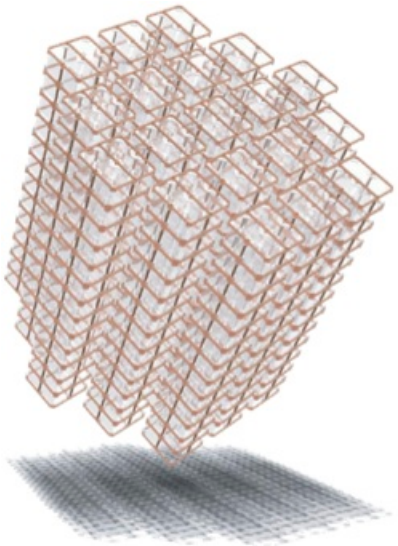
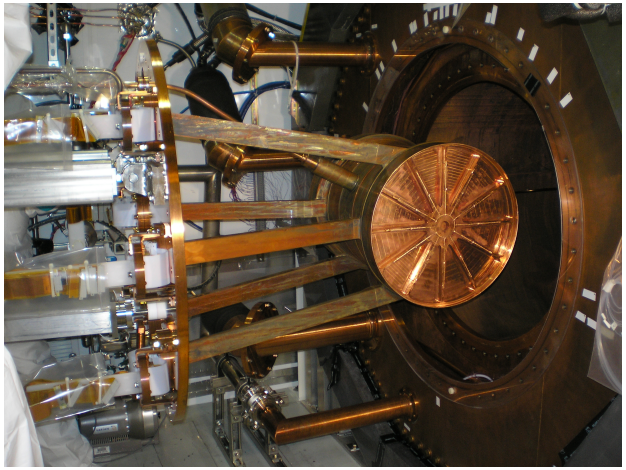


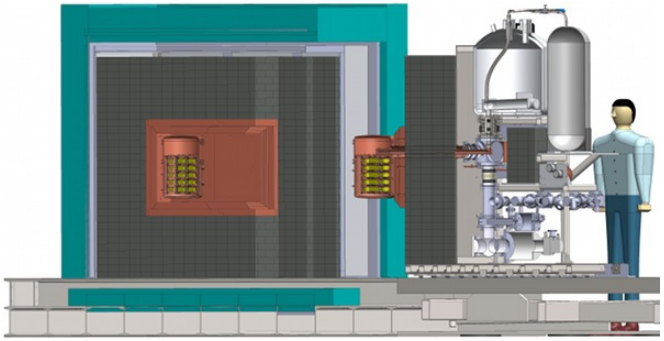


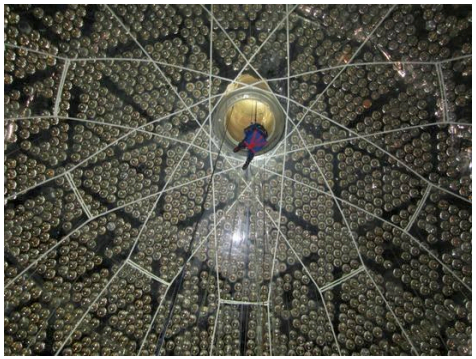
Nu2: Majorana vs Dirac

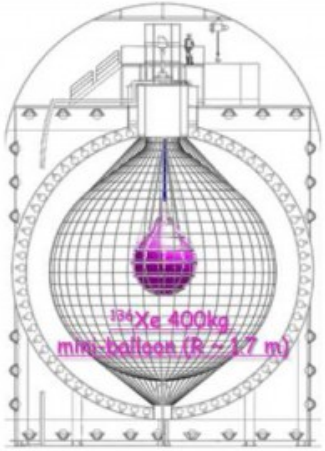
Conveners: Steve Elliott (Los Alamos National Lab)

Lisa Kaufman (Indiana University)

Community Summer Study 2013



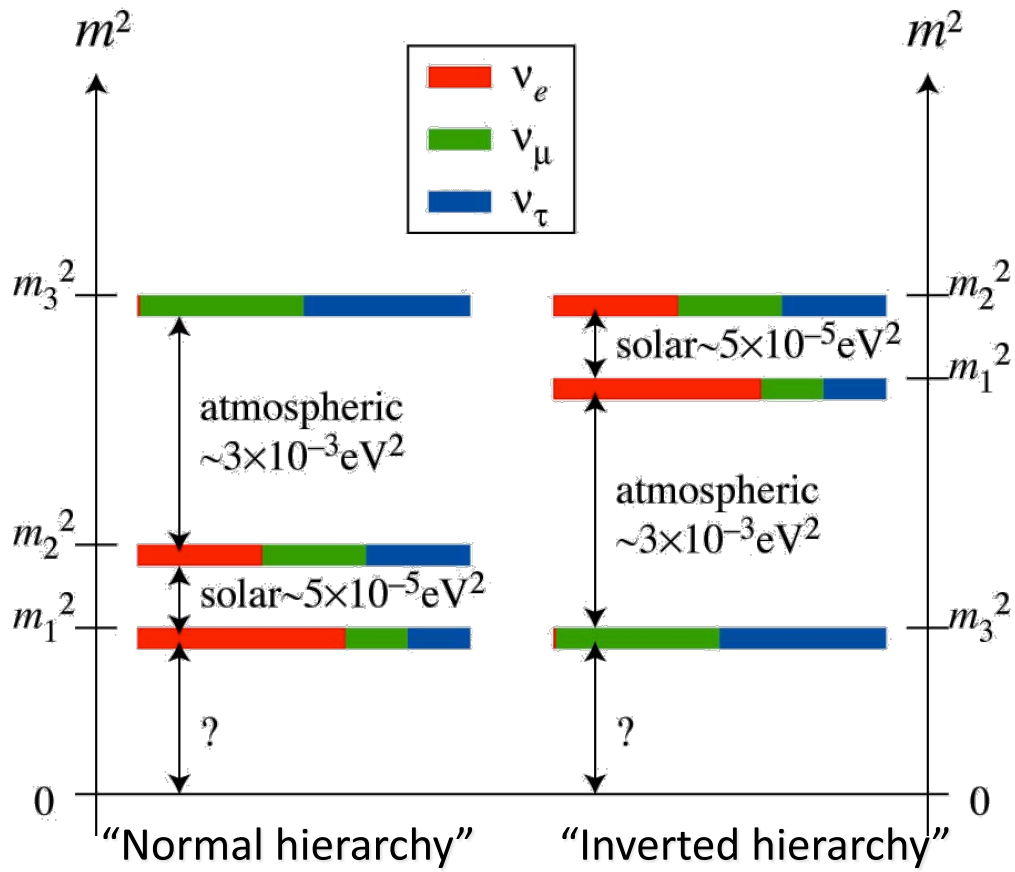




Unknown properties of the neutrino

Major Questions in Neutrino Physics

- Is the neutrino a Dirac or Majorana particle, (i.e. is it its own antiparticle?)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- CP violation phase
- Are there sterile neutrinos?



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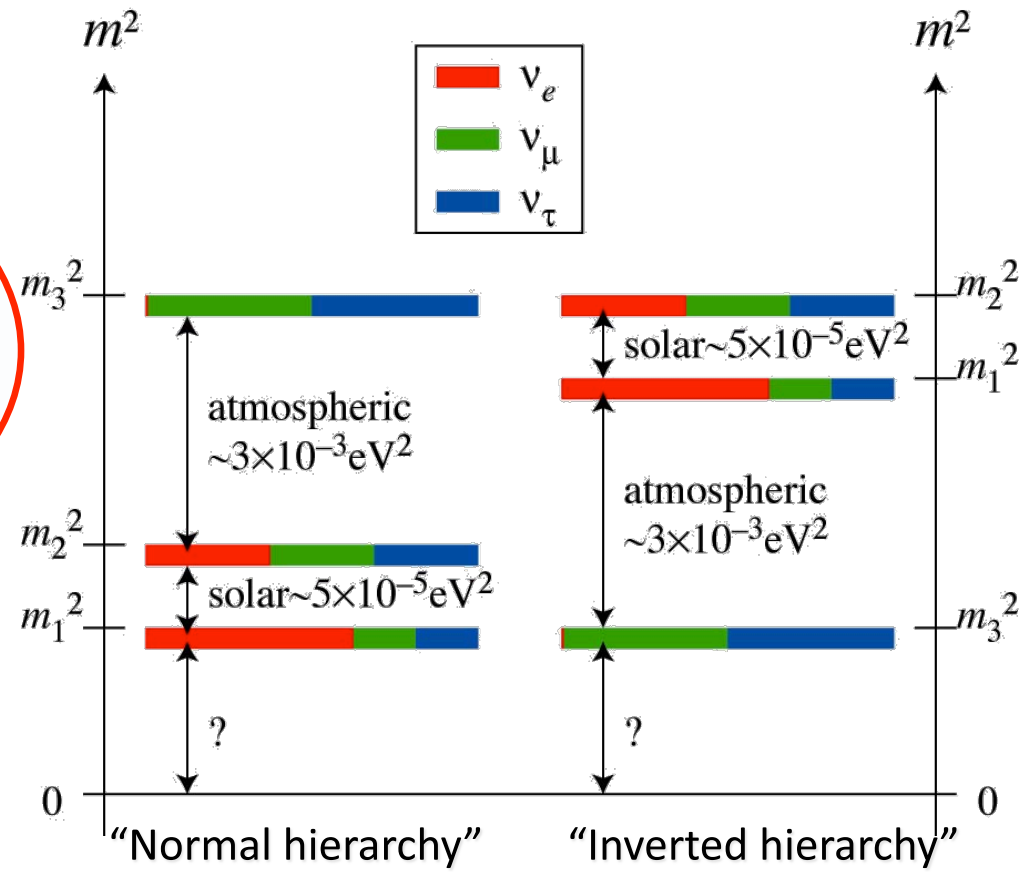
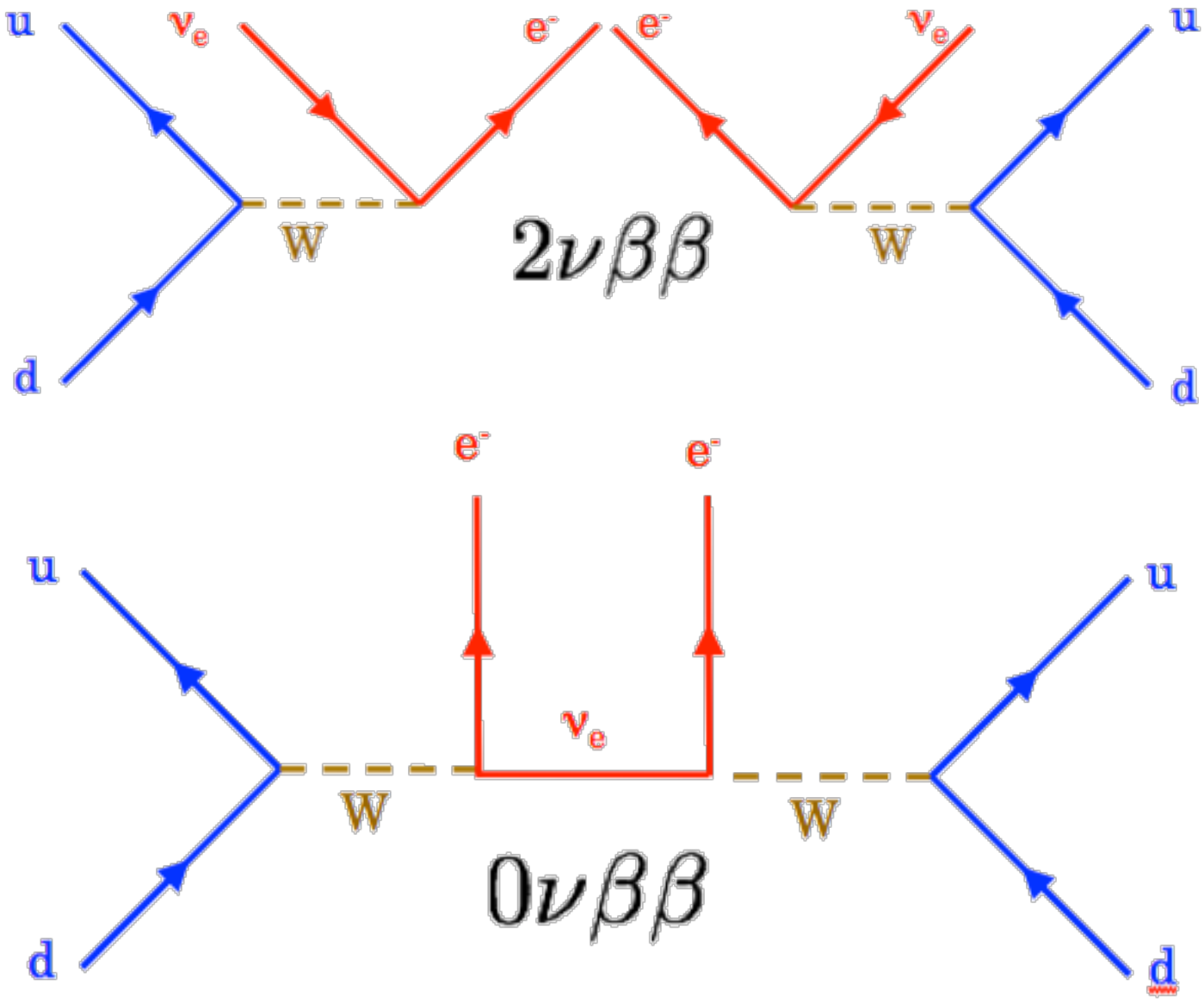


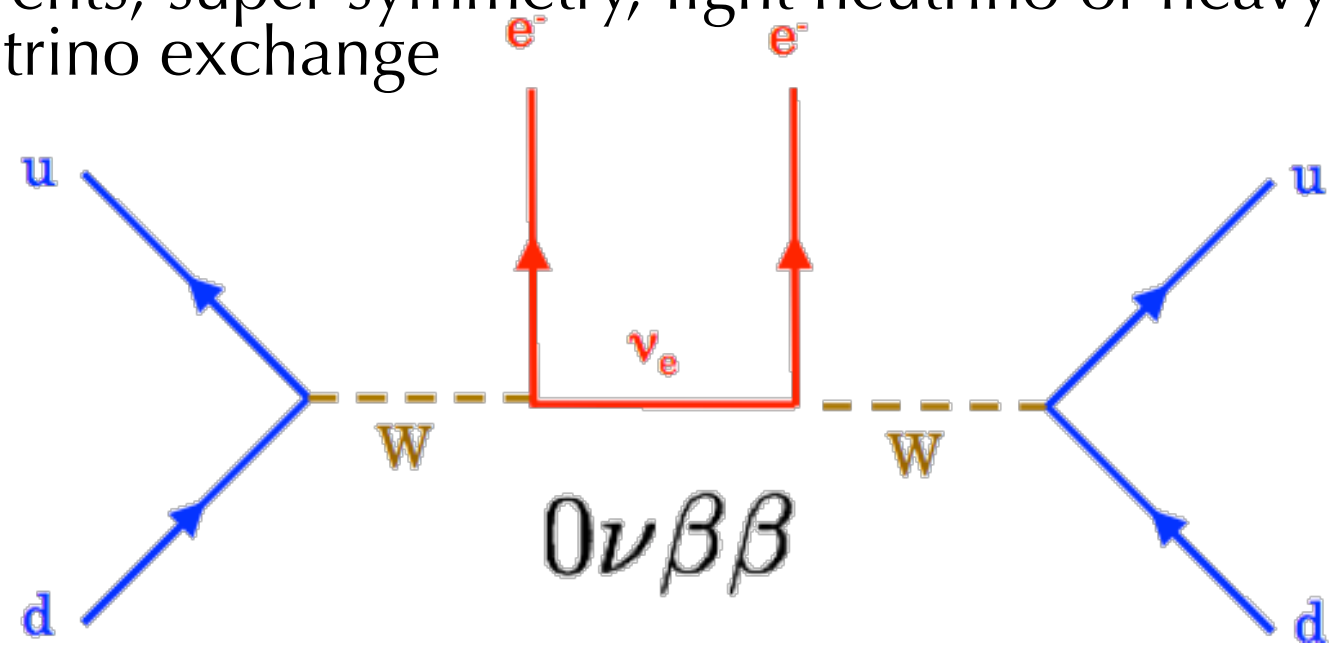
The search for neutrinoless double beta decay can shed light on the first three questions.

Double Beta Decay



Neutrinoless Double Beta Decay

- $0\nu\beta\beta$ can only occur if neutrinos have mass and are their own antiparticle (Majorana)
- Process violates lepton number conservation (by 2!) – necessary for leptogenesis
- New Physics – beyond the SM!
- Several theories for the mechanism: right-handed currents, super-symmetry, light neutrino or heavy neutrino exchange



We Measure the Decay Half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\left|f_b\left(m_i,U_{ei}\right)\right|^2$$

$G^{0\nu}(Q,Z)$ Calculable phase space factor $\sim Q^5$

$\left|M^{0\nu}\right|^2$ Nuclear matrix elements are difficult to calculate

$\left|f_b\left(m_i,U_{ei}\right)\right|^2$ New Physics: lepton-number violating term

We Measure the Decay Half-life

Assuming light Majorana neutrinos:

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

$G^{0\nu}(Q,Z)$ Calculable phase space factor $\sim Q^5$

$\left|M^{0\nu}\right|^2$ Nuclear matrix elements are difficult to calculate

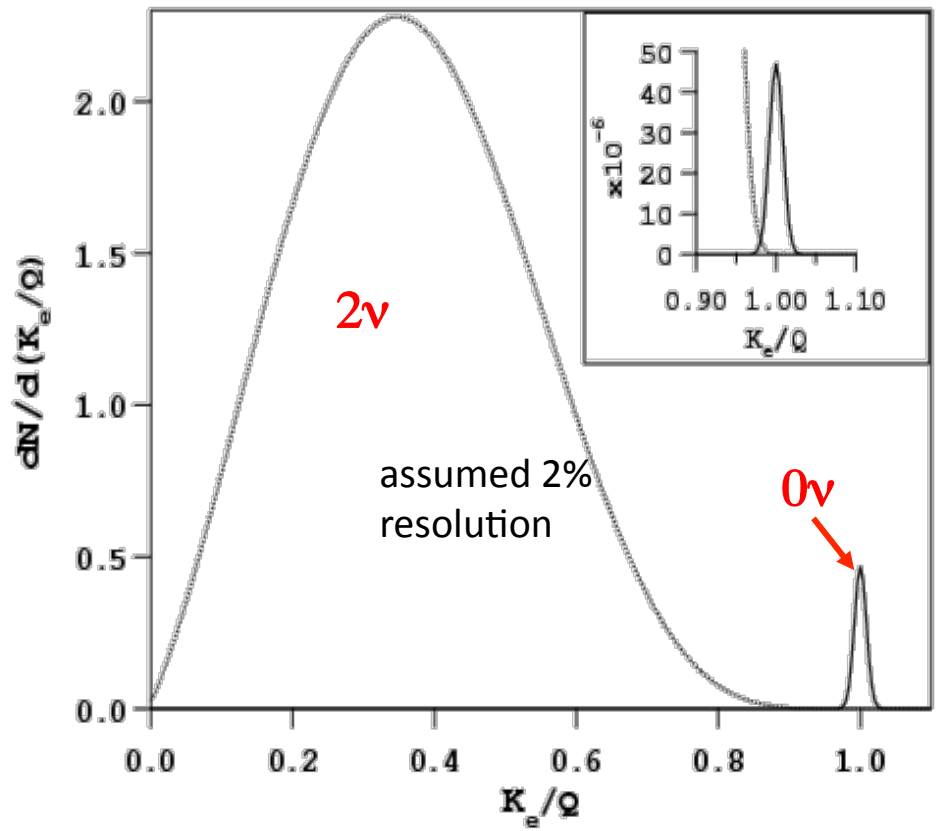
$\langle m_{\beta\beta}\rangle^2$ Effective Majorana mass $= \left|\sum_{i=1}^{3} \eta_i U_{ei}^2 m_i\right|^2$

Neutrino masses

CP phases

Neutrino mixing matrix

How do we Measure the Rate?

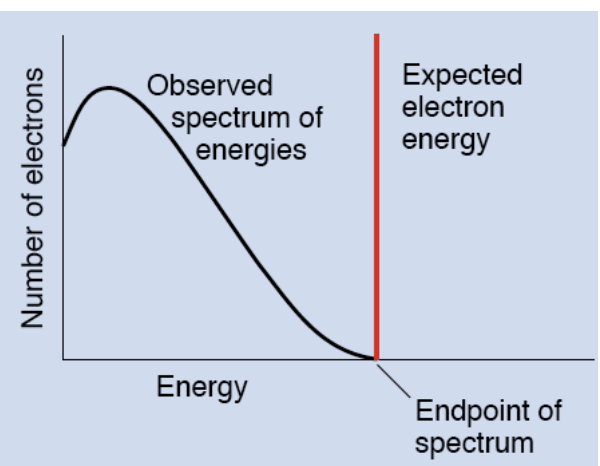


assumed rate ratio $1:10^6$

assumed rate ratio $1:10^2$

Elliott, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Summed electron energy in units of the kinematic endpoint (Q)



Sensitivity

$$S^{0\nu}_{1/2} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

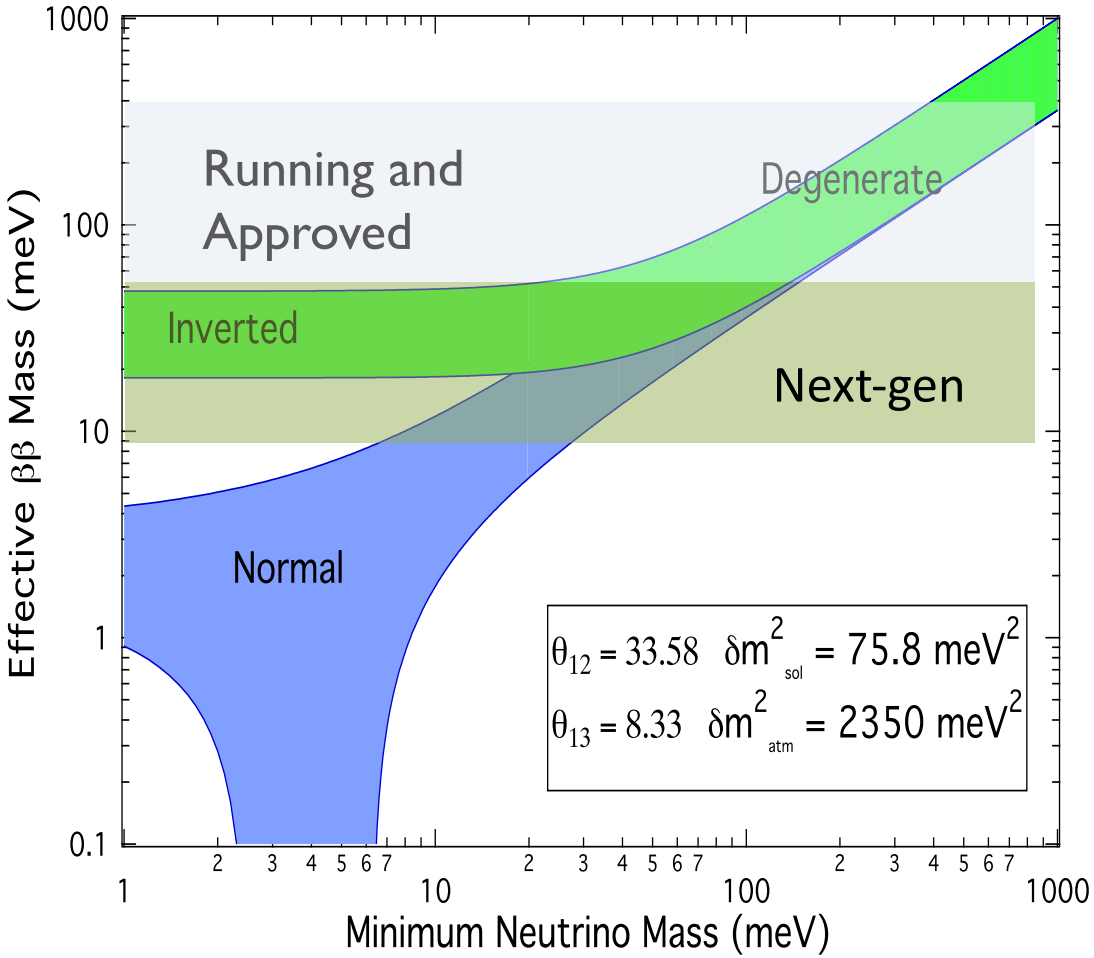
To maximize sensitivity:

- Large mass
- Low background
- High detection efficiency
- Good energy resolution

Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Goals for Next-Generation 0νββ



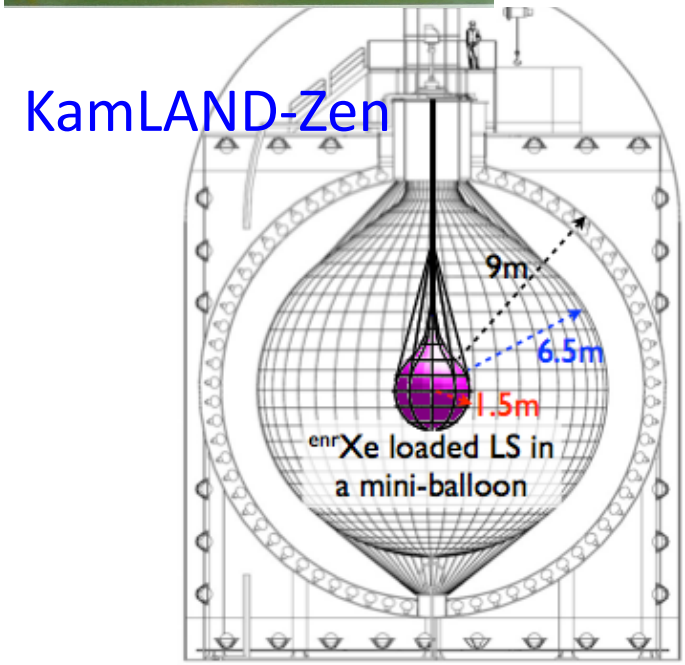
- Majorana vs Dirac
- Absolute Neutrino Mass
- Lepton Number Violation

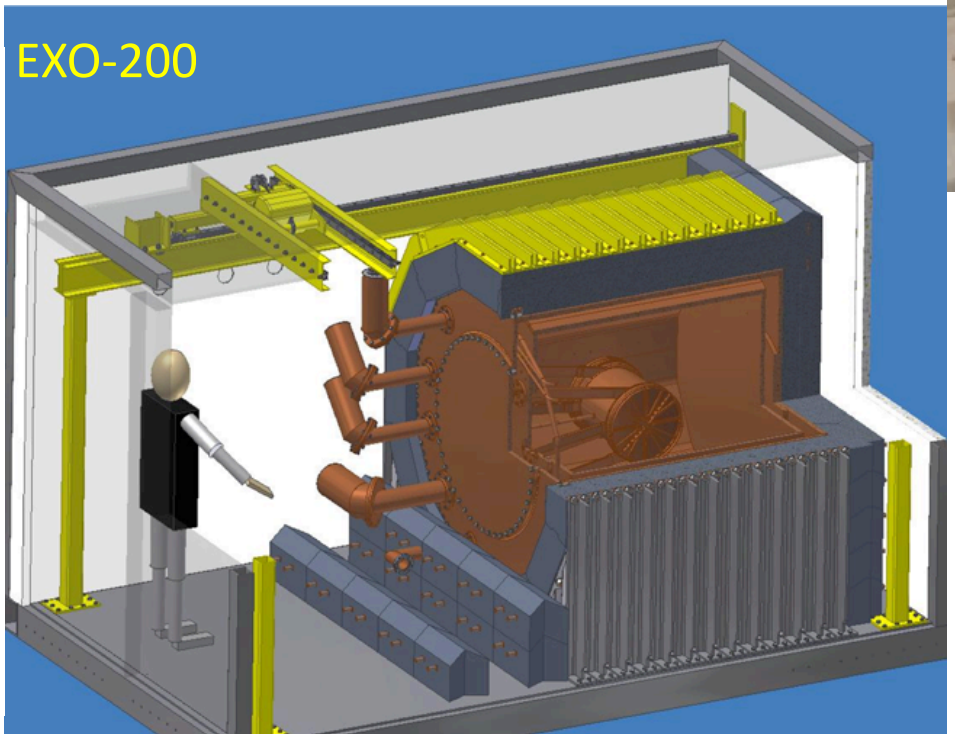
- Next-generation ββ experiments must cover the entire allowed region of the inverted hierarchy

- Ideas for probing the normal hierarchy exist

Experimental Technique

These experiments are currently running – but there are others being constructed and designed for the future.





Several Experiments Running or Nearly Running to get down to 100 meV $m_{\beta\beta}$-scale

- ^{136}Xe
  - EXO-200 and KamLAND-Zen currently running
  - Combined result: $m_{\beta\beta}$ <120 - 250 meV
  - NEXT to be running in 2014
  - (LZ)
- ^{76}Ge
  - GERDA running
  - MAJORANA DEMONSTRATOR coming online in the next few months
- Tellurium
  - CUORE0 online
  - CUORE online in 2015
  - SNO+ will come online in 2014
- Selenium
  - SuperNEMO Demonstrator online in 2015

Several Ideas to Get US to the Inverted Hierarchy

- Several isotopes and several complementary experiments (needed for confirmation of signal)
  - Xenon
    - nEXO (Liquid Xe TPC)
    - NEXT (High pressure Xe Gas EL TPC)
    - KamLAND-Zen (Xe-loaded Liquid Scintillator)
  - Germanium
    - MAJORANA/GERDA (Ge Semiconductor)
  - Tellurium
    - CUORE/Enriched CUORE (TeO_2 Bolometers)
    - SNO+/Enriched SNO+ (Te-loaded Liquid Scintillator)
  - Selenium
    - SuperNEMO (Se foils/tracking)

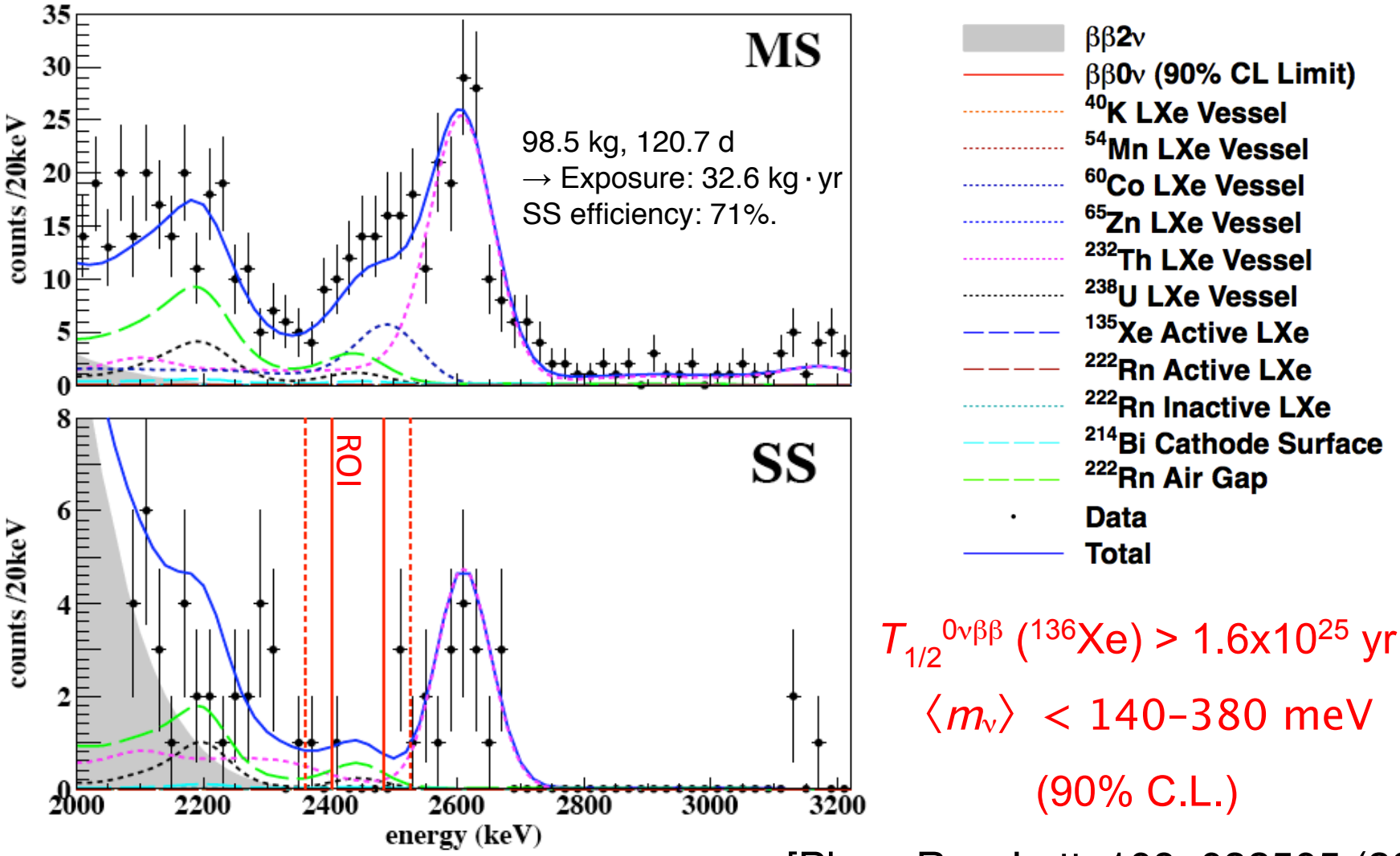
Summary of All Proposals and Experiments

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE[22, 23]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[24]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[25]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA[26]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[8]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE[8]	^{130}Te	203 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA[27]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[9, 10, 11]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO[12]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA[28][7]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[29]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[14, 16]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[30, 31]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [4, 5, 6]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [32]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem[20]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[20]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [17, 18]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
LZ [19]	^{136}Xe	600 kg	Two-phase (liquid/gas) ^{nat}Xe TPC/scint	Proposal	SURF
SNO+[33, 34, 13]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Table 1-1. *A summary list of neutrinoless double-beta decay proposals and experiments.*

Current EXO-200 0νββ Results

No peak observed at $Q_{\beta\beta}$. Use the background model to construct a limit 0νββ via a likelihood ratio hypothesis test.



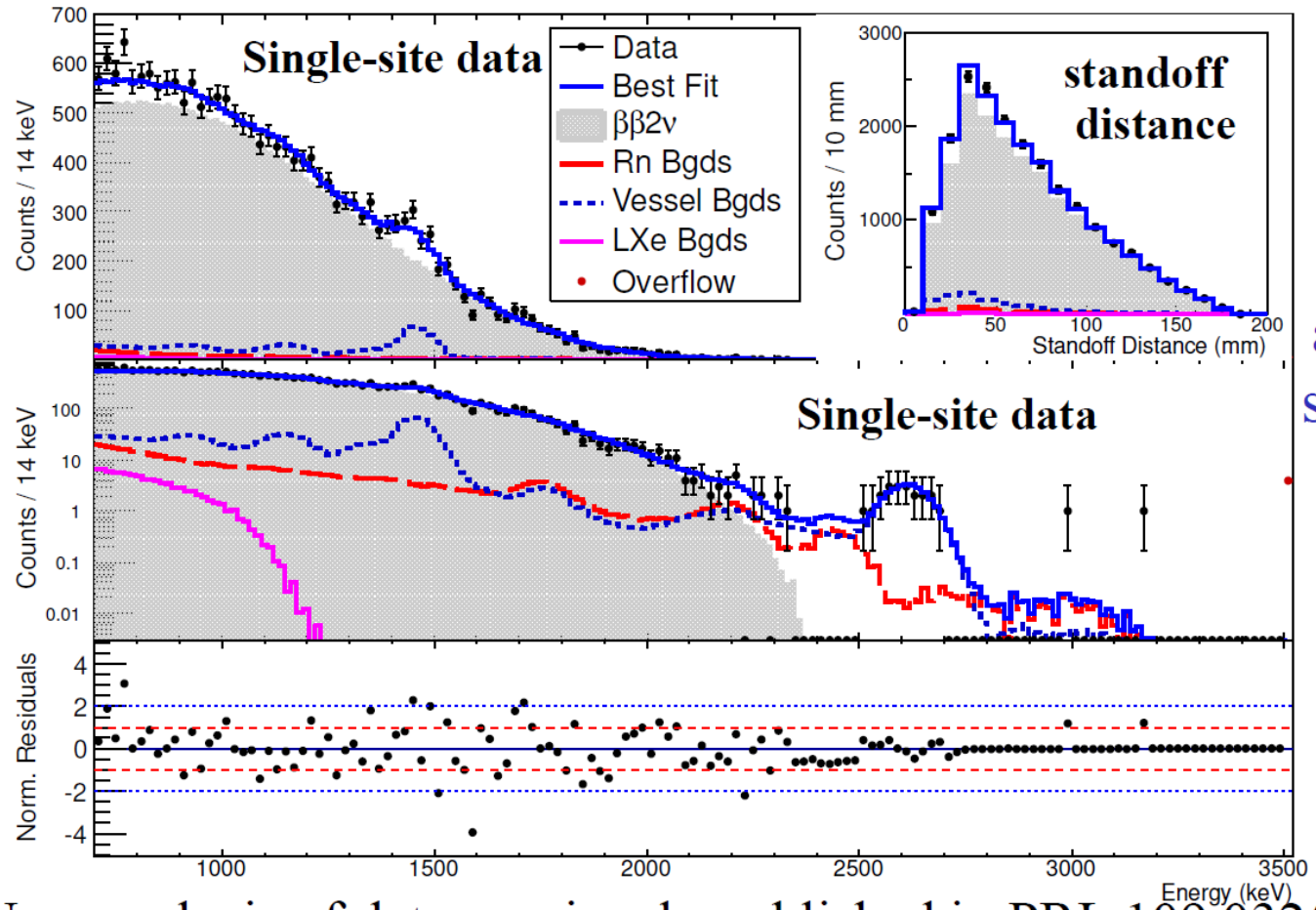
$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > 1.6x10^{25} yr

$\langle m_\nu \rangle$ < 140–380 meV

(90% C.L.)

[Phys. Rev. Lett. 109, 032505 (2012)]

New result: Improved measurement of the ββ2ν half-life of ^{136}Xe



arXiv:1306.6106, submitted to PRC.

New analysis of data previously published in PRL 109 032505 (2012).

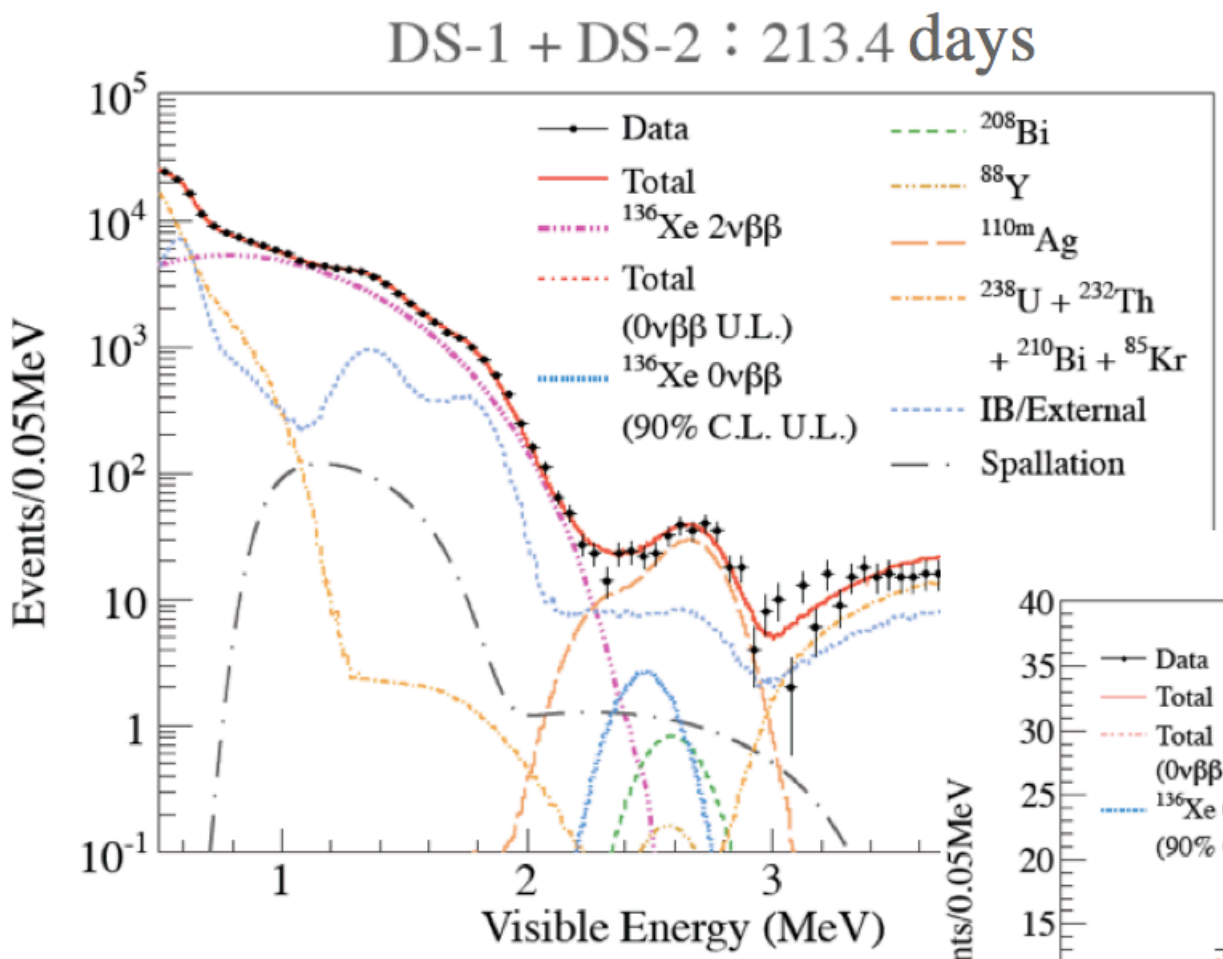
$T_{1/2} = 2.172 \pm 0.017$ (stat) $\pm$ 0.060 (sys) x 10^{21} years (2.85 % uncert.)

Twice as precise as any other ββ2ν decay of any isotope.

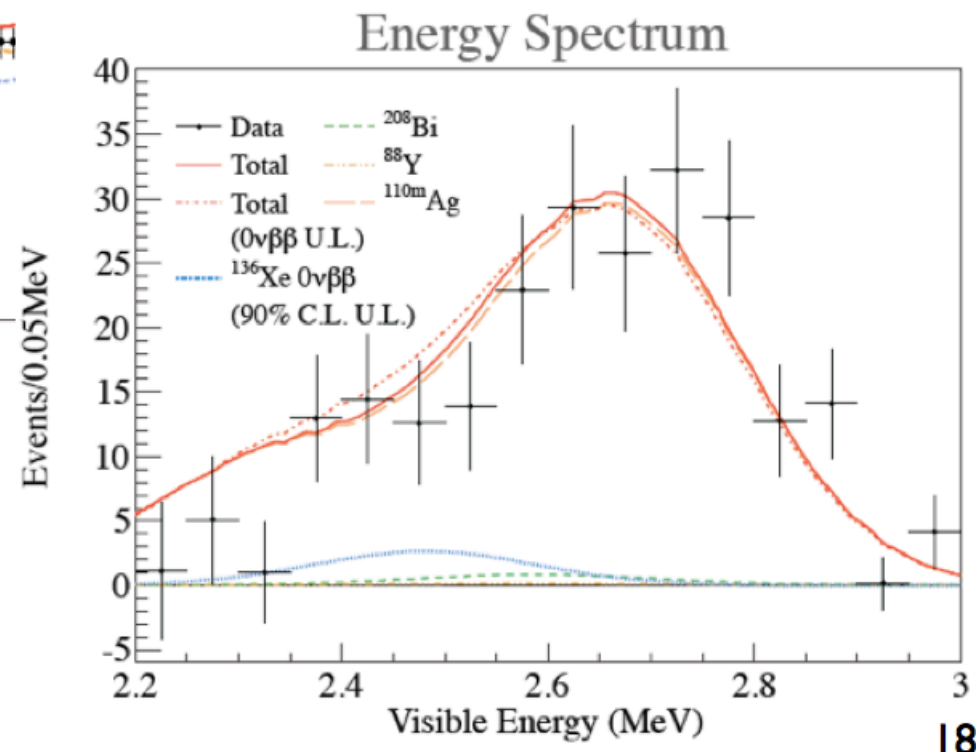
EXO-200

Results from KamLAND-Zen phase I

Phys.Rev.Lett. 110 (2013) 062502

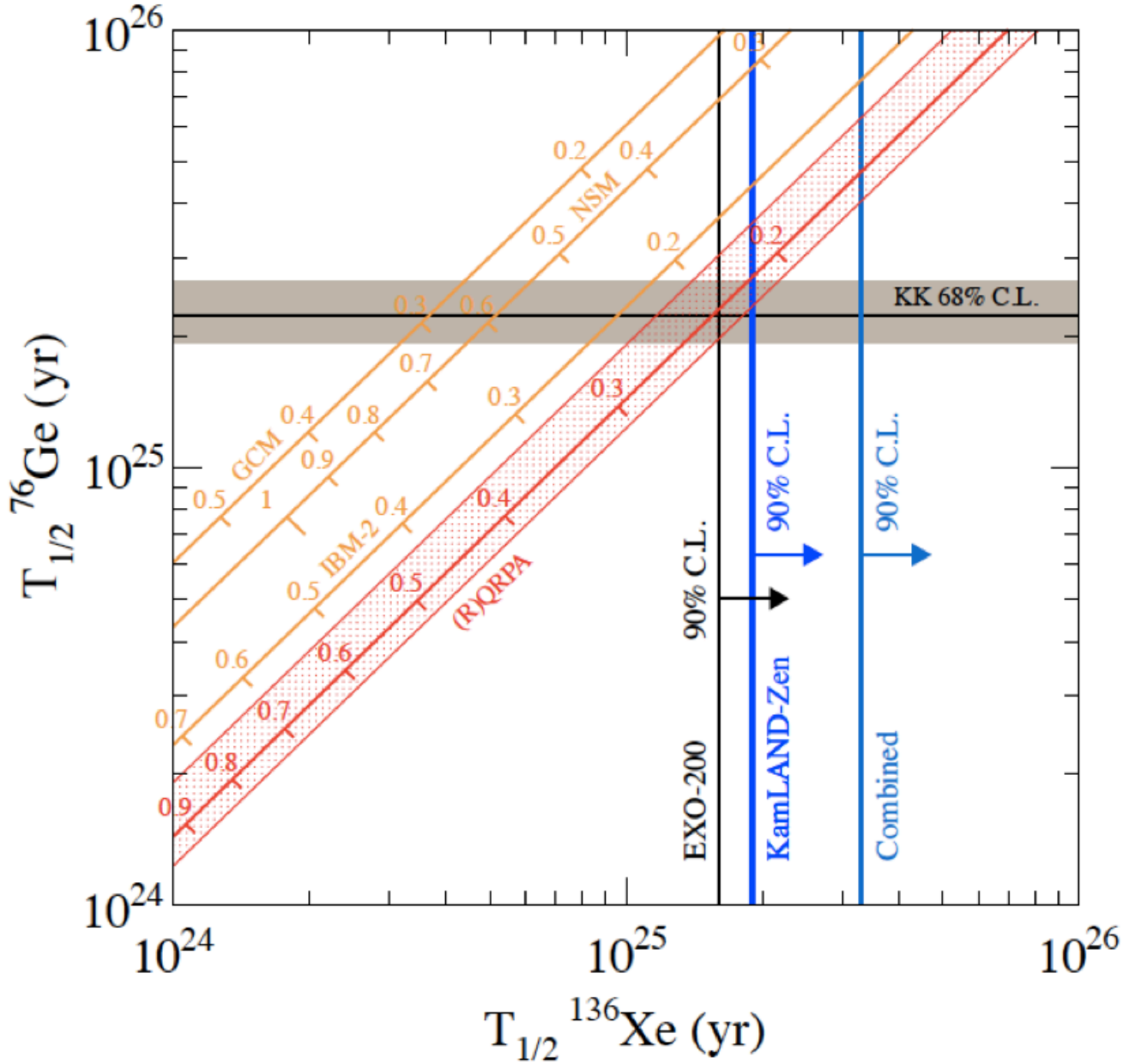


$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > 1.9x10^{25} yr
(90% C.L.)



$\langle m_{\beta\beta} \rangle$ <160~330 meV

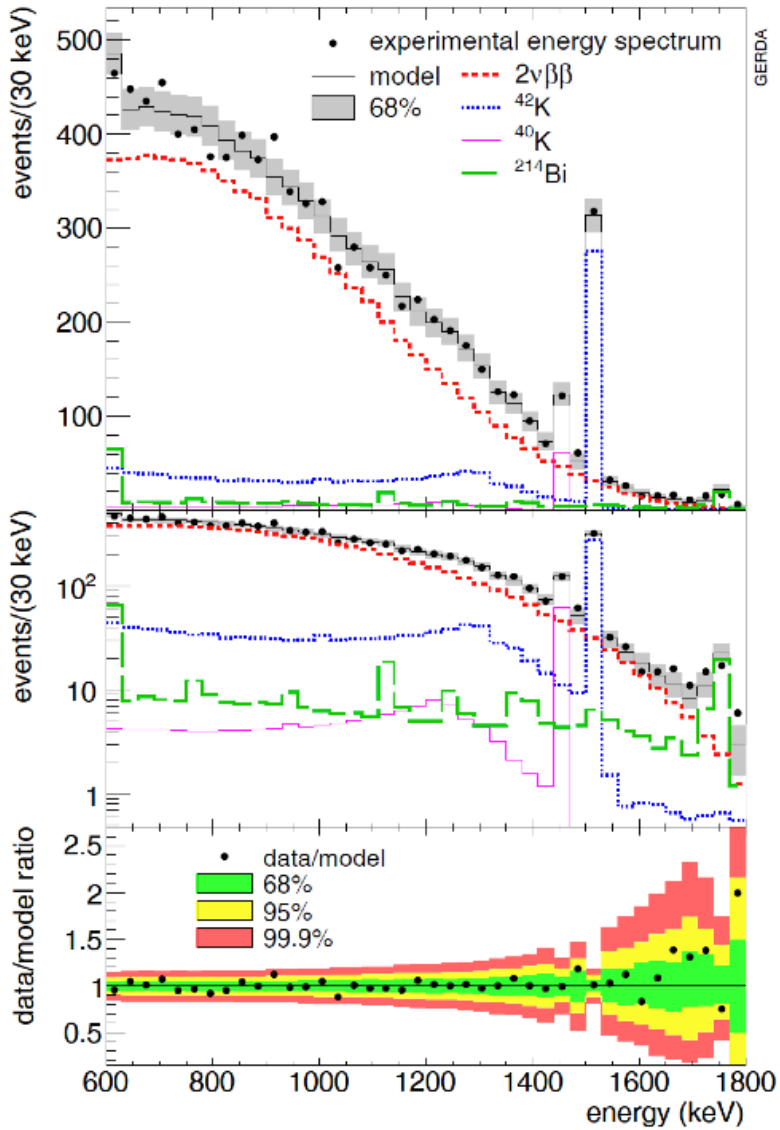
^{76}Ge discovery claim is in tension with ^{136}Xe results



KamLAND-Zen & EXO-200

Phys. Rev. Lett. 110 062502 (2013)

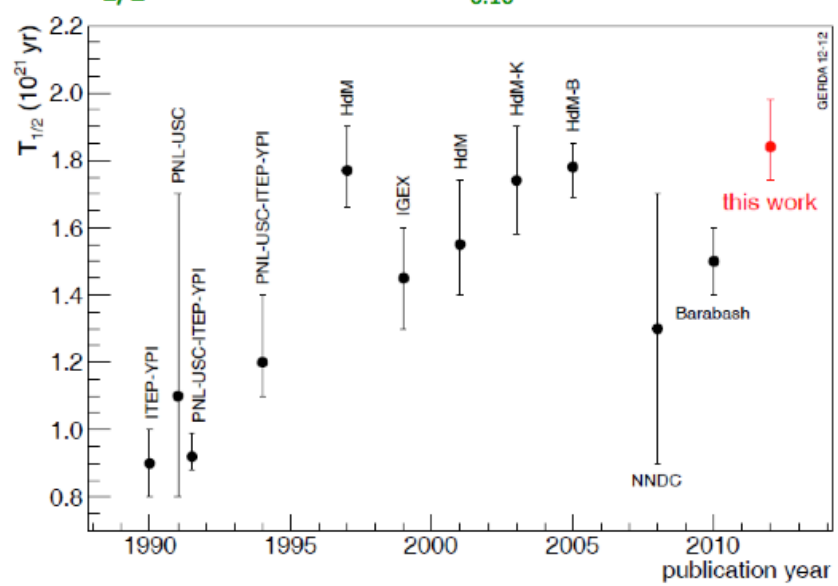
Measurement of $T^{2\nu}_{1/2}$ (^{76}Ge)



IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

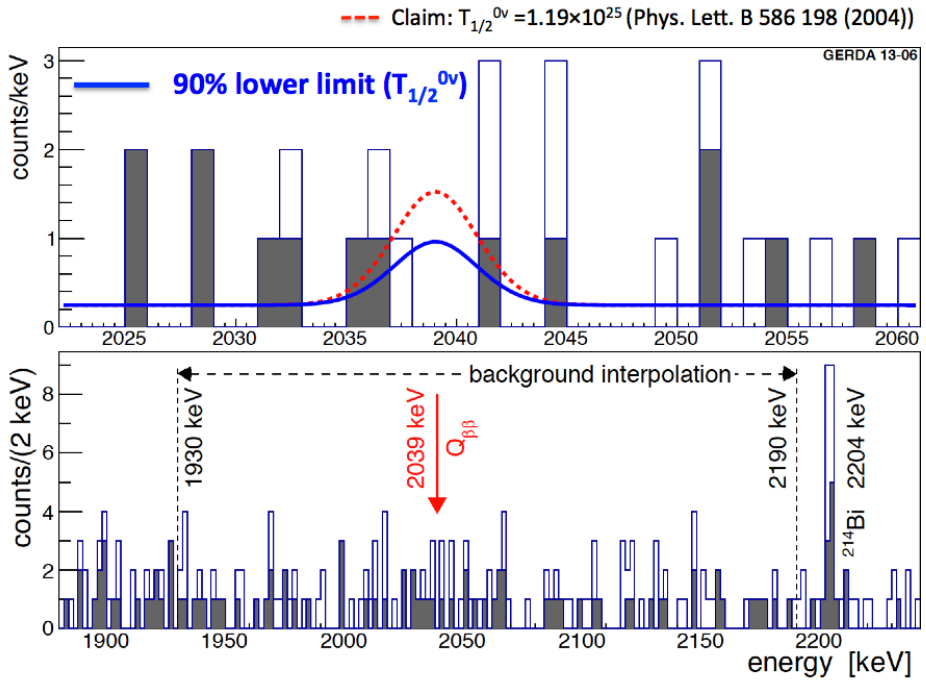
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

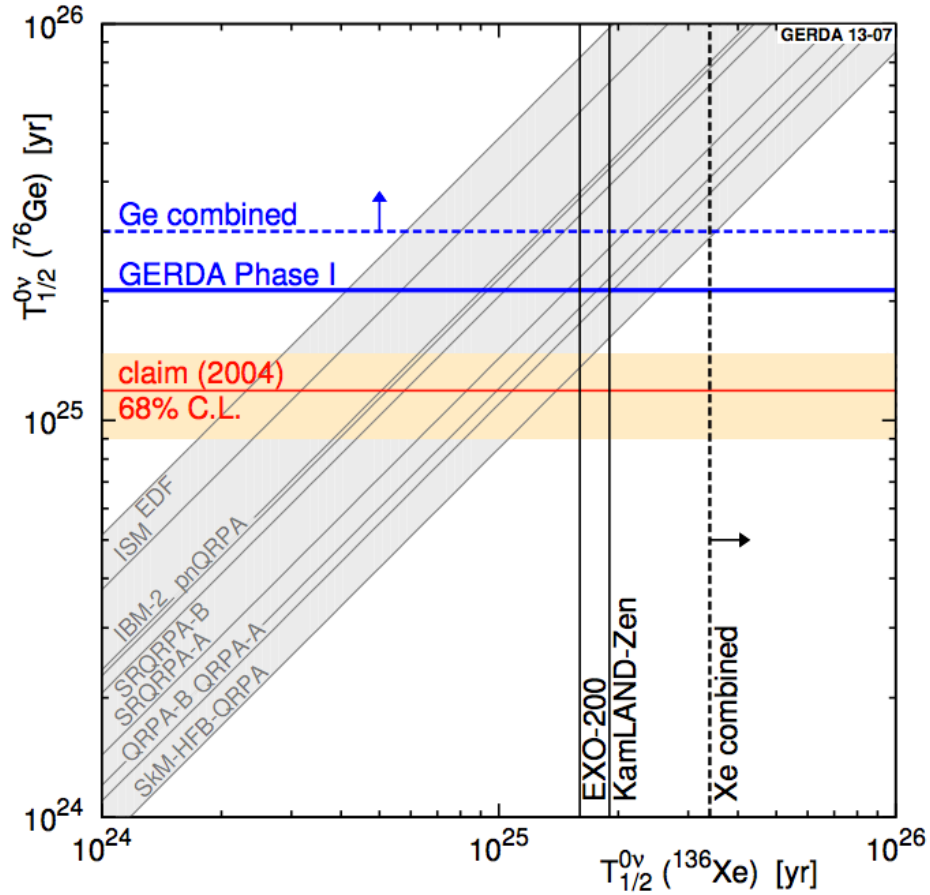
$$T^{2\nu}_{1/2}(^{76}Ge) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\ yr$$



LAB Talk of J. Phys. G Feb. 2013 issue:
http://iopscience.iop.org/0954-3899/labtalk-article/52398

GERDA 0νββ Results – Phase I





$T_{1/2}^{0\nu\beta\beta}$ (^{76}Ge) > 2.1x10^{25} yr

(90% C.L.)

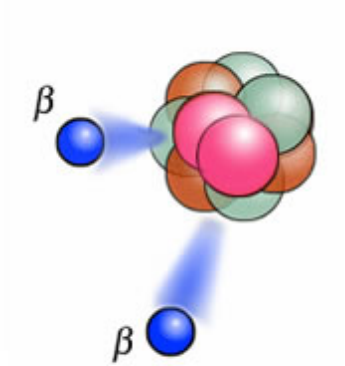
Klapdor-Kleingrothaus claim is ruled out with high probability by all recent experiments!

From Michael Salamon at DURA Meeting in March 2013

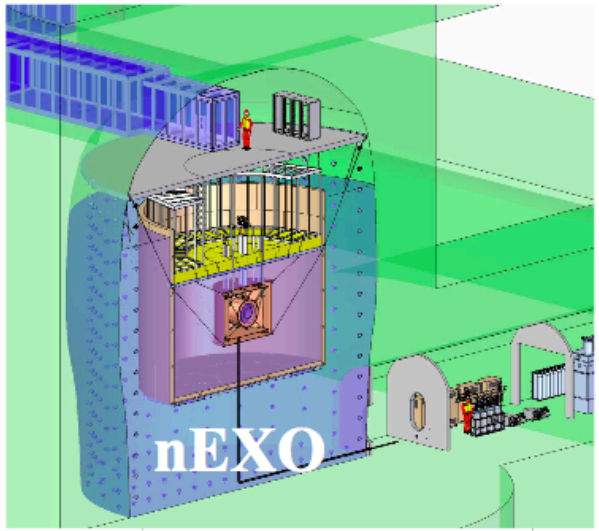
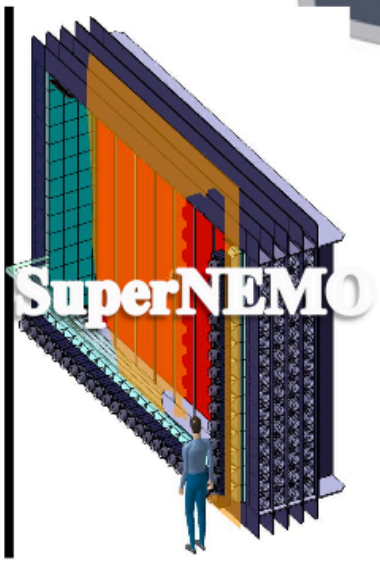
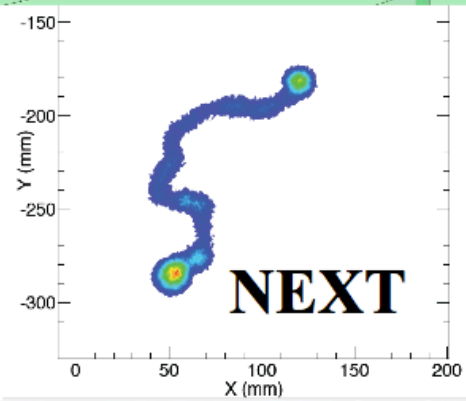
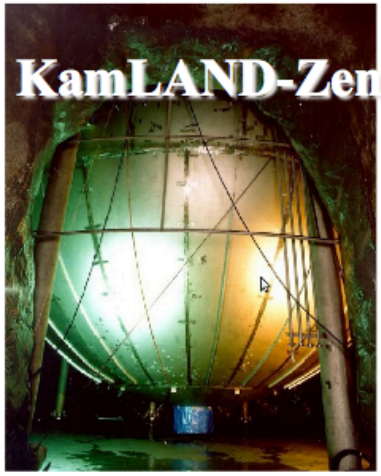
DOE Double Beta Decay: Comments

- DOE/Nuclear Physics is the steward for next-generation double beta decay experiments at DOE.
- DOE/HEP, however, is supporting EXO-200 for historical reasons, along with DOE/NP research and NSF support
- DOE/HEP (along with NSF) also is supporting all the R&D activities for the proposed 1-tonne scale next generation EXO, "nEXO."
- DOE/HEP and NP will establish a joint process to determine a selection process that involves both HEP and NP communities.
- After the time of selection, DOE/NP will become the sole DOE office supporting next-generation DBD projects.

A significant amount of the **technologies** and **facilities** used for double-beta decay overlap with the dark matter community, funded by DOE HEP.



Summary

- The physics of double beta decay is well-motivated with the ability to answer or shed light on key questions in neutrino physics and physics beyond the Standard Model
- The double beta decay program is strongly endorsed by the community
- The community has several promising ideas for covering the inverted neutrino mass hierarchy

The future of ββ0ν