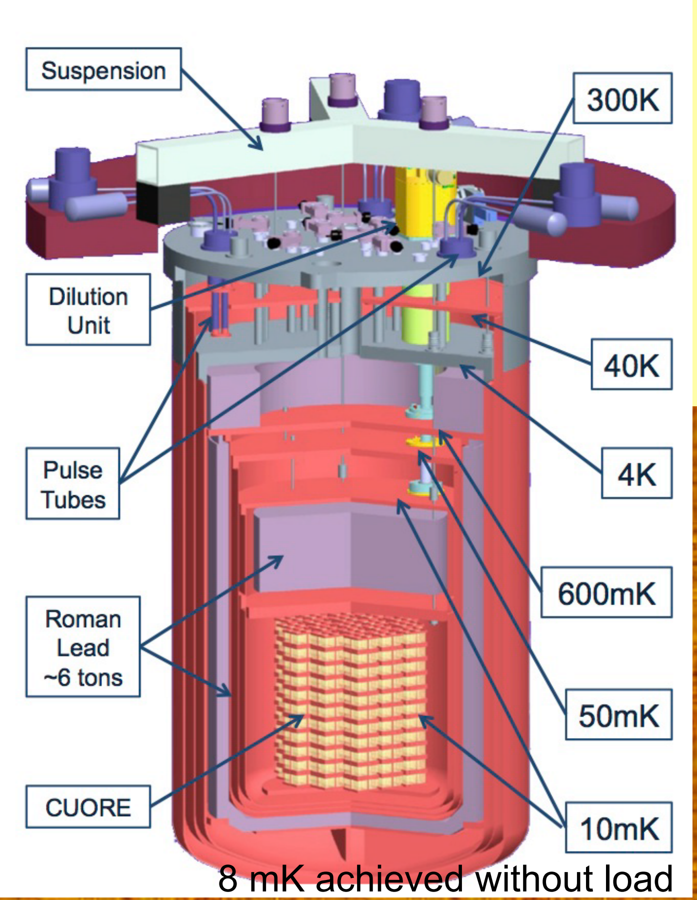
- *Majorana & GERDA work toward unified international collaboration*
- *Down-select best technologies based on demonstrated results from the two exp'ts*
- *Propose staged approach: 250 → 500 → 1000 kg*
- *Aim for <1 background count/ROI/tonne-year (self-shielding helps)*

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*

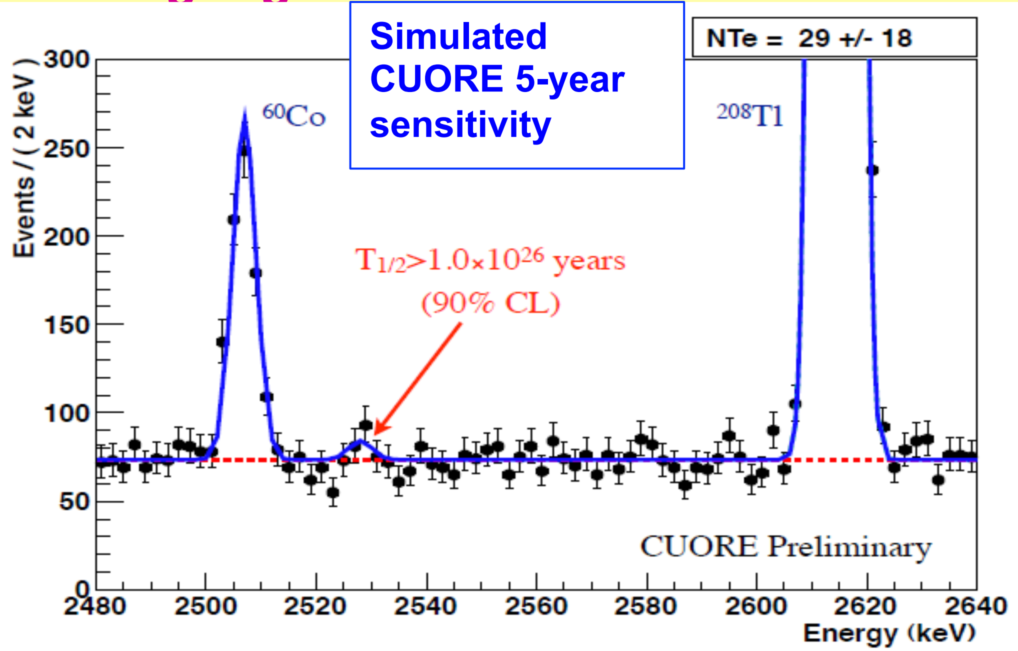


Bolometer Searches: Current



CUORE: *nat. 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 α bkgd. goals for CUORE*



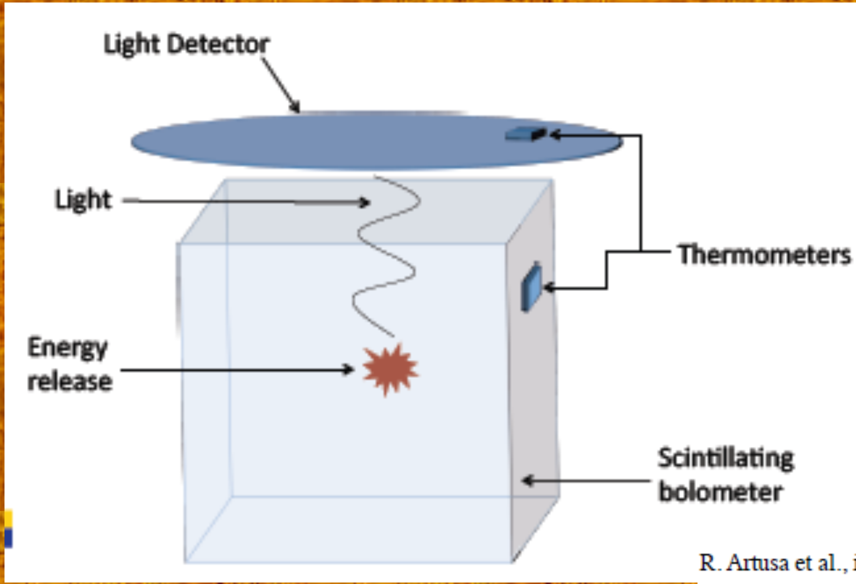
Advantages: *cost-effective nat. Te*

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

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

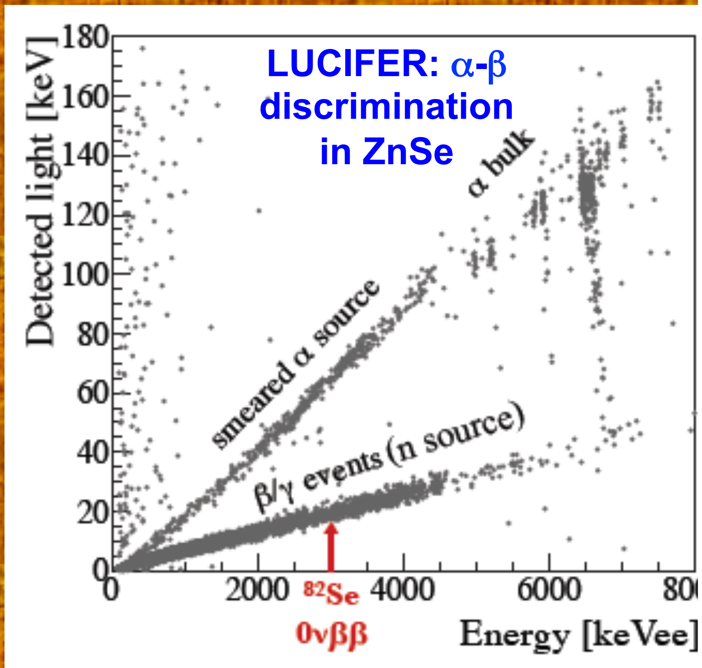
- *~flat, but sizable bkgd. (~50 cts/ROI/tonne-year, scaled from CUORE-0)*
- *U- and Th-chain contaminants on crystal and copper surfaces*

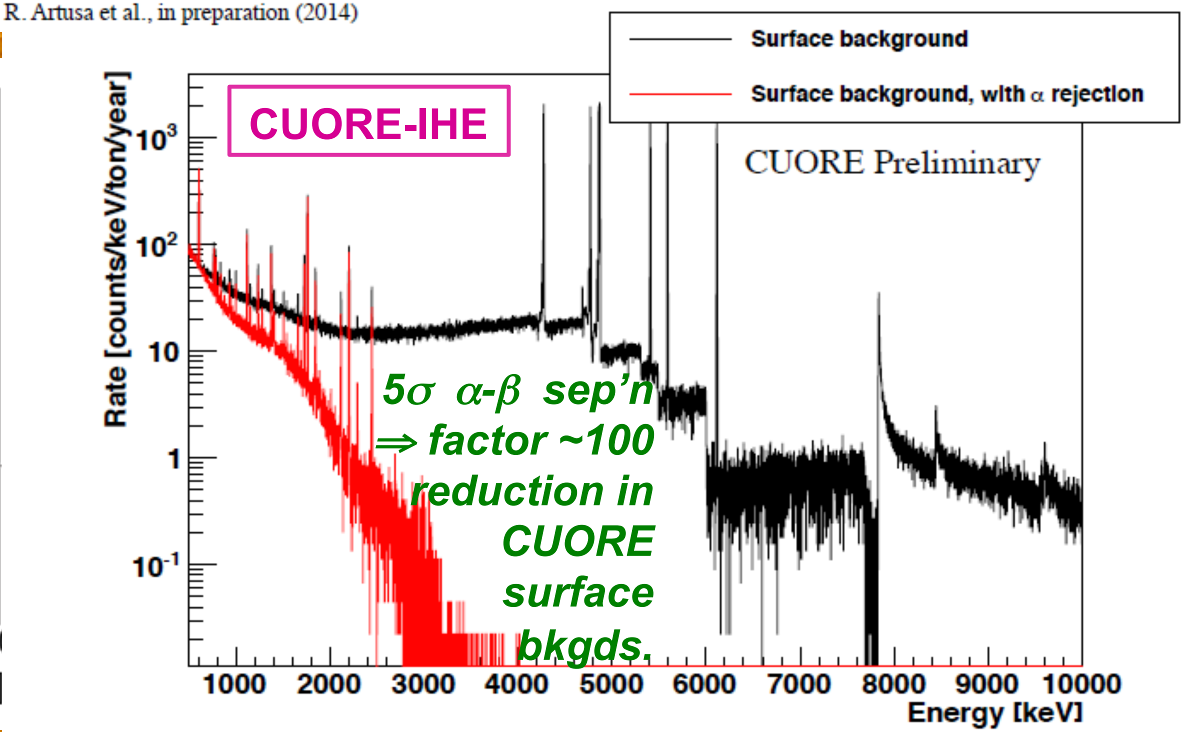
Bolometer Searches: Next Generation



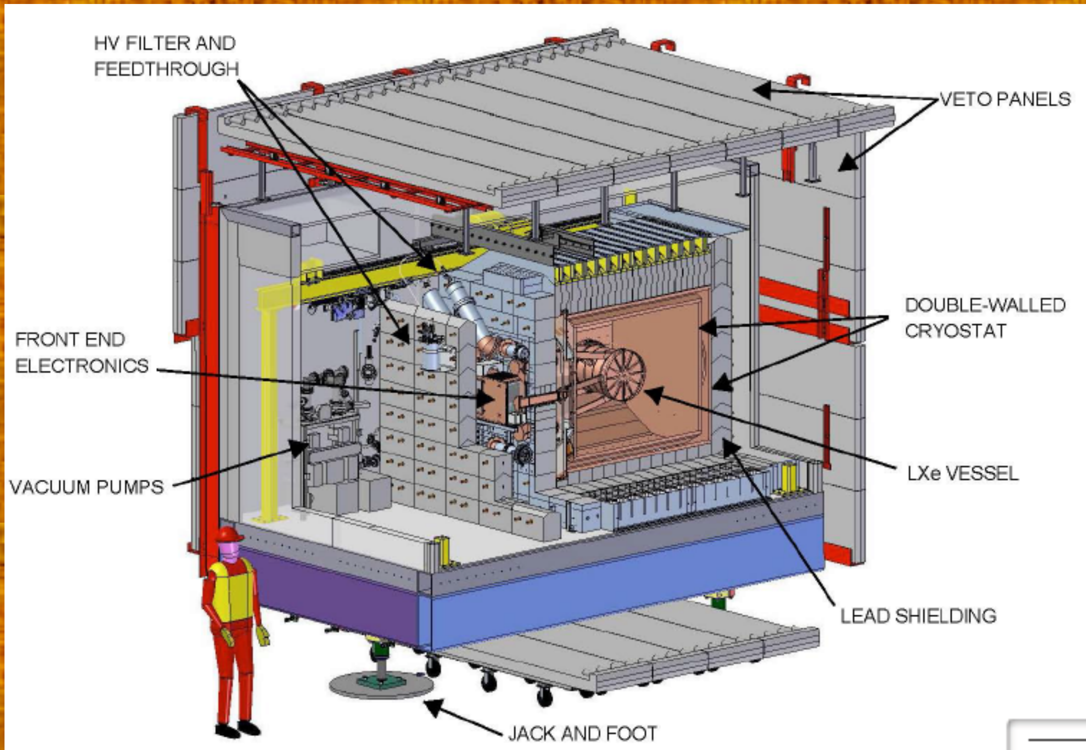
- **Similar configuration to CUORE, but with *combined light + heat* readout of bolometers, to provide *α vs. β discrim.***
- **Scintillating bolometers under development by LUCIFER and others: $Zn^{82}Se$ (8.9kg isotope); $Zn^{100}MoO_4$; $^{116}CdWO_4$**
- ***TeO_2: Čerenkov light only ⇒ poorer discrimination;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

R. Artusa et al., in preparation (2014)





^{136}Xe TPC Searches: Current

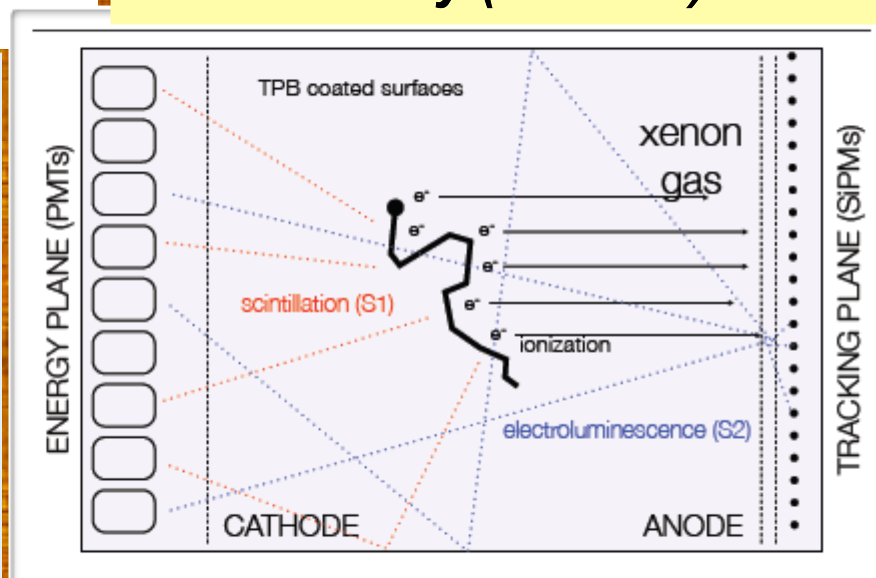


EXO-200: *LXe TPC @ WIPP*

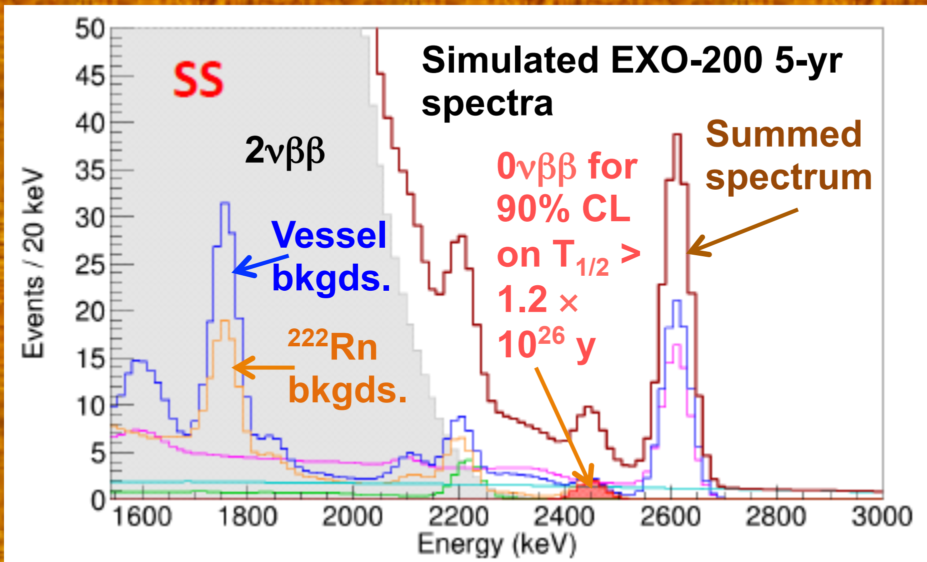
- *Simultaneous readout of ionization and scintillation*
- *200 kg enriched Xe on hand; 79 kg fiducial ^{136}Xe*
- *Moderate E resolution: 88 keV FWHM now → 58 keV after electronics upgrade*
- *Taking data since May 2011 ⇒ 2014 result: $T_{1/2}$ > 1.1 × 10^{25} y (90% CL)*

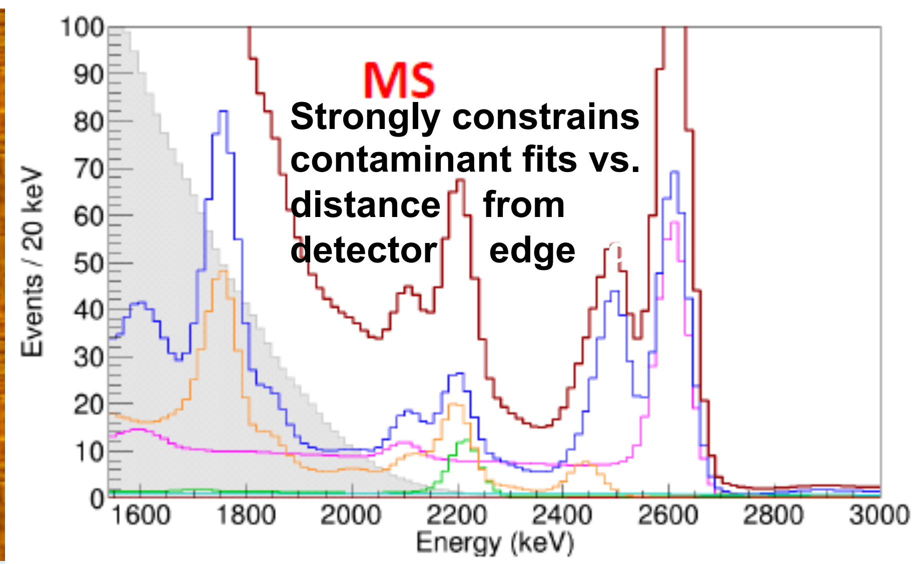
NEXT-100: *HPXe (15 bar) gas TPC @ Canfranc (Spain)*

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



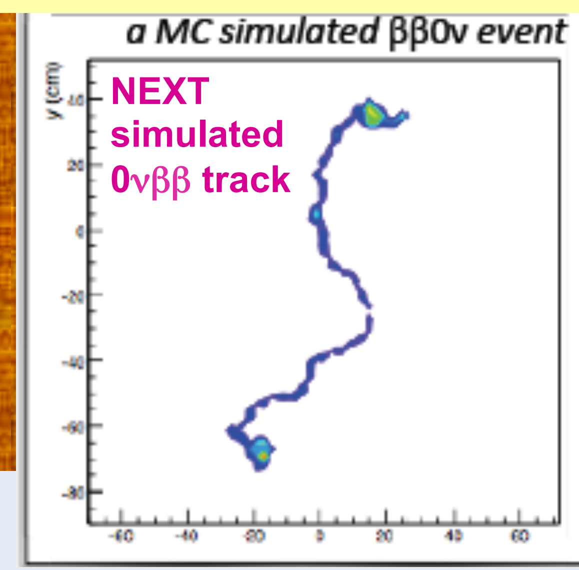
^{136}Xe TPC Searches: Current





Advantages:

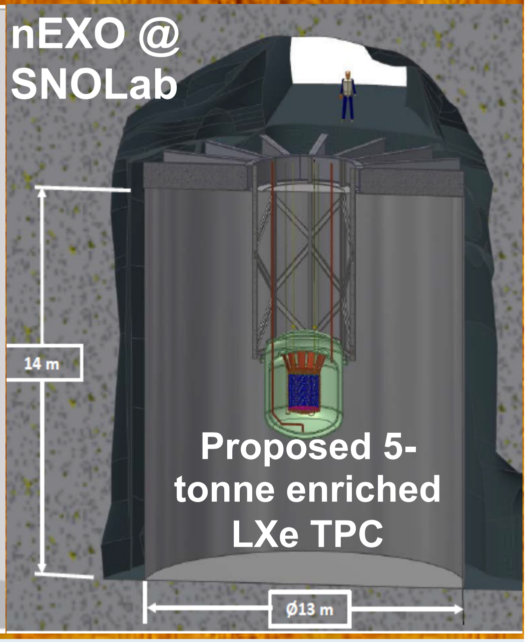
- *Relatively low isotope cost and easy re-purification options*
- *Can replace enriched with nat. Xe to verify a non-null signal*
- *3D pos'n info ⇒ discrim. single- (SS) from multi- (MS) site events*
- *NEXT adds topological ID of ~10 cm ββ track with 2 end blobs ⇒ suppress primary γ bkgrds. >~ 100× @ 55% ββ survival*

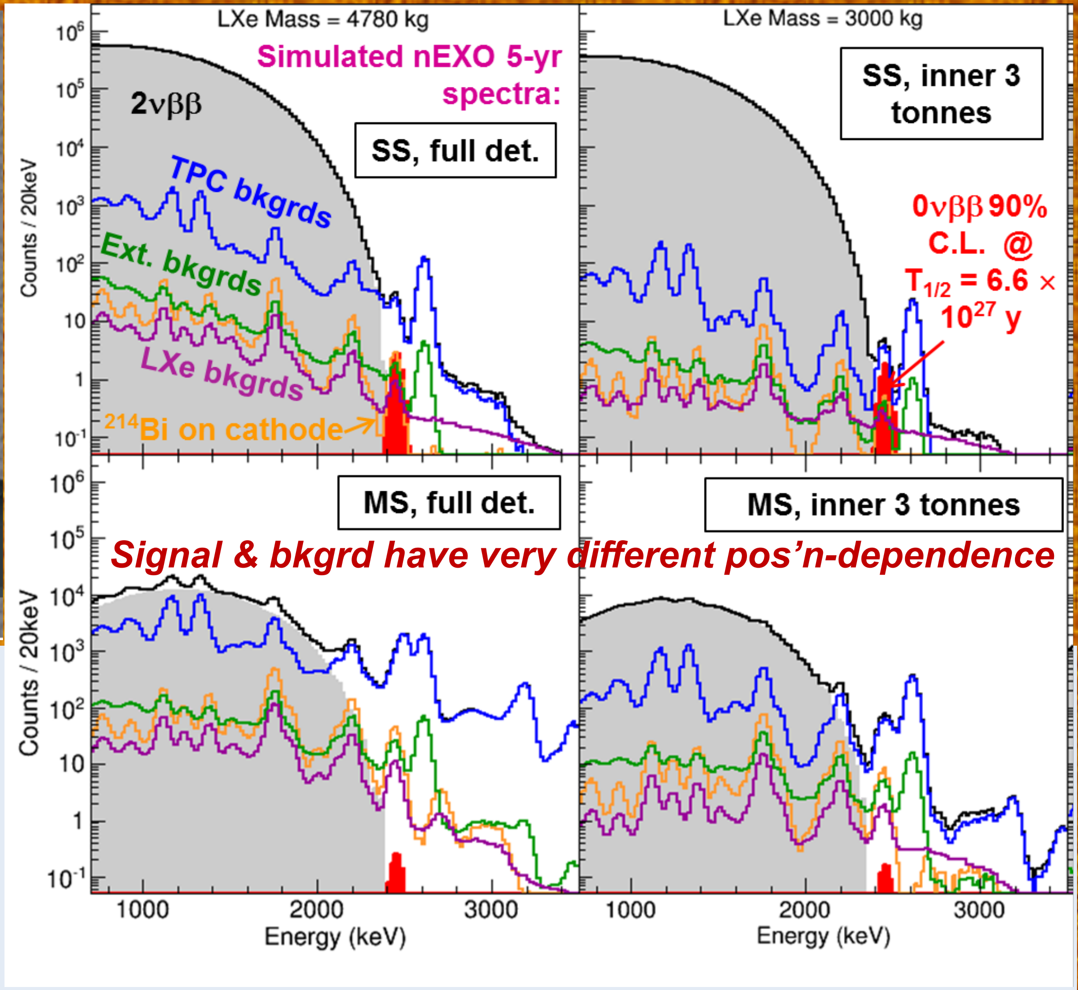


Challenges: *Radio-impurity peaks from ^{214}Bi and ^{208}Tl decay close to 0νββ ROI ⇒ structured bkgd.*

- *Rely on detailed detector + contaminant model to extract convincing signal*

^{136}Xe TPC Searches: Next Generation

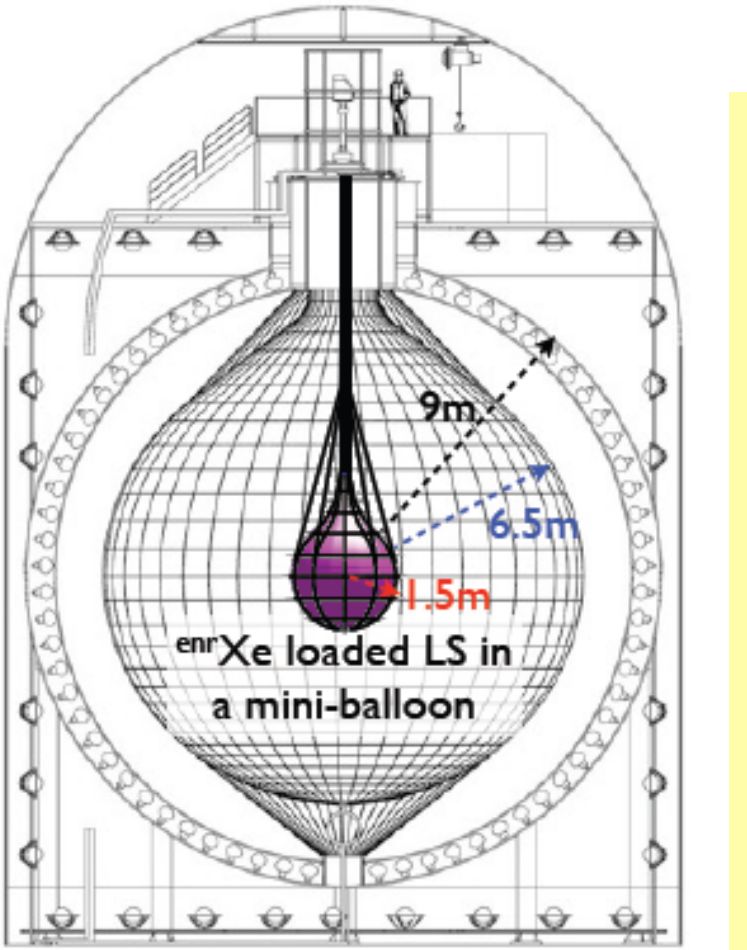




Comments:

- *Larger TPC ⇒ enhanced self-shielding & 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

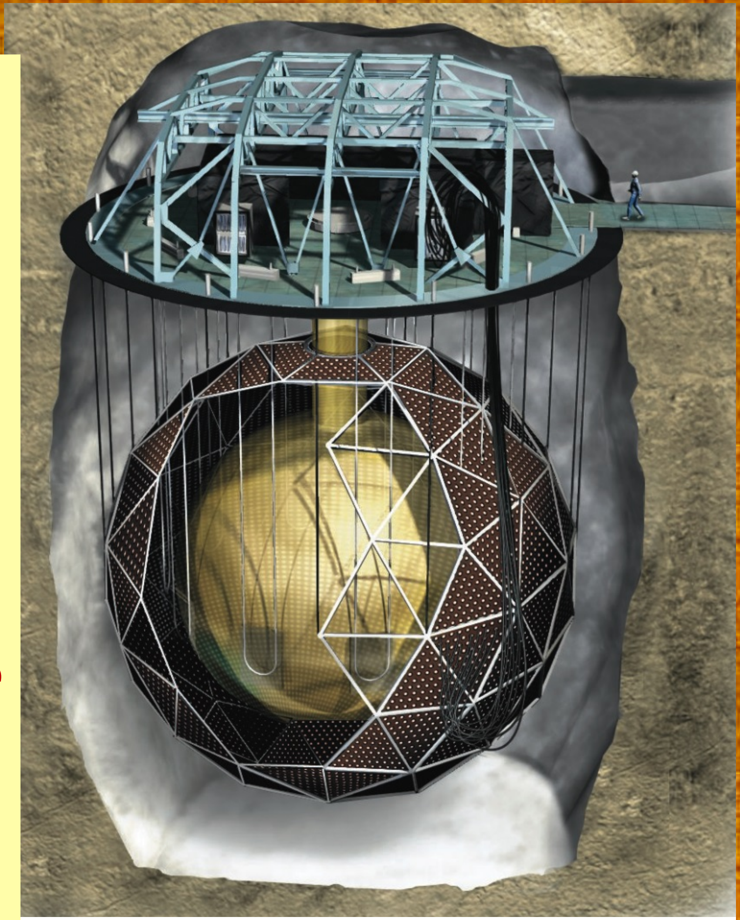


KamLAND-Zen started 9/2011

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

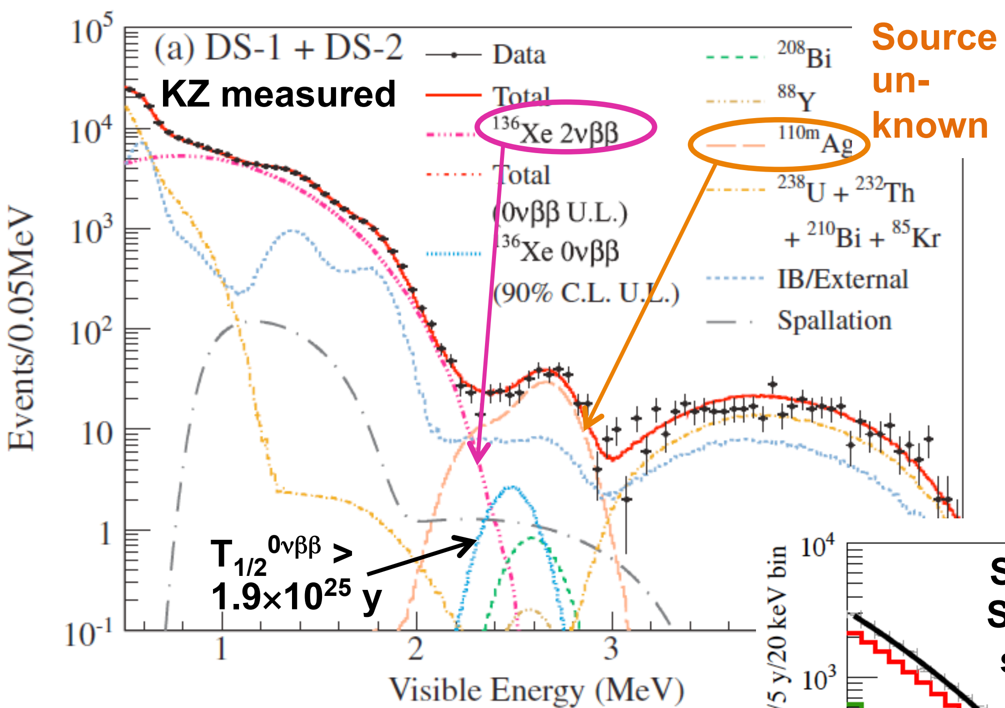
Add Xe in hand ⇒ 434 kg fiducial isotope mass for 2015 data-taking

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



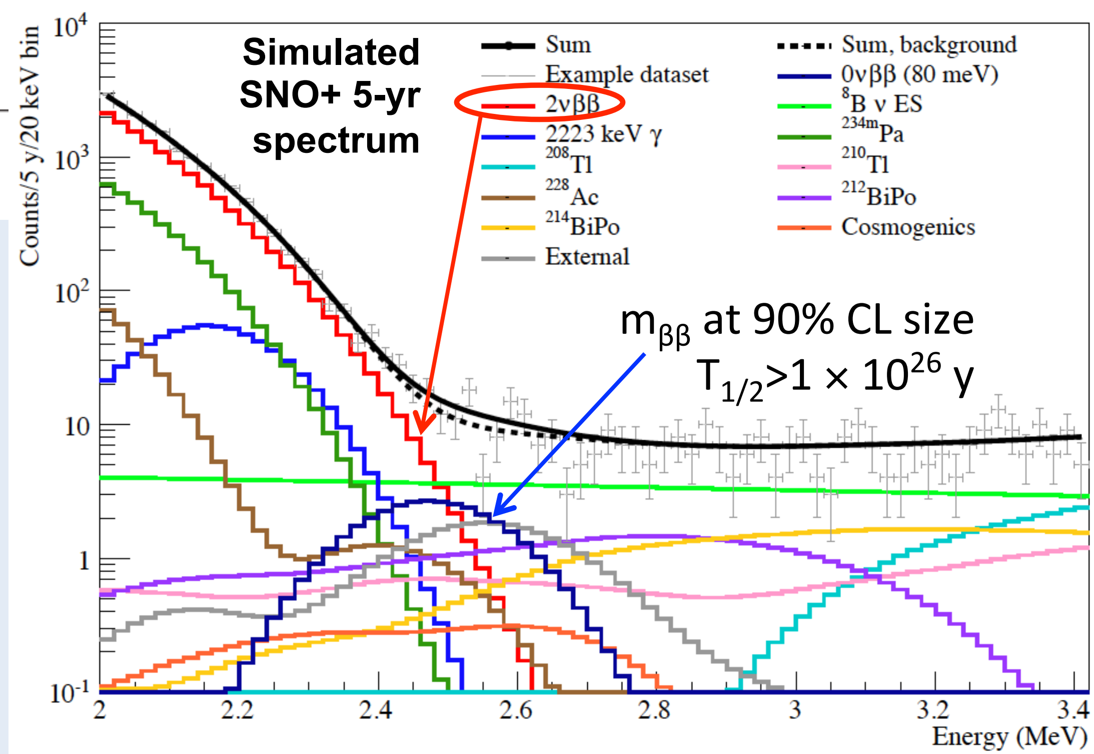
SNO+: 780 tonnes of LS loaded 0.3% with nat'l Te – start data-taking late 2015 ⇒ fiducial ^{130}Te mass ≅ 160 kg

Loaded Liquid Scintillator Searches: Current



Advantages:

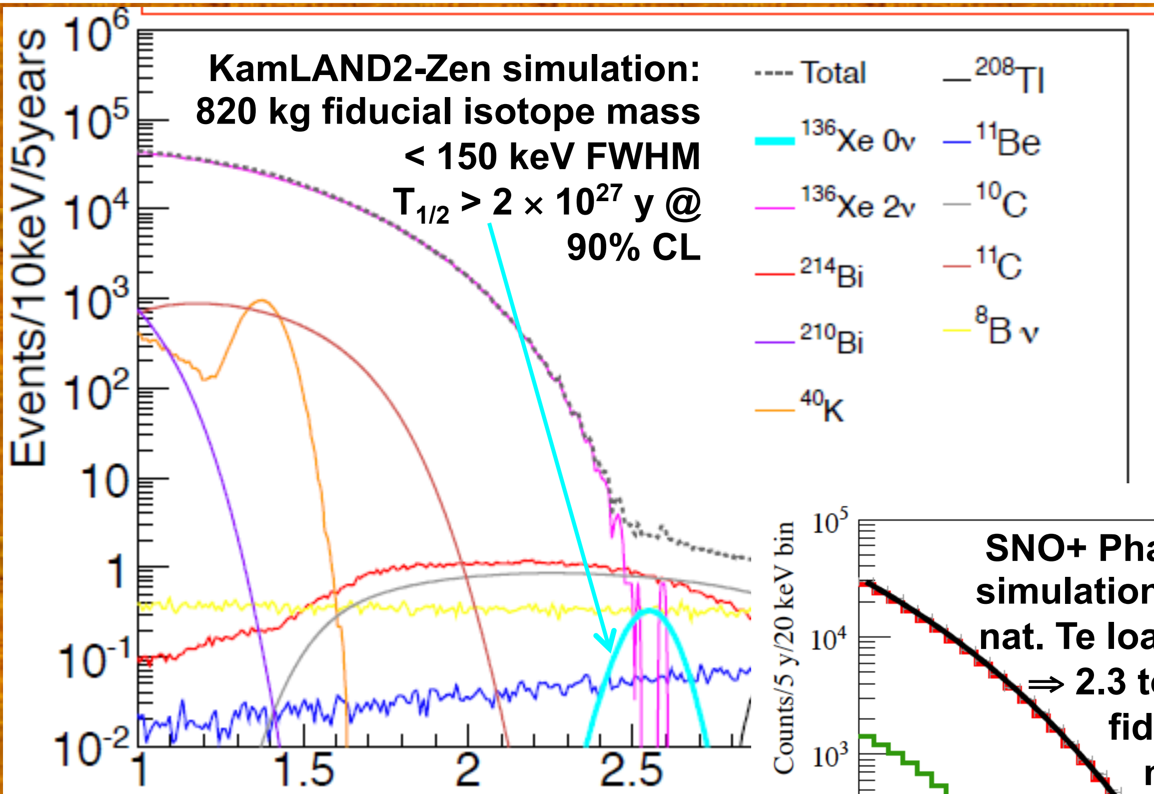
- ***Cost-effectiveness, scalability to quite large isotope masses***
- ***Ease of repurifying, removing or changing isotope loading***
- ***Shielding of external bkgds. by large LS volume ⇒ low (~5 × 10^{-4}) bkgd. counts/y/kg/keV***
- ***Adaptability to other isotopes***



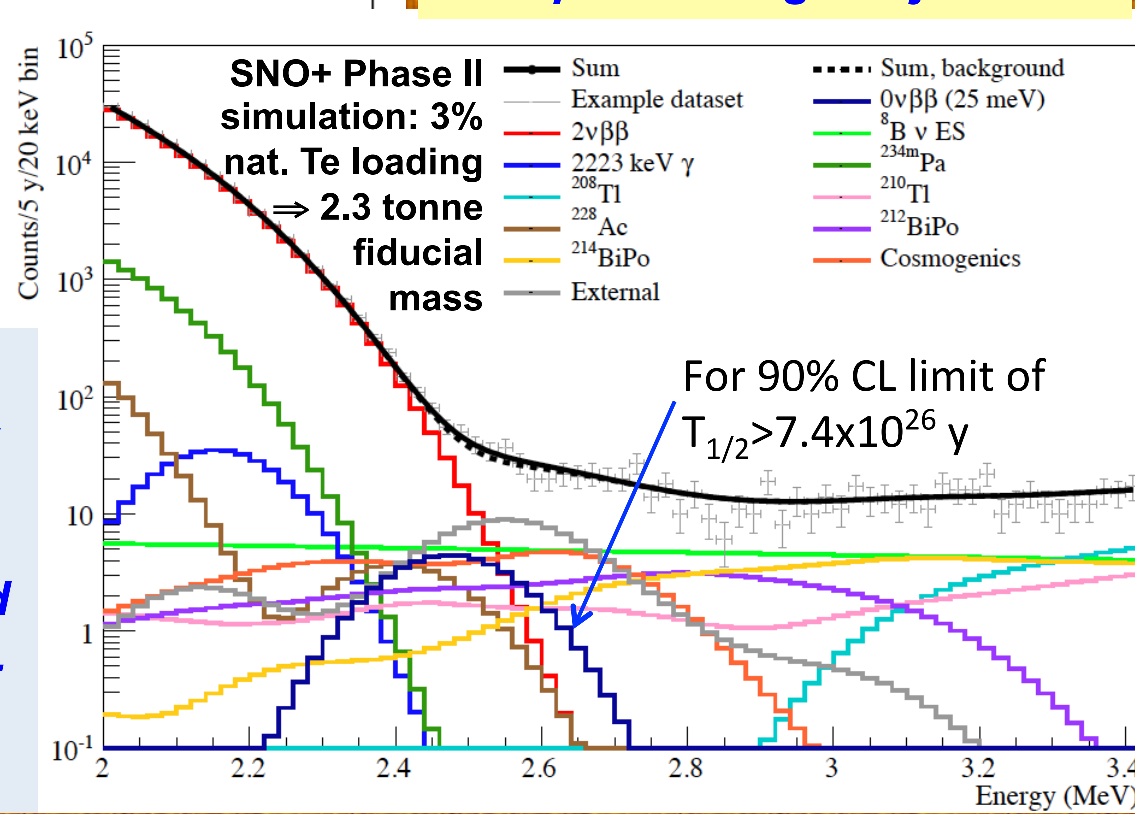
Challenges:

- ***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



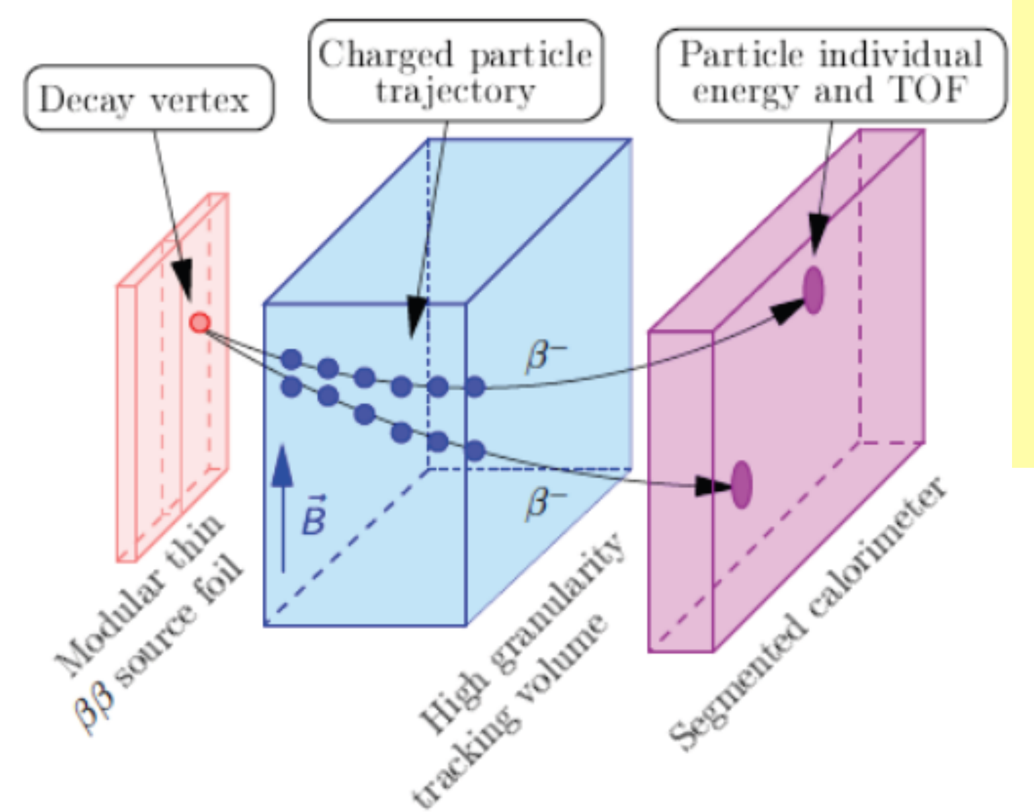
- *Replace PMTs, increase light yield for improved resolution (~150 keV KZ, ~200 keV SNO+)*
- *More mass (for SNO+ via enriched or higher % nat. Te loading -- needs R&D)*
- *Improved bkgd. rejection*



Comments:

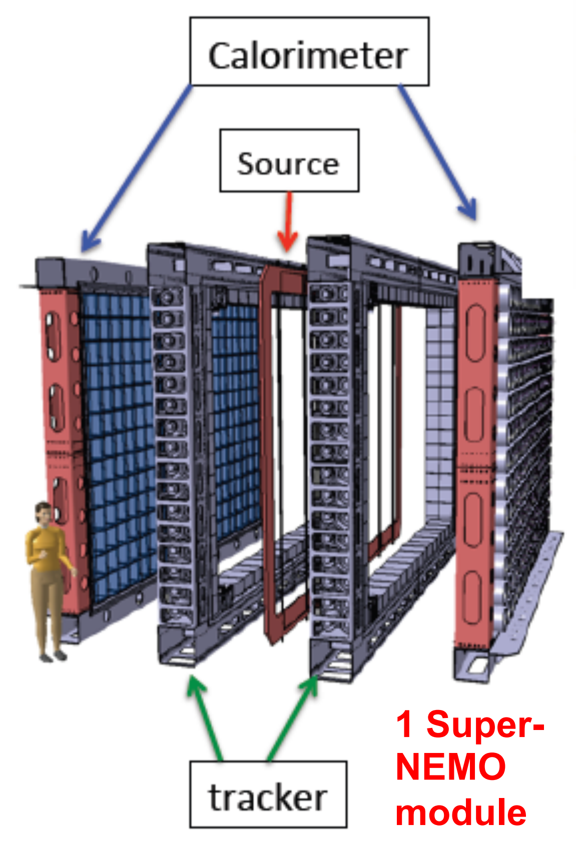
- *Large mass capability may ⇒ best near-term lower limits*
- *Bkgd. R&D options: loading Te (5% achieved), pressurized Xe, scint. mini-balloon film, …*
- *Limited E resolution limits discovery potential*

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

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

Advantages:

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

Challenges:

- ***Background levels not yet verified. Large surface-to-volume ratio ⇒ 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 ⇒ challenging to scale to tonne-level apparatus***

Current Projects: NSAC Recommendation

- *Impressive suite of promising complementary approaches*
- *Each has significant advantages, but also daunting challenges to reach required next-generation sensitivity*

$\Rightarrow$ *NSAC Subcommittee Recommendations:*

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.

NSAC 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) **<u>Discovery potential</u>: 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) **<u>Staging</u>: 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) **<u>Standard of proof</u>: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.**

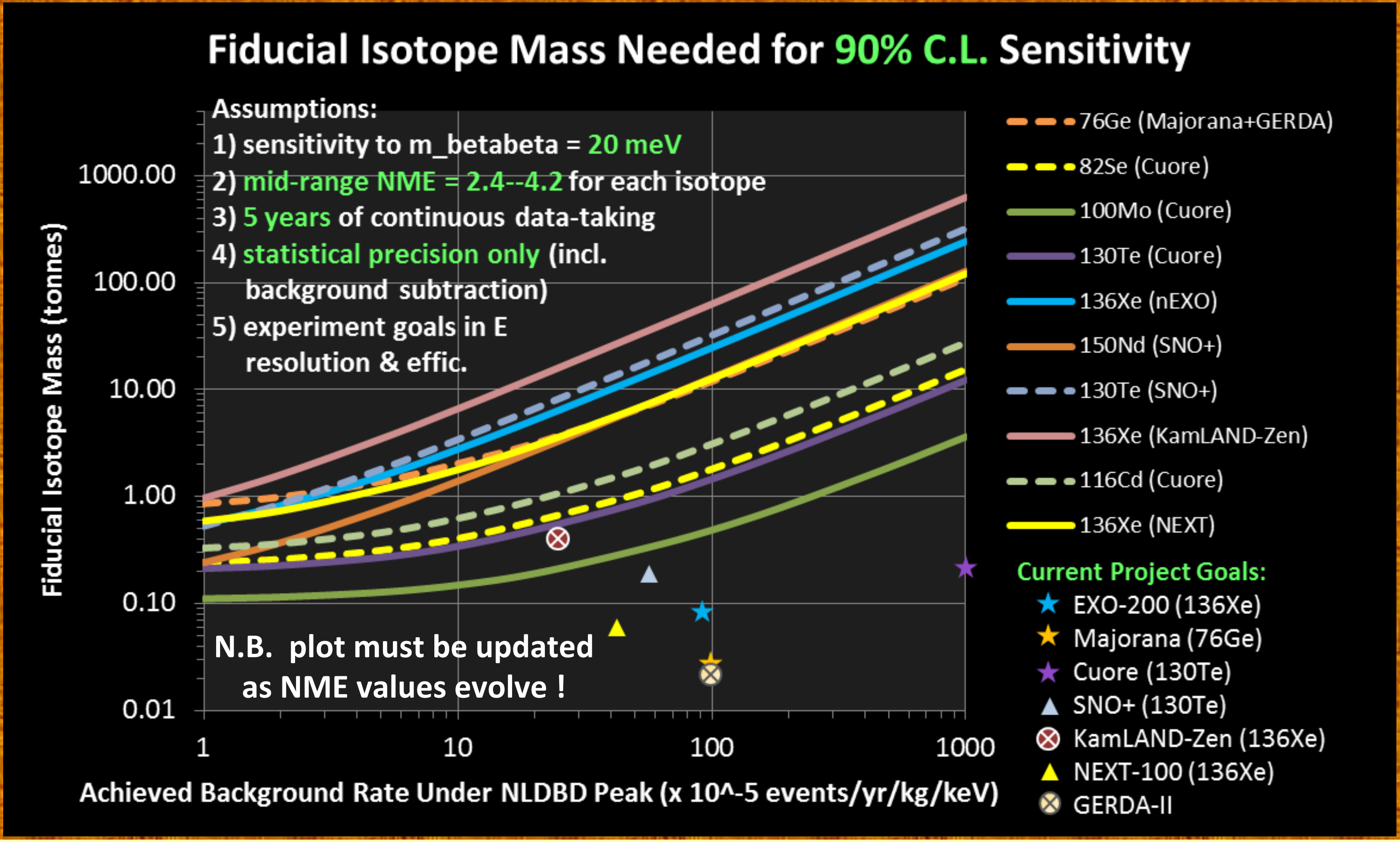
NSAC Guidelines for the Future

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.

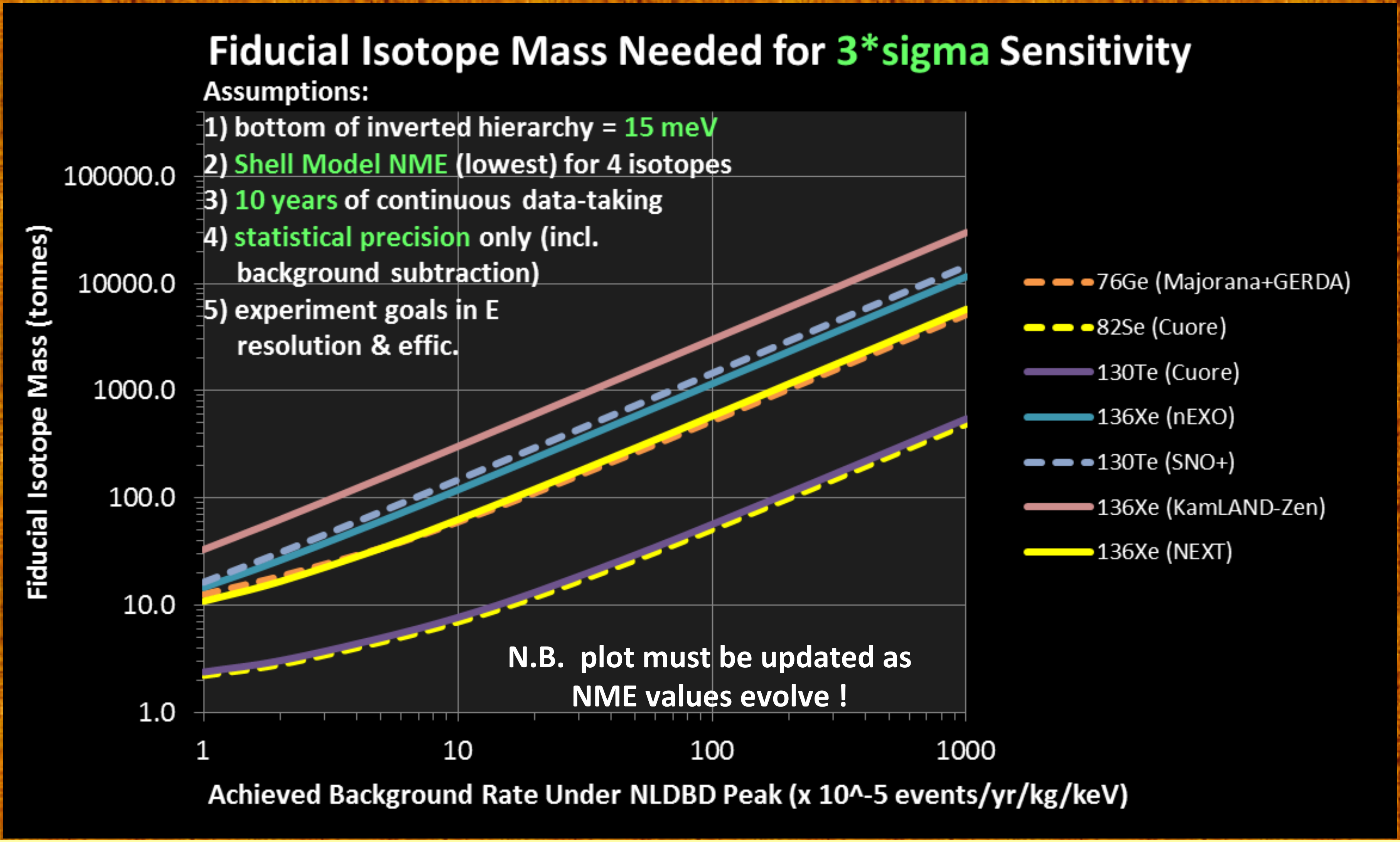
6) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

Possible 1st Stage of Next Generation



- **Some "current goals" (points) are still beyond *demonstrated* performance**
- **Need typically ~2 orders of magnitude *further* improvement for this 1st stage**
- **1st stage target ⇒ significant discovery pot'l + opportunity to demonstrate bkgrd levels needed for definitive answer re inverted hierarchy Majorana ν's**

The Leap to the Next Generation



NSAC recommended next-generation target sensitivity is an *additional 1-2 orders of magnitude* beyond 1st stage target of previous slide!
Long, long way to Tipperary…but a goal to be pursued aggressively!

Why Not 5σ?

Requires "only" another factor of 3 in exposure to go 3σ → 5σ

10 years counting → 30 years ??

~$200M project → ~$600M ??

HEP community now debating "universality" of 5σ discovery criterion:

Seems arbitrary to require same precision level for peak search at a priori unknown energy (e.g., Higgs) as for 0$\nu\beta\beta$, where peak location is already precisely known.

If 3σ signals are found in two independent worldwide searches, can combine to ⇒ >4σ discovery evidence.

If one finds 3σ evidence, will want to design more sophisticated next-to-next generation experiments to probe kinematics & mechanism.

If one sees no evidence at 3σ level and/or inverted hierarchy is otherwise ruled out ⇒ reset to consider normal hierarchy.

What Should LRP Recommend?

Very high priority for U.S. leadership in a staged next-generation neutrinoless double beta decay experiment capable of discovering lepton number non-conservation if the light neutrinos are Majorana particles in an inverted mass hierarchy.

- ***Requires support for R&D efforts to attain the extremely low background rates necessary for such a search***
- ***Urge additional modest-level support for U.S. participation in a second international $0\nu\beta\beta$ search***
- ***Requires support for nuclear theory efforts to constrain better the ranges of possible $0\nu\beta\beta$ nuclear matrix elements***

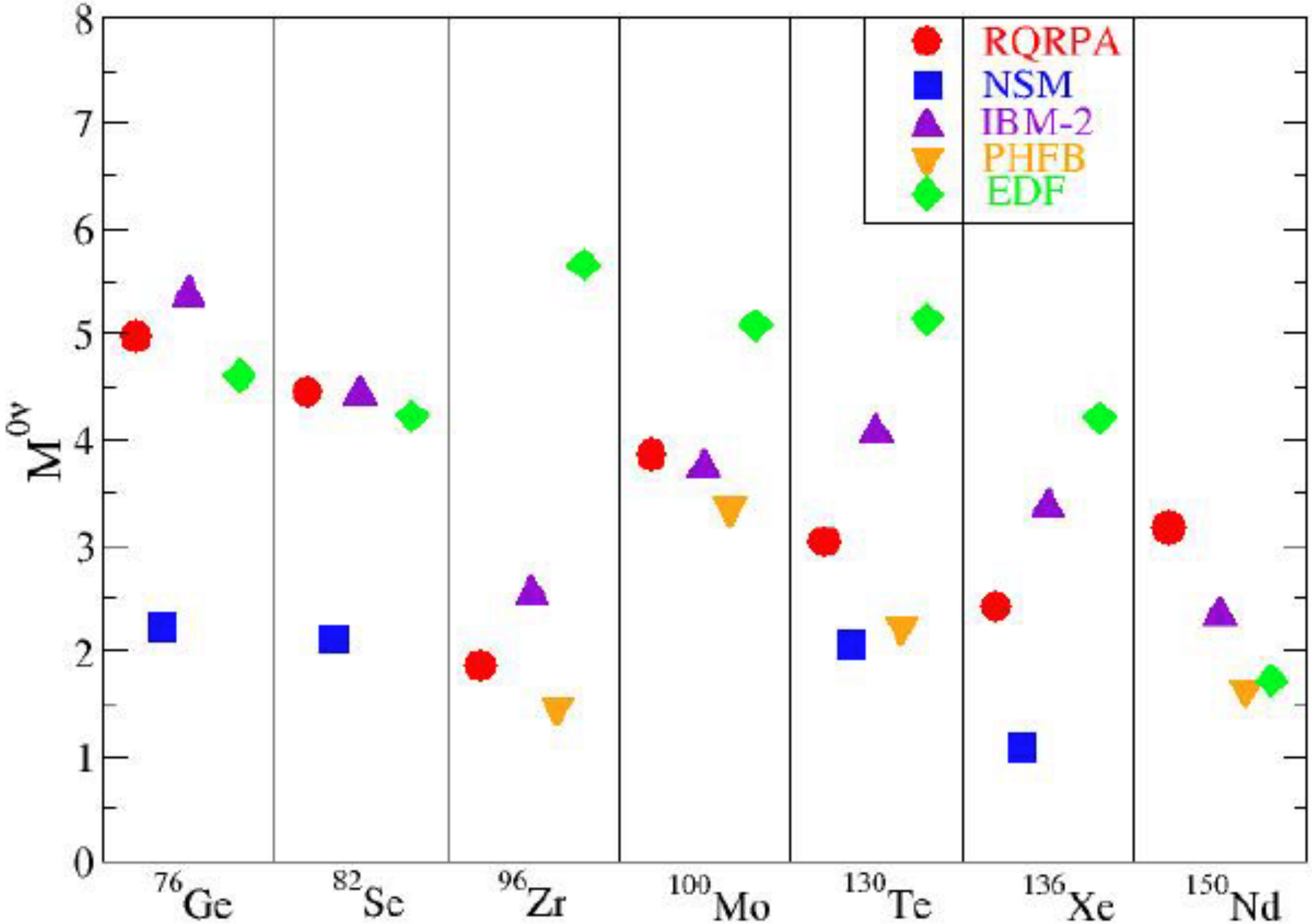
Which experiment? From NSAC report:

"However, it is unlikely that any one approach will achieve *all* of these desirable features. It is best to support the approach that provides the combination of these features most likely to reach the desired sensitivity at a cost that can be funded on a competitive time schedule."

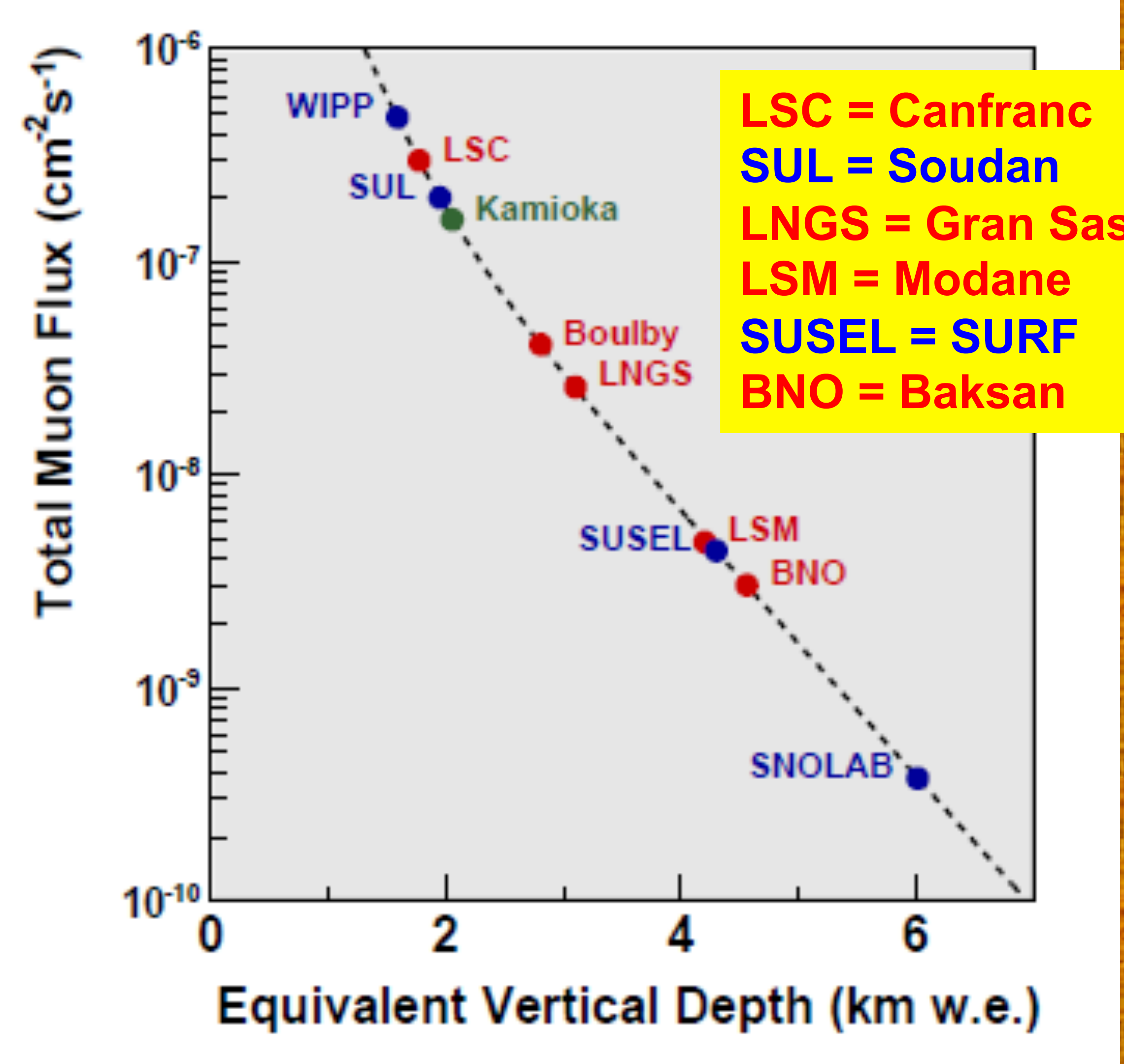
Backup Slides

Nuclear Matrix Elements from P. Vogel

Nuclear matrix elements $M^{0\nu}$ for various methods: IBM-2 is Interactiong Boson Model -2, PHFB is Projected Hartree-Fock-Bogolyubov and EDF (or GCM) is Energy Density Functional or Generator Coordinate Method and RQRPA is the renormalized quasiparticle RPA.
Note the relatively smooth dependence on A,Z in each method, but differences by the factor ~2 between the different methods. In particular, NSM is typically smaller and other methods agree with each other a bit better.



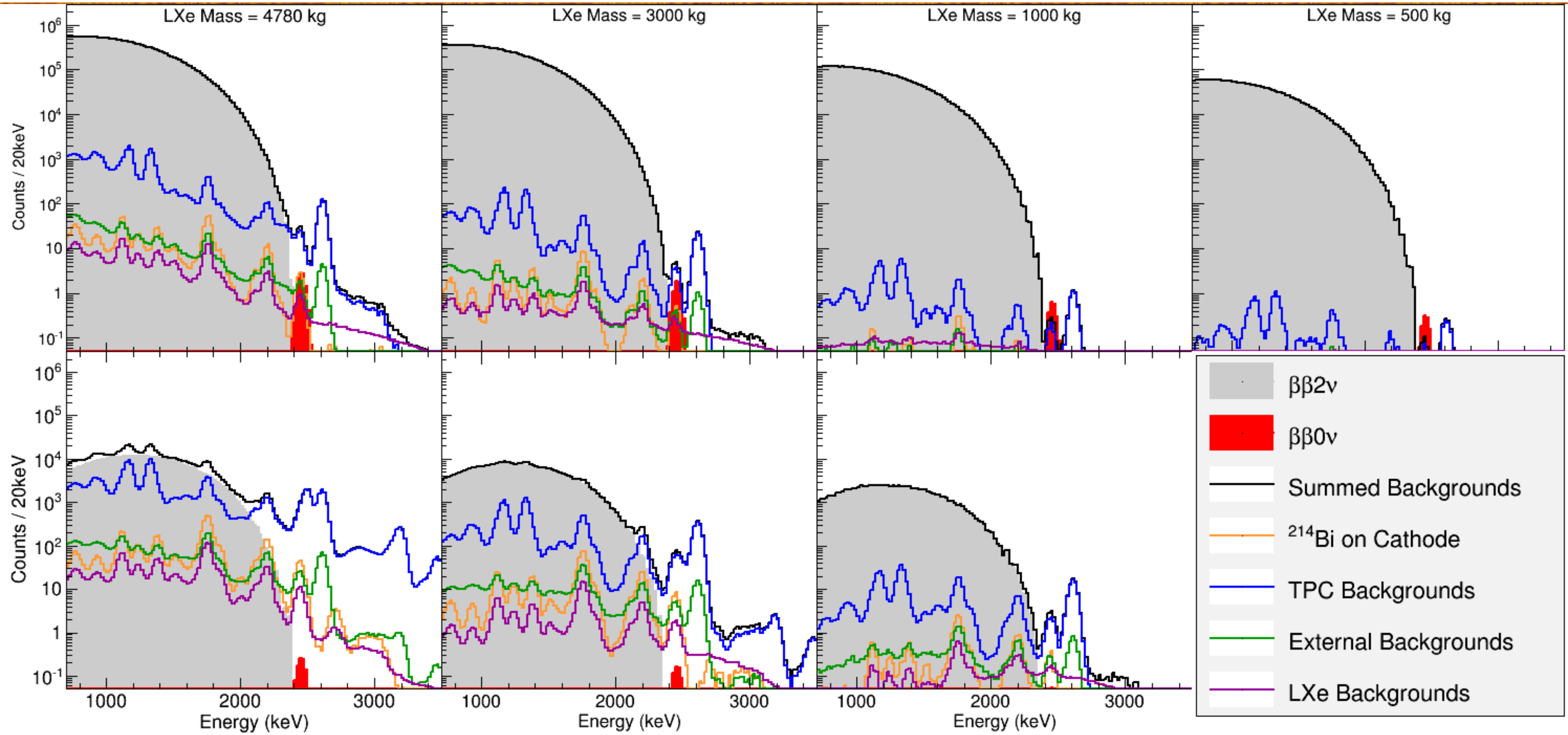
Overburdens



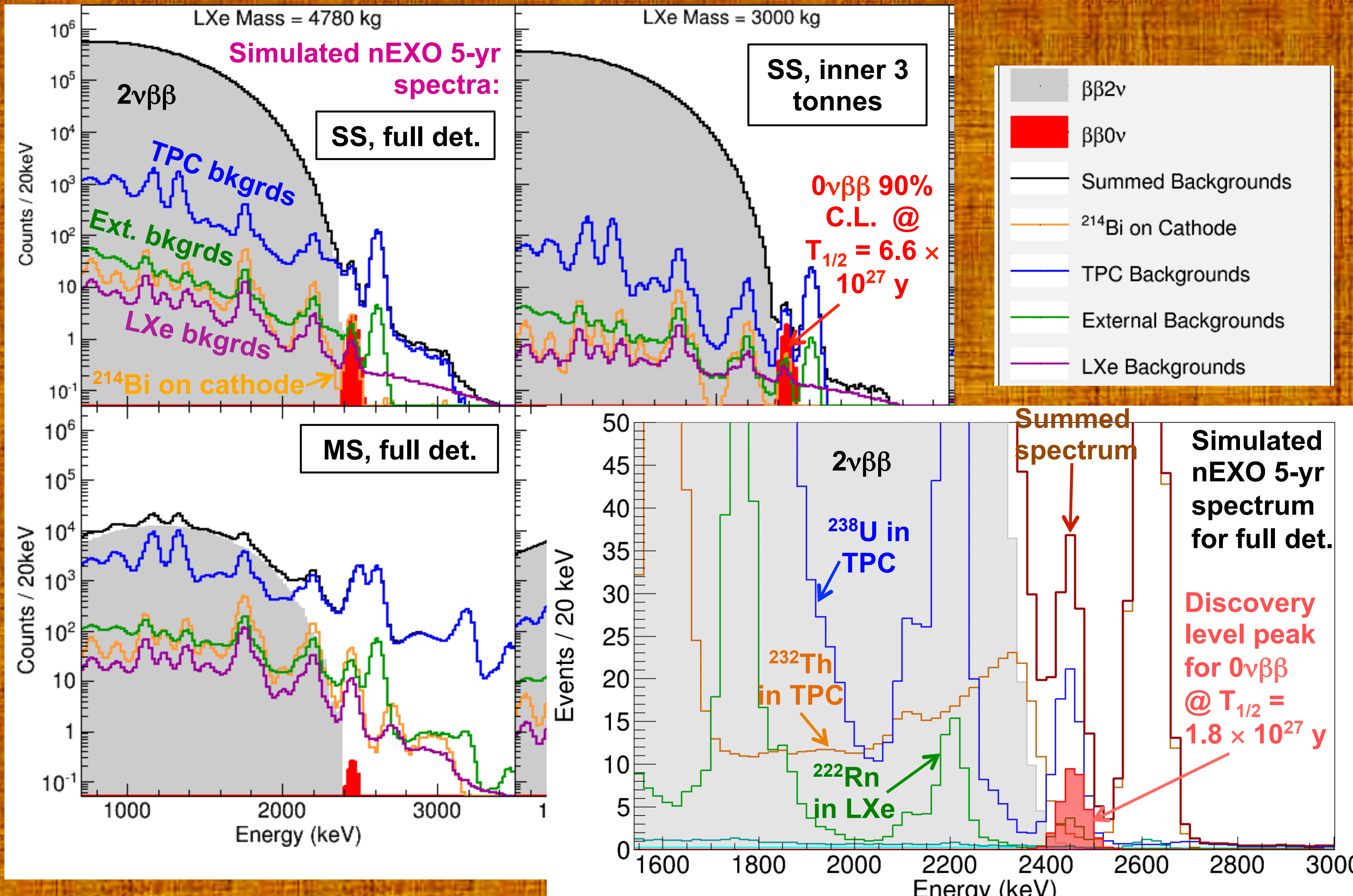
LSC = Canfranc
SUL = Soudan
LNGS = Gran Sasso
LSM = Modane
SUSEL = SURF
BNO = Baksan

nEXO Background Simulations

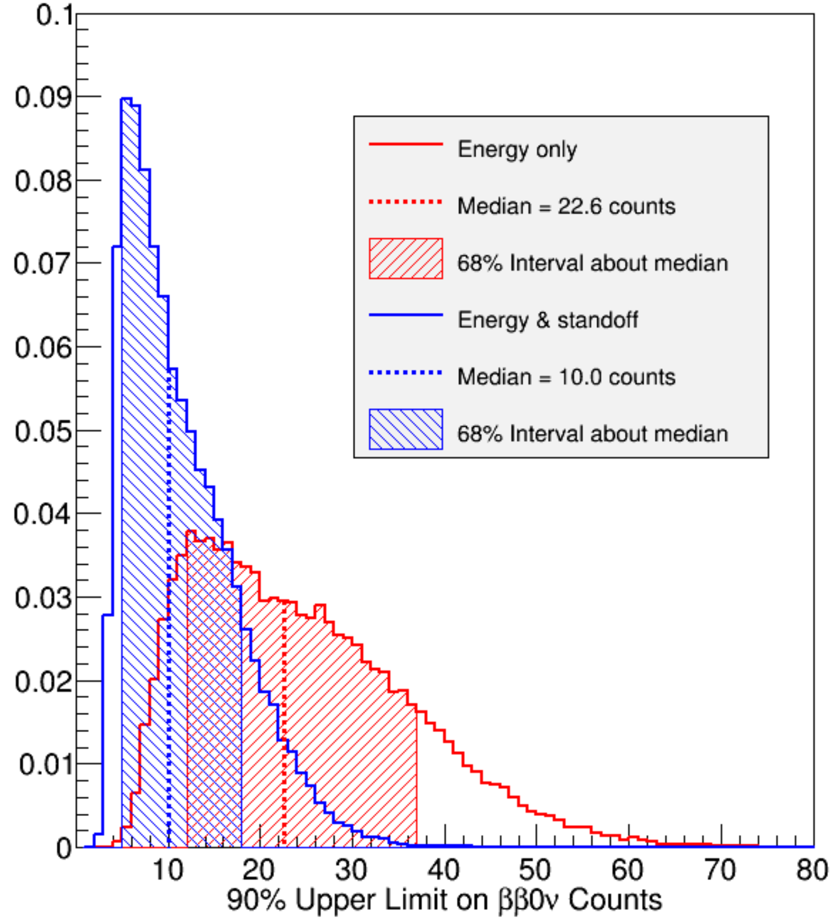
This series of plots shows the energy spectra for different LXe masses. The background pdfs have been normalized to their mean expected number of events for nEXO at 5 yrs exposure. The number of 0νββ counts has been normalized to its median 90% upper limit (≈10 in 5 yr), corresponding to $T_{1/2}=6.6\cdot10^{27}$ yr. This plot displays the energy discrimination at different positions in the detector without statistical fluctuations.

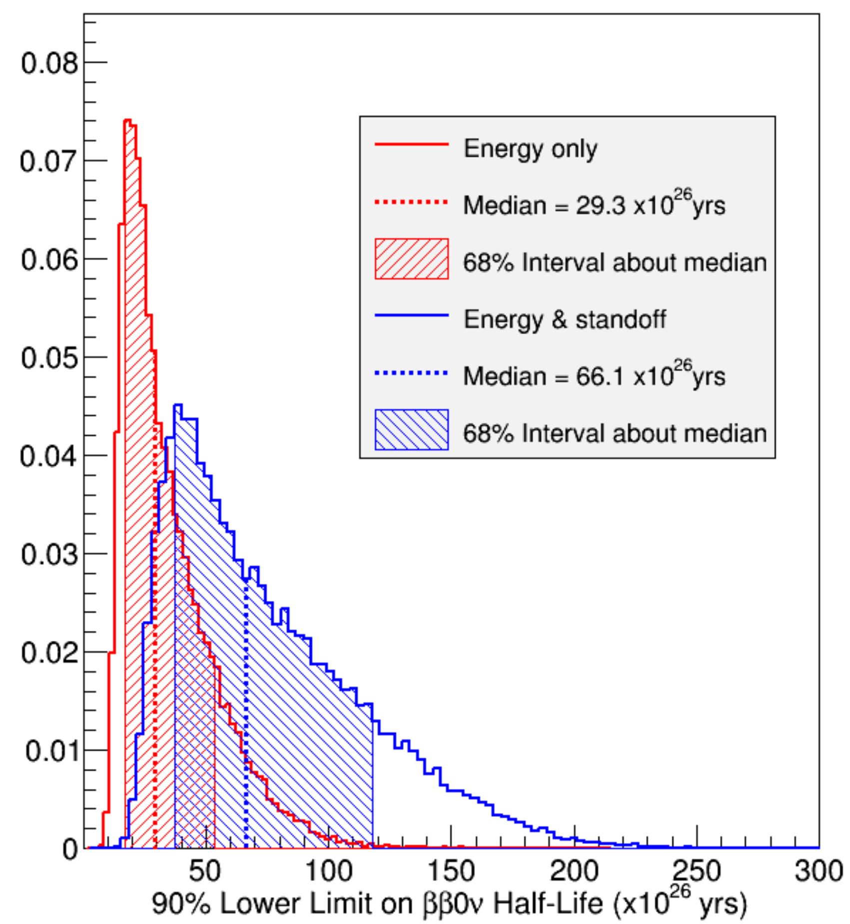


nEXO Background Simulations



Left: The nEXO distributions of the 90% UL on the number of $0\nu\beta\beta$ counts in 5 yrs for the energy-only (red), and energy + standoff-distance (blue) analyses. **Right:** The distributions of the 90% LL on the bb0n half-life attained using the energy-only (red), and energy + standoff-distance (blue) analyses.

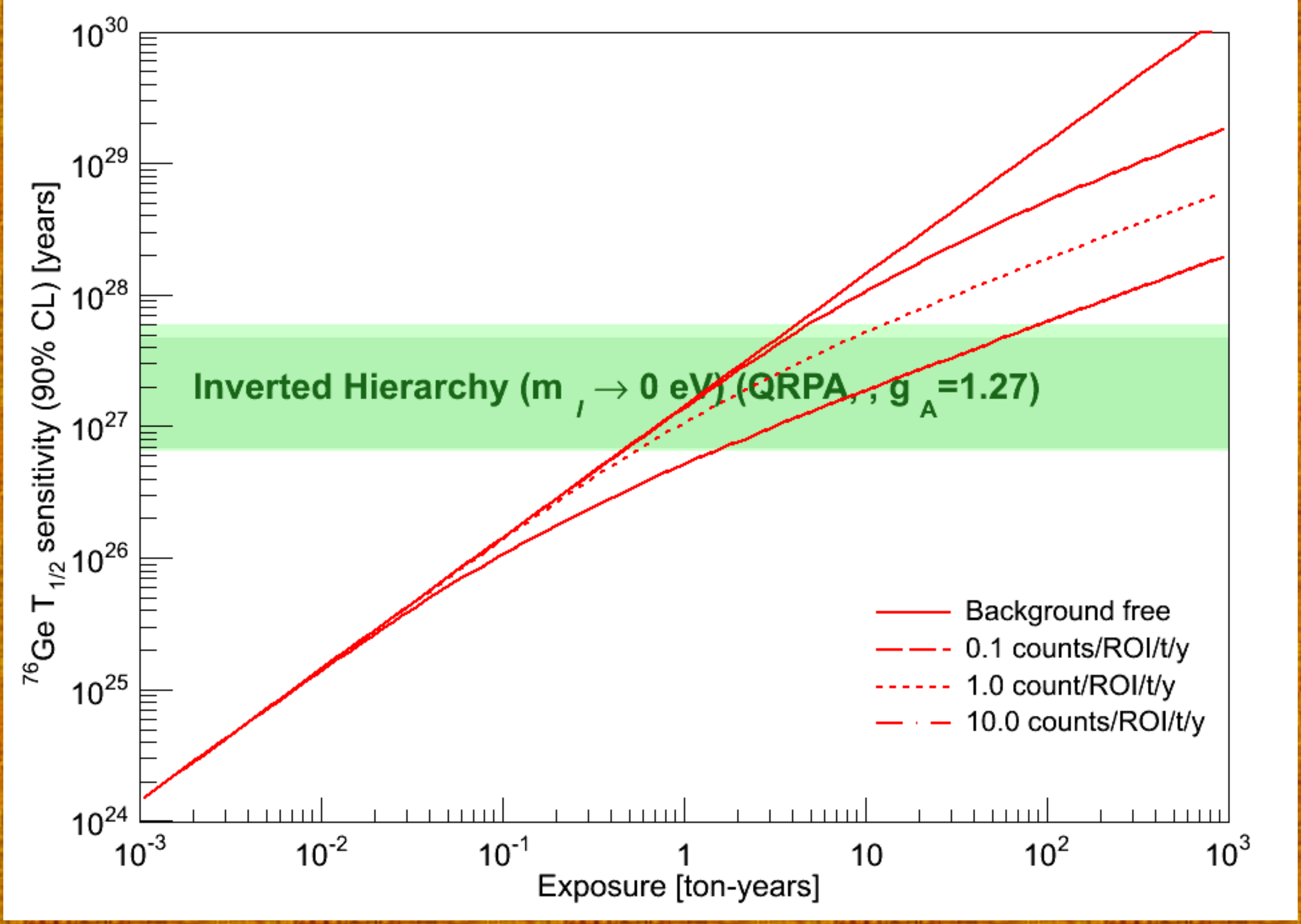




Using standoff distance has an equivalent effect on sensitivity as a 4 times reduction in background! (For a background-limited experiment). Improves half-life sensitivity by more than a factor of 2.

90% C.L. Sensitivity vs. Background (^{76}Ge)

J. Detwiler



SNO+ Backgrounds