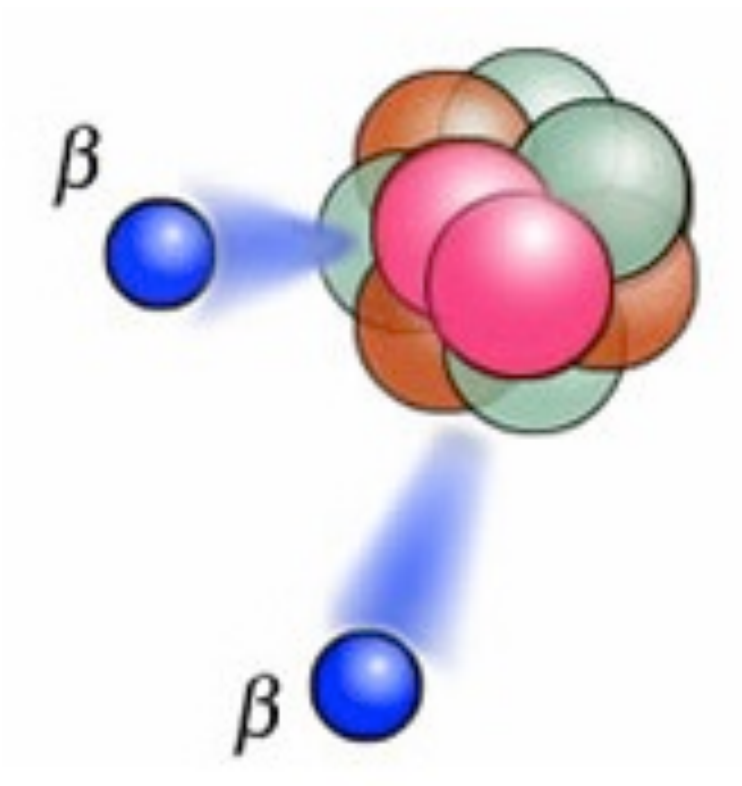
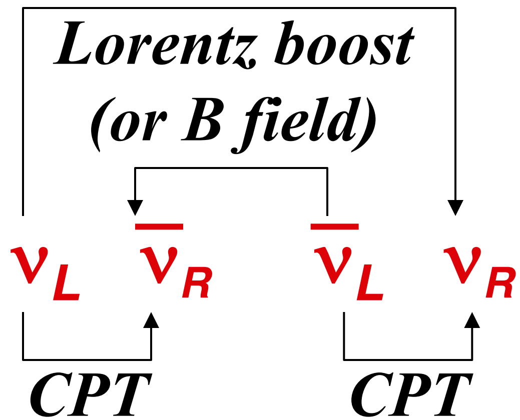
Neutrino Physics 3



Michelle Dolinski
Drexel University
NNPSS, 11 July 2019

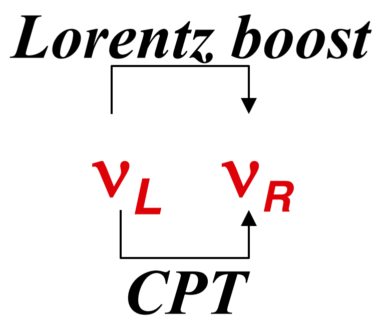
Massive neutrinos

"Dirac" neutrinos



"Majorana" neutrinos

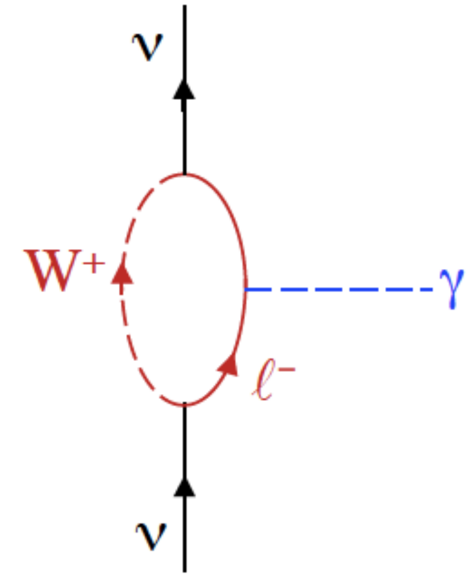
No lepton number conservation!



The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Electromagnetic properties of ν

Electromagnetic properties arise at the loop level. Dirac masses in the standard model give a prediction that the diagonal moments are proportional to the neutrino mass:



$$\mu_\nu = \frac{3 m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV}\right) \mu_B$$

In an extension with right handed neutrinos, the electric dipole vanishes for both Dirac and Majorana neutrinos, but the magnet moment also vanishes for Majorana neutrinos (can still have transition magnetic moments).

Experimental search for μ_ν

$$\mu_\nu = \frac{3m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV}\right) \mu_B$$

With known limits on neutrino mass, the "SM prediction" is small, so experimentally the search is for an anomalous magnetic moment of the neutrino. This is typically done by solar or reactor neutrino experiments, and neutrino oscillation parameters are taken into account.

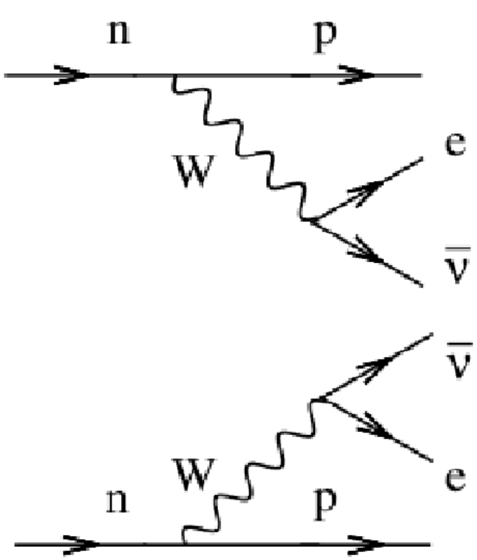
The best direct limit comes from Borexino using the spectral shape of electron recoils due to solar neutrinos (which would be affected if there were additional contributions to the cross-section due to an electromagnetic interaction term):

$$\mu_\nu^{eff} < 2.8{\cdot}10^{-11} \ \mu_B \text{ at } 90\% \text{ c.l.}$$

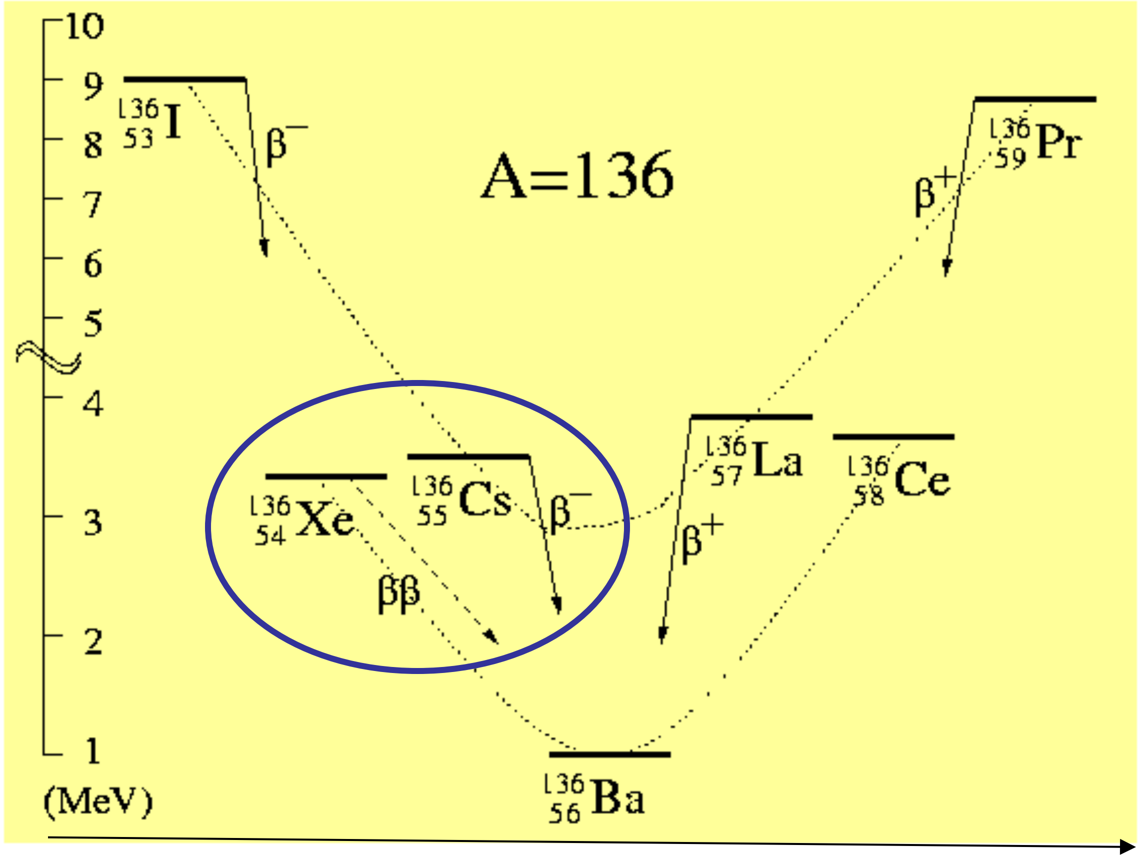
Agostini et al. Phys. Rev. D 96, 091103 (2017)

Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512



$2\nu\beta\beta$



Atomic number (Z)

Some candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

S. R. Elliott, A. A. Hahn, and M. K. Moe
Department of Physics, University of California, Irvine, Irvine, California 92717
(Received 31 August 1987)

The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

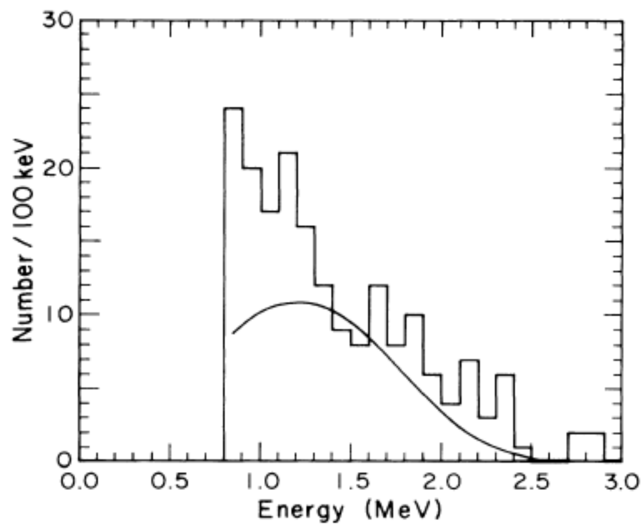
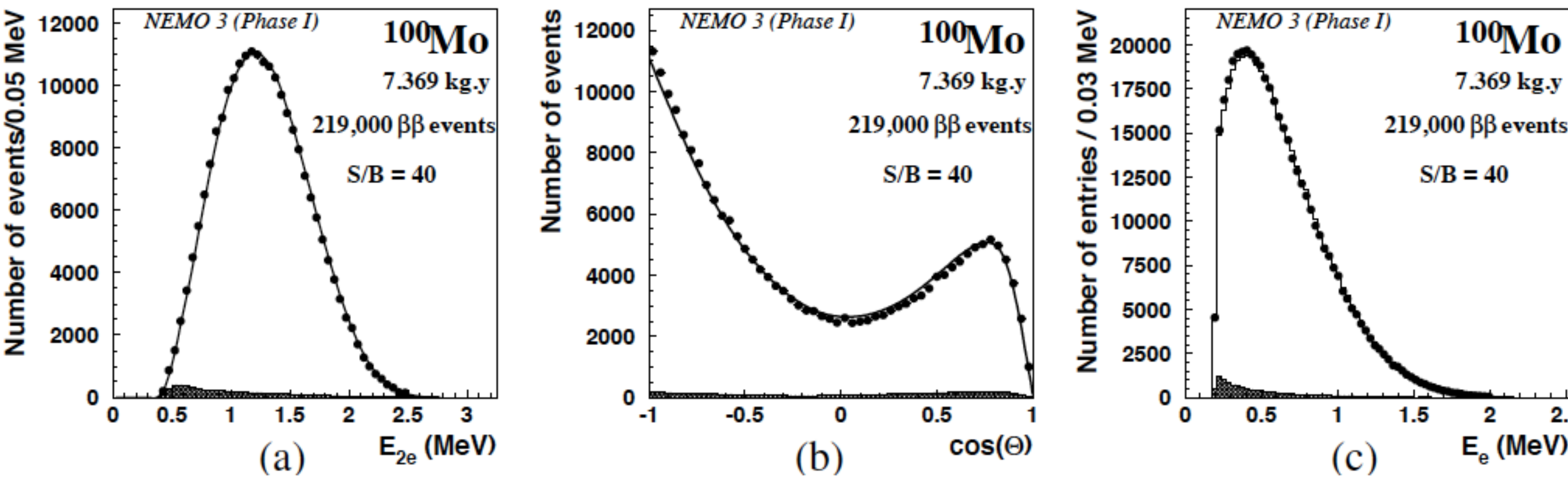


FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

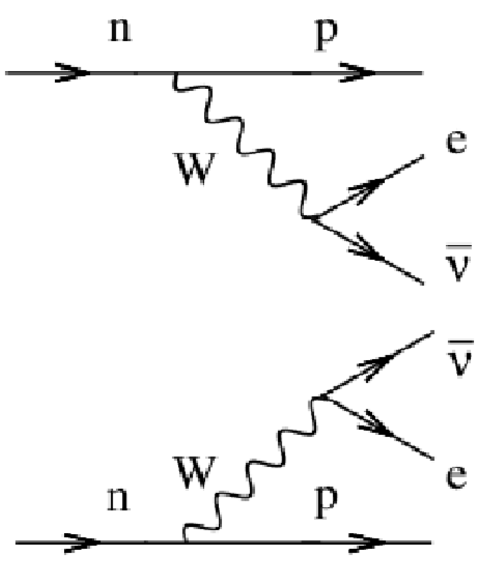
S.R. Elliott, A.A. Hahn, M.K. Moe *Phys. Rev. Lett.* **59** (1987) 2020-2023

Measured $2\nu\beta\beta$ half-lives

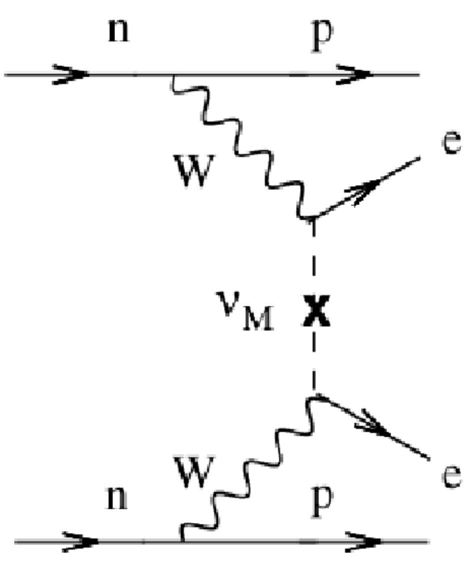
Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm \text{stat} \pm \text{sys}$ [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.2}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)



Neutrinoless double beta decay



$2\nu\beta\beta$

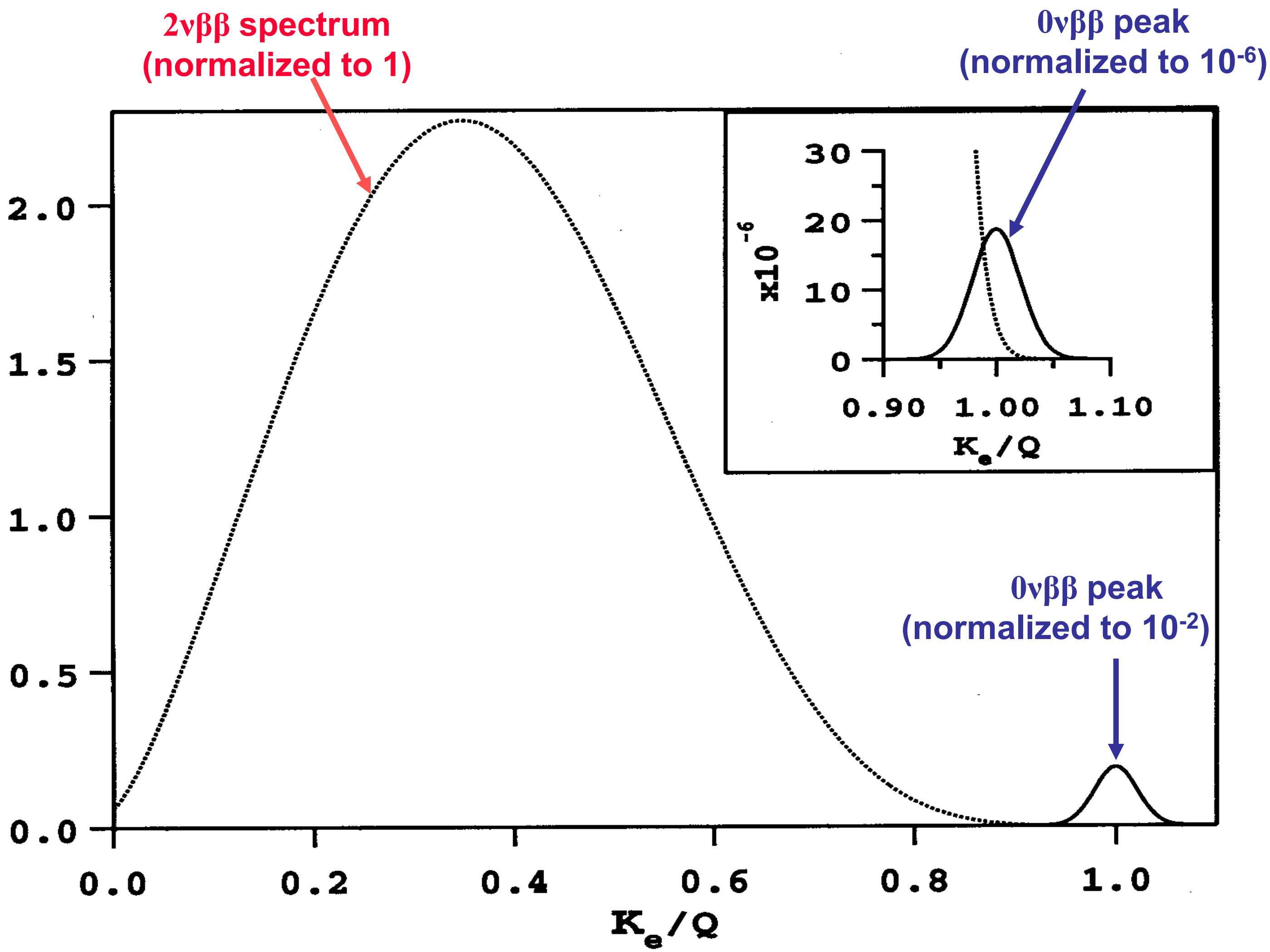


$0\nu\beta\beta$

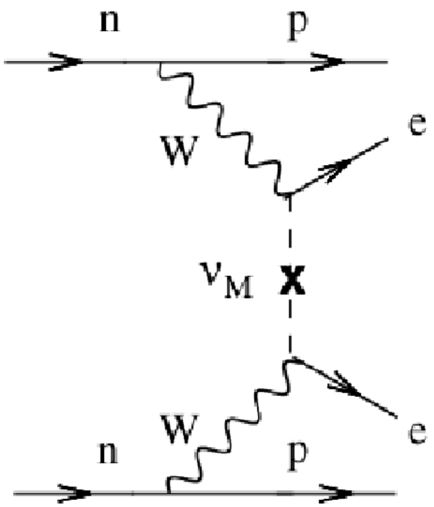
This process can only occur for a Majorana neutrino!

Same candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Double beta decay spectrum



$0\nu\beta\beta$ rate



If we assume that the mechanism is light neutrino exchange, we can write the rate for $0\nu\beta\beta$:

Phase space factor ~Q^5

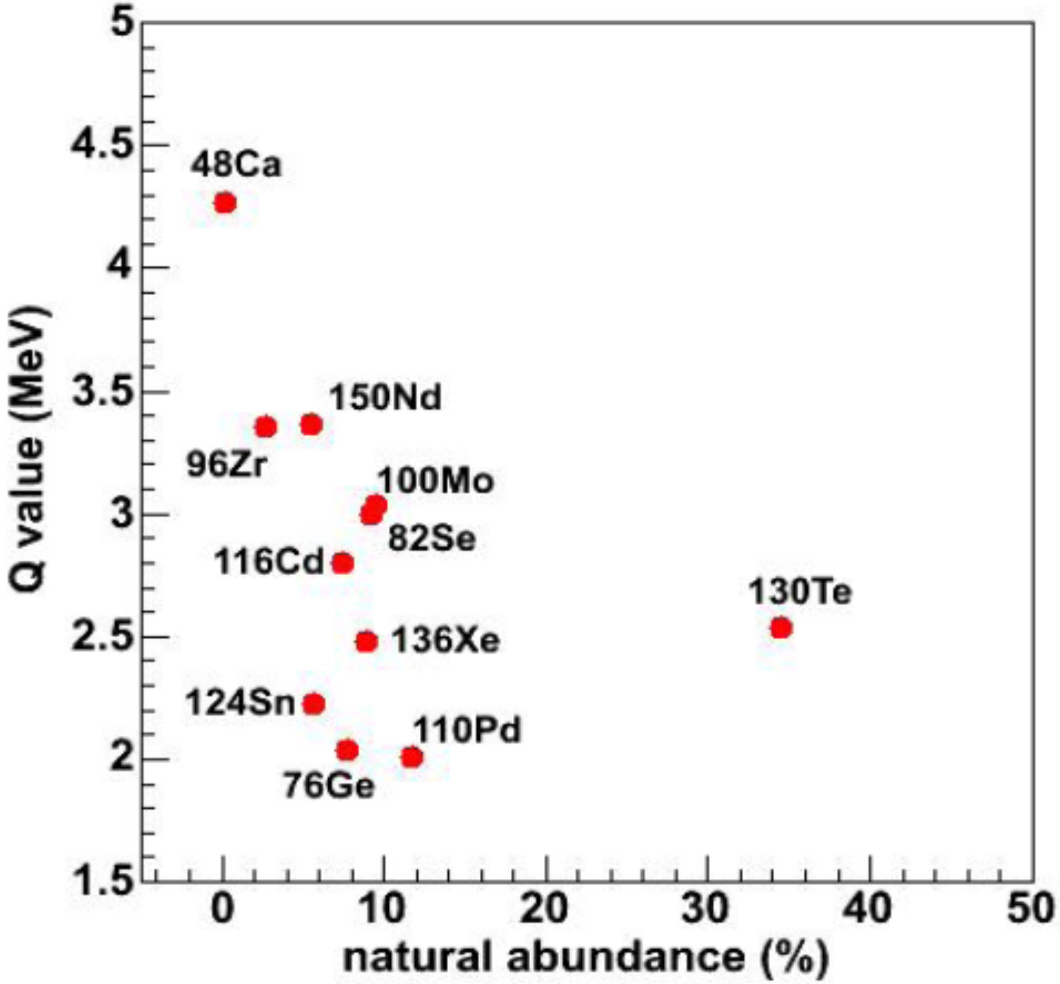
Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_\nu \rangle^2$$

Nuclear matrix element

Isotopes of interest

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \left\langle m_{\beta\beta}\right\rangle^2$$



Nuclear matrix elements

Nuclear structure approaches

In NSM (Madrid-Strassbourg group) a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few $0\nu\beta\beta$-decay calculations

In QRPA (Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups) a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more $0\nu\beta\beta$–decay calculations

In IBM (Iachello, Barea) the low lying states of the nucleus are modeled in terms of bosons. The bosons have either L=0 (s boson) or L=2 (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.

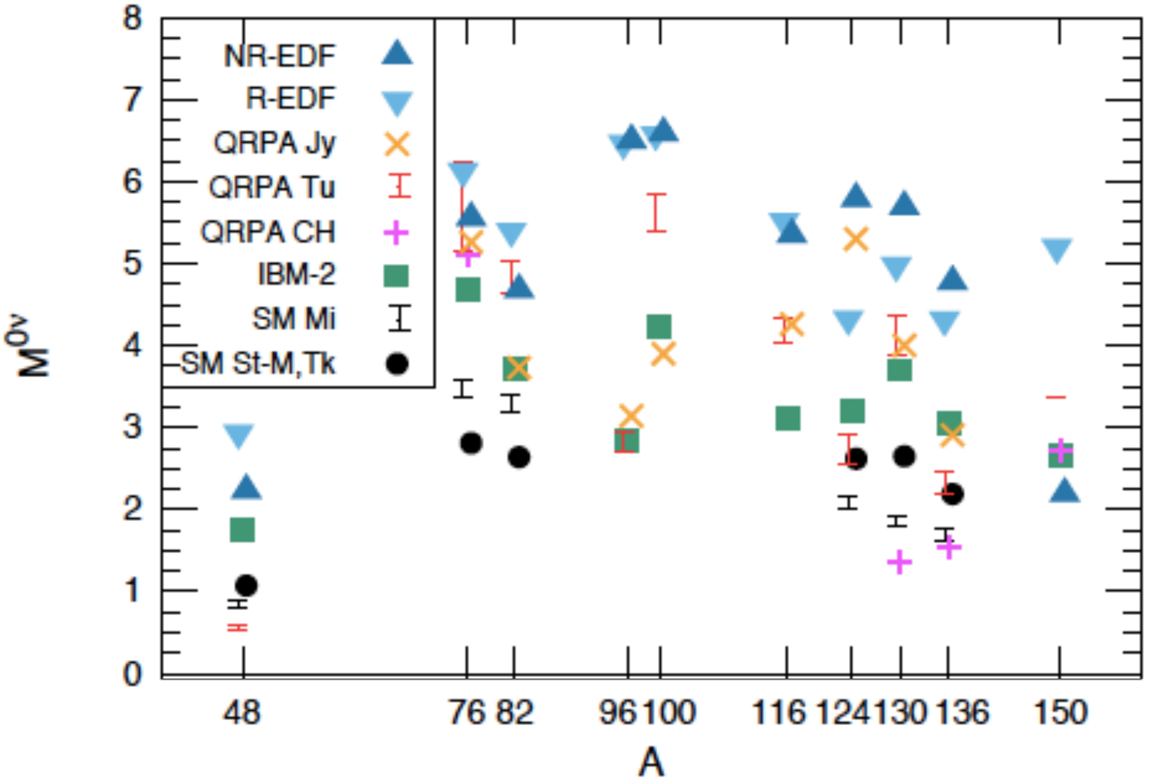
In PHFB (India/Mexico groups) w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.

Differences: i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation

F. Simkovic, Neutrino 2010

NME calculations

$$\langle m_{\beta\beta}\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\, G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$



Engel and Menendez, Reports on Progress in Physics 80, 046301 (2017)

•The uncertainties on individual isotopes are related to nuclear structure.

•In addition there is an overall uncertainty (not shown) on the effective value to be used for g_A.

Differences in the models include:

•Mean field
•Residual interaction
•Size of the model space
•Many-body approximation

F. Simkovic, Neutrino 2010

Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_{\beta\beta}\rangle^2$$

Using the standard representation of the PNMS matrix, the effective Majorana neutrino mass is given as:

$$\langle m_{\beta\beta}\rangle = \Big| m_1 \cdot (1-\sin^2\theta_{12}) \cdot (1-\sin^2\theta_{13}) + m_2 \cdot \sin^2\theta_{12} \cdot (1-\sin^2\theta_{13}) \cdot e^{i\cdot(\alpha_2-\alpha_1)} + m_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3} \Big|$$

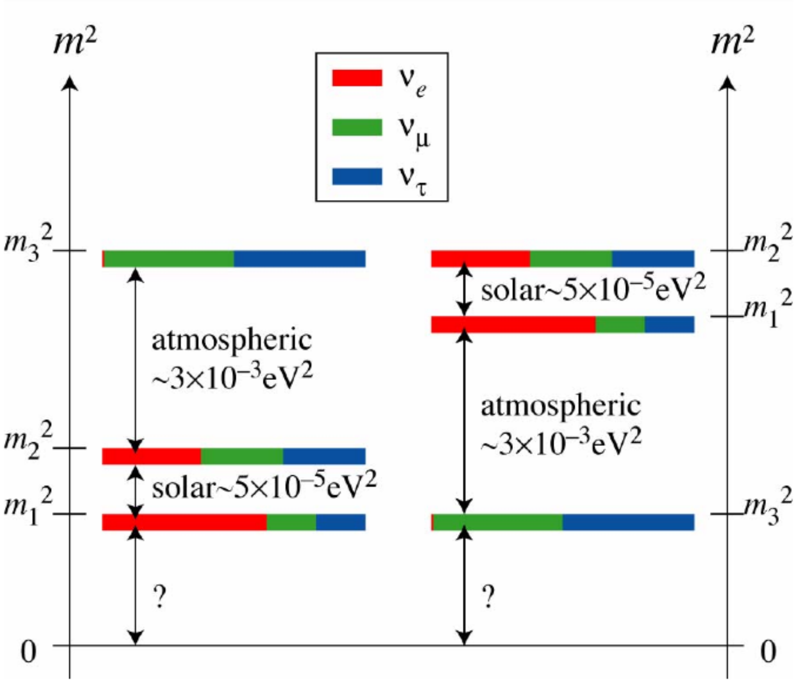
The three CP phases α_1, α_2, and α_3 are unknown. This uncertainty is expressed by varying:

$$\langle m_{\beta\beta}\rangle = \Big| m_1 \cdot (1-\sin^2\theta_{12}) \cdot (1-\sin^2\theta_{13}) \pm_{(1)} m_2 \cdot \sin^2\theta_{12} \cdot (1-\sin^2\theta_{13}) \pm_{(2)} m_3 \cdot \sin^2\theta_{13} \Big|$$

Neutrino mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_{\beta\beta} \rangle^2$$

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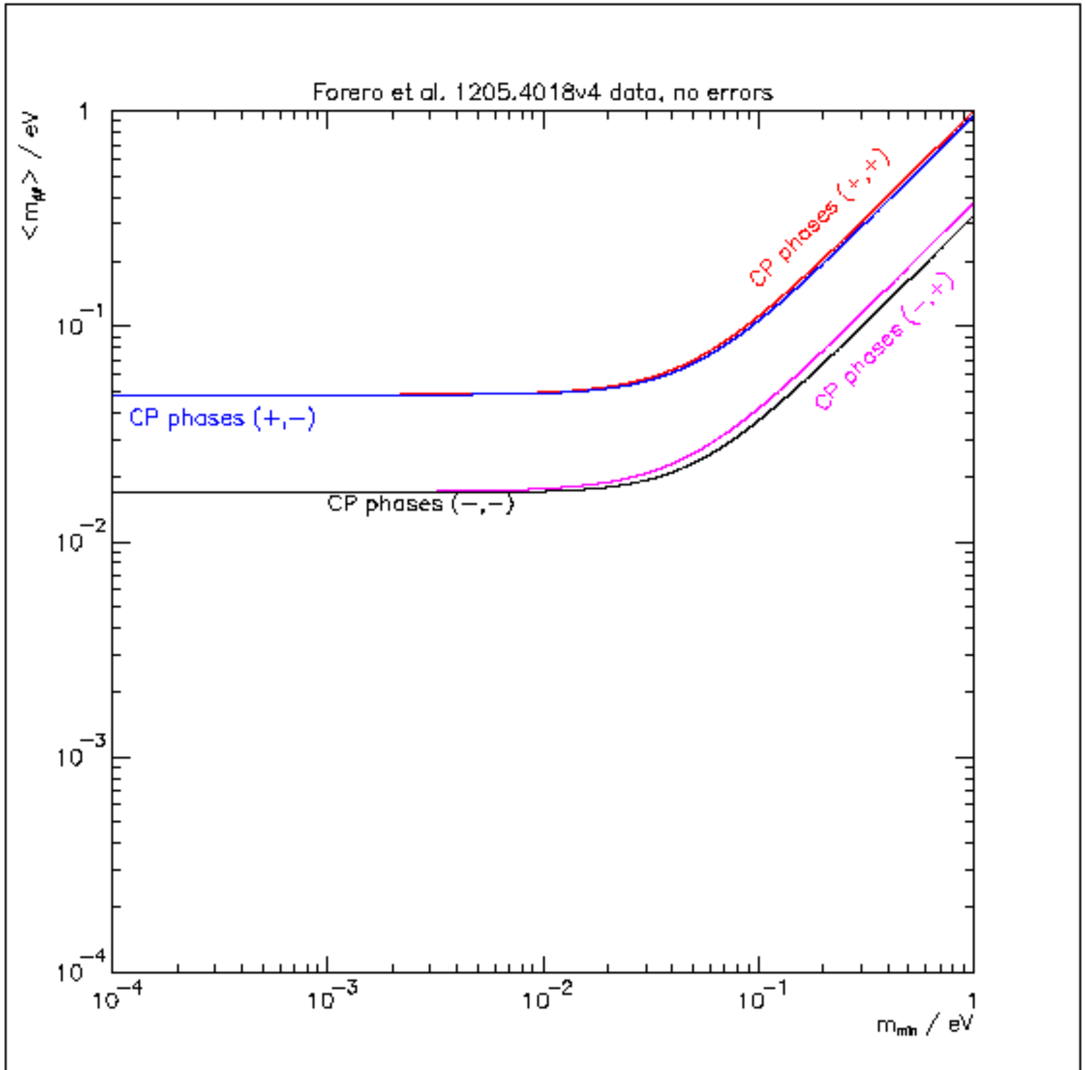
$$\langle m_{\beta\beta} \rangle = \left| m_1 \cdot (1 - \sin^2\theta_{12}) \cdot (1 - \sin^2\theta_{13}) + m_2 \cdot \sin^2\theta_{12} \cdot (1 - \sin^2\theta_{13}) \cdot e^{i\cdot(\alpha_2 - \alpha_1)} + m_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3} \right|$$

The three CP phases α_1, α_2, and α_3 are unknown. This uncertainty is expressed by varying:

$$\langle m_{\beta\beta} \rangle = \left| m_1 \cdot (1 - \sin^2\theta_{12}) \cdot (1 - \sin^2\theta_{13}) \pm_{(1)} m_2 \cdot \sin^2\theta_{12} \cdot (1 - \sin^2\theta_{13}) \pm_{(2)} m_3 \cdot \sin^2\theta_{13} \right|$$

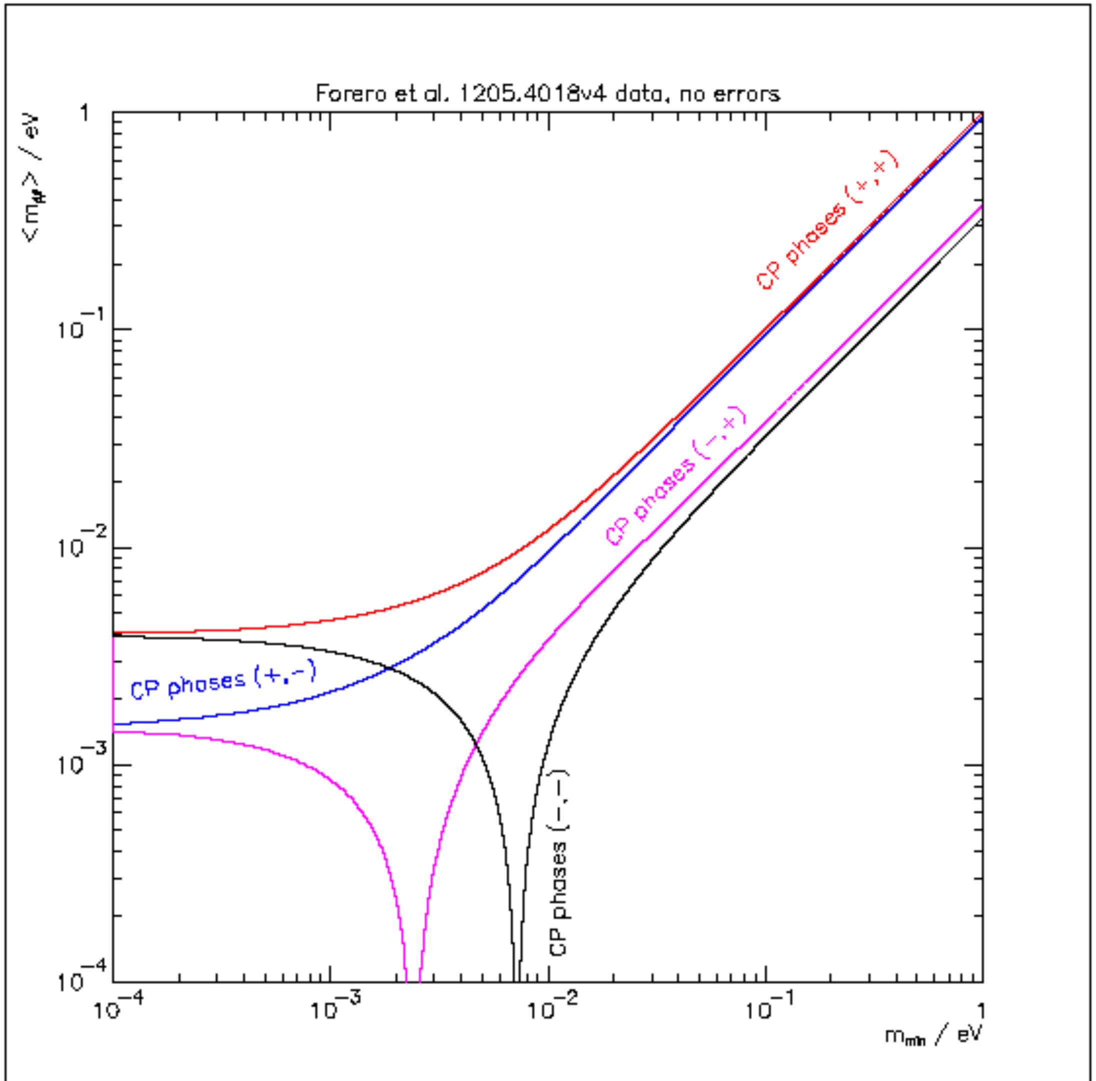
Inverted hierarchy



Now we insert the standard neutrino oscillation parameters (central values). No total cancellation is possible for the inverted hierarchy.

Plots courtesy Andreas Piepke.

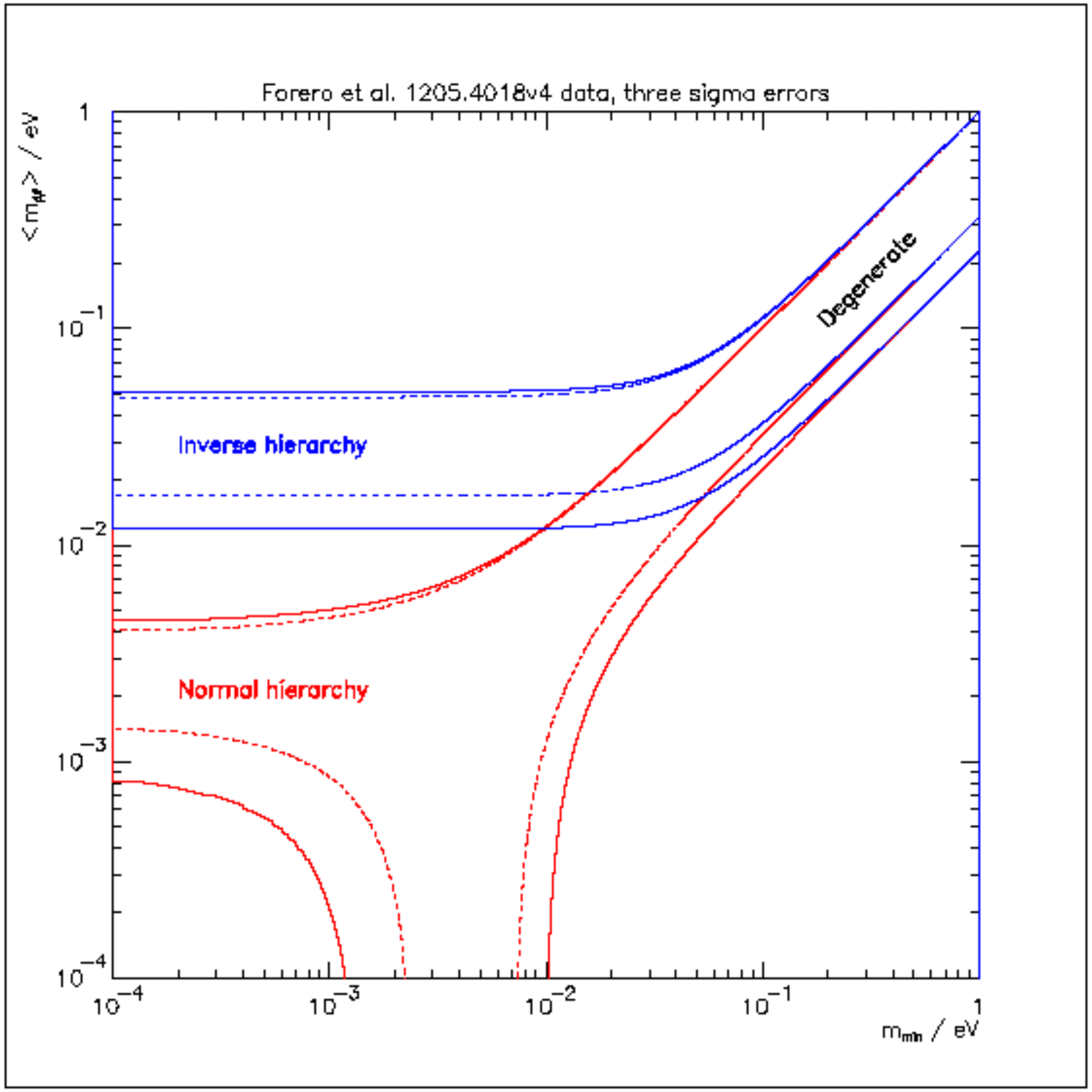
Normal hierarchy



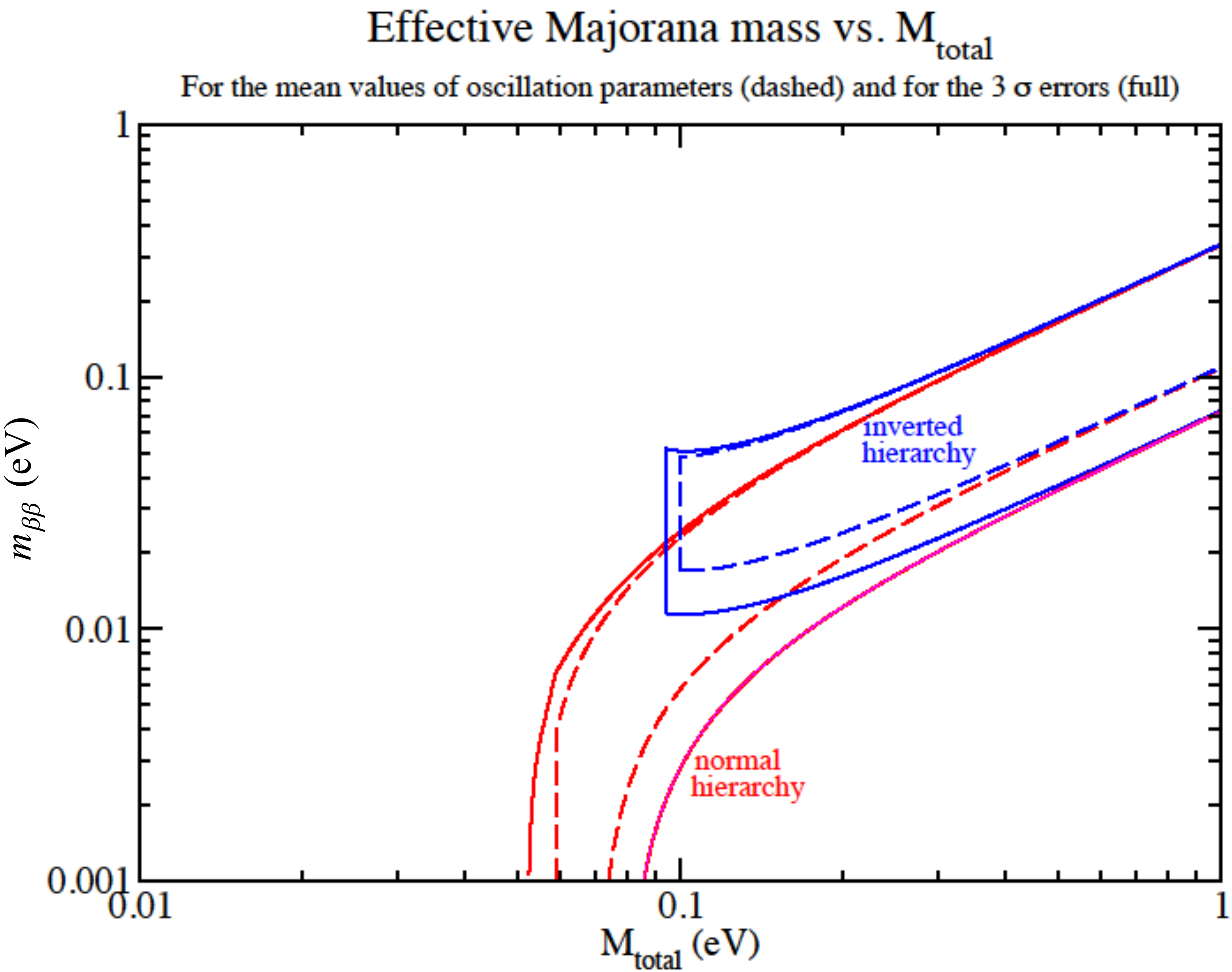
For the normal hierarchy variation of the unknown CP-phases introduces:

1) considerable variation of the effective mass,
2) allows destructive interference for certain values of m_{min} and choice of phases.

Combined phase space



Inverted and normal hierarchy including 3σ errors on oscillation parameters.


Effective Majorana mass vs. M_{total}
For the mean values of oscillation parameters (dashed) and for the 3 σ errors (full)
1
0.1
0.01
0.001
$m_{\beta\beta}$ (eV)
0.01
0.1
1
M_{total} (eV)
inverted
hierarchy
normal
hierarchy

A Global Bayesian Analysis of Neutrino Mass Data

Allen Caldwell,[1,*] Alexander Merle,[1,†] Oliver Schulz,[1,‡] and Maximilian Totzauer[1,§]
[1] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
(Dated: May 8, 2017)

We perform a global Bayesian analysis of currently available neutrino data, putting data from oscillation experiments, neutrinoless double beta decay ($0\nu\beta\beta$), and precision cosmology on an equal footing. We evaluate the discovery potential of future $0\nu\beta\beta$ experiments and the Bayes factor of the two possible neutrino mass ordering schemes for different prior choices. We show that the indication for normal ordering is still very mild and does not strongly depend on realistic prior assumptions or different combinations of cosmological data sets. We find a wide range for $0\nu\beta\beta$ discovery potential, depending on the absolute neutrino mass scale, mass ordering and achievable background level.

Caldwell, *et al.*
arXiv:1705.01945v1

Discovery probability of next-generation neutrinoless double-β decay experiments

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Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 74720 - USA

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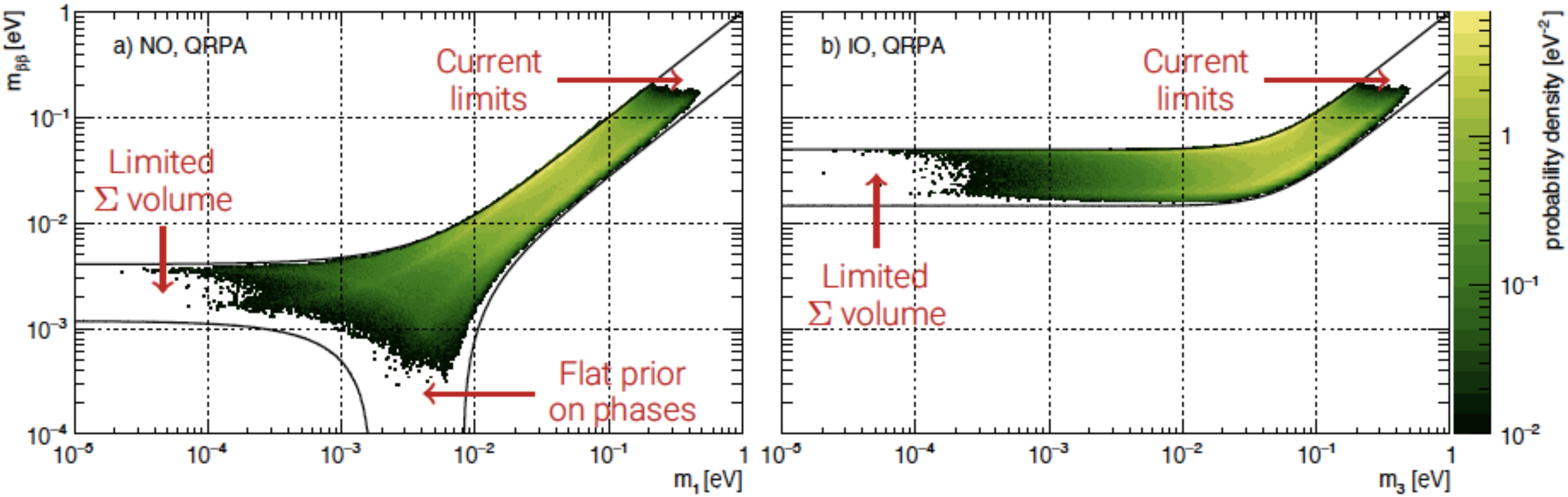
Center for Experimental Nuclear Physics and Astrophysics,
and Department of Physics, University of Washington, Seattle, WA 98115 - USA

(Dated: May 9, 2017)

The Bayesian discovery probability of future experiments searching for neutrinoless double-β decay is evaluated under the popular assumption that neutrinos are their own antiparticles. A Bayesian global fit is performed to construct a probability distribution for the effective Majorana mass, the observable of interest for these experiments. This probability distribution is then combined with the sensitivity of each experiment derived from a heuristic counting analysis. The discovery probability strongly depends on whether the neutrino mass ordering is normal or inverted, and is found to be higher than previously considered for both mass orderings. In the absence of neutrino mass mechanisms that drive the lightest state or the effective Majorana mass to zero, for the inverted ordering next-generation experiments are likely to observe a signal already during their first operational stages. Even for the normal ordering, the probability of discovering neutrinoless double-β decay reaches $\sim$50% or more in the most promising experiments.

Agostini, *et al.*
arXiv:1705.02996v1

Phase space

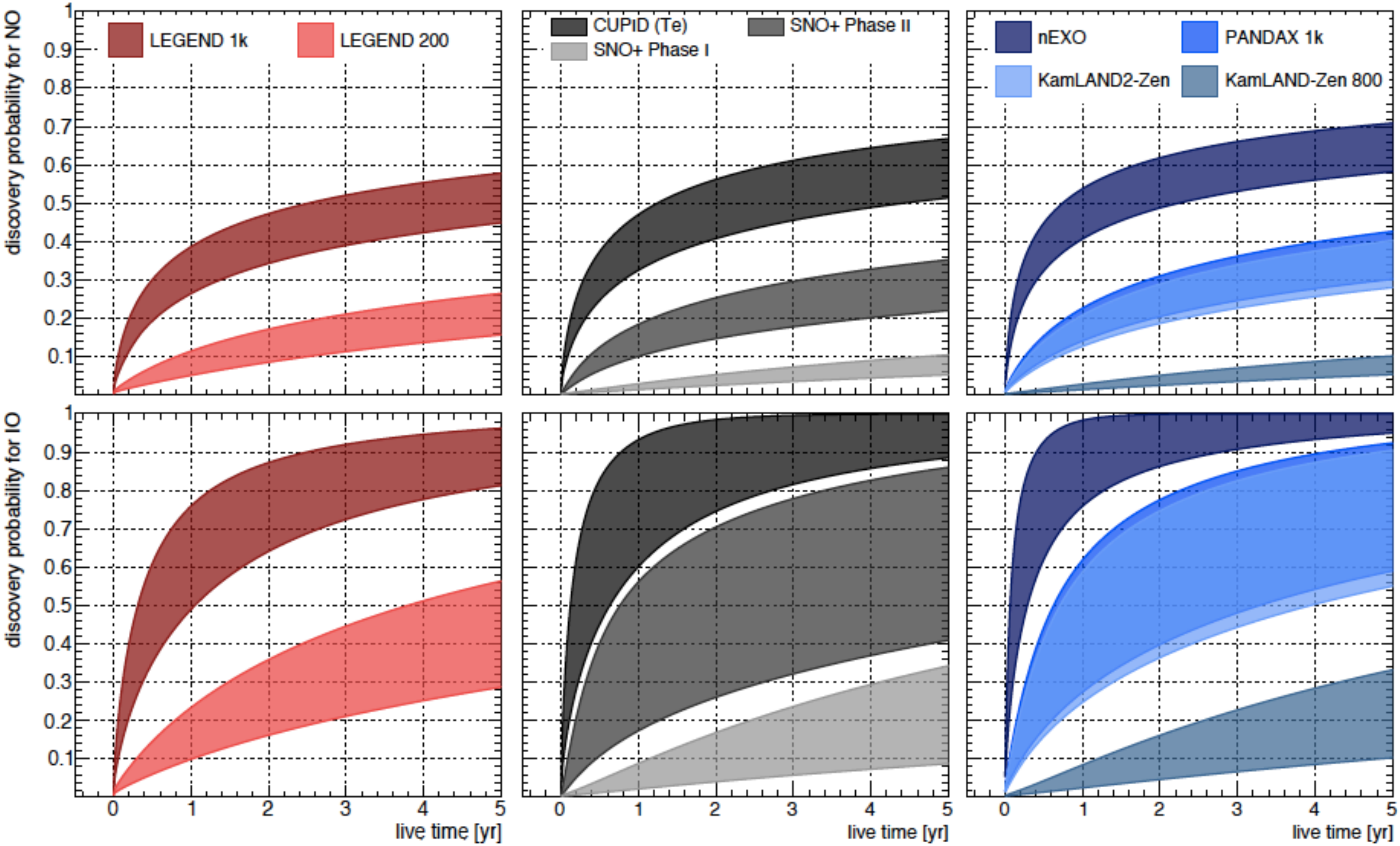


Caveats

- In NO, a flavor symmetry could induce an apparent fine tuning of the Majorana phases and a vanishing $m_{\beta\beta}$
- Mass mechanisms that drive m_l to zero are not considered
  $\Rightarrow$ Just extrapolate down the horizontal bands

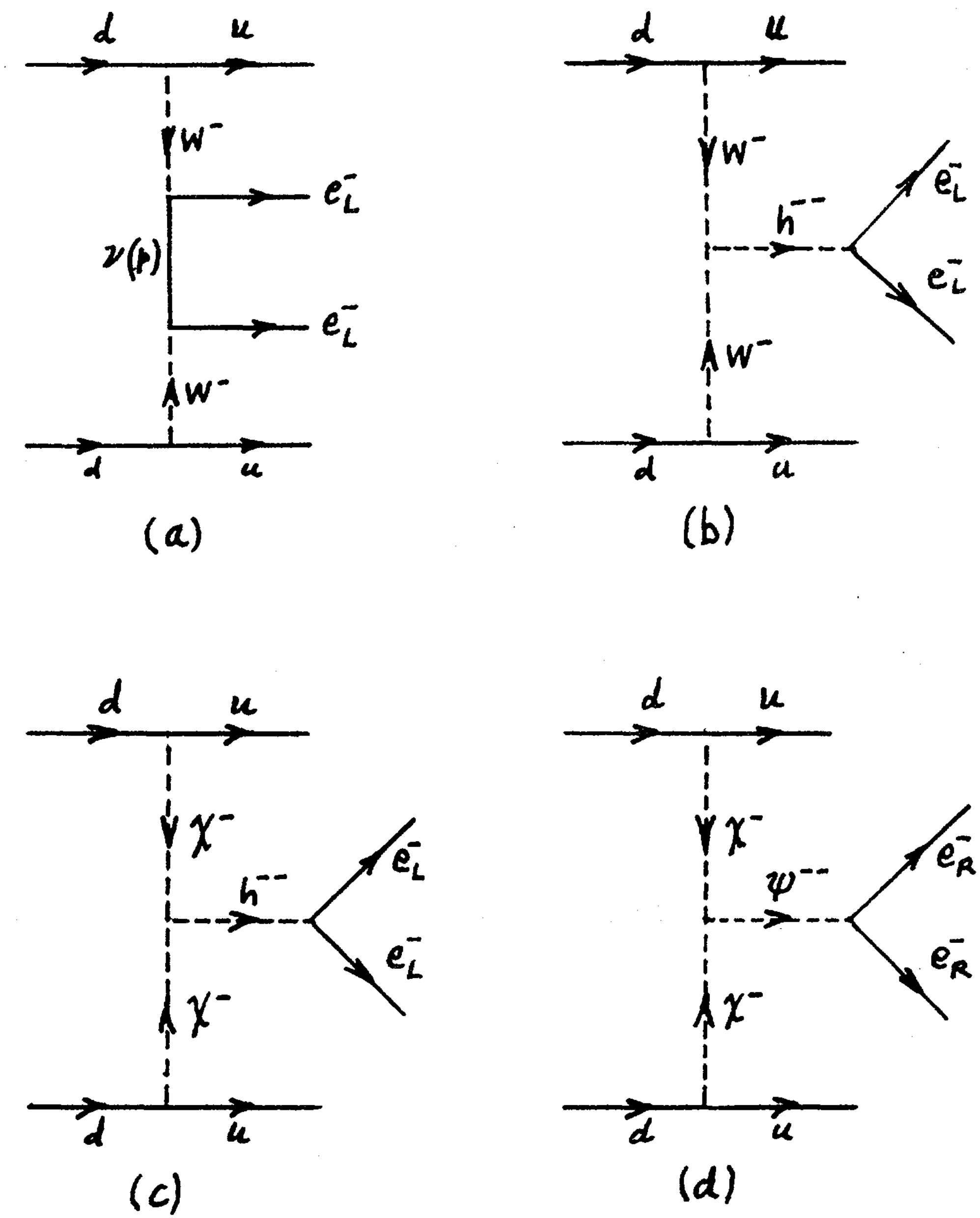
Benato, TAUP 2017 and
Agostini, *et al.* arXiv:1705.02996v1

Discovery potential



Agostini, *et al*. arXiv:1705.02996v1

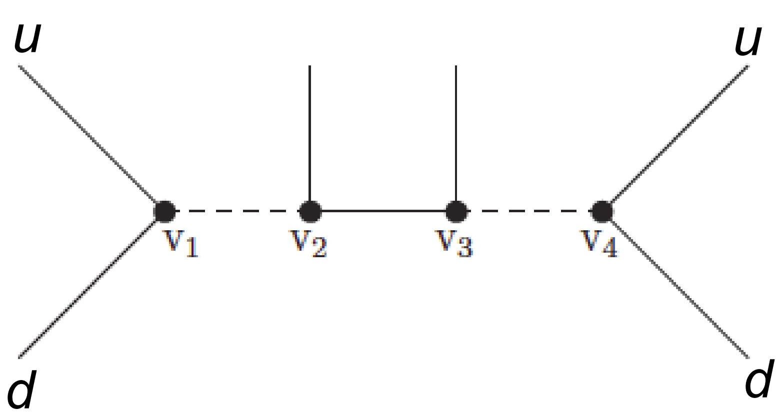
Mechanism?

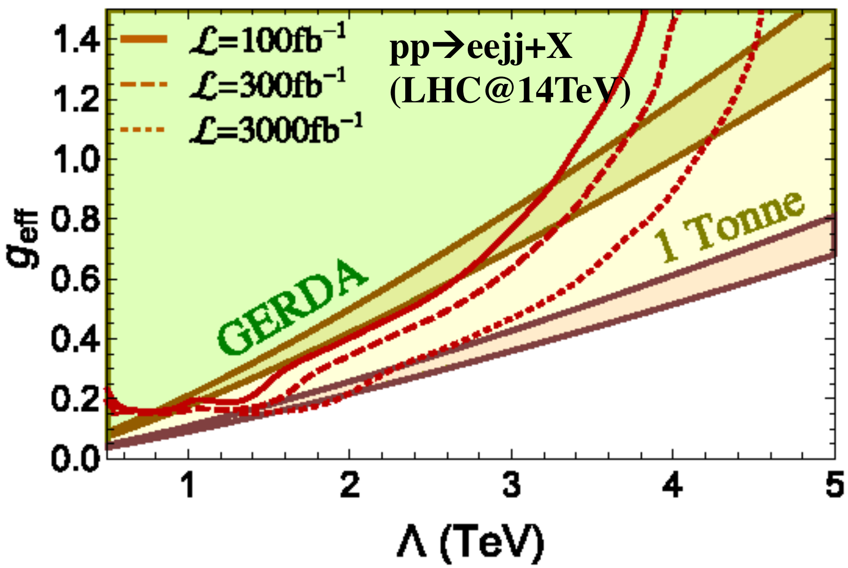


In some cases, it's possible to determine the mechanism by measuring the opening angle between the electrons.

LHC complementarity

One more SUSY-inspired example:





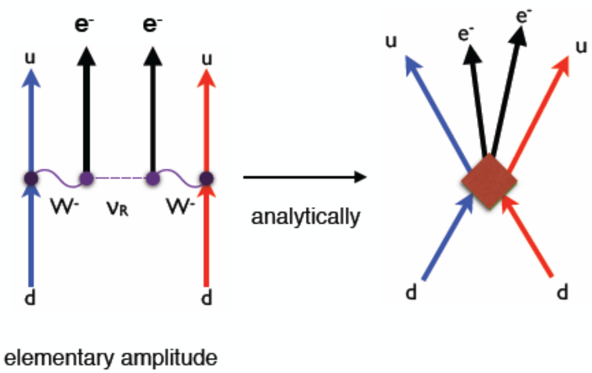
Peng, Ramsey-Musolf, Winslow, PRD 93, 093002 (2016)

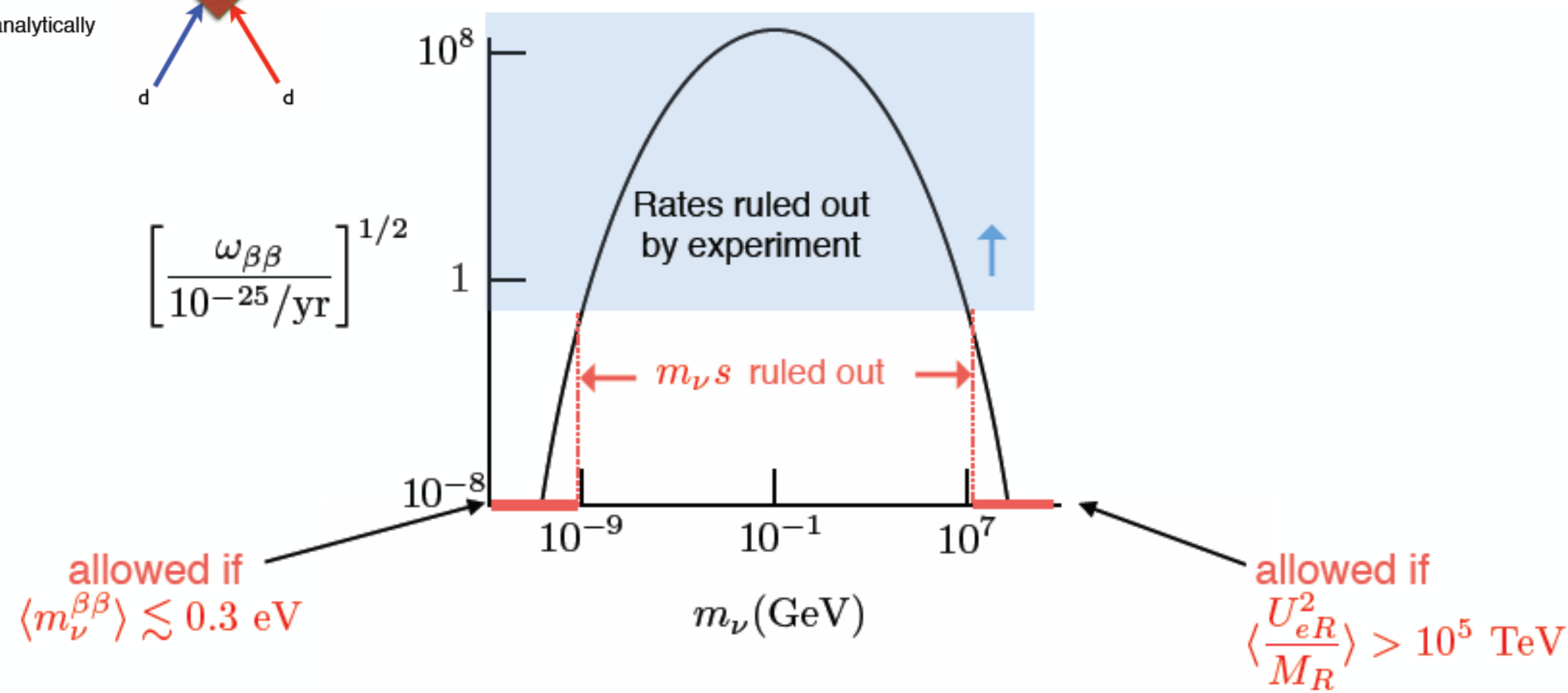
Note that even in this case the decay implies Majorana masses, except the relationship to the half-life is now a different one.

0νββ decay always implies new physics!

Other mechanisms

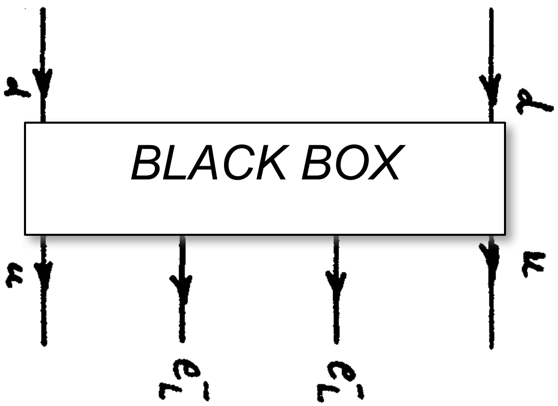
While it is convenient to think in terms of the light neutrino exchange mechanism, it may not be the dominant mechanism.

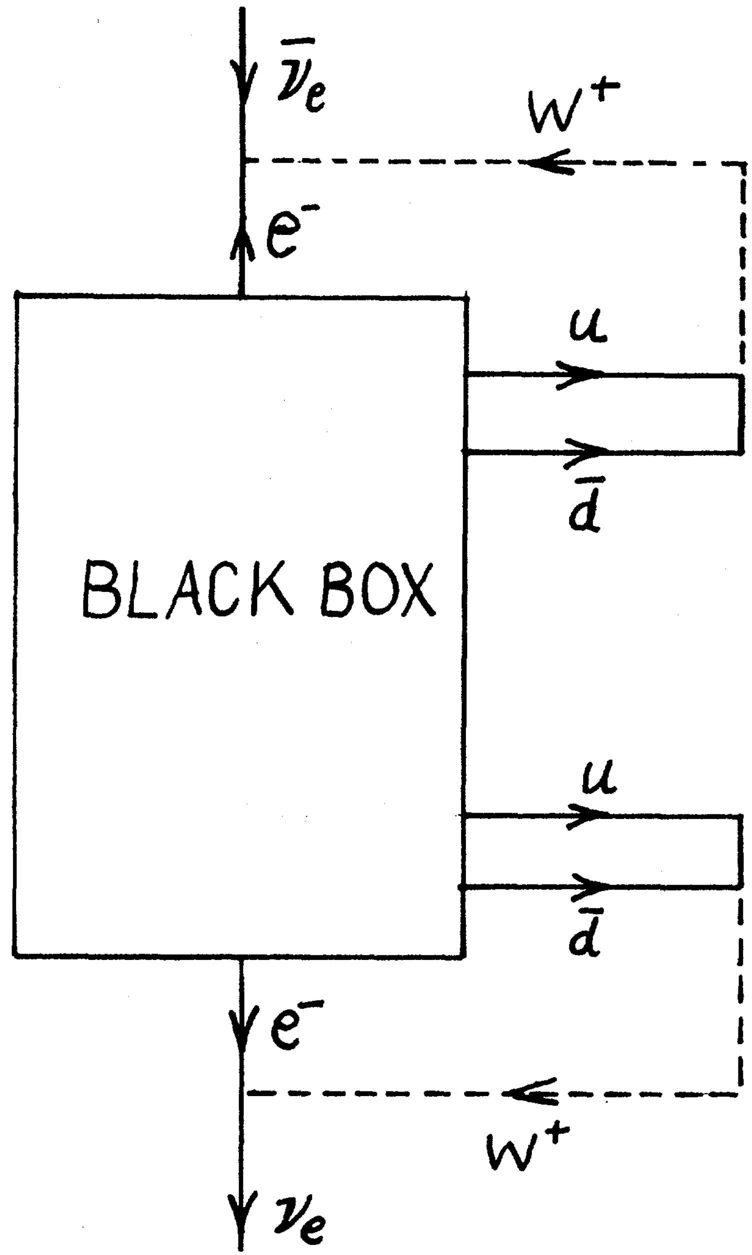




Wick Haxton, DNP 2016

Black box theorem (Schechter and Valle)

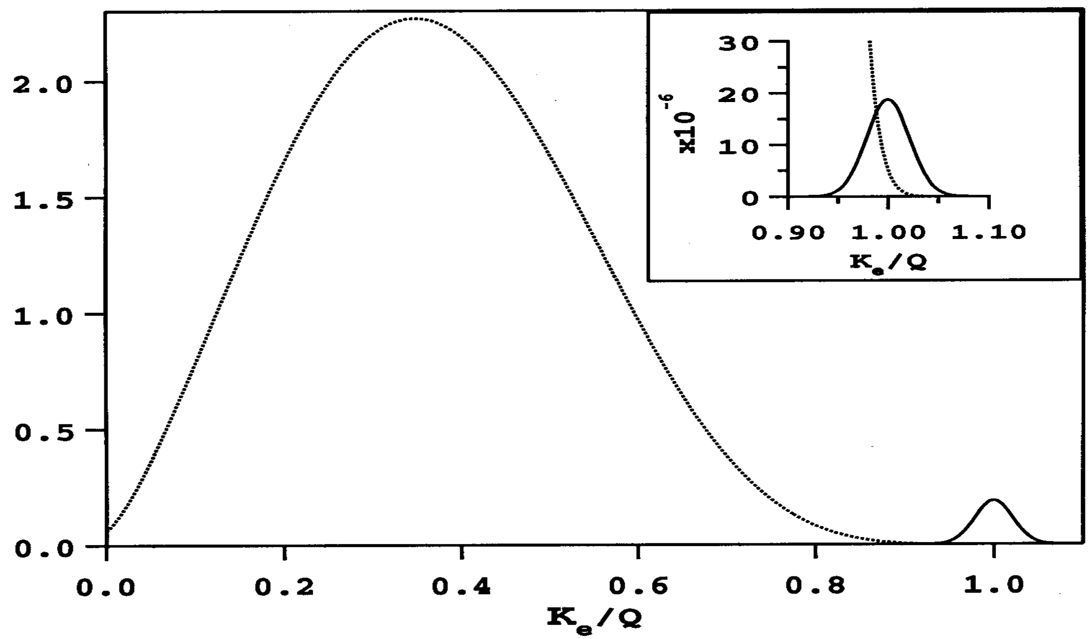


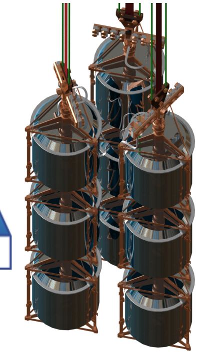


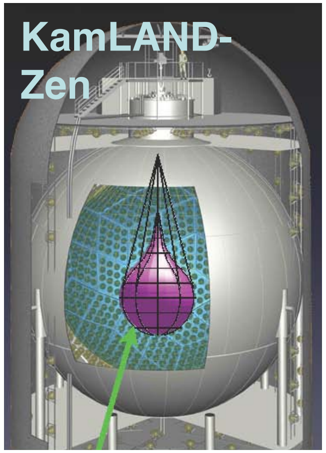
See also JHEP 1106:091, 2011

Experimental search

How to search for $0\nu\beta\beta$?

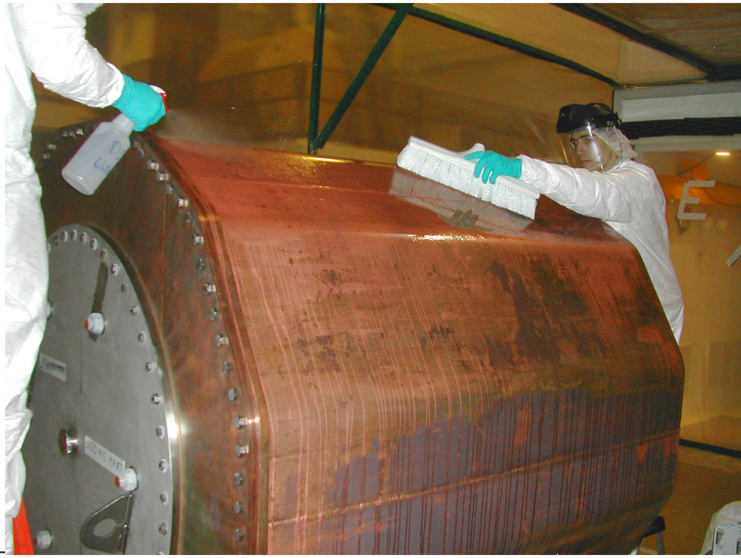






- Large exposure
- High isotopic abundance
- Good energy resolution
- Low background
- High detection efficiency

Low background



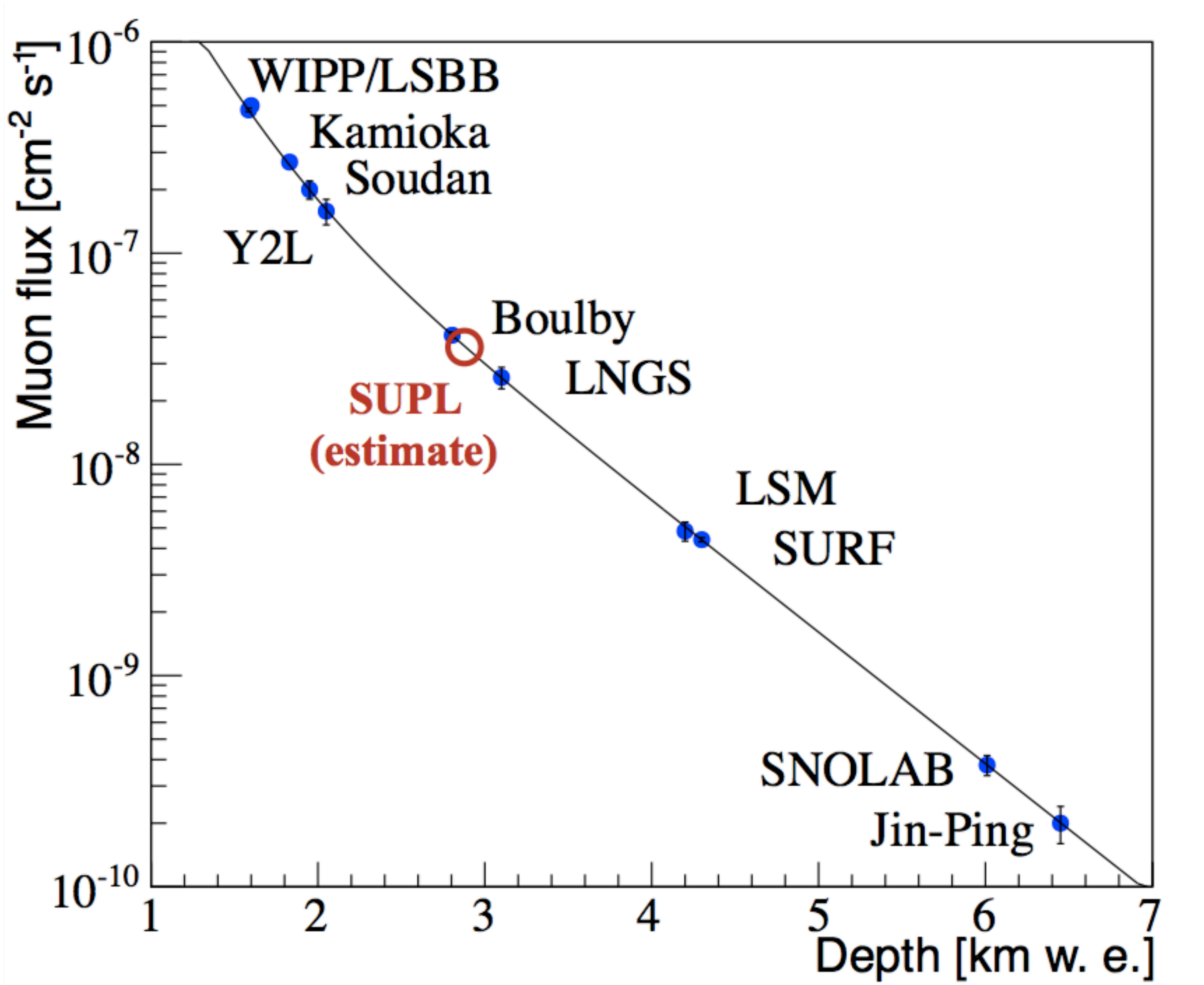
Massive effort on material radioactive qualification using:

- Neutron activation analysis
- Low background γ-ray spectroscopy
- α-counting and radon counting
- High sensitivity GD-MS and ICP-MS

At present the database of characterized materials includes over 300 entries. See D.Leonard et al., *Nucl. Instr. Meth*. A**591**, 490 (2008).

Material	Method	K conc. (10^{-9} g/g)	Th conc. (10^{-12} g/g)	U conc. (10^{-12} g/g)
Bulk copper				
Norddeutsche Affinerie, NOSV copper made May 2002	Shiva Inc. GD-MS	0.4	<5	<5
Norddeutsche Affinerie, NOSV copper made May 2002	Ge	<120	<35	<63
Norddeutsche Affinerie OFRP copper made May 2006, batch E263/2E1	ICP-MS	<55	<2.4	<2.9
Norddeutsche Affinerie OFRP copper made May 2006 batch E262/3E1	ICP-MS	<50	<2.4	<2.9
Rolled Norddeutsche Affinerie OFRP copper, May 2006 production. Rolled by Carl-Schreiber GmbH	ICP-MS	–	<3.1	<3.8
TIG welded Norddeutsche Affinerie OFRP copper made May 2002. No cleaning after welding. Results are normalized to length of weld	ICP-MS	–	<9.8 pg/cm	10.2 ± 3.4 pg/cm
Valcool VNT 700 metal working lubricant, concentrate	A.G. Ge	38 000 ± 11 000	<10 000	<3700
Water alcohol mixture, lubricant for machining of Cu parts	A.G. Ge	<44 000	<18 000	<3800

Underground physics



Mei, Dongming *et al.* Phys.Rev. D73 (2006) 053004

Liquid (organic) scintillators:
- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)

Pros: “Simple”, large detectors exist, self-shielding
Cons: Poor energy resolution, 2v background

Crystals:
- GERDA, Majorana Demonstrator, LEGEND (^{76}Ge)
- CUORE, CUPID (^{130}Te)

Pros: Superb energy resolution, possibly 2-parameter measurement
Cons: Intrinsically fragmented

Low density trackers:
- NEXT, PandaX (^{136}Xe gas TPC)
- SuperNEMO (foils and gas tracking, ^{82}Se)

Pros: Superb topological information
Cons: Very large size

Liquid TPC:
- EXO-200, nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology
Cons: Does not excel in any single parameter

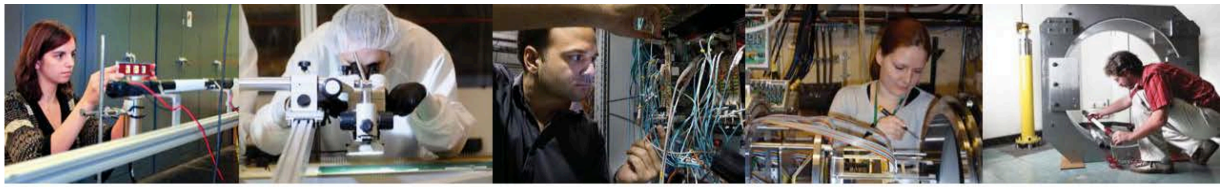
Current best $0\nu\beta\beta$ sensitivities

Isotope	Experiment	Exposure (kg yr)	$T_{1/2}^{0\nu\beta\beta}$ average sensitivity (10^{25}yr)	$T_{1/2}^{0\nu\beta\beta}$ (10^{25}yr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	GERDA	82.4	11	>9.0	<113-254	Agostini et al. PRL 120 (2018) 132503
	MJD	29.7	4.8	>2.7	<200-433	Alvis et al. arXiv:1902.02299 (2019)
^{130}Te	CUORE	24.0	0.7	>1.5	<110-520	Alduino et al. PRL 120 (2018) 132501
^{136}Xe	EXO-200	234.1	5.0	>3.5	<93-286	Anton et al. arXiv:1906.02723 (2019)
	KamLAND-ZEN	504	5.6	>10.7	<60-161	Gando et al., PRL 117 (2016) 082503

Note that the range of NME is chosen by the experiments, uncertainties related to g_A not included.

To achieve higher sensitivity, the next generation of experiments will be at the ton scale.

A priority for nuclear physics



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

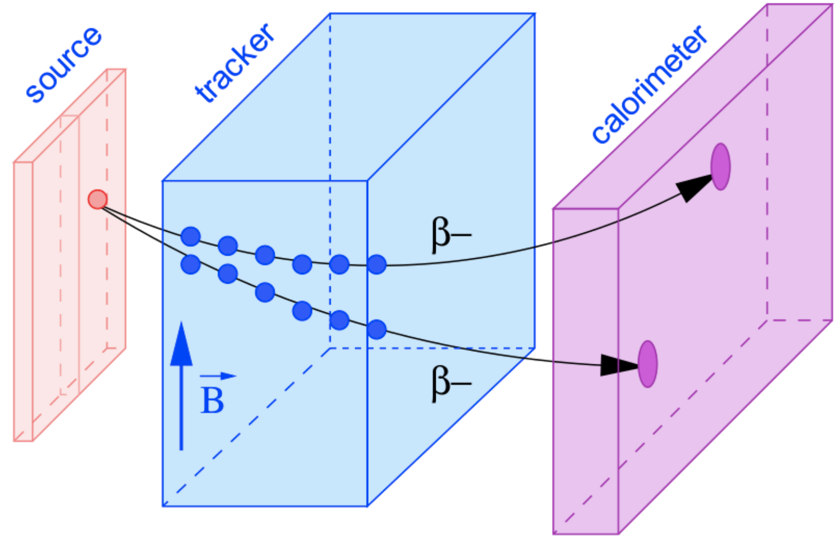
RECOMMENDATION II:
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.
"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

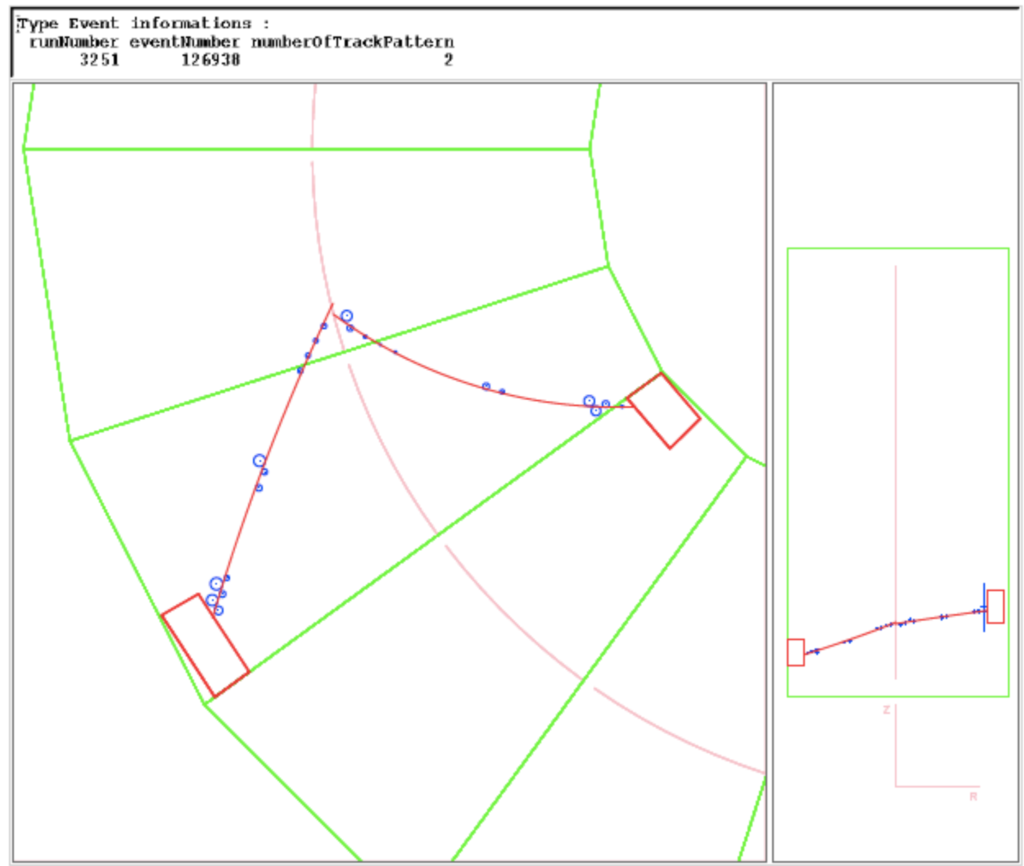
INITIATIVE B:
"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

Tour of Experiments

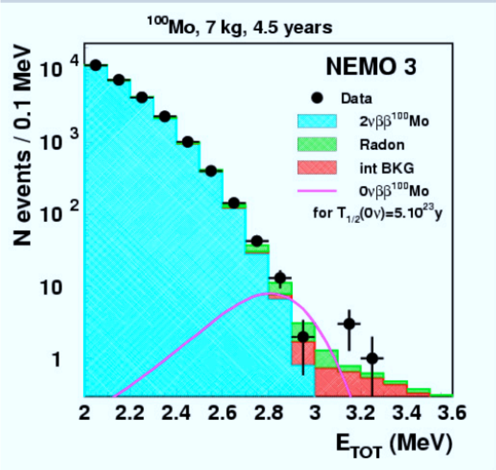
NEMO-3

Like the first observation of $2\nu\beta\beta$ in the laboratory, NEMO-3 uses source foils in a gas TPC.





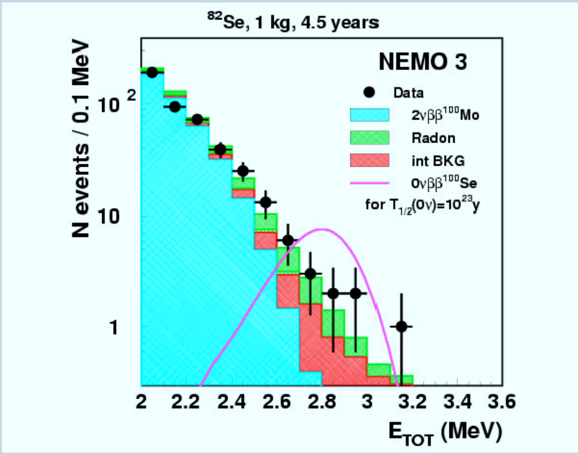
NEMO-3 to SuperNEMO



[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

$\langle m_\nu \rangle < (0.47 - 0.96)$ eV



[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

$\langle m_\nu \rangle < (0.94 - 2.5)$ eV

supernemo collaboration

SuperNEMO will scale up to ~100 kg in Modane (LSM). Working on demonstrator module now.

- 2034 drift cells working in Geiger mode
- Ultrapure materials : copper, steel, duracon. HPGe and radon tested.
- Robotic construction
- Radiopure gas flow, anti-radon sealing
- < 1 % of dead channels

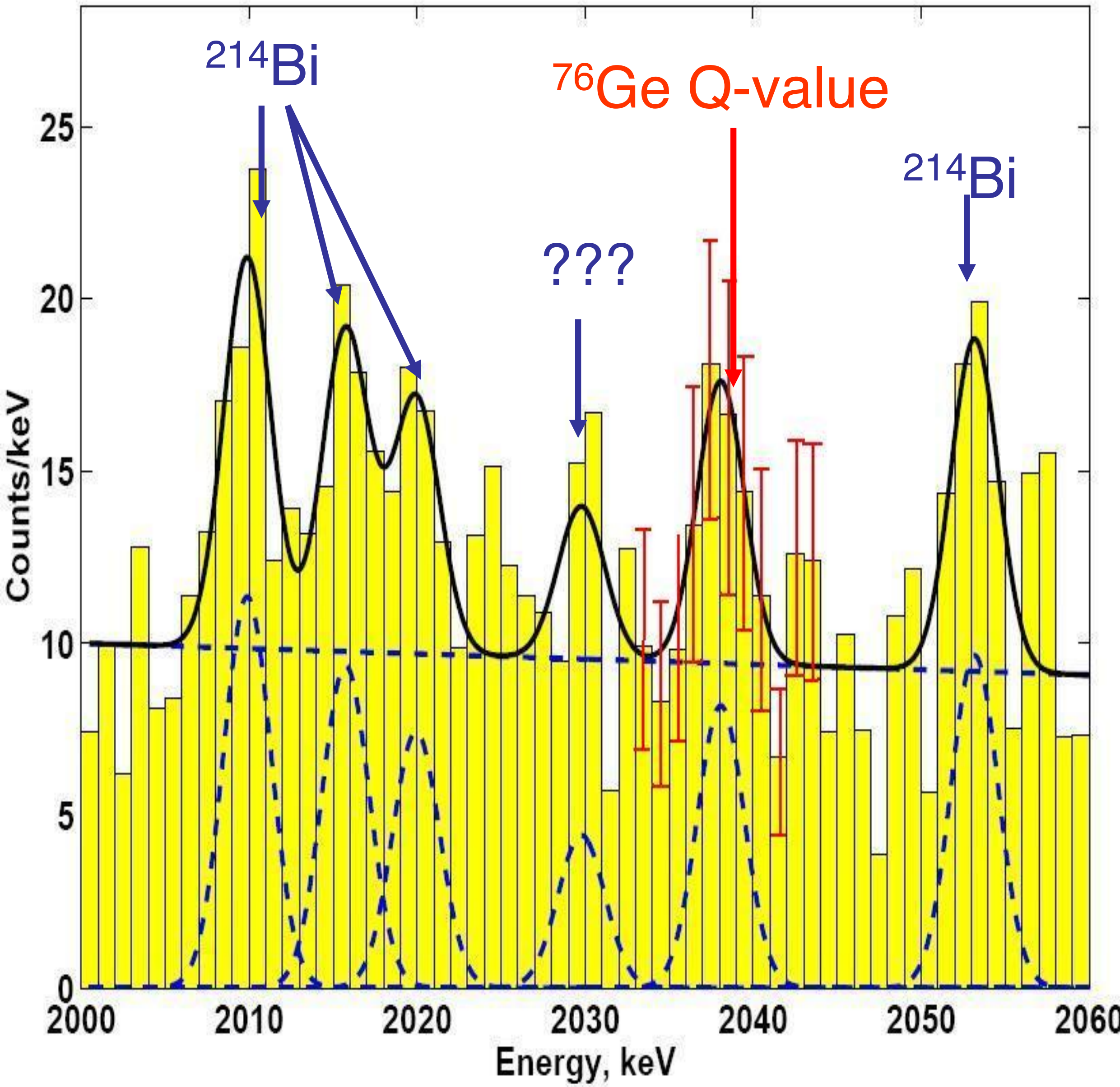
Source = detector

For source = detector configuration, the figure of merit $F_{0\nu}$:

$$F_{0\nu} = \ln 2 \cdot N_A \frac{f}{A}\left(\frac{Mt}{B\Delta E}\right)^{1/2} \varepsilon$$

f is the number of atoms of the ββ isotope/molecule;
A is the molecular mass;
M is the mass;
t is the running time;
B is the number of background counts/keV/kg/year;
ΔE is the energy resolution of the detector in keV;
ε is the detector efficiency in the ββ region

Claim for observation of 0νββ



Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{\beta\beta}$
28.75 ± 6.86 → 4.2 σ

$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\, yr$$

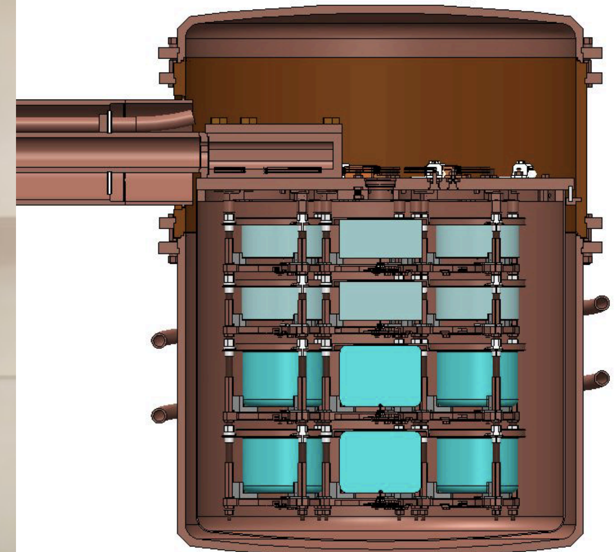
$$\langle m_\nu \rangle = 0.32 \pm 0.03\ eV$$

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

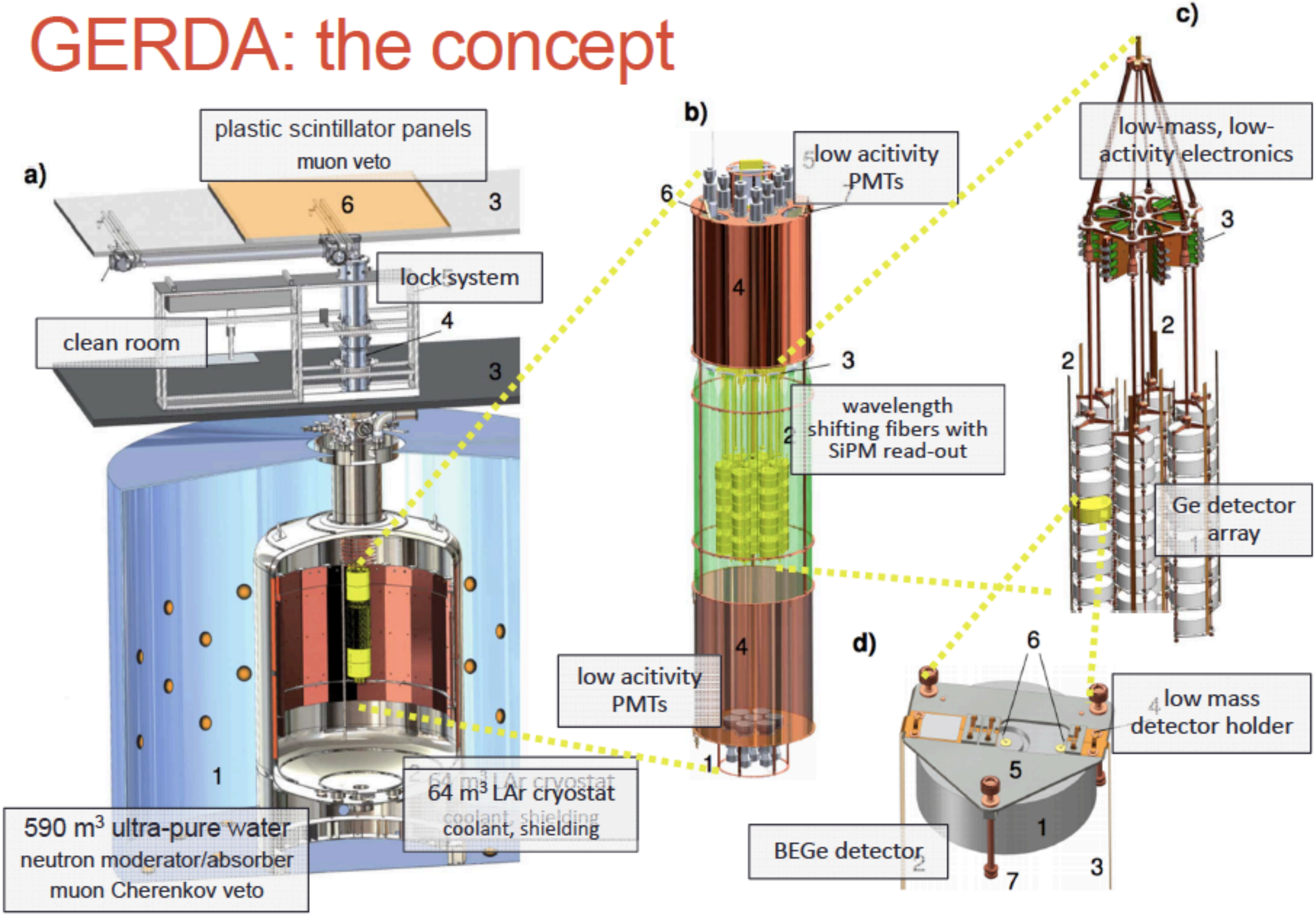
Heidelberg-Moscow Collaboration split over this result, and it is still controversial.

Current ^{76}Ge diode experiments

Majorana Demonstrator



GERDA: the concept

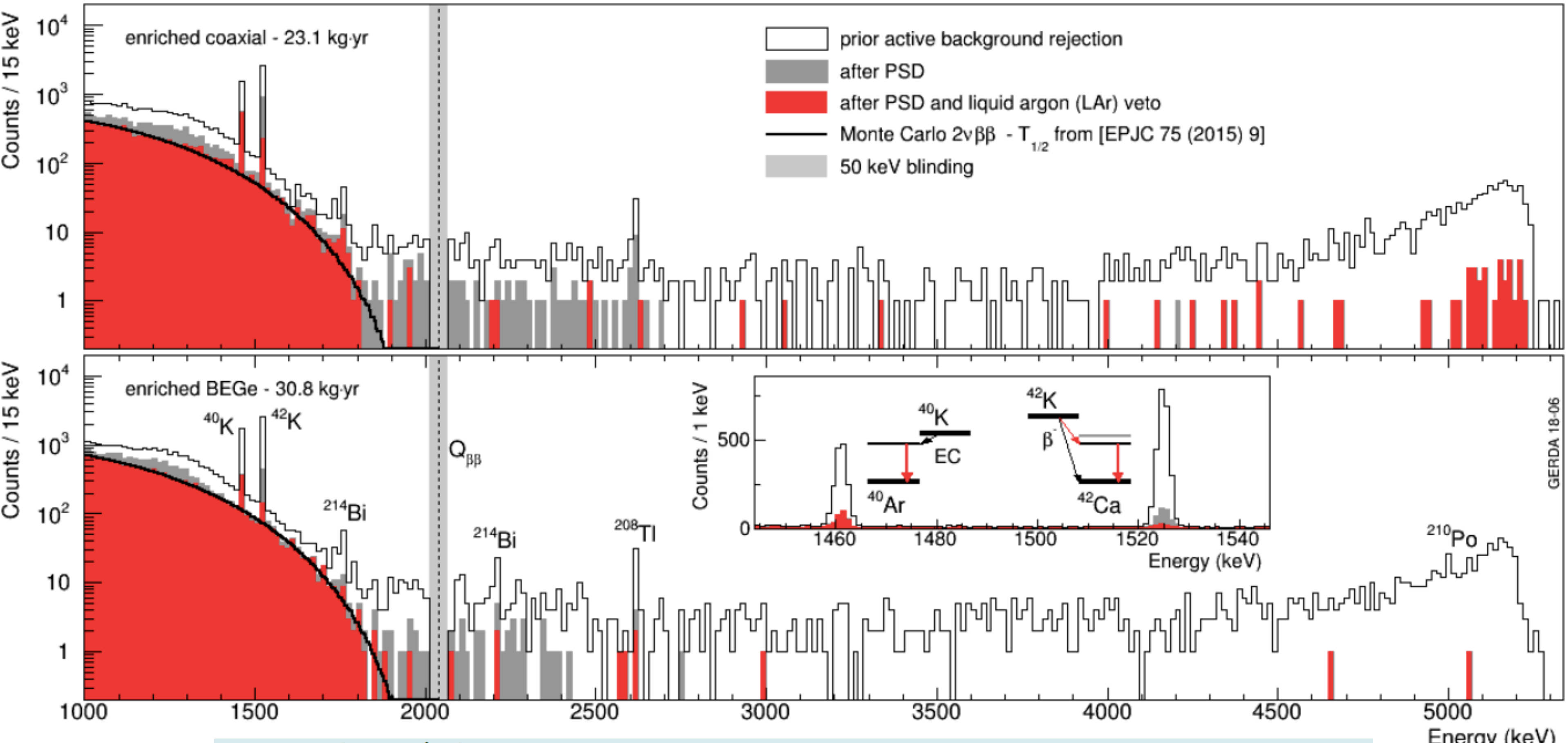


Pandola, TAUP 2017

82.4 kg y total exposure

GERDA results

Agostini et al. PRL 120, 132503 (2018)



Frequentist analysis:

- Best fit → no signal.
- **$T_{1/2}$ > 0.9·10^26 yr** (median sensitivity for limit **1.1 ·10^26 yr**) @ 90% C.L.

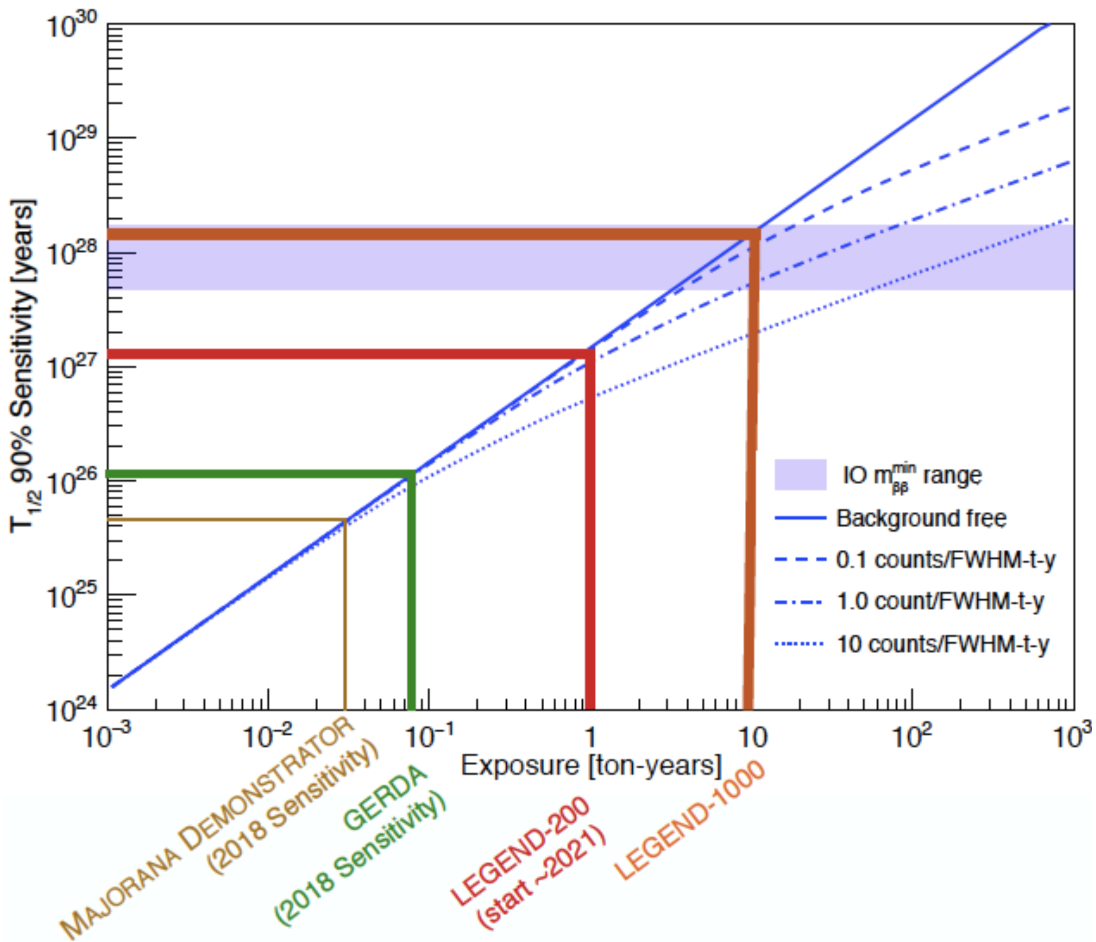
Bayesian analysis:

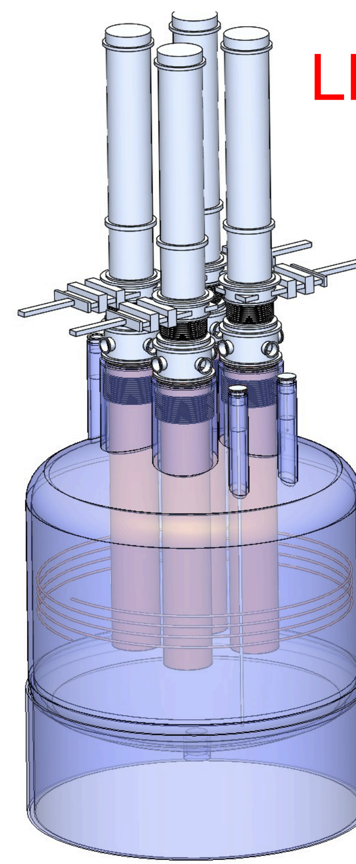
- Best fit → no signal. Bayes factor = 0.054
- $T_{1/2}$ > 0.8·10^26 yr (median sensitivity for limit 0.8 ·10^26 yr) @ 90% C.I.

The median limit on effective Majorana mass is **< (0.11-0.26) eV** NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]

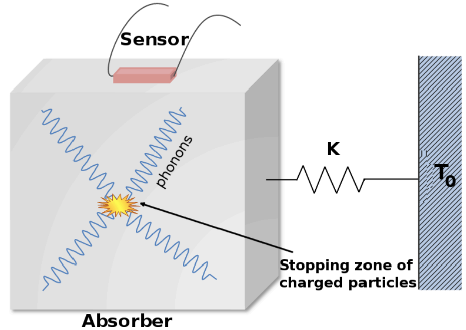
Next generation ton-scale ^{76}Ge $0\nu\beta\beta$

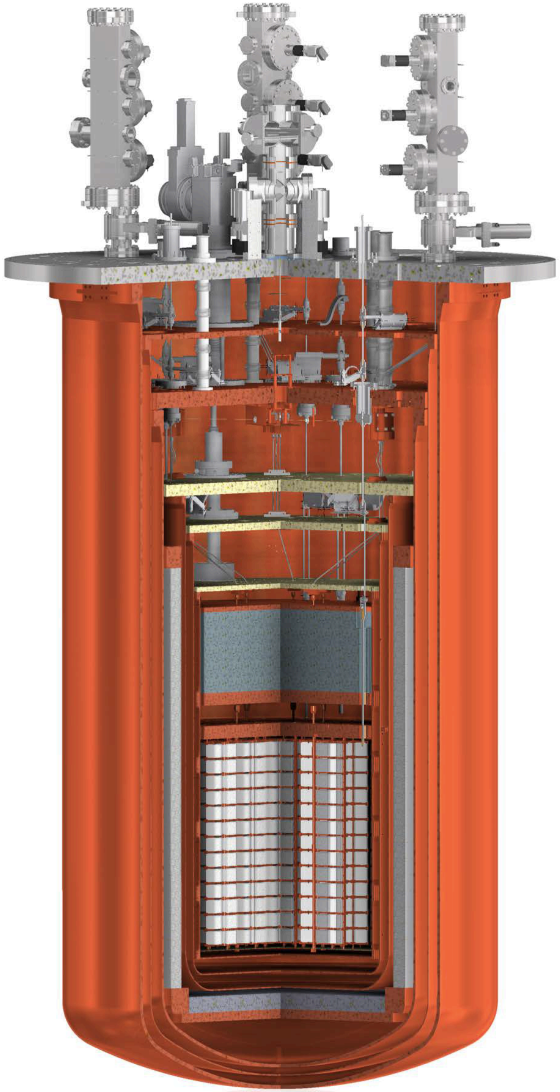
- Build on the experience of GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Design sensitivity of ~1x10^{28} y with a background of 0.1 cnt/tonne-yr in the region of interest (background reduction of ~6-20 relative to existing)

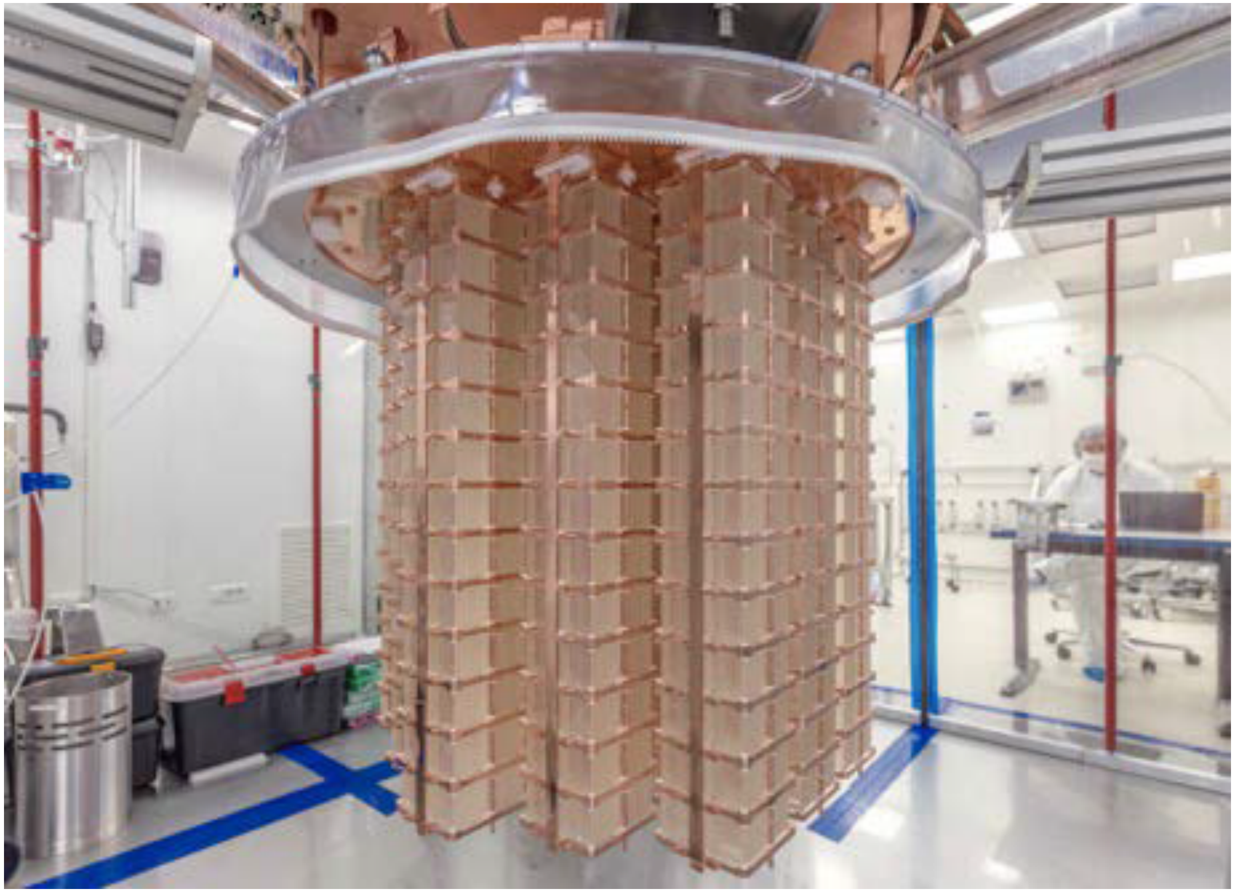




CUORE



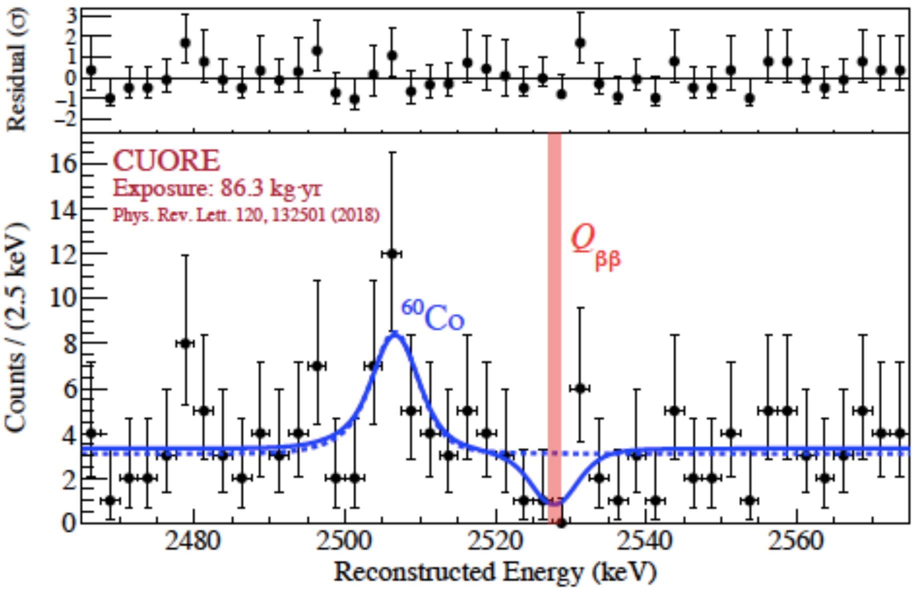


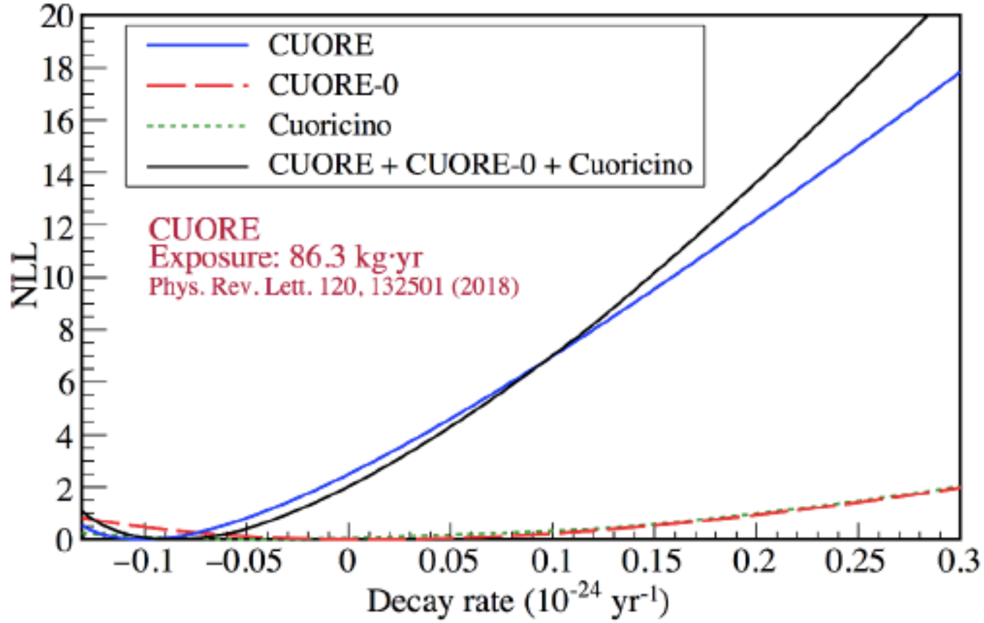


$^{nat}TeO_2$ bolometers operated in a low background dilution refrigerator at LNGS

~200 kg ^{130}Te

CUORE results





Alduino et al. *PRL* 120, 132501 (2018)

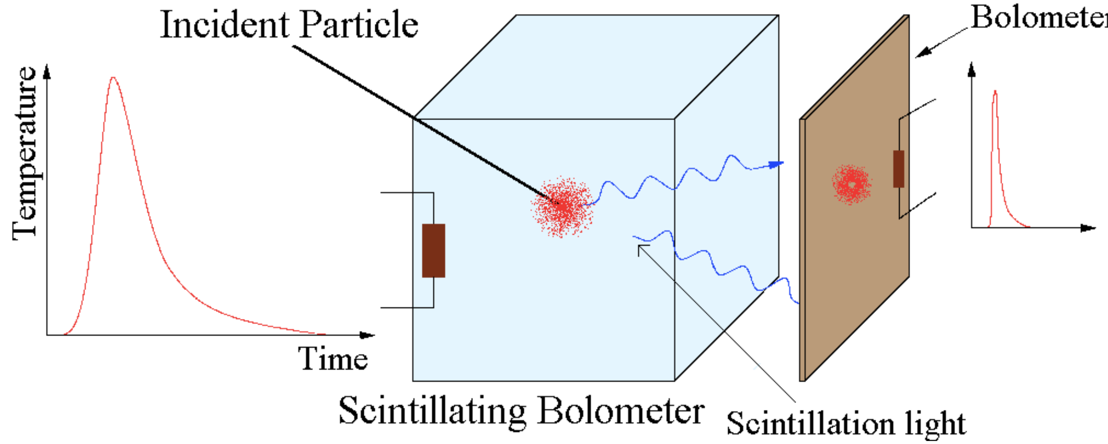
Limits combining CUORE with CUORE-0 and Cuoricino:

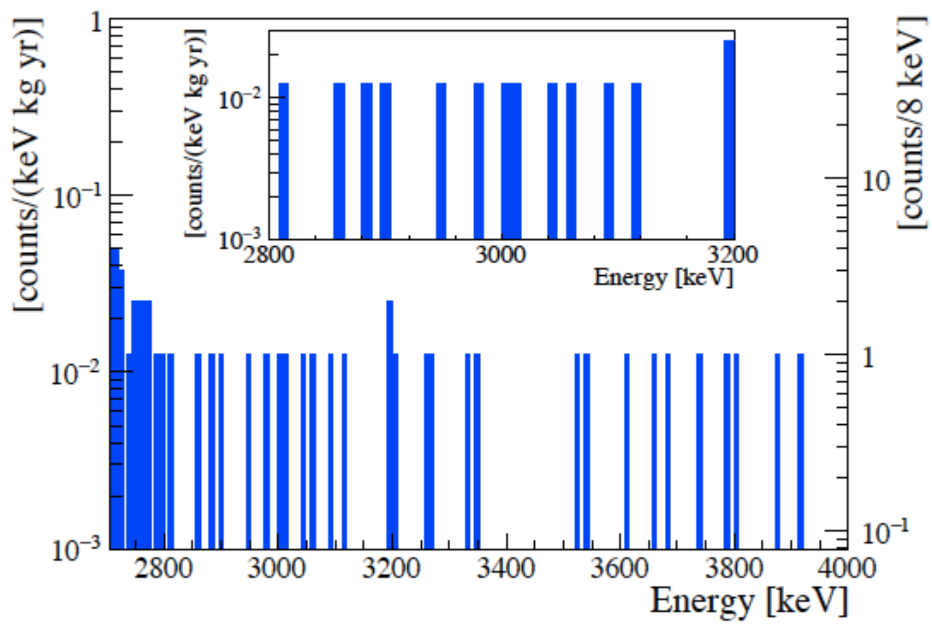
- Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$): 1.5×10^{25} yr
- Profile likelihood ("frequentist") limit @ 90% CL: 2.2×10^{25} yr

$m_{\beta\beta}$ < 110 - 520 meV

Back to data taking since May 2018!

Beyond CUORE: CUPID





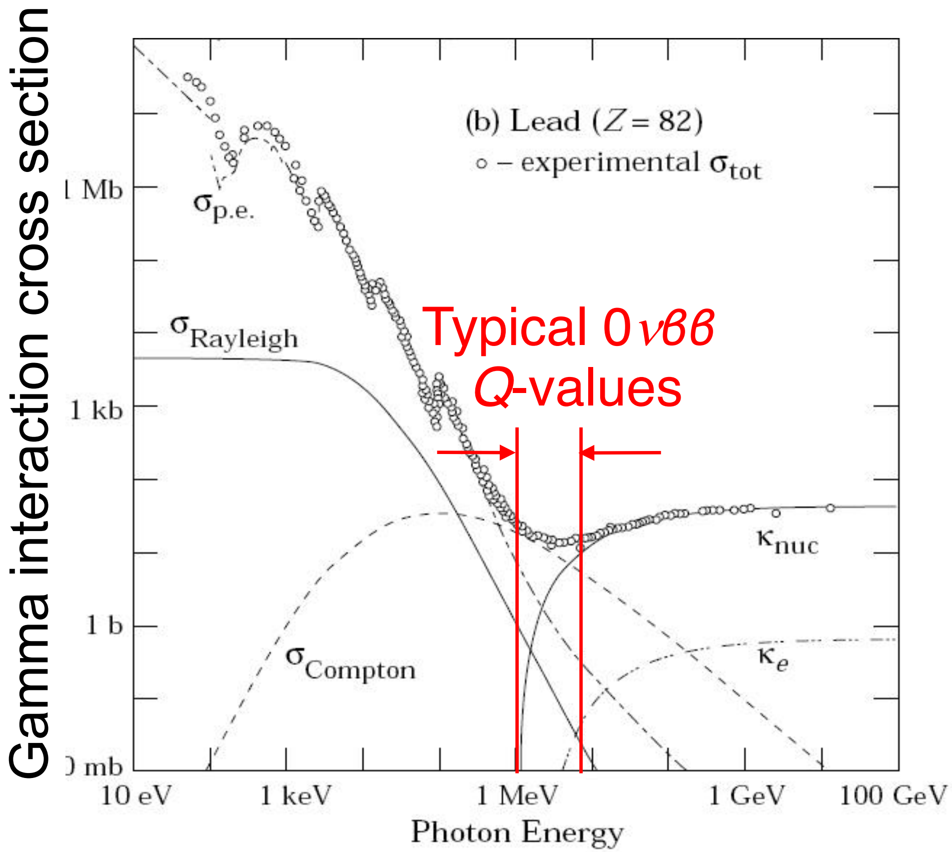
$$(3.5^{+1.0}_{-0.9}) \times 10^{-3} \text{ counts/(keV kg yr)}$$

24 Zn^{82}Se bolometers, for a total mass ≈ 5.1 kg of ^{82}Se

Exposure of 5.29 kg yr gives a limit of > 3.5 x 10^{24} yr at 90% C.L.

arXiv:1906.05001

Challenges of the ton-scale



Shielding a detector from MeV gammas is difficult!

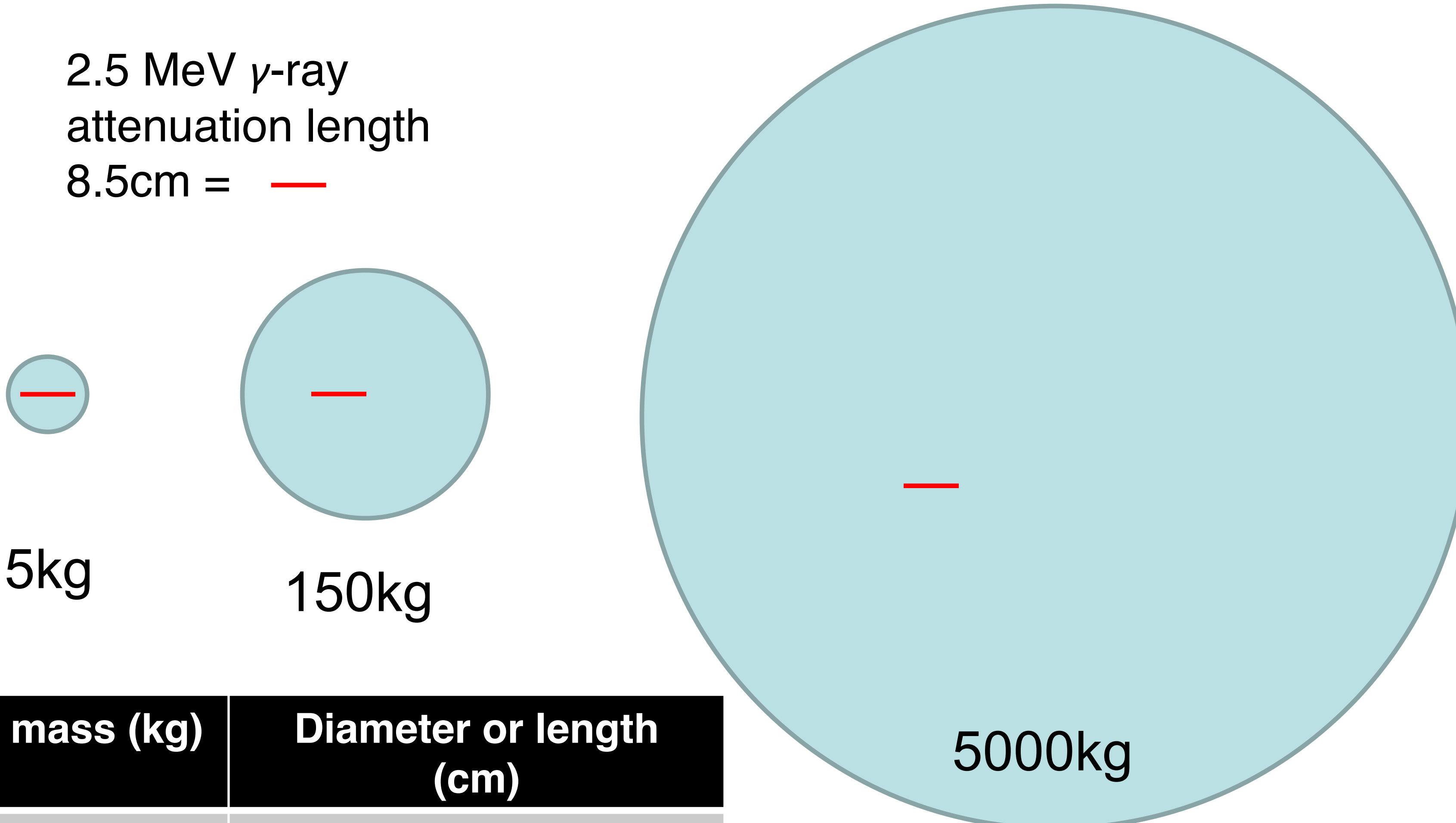
Example:
γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding $0\nu\beta\beta$ decay detectors is much harder than shielding dark matter detectors

We are entering the "golden era" of $0\nu\beta\beta$ decay experiments as detector sizes exceed interaction length

Monolithic detectors

2.5 MeV γ-ray
attenuation length
8.5cm = —

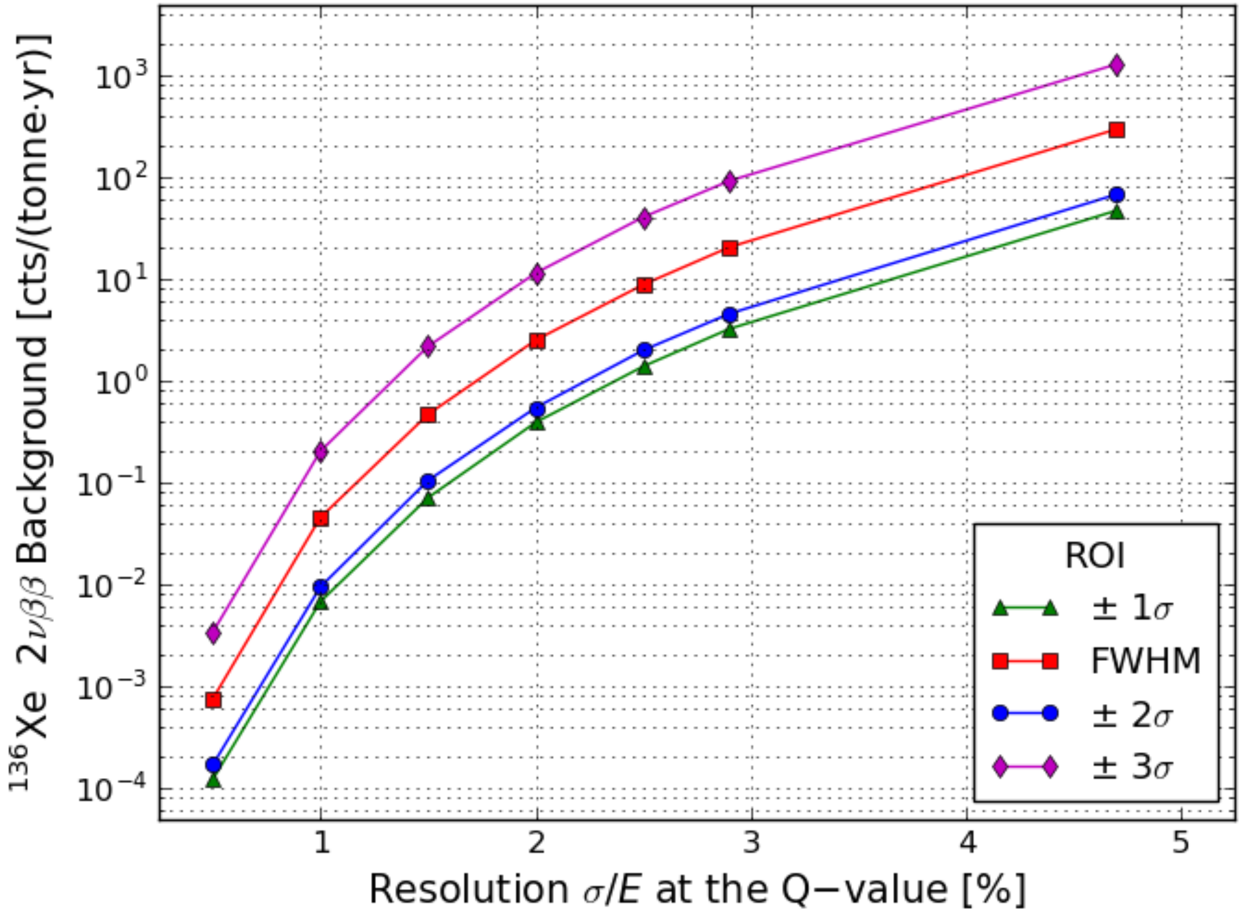


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

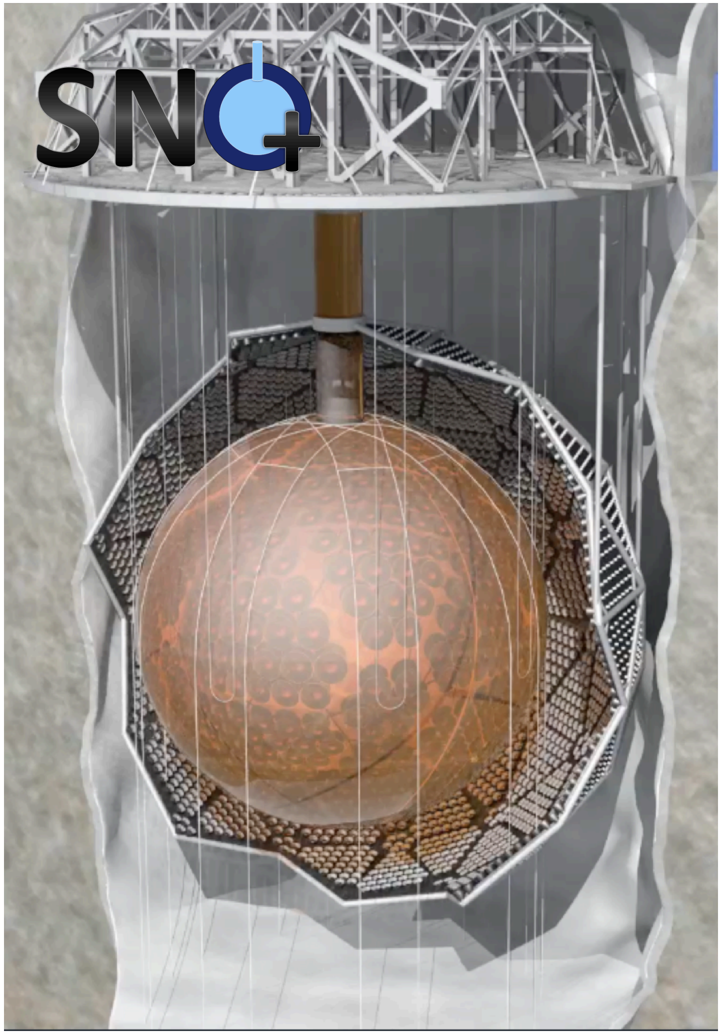
Background suppression

All observables have a role in separating signal from background.

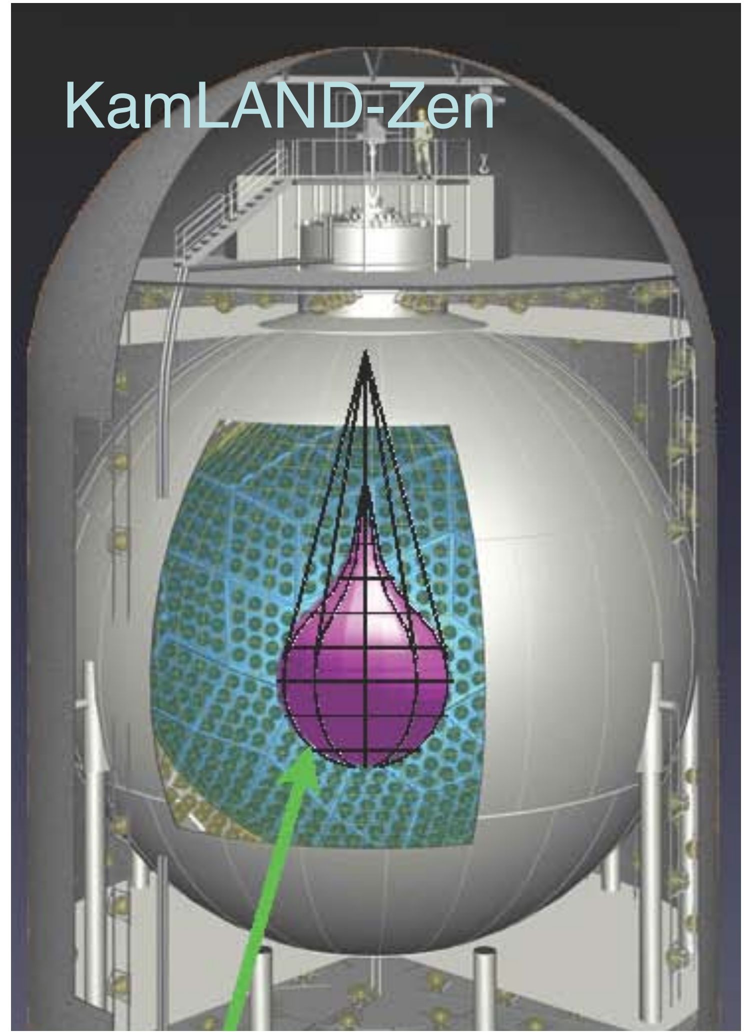
A very large, homogeneous detector has great advantages but only if its energy resolution is sufficient to sufficiently suppress the $2\nu\beta\beta$ mode.



Scintillator-based detectors

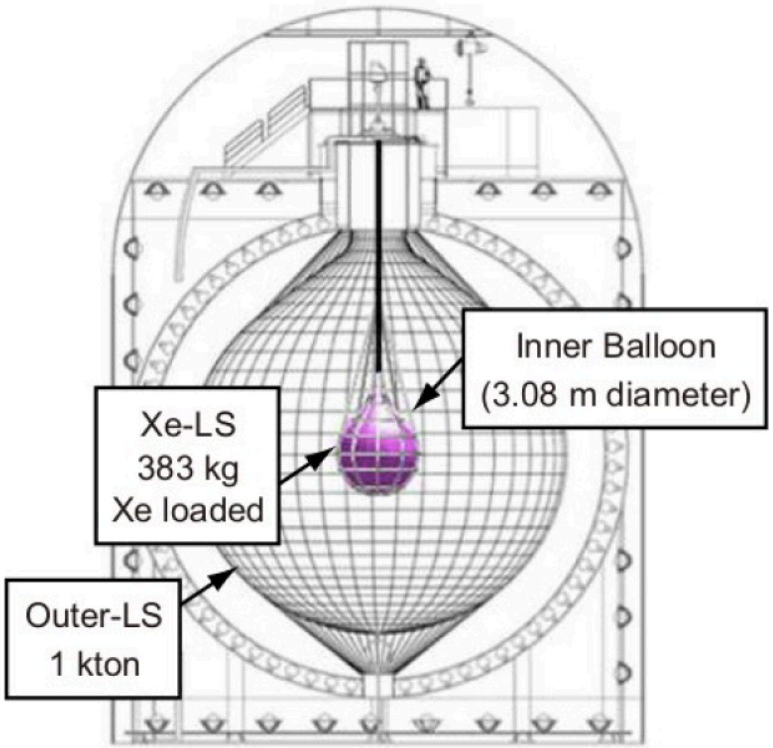


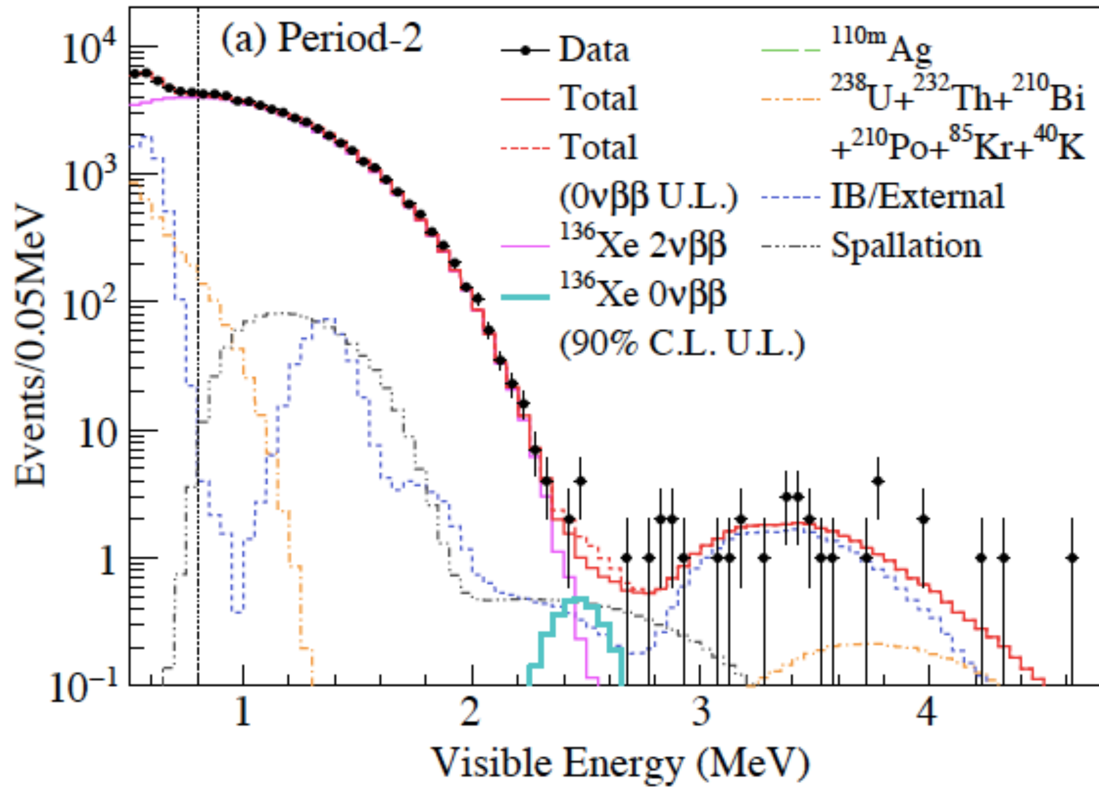
3.9 t natural Te dissolved in liquid scintillator in the upgraded SNO detector



Up to 800 kg 90% enriched Xe dissolved in inner volume of KamLAND

KamLAND-Zen





Enriched xenon (90% ^{136}Xe) dissolved in scintillator in the inner volume of the KamLAND detector in Japan.

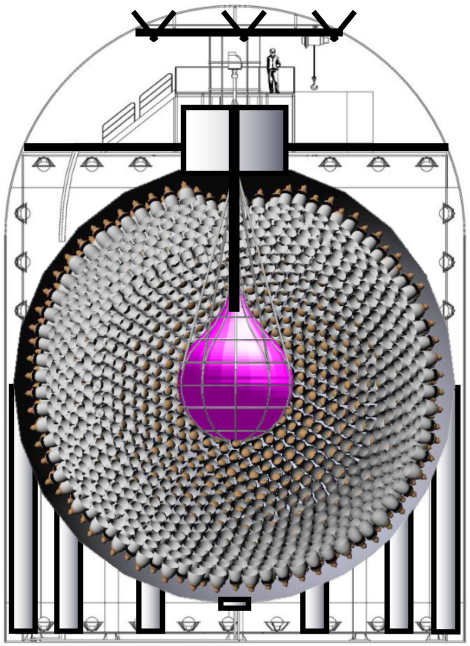
$$T_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26} \text{ yr}$$

$$\langle m_{\beta\beta} \rangle < 61 - 165 \text{ meV}$$

Gando et al., Phys. Rev. Lett. 117, 082503 (2016)

Beyond KamLAND-Zen 800

Higher energy resolution = lower 2ν background: KamLAND2-ZEN



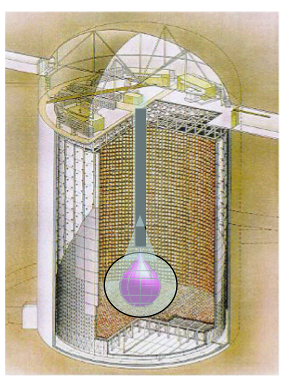
1000+ kg xenon

	Light collection gain
Winston cones	x1.8
Higher q.e. PMTs	x1.9
LAB-based liquid scint	x1.4
Overall	x4.8

expected σ(2.6MeV)= 4% → ~2%

target sensitivity 20 meV

Beyond?



Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

But eventually 2ν background becomes dominant

NEXT-100

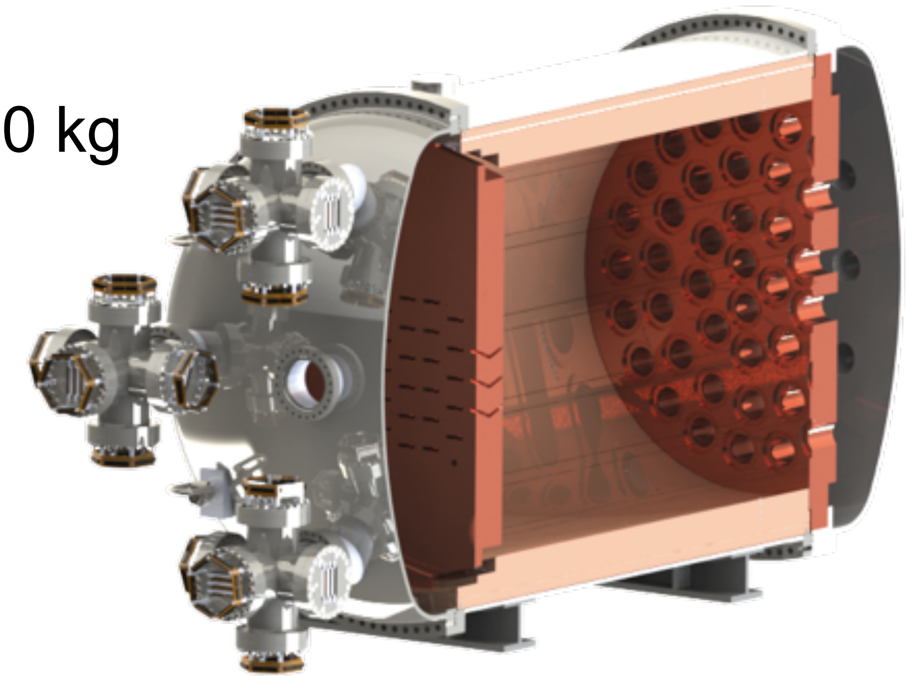
•15 bar high pressure gas Xe time projection chamber (TPC) with ~100 kg fiducial mass. SiPMs (MPPCs) for tracking and PMTs for energy.

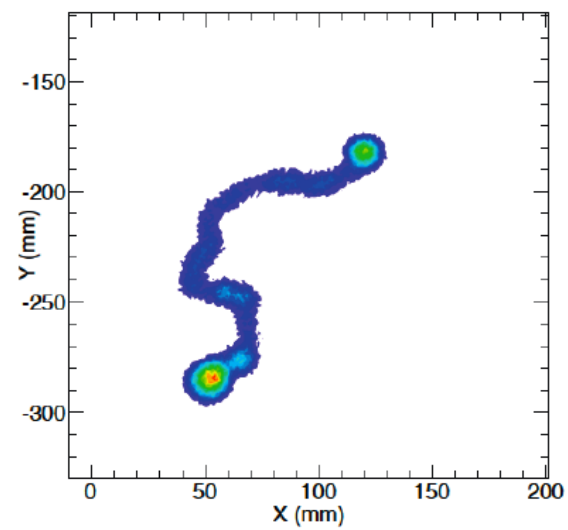
•Proportional electroluminescent amplification for large photon yield.

•Tracking and event topology reconstruction.

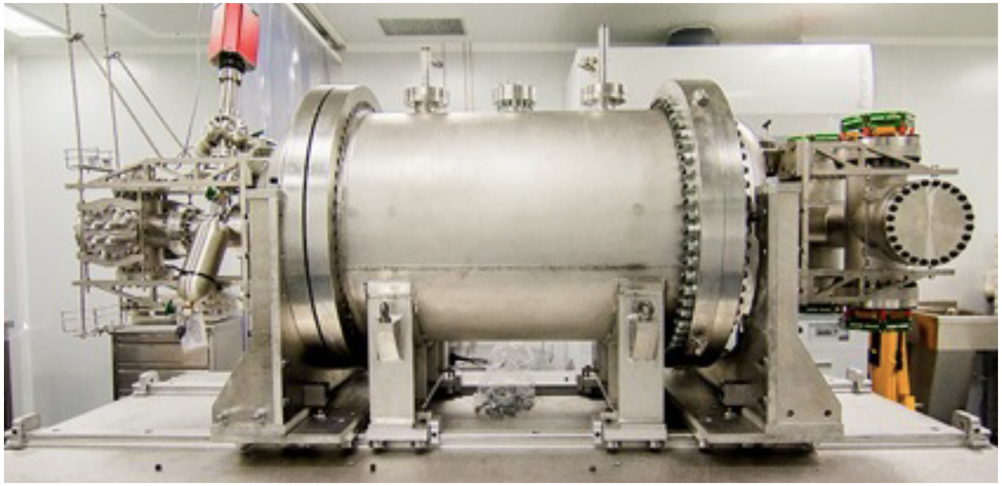
•Good energy resolution. Demonstrated <0.9% energy resolution achievable at $0\nu\beta\beta$ Q-value.

•Will be sited at the Canfranc laboratory (LSC). Projected 3 year sensitivity of 5×10^{25} y. Commissioning in ~2020.



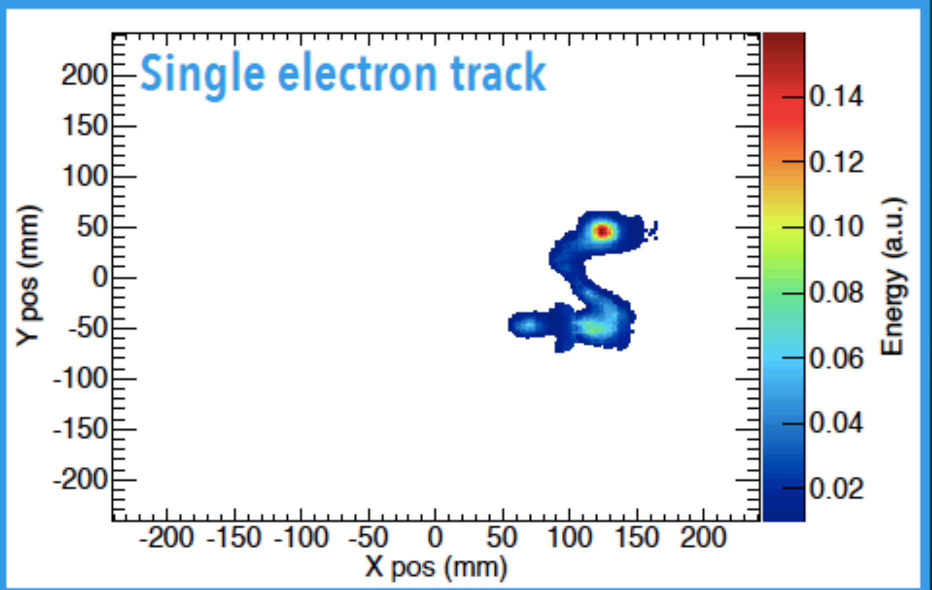


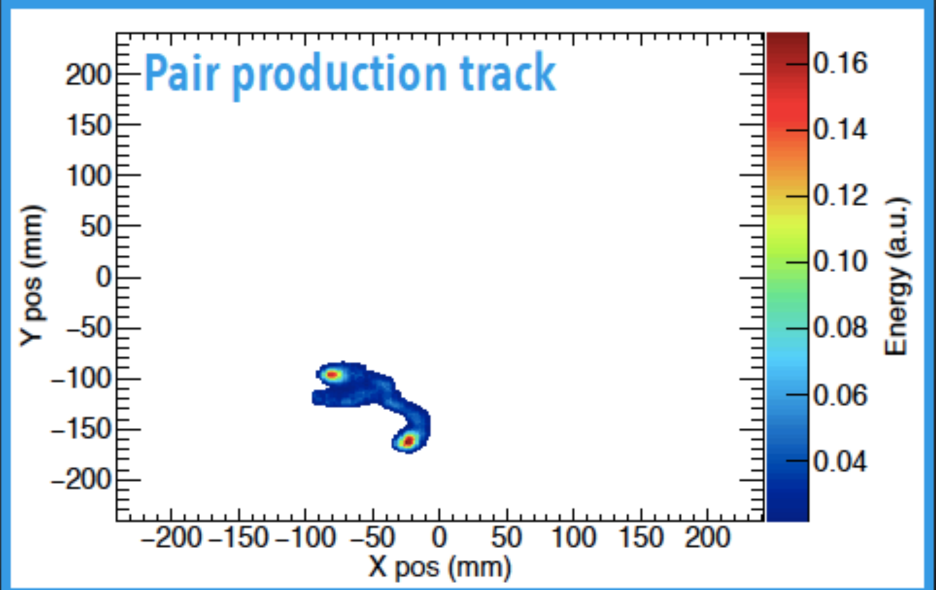
NEXT R&D



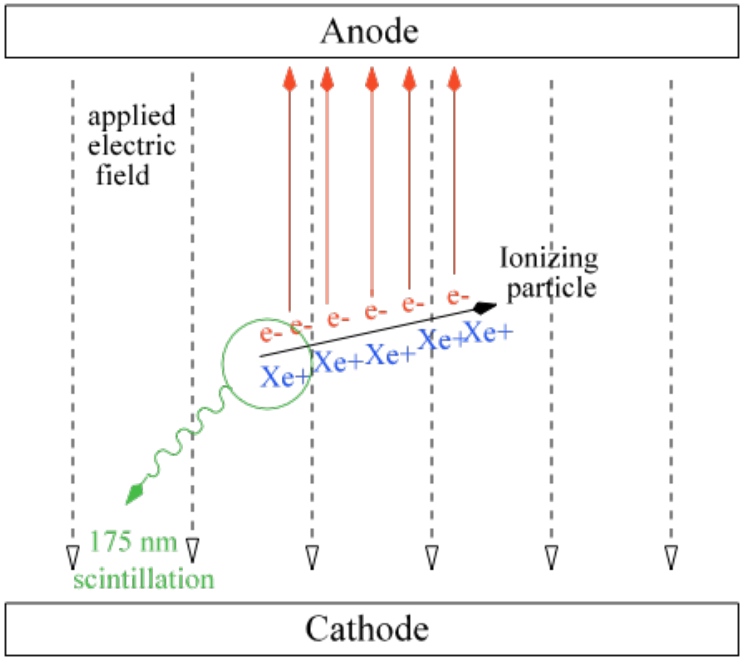
- Multiple prototypes at the ~kg scale (IFIC, LBL, Canfranc).
- Study of ^{60}Co calibration data for event topology.

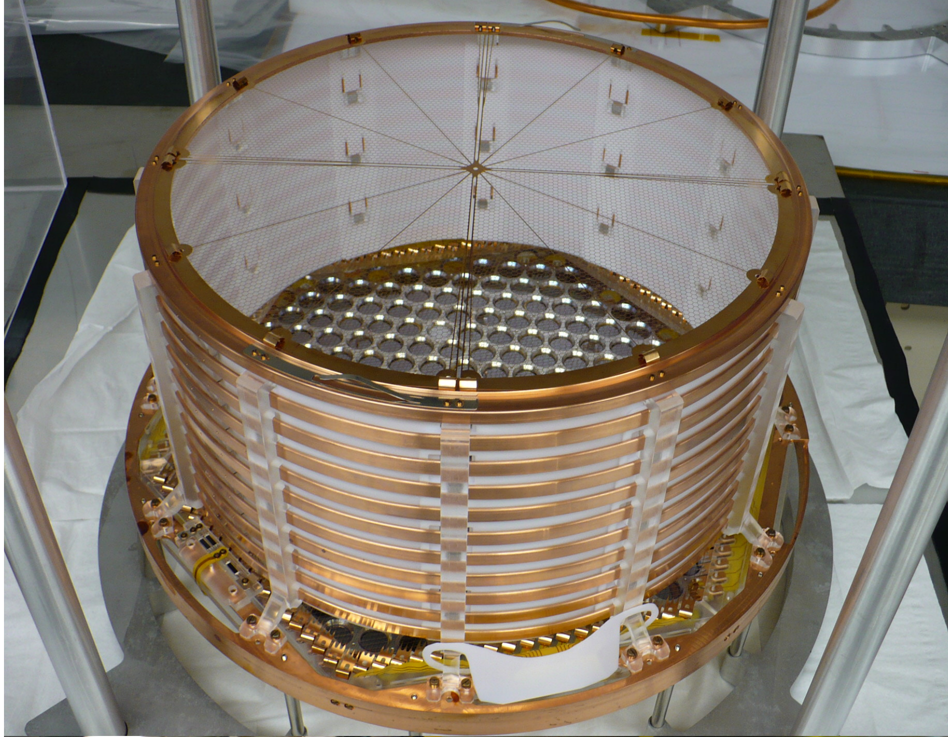
Ander Simón Estévez, TAUP 2017

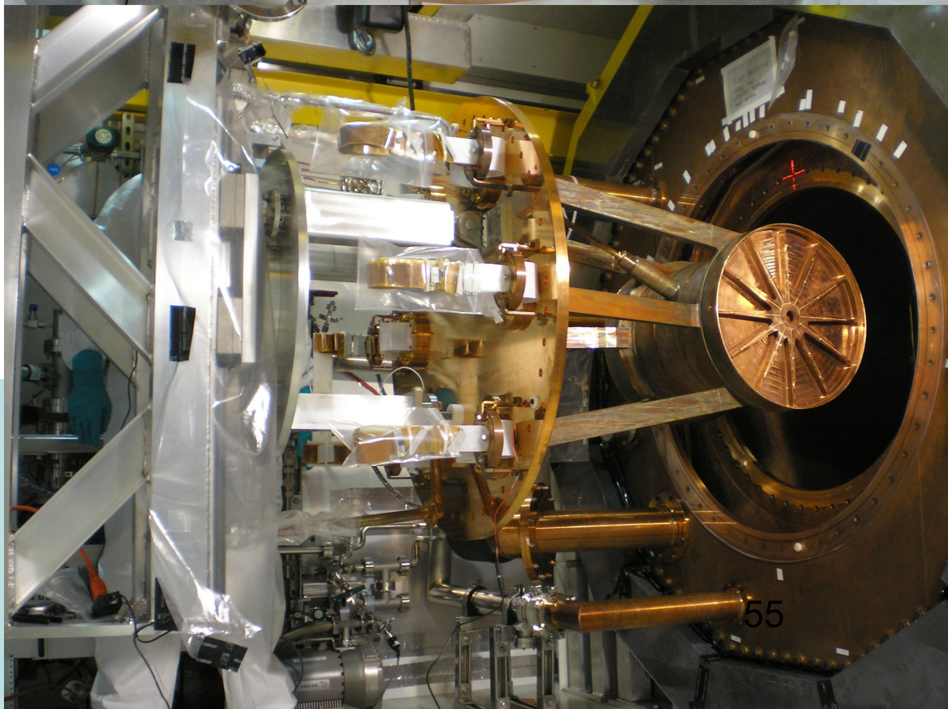




EXO-200
Liquid Xe TPC



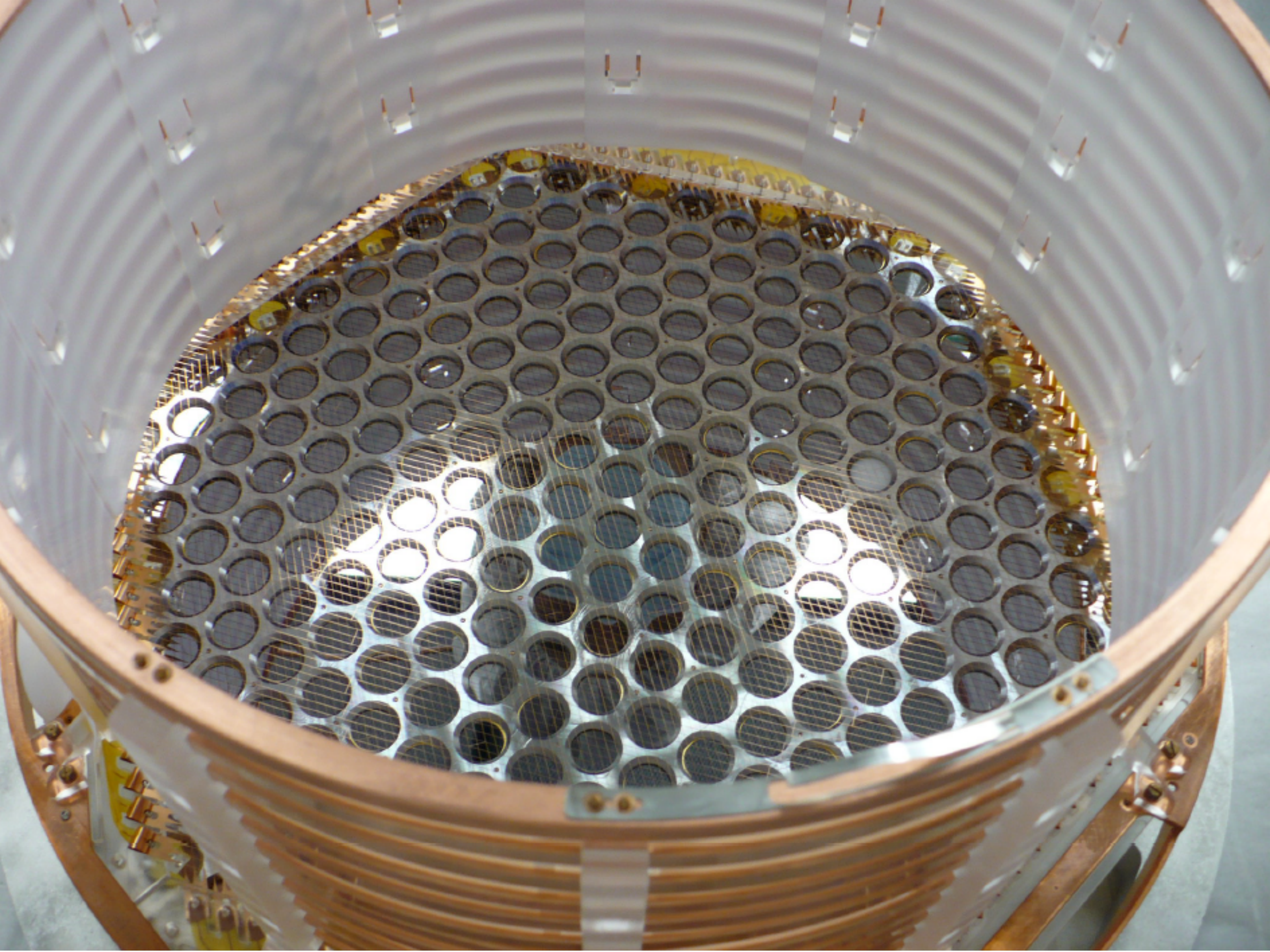




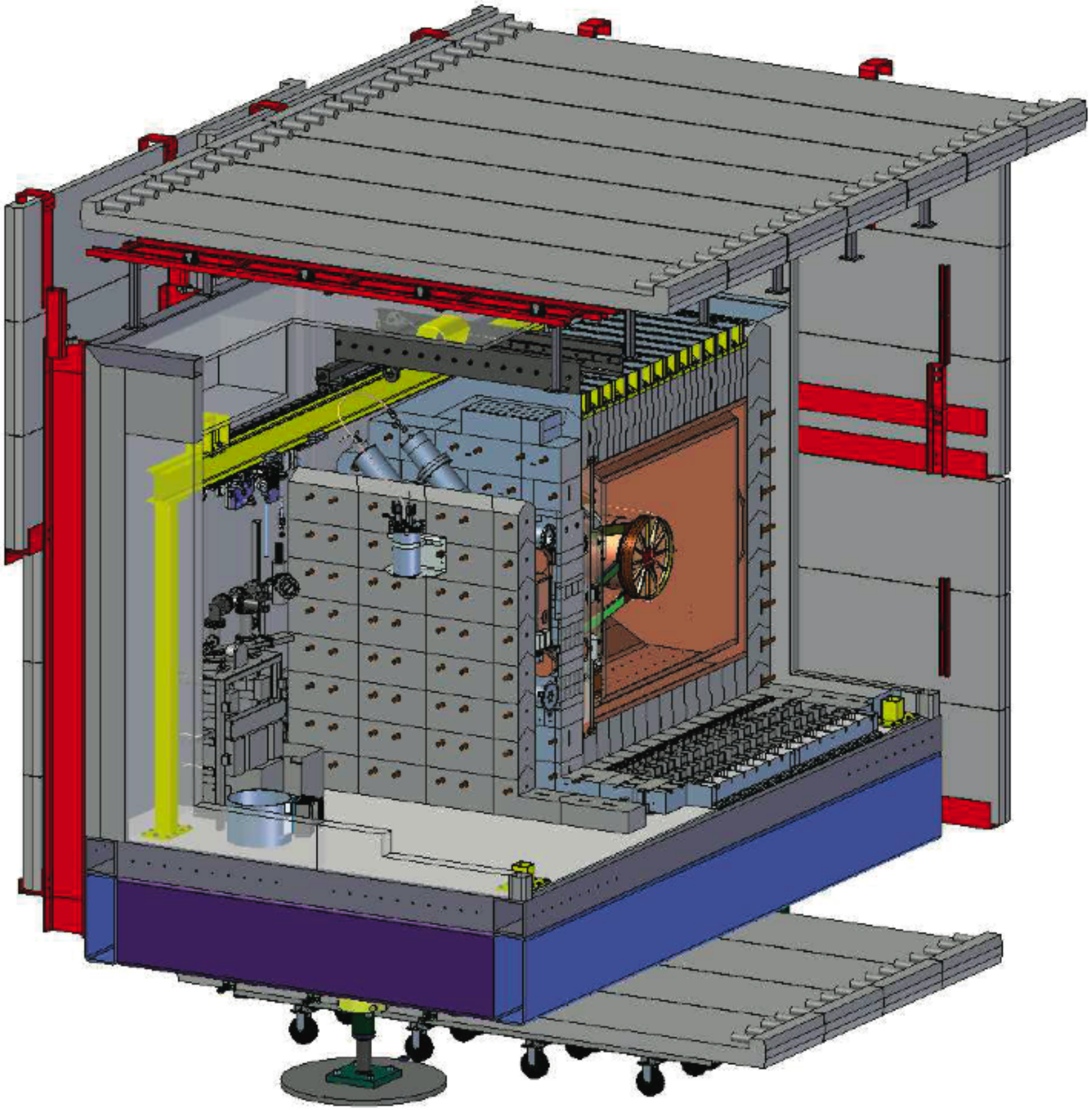
~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe, ultralow background construction.

Readout plane is made up of LAAPDs + crossed wire grid.

Operating with enriched Xe at the Waste Isolation Pilot Plant since May 2011.



EXO-200 @ WIPP



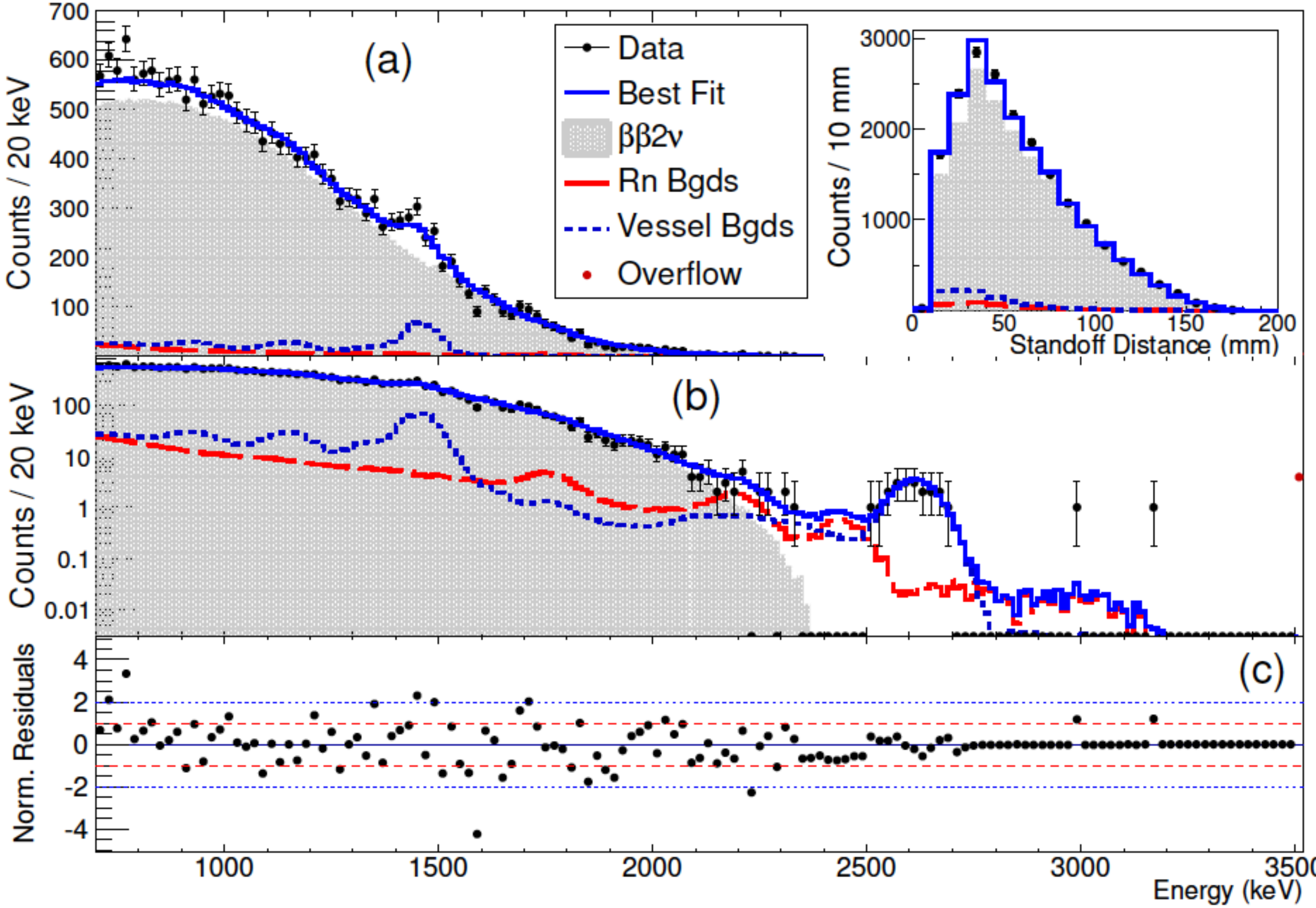
EXO-200 was located at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, a DOE facility for the disposal of radioactive waste. Provides ~1600 m.w.e. shielding and low U, Th, and Rn.

- TPC housed in thin-walled copper vessel.
- Vacuum insulated cryostat with HFE-7000 for shielding and thermal bath.
- Lead shield.
- Clean room environment.
- Active muon veto.
- Other support systems not shown here (refrigeration, gas handling, etc.).

Operated with enriched Xe from May 2011 to Feb. 2014 (Phase I)

Upgraded detector ran from June 2016 to December 2018 (Phase II)

$2\nu\beta\beta$ precision measurement



$2\nu\beta\beta$ signal to background ratio: **11: 1**

Inner 40% fiducial volume signal to background ratio: **19: 1**

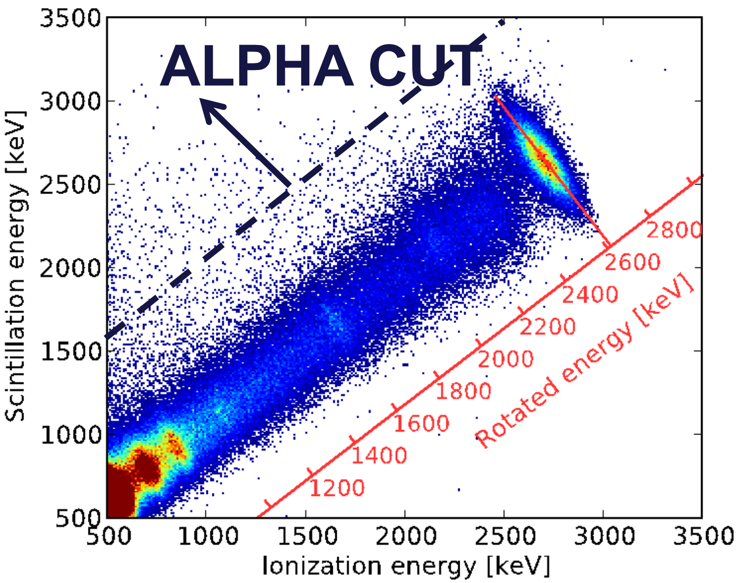
Most precise measurement of the $2\nu\beta\beta$ half-life

$T_{1/2}^{2\nu\beta\beta} = 2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{sys}) \times 10^{21}$ yr

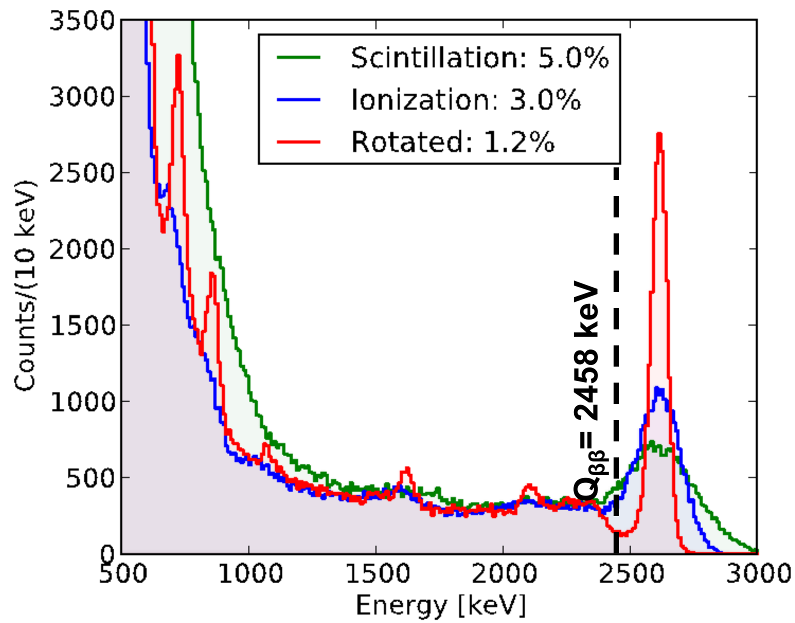
[PRC **89**, 015502 (2014)]

Energy measurement

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:

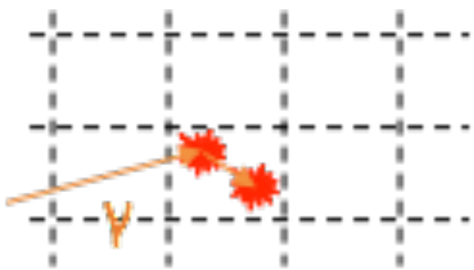


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- In the most recent analysis, EXO-200 has achieved 1.15% σ/E energy resolution at the Q-value in Phase II.

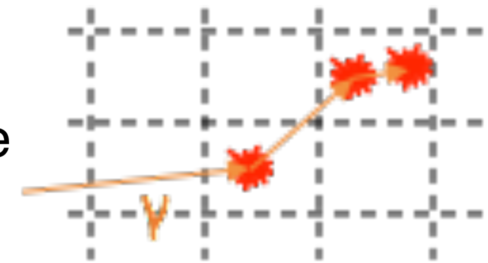
Position and multiplicity

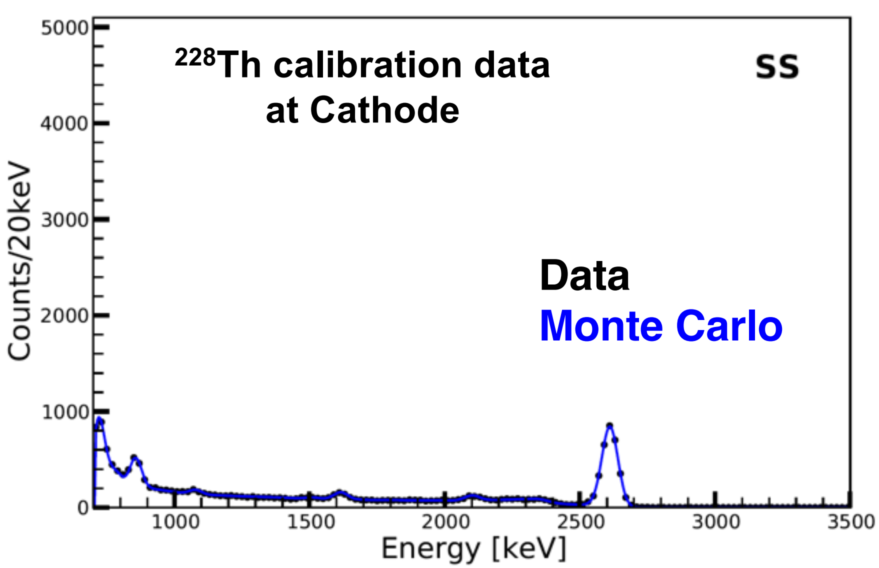
Allows for background measurement and reduction

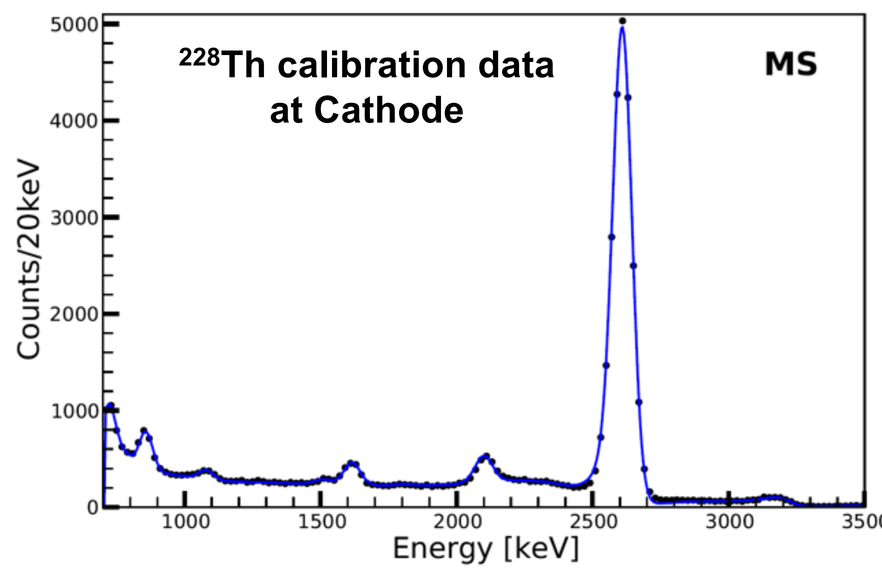
Events with **> 1** charge cluster: multi-site events
Events with **1** charge cluster: single-site events.



$0\nu\beta\beta$: ~90% SS
γ-rays: ~12% SS at $0\nu\beta\beta$ Q-value







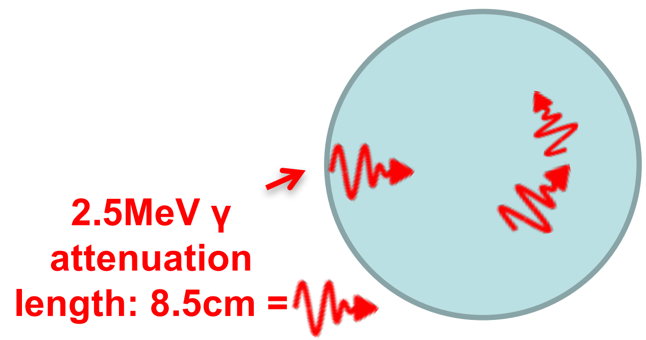
Improved γ-background Rejection

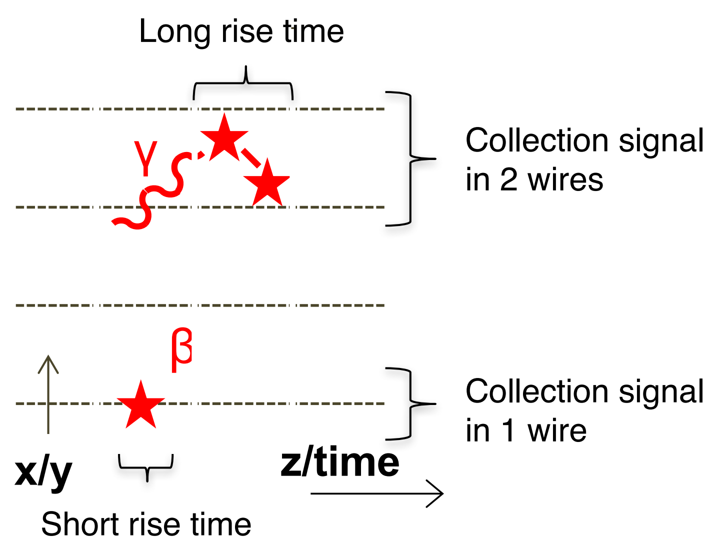
Additional discrimination in SS using *spatial distribution* and *cluster size*

Entering γ-rays are exponentially attenuated by LXe self-shielding, providing an independent measurement of γ-backgrounds. We call this standoff distance.

The size of individual events is estimated from pulse rise time (longitudinal direction) and the number of wires with a charge collection signal (transverse).

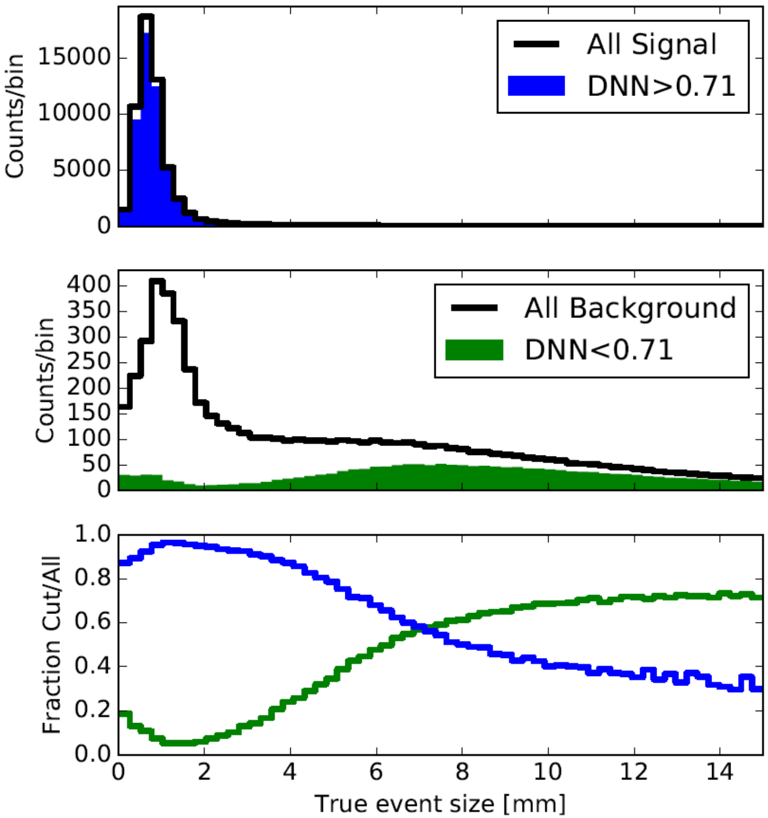
LXe self-shielding:

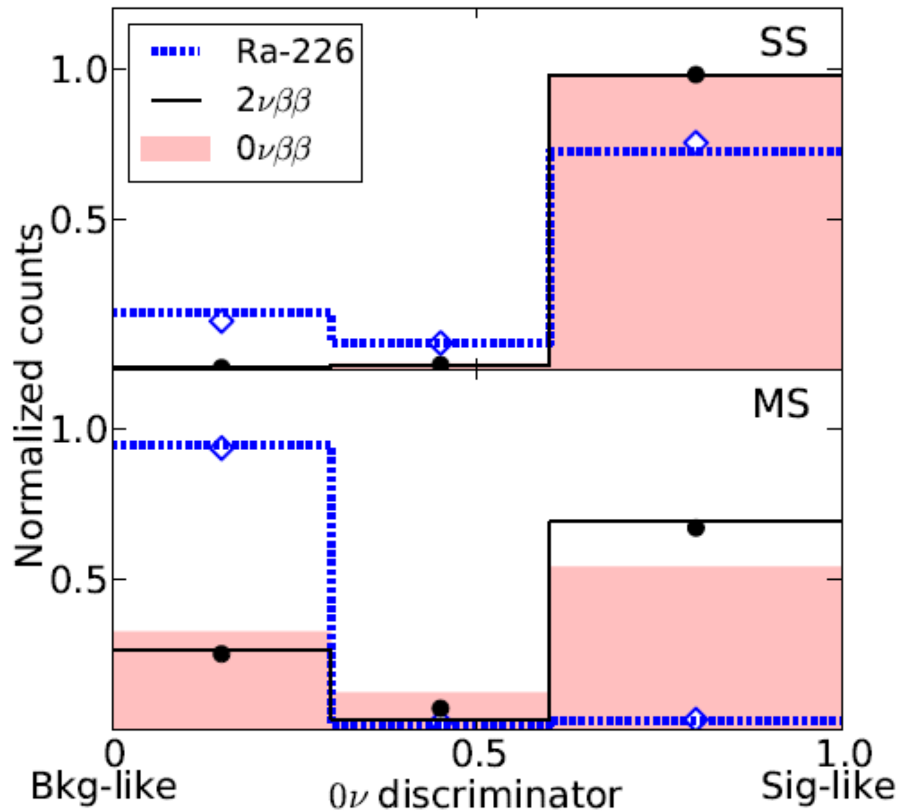




Optimal $0\nu\beta\beta$ Discrimination

Use Deep Neural Network (DNN) based $0\nu\beta\beta$ discriminator, more powerful than previous method using BDT



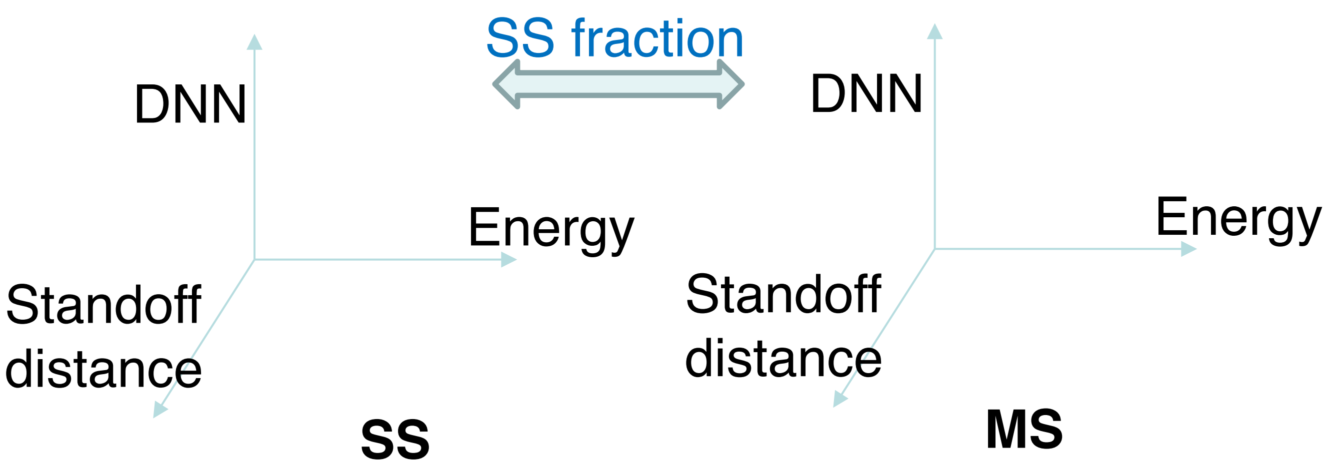


- DNN trained on images built from U-wire waveforms
- Signal/background identification efficiency clearly correlates with the true event size

- Data/MC agreement validated with different data
  - γ: Ra-226, Th-228, Co-60 sources
  - β: $2\nu\beta\beta$ data
- Showed consistent and reasonable agreement

Analysis strategy

- SS/MS classification
- 3-dimensional fit in both SS and MS: Energy + DNN + standoff distance
  - Energy, event topology and spatial information
  - Make the most use of multi-parameters for background rejection
  - SS, MS relative contributions constrained by SS fraction
- Improvement of ~25% in $0\nu\beta\beta$ half-life sensitivity compared with using energy spectra + SS/MS alone

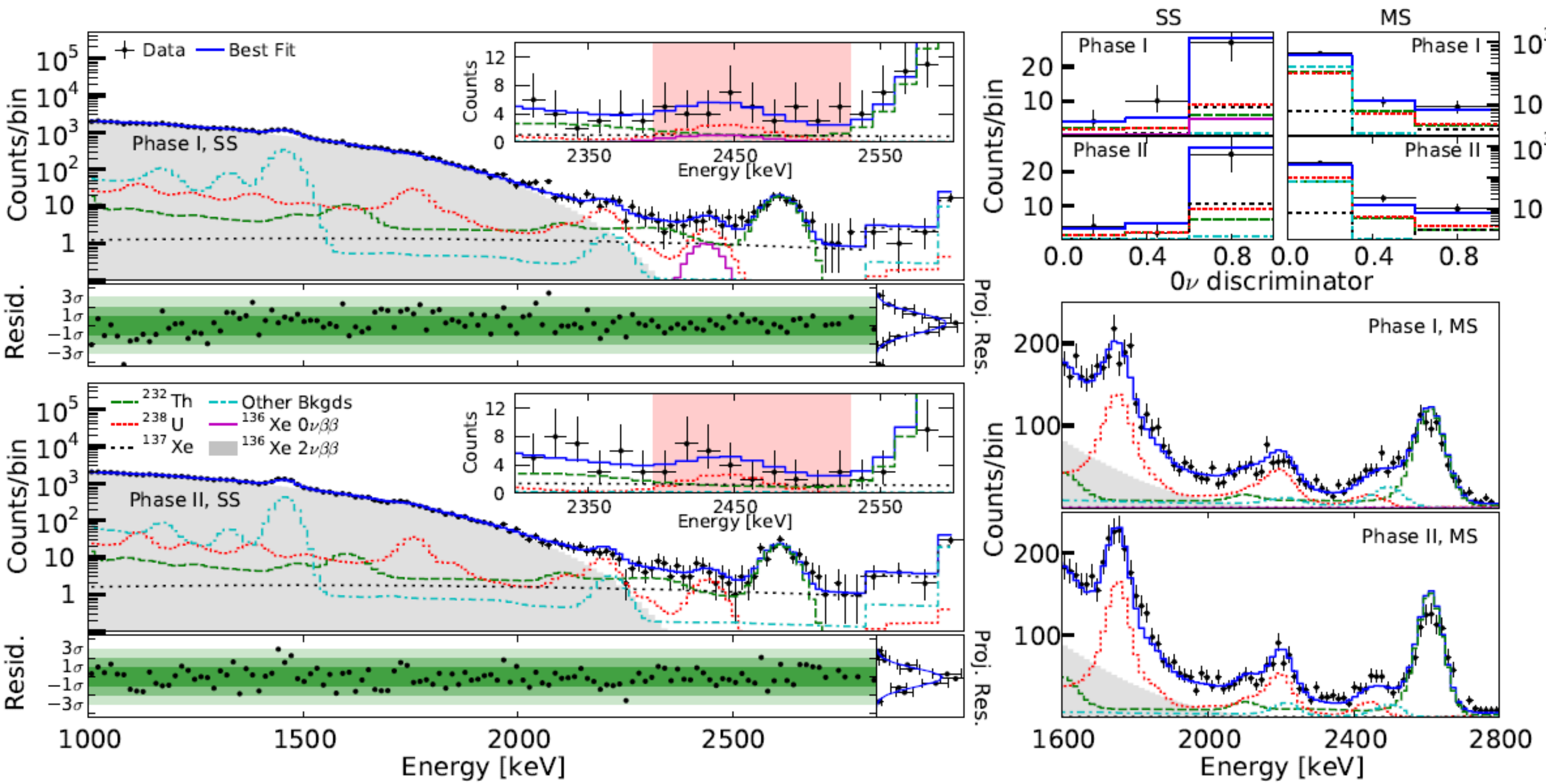


Results

arXiv:1906.02723

Background contributio

(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26



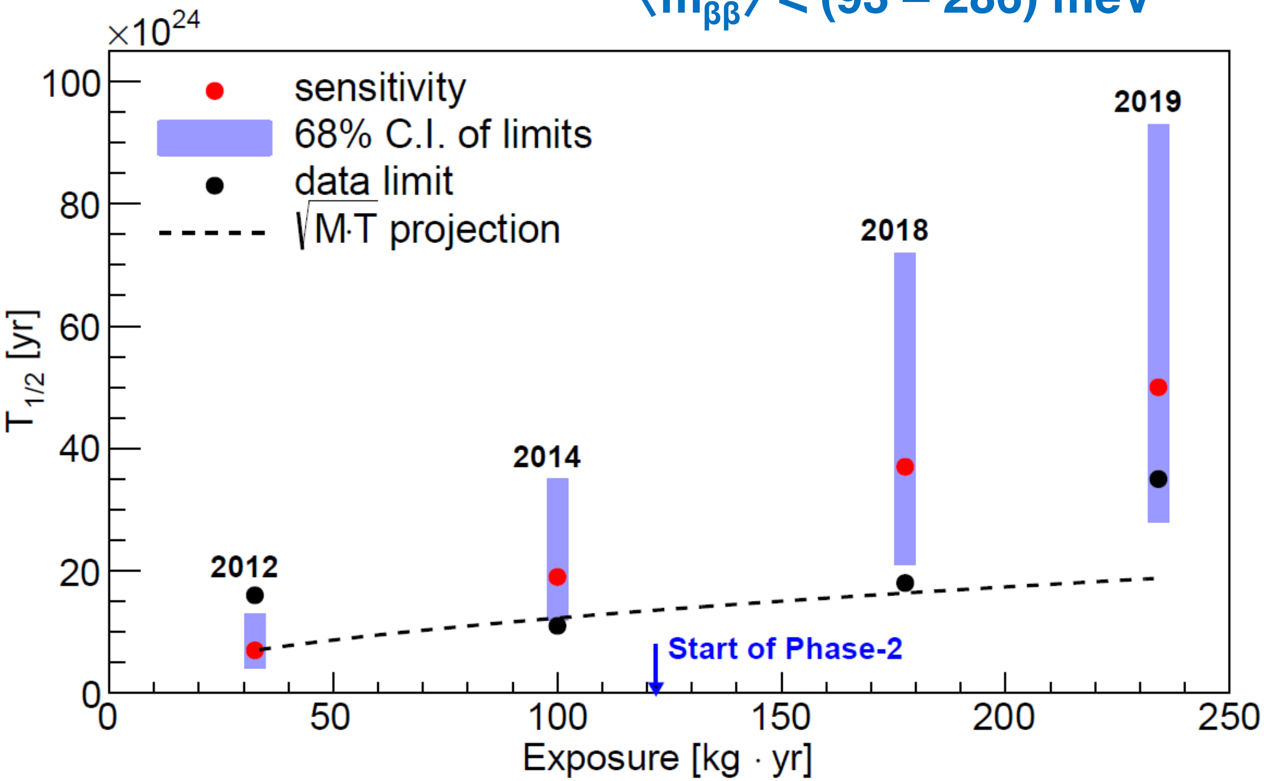
Sensitivity & Limits

Combined Phase I + II: **Total exposure = 234.1 kg.yr**

Sensitivity 5.0x10[25] yr

Limit $T_{1/2}^{0\nu\beta\beta}$ > 3.5 x 10[25] yr (90% C.L.)

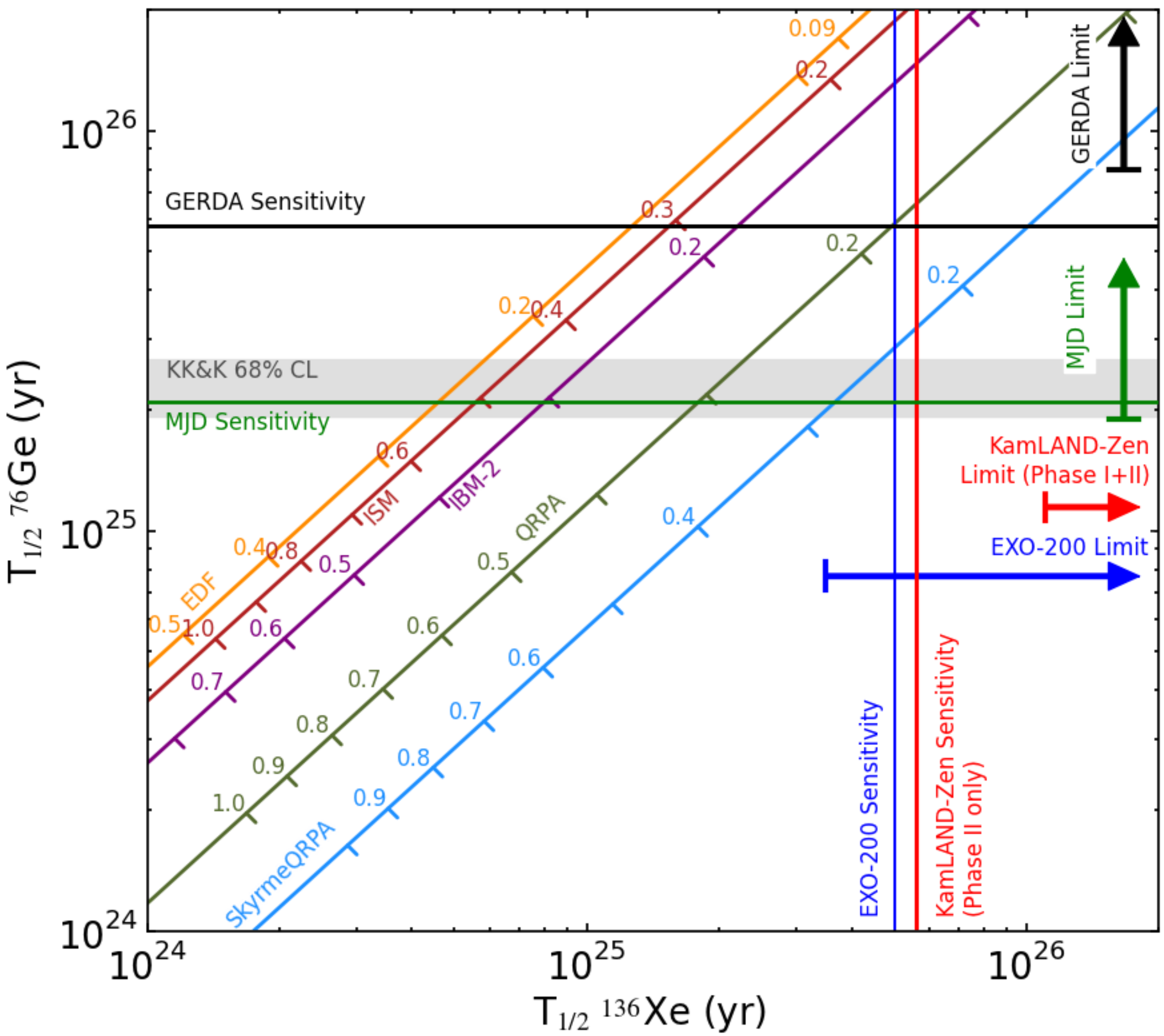
$\langle m_{\beta\beta} \rangle$ < (93 – 286) meV



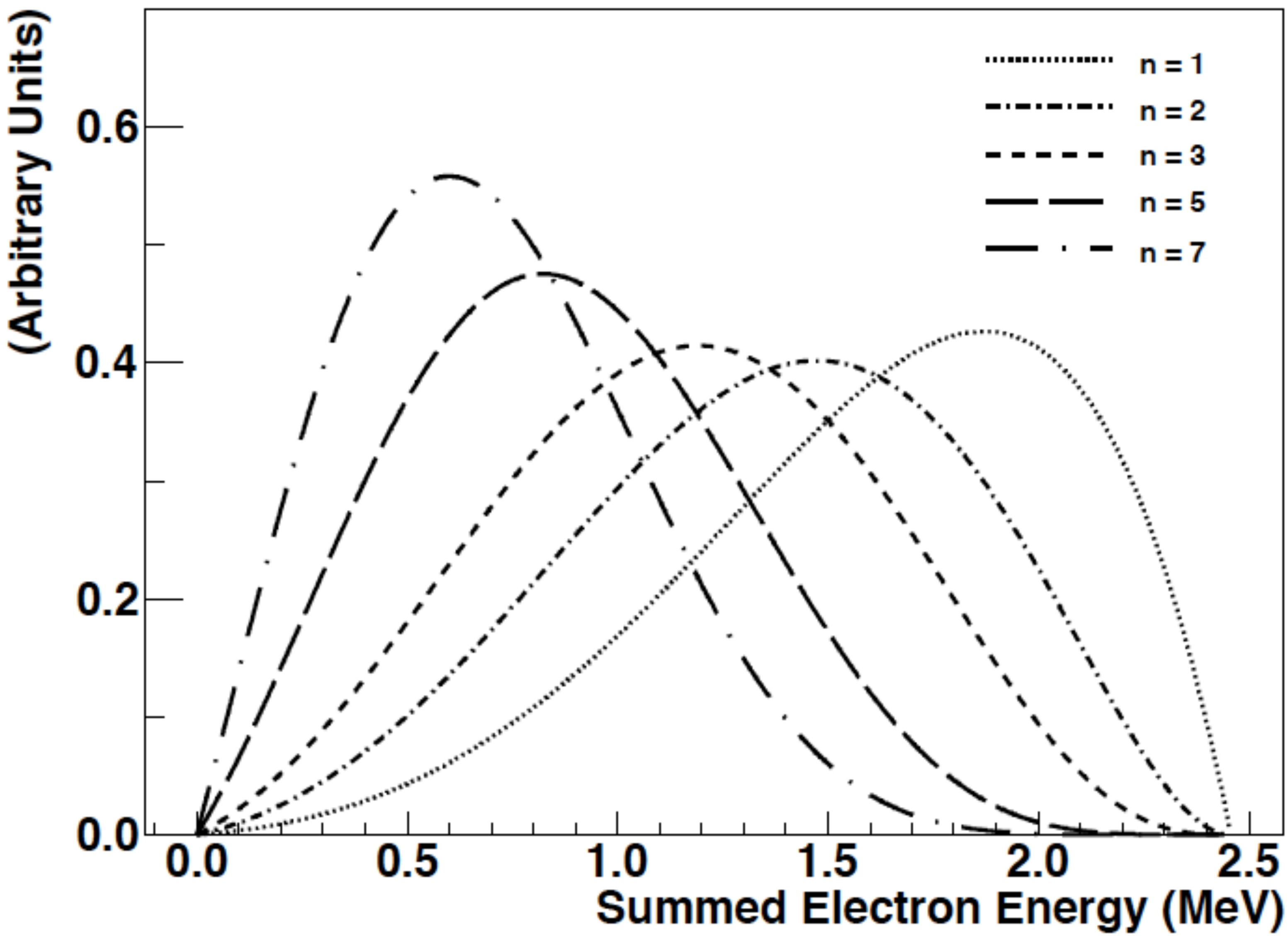
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120 (2018) 072701
2019: arXiv:1906.02723

Comparison across isotopes

Current limits, ^{76}Ge vs. ^{136}Xe

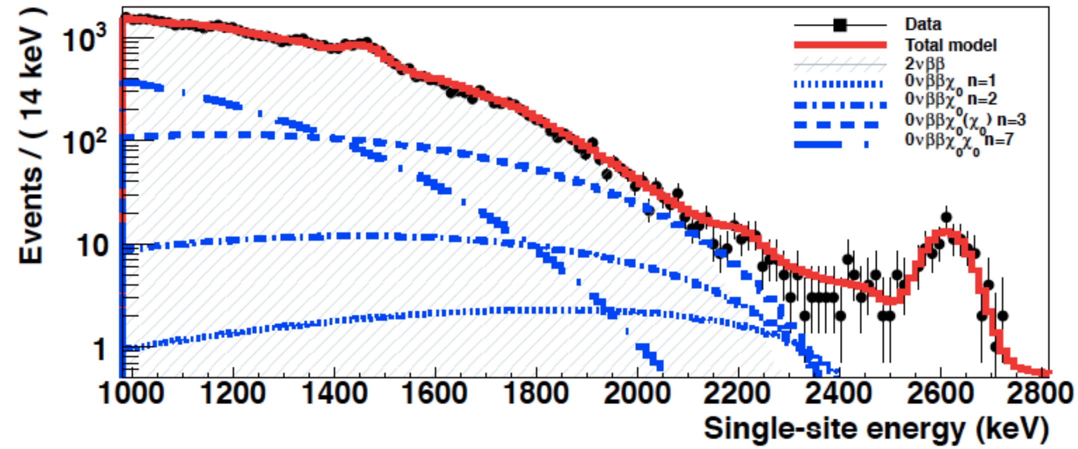


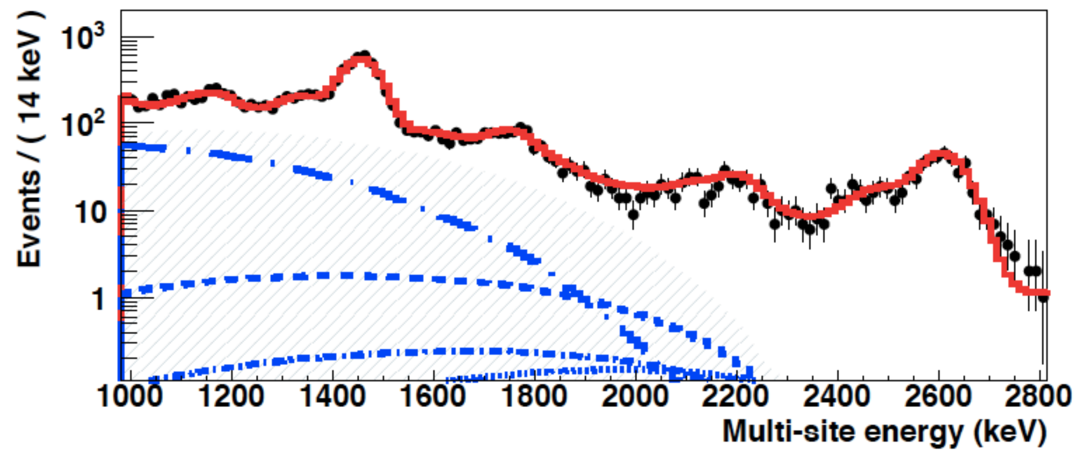
Majoron modes in Xe



Majoron Search in EXO-200

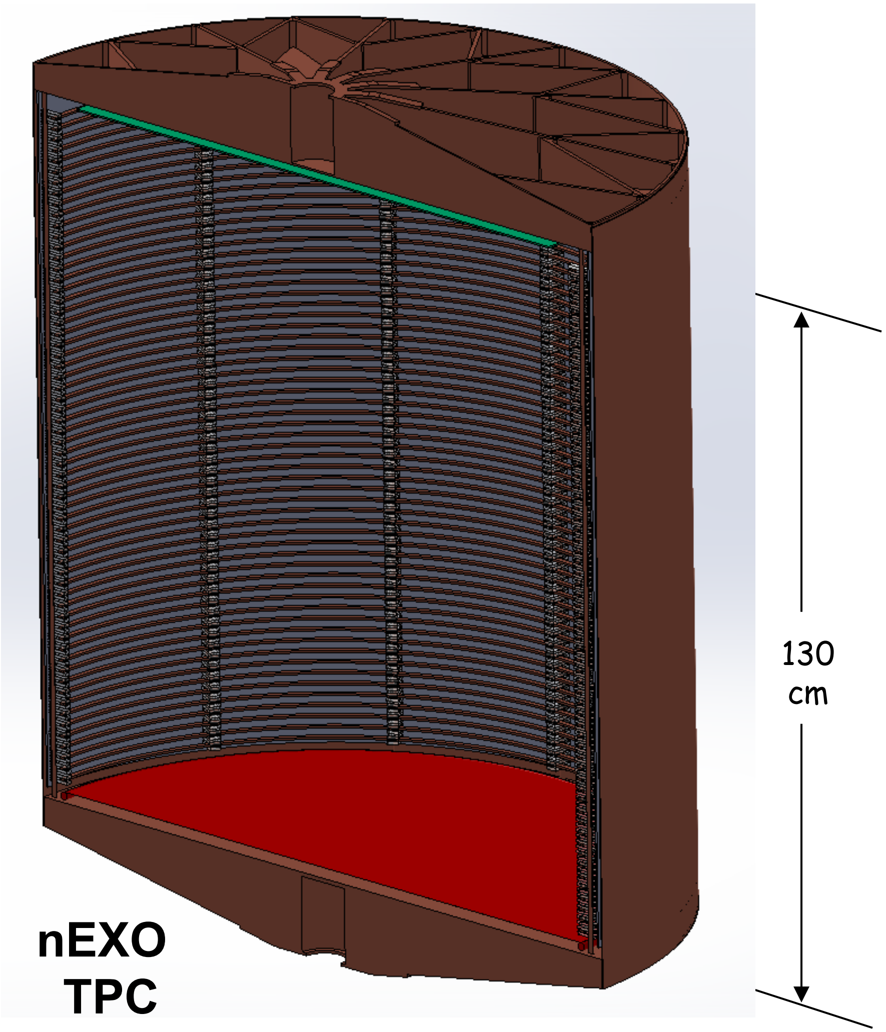
Phys. Rev. D 90, 092004 (2014)

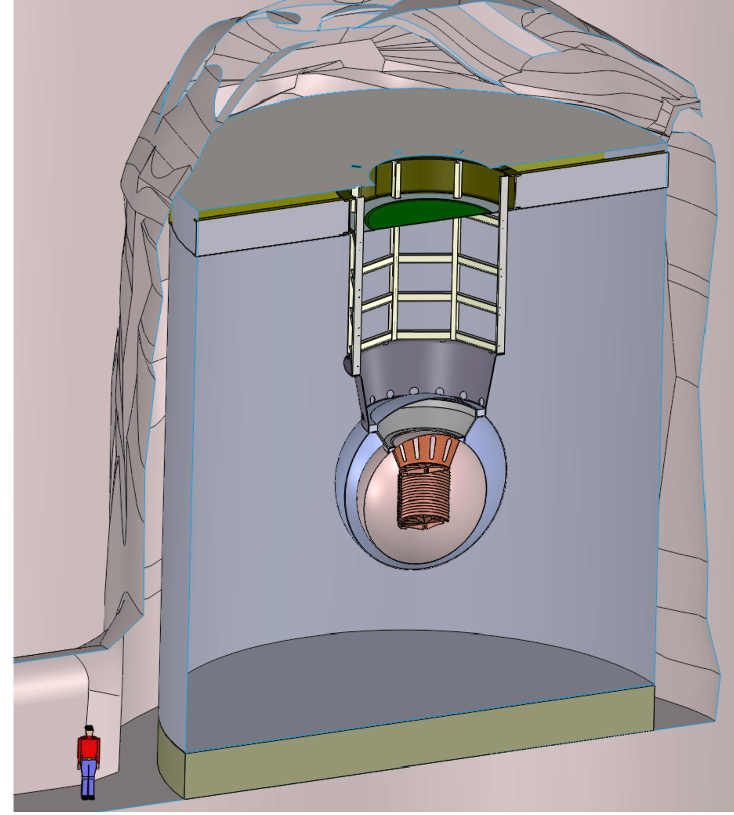




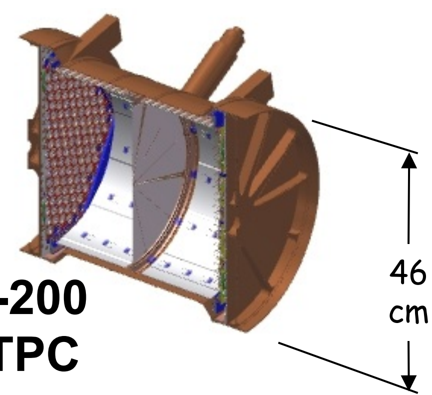
Decay mode	Spectral index, n	Model types	$T_{1/2}$, yr	$\lvert\langle g^M_{ee}\rangle\rvert$
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$>1.2\cdot10^{24}$	$<(0.8\text{-}1.7)\cdot10^{-5}$
$0\nu\beta\beta\chi_0$	2	"Bulk"	$>2.5\cdot10^{23}$	–
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$>2.7\cdot10^{22}$	$<(0.6\text{-}5.5)$
$0\nu\beta\beta\chi_0$	3	IIC, IIF	$>2.7\cdot10^{22}$	<0.06
$0\nu\beta\beta\chi_0\chi_0$	7	IIE	$>6.1\cdot10^{21}$	$<(0.5\text{-}4.7)$

EXO-200 to nEXO



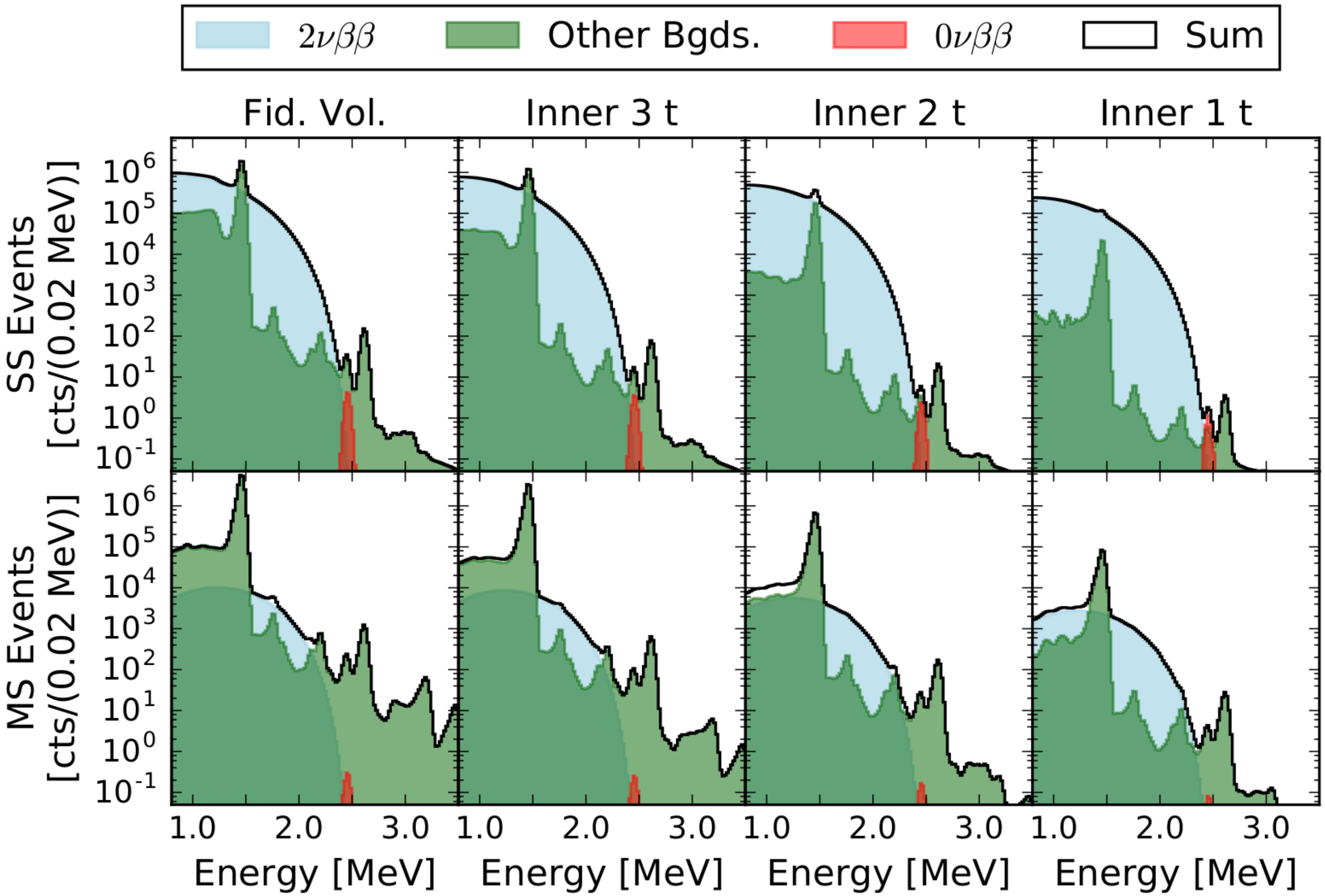


Preliminary artist view of nEXO in the SNOlab Cryopit



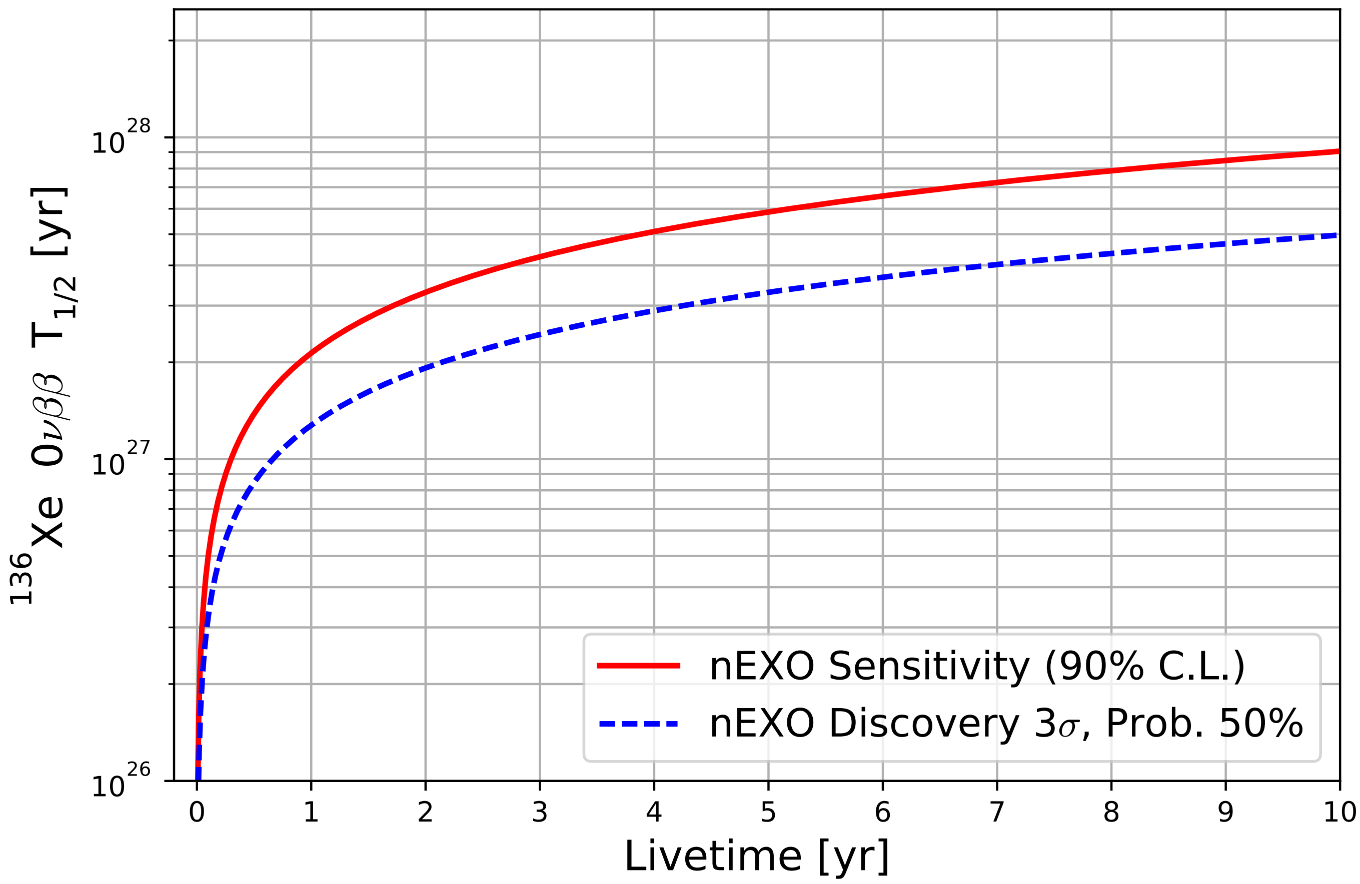
A 5000 kg enriched LXe TPC, based on success ofEXO-200

nEXO discovery potential



nEXO 10 year discovery potential at $T_{1/2}$=5x10^{27} yr

nEXO sensitivity



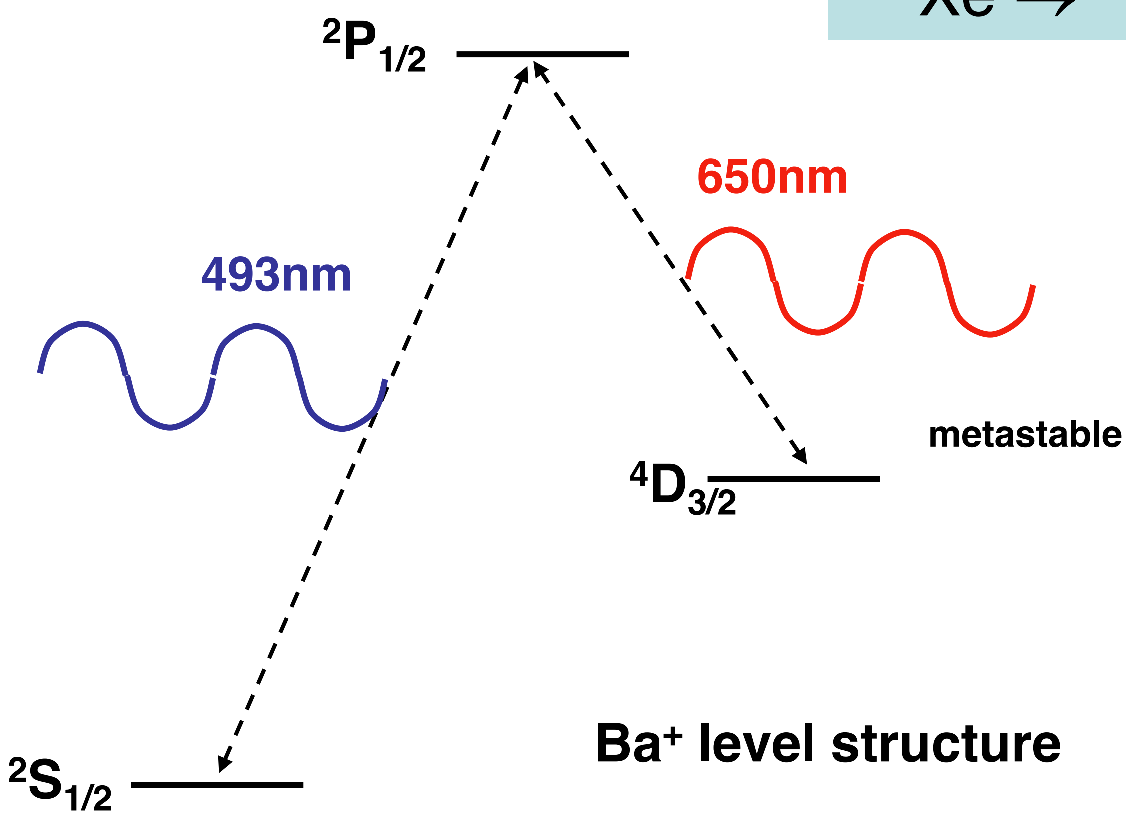
Baseline design assumes:

- Existing measured materials
- 1% σ/E energy resolution
- Factor of two improvement in SS/MS discrimination

Ba⁺ tagging

If you could identify the daughter nucleus as ^{136}Ba on an event-by-event basis, you could eliminate all backgrounds other than $2\nu\beta\beta$.

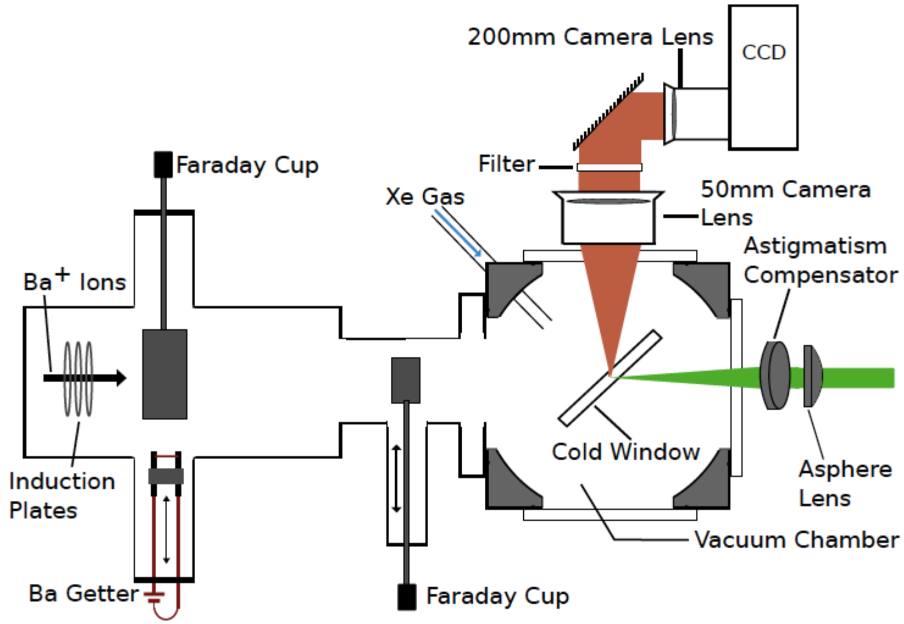
$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$$

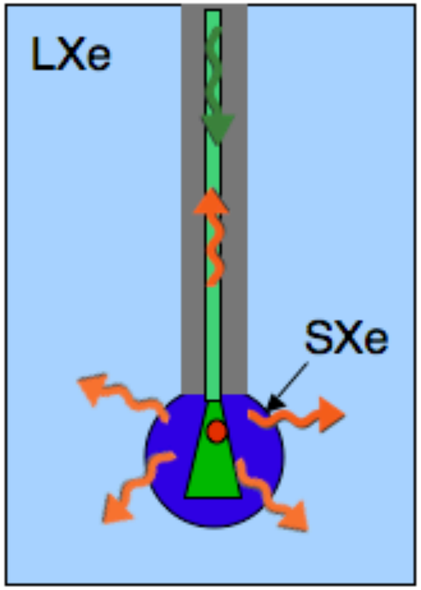


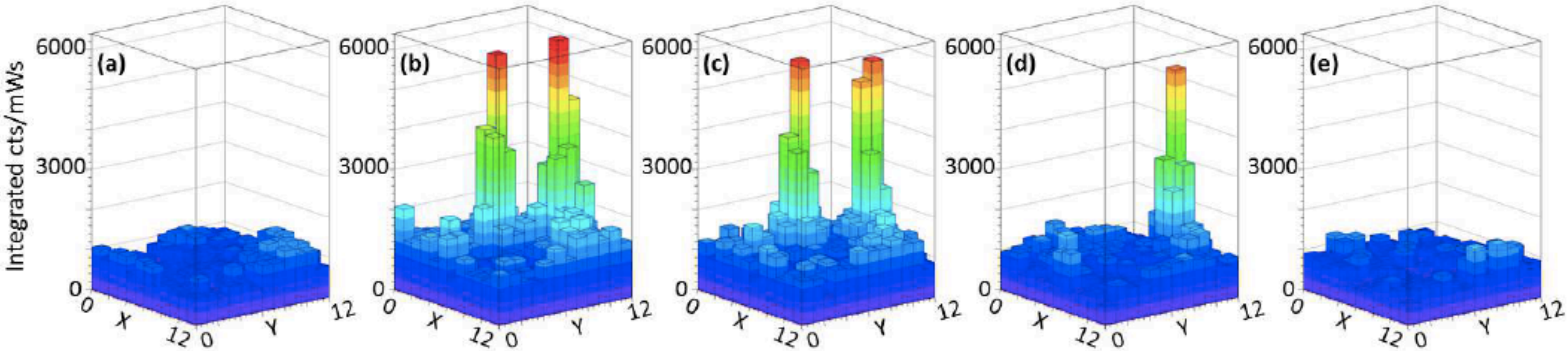
Ba⁺ level structure

- Ba⁺ system is well studied. See H. Dehmelt et al. *Phys. Rev*. A**22**, 1137 (1980).
- Very specific signature with laser induced fluorescence.
- Single ions can be detected from a photon rate of 10^7/s

Barium tagging: Solid xenon







Images of few Ba atoms in solid xenon.
C. Chambers, et al. Nature **569**, 203–207 (2019)

Summary

- Neutrino masses are an open window into physics beyond the Standard Model.
- Majorana neutrino masses may be the key to understanding the matter-antimatter asymmetry of the universe.
- Neutrinoless double beta decay is the most sensitive experimental probe of whether neutrinos have Majorana masses.
- There is a varied experimental program to search for neutrinoless double beta decay.
- We need nuclear theorists, too!