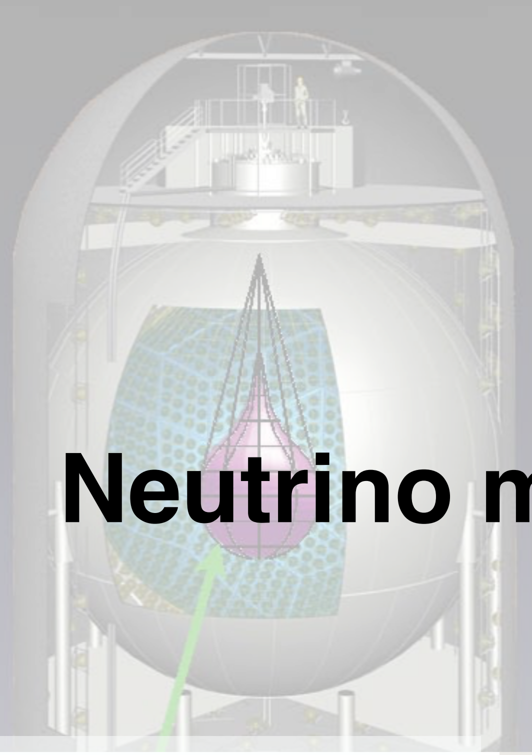
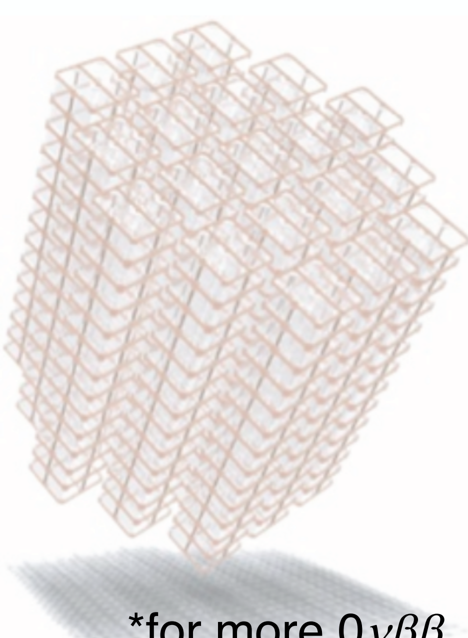
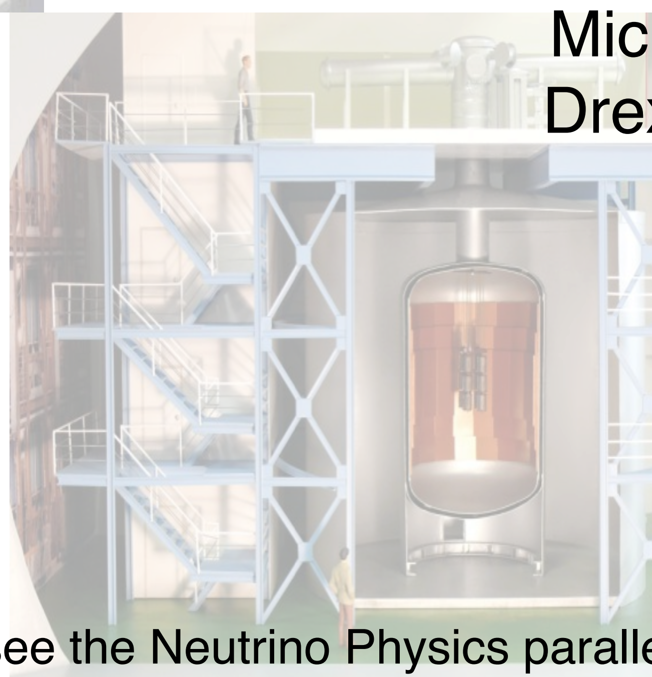
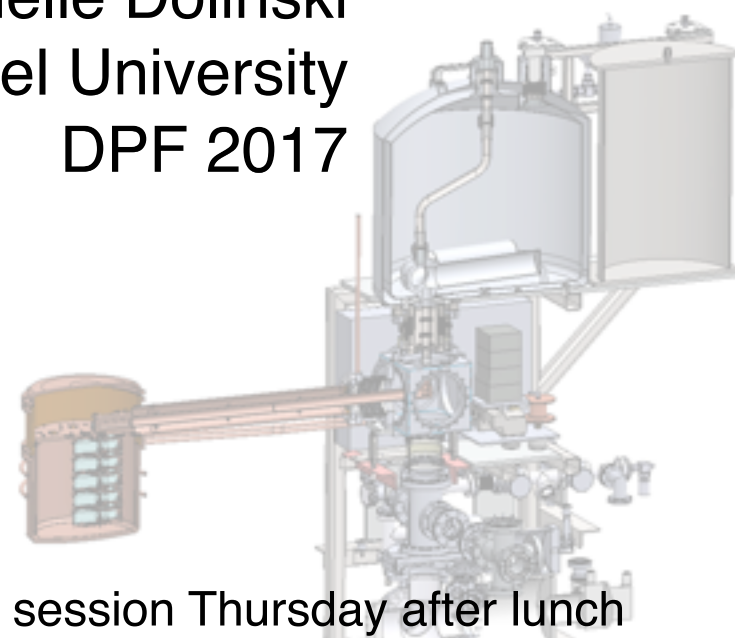


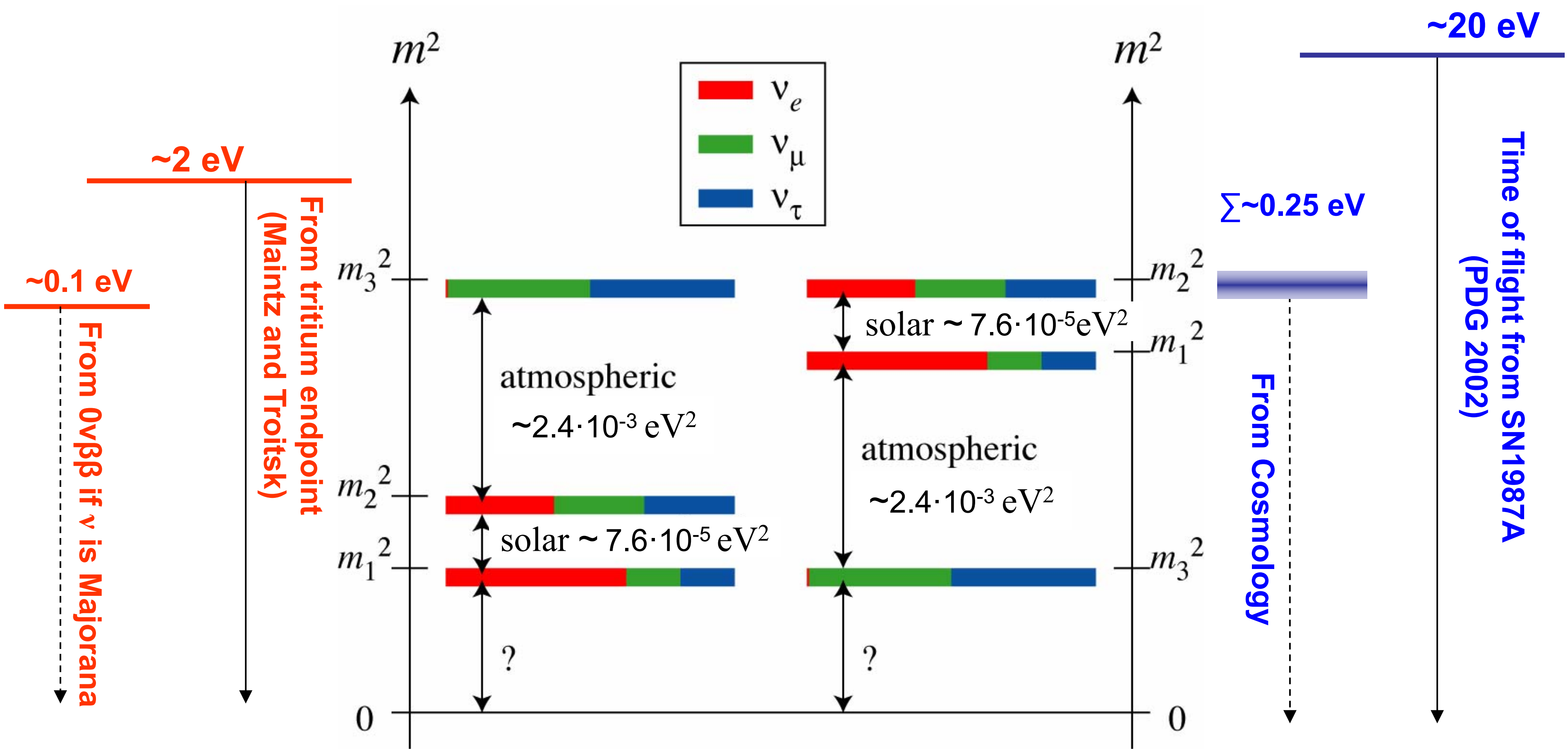
Neutrino mass and neutrinoless double beta decay*

Michelle Dolinski
Drexel University
DPF 2017

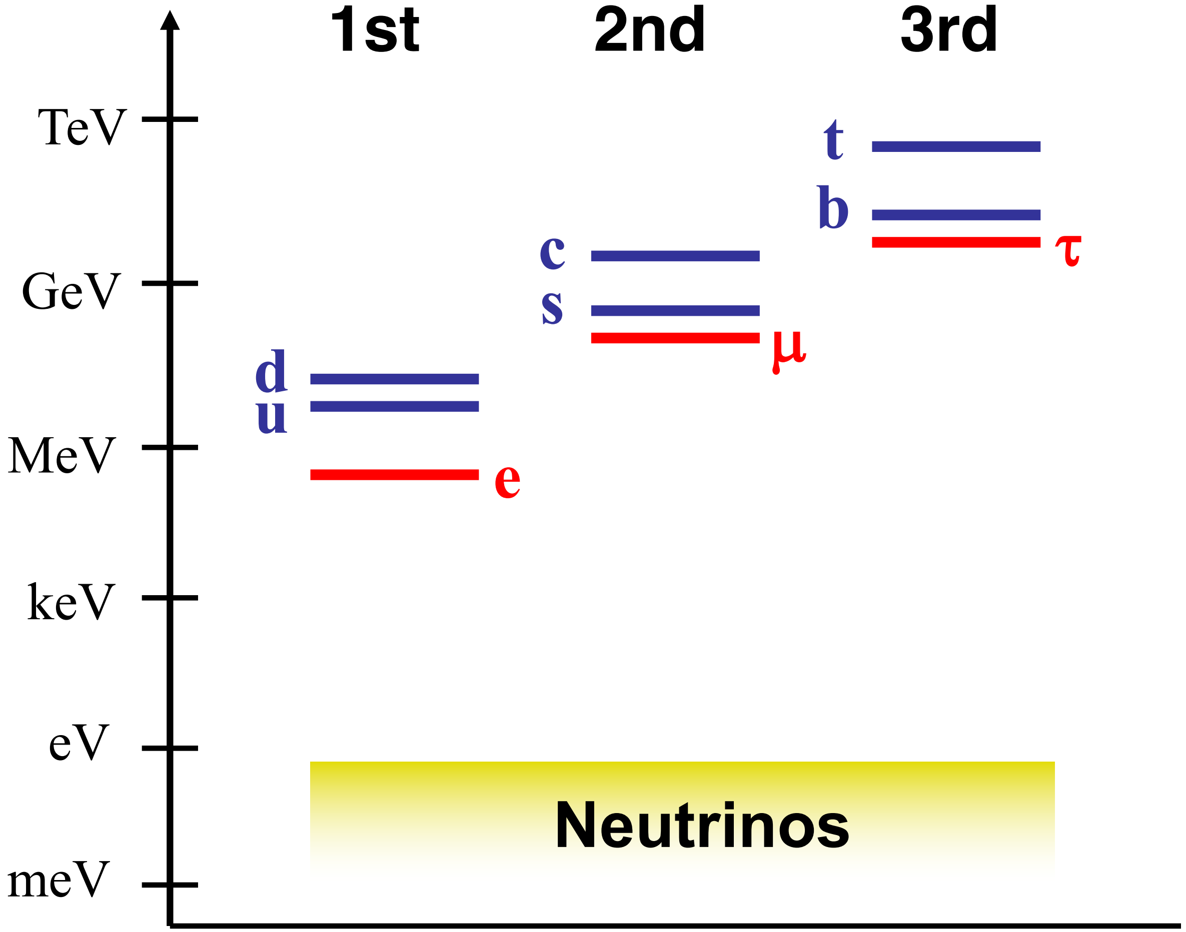




*for more $0\nu\beta\beta$, see the Neutrino Physics parallel session Thursday after lunch

What we know about neutrinos



Neutrino mass



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

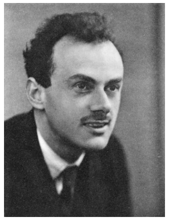
The matter-antimatter asymmetry

"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*.

Neutrinos could be the key to explaining the matter-antimatter asymmetry in the universe…

"Dirac" neutrinos $\nu \neq \bar{\nu}$



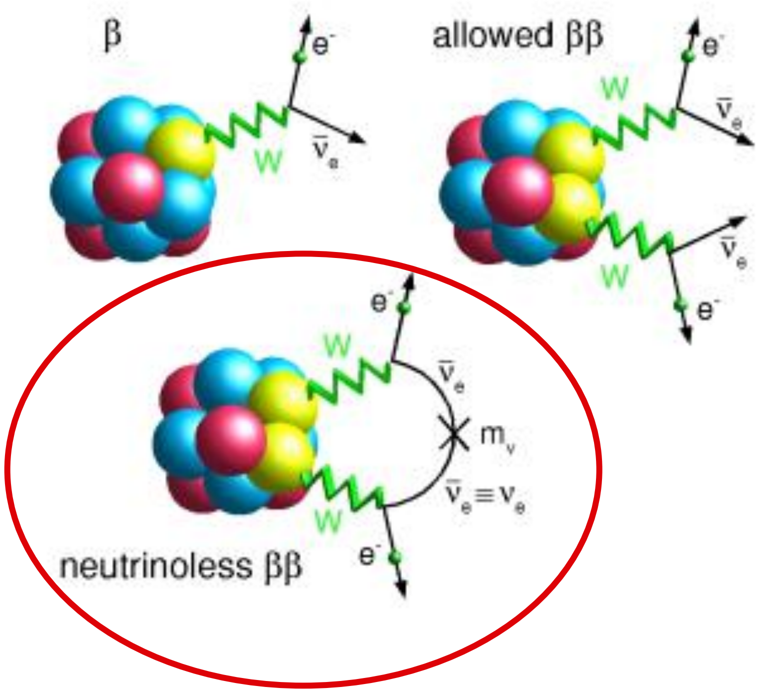
"Majorana" neutrinos $\nu = \bar{\nu}$

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

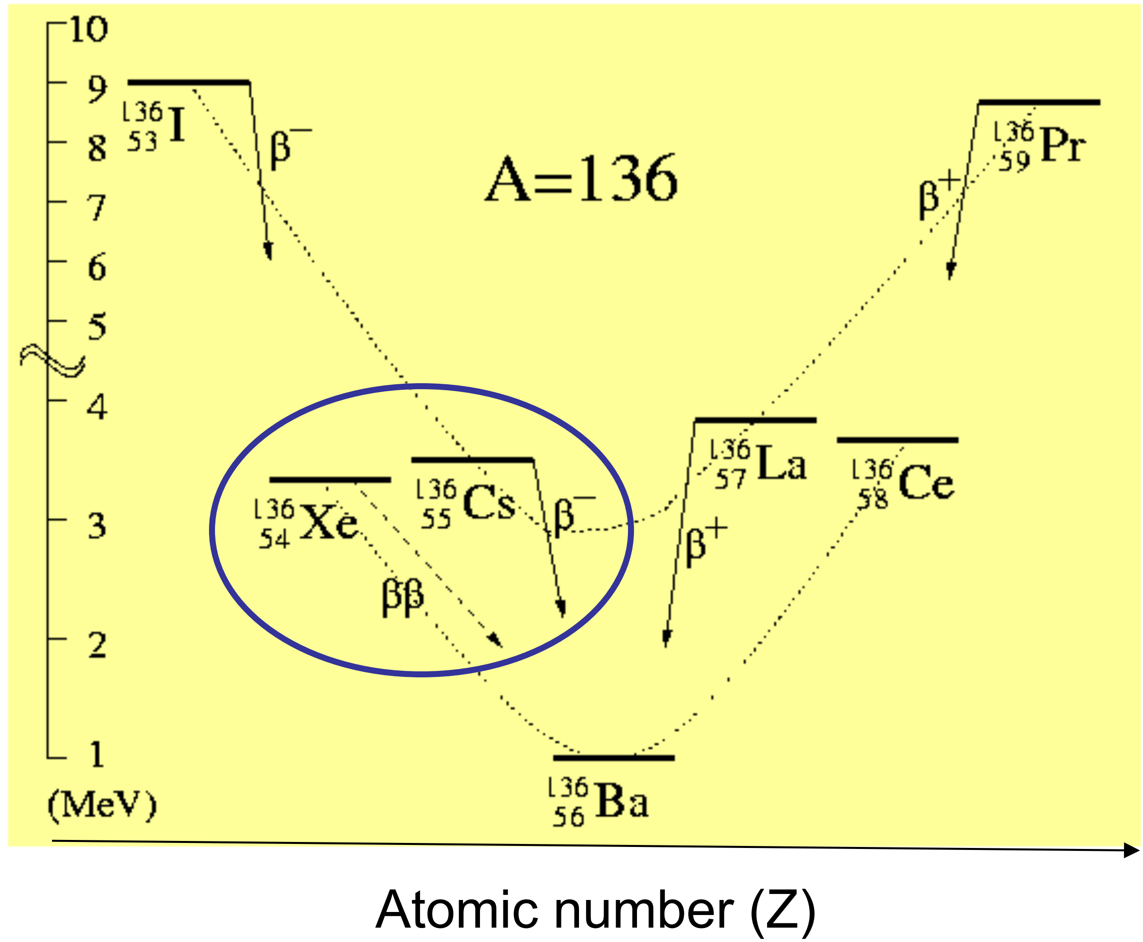
As a bonus, Majorana νs may be tied to the mystery of small ν masses

Double beta decay

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

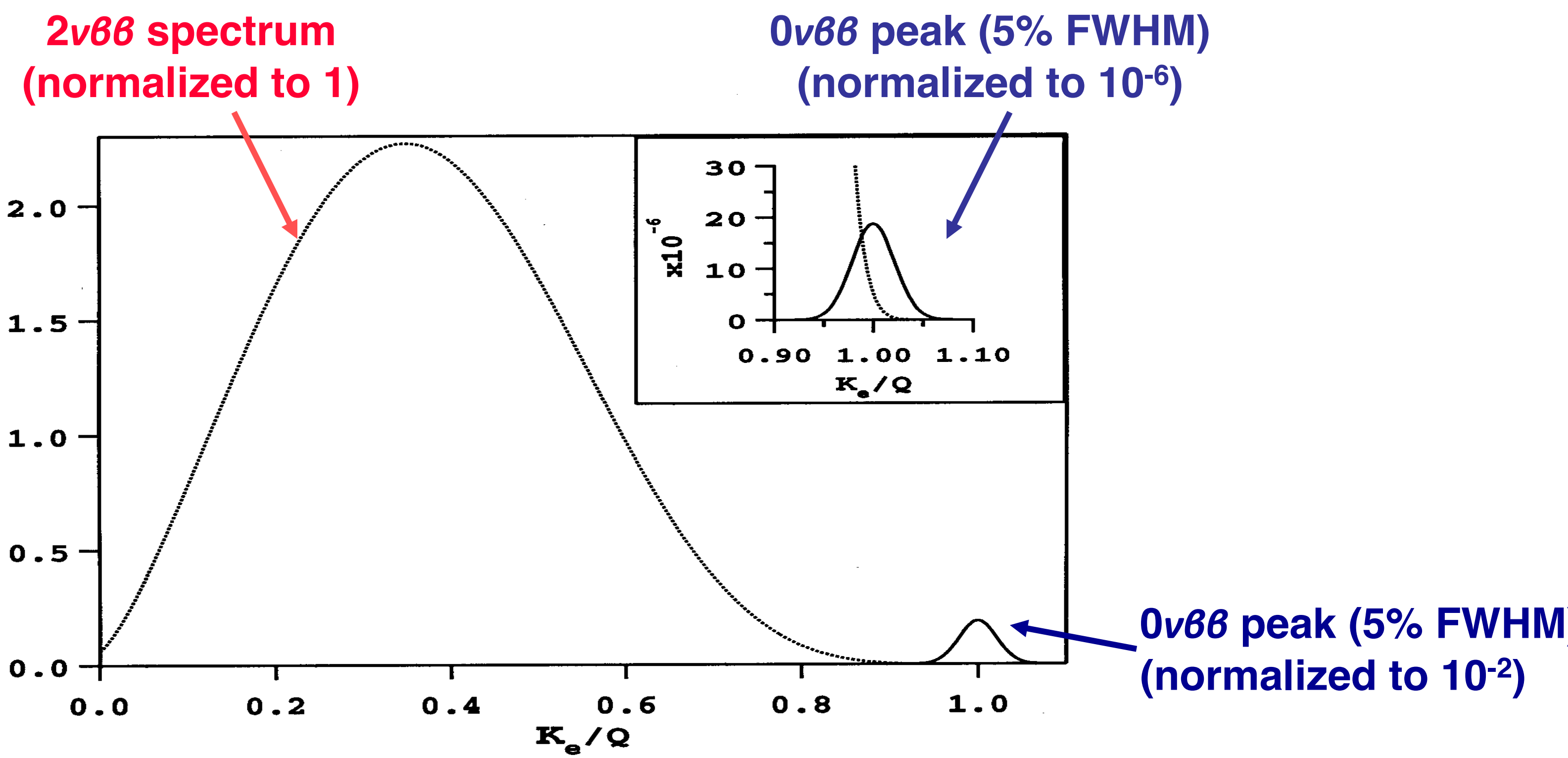


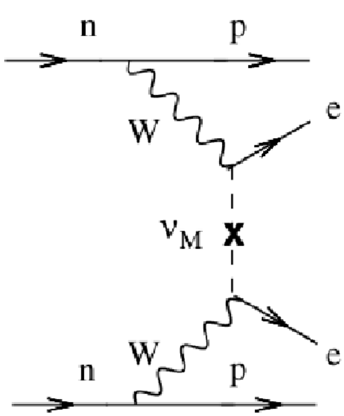
This process can only occur for a Majorana neutrino!



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

Neutrinoless double beta decay

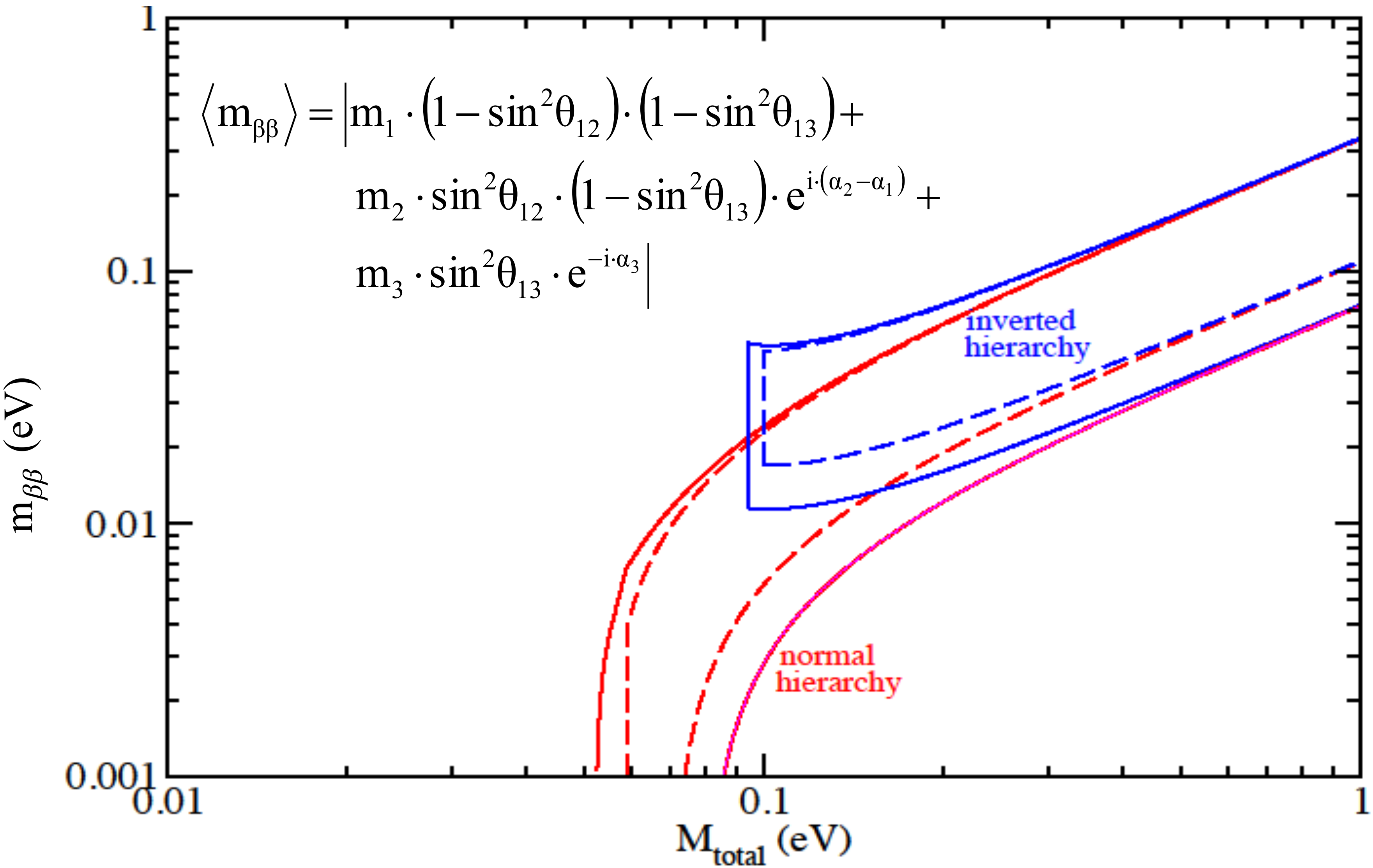




$$\langle m_{\beta\beta}\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\, G^{0\nu\beta\beta}(E_0,Z)\left|M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta}\right|^2\right)^{-1}$$

(light Majorana neutrino exchange mechanism ONLY)

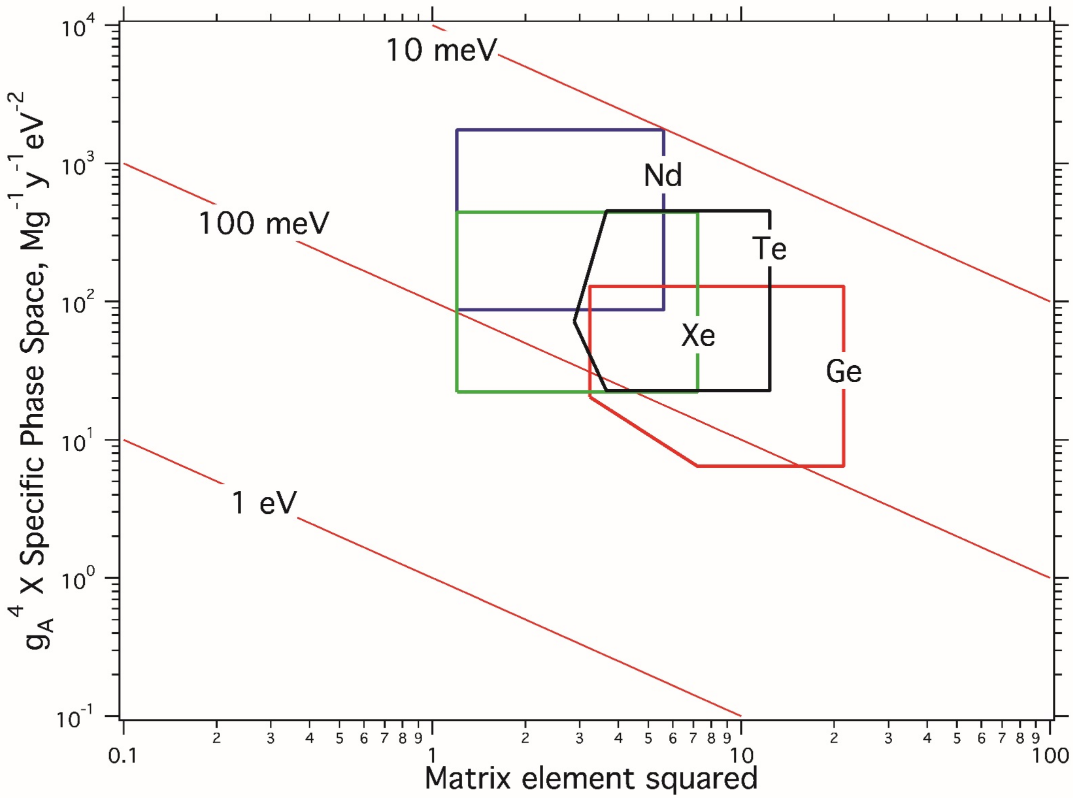
Effective Majorana mass



(light Majorana neutrino exchange mechanism ONLY)

Nuclear physics considerations

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



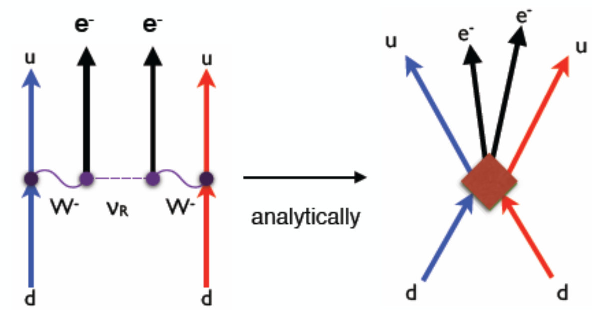
R.G.H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).

- The uncertainties on individual isotopes are related to nuclear structure.
- There is not a clear winner based on phase space and matrix element considerations.

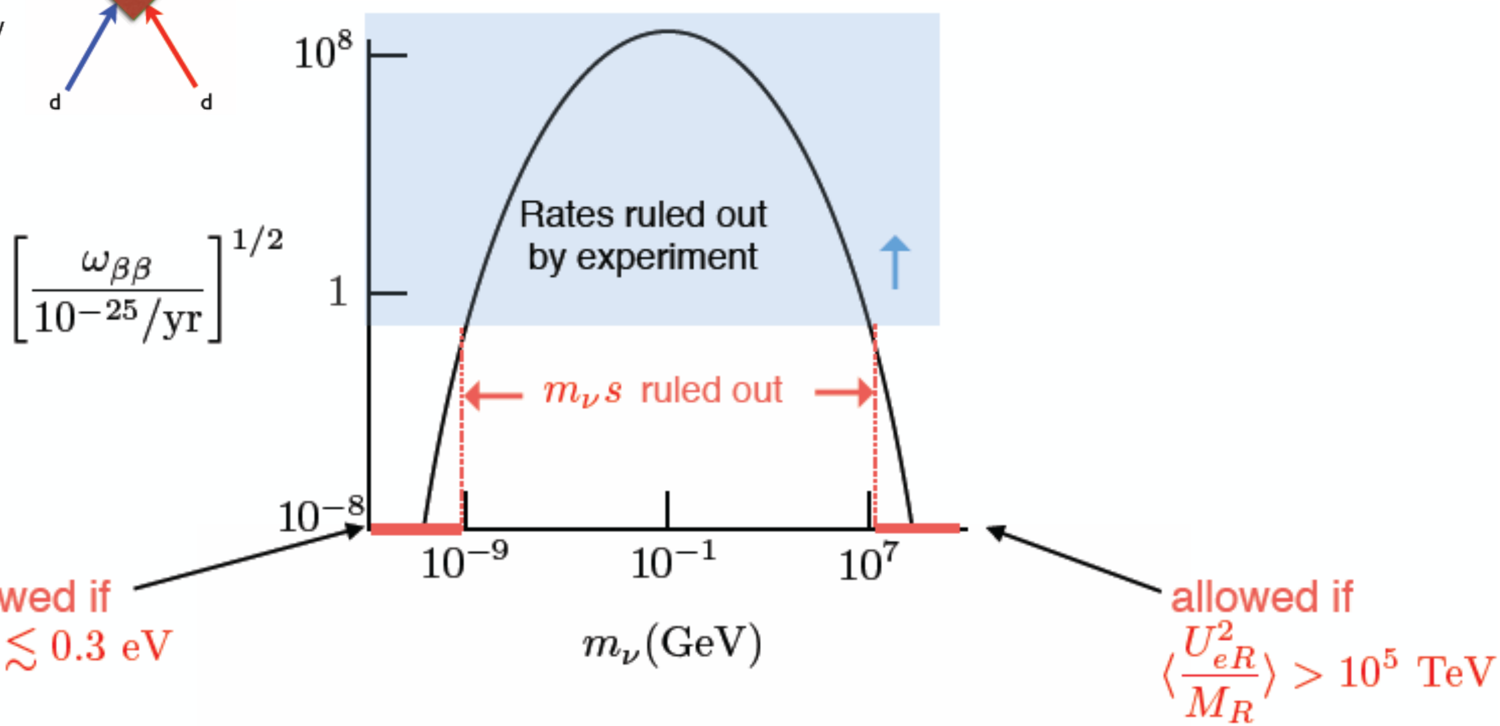
Ideally, we would observe $0\nu\beta\beta$ in more than one isotope!

Other mechanisms

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



elementary amplitude

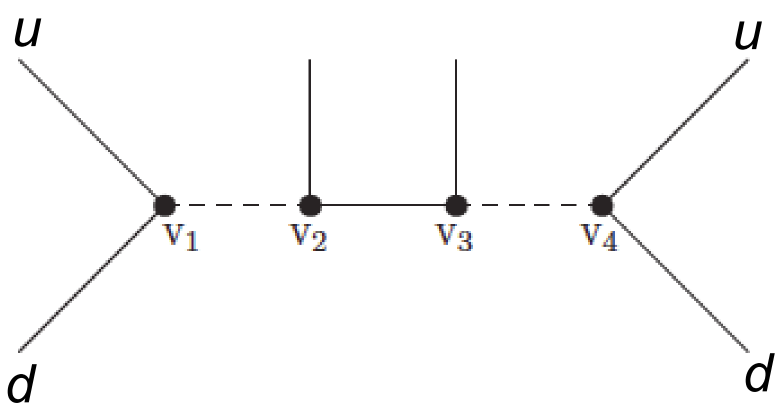


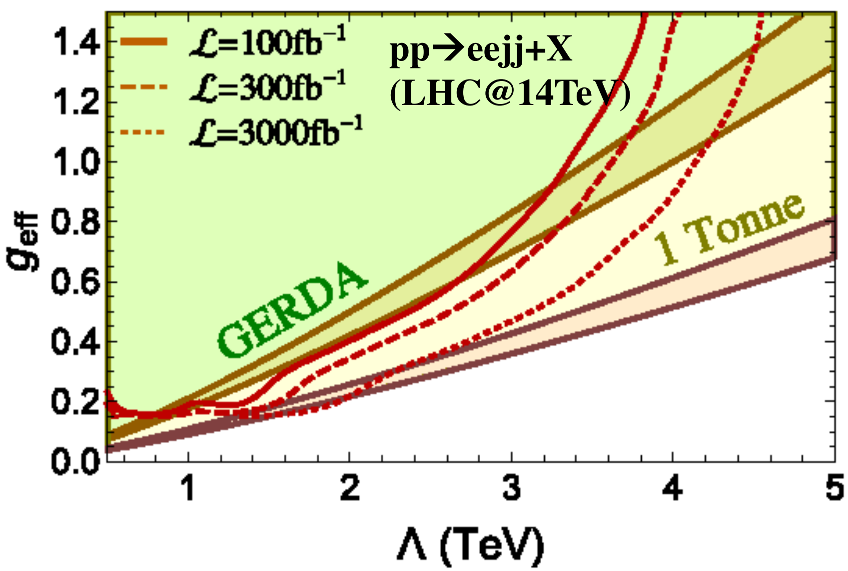
Wick Haxton, DNP 2016

Connections to LHC physics

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

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

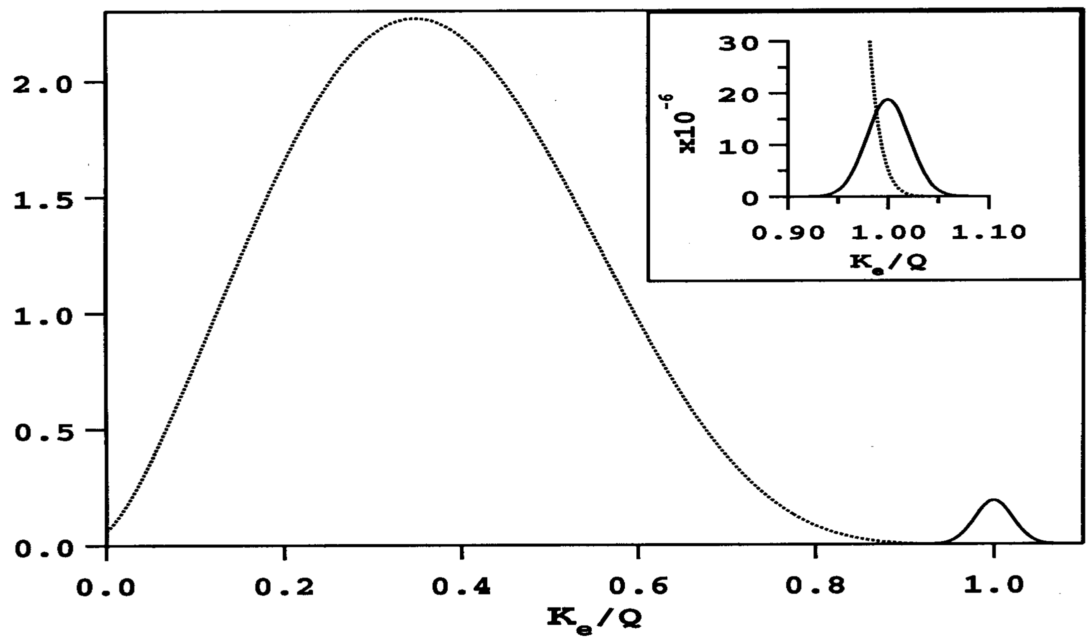


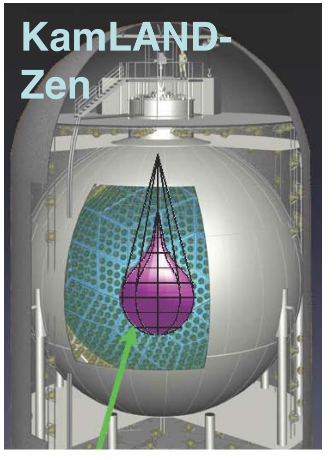


Peng, Ramsey-Musolf, Winslow, PRD 93, 093002 (2016)

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

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 purification and qualification using:

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

Just for EXO-200, the database of characterized materials includes over 300 entries. See D.S.Leonard et al., *Nucl. Instr. Meth*. A**591**, 490 (2008) and D.S. Leonard et al., arXiv:1703.10799

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

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

Recent results (> 10^{25} yr half-life)

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	46.7	5.8	>8.0	<120-270	L. Pandola for GERDA Collab, TAUP 2017
^{136}Xe	EXO-200	177.6	3.7	>1.8	<147-398	Albert et al. arXiv: 1707.08707 (2017)
	KamLAND-ZEN	504**	4.9	>11 (run 2)	<60-161	Gando et al., PRL 117 (2016) 082503

* Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included

** All Xe. Fiducial Xe is more like ~150 kg yr

To achieve 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 observationof neutrinoless double-beta decay. These are questions and experiments of the greatest interest to particle physics."

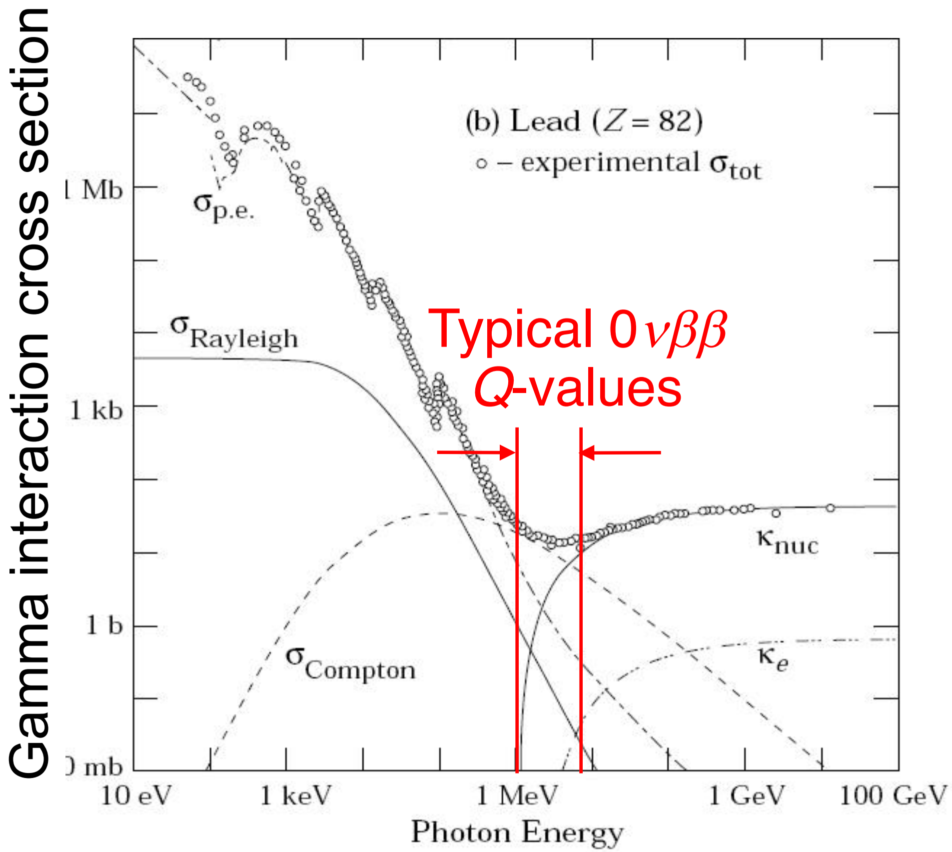
"Next-generation experiments will continue to benefit from strong HEP and PA participation."


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

Challenges of the tonne-scale



Shielding a detector from MeV gammas is difficult!

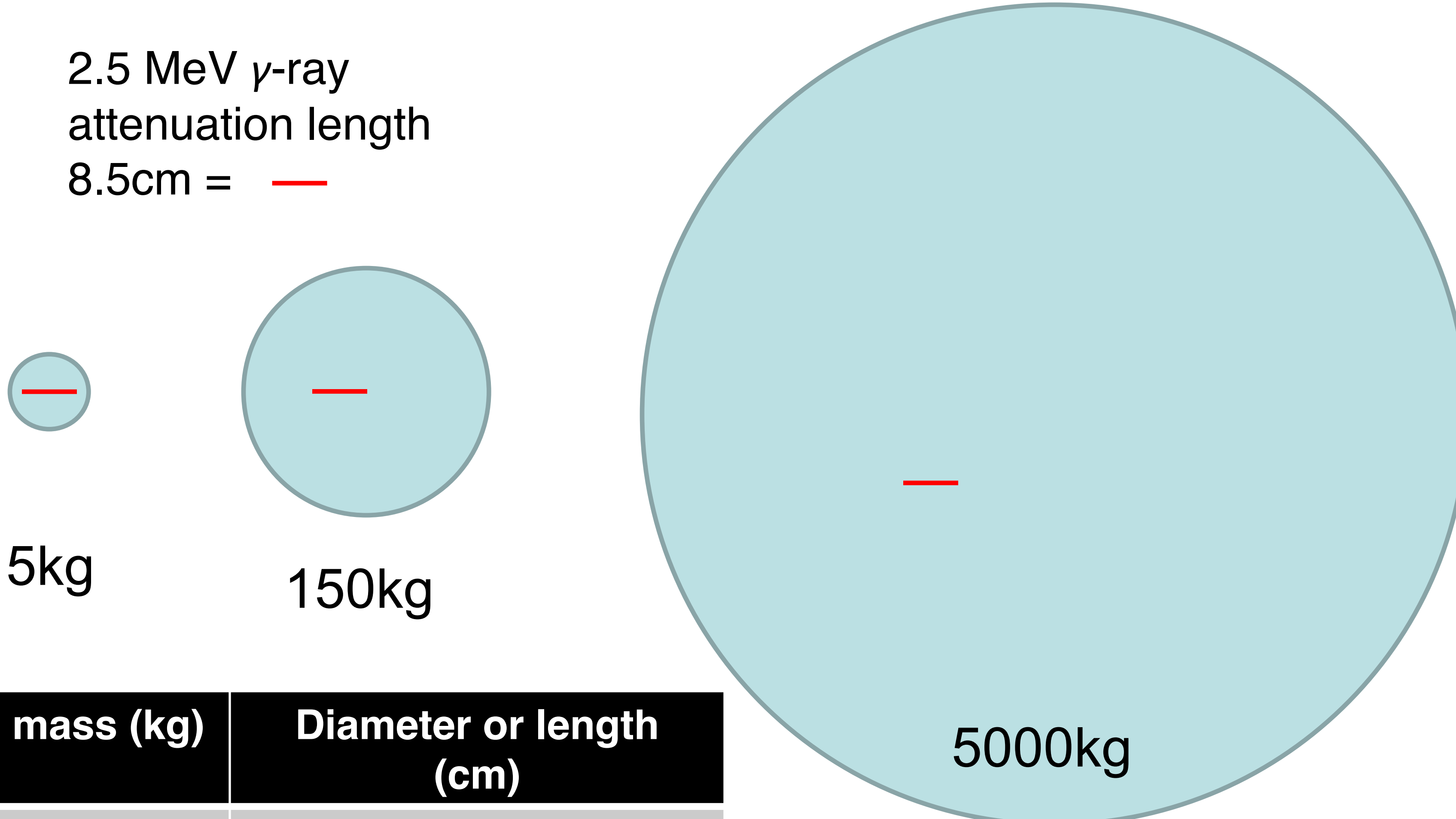
Example:
γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

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

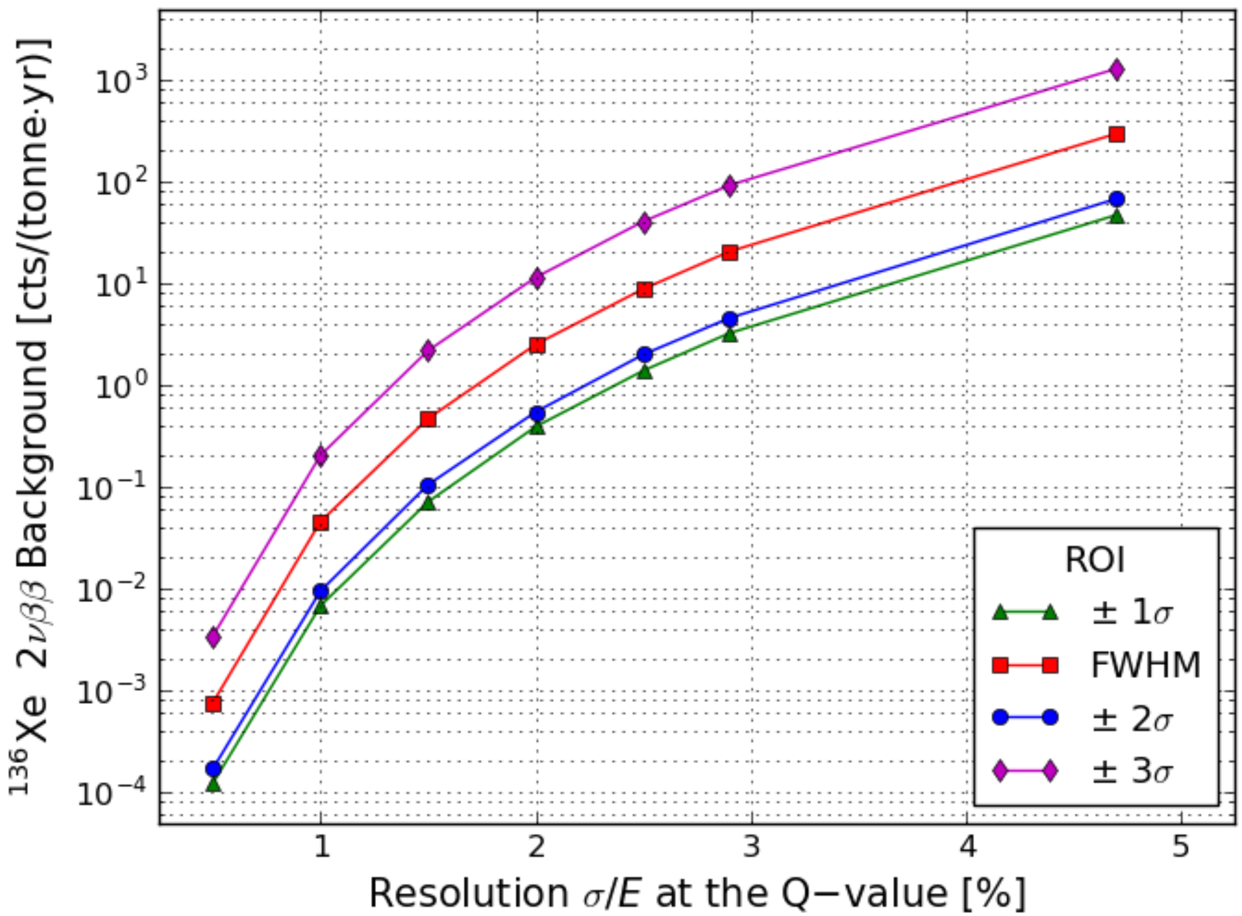
2.5 MeV γ-ray attenuation length 8.5cm =



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

Background suppression

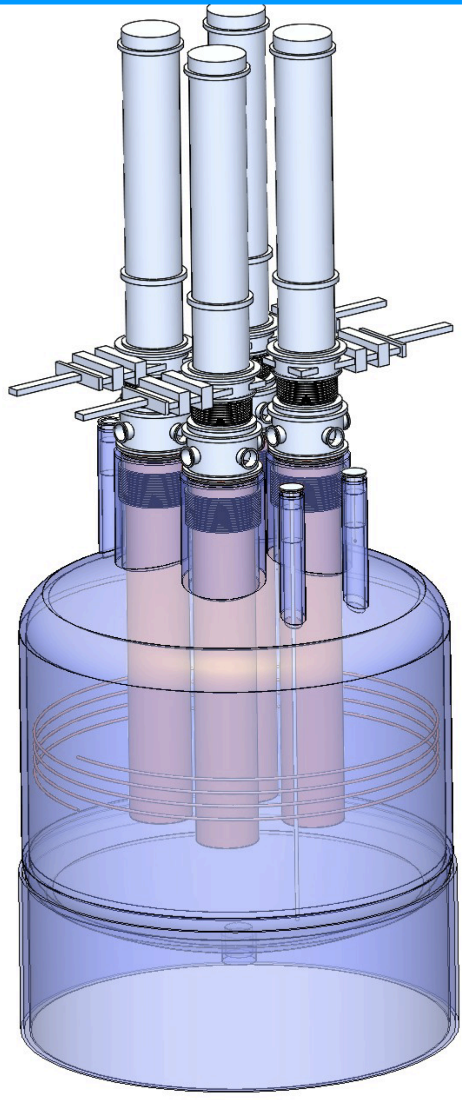
All observables have a role in separating signal from background.
A very large, homogeneous detector has great advantages but only if its energy resolution is sufficient to sufficiently suppress the $2\nu\beta\beta$ mode.



Example #1: the high resolution approach
Next Generation ton scale ^{76}Ge 0νββ

- **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 for a background of 0.1 cnt/tonne-yr in the region of interest**
- **Requires background reduction of 30 relative to GERDA and MAJORANA DEMONSTRATOR.**
- **Envision a phased, stepwise implementation, starting with increased source mass in the GERDA cryostat:**

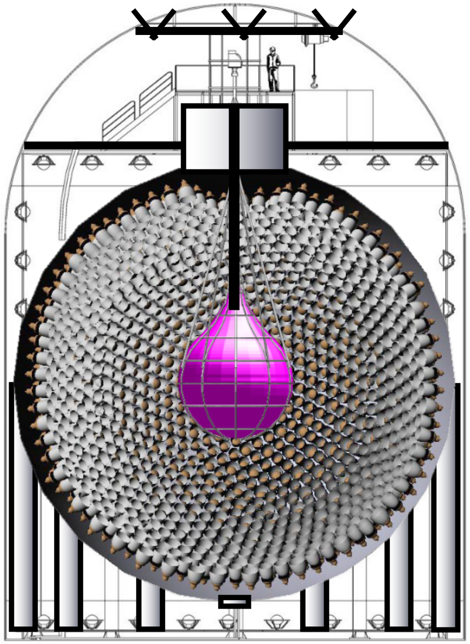
  ***e.g.* 200 → 500-1000 kg**



LEGEND

Example #2: the very large Liquid scintillator approach Beyond KamLAND-Zen 800

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



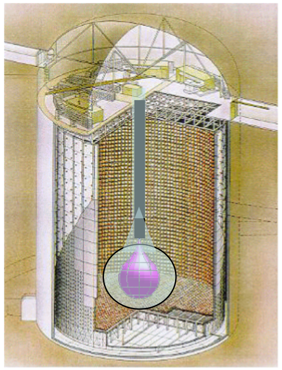
1000+ kg xenon

	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?



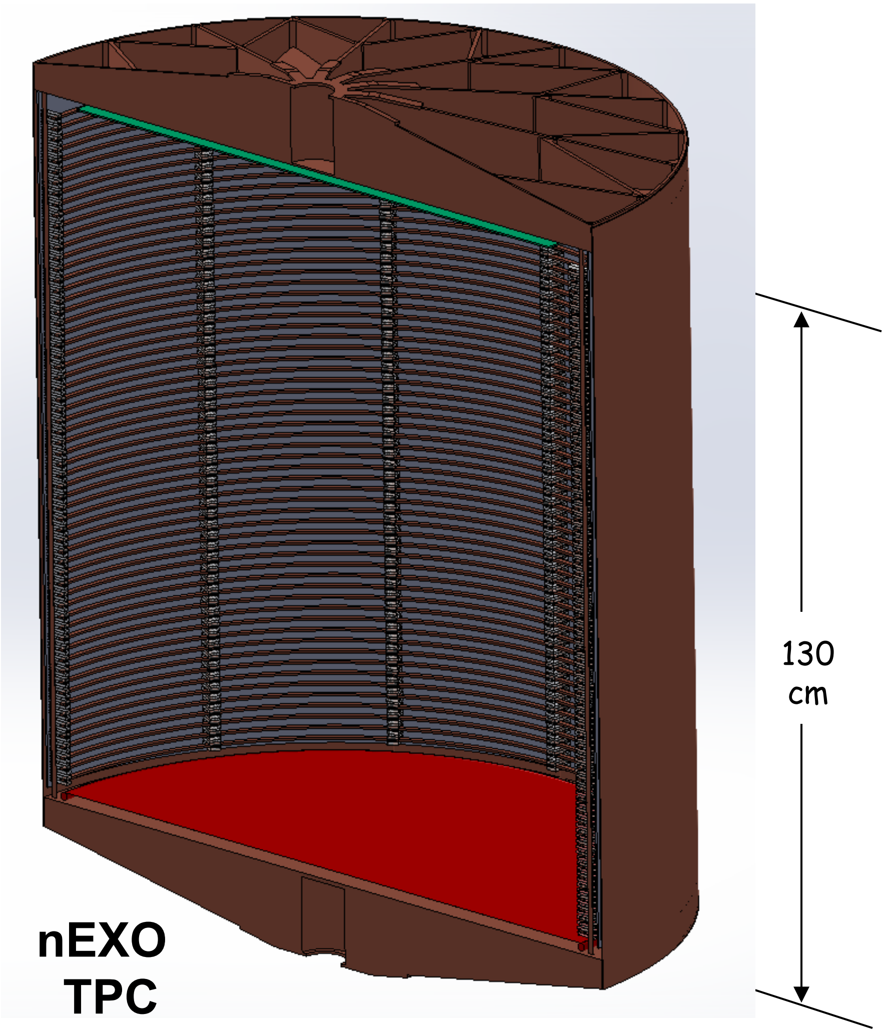
Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

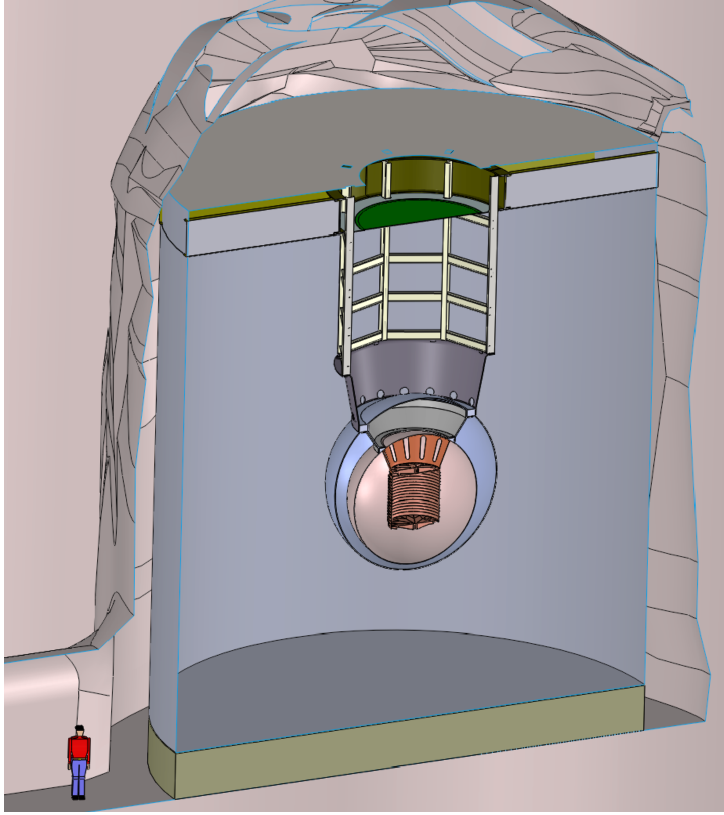
But eventually 2v background becomes dominant

Example #3: The nEXO detector

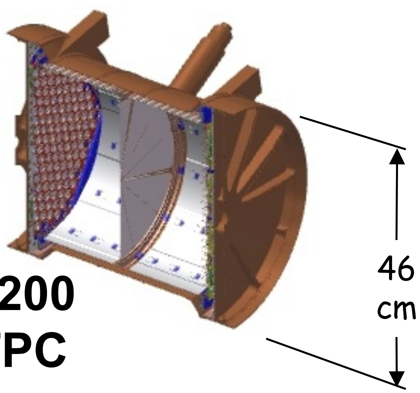
A 5000 kg enriched LXe TPC, directly extrapolated from EXO-200



nEXO TPC

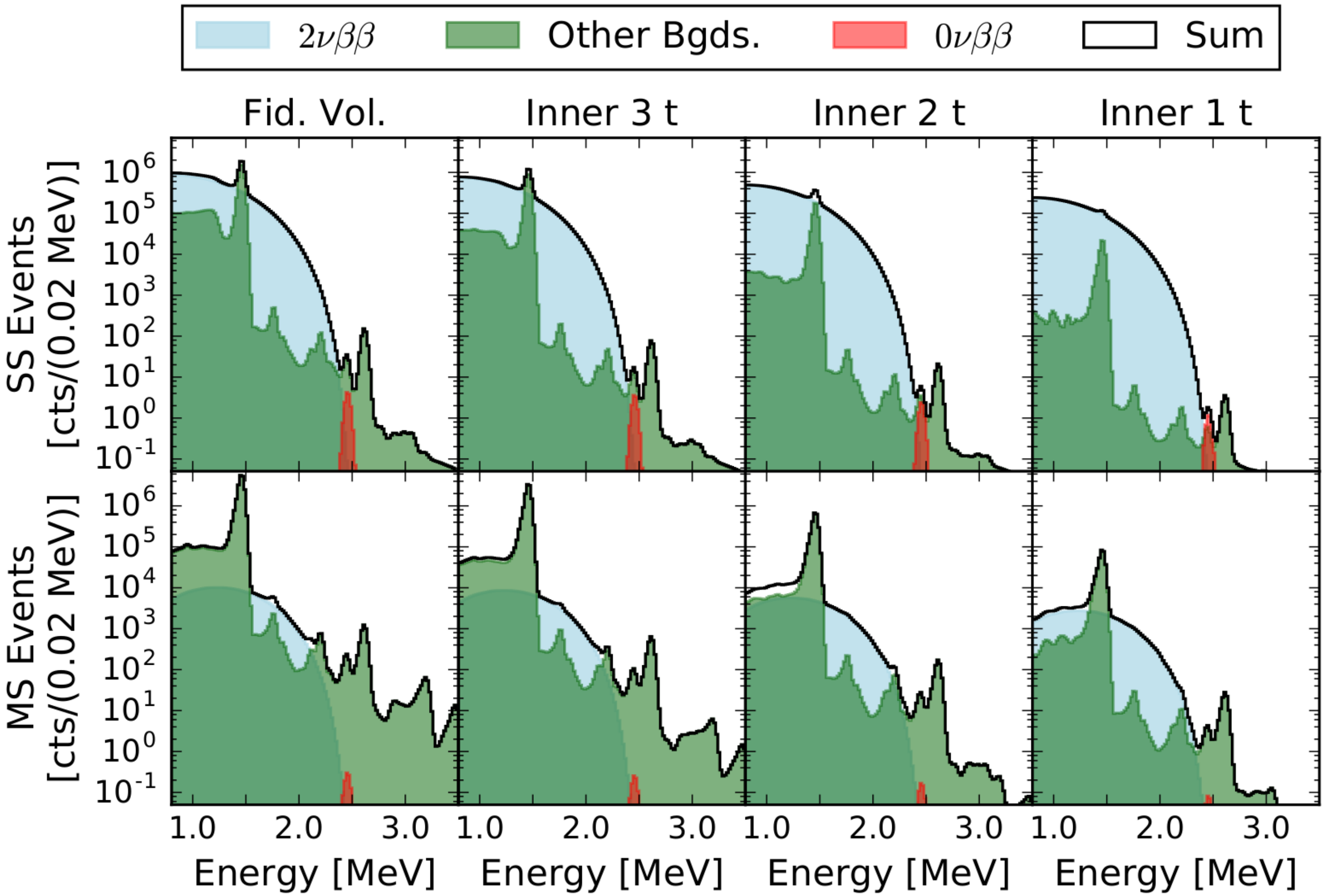


Preliminary artist view of nEXO in the SNOlab Cryopit



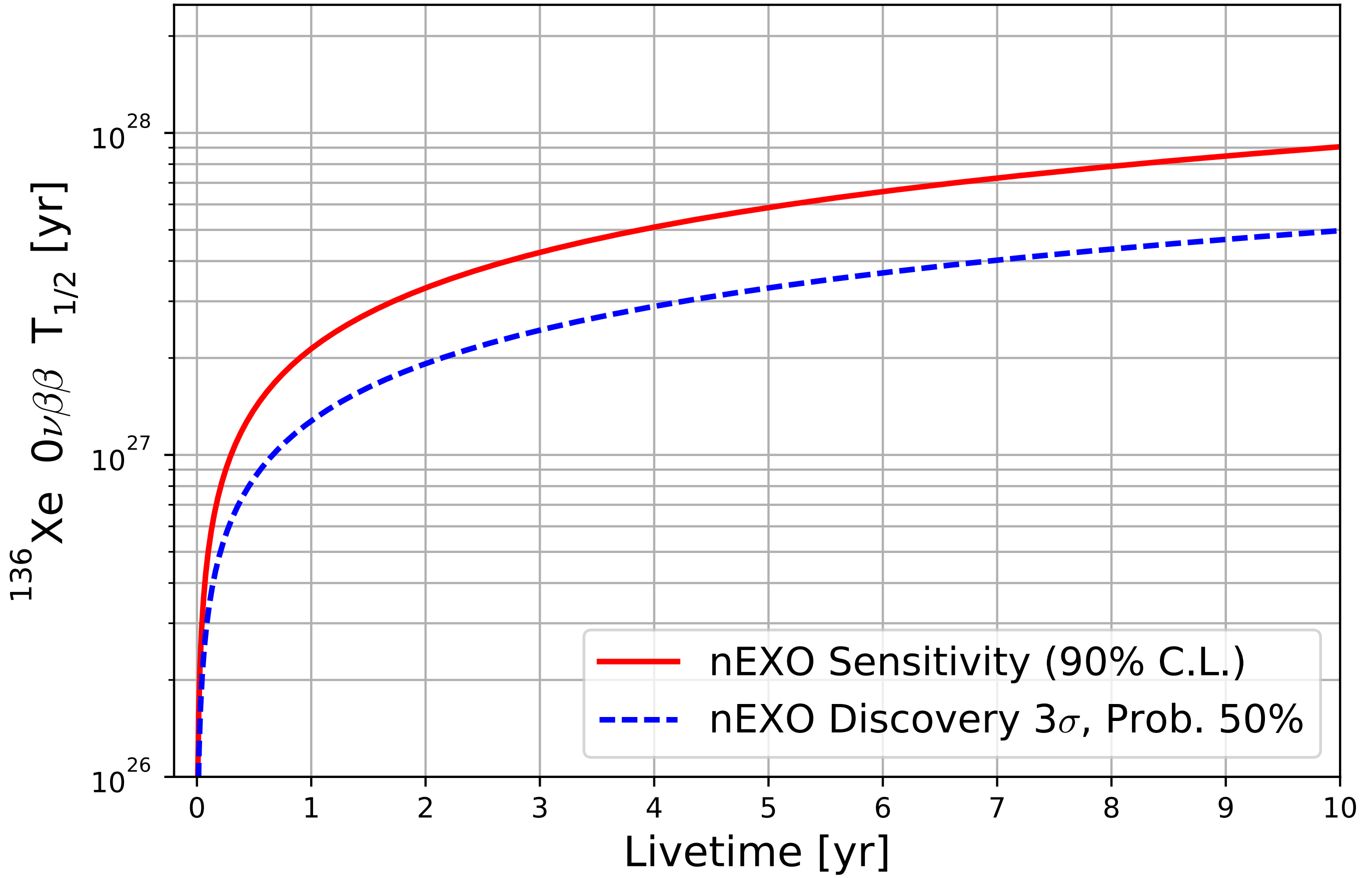
EXO-200 TPC

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

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.