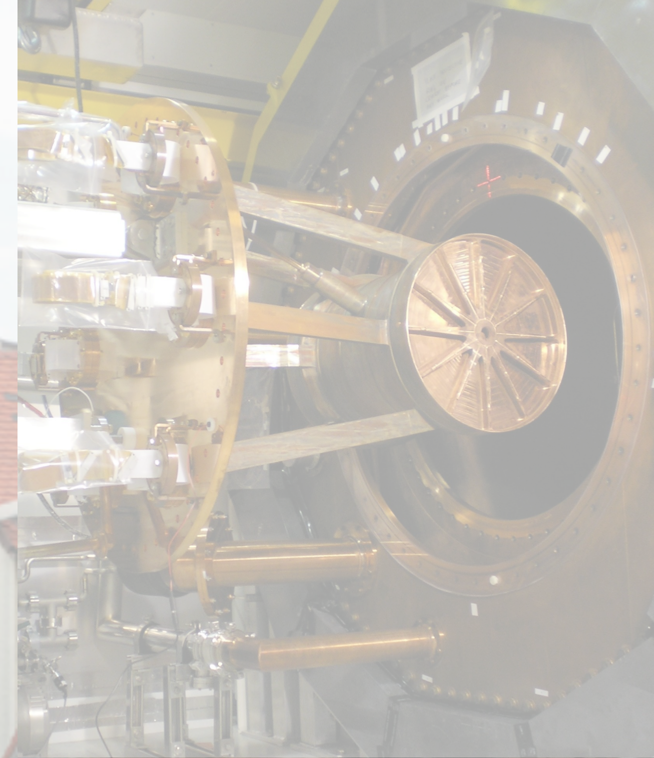
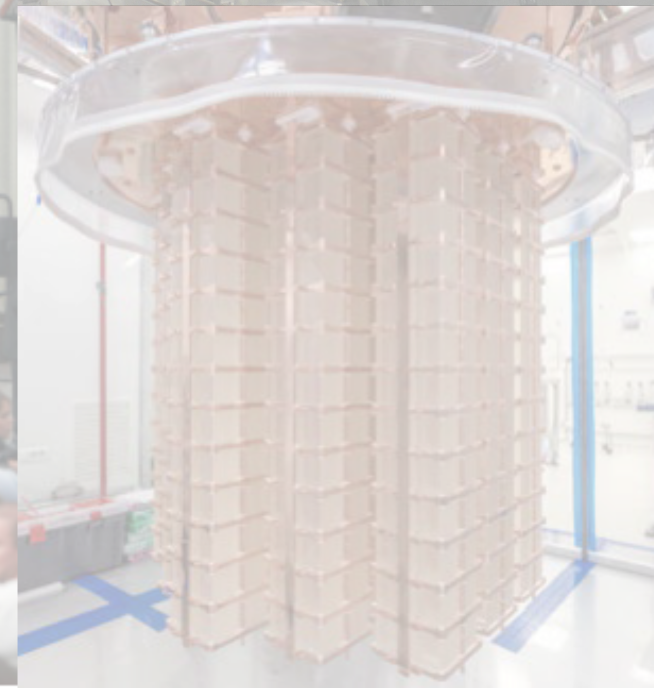
Neutrino mass overview

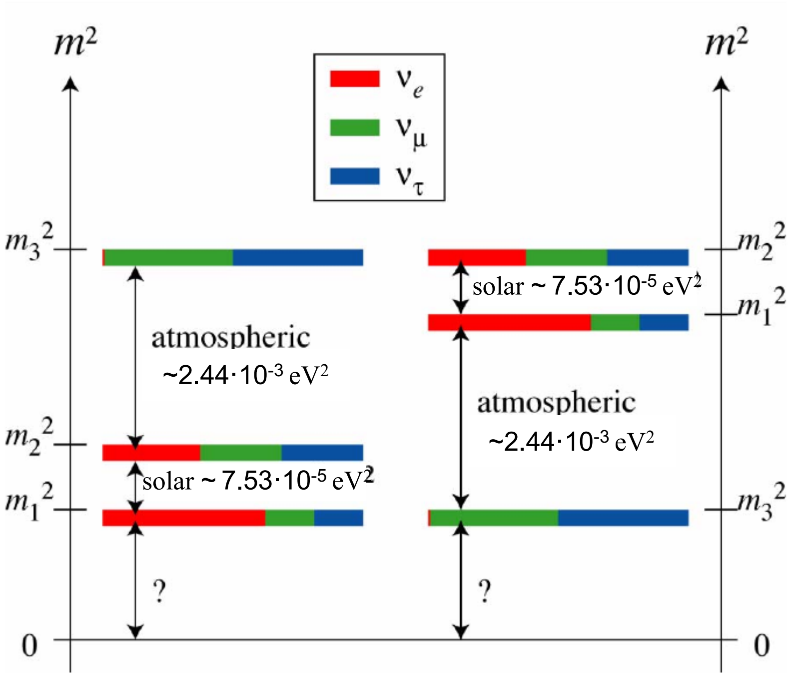




Michelle Dolinski
Drexel University

Topics in Cosmic Neutrinos workshop
10/10/2019

Neutrino mass and mixing



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

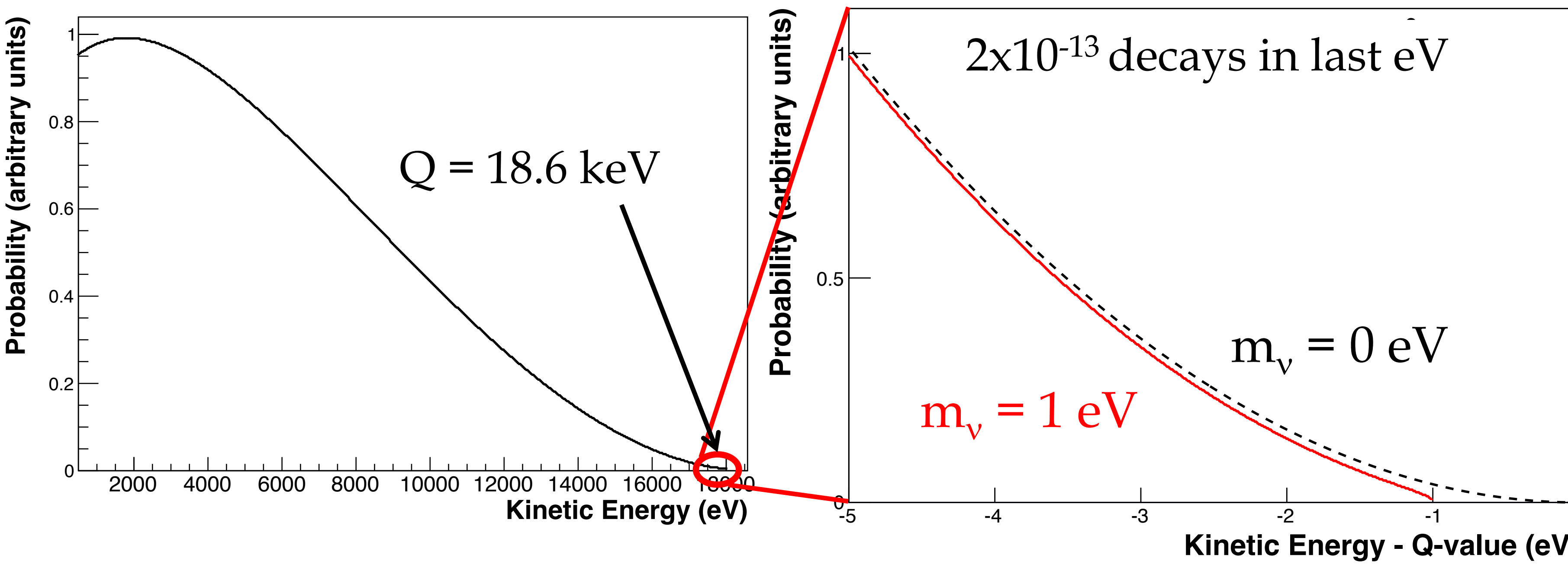
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{“atmospheric”}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{“reactor”}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“solar”}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$\sin^2\theta_{23}$ $\sin^2\theta_{13}$ $\sin^2\theta_{12}$

Beta decay

Nonzero neutrino mass distorts the b-decay spectrum near the end point. Taking mass eigenstates into account, the relevant mass parameter m_ν is given by

$$m_\nu^2 = \Sigma|U_{ei}|^2 m_i^2$$



Beta decay limits

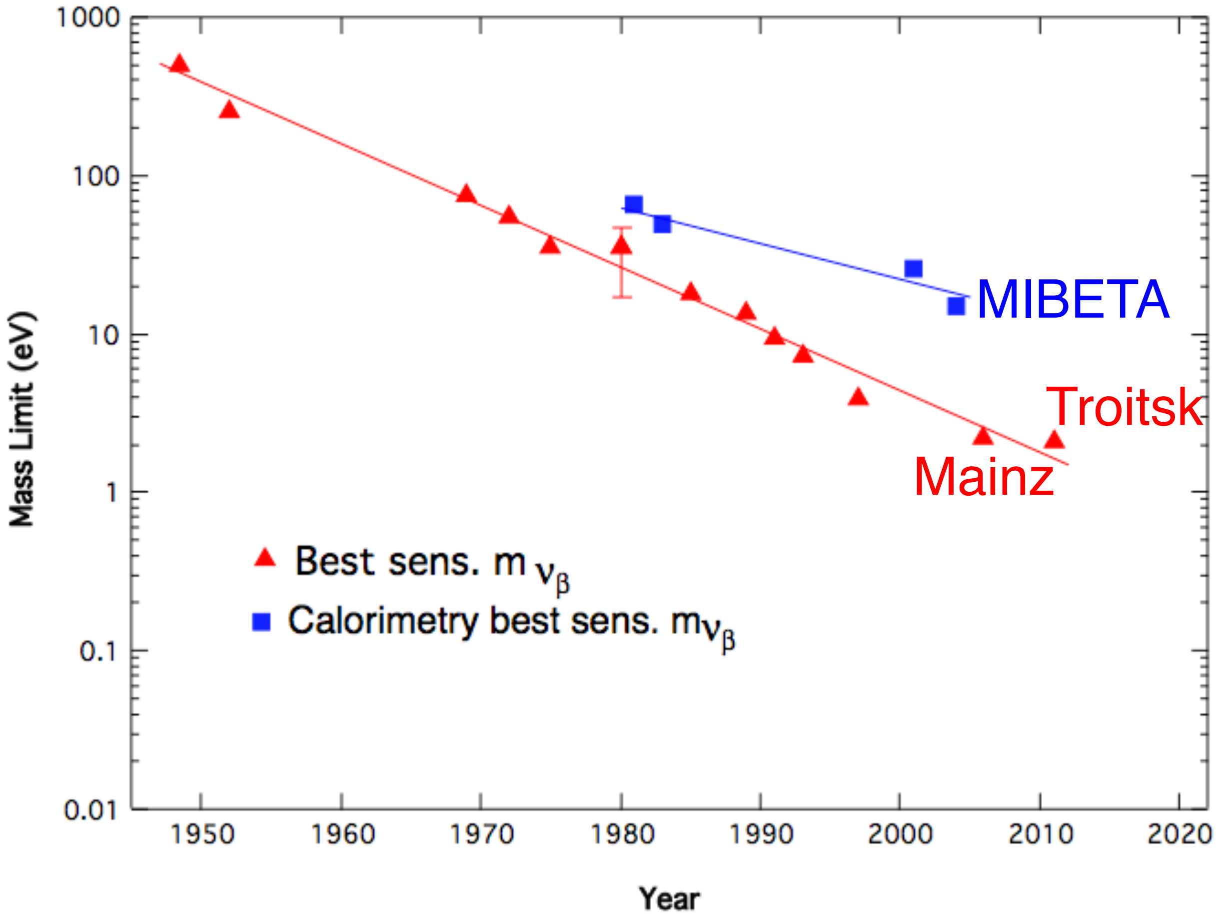
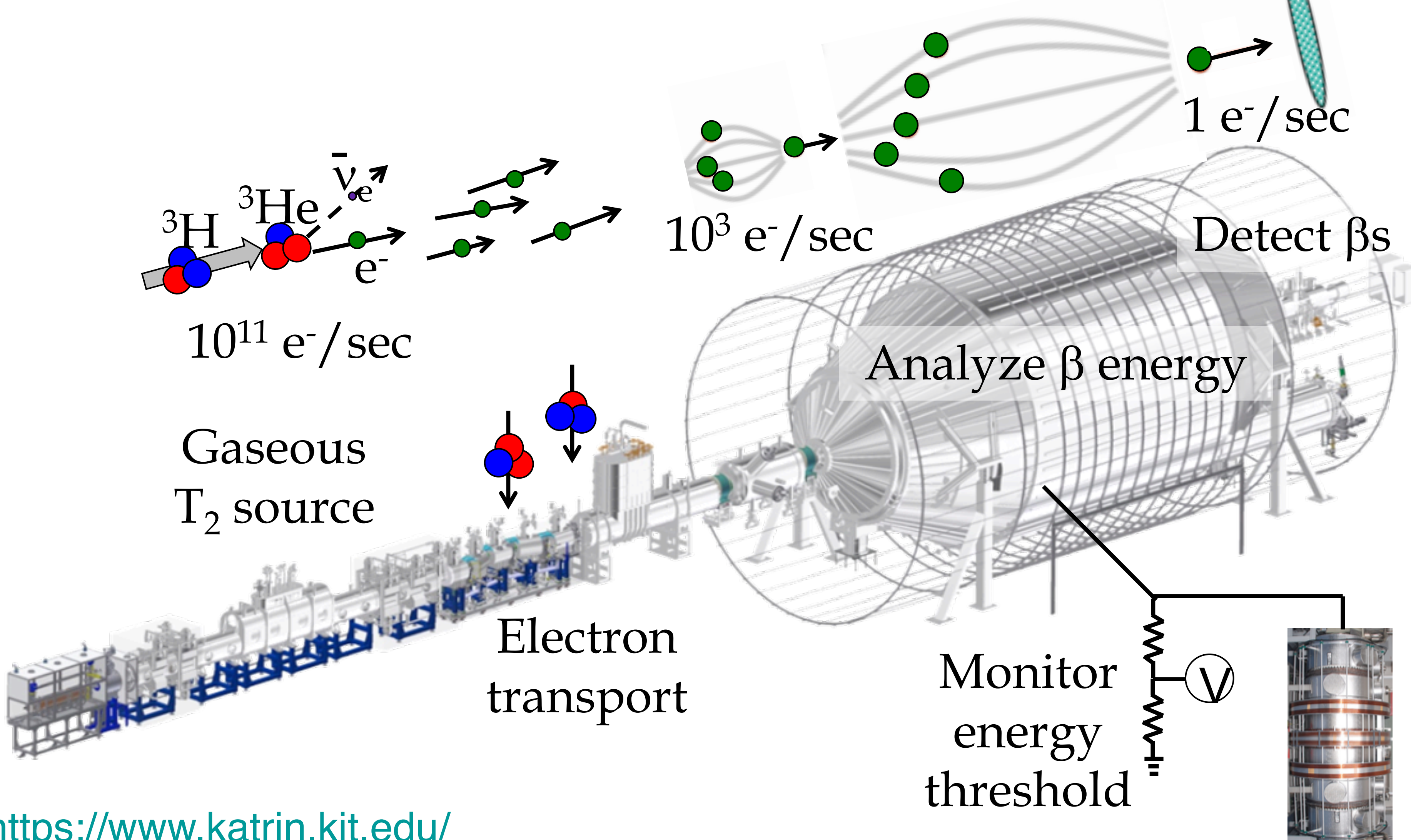


Figure from J. Wilkerson, Neutrino 2012

^{187}Re
Q = 2.47 keV
$T_{1/2}$ = 4.5 x 10^9 y
Forbidden

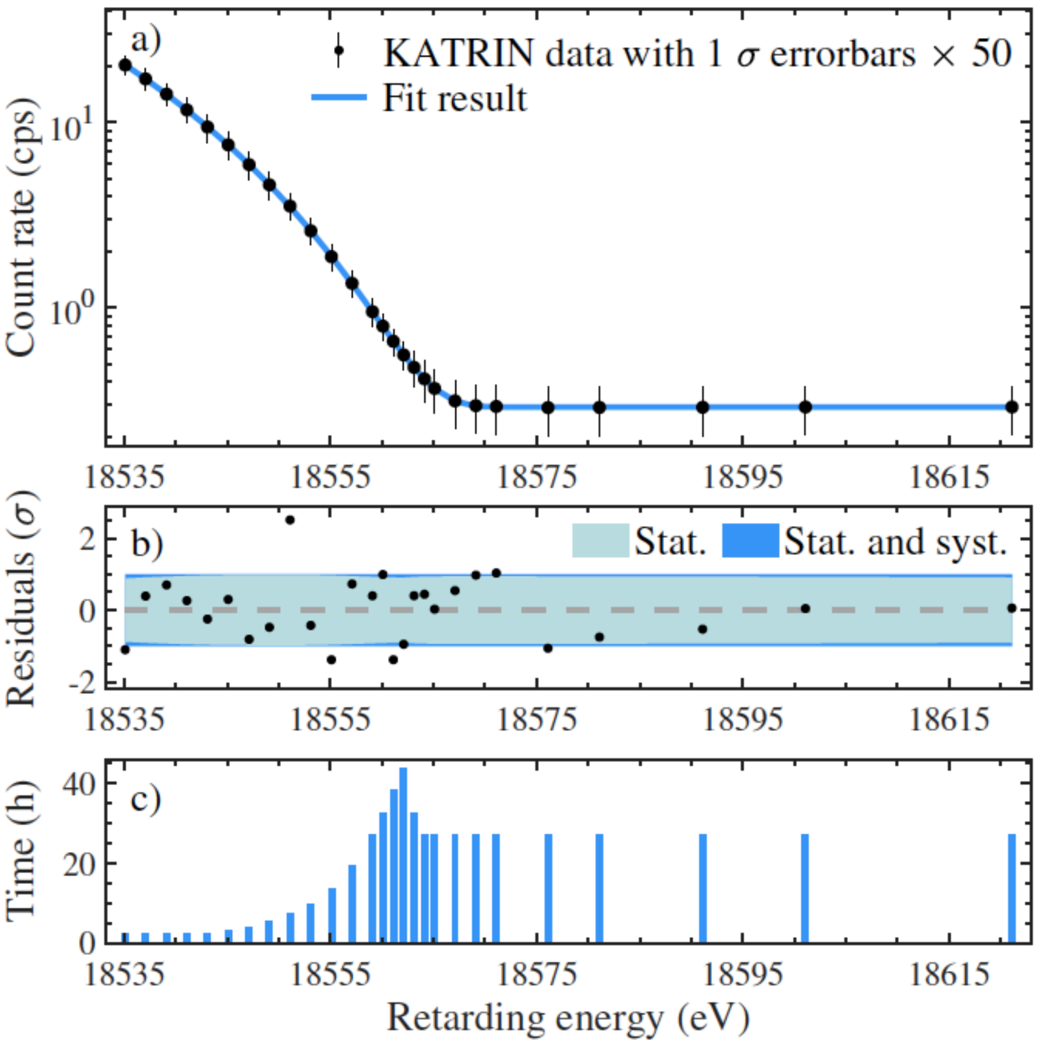
^{3}H (tritium)
Q = 18.6 keV
$T_{1/2}$ = 12.3 y
Super-allowed

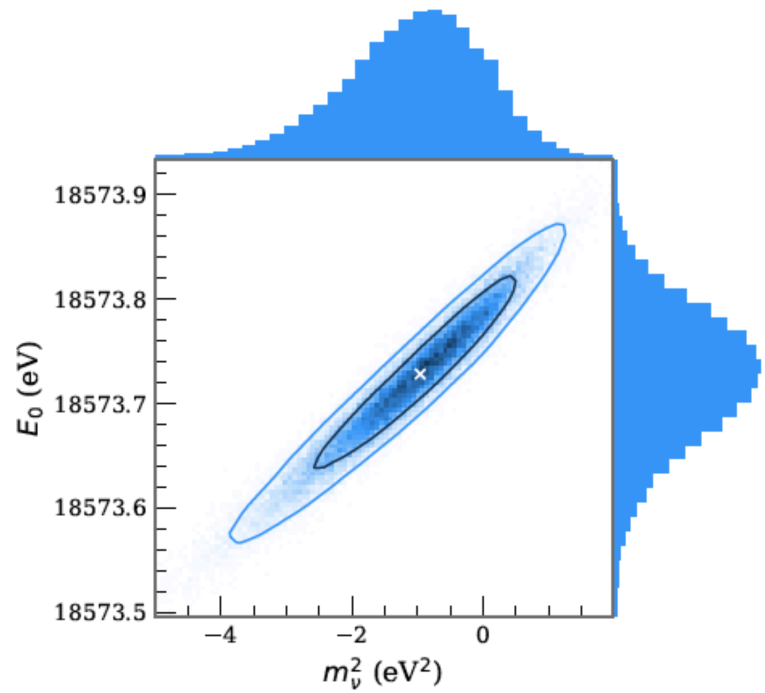
KArlsruhe **TRI**tium **N**eutrino experiment



https://www.katrin.kit.edu/

KATRIN first results





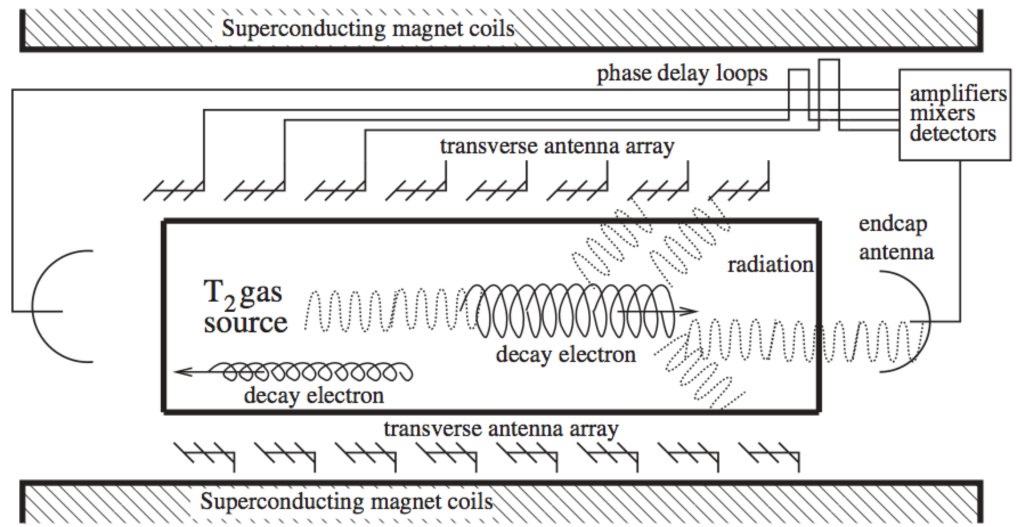
$m_\nu < 1.1$ eV at 90% C.L.

arXiv:1909.06048v1

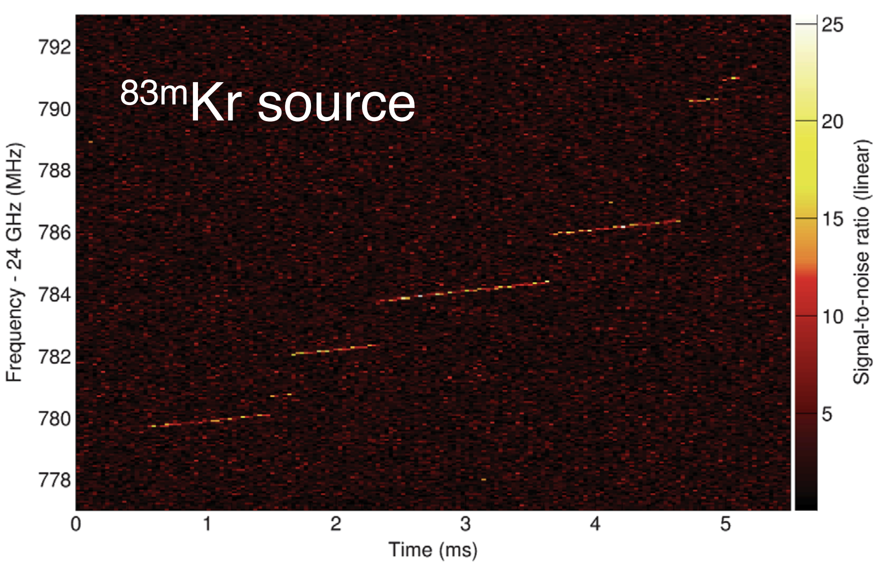
New approach

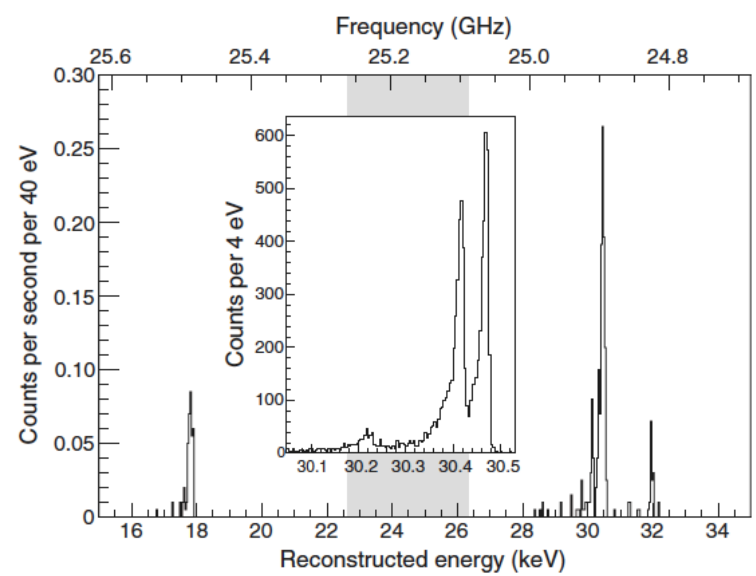
Measure entire beta spectrum at once: **C**yclotron **R**adiation **E**mission **S**pectroscopy (**CRES**)

$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi}\frac{1}{m_e + {}^1\!/_{c^2} E_\beta}$$



*Monreal and Formaggio, PRD **80** (2009)*

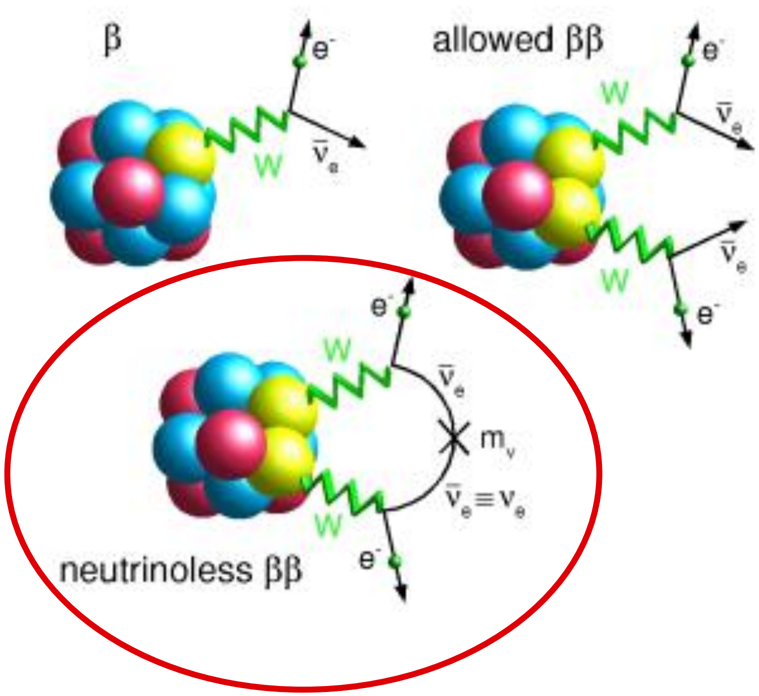




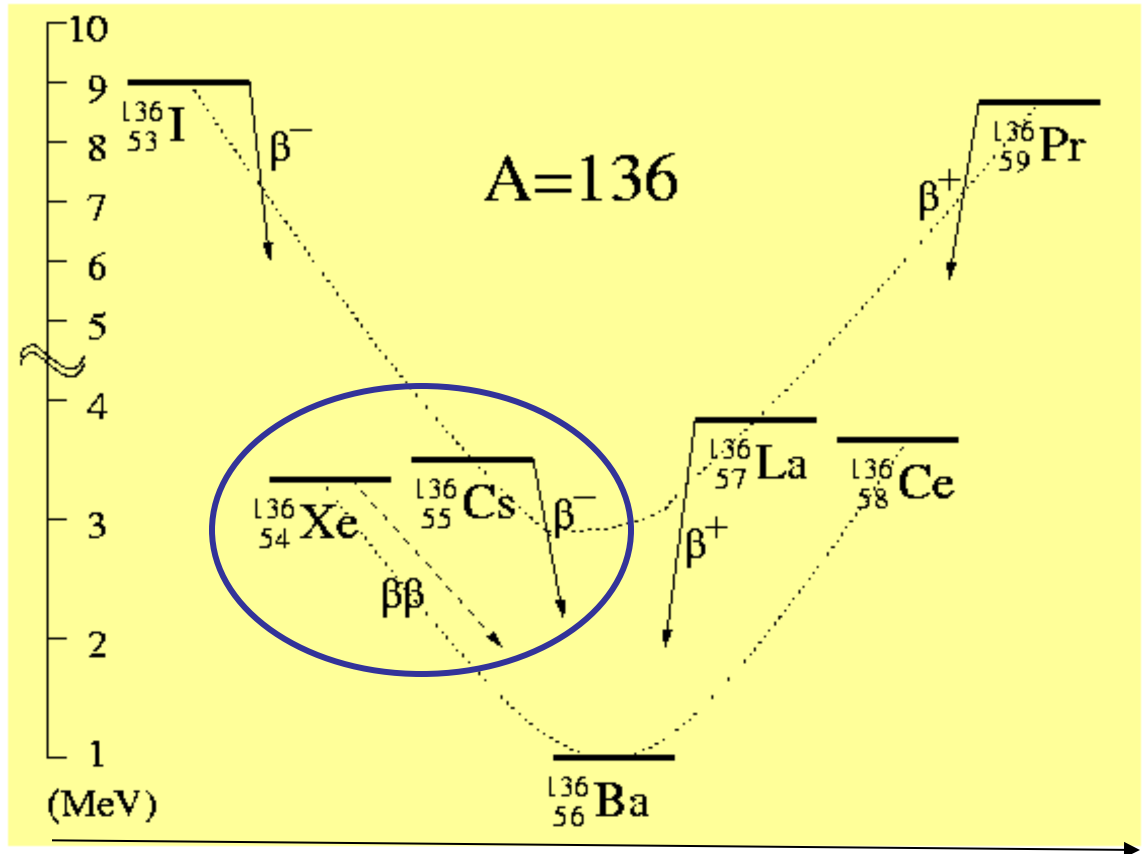
*PRL **114**, 162501 (2015)*

Double beta decay

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



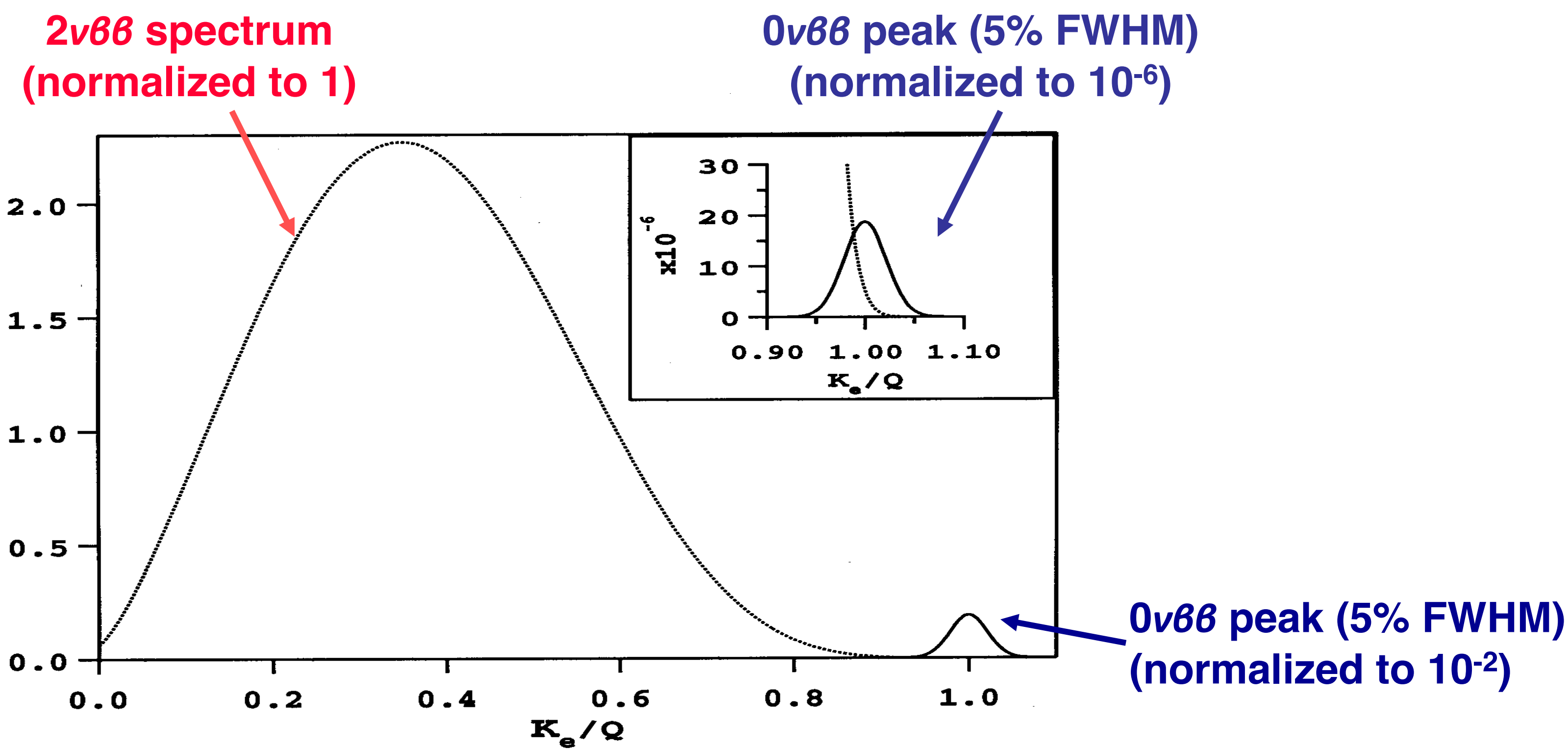
This process can only occur for a Majorana neutrino!

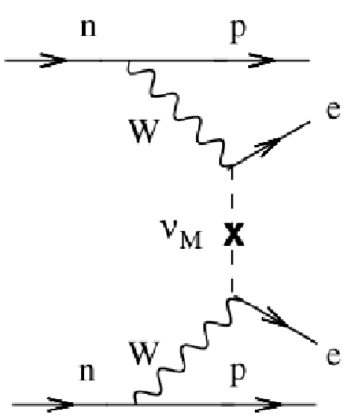


Atomic number (Z)

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

Neutrinoless double beta decay





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

(light Majorana neutrino exchange mechanism ONLY)

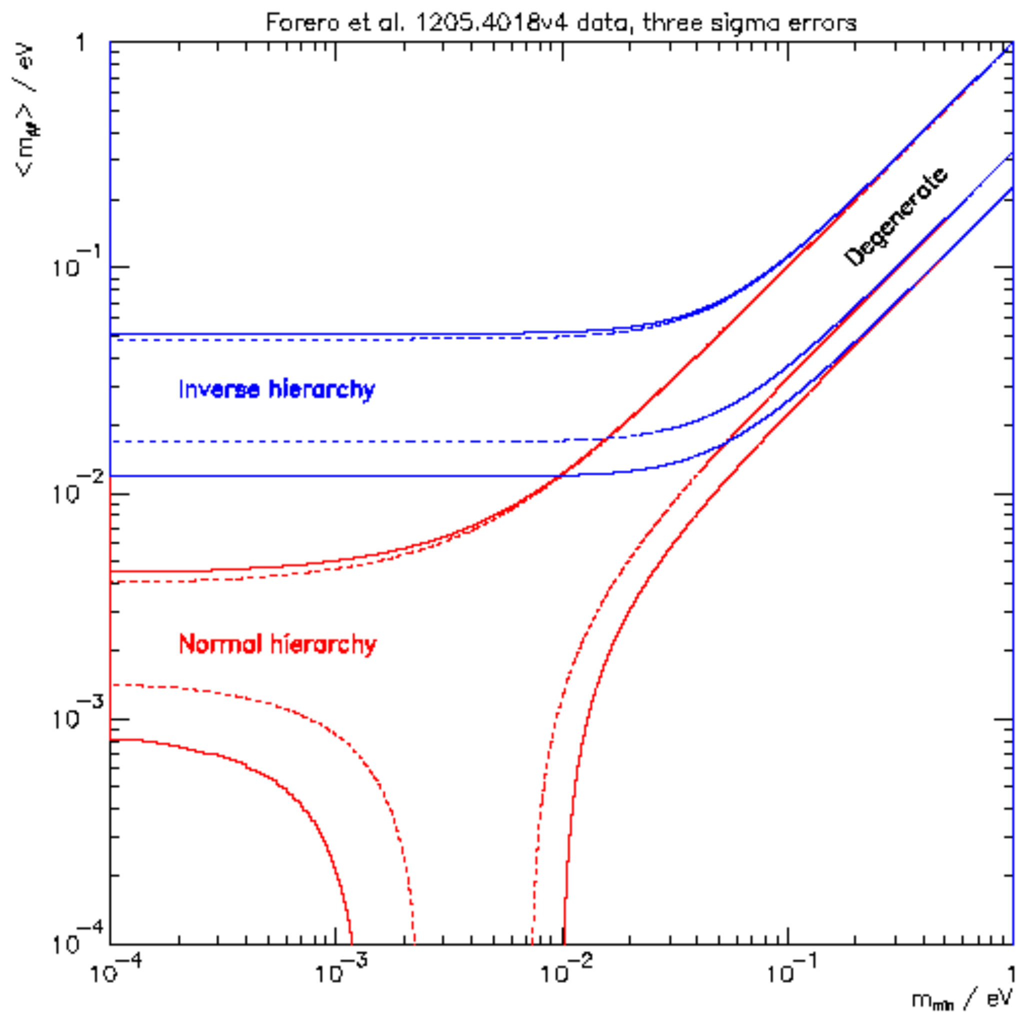
Effective Majorana mass

Phase space considering light Majorana neutrino exchange mechanism ONLY.

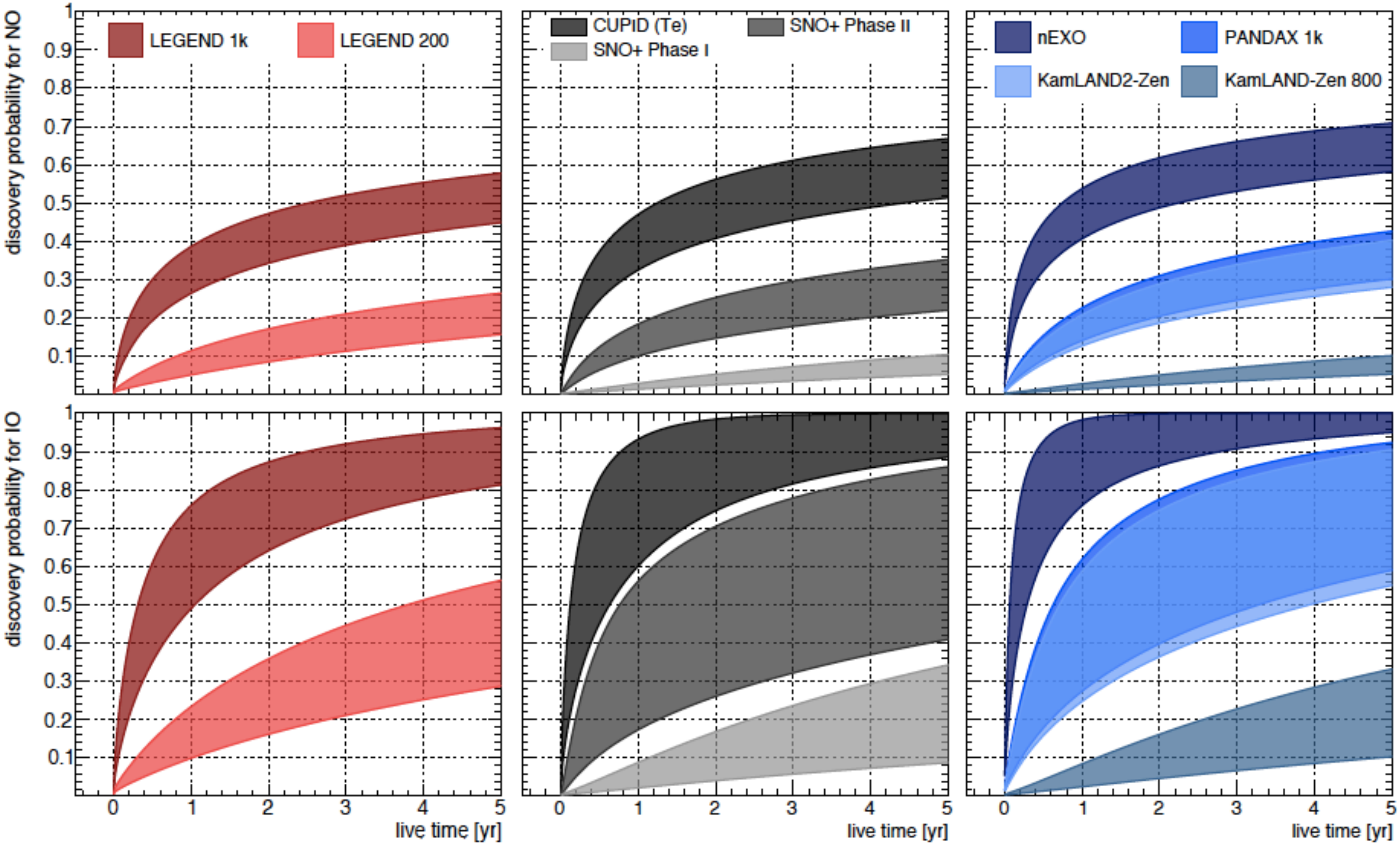
$$\langle m_{\beta\beta}\rangle = \left| m_1 \cdot (1-\sin^2\theta_{12}) \cdot (1-\sin^2\theta_{13}) + m_2 \cdot \sin^2\theta_{12} \cdot (1-\sin^2\theta_{13}) \cdot e^{i\cdot(\alpha_2-\alpha_1)} + m_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3} \right|$$

Reach of a particular experiment requires knowledge of nuclear matrix elements for that isotope. See for example Engel and Menendez, Reports on Progress in Physics 80, 046301 (2017).

Plot courtesy Andreas Piepke.



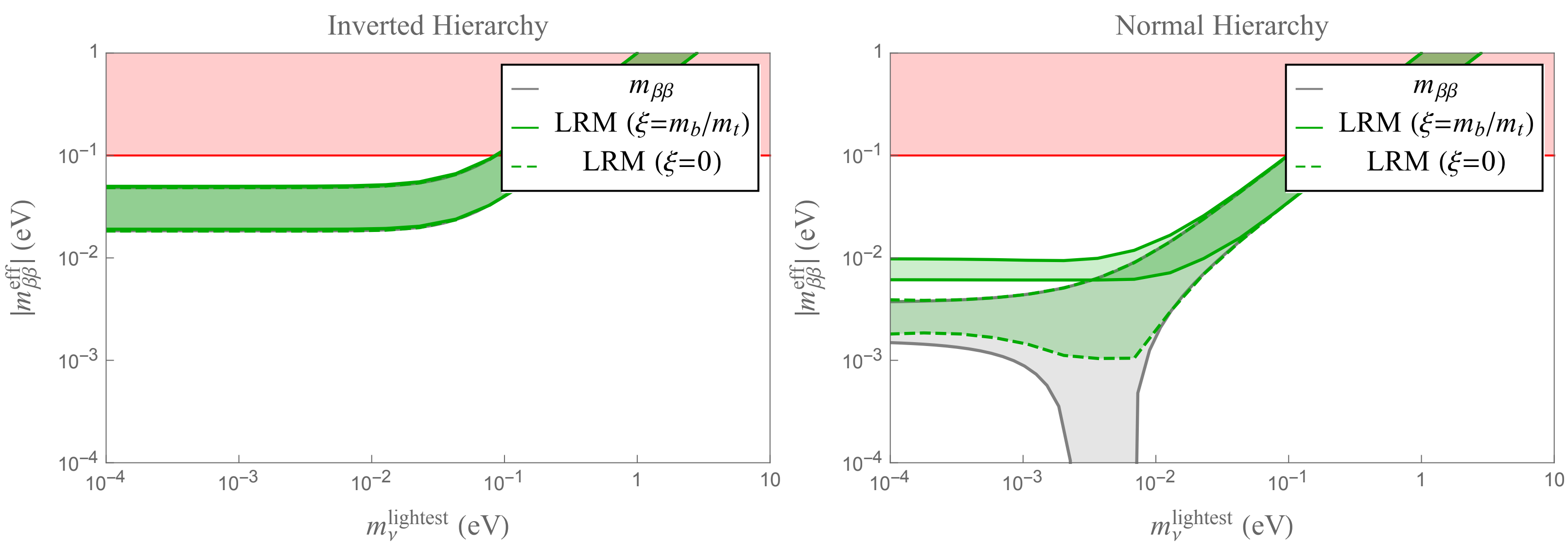
Discovery potential



Analysis assumes free value of g_A and uses a Bayesian analysis with flatly distributed priors [Agostini, Benato, Detwiler, *PRD* 96 (2017) 053001].
See also A. Caldwell et al., *PRD* 96 (2017) 073001.

Other mechanisms

While it is convenient to think in terms of the light neutrino exchange mechanism, no reason to think it's dominant!



Consider a model with 10 TeV right-handed neutrinos in the minimal left-right symmetric model, symmetric under charge conjugation (assuming that the mixing matrix of the right-handed neutrinos is the same as the PMNS matrix).

See Cirigliano, V., Dekens, W., de Vries, J. et al. "A neutrinoless double beta decay master formula from effective field theory," J. High Energ. Phys. (2018) 2018: 97. Thanks to Wouter Dekens for help with this material.

Other mechanisms

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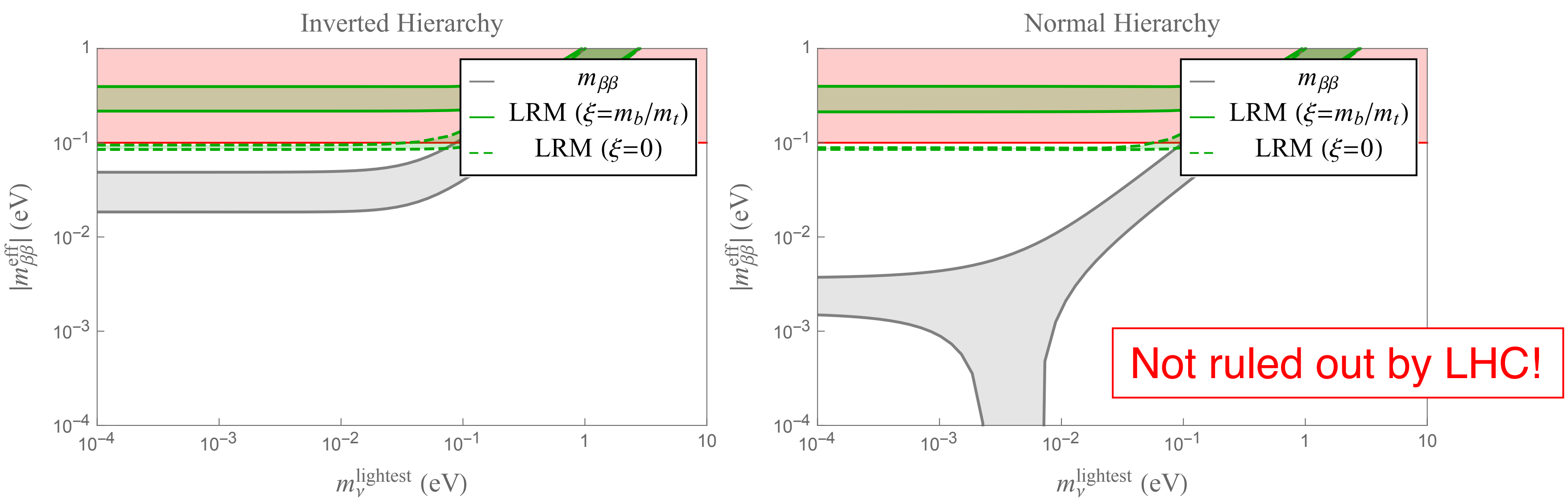
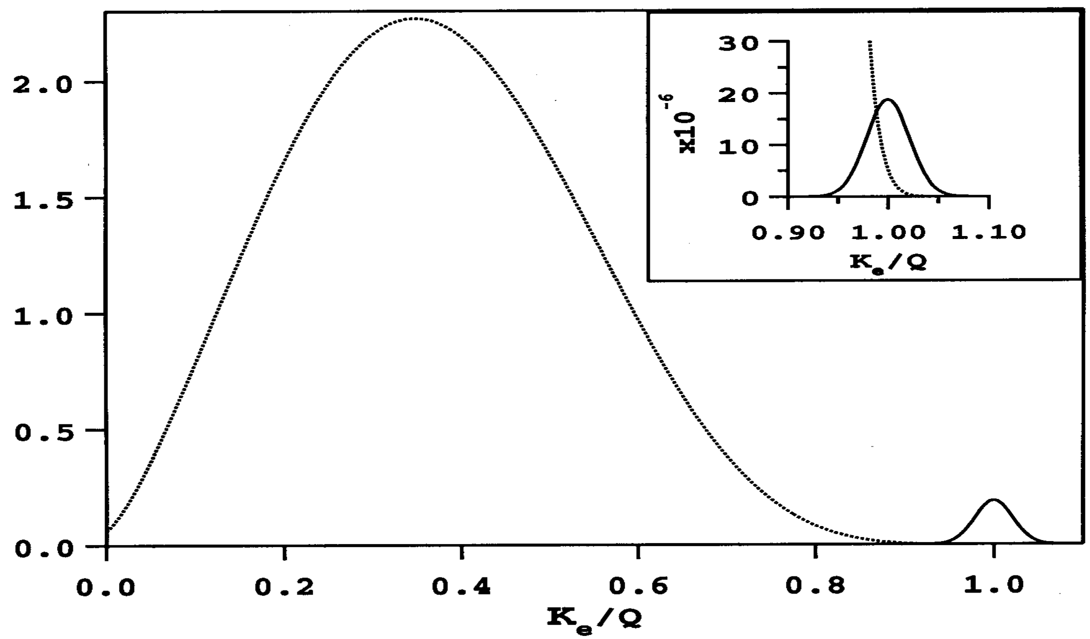
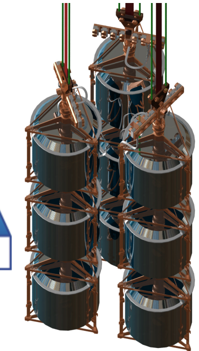


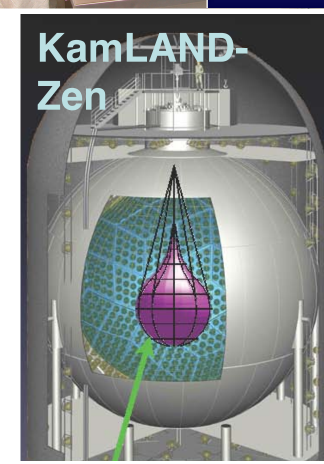
Now consider the same model with 10 GeV right-handed neutrinos in the minimal left-right symmetric model, symmetric under charge conjugation. Alternate mechanism would dominate over light Majorana neutrino exchange.

See Cirigliano, V., Dekens, W., de Vries, J. et al. "A neutrinoless double beta decay master formula from effective field theory," J. High Energ. Phys. (2018) 2018: 97. Thanks to Wouter Dekens for help with this material.

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



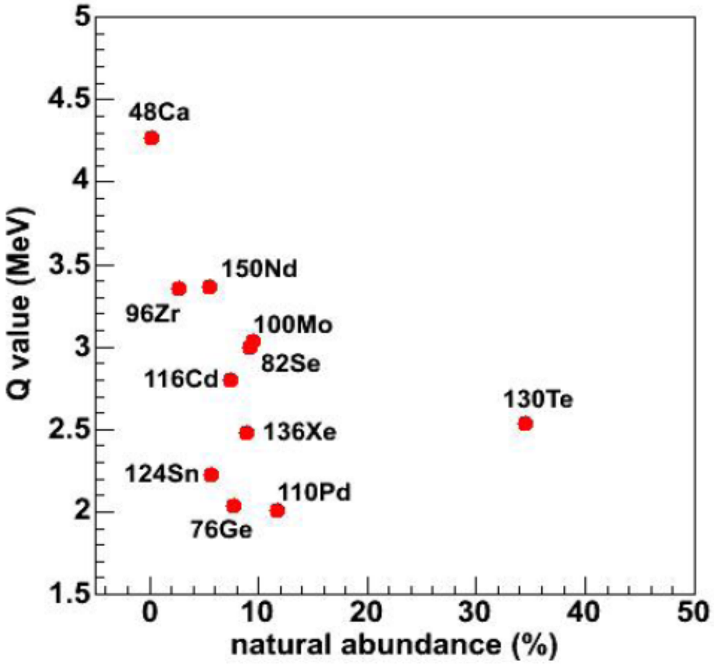


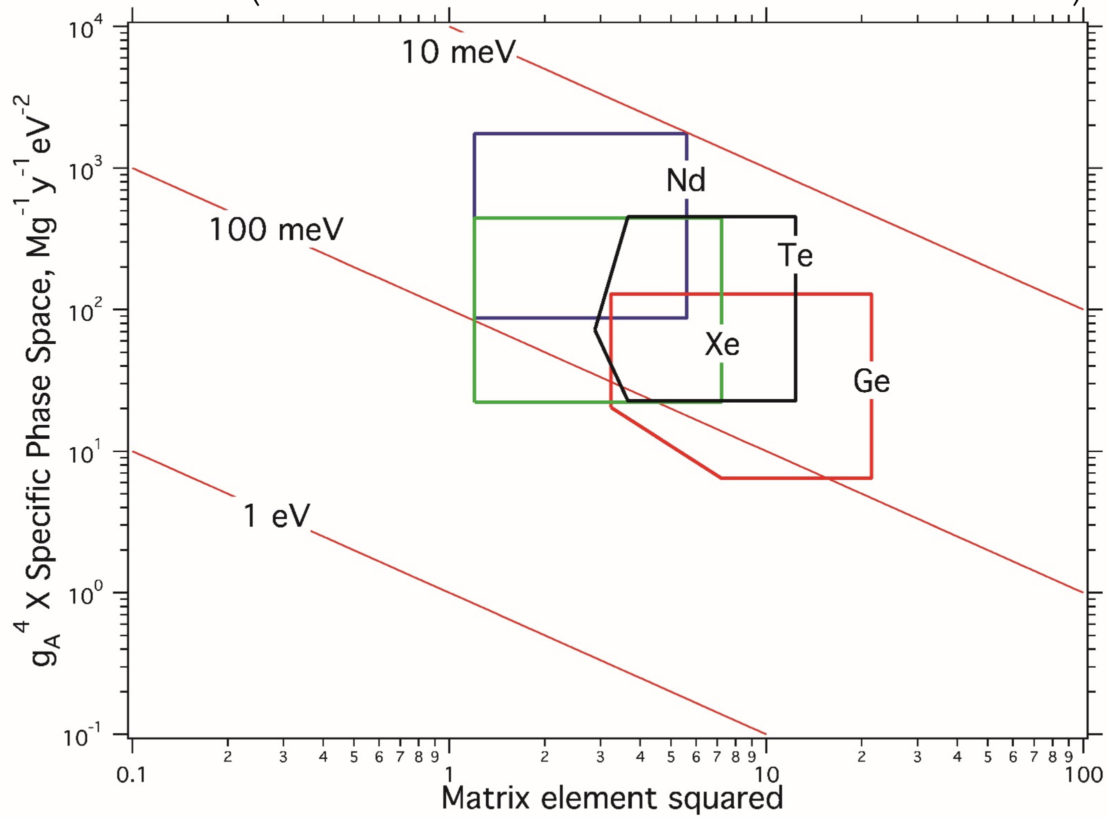


- **Large exposure**
- **Low background**
- Good energy resolution
- High detection efficiency

Isotope choice

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





There is not a clear winner based on phase space and matrix element considerations.

R.G.H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).

Ideally, we would observe $0\nu\beta\beta$ in more than one isotope!

Crystals:

- **GERDA**, **Majorana Demonstrator**, LEGEND (^{76}Ge diodes)
- **CUORE*** (^{130}Te bolometers)
- CUPID (^{100}Mo/^{130}Te bolometers with light)

Pros: Excellent energy resolution, possibly 2-parameter measurement

Cons: Intrinsically fragmented

Liquid (organic) scintillators:

- **KamLAND-ZEN** (^{136}Xe)
- SNO+ (^{130}Te)

Pros: Large detectors exist, self-shielding

Cons: Poor energy resolution, 2ν background

Low density trackers:

- NEXT*, PandaX-III (^{136}Xe gas TPC)
- SuperNEMO (^{82}Se foils and gas tracking)

Pros: Superb topological information

Cons: Very large size

Liquid TPC:

- **EXO-200**, nEXO (^{136}Xe)
- XENON-nT, LZ, PandaX, DARWIN (^{136}Xe, optimized for direct dark matter search)

Pros: Homogeneous with good E resolution and topology

Cons: Does not excel in any single parameter

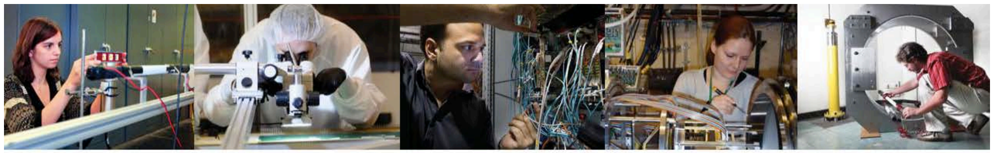
Current best $0\nu\beta\beta$ sensitivities

Isotope	Experiment	Exposure (kg yr)	Average half-life sensitivity (10^{25} y)	Half-life limit (10^{25} y) 90% C.L.	Effective mass limit (meV) Range from NME*	Reference
^{76}Ge	GERDA	82.4	11	> 9.0	< 113–254	Agostini et al. PRL 120, 132503 (2018)
	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, 132501 (2018)
^{136}Xe	EXO-200	234.1	5.0	> 3.5	< 93-286	Anton et al. to appear in PRL arXiv:1906.02723 (2019)
	KamLAND-ZEN	504	5.6	> 10.7	< 60-161	Gando et al., PRL 117, 082503 (2016)

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 tonne-scale.

A priority for nuclear physics, an opportunity for particle physics



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5) May 2014

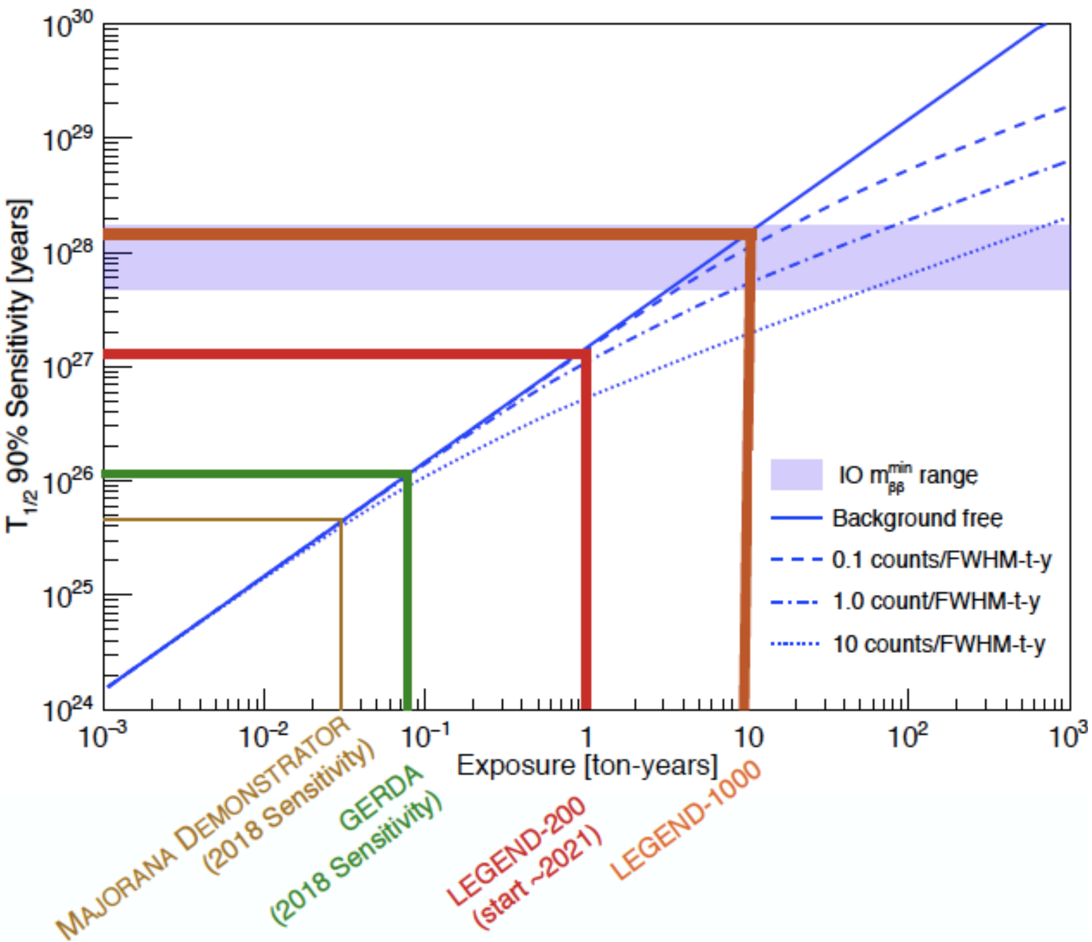
RECOMMENDATION II:
"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

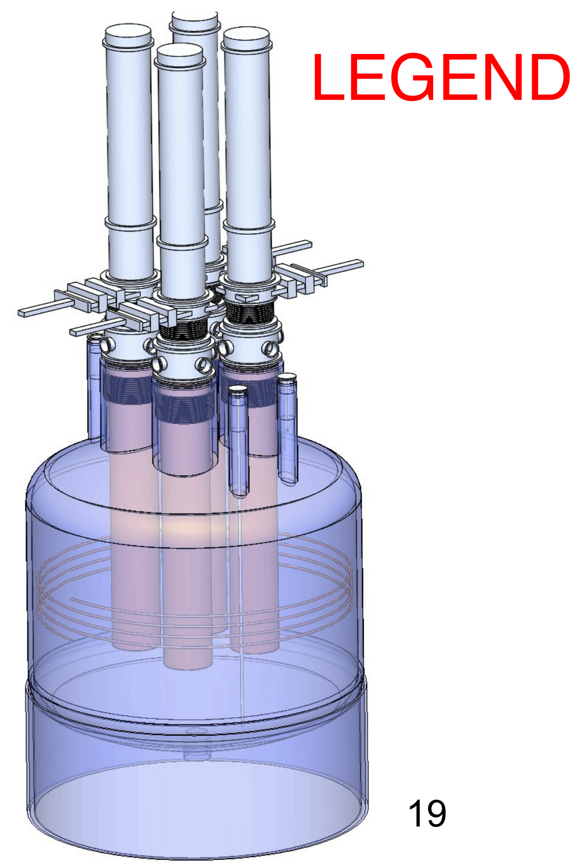
The most powerful probe of lepton number conservation, and whether neutrinos are Dirac or Majorana, is the observation of neutrinoless double-beta decay. These are questions and experiments of the greatest interest to particle physics."

"Next-generation experiments will continue to benefit from strong HEP and PA participation."

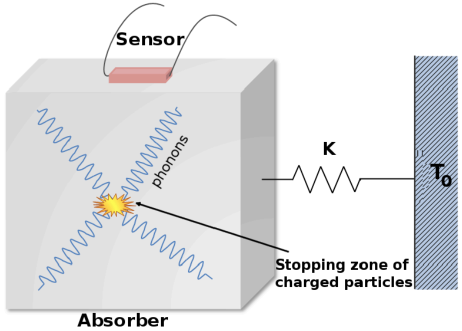
Next generation ton-scale ^{76}Ge $0\nu\beta\beta$

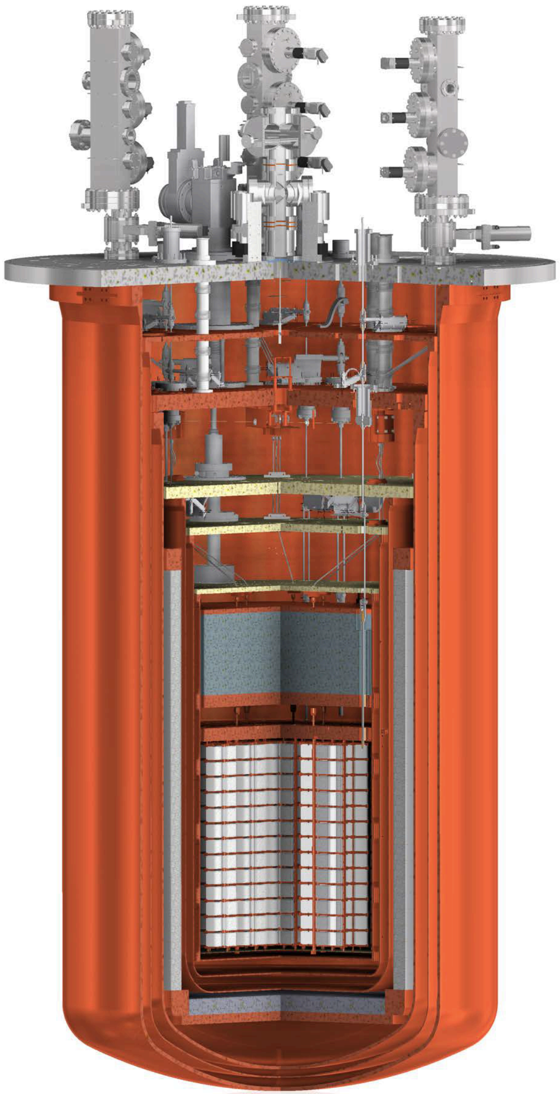
- Build on the experience of GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Design sensitivity of ~1x10^{28} y with a background of 0.1 cnt/tonne-yr in the region of interest (background reduction of ~6-20 relative to existing)

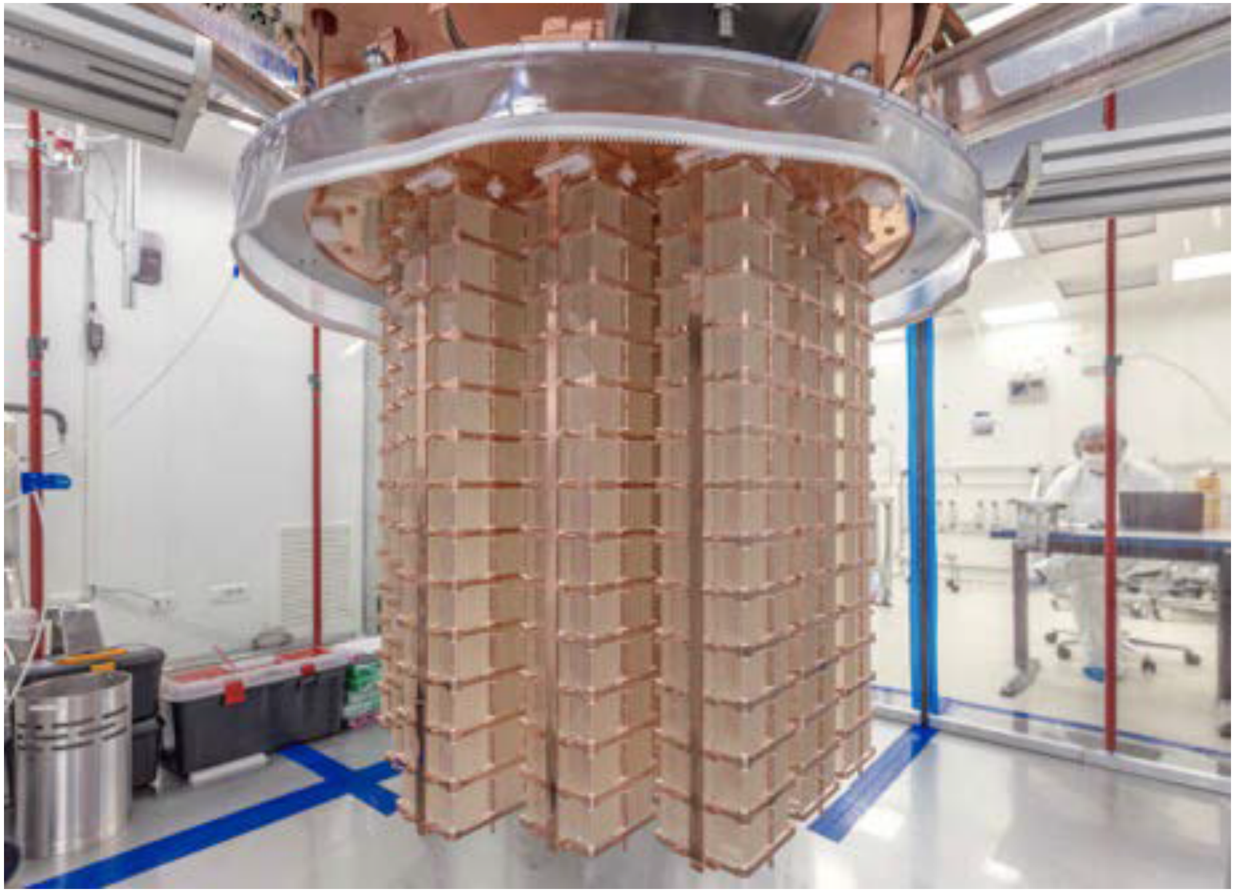




CUORE



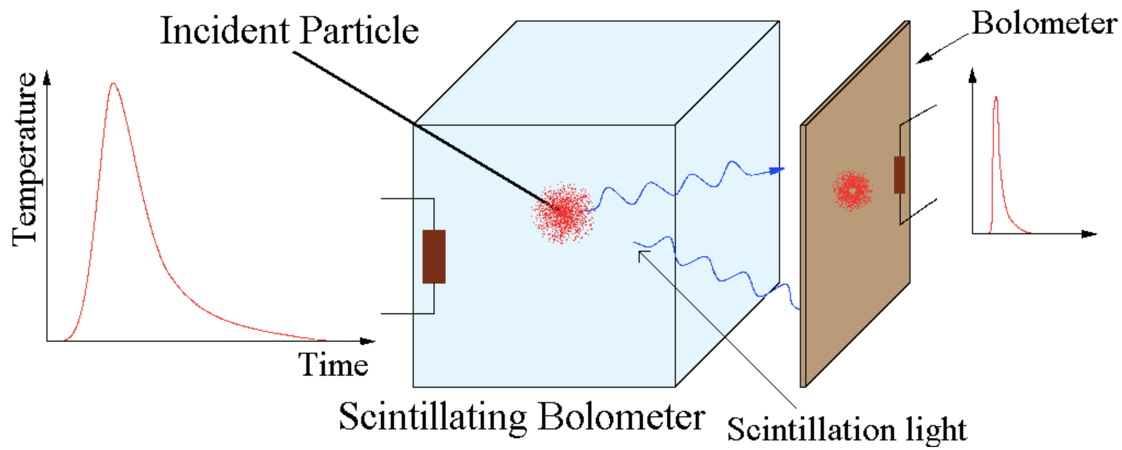


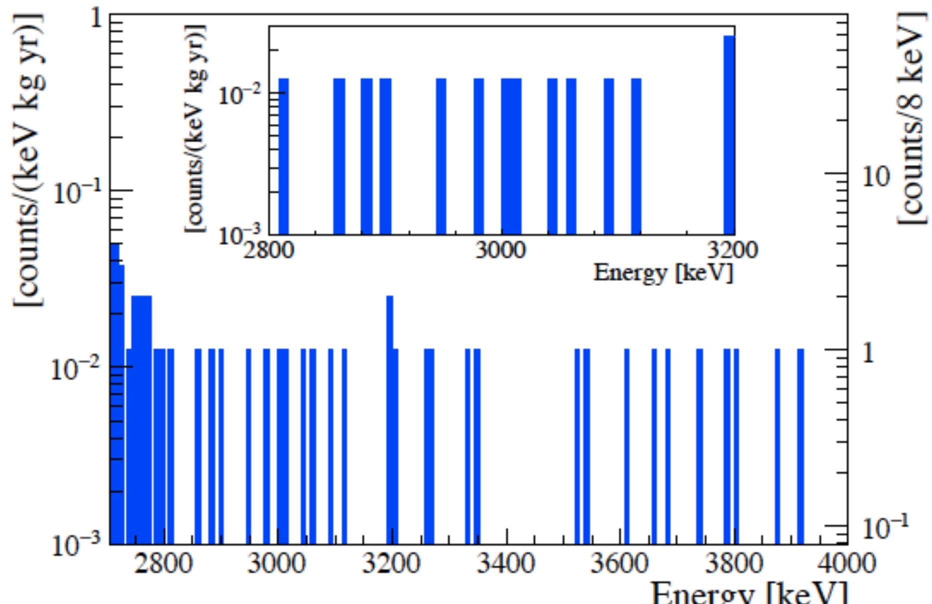


$^{nat}TeO_2$ bolometers operated in a low background dilution refrigerator at LNGS

~200 kg ^{130}Te

Beyond CUORE: CUPID

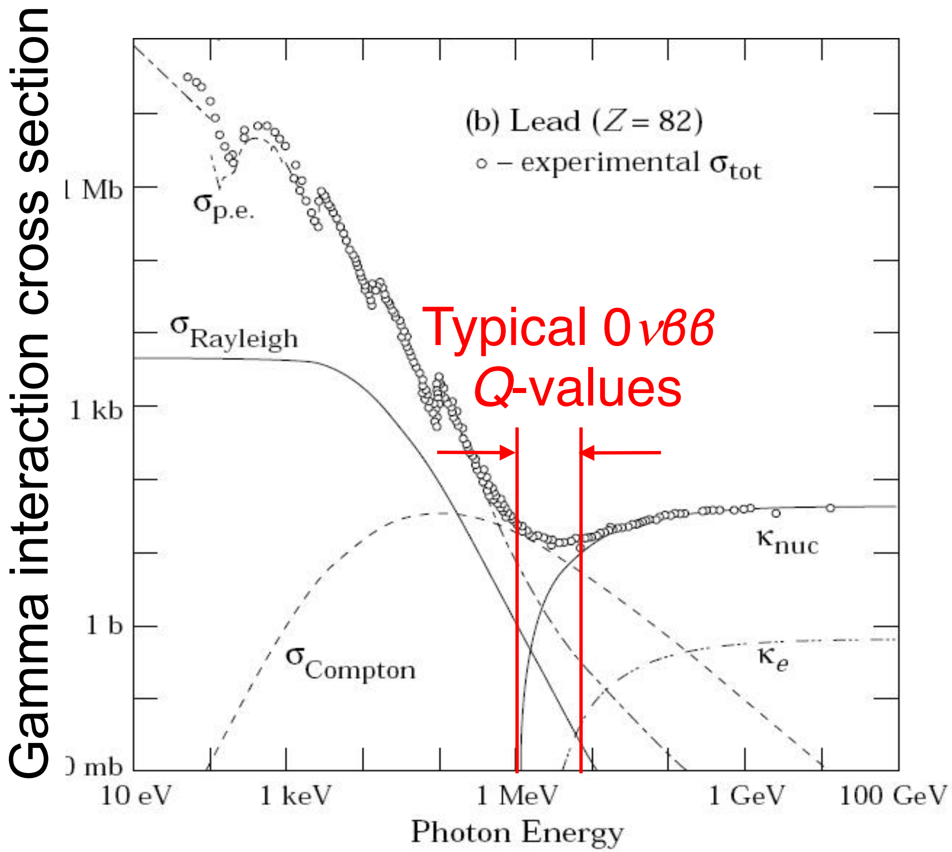




$$(3.5^{+1.0}_{-0.9}) \times 10^{-3}\ \text{counts}/(\text{keV kg yr})$$

Mulitple isotopes of interest possible. CUPID initial demonstrations with both ^{82}Se and ^{100}Mo. arXiv:1906.05001

Challenges of the ton-scale



Shielding a detector from MeV gammas is difficult!

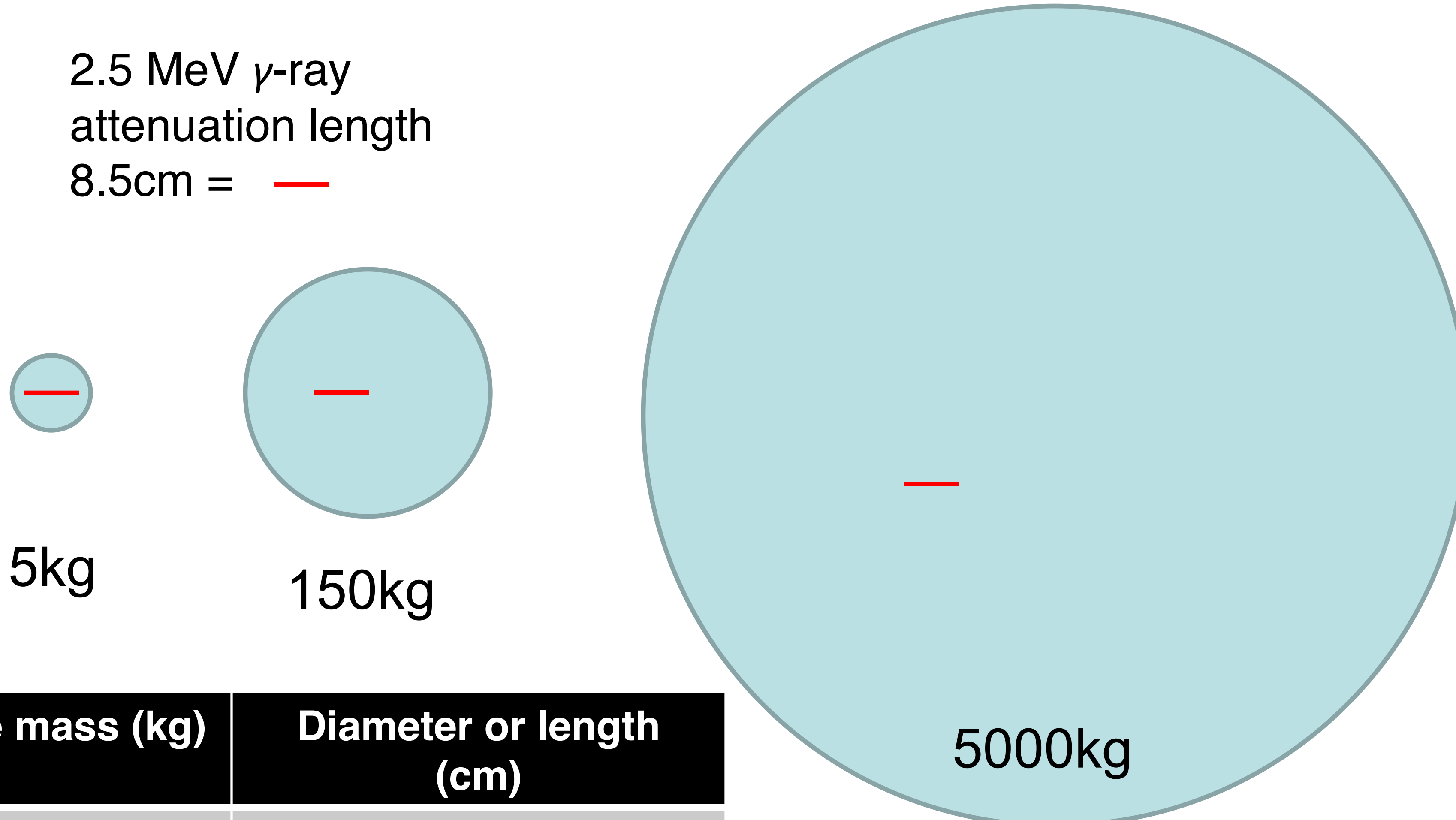
Example:
γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

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 =

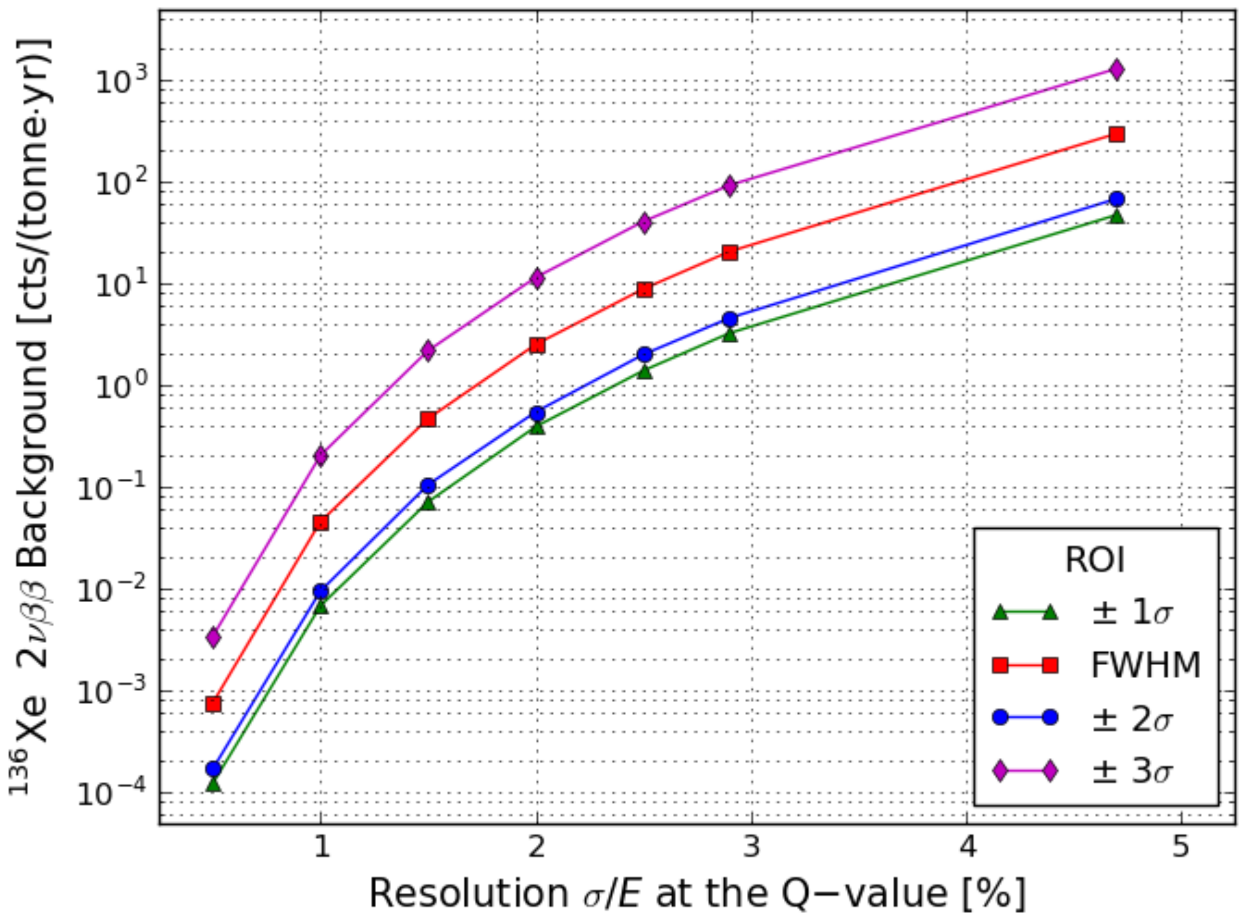


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

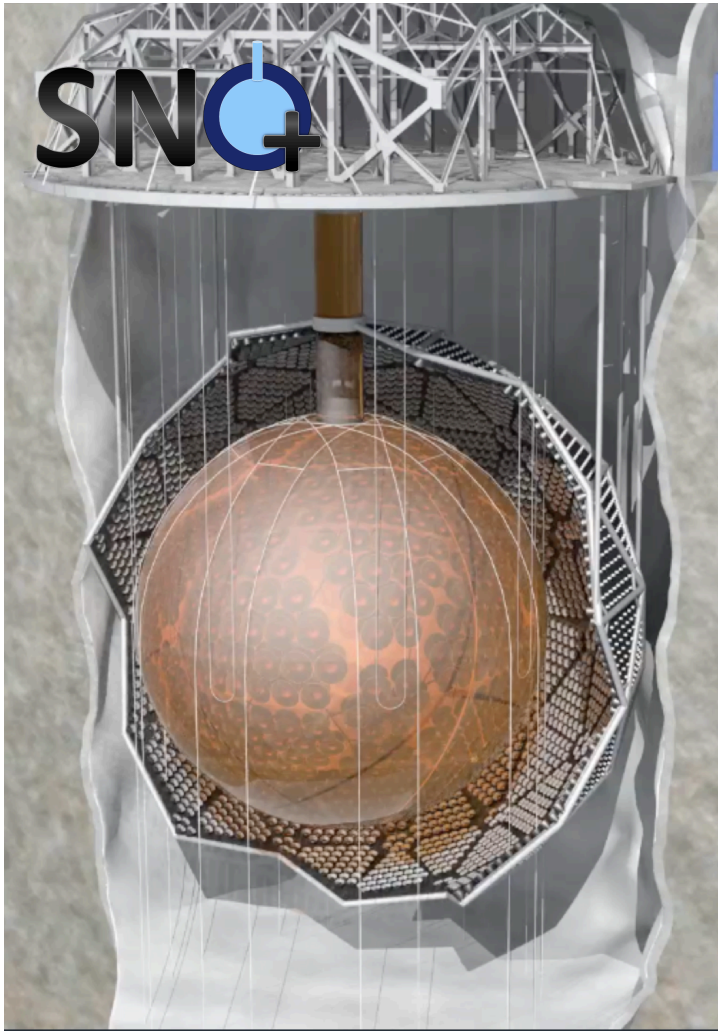
Background suppression

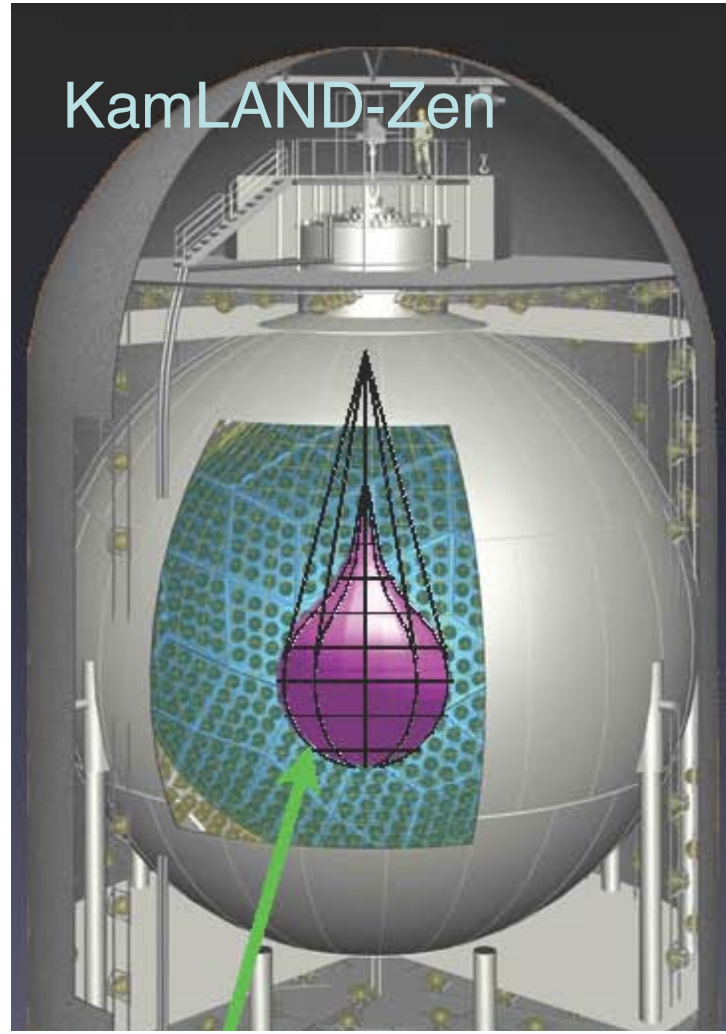
All observables have a role in separating signal from background.

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



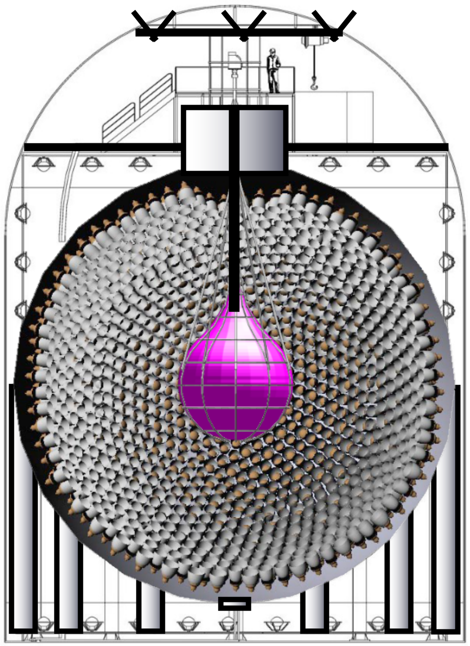


3.9 t ^{nat}Te dissolved in liquid scintillator in the upgraded SNO detector

~745 kg 90% ^{enr}Xe dissolved in inner volume of KamLAND since Jan. 2019

Beyond KamLAND-Zen 800

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



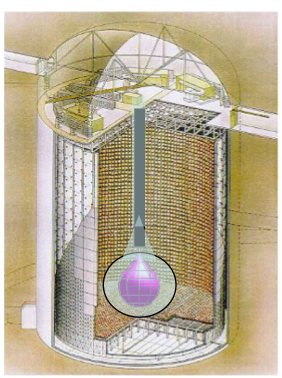
1000+ kg xenon

	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?



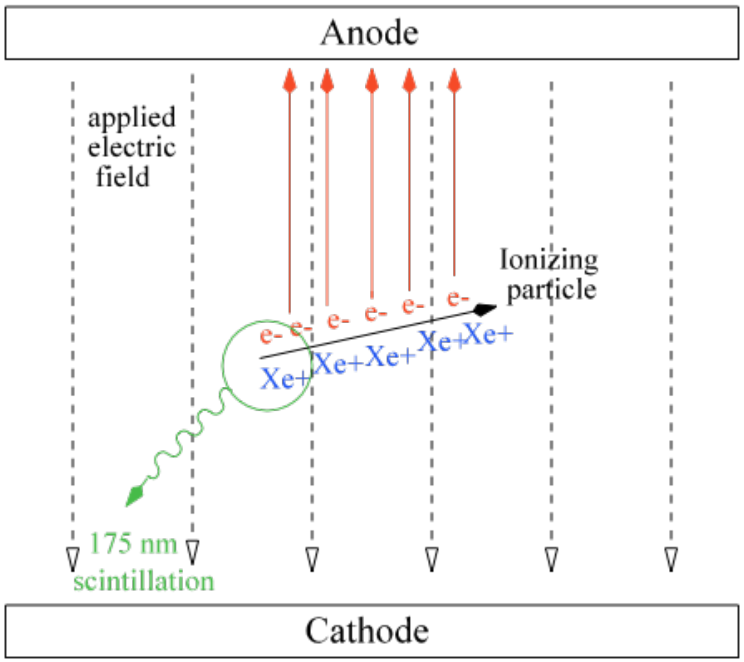
Super-KamLAND-Zen

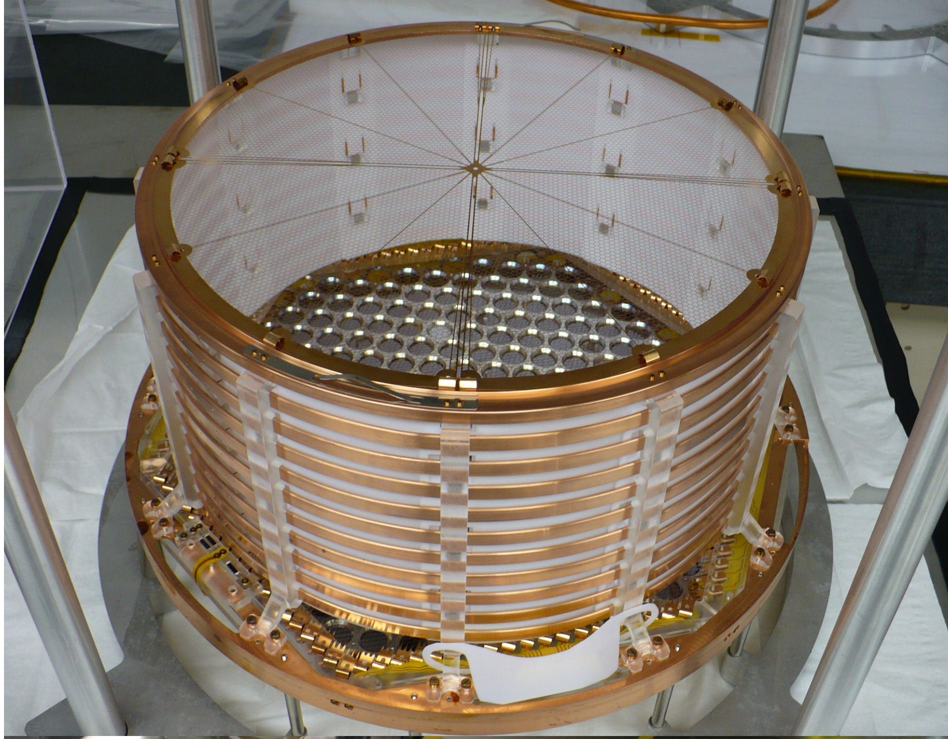
in connection with Hyper-Kamiokande

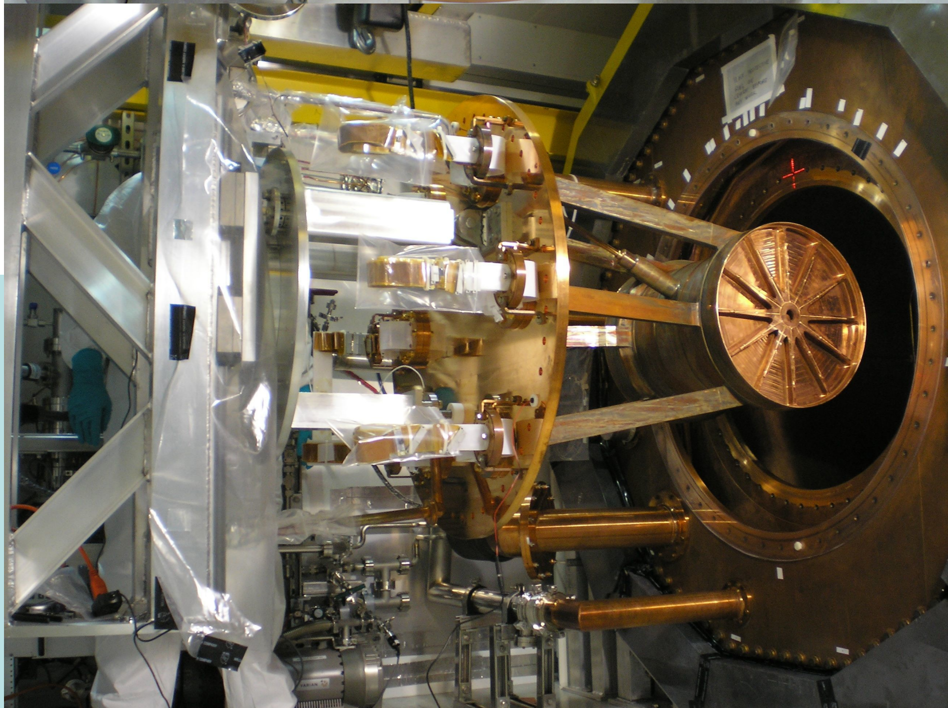
target sensitivity 8 meV

But eventually 2ν background becomes dominant

EXO-200 Liquid Xe TPC





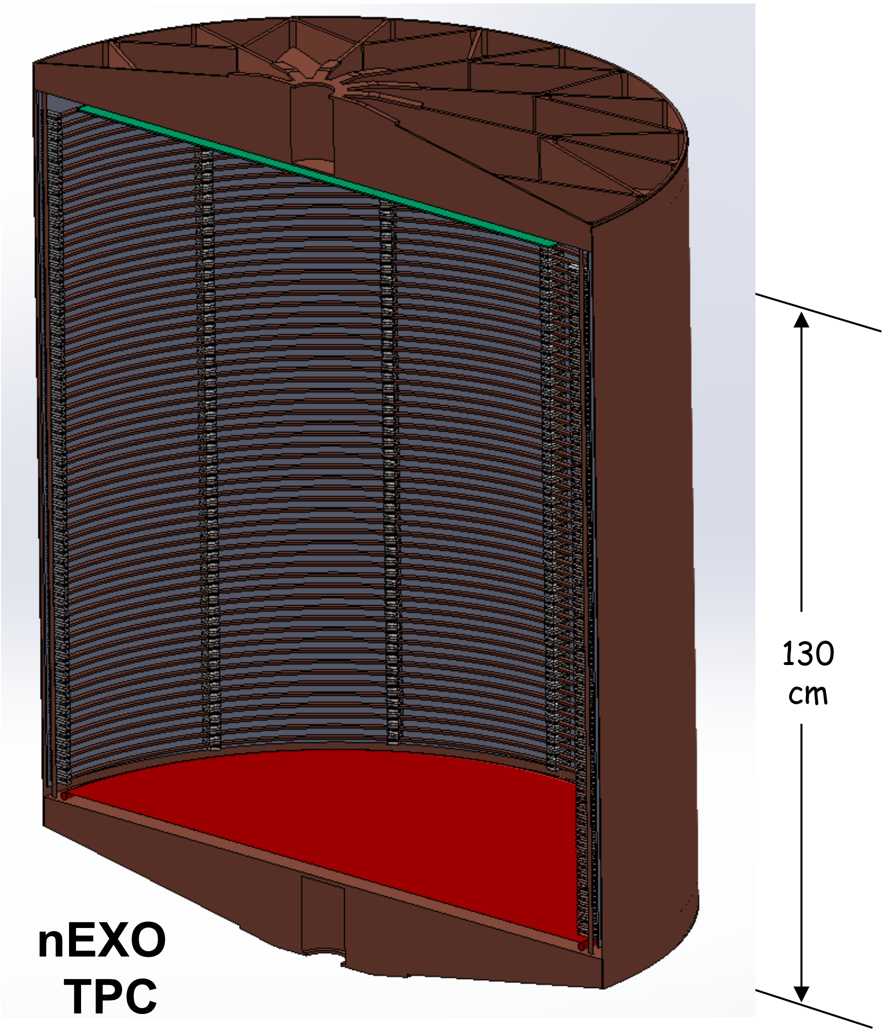


~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe, ultralow background construction.

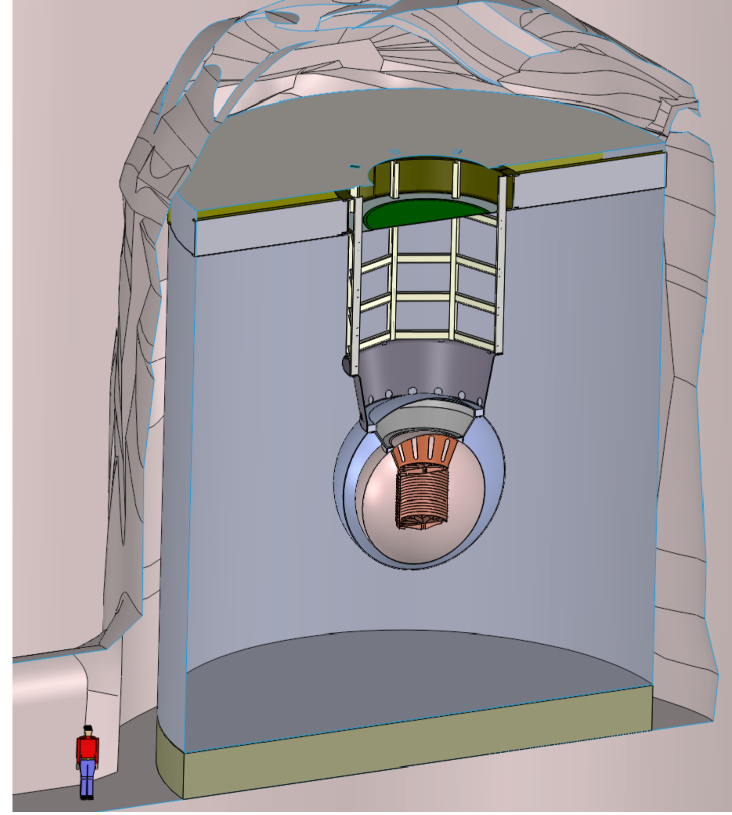
Readout plane is made up of LAAPDs + crossed wire grid.

Operating with enriched Xe at the Waste Isolation Pilot Plant from May 2011 to Feb. 2014 (Phase I) and June 2016 to December 2018 (Phase II).

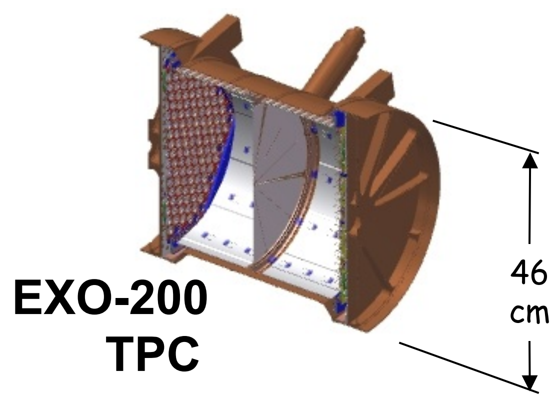
EXO-200 to nEXO



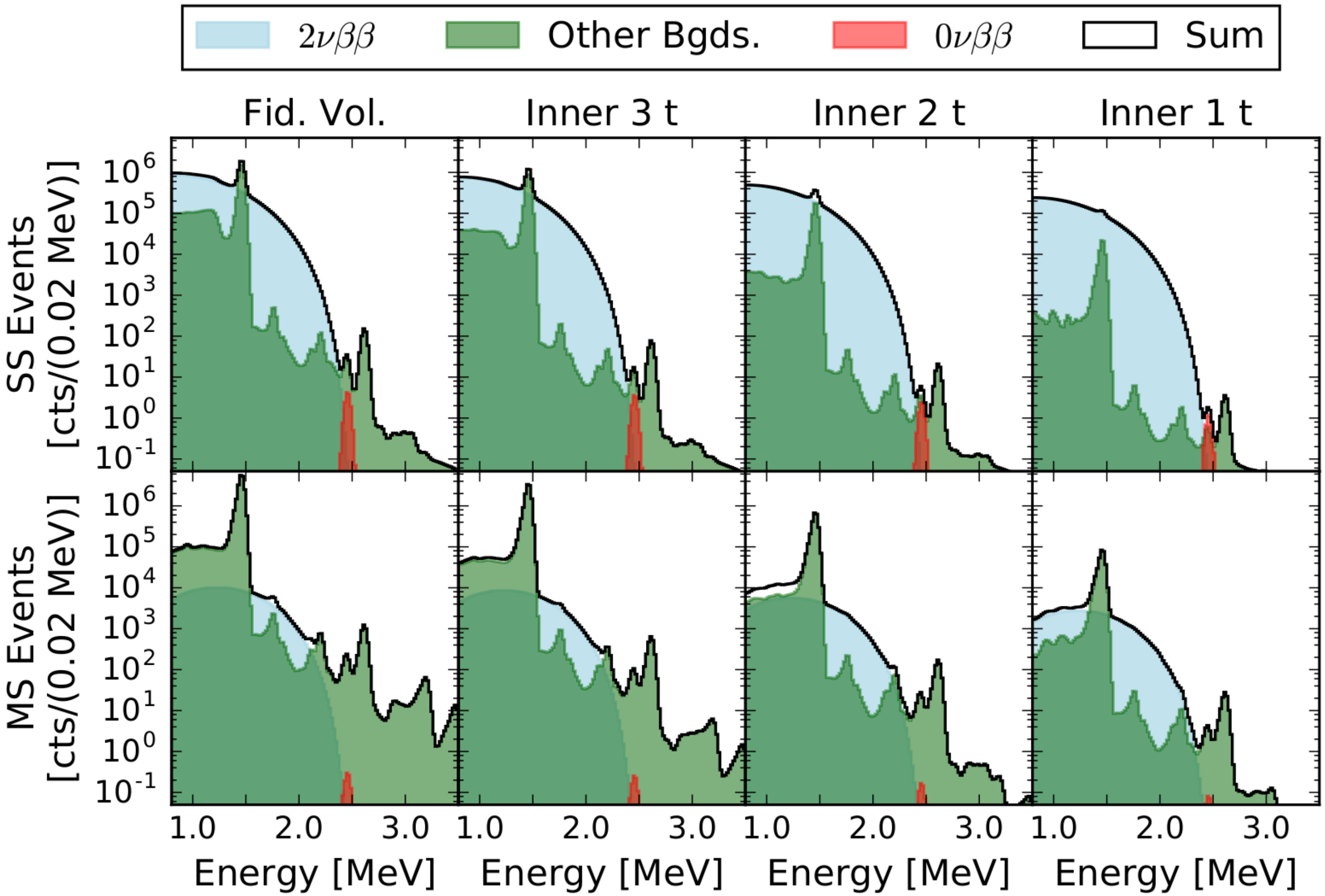
A 5000 kg enriched LXe TPC, based on success ofEXO-200



Preliminary artist view of nEXO in the SNOlab Cryopit



nEXO discovery potential



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

Discovery potential of next gen experiments

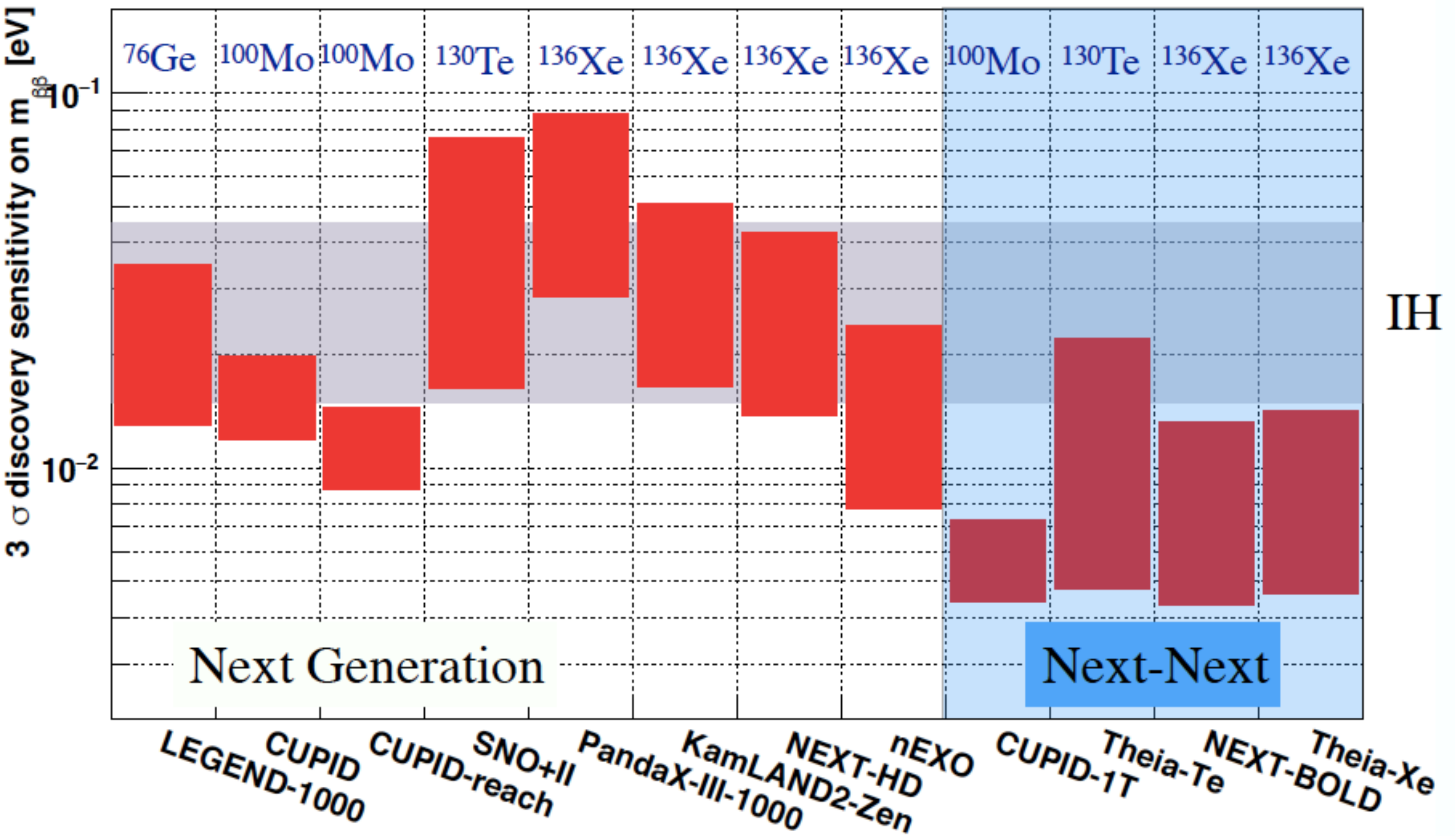


Figure from G. Benato, Y.G. Kolomensky
Methodology from Phys. Rev. D96, 053001 (2017)

Conclusions

- β-decay end point measurement provides a model-independent measurement of neutrino mass.
- KATRIN first results are in, $m_\beta < 1.1$ eV. Stay tuned for sensitivity down to 0.2 eV. Other experiments plan to compete.
- $0\nu\beta\beta$ is the most practical way to test the Majorana nature of neutrinos. An observation of $0\nu\beta\beta$ always implies new physics!
- Results from ~100 kg yr searches are here with sensitivities to half-lives > 10^{25} yr! No discovery yet…
- Tonne-scale searches for $0\nu\beta\beta$ are complementary to other searches for new physics in the particle physics community.