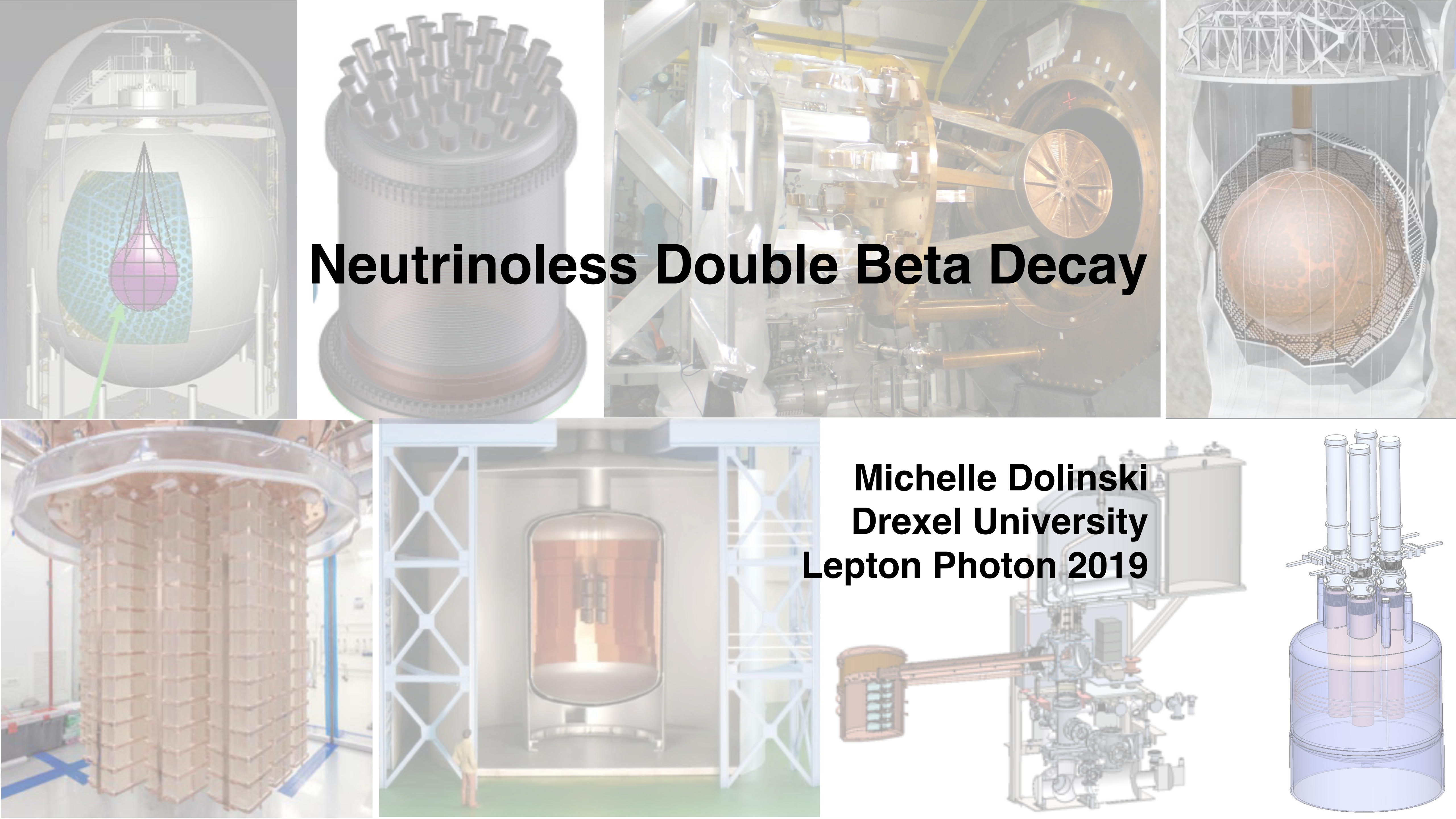
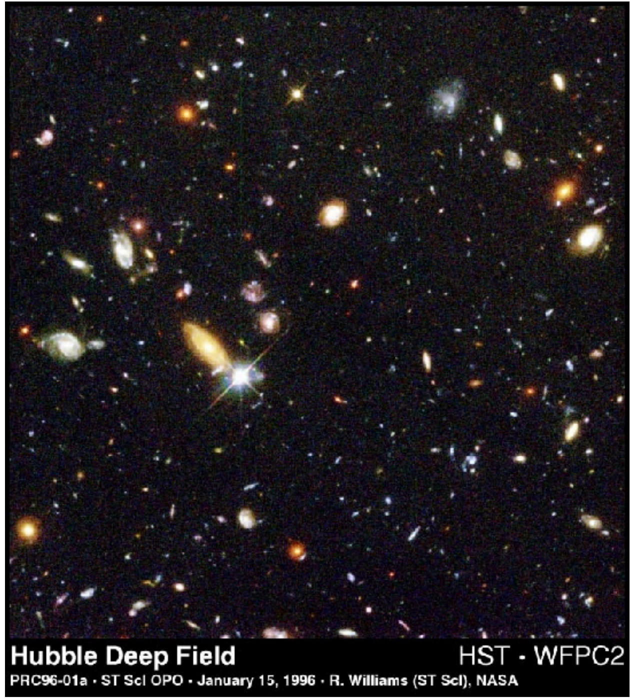


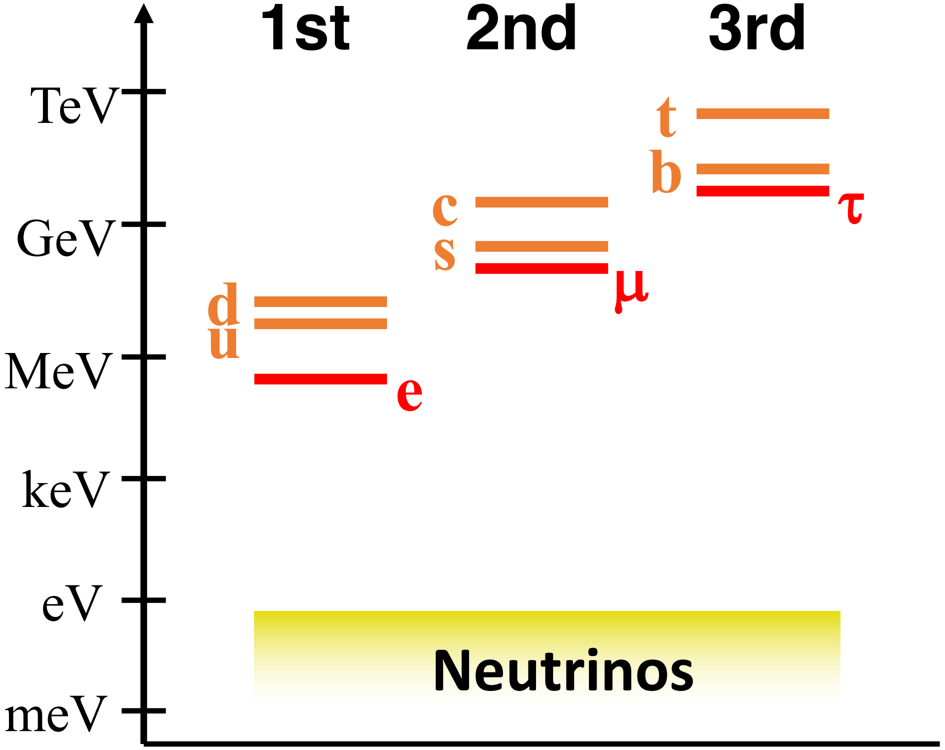
Neutrinoless Double Beta Decay

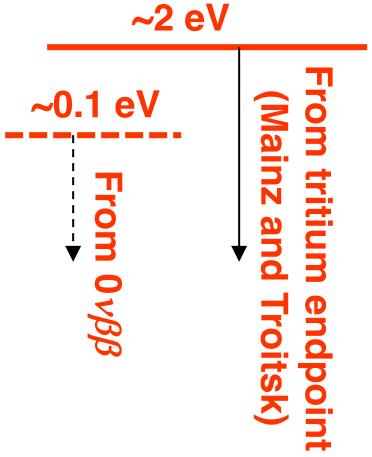
Michelle Dolinski
Drexel University
Lepton Photon 2019

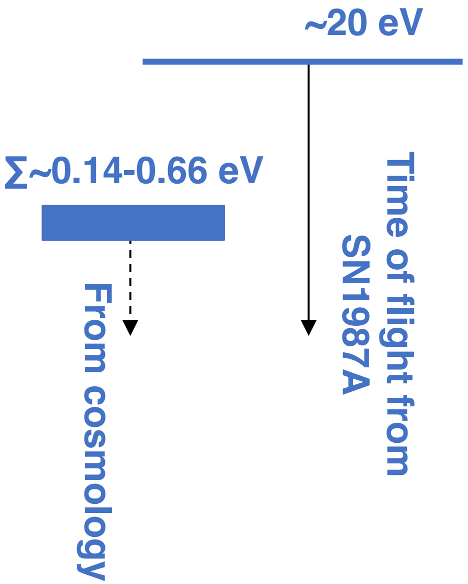
Neutrino masses

"The tiny masses of neutrinos indicate that they may interact with the Higgs sector in a special way."









Neutrino mass and leptogenesis

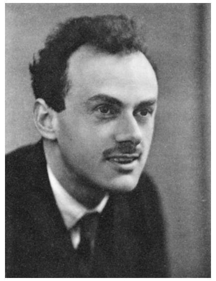
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science."

Instead of starting with a baryon number violating process (baryogensis), leptogenesis relies on violating **lepton number**, *then* converting *L* into *B*.

Majorana neutrinos, which break lepton number, could be the key to explaining the matter-antimatter asymmetry in the universe and may be tied to the mystery of small ν masses via the Seesaw Mechanism.

$$\mathcal{L}_{\mathrm{Y,M}}(x) = \left(\lambda_{il}\,\overline{N_{iR}}(x)\,\Phi^{\dagger}(x)\,\psi_{lL}(x) + \mathrm{h.c.}\right) - \frac{1}{2}M_i\,\overline{N_i}(x)\,N_i(x)$$

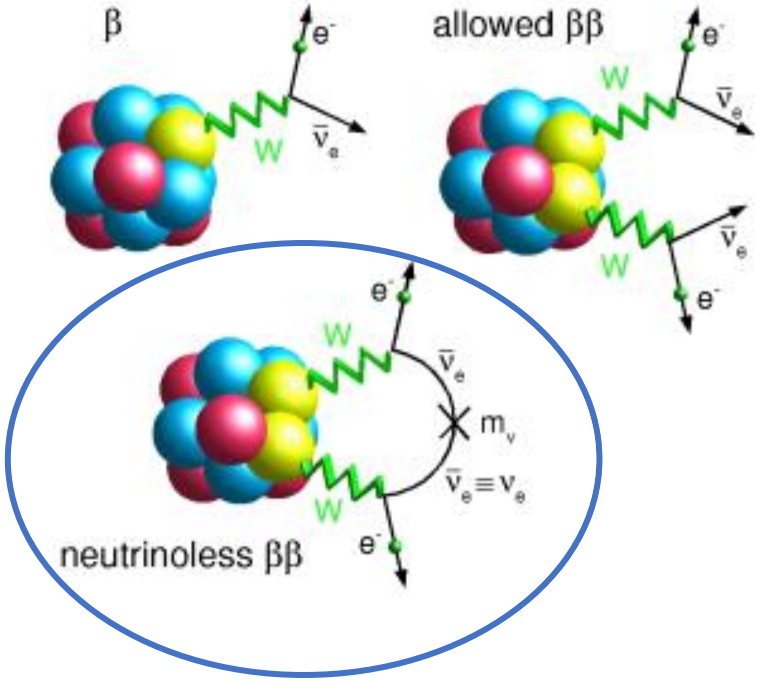
"Dirac" neutrinos **$\nu \neq \overline{\nu}$**



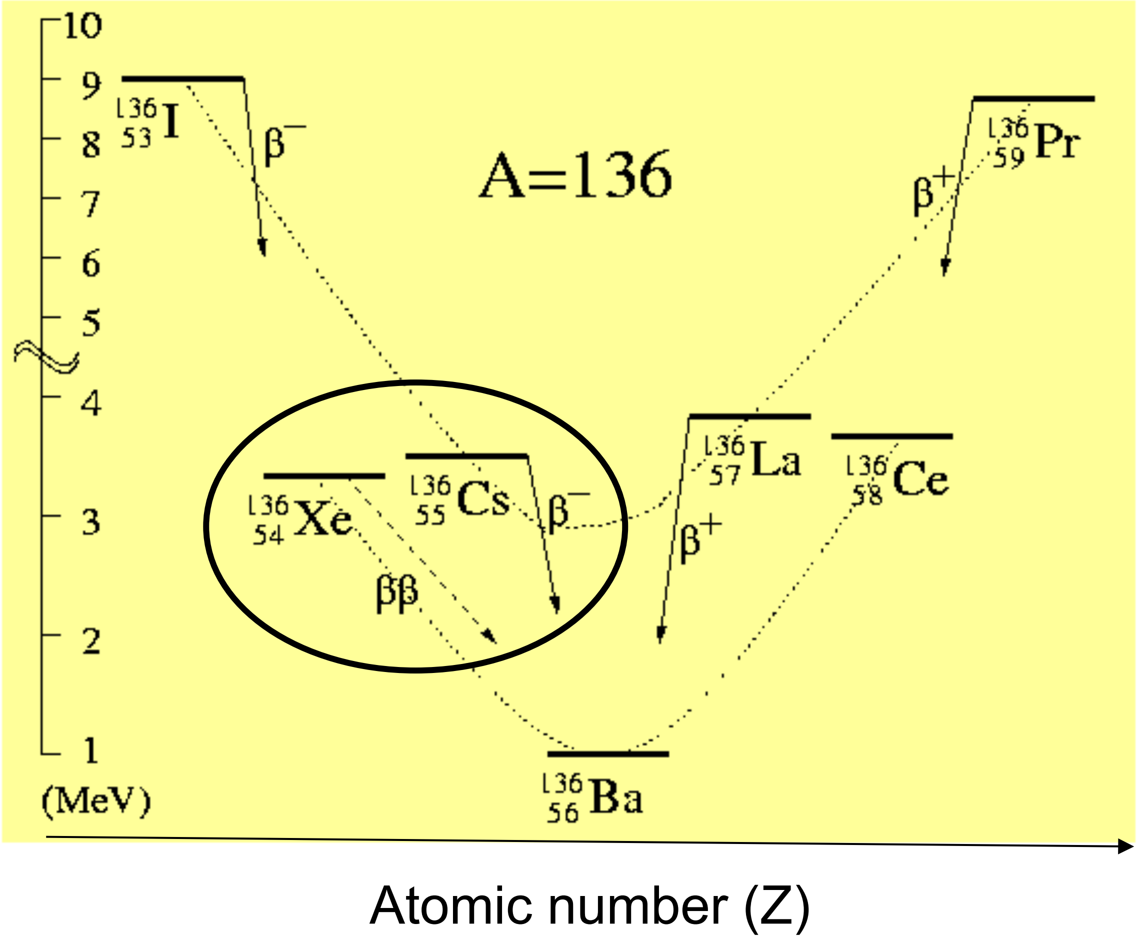
"Majorana" neutrinos **$\nu = \overline{\nu}$**

Double beta decay ($2\nu\beta\beta$ and $0\nu\beta\beta$)

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



This **lepton number violating** process can only occur for a Majorana neutrino!

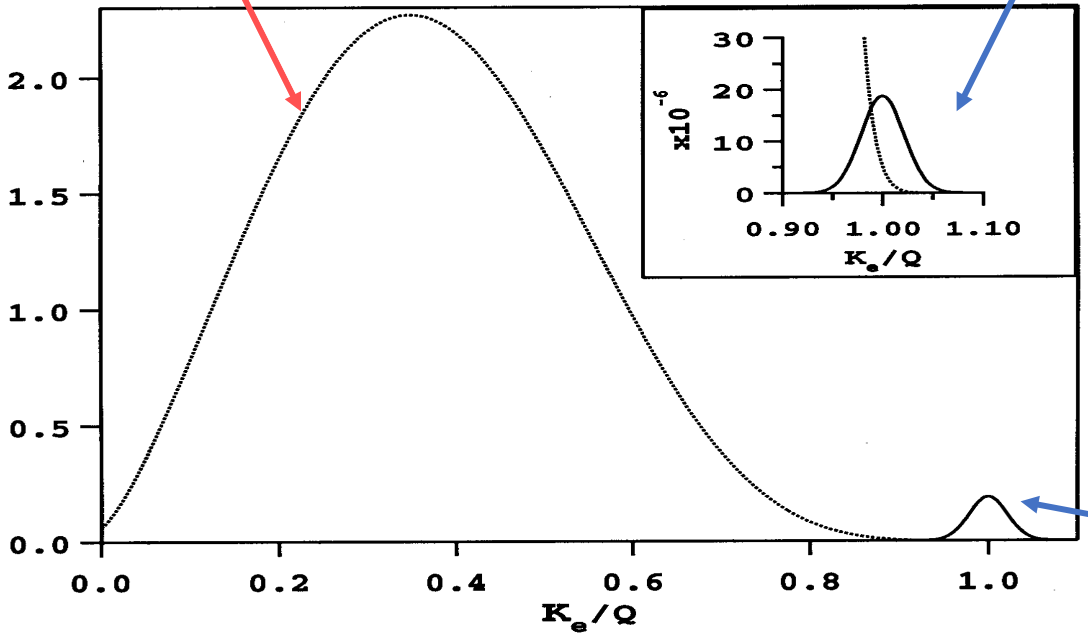


The remarkable sensitivity of $0\nu\beta\beta$ searches is due to the power of Avogadro's Number.
Lots of candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

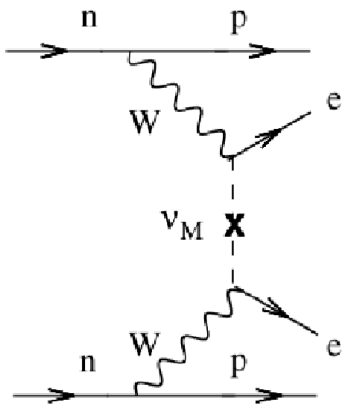
Neutrinoless double beta decay

$2\nu\beta\beta$ spectrum (normalized to 1)

$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-6})



$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-2})



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

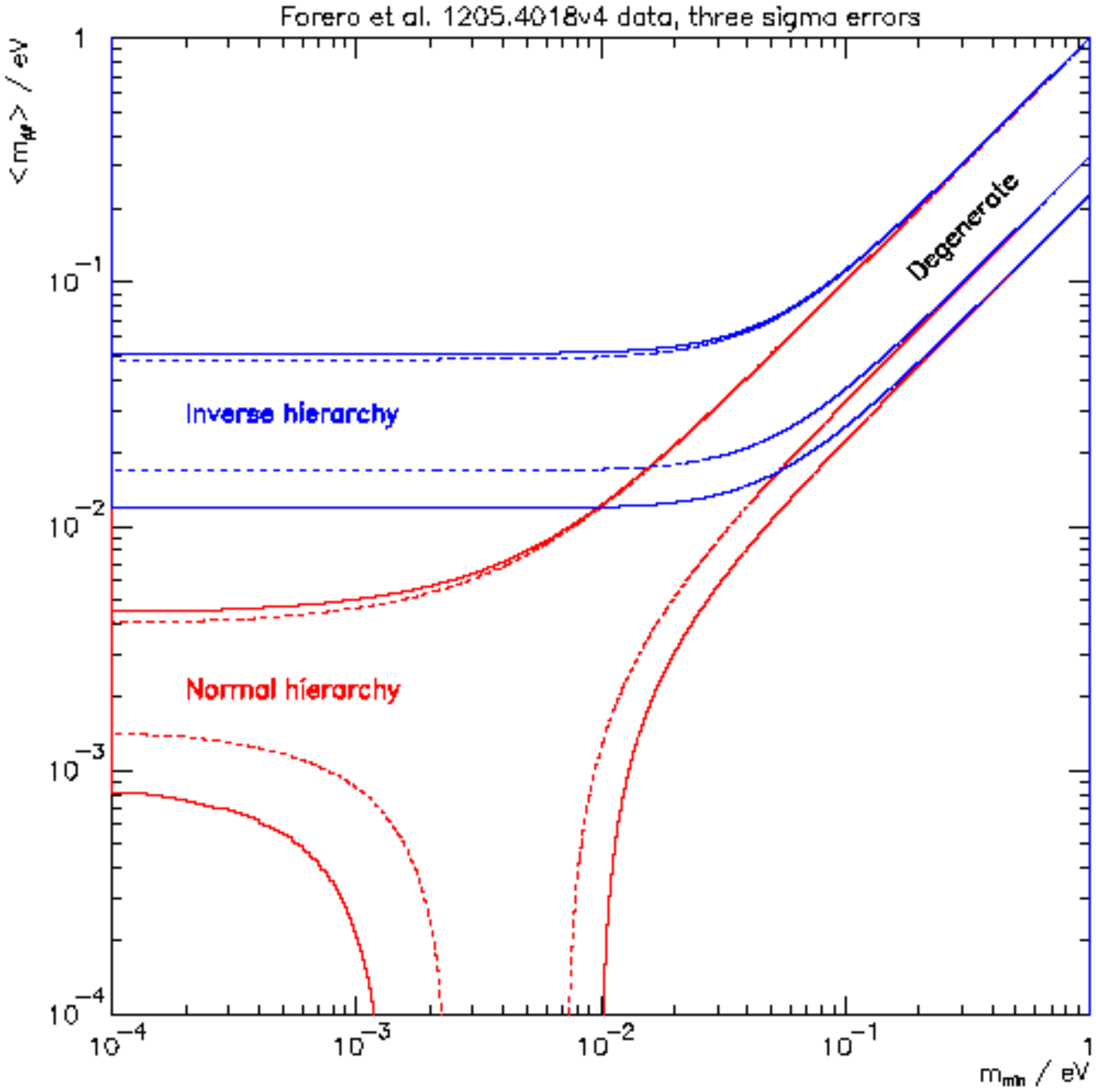
(light Majorana neutrino exchange mechanism ONLY)

Effective Majorana mass

Phase space considering light Majorana neutrino exchange mechanism ONLY.

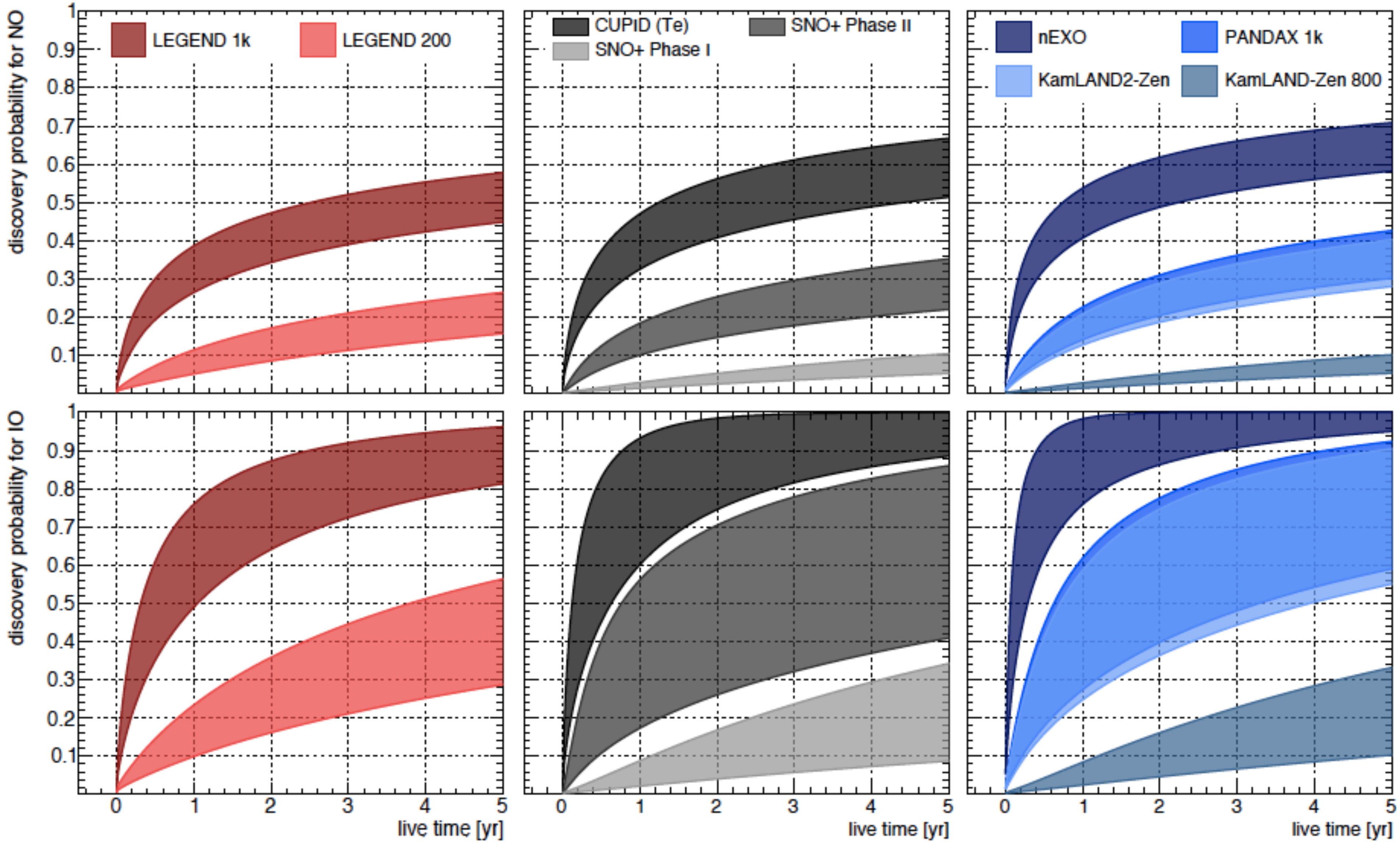
$$\langle m_{\beta\beta}\rangle = \left| m_1 \cdot \left(1-\sin^2\theta_{12}\right)\cdot\left(1-\sin^2\theta_{13}\right) + m_2 \cdot \sin^2\theta_{12} \cdot \left(1-\sin^2\theta_{13}\right)\cdot e^{i\cdot(\alpha_2-\alpha_1)} + m_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3} \right|$$

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.

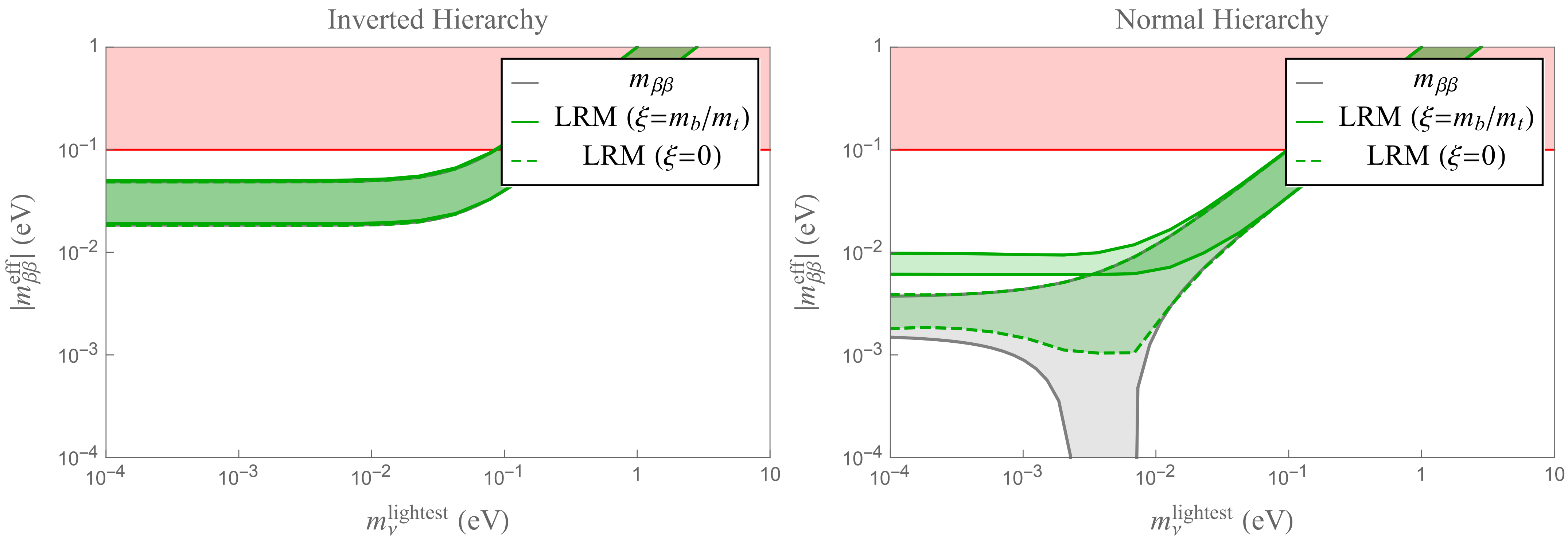
Agostini, Benato, Detwiler, *PRD* 96 (2017) 053001

See also A. Caldwell et al., *PRD* 96 (2017) 073001

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

Other mechanisms

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

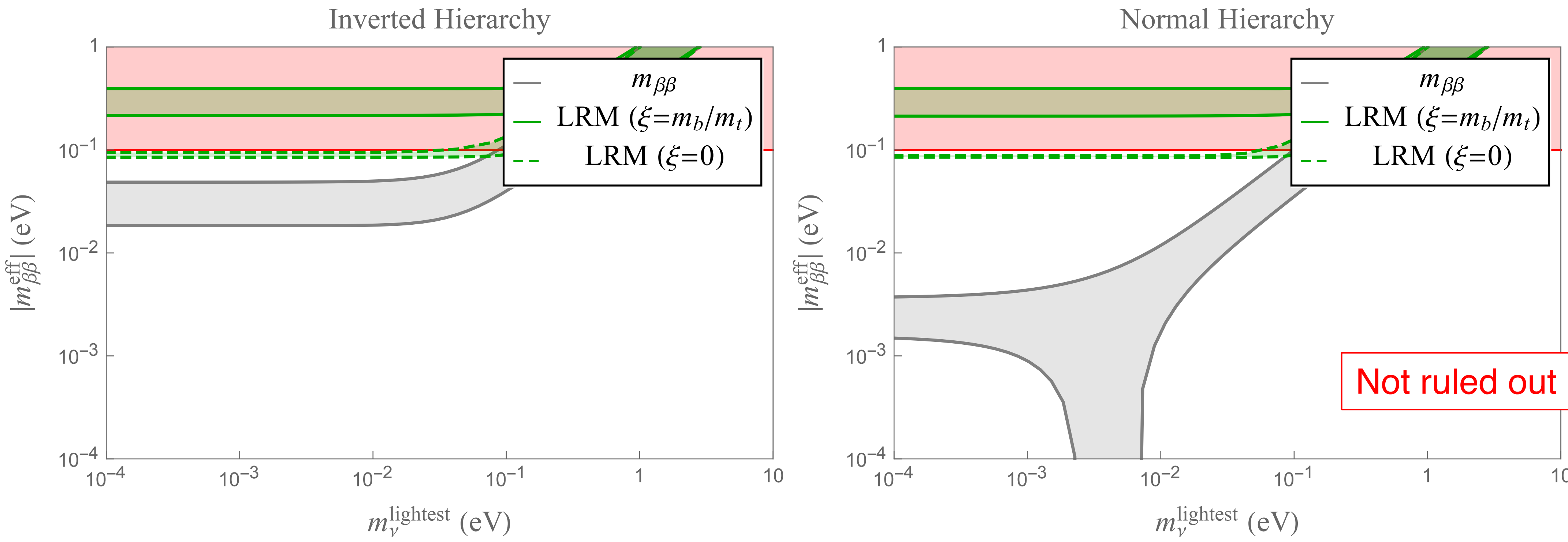


Consider a model with 10 TeV right-handed neutrinos in the minimal left-right symmetric model, symmetric under charge conjugation (assuming that the mixing matrix of the right-handed neutrinos is the same as the PMNS matrix).

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

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

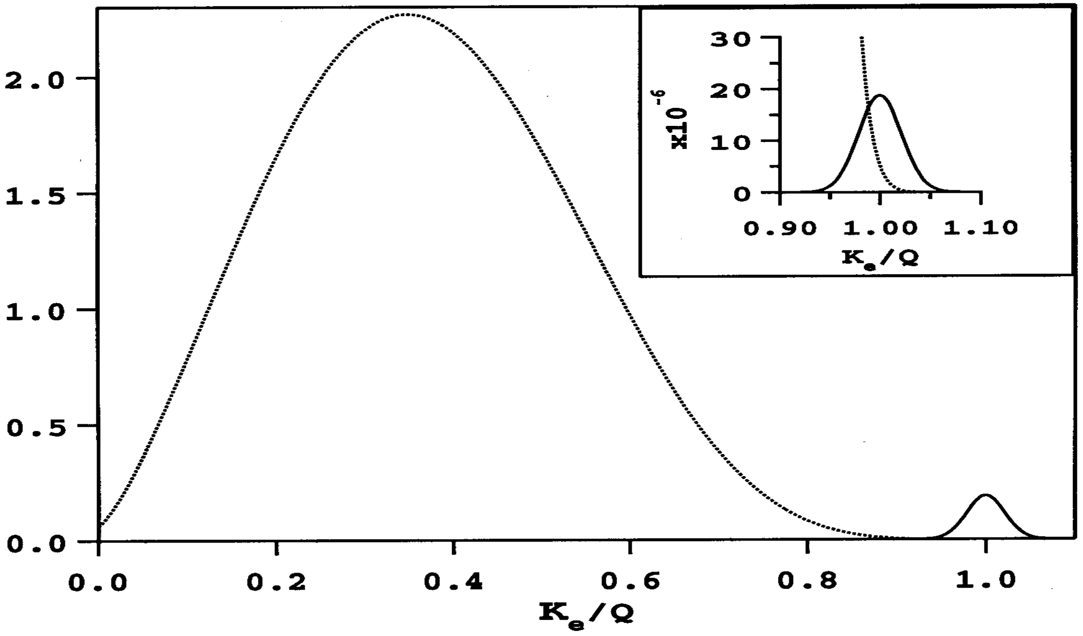


Not ruled out by LHC!

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.

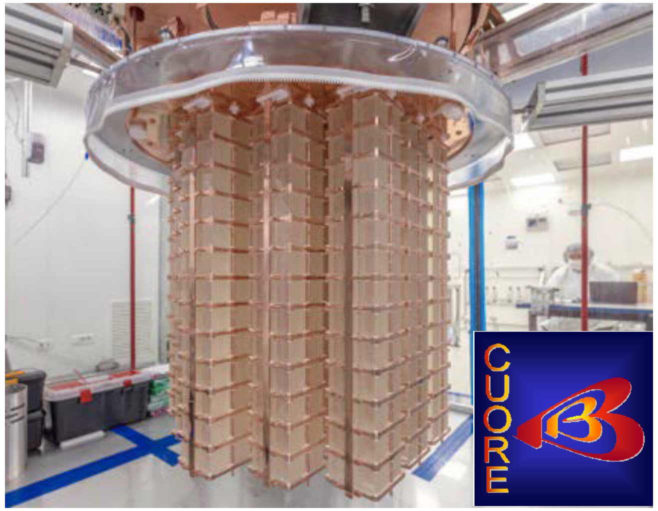
See Cirigliano, V., Dekens, W., de Vries, J. et al. “A neutrinoless double beta decay master formula from effective field theory,” J. High Energ. Phys. (2018) 2018: 97. Thanks to Wouter Dekens for help with this material.

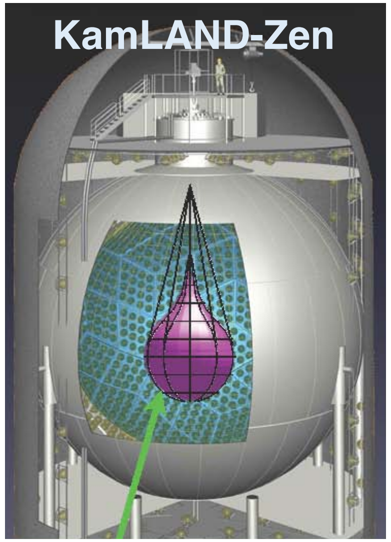
How to search for $0\nu\beta\beta$?

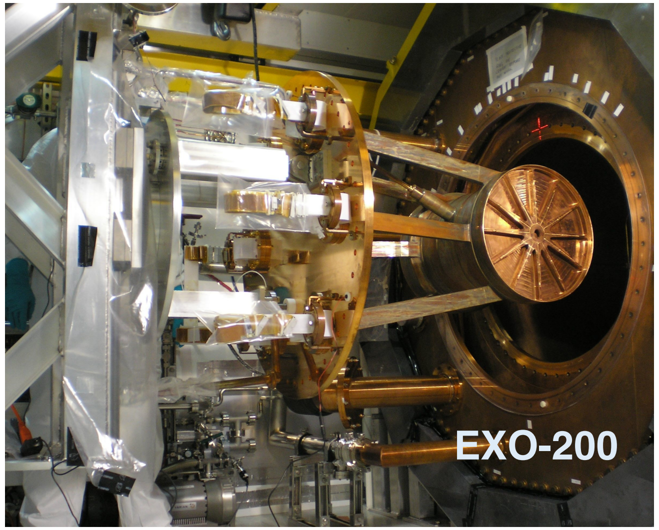


- Large exposure
- High isotopic abundance
- Good energy resolution
- Low background
- High detection efficiency

GERDA







Liquid (organic) scintillators:

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

Pros: Large detectors exist, self-shielding

Cons: Poor energy resolution, 2ν background

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

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:

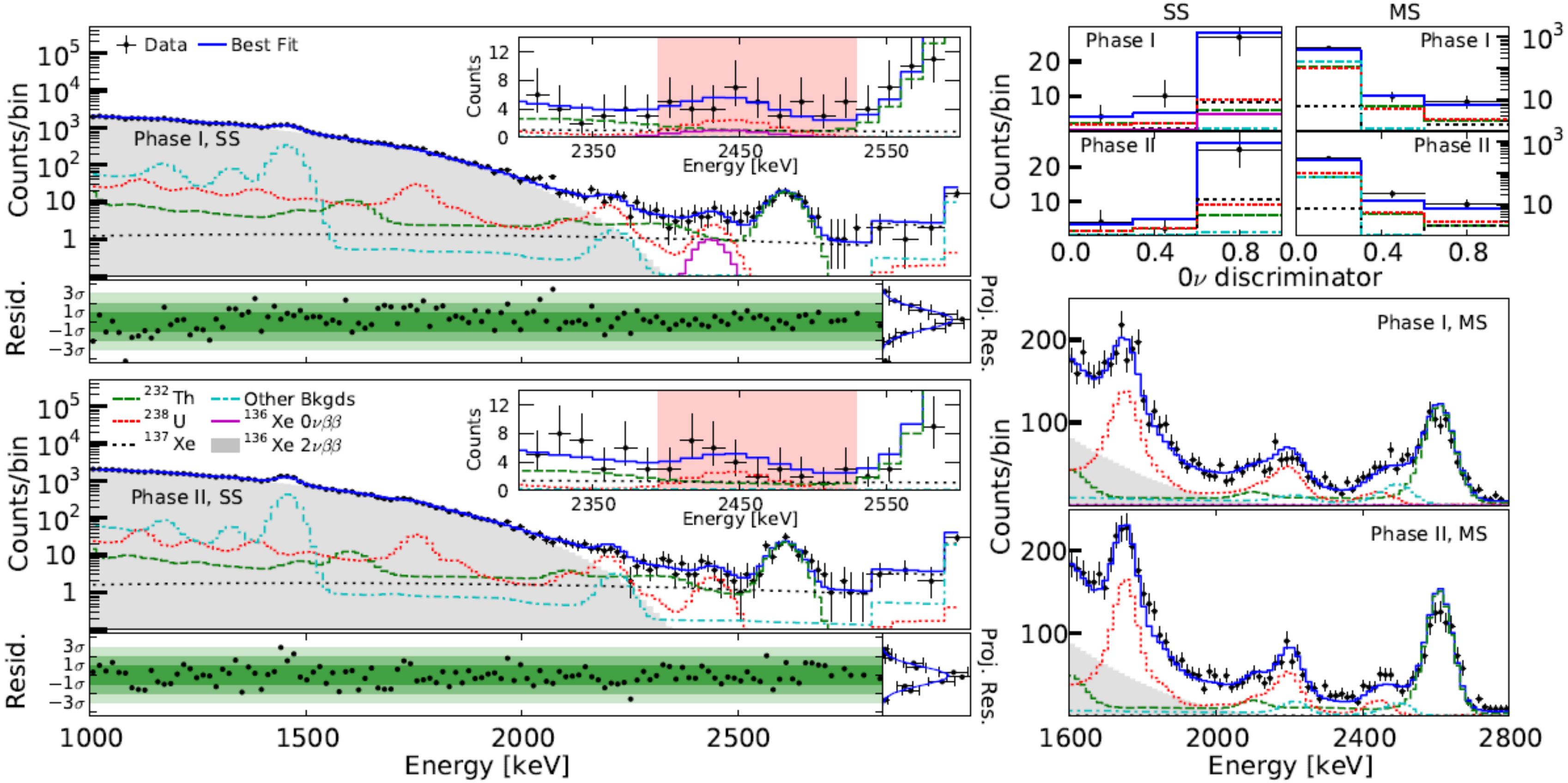
- **EXO-200**, nEXO (^{136}Xe)
- XENON-nT, LZ, PandaX, DARWIN (^{136}Xe, optimized for direct dark matter search)

Pros: Homogeneous with good E resolution and topology

Cons: Does not excel in any single parameter

*talks at yesterday's parallel ν session

EXO-200 0νββ search with complete dataset



Combined Phase I + II:

[arXiv:1906.02723]

Total exposure = 234.1 kg.yr

Sensitivity 5.0x10^{25} yr

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

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

The experiment:

- Ultralow background single phase liquid Xe time projection chamber.
- ~100 kg Xe fiducial mass enriched to 80% in ^{136}Xe.
- Readout plane made up of LAAPDs (scintillation) and crossed wire grids (ionization).
- Data taking in two phases:
  - Phase I from 2011-2014
  - Phase II (with upgrades) from 2016-2018.

The analysis:

- Single site (SS)/multi-site (MS) discrimination
- New 0ν discriminator built using a deep neural network (DNN)
- 3-dimensional fit in both SS and MS: Energy+DNN+standoff distance.

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. 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, and uncertainties related to g_A are not included.

For higher sensitivity, the next generation of experiments will be at the tonne scale.

An opportunity for particle physics

“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.”

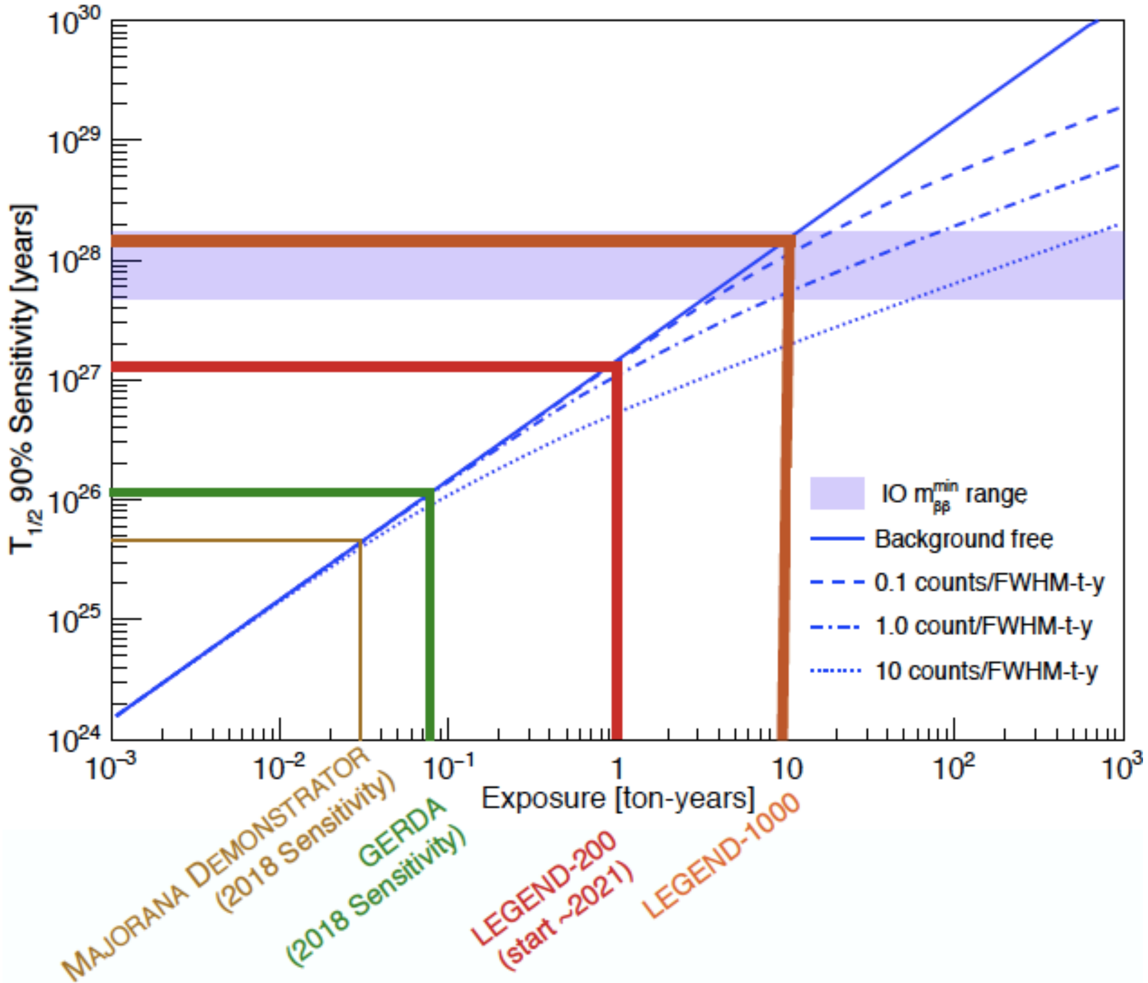
Building for Discovery

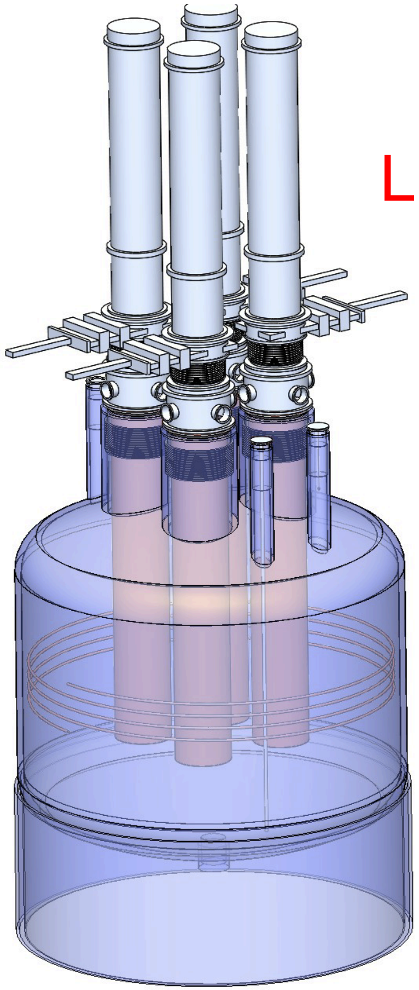
Strategic Plan for U.S. Particle Physics in the Global Context

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

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

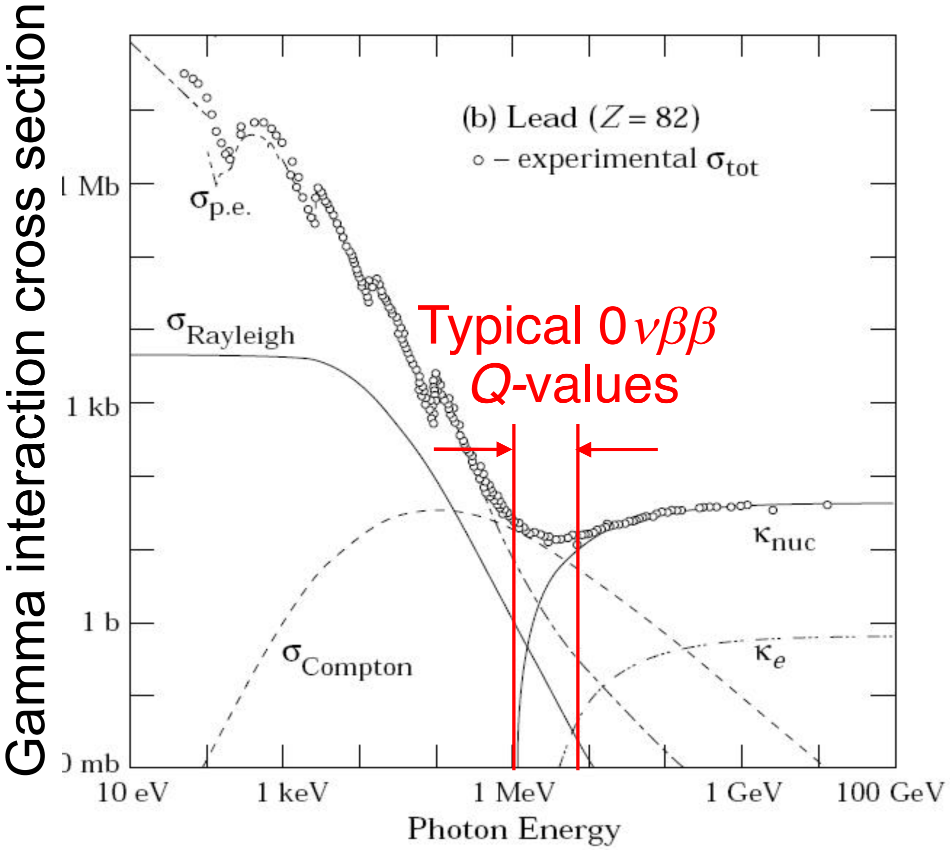
- Build on the experience of GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Design sensitivity of ~1×10^{28} y with a background of 0.1 cnt/tonne-yr in the region of interest (background reduction of ~6-20 relative to existing)





LEGEND

Challenges of the tonne-scale

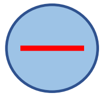


Typical $0\nu\beta\beta$ Q-values

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.

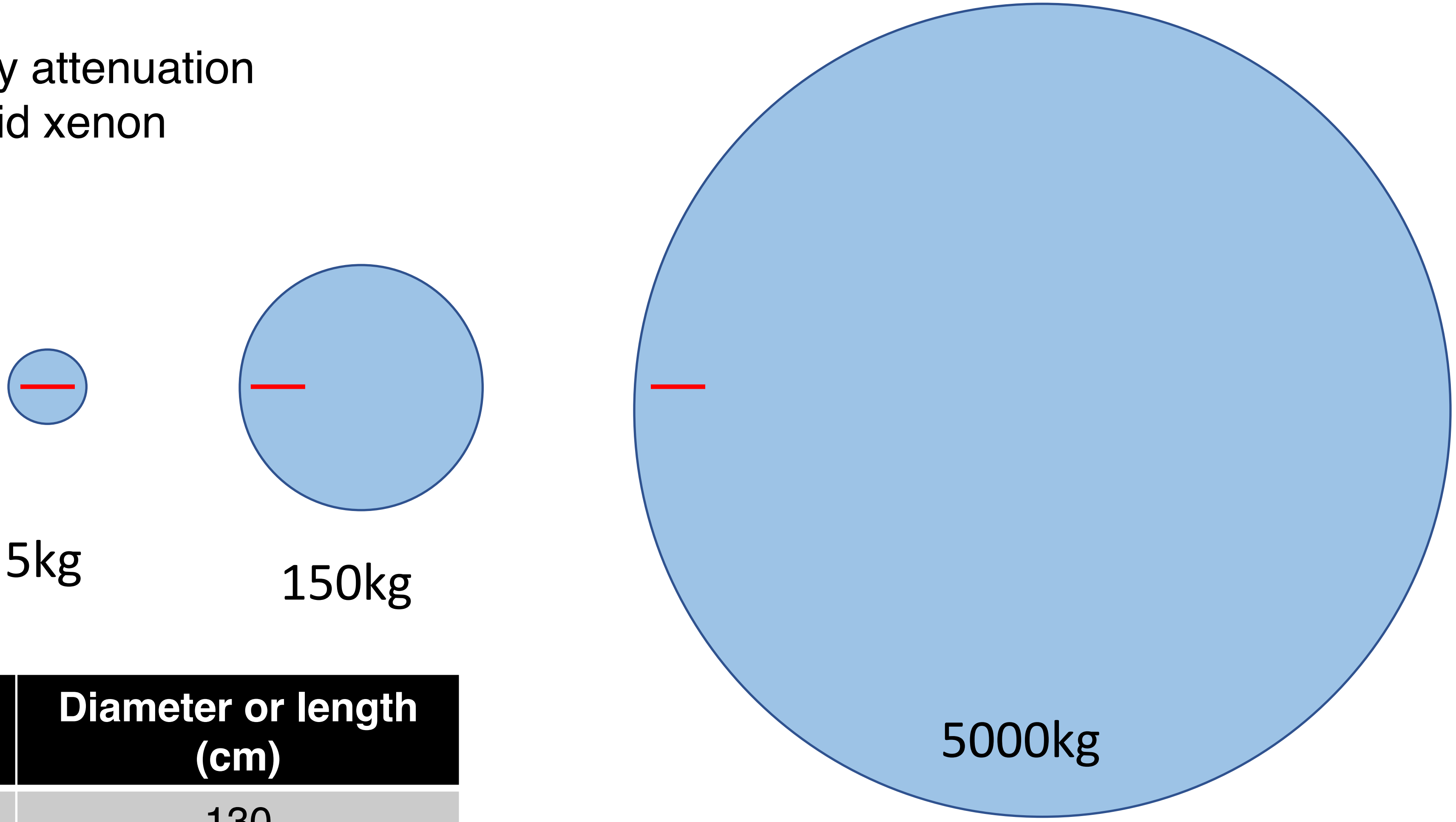


Shielding $0\nu\beta\beta$ decay detectors is much harder than shielding dark matter detectors

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 in liquid xenon
8.5 cm = —

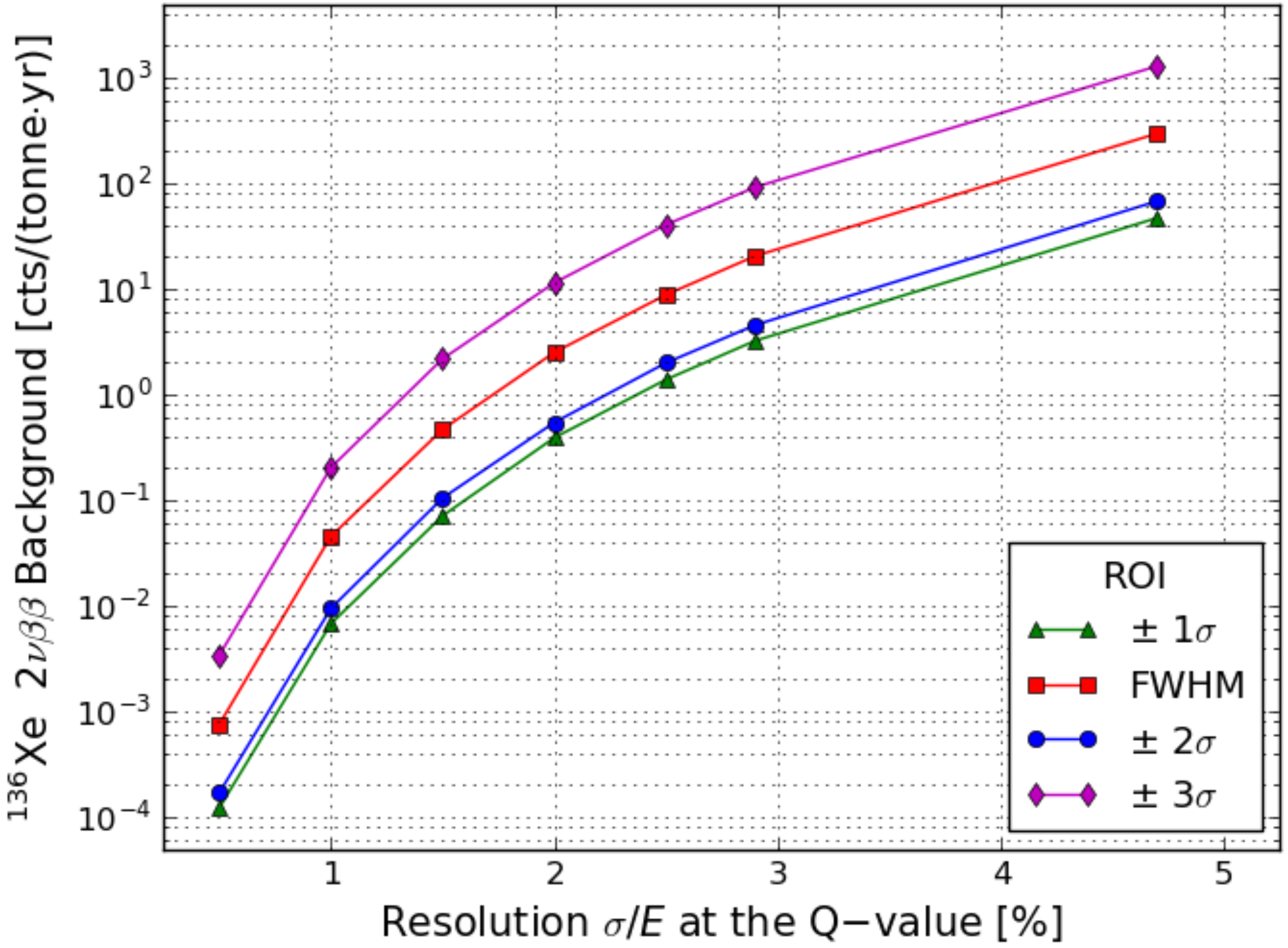


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

Background suppression

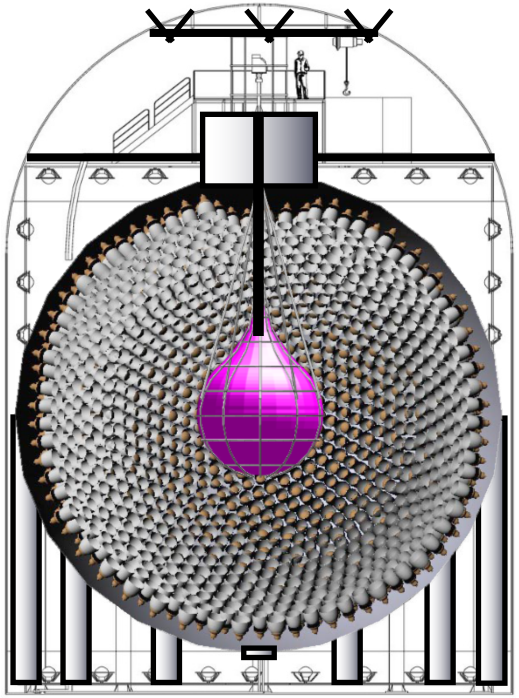
All observables have a role in separating signal from background.

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.



Beyond KamLAND-Zen

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



1000+ kg xenon

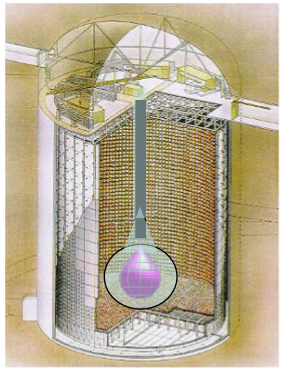
To improve energy resolution, increase light collection!

	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?



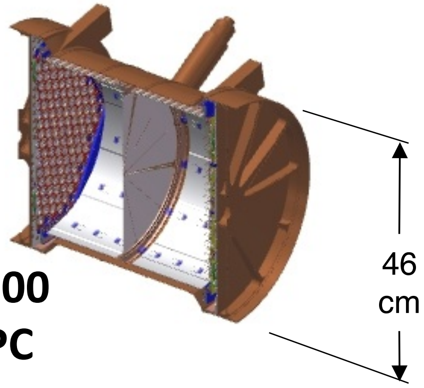
Super-KamLAND-Zen

in connection with Hyper-Kamiokande

target sensitivity 8 meV

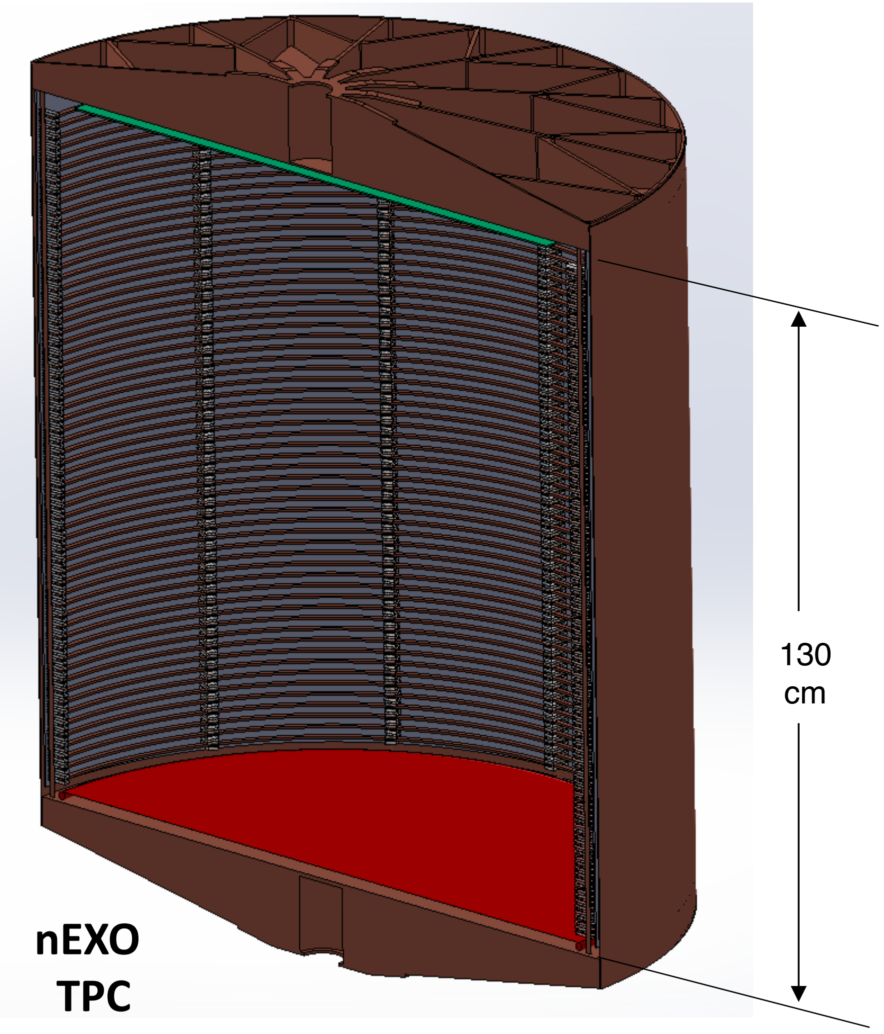
But eventually 2ν background becomes dominant

Scaling up EXO-200 to nEXO

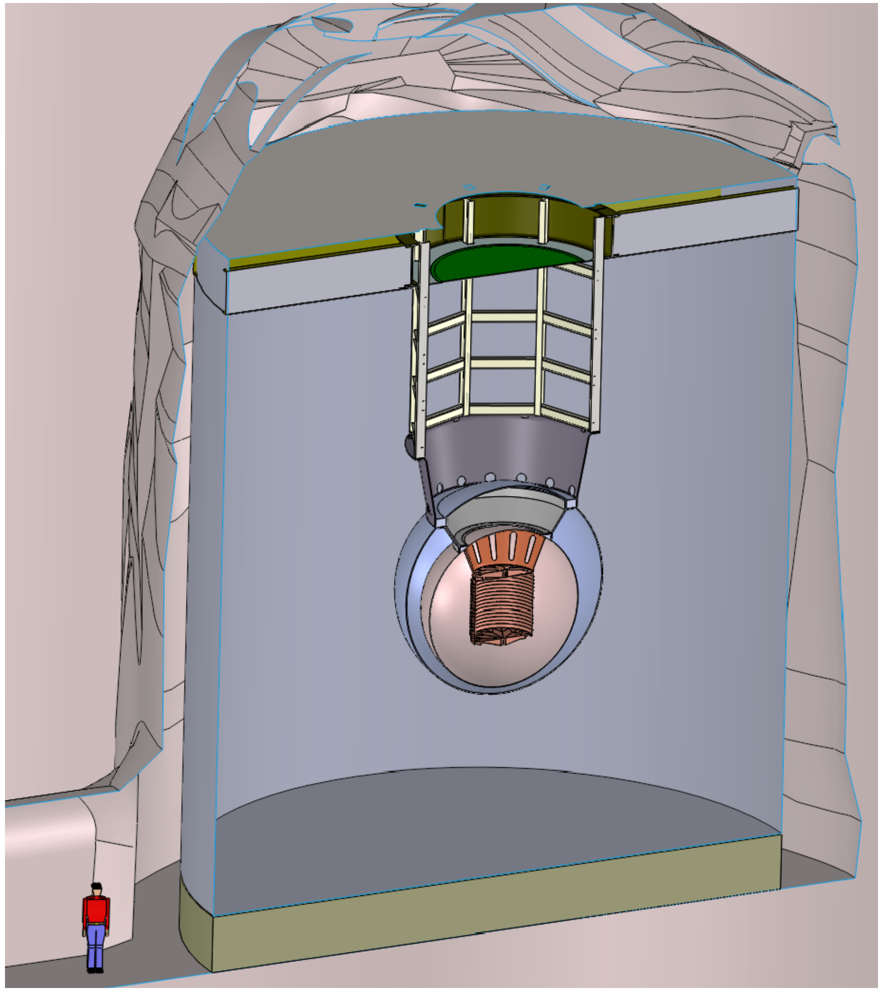


EXO-200 TPC

- 5000 kg enriched LXe TPC, based on the success of EXO-200.
- Upgraded scintillation and ionization detection technologies for 1% σ/E energy resolution.
- Pre-CDR available at arXiv:1805.11142

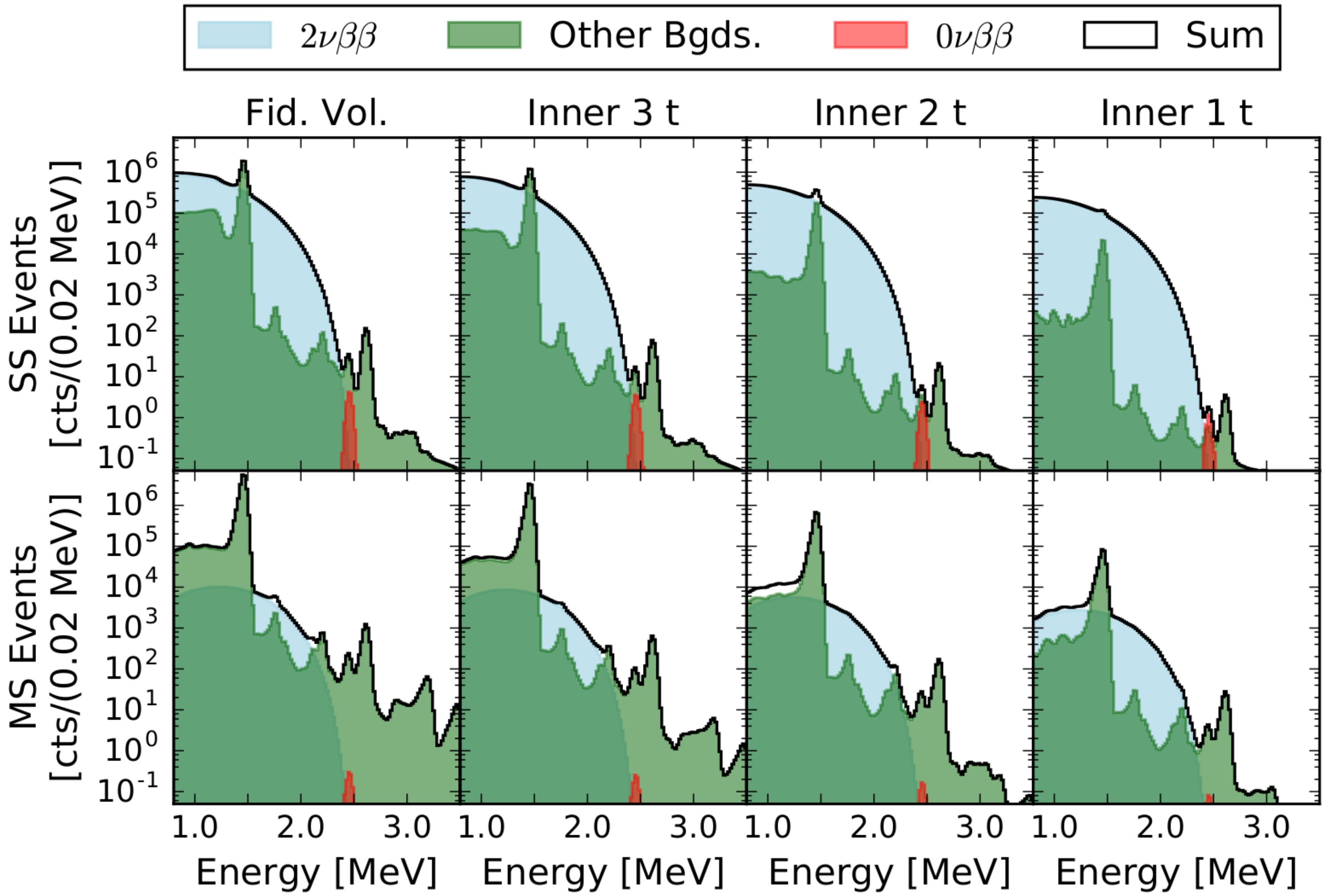


nEXO TPC



Preliminary artist view of nEXO in the SNOLAB Cryopit

nEXO discovery potential



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

Baseline design assumes:

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

In the absence of a signal, nEXO will have a 10 year half-life sensitivity of approximately 10^{28} yr.

See J. B. Albert et al. Phys. Rev. C 97, 065503 (2018).

Discovery potential of next gen experiments

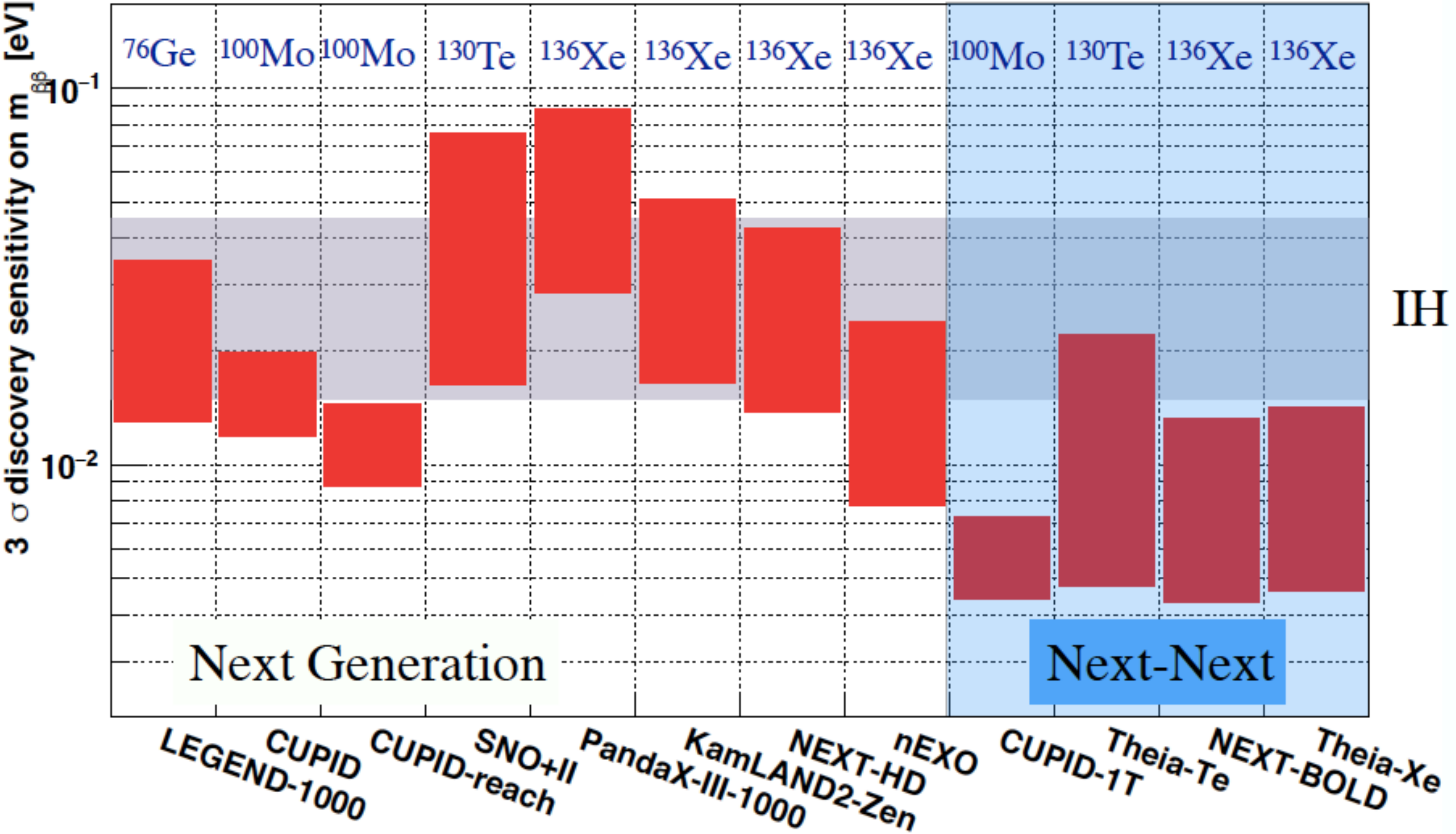


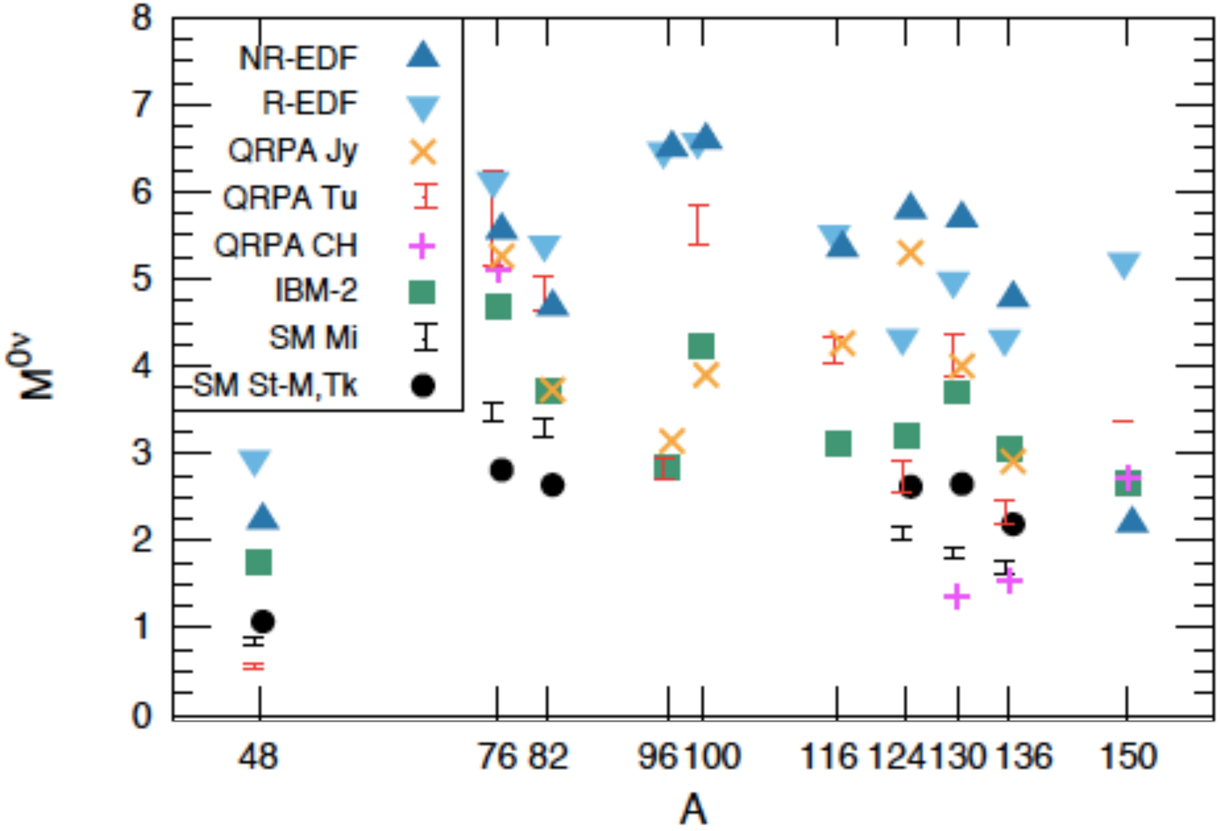
Figure from G. Benato, Y.G. Kolomensky
Methodology from Phys. Rev. D96, 053001 (2017)

Conclusions

- $0\nu\beta\beta$ 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.
- The underlying physics of neutrino mass is within reach.

Nuclear physics considerations

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



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

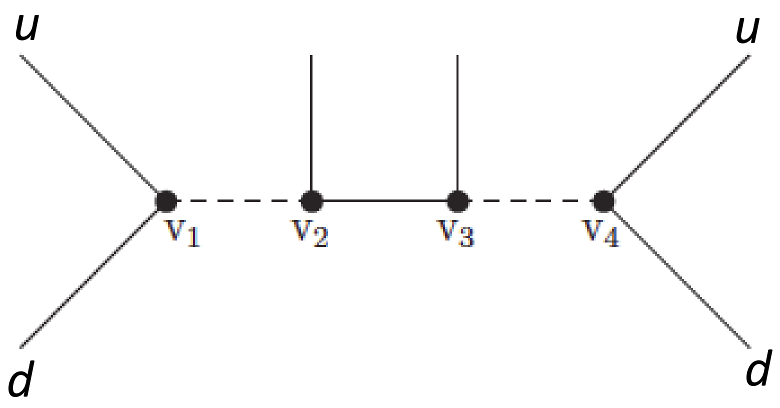
- The uncertainties on individual isotopes are related to nuclear structure.
- In addition there is an overall uncertainty (not shown) on the effective value to be used for g_A.
- The product of specific phase space and nuclear matrix element does not clearly identify one isotope as the ideal target for $0\nu\beta\beta$ search.

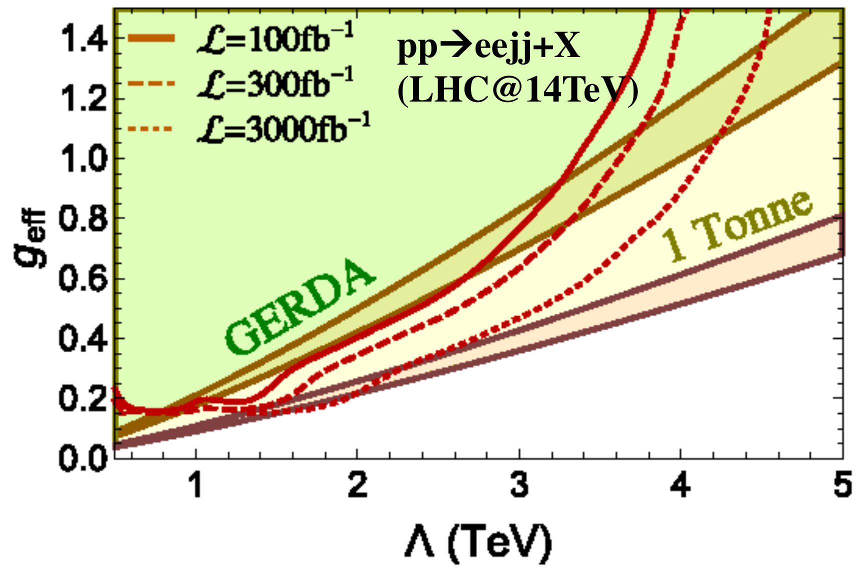
Ideally, we would observe $0\nu\beta\beta$ in more than one isotope!

Connections to LHC physics

An observation of $0\nu\beta\beta$ is an observation of **lepton number violation** ($\Delta L = 2$), so collider searches are complementary.

Here's a SUSY-inspired example, with generic LNV physics inserted at the TeV scale:

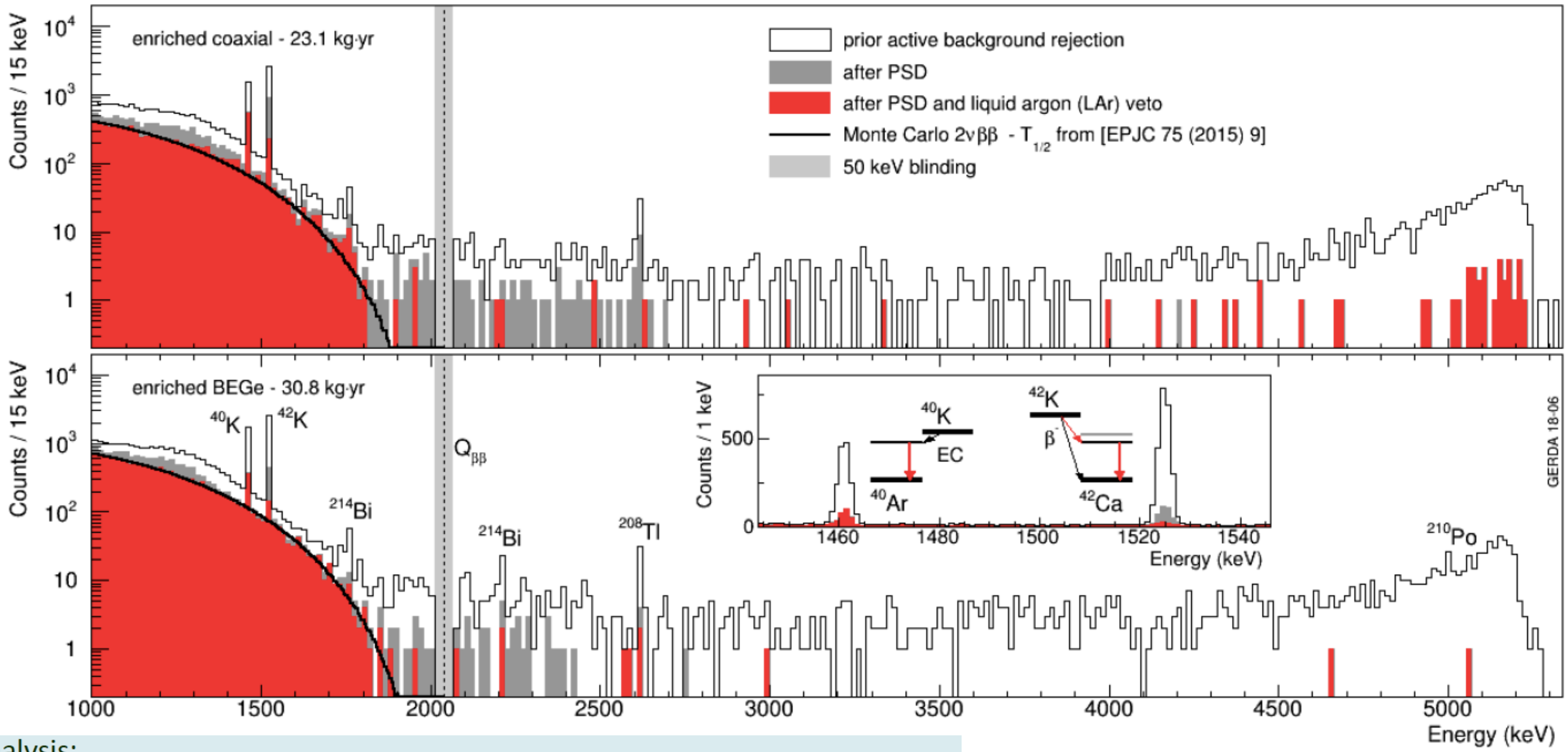




Peng, Ramsey-Musolf, Winslow, PRD 93, 093002 (2016)

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

GERDA recent results



Frequentist analysis:

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

Bayesian analysis:

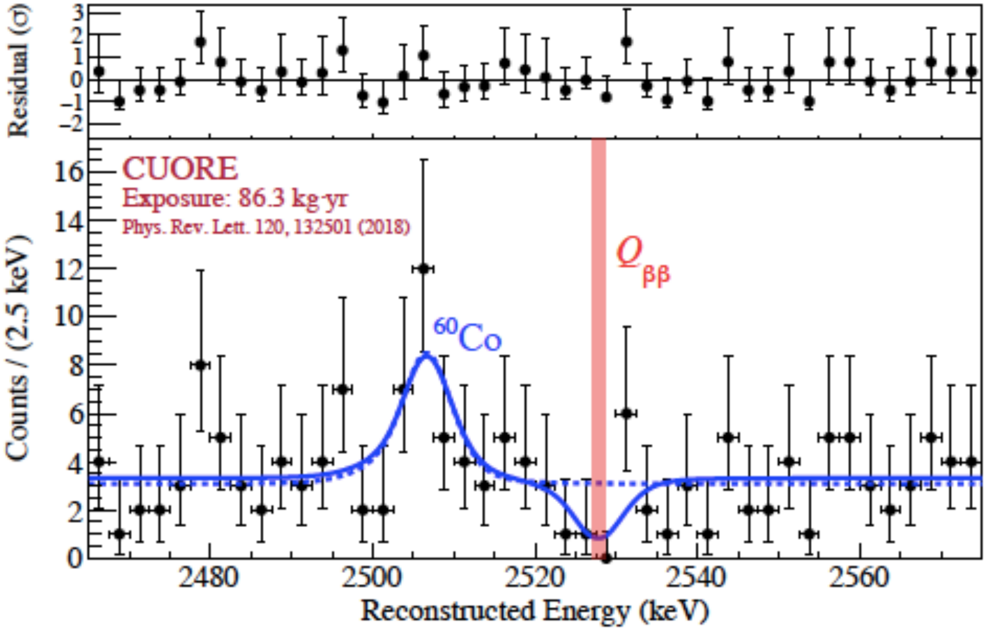
- Best fit → no signal. Bayes factor = 0.054
- $T_{1/2} > 0.8 \cdot 10^{26}$ yr (median sensitivity for limit $0.8 \cdot 10^{26}$ yr) @ 90% C.I.

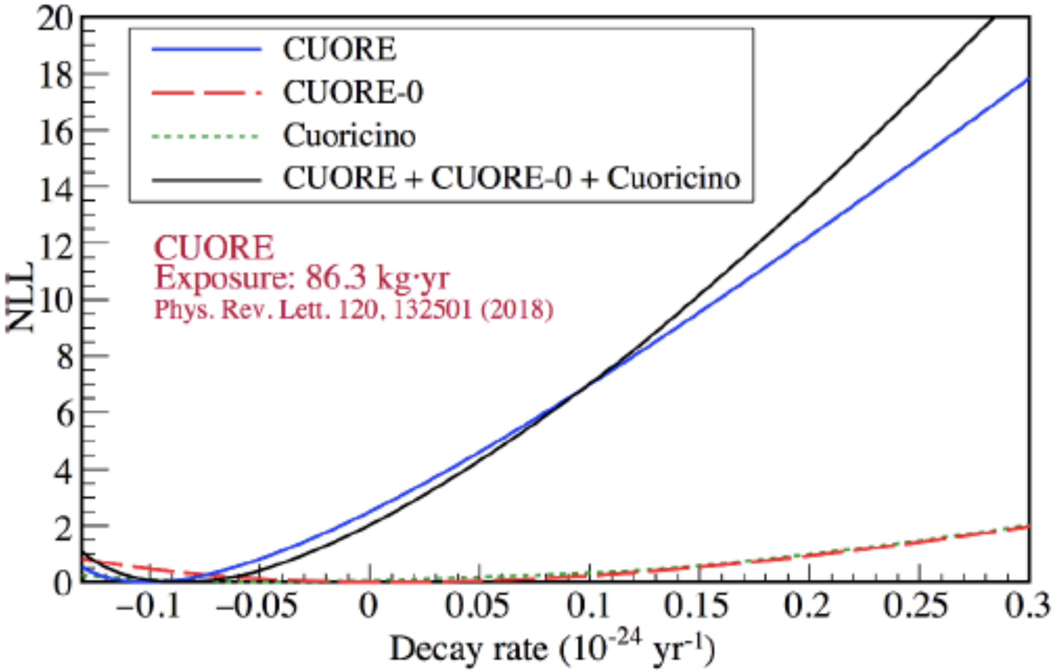
The median limit on effective Majorana mass is **< (0.11-0.26) eV** NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]

82.4 kg y total exposure

Agostini et al. PRL 120, 132503 (2018)

CUORE recent results





Limits combining CUORE with CUORE-0 and Cuoricino:

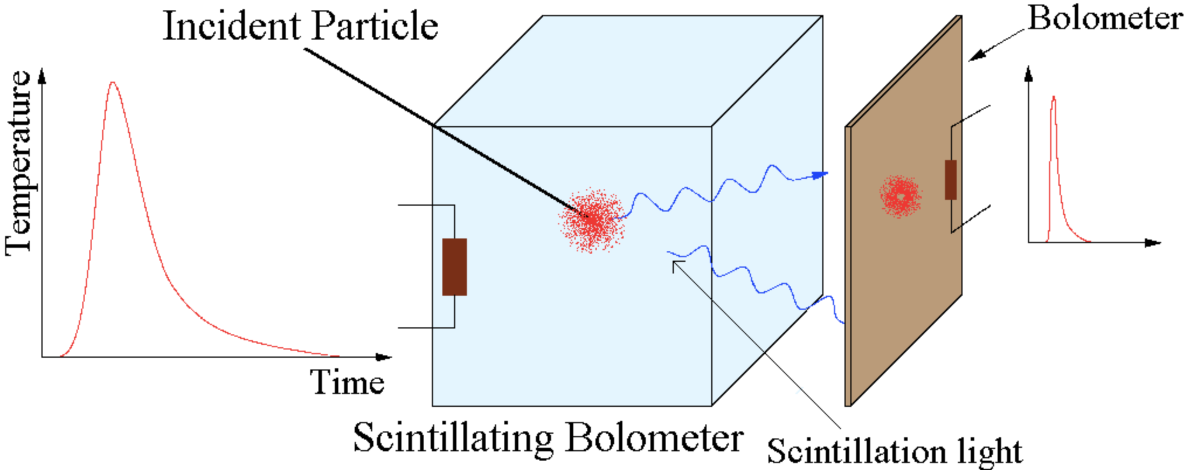
- Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$):
  1.5×10^{25} yr
- Profile likelihood ("frequentist") limit @ 90% CL:
  2.2×10^{25} yr

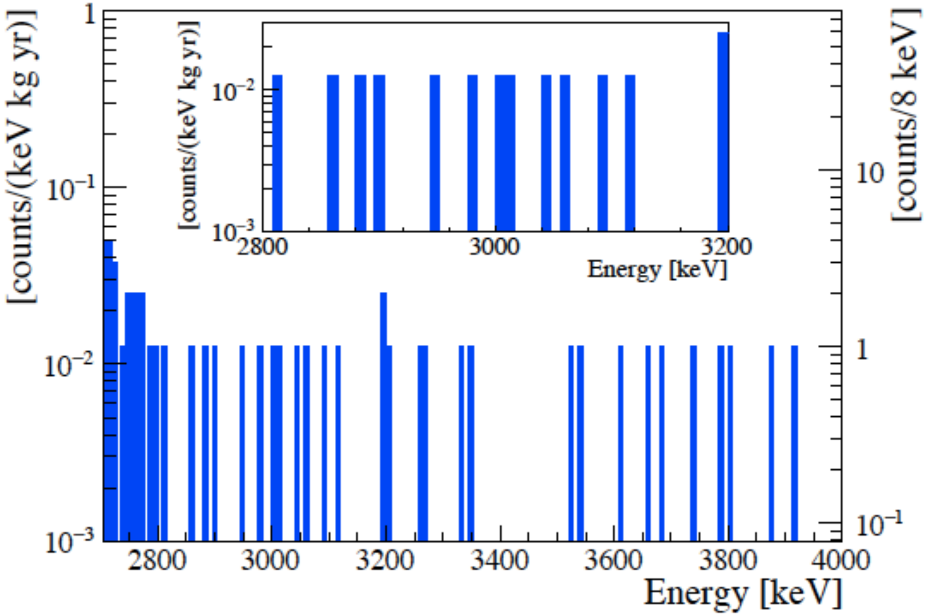
$\boxed{m_{\beta\beta} < 110 - 520 \text{ meV}}$

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

Back to data taking since May 2018!

CUPID recent results





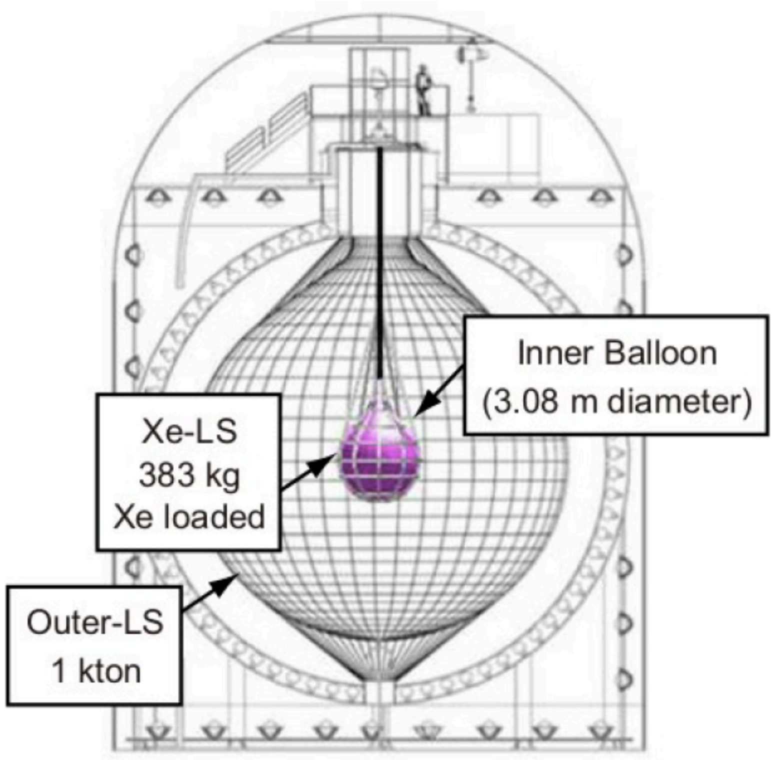
$$(3.5^{+1.0}_{-0.9}) \times 10^{-3}\ \text{counts}/(\text{keV kg yr})$$

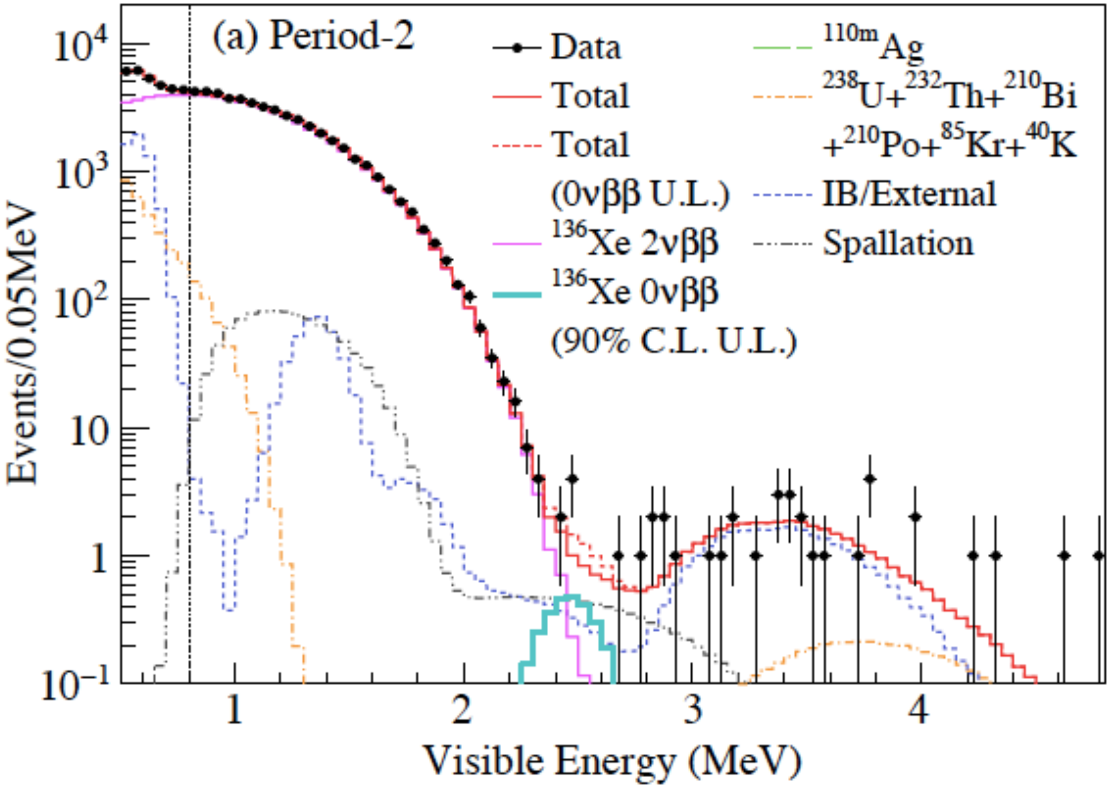
24 Zn^{82}Se bolometers, for a total mass ≈ 5.1 kg of ^{82}Se

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

arXiv:1906.05001

KamLAND-Zen recent results





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

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

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

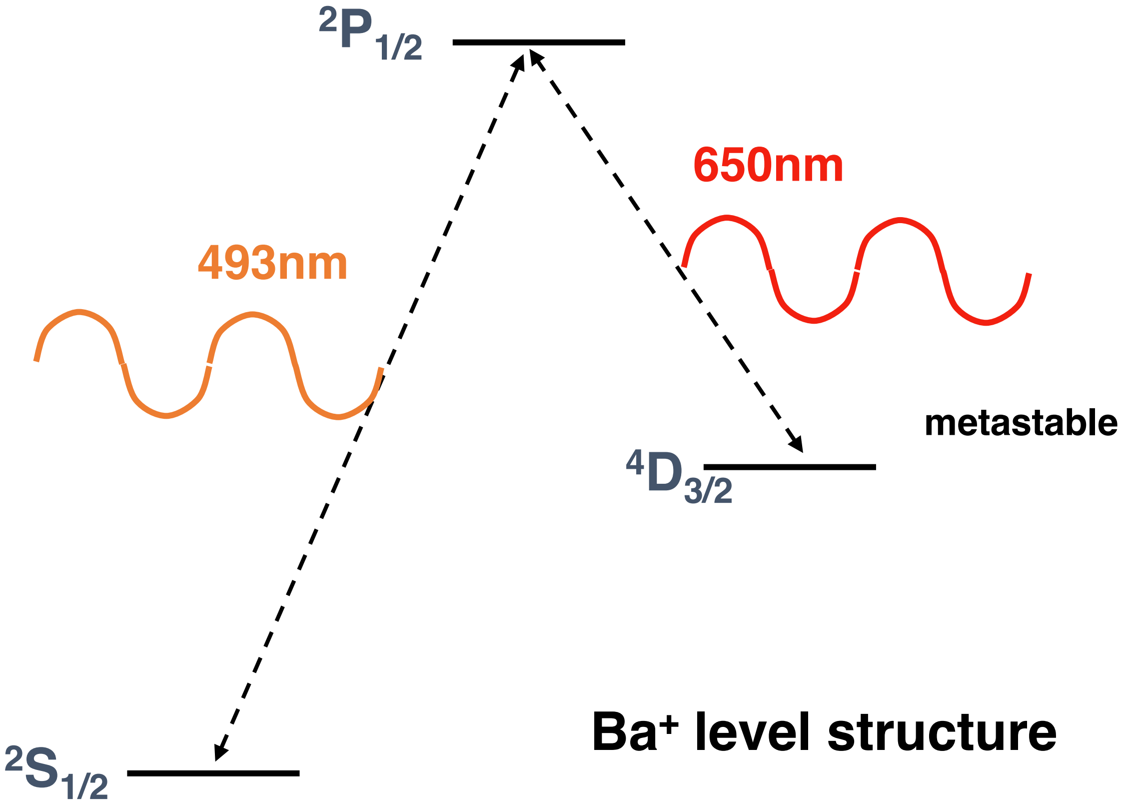
Gando et al., Phys. Rev. Lett. 117, 082503 (2016)

~745 kg 90% ^{enr}Xe dissolved in inner volume of KamLAND since Jan. 2019, expect new results at TAUP!

Ba⁺ tagging

In ^{136}Xe based detectors, if you could identify the daughter nucleus as barium on an event-by-event basis, you could eliminate all backgrounds other than $2\nu\beta\beta$.

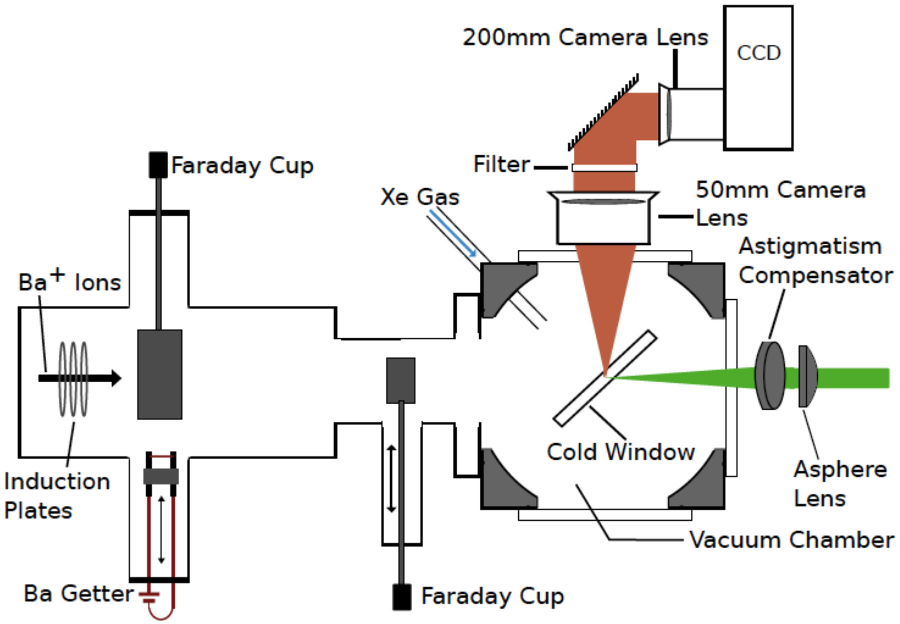
$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-}$$

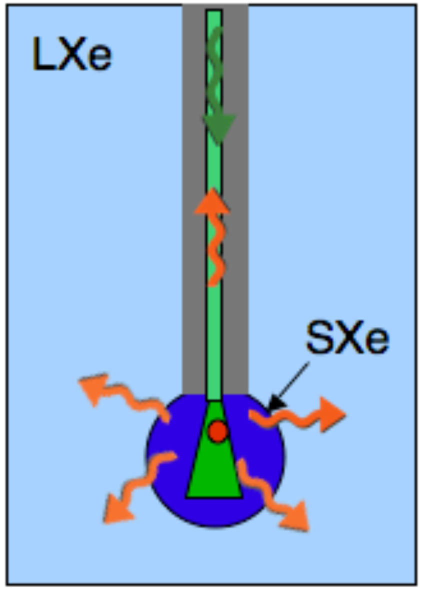


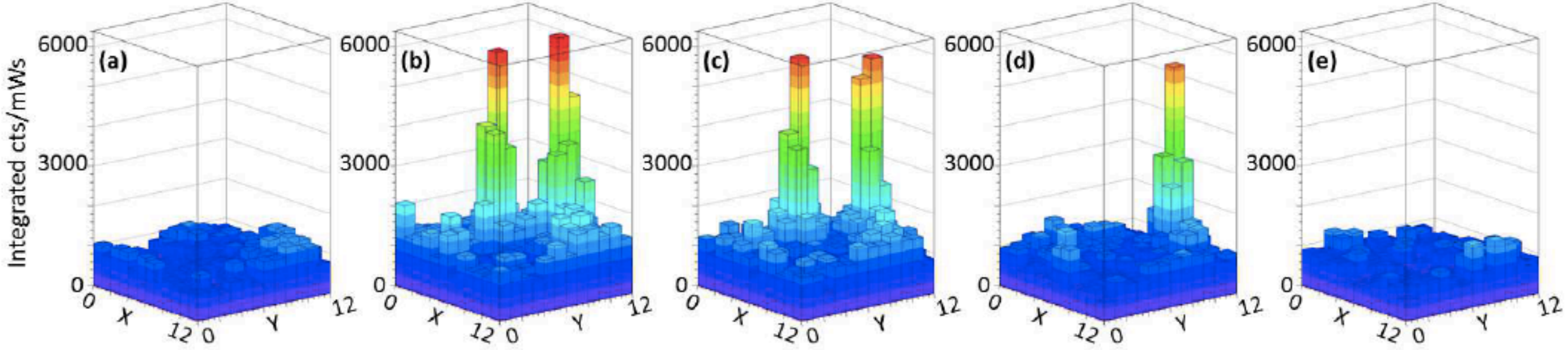
Ba⁺ level structure

- •Ba⁺ system is well studied. See for example 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.
- •Recent progress from both nEXO and NEXT collaborations.

Barium tagging in solid xenon







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