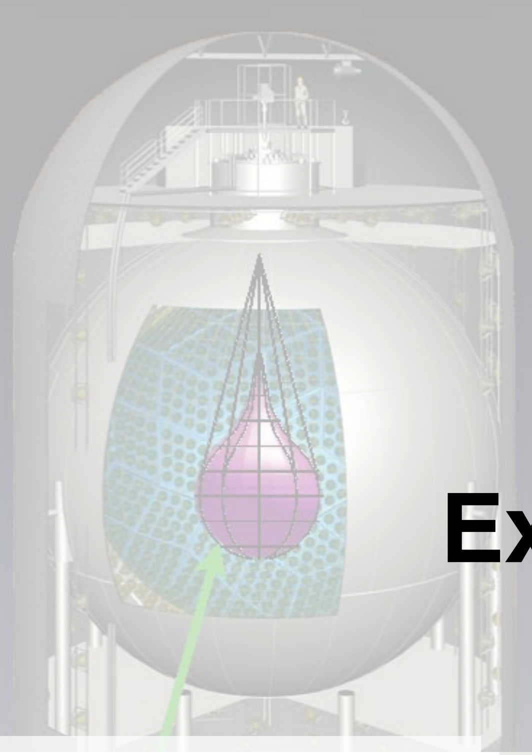
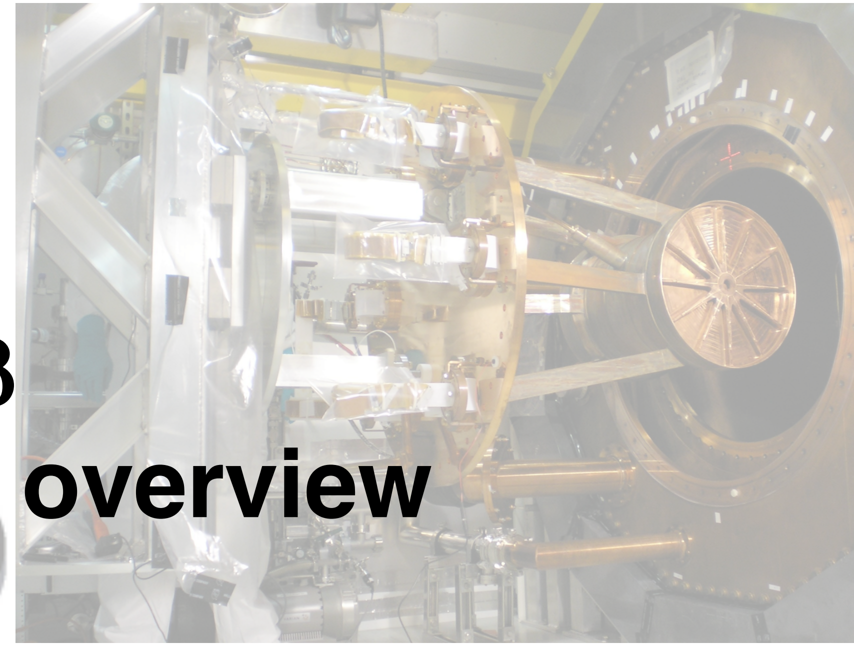
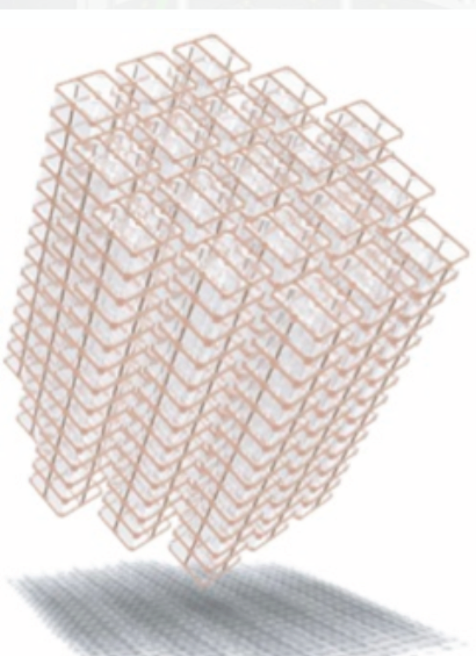




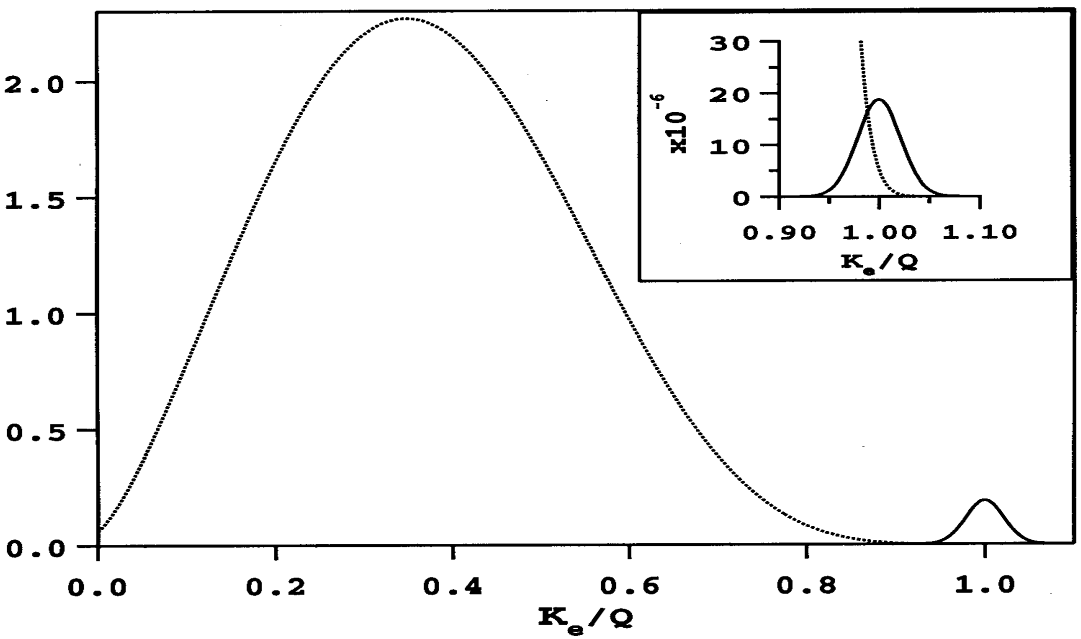
$0\nu\beta\beta$
Experimental overview



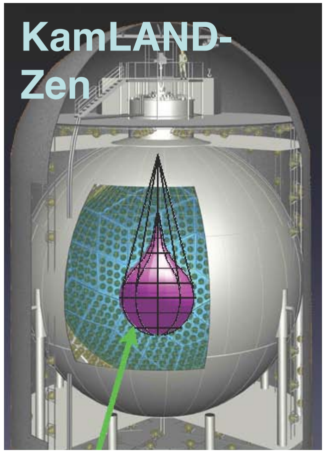
Michelle Dolinski
Drexel University

ECT* workshop
7/15/2019

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



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



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-III (^{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

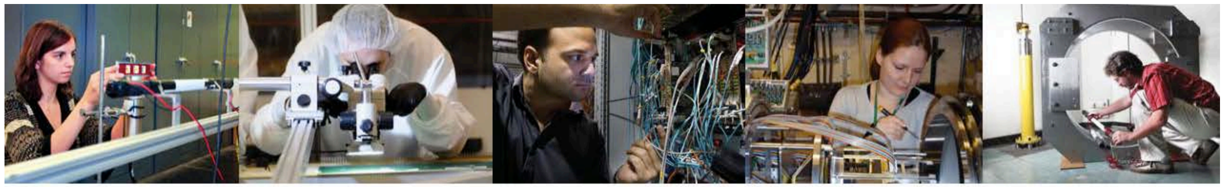
Current best $0\nu\beta\beta$ sensitivities

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 US nuclear physics



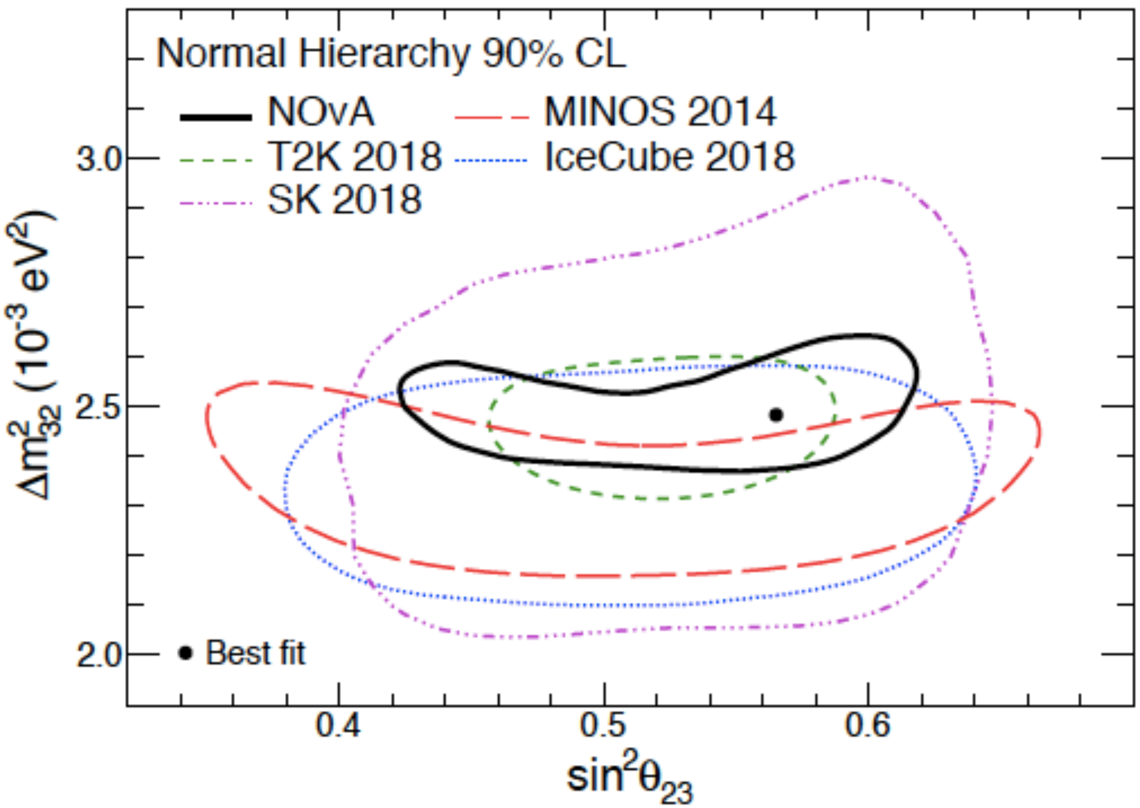
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

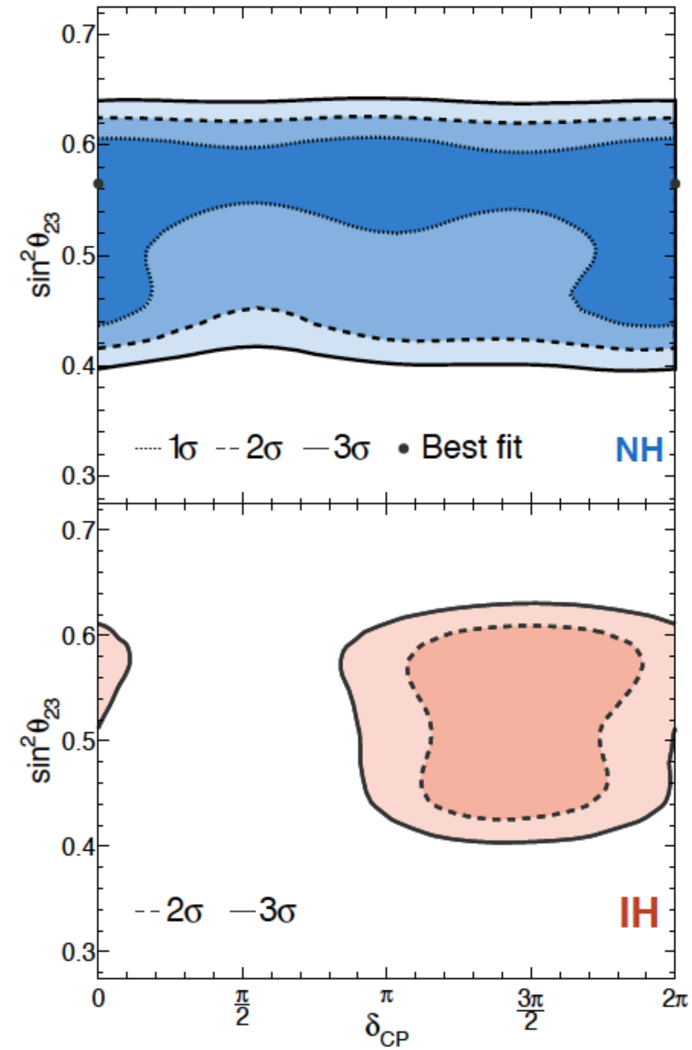
RECOMMENDATION II:
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications 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."

NOνA recent results

arXiv:1906.04907v2 (14 June 2019)

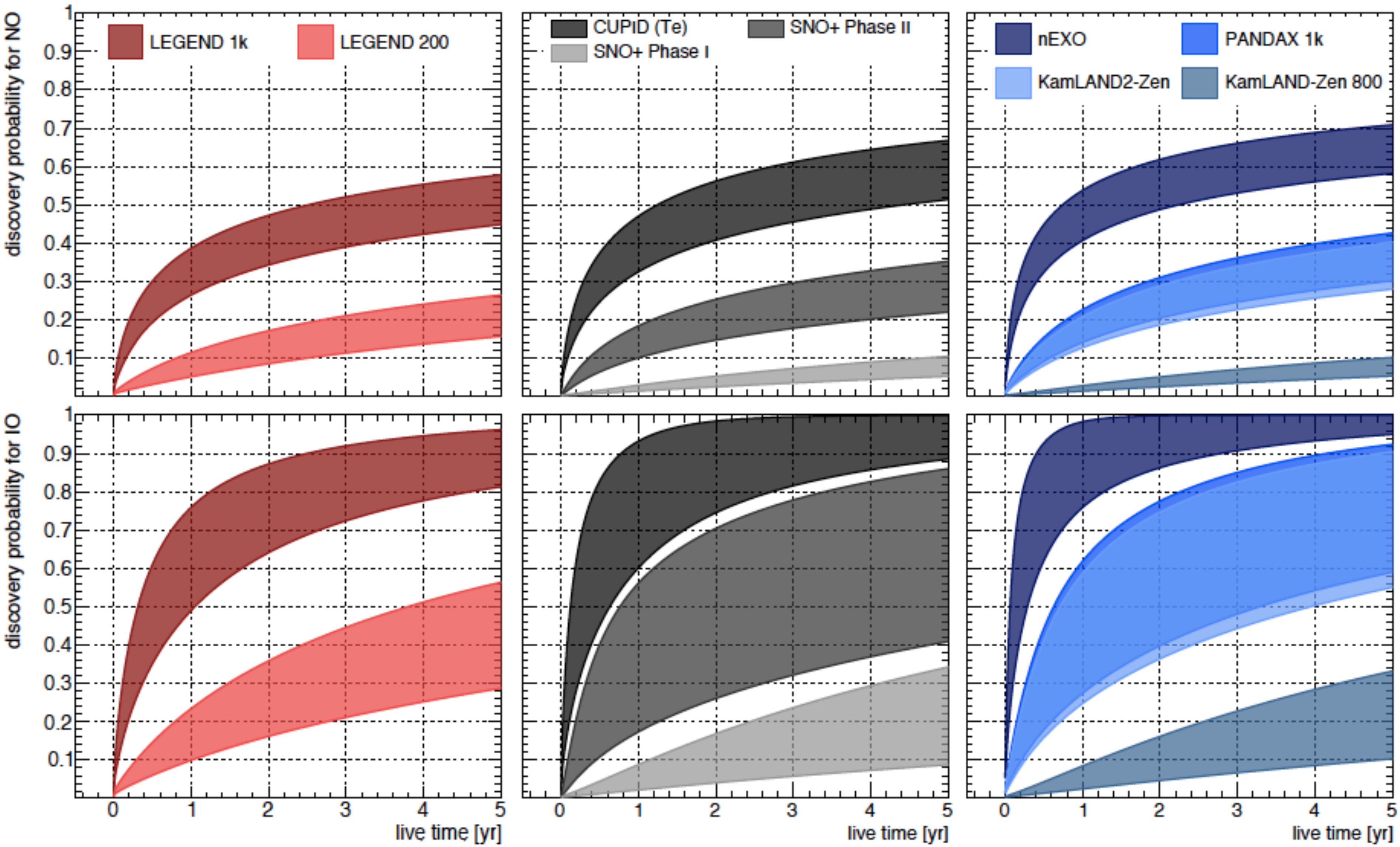




$$|\Delta m^2_{32}| = 2.48^{+0.11}_{-0.06} \times 10^{-3}\ \mathrm{eV}^2/c^4,\ \sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

The data favor the normal neutrino mass hierarchy by 1.9σ

Discovery potential

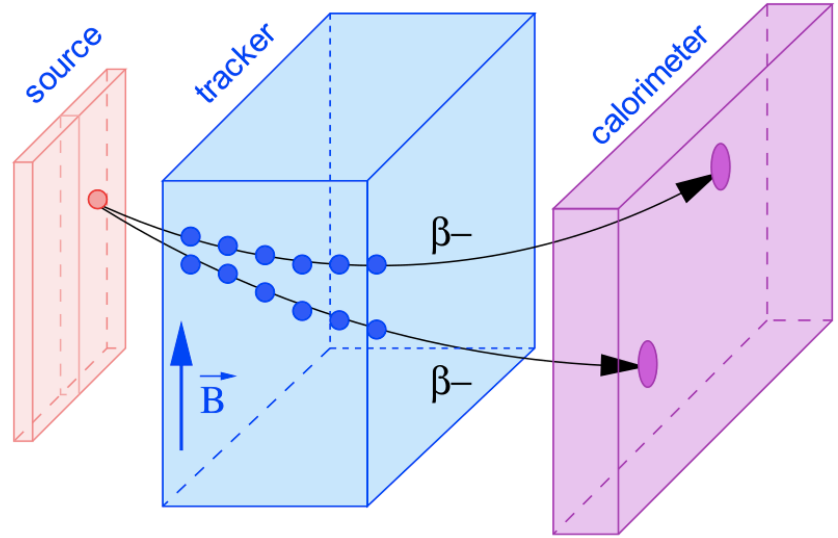


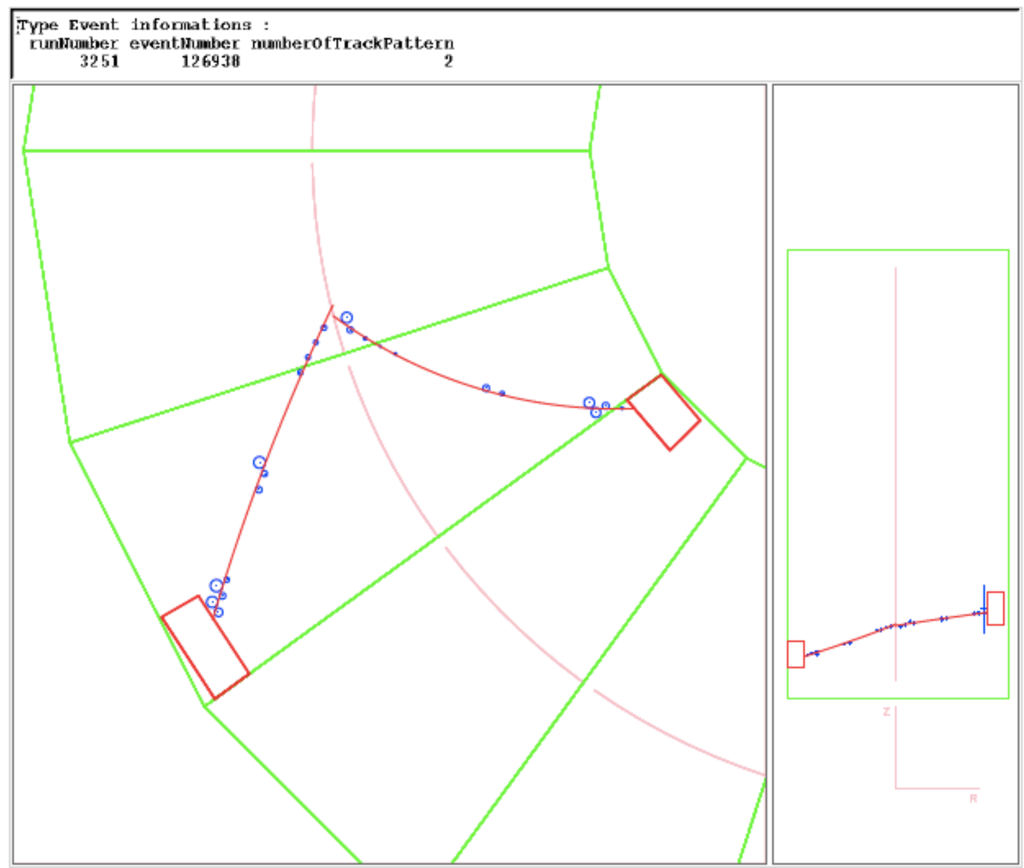
Agostini, Benato, Detwiler, *PRD* 96 (2017) 053001

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

NEMO-3

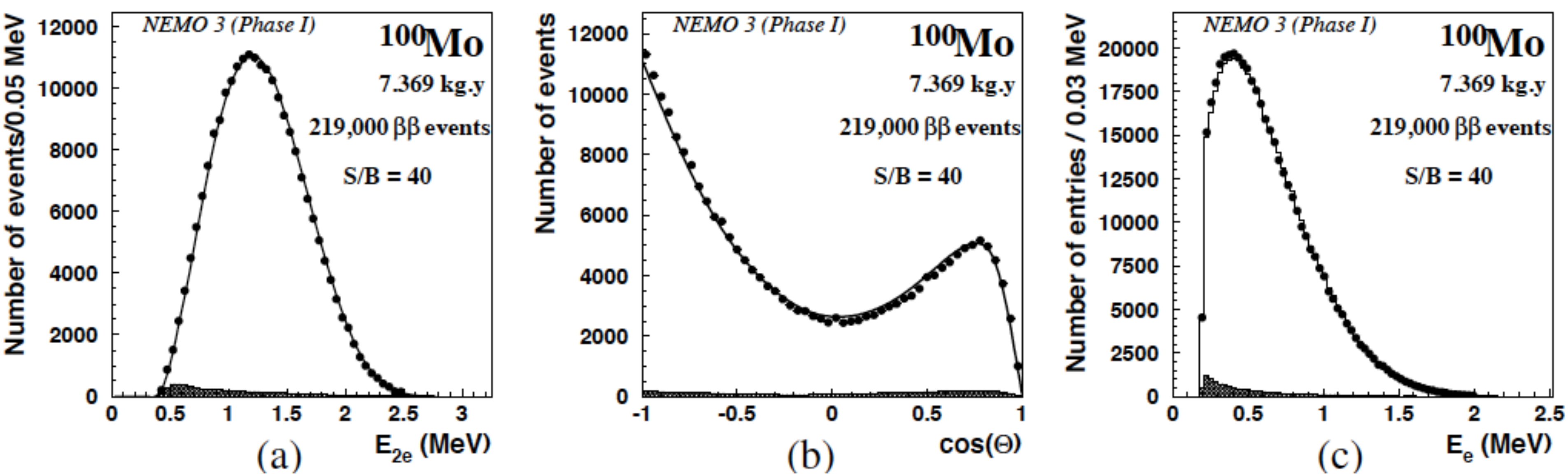
NEMO-3 uses source foils in a gas tracking detector with a calorimetric detector plane.





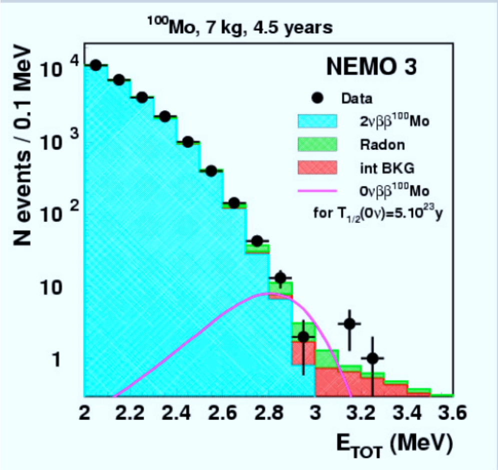
Measured $2\nu\beta\beta$ half-lives

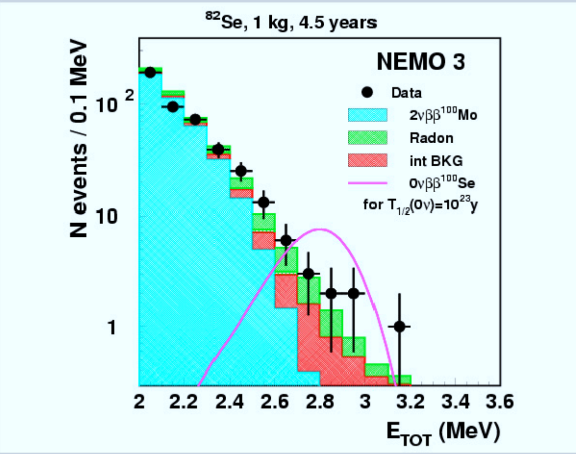
Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (2014)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	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)



NEMO-3 to SuperNEMO

supernemo collaboration





[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

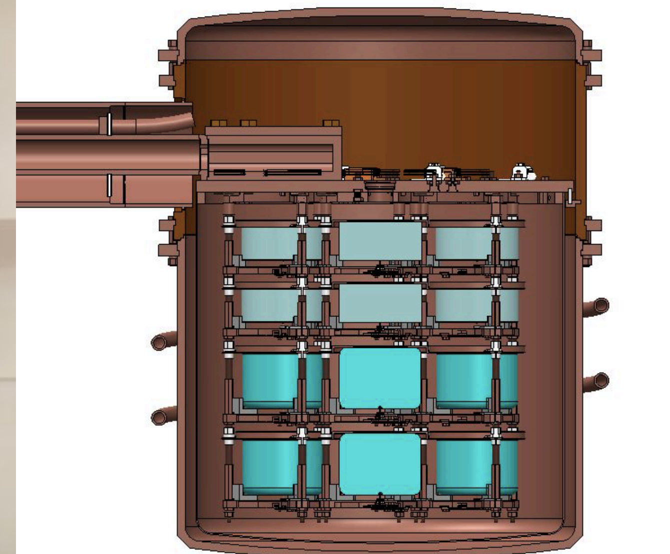
$\langle m_\nu \rangle < (0.94 - 2.5)$ eV

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

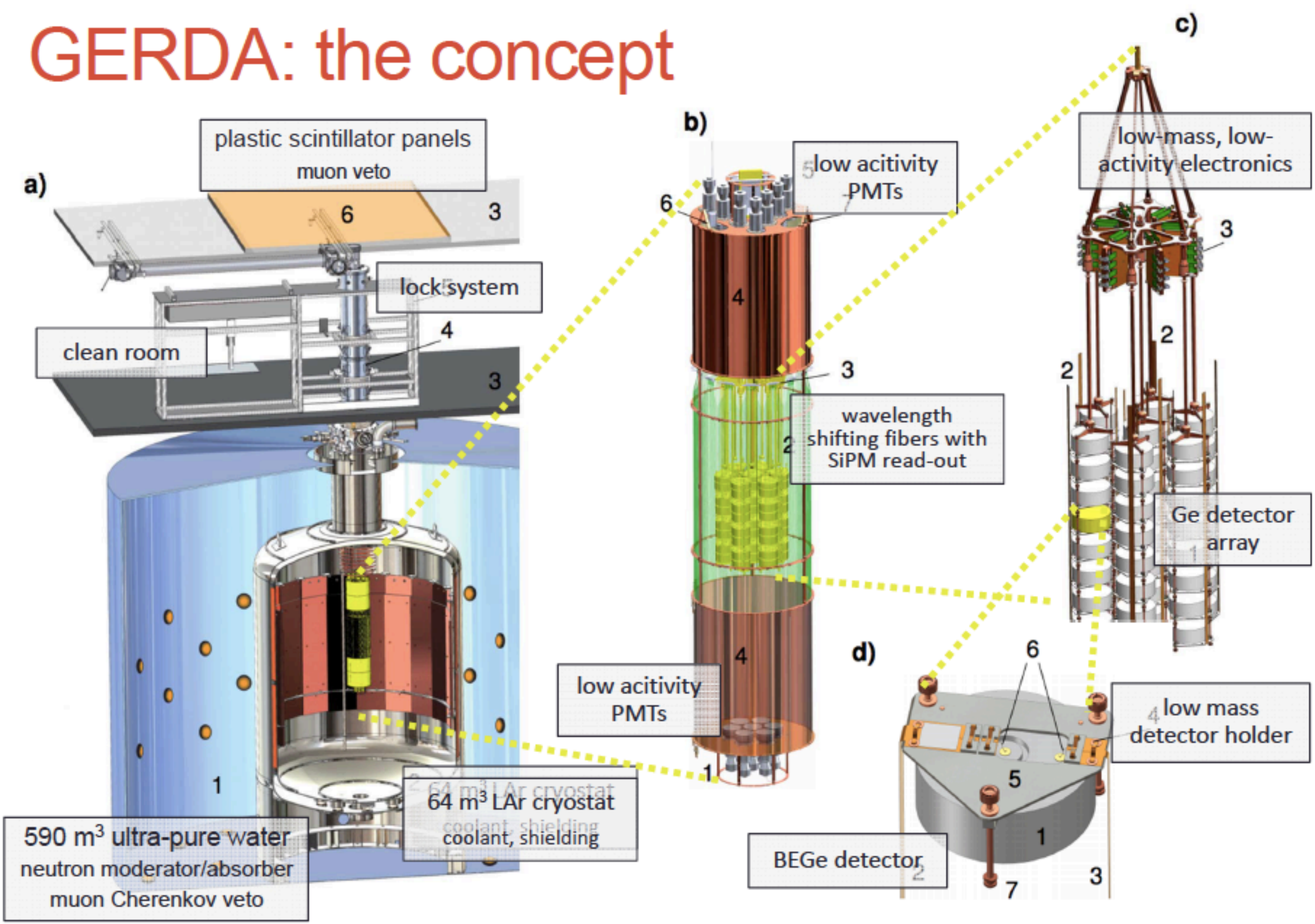
- 2034 drift cells working in Geiger mode
- Ultrapure materials : copper, steel, duracon. HPGe and radon tested.
- Robotic construction
- Radiopure gas flow, anti-radon sealing
- < 1 % of dead channels

Current ^{76}Ge diode experiments

Majorana
Demonstrator



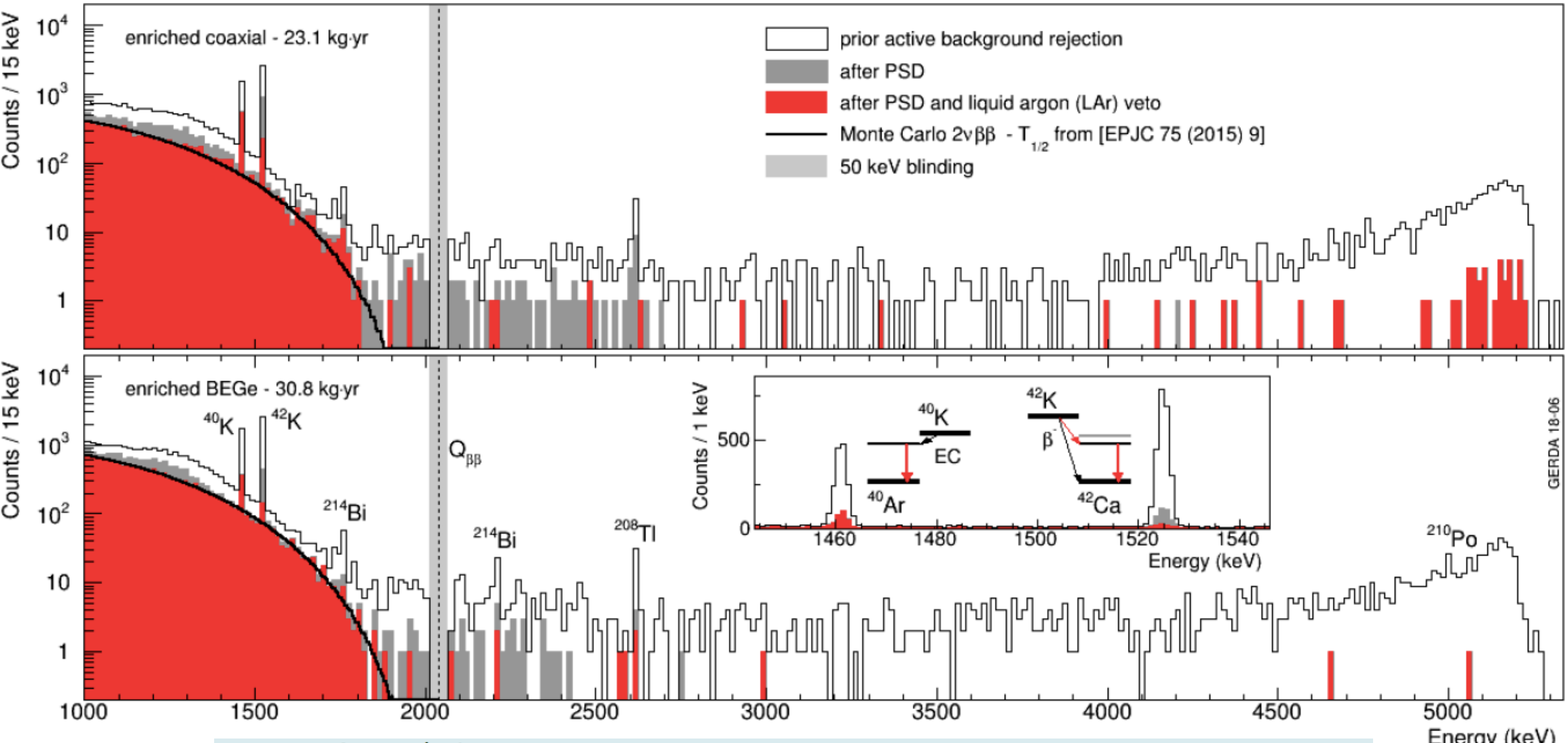
GERDA: the concept



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.

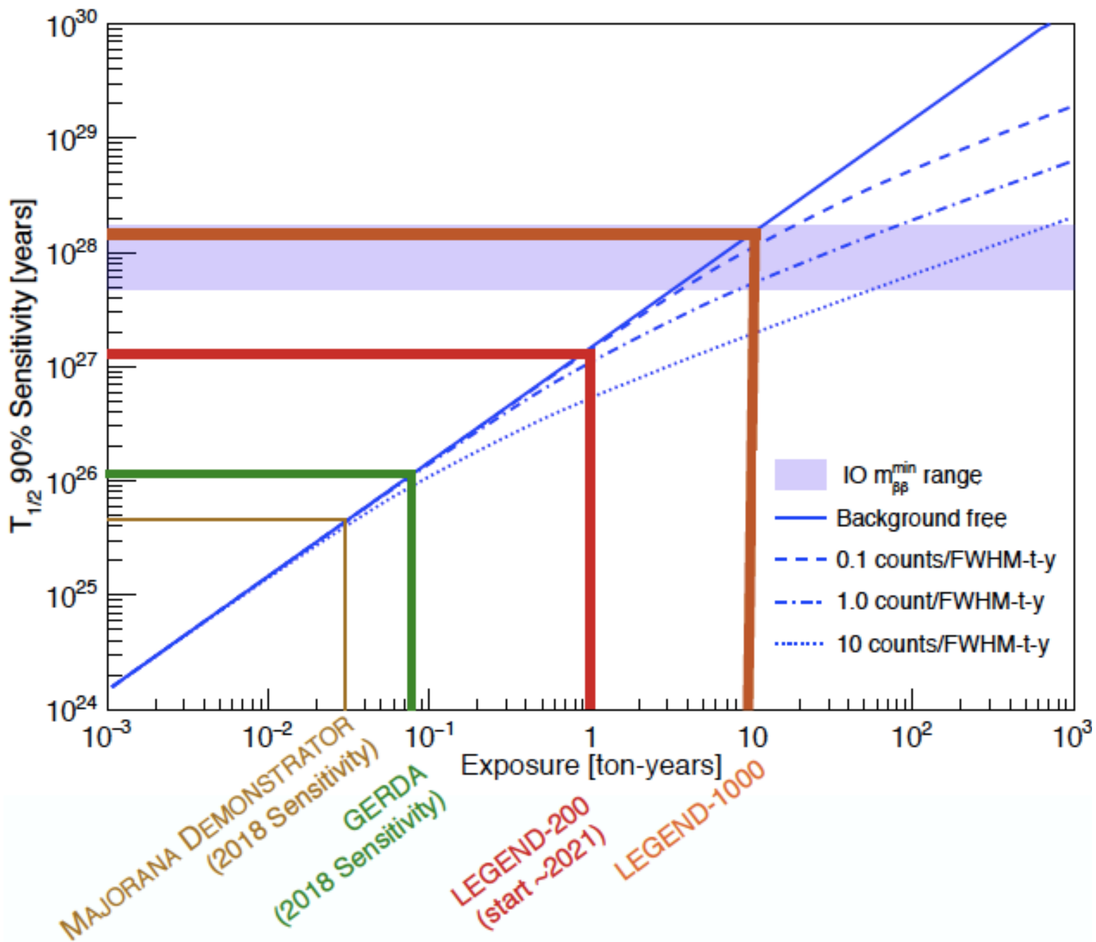
Bayesian analysis:

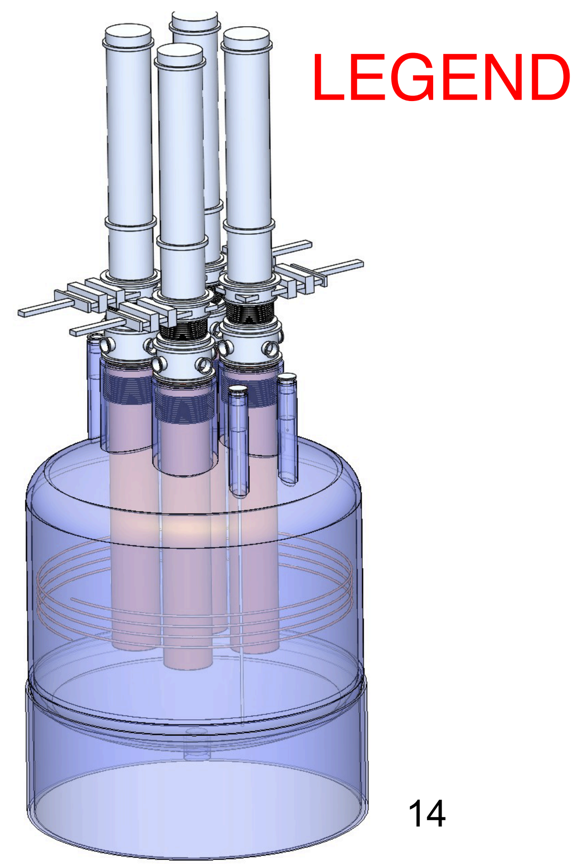
- Best fit → no signal. Bayes factor = 0.054
- $T_{1/2}$ > 0.8·10^{26} yr (median sensitivity for limit 0.8 ·10^{26} yr) @ 90% C.I.

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

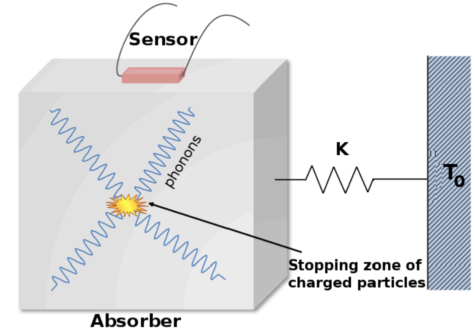
Next generation ton-scale ^{76}Ge $0\nu\beta\beta$

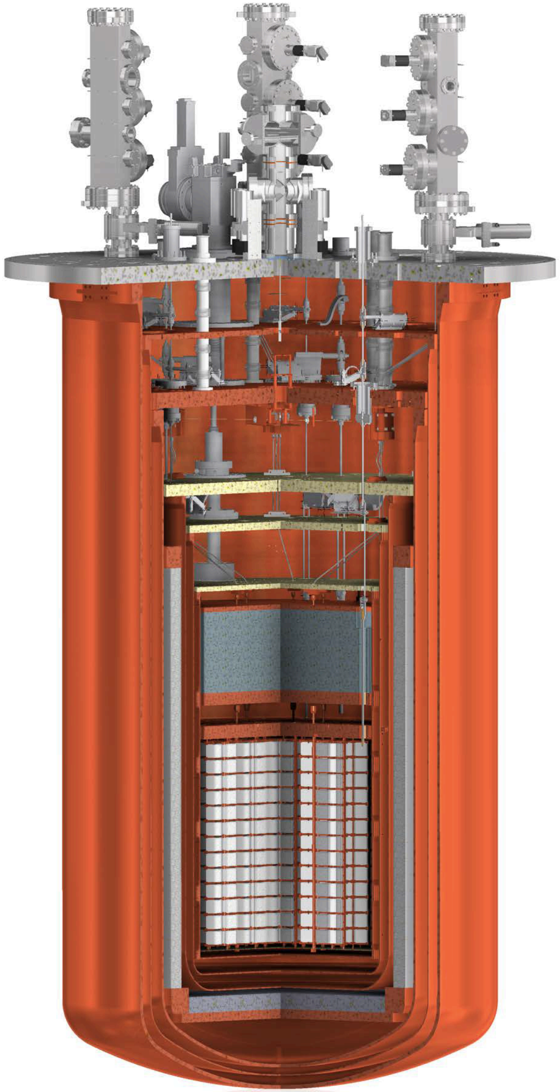
- Build on the experience of GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Design sensitivity of ~1x10^{28} y with a background of 0.1 cnt/tonne-yr in the region of interest (background reduction of ~6-20 relative to existing)

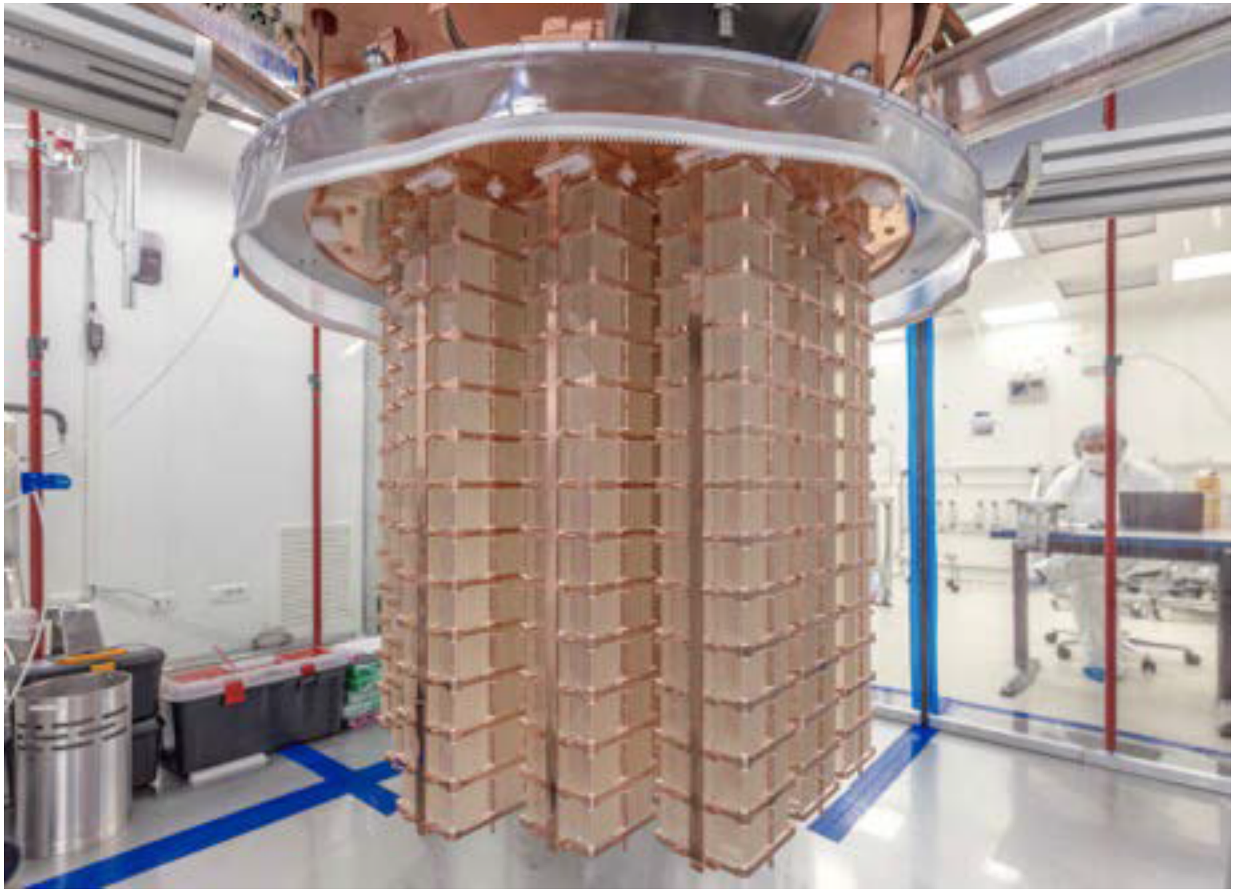




CUORE

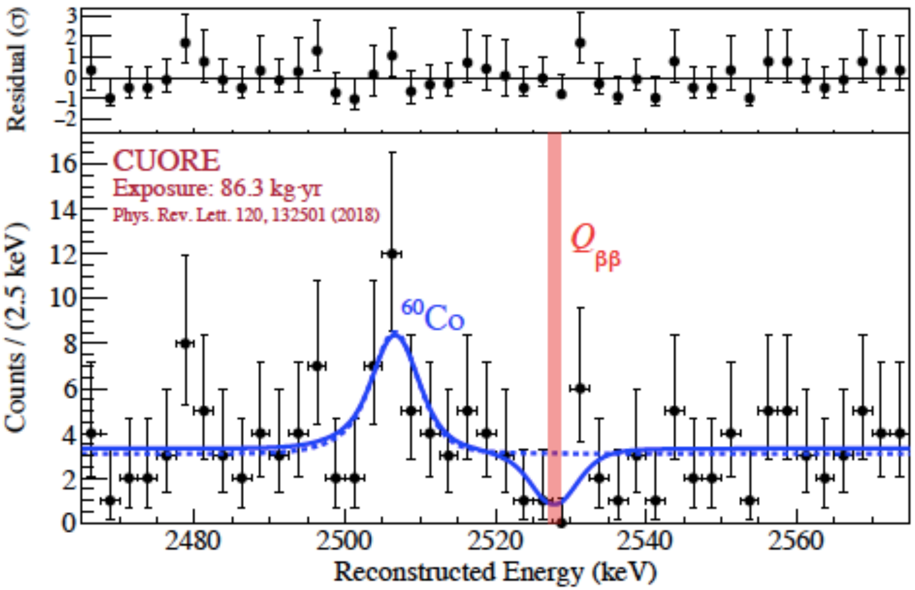


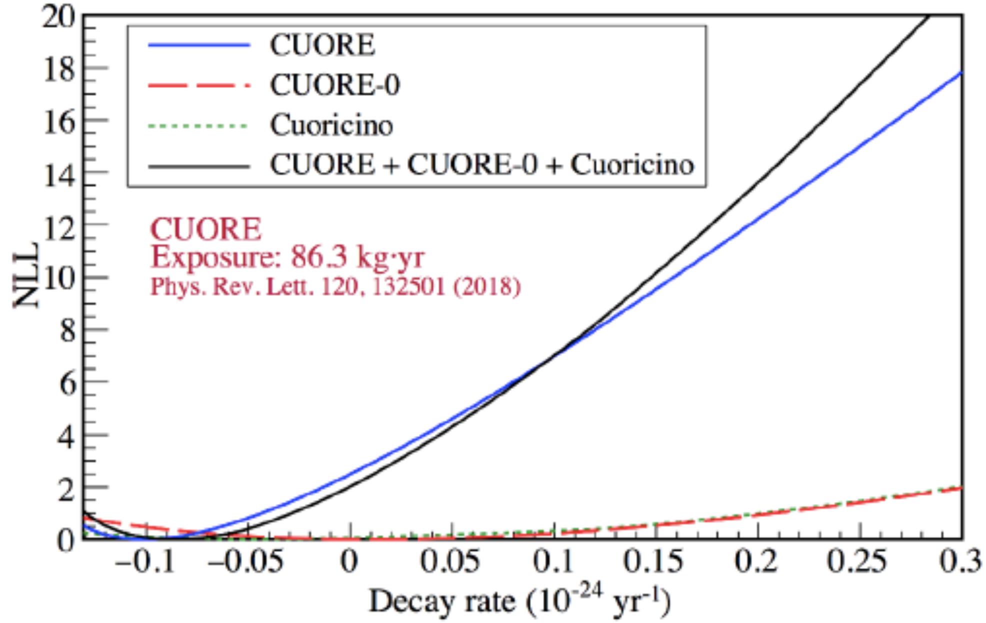




$^{nat}TeO_2$ bolometers operated in a low background dilution refrigerator at LNGS
~200 kg ^{130}Te

CUORE results





Limits combining CUORE with CUORE-0 and Cuoricino:

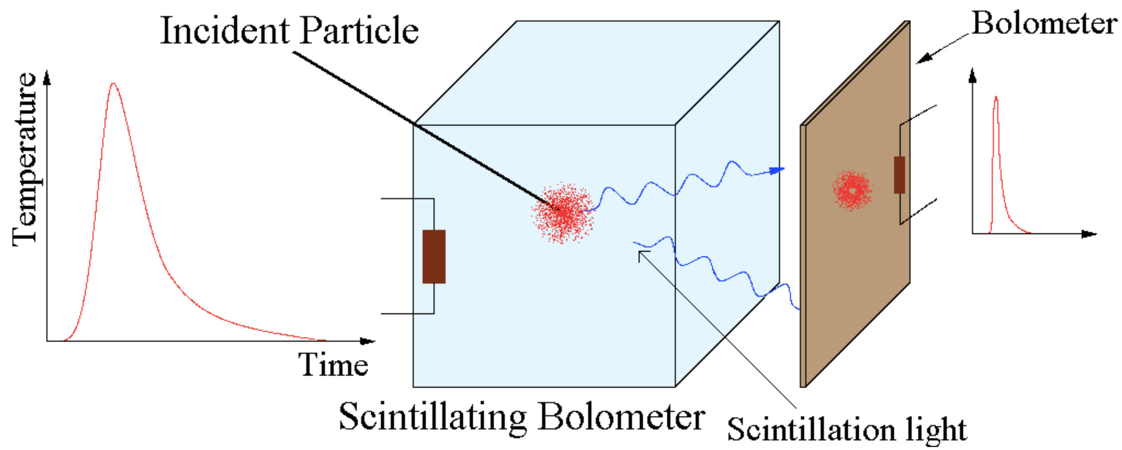
Alduino et al. *PRL* 120, 132501 (2018)

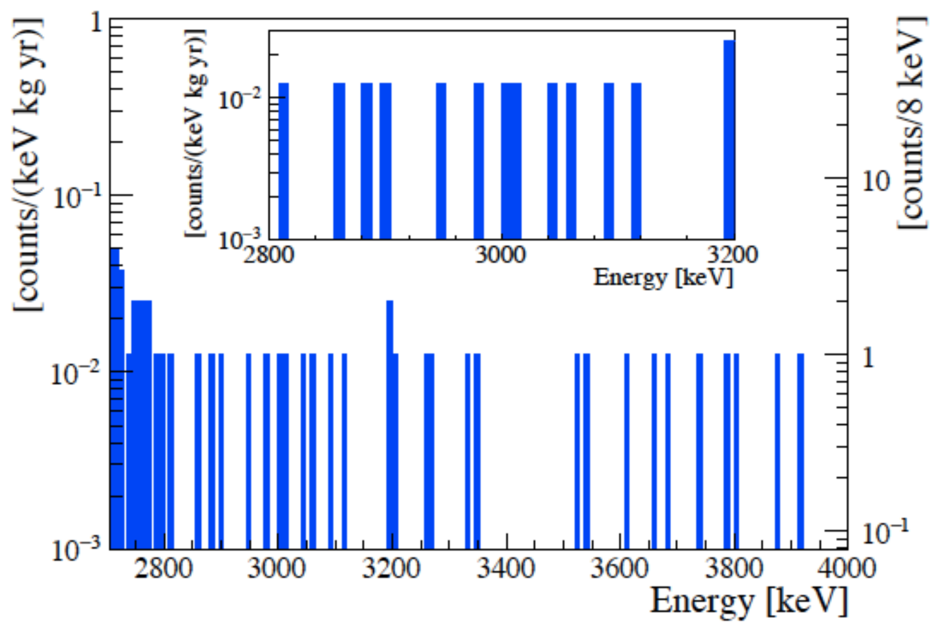
- Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$): 1.5×10^{25} yr
- Profile likelihood ("frequentist") limit @ 90% CL: 2.2×10^{25} yr

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

Back to data taking since May 2018!

Beyond CUORE: CUPID





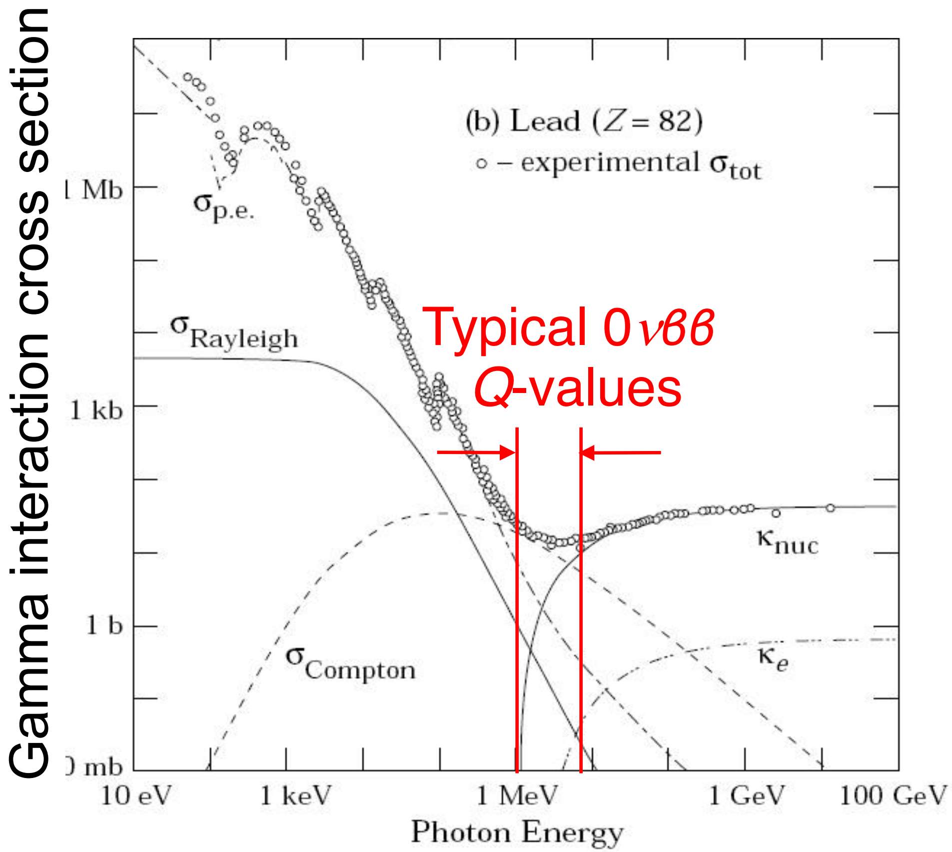
$$(3.5^{+1.0}_{-0.9}) \times 10^{-3} \text{ counts/(keV kg yr)}$$

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!

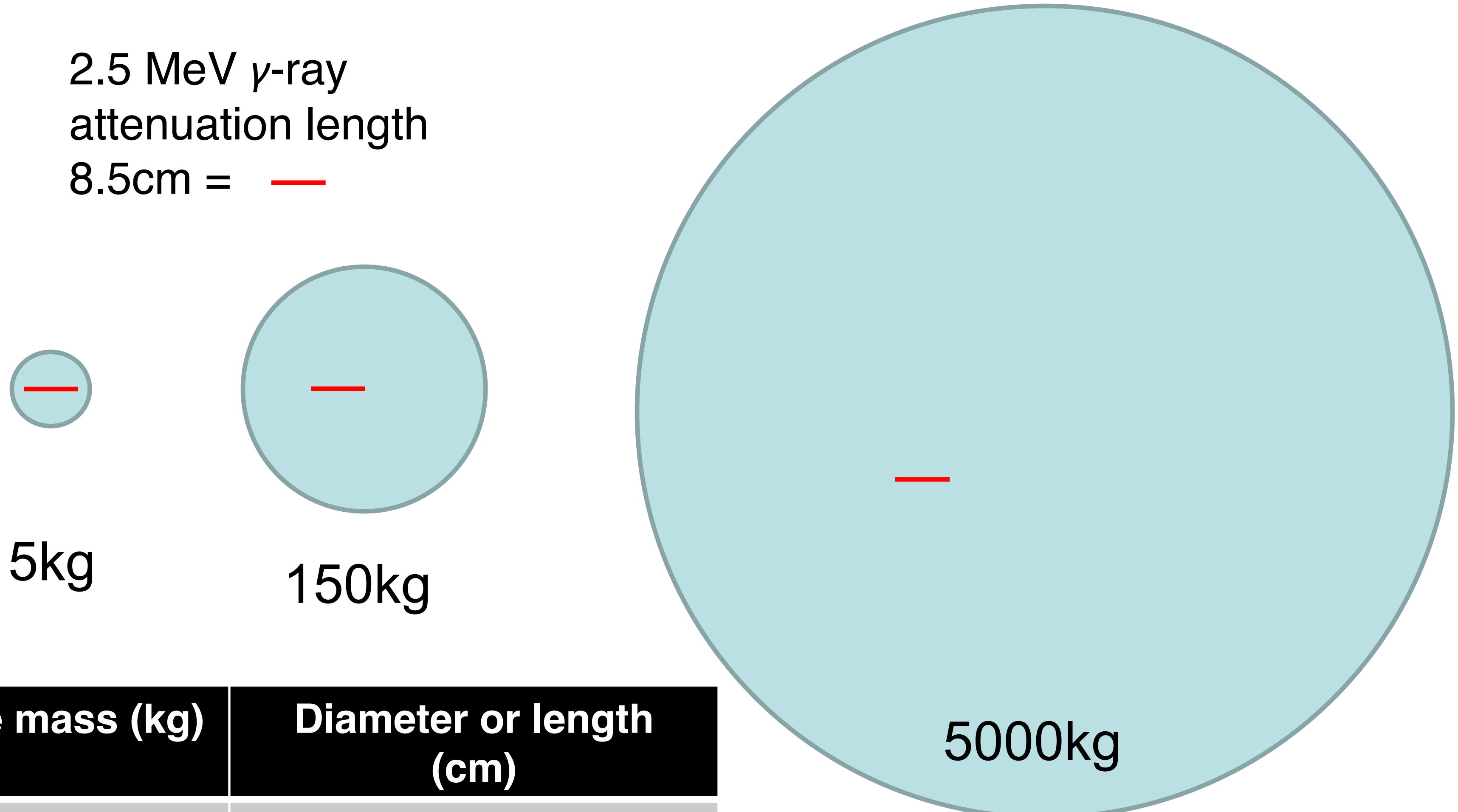
Example:
γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

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 =

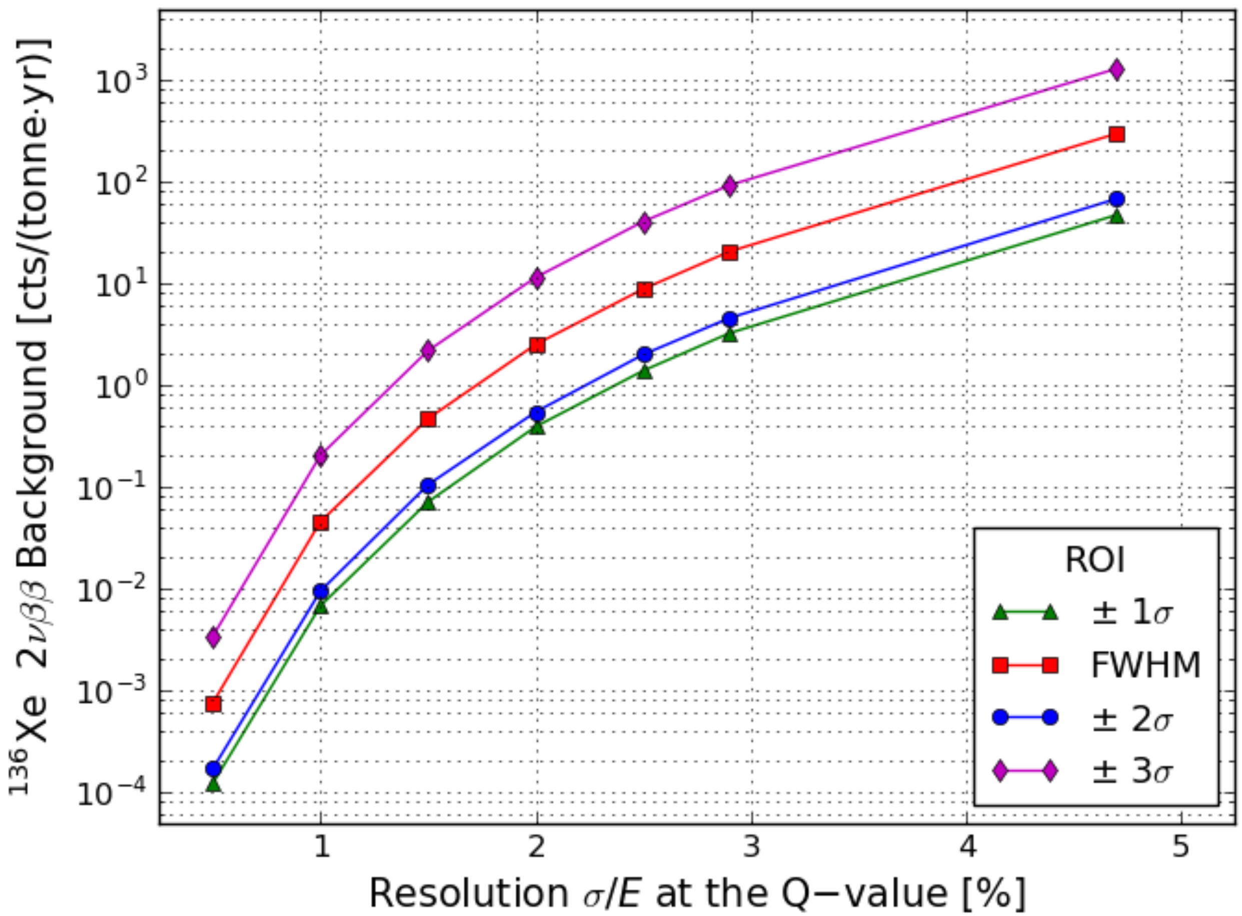


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

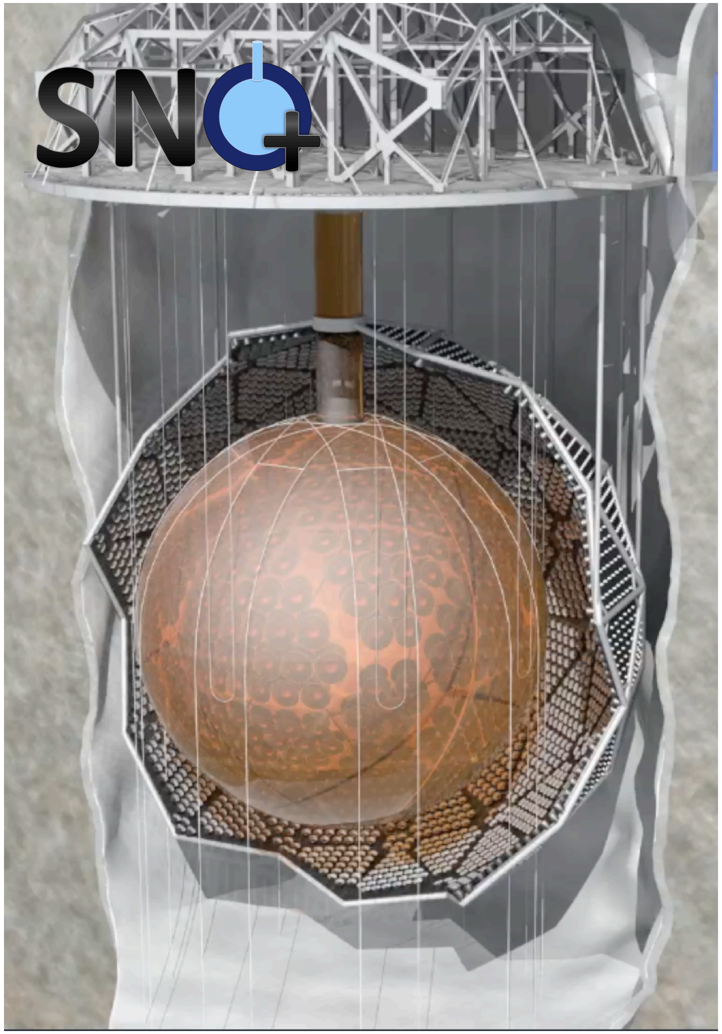
Background suppression

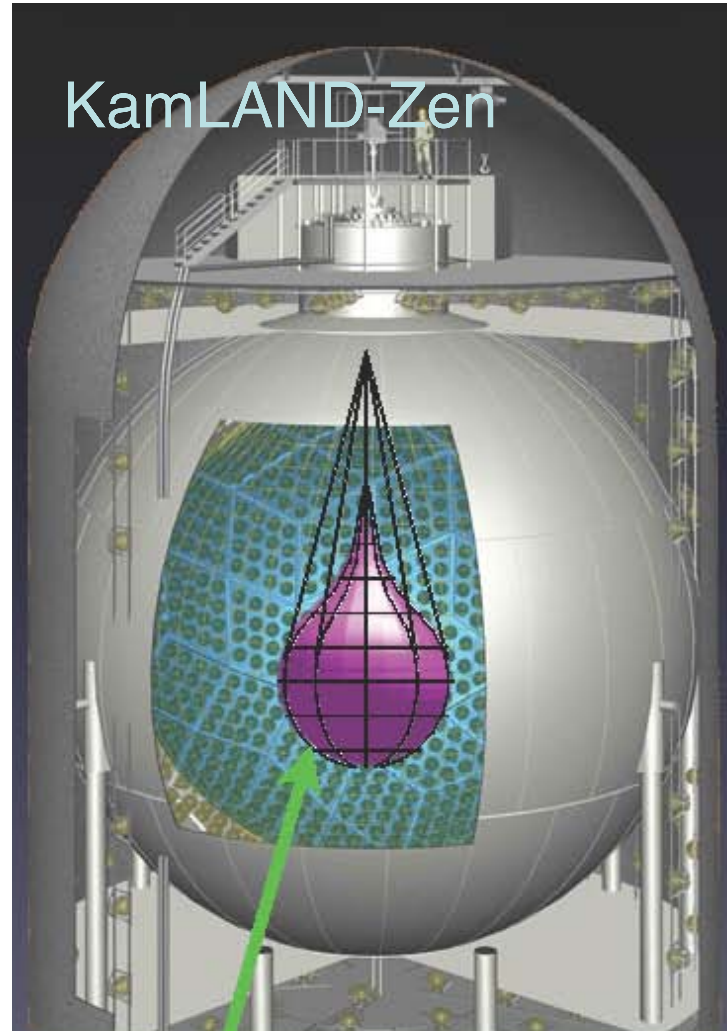
All observables have a role in separating signal from background.

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

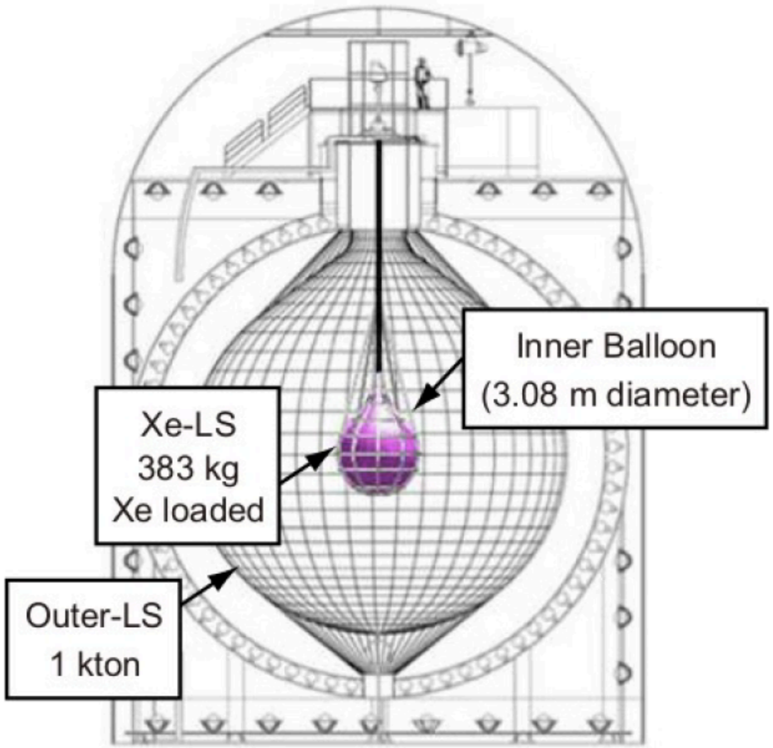


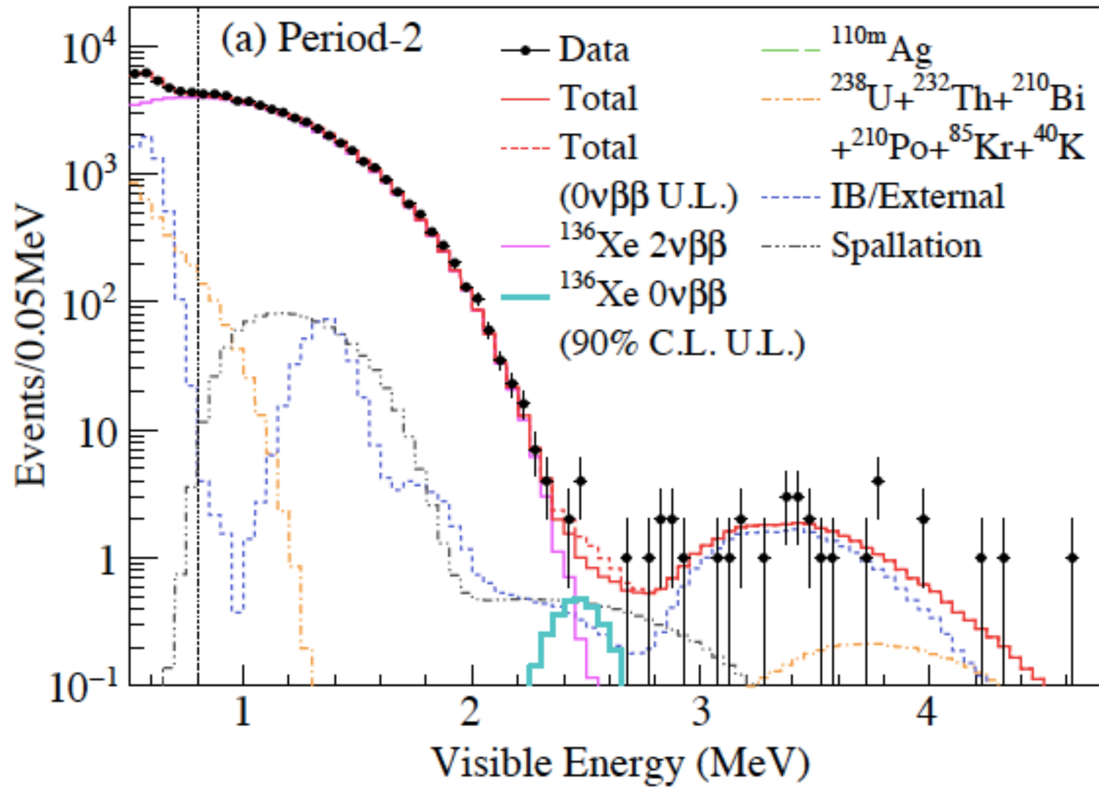


3.9 t ^{nat}Te dissolved in liquid scintillator in the upgraded SNO detector

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

KamLAND-Zen





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

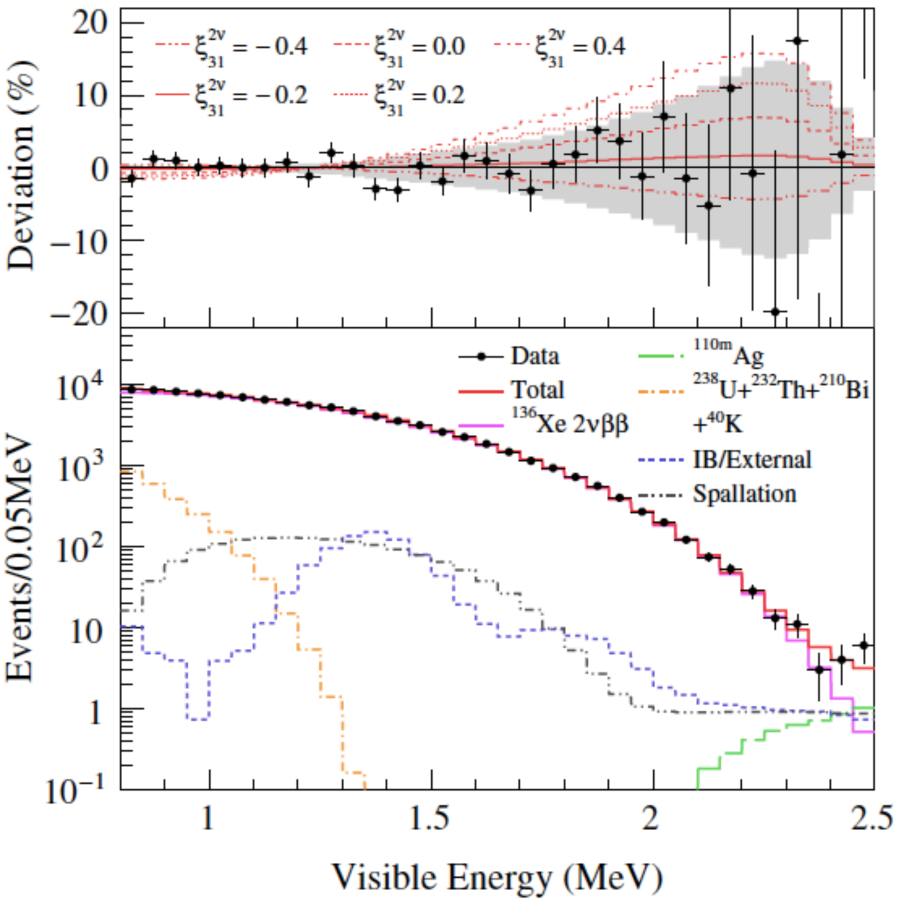
$$T_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26}\ \mathrm{yr}$$

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

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

$2\nu\beta\beta$ precision measurement

Gando et al. *PRL* **122**, 192501 (2019)

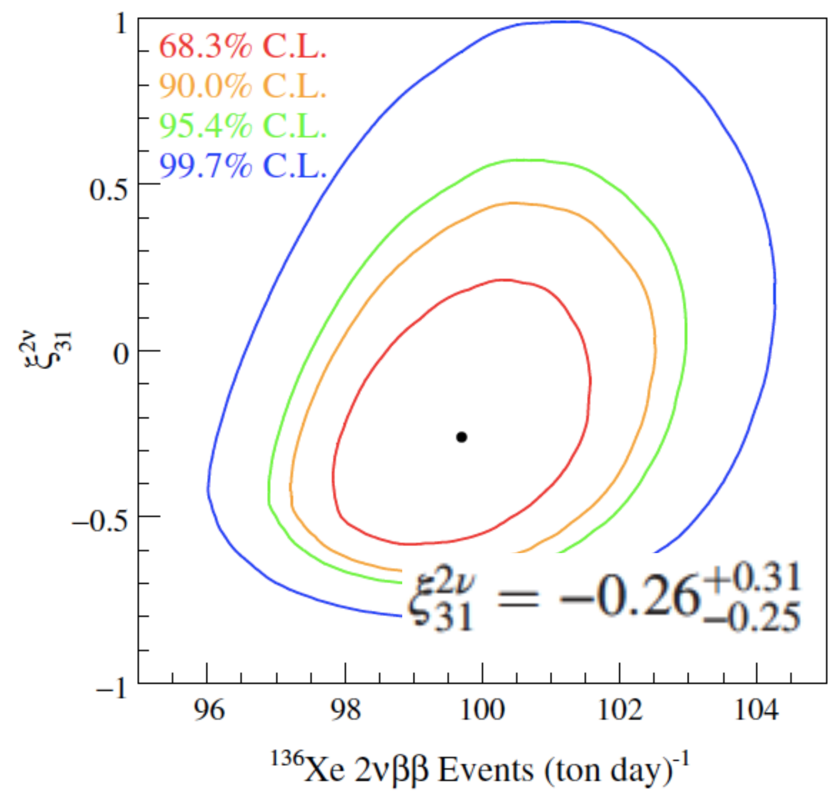


90% C.L. upper limit of $\xi^{2\nu}_{31} < 0.26$

$$(T^{2\nu}_{1/2})^{-1} \simeq (g_A^{\text{eff}})^4 |(M^{2\nu}_{GT})^2 G^{2\nu}_0 + M^{2\nu}_{GT} M^{2\nu}_{GT-3} G^{2\nu}_2|$$

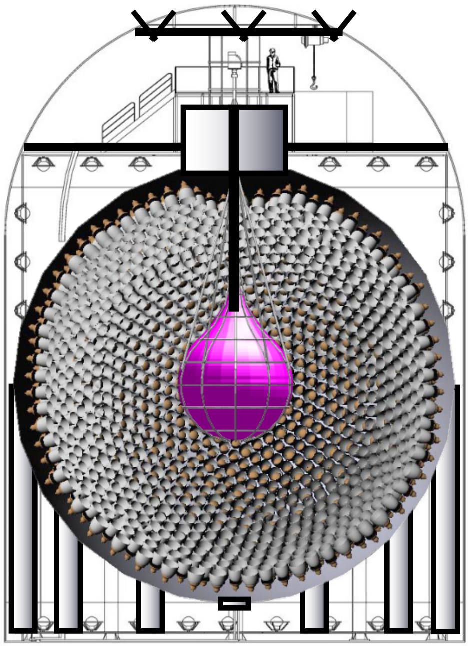
$$= (g_A^{\text{eff}})^4 |M^{2\nu}_{GT-3}|^2 \frac{1}{|\xi^{2\nu}_{31}|^2} |G^{2\nu}_0 + \xi^{2\nu}_{31} G^{2\nu}_2|$$

F. Šimkovic, R. Dvornický, D. Štefánik, and A. Faessler, Phys. Rev. C **97**, 034315 (2018).



Beyond KamLAND-Zen 800

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



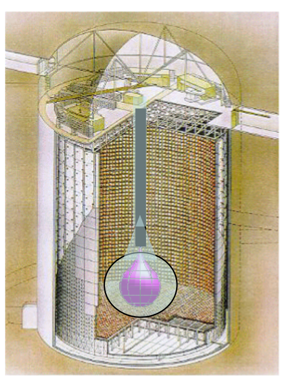
1000+ kg xenon

	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?



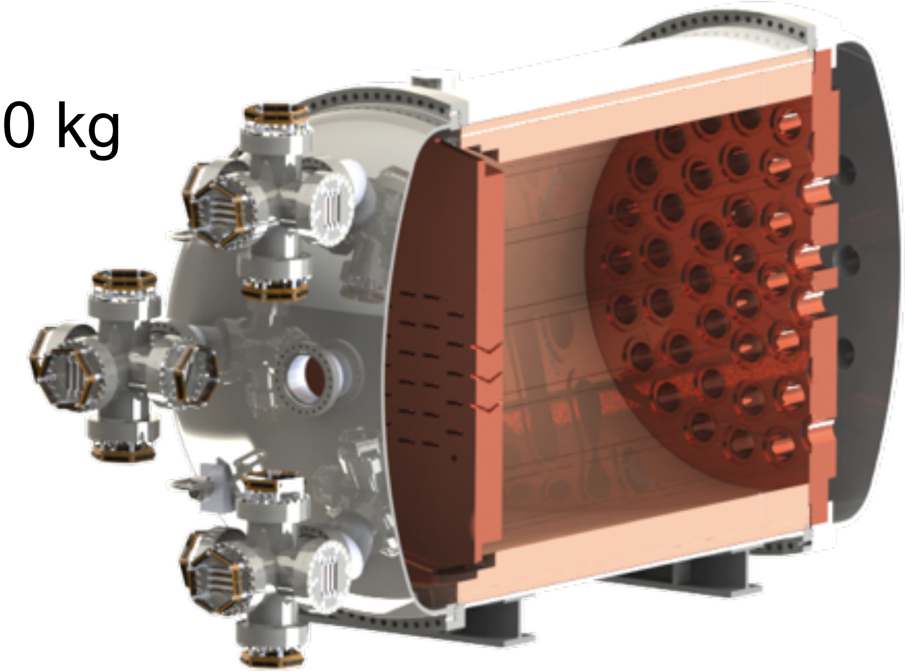
Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

But eventually 2ν background becomes dominant

NEXT-100

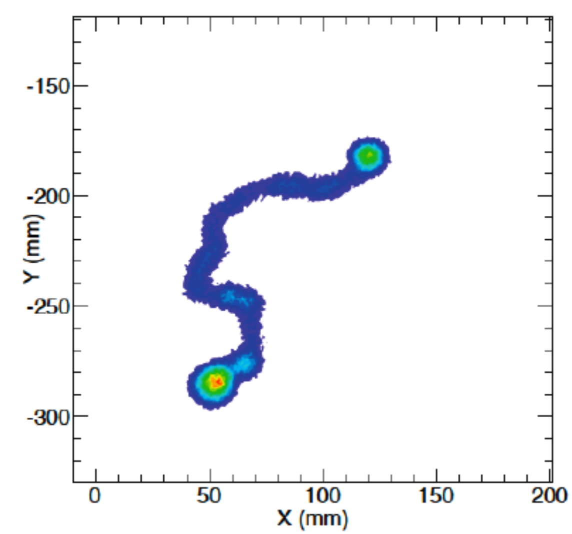
•15 bar high pressure gas Xe time projection chamber (TPC) with ~100 kg fiducial mass. SiPMs (MPPCs) for tracking and PMTs for energy.



•Proportional electroluminescent amplification for large photon yield.

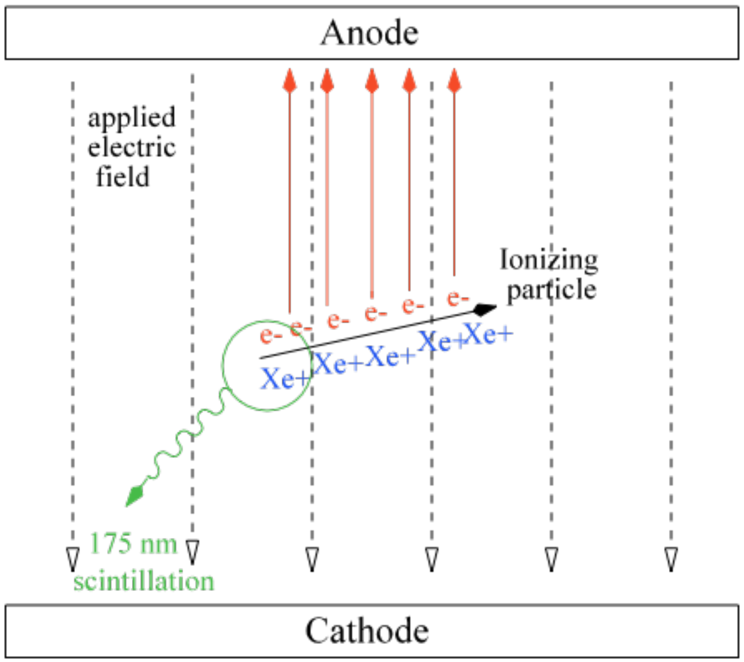
•Tracking and event topology reconstruction.

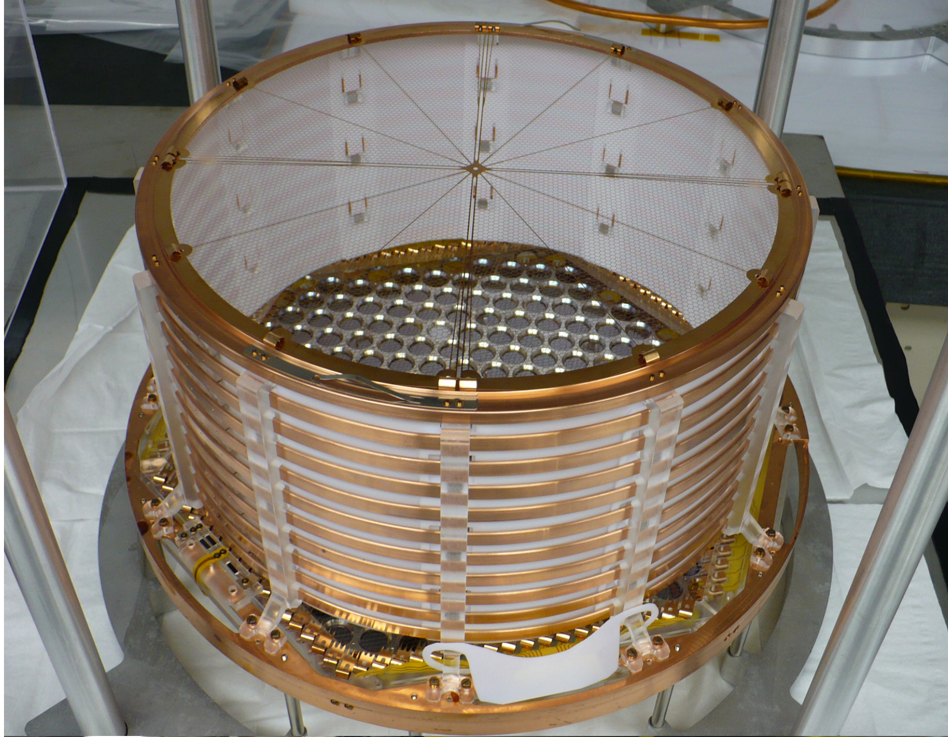
•Good energy resolution. Demonstrated <0.9% energy resolution achievable at $0\nu\beta\beta$ Q-value.

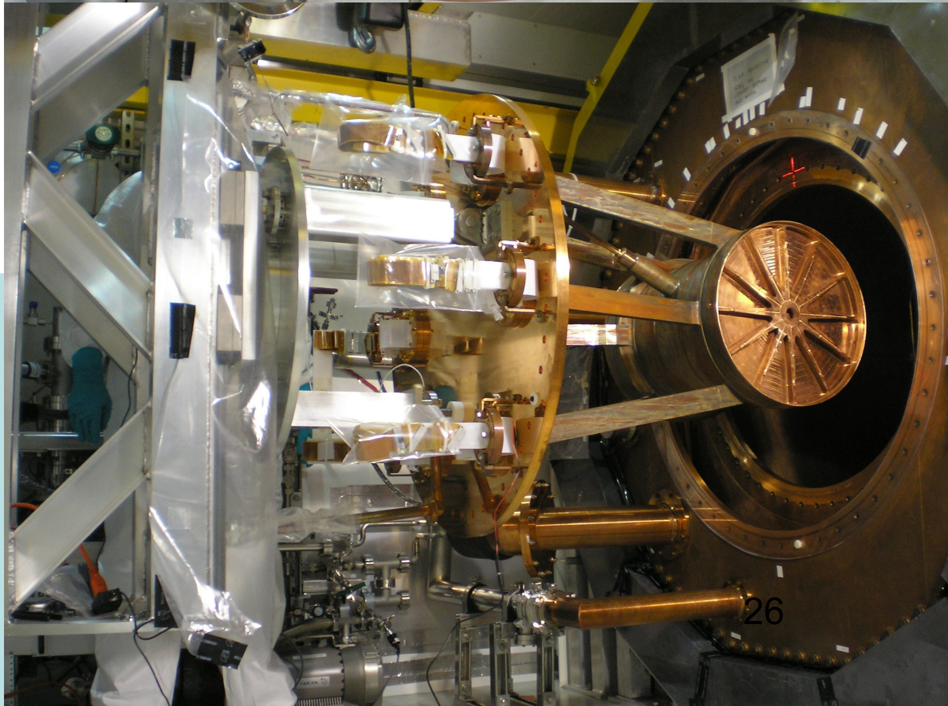


•Will be sited at the Canfranc laboratory (LSC). Projected 3 year sensitivity of $5\text{x}10^{25}$ y. Commissioning in ~2020.

EXO-200 Liquid Xe TPC



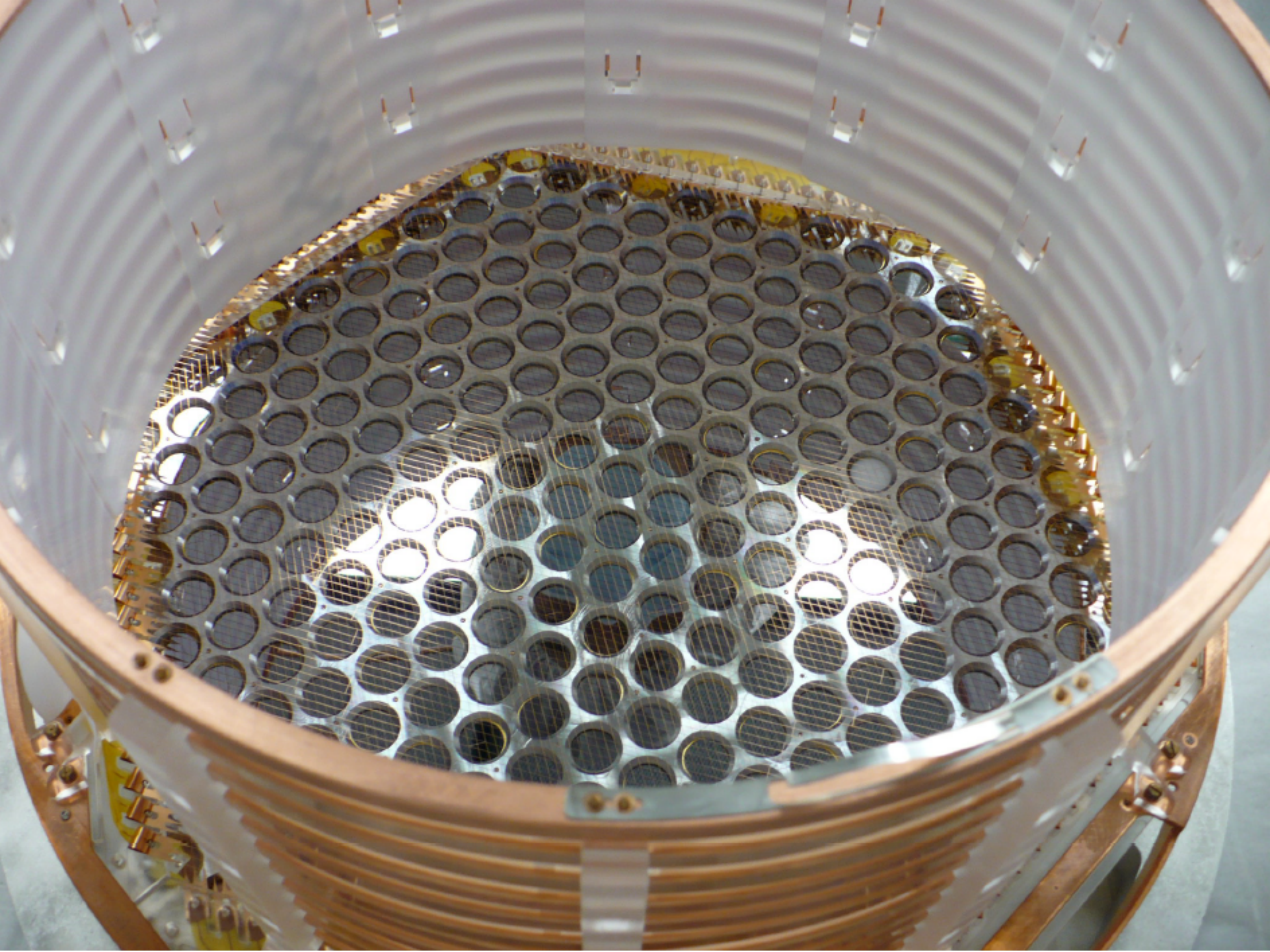




~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe, ultralow background construction.

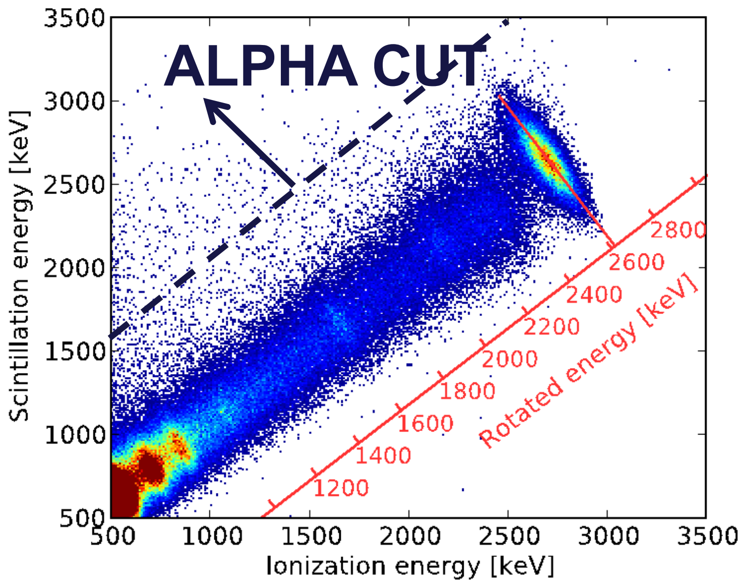
Readout plane is made up of LAAPDs + crossed wire grid.

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).

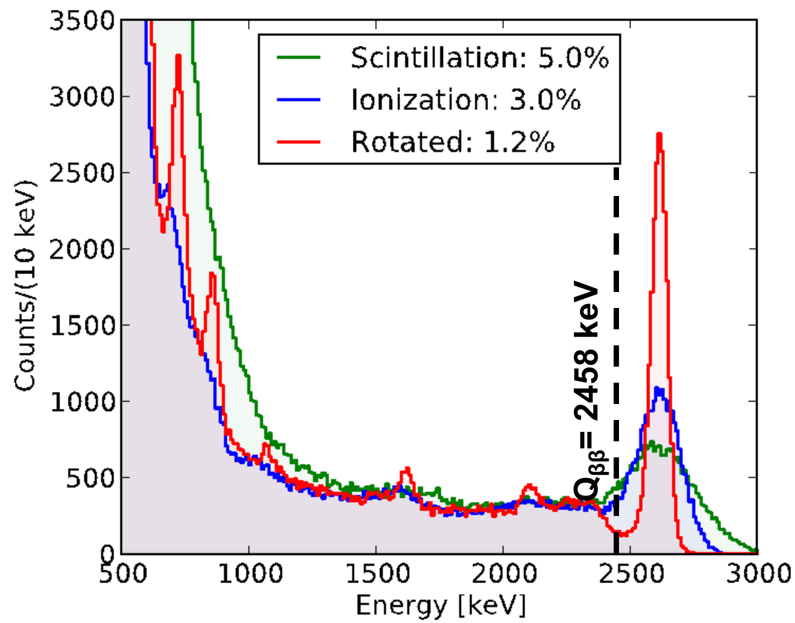


Energy measurement

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



Reconstructed energy, ^{228}Th calibration:

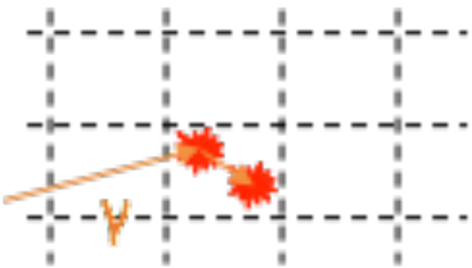


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- In the most recent analysis, EXO-200 has achieved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

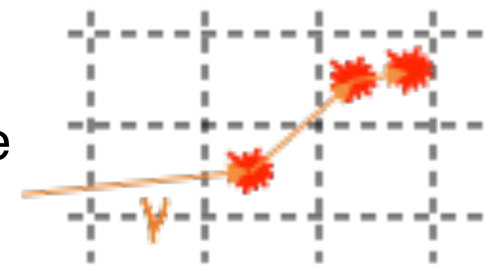
Position and multiplicity

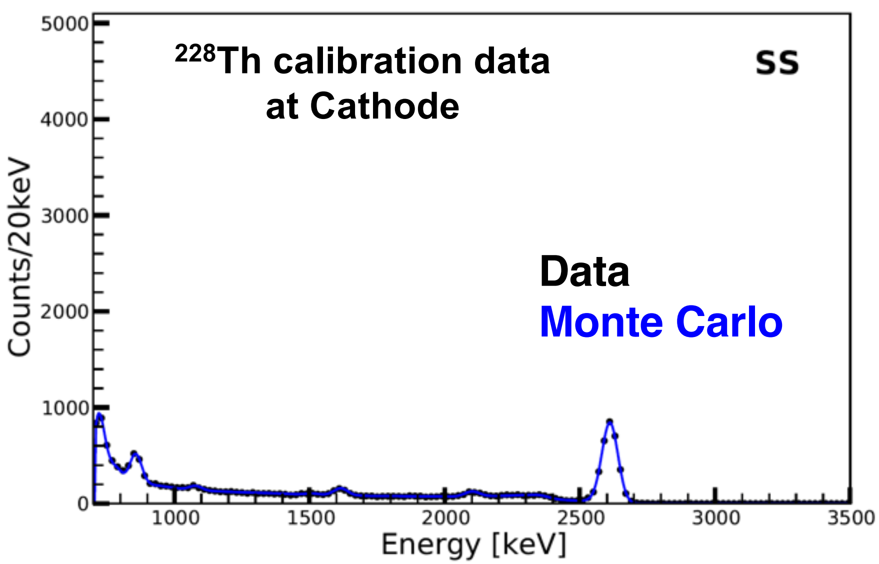
Allows for background measurement and reduction

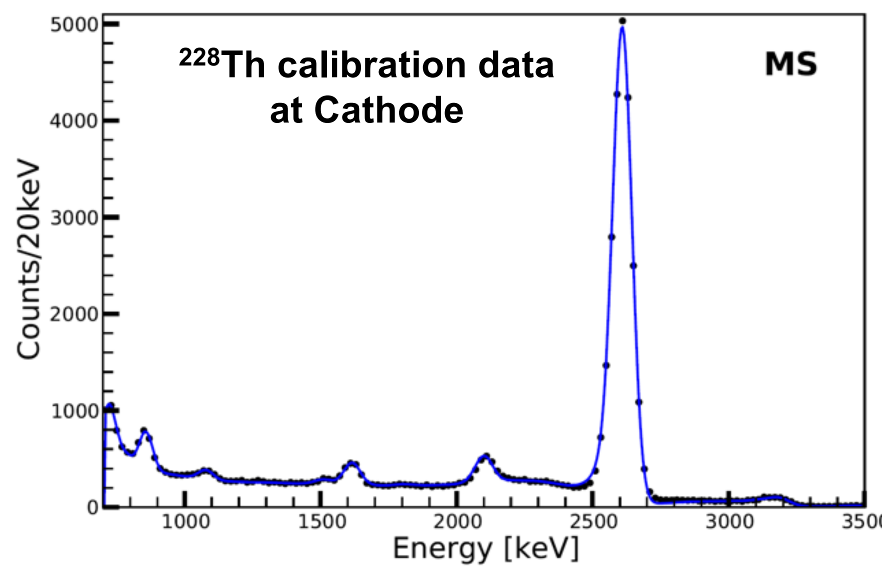
Events with **> 1** charge cluster: multi-site events
Events with **1** charge cluster: single-site events.



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





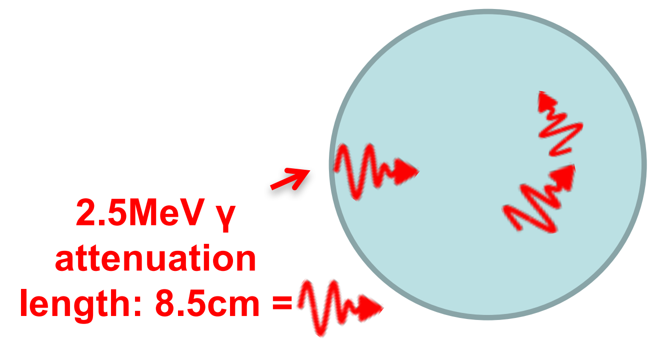


Improved γ-background Rejection

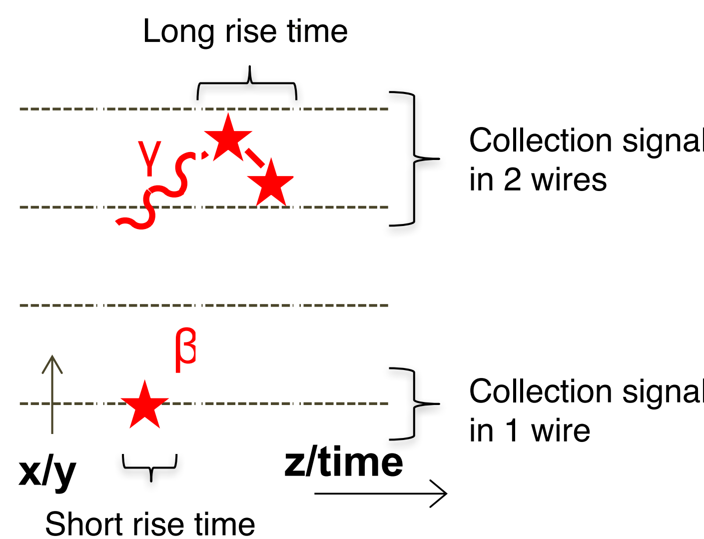
Additional discrimination in SS using *spatial distribution* and *cluster size*

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

LXe self-shielding:

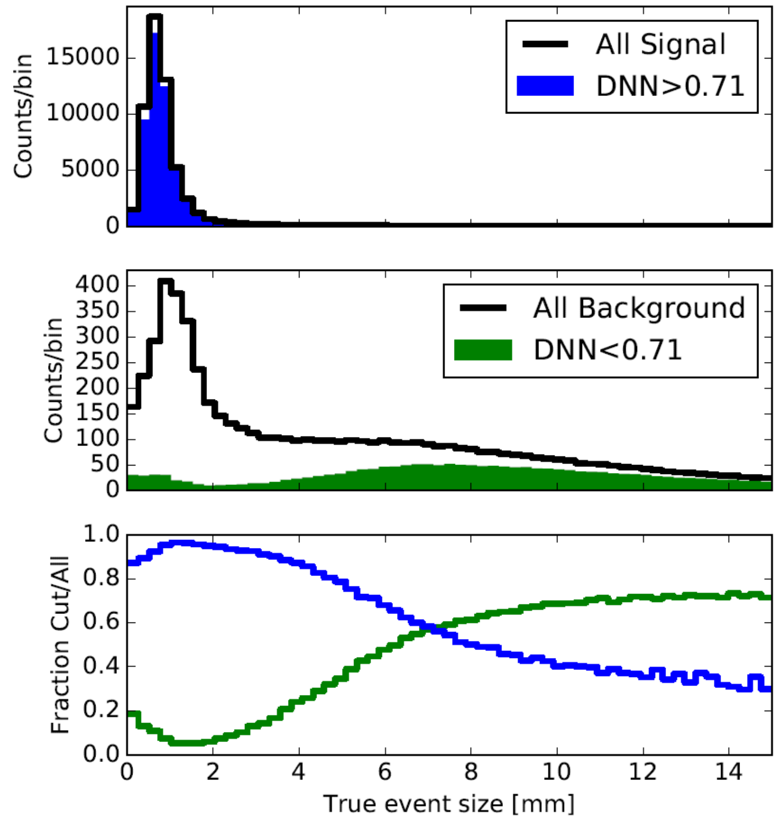


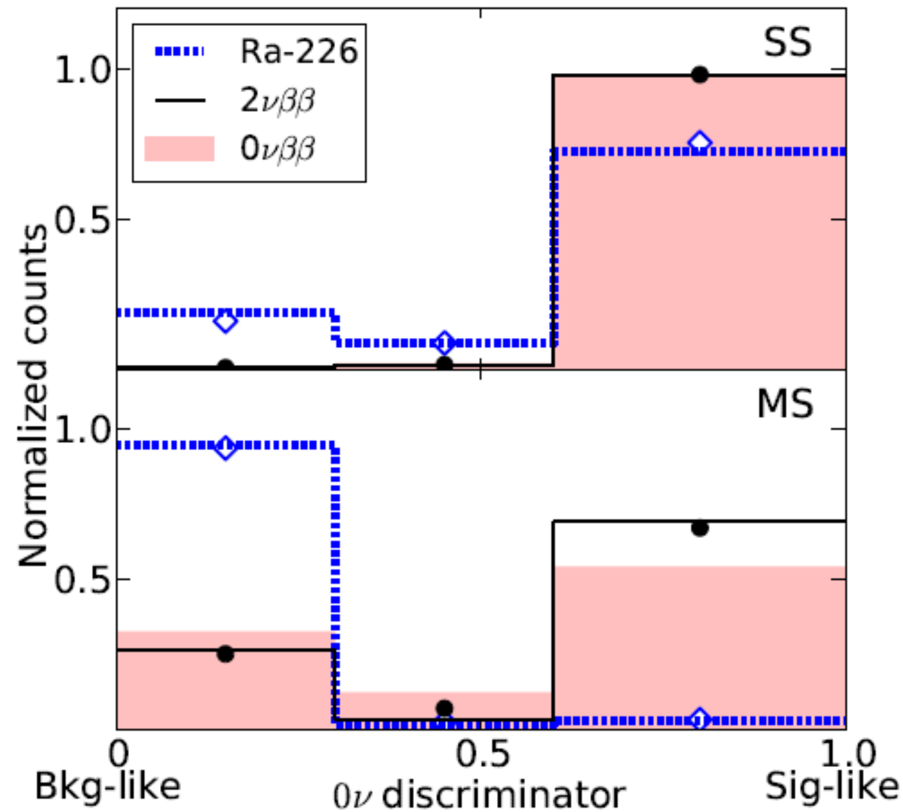
The size of individual events is estimated from pulse rise time (longitudinal direction) and the number of wires with a charge collection signal (transverse).



Optimal $0\nu\beta\beta$ Discrimination

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



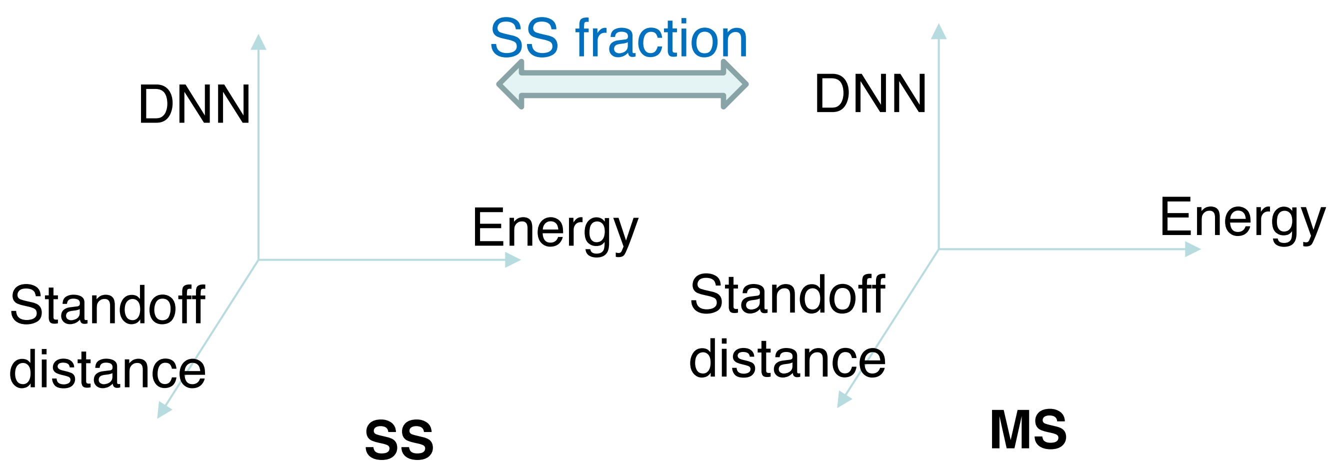


- DNN trained on images built from U-wire waveforms
- Signal/background identification efficiency clearly correlates with the true event size

- 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

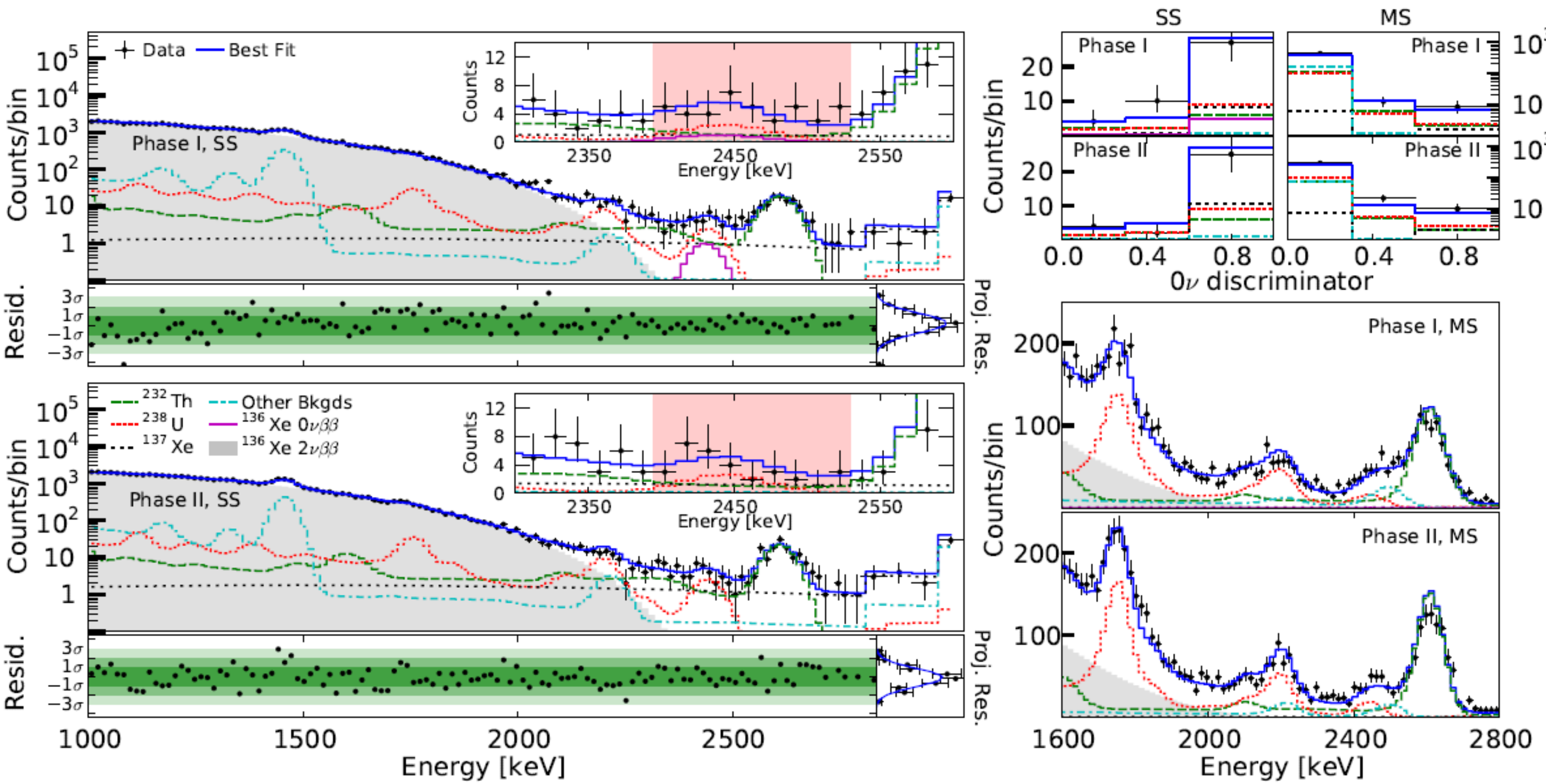


Results

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



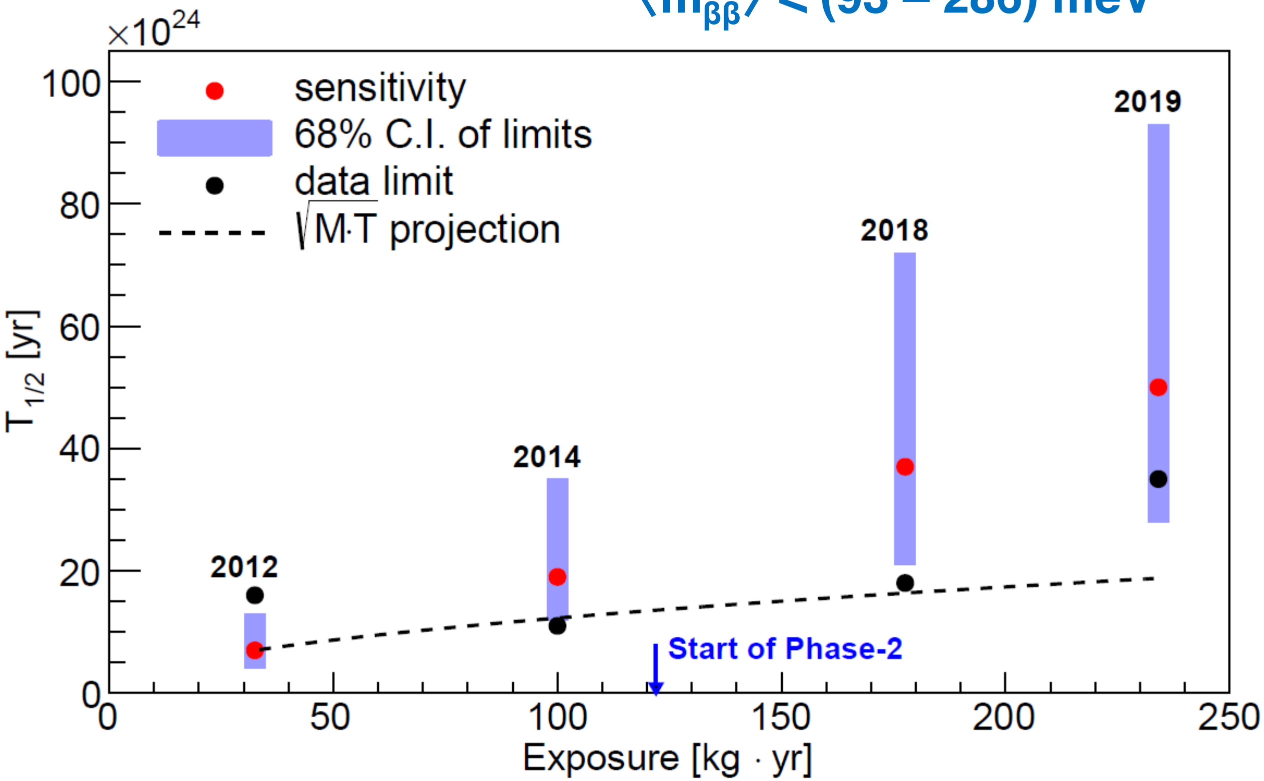
Sensitivity & Limits

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

Sensitivity 5.0×10^{25} yr

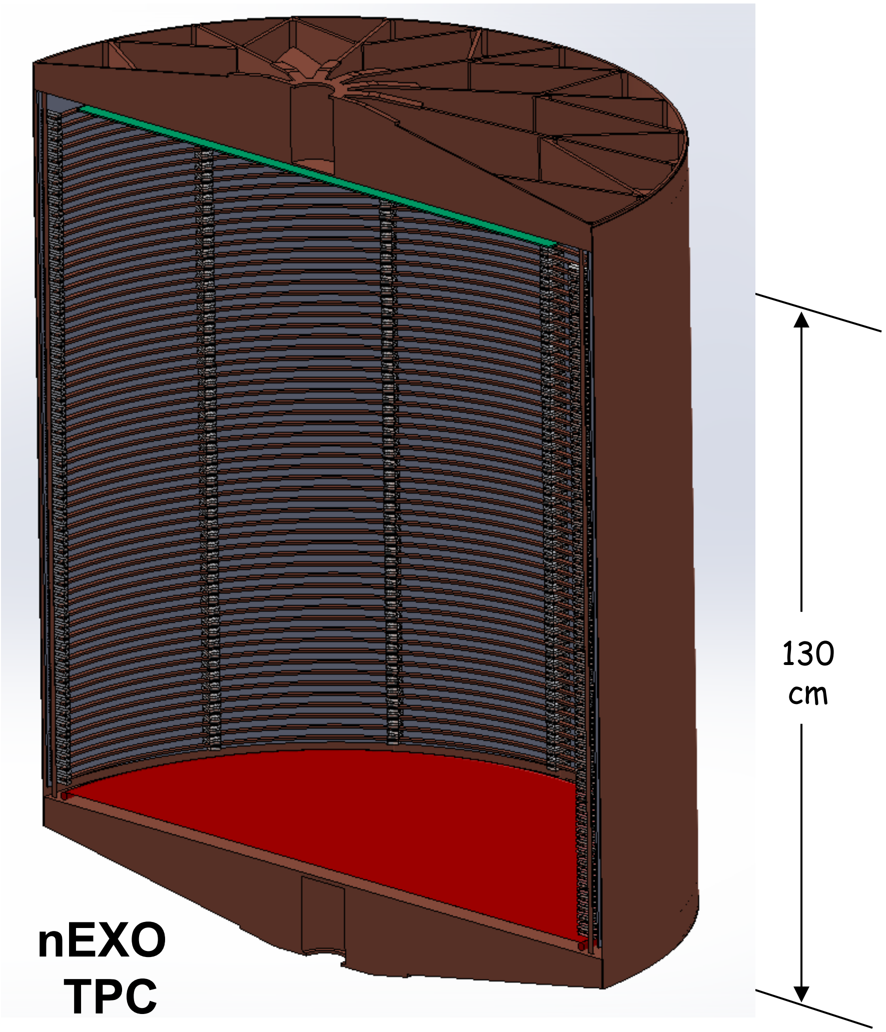
Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

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

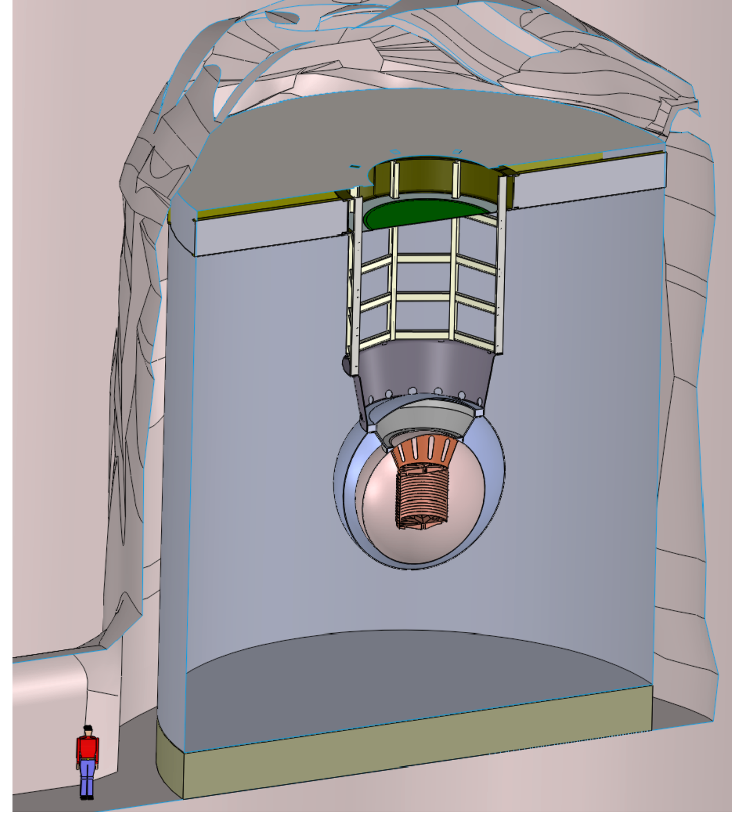


2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120 (2018) 072701
2019: arXiv:1906.02723

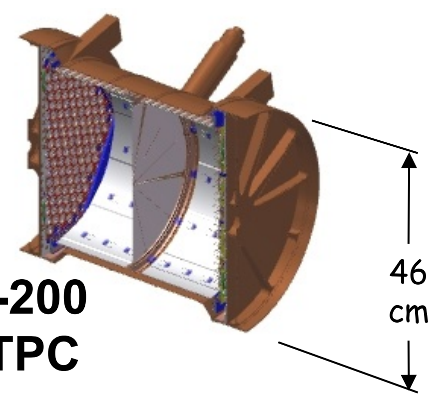
EXO-200 to nEXO



nEXO TPC



Preliminary artist view of nEXO in the SNOlab Cryopit

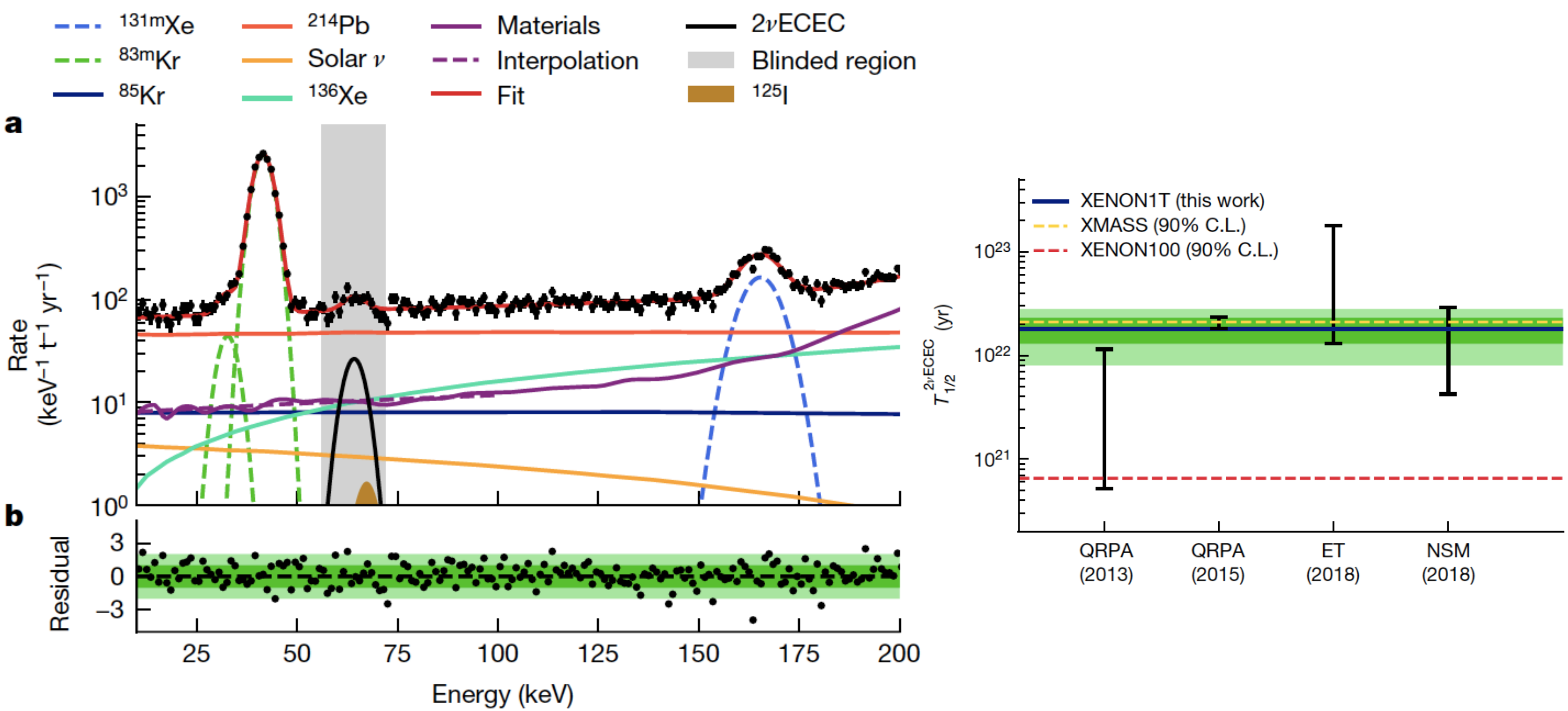


EXO-200 TPC

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

XENON-1t: 2νECEC observation

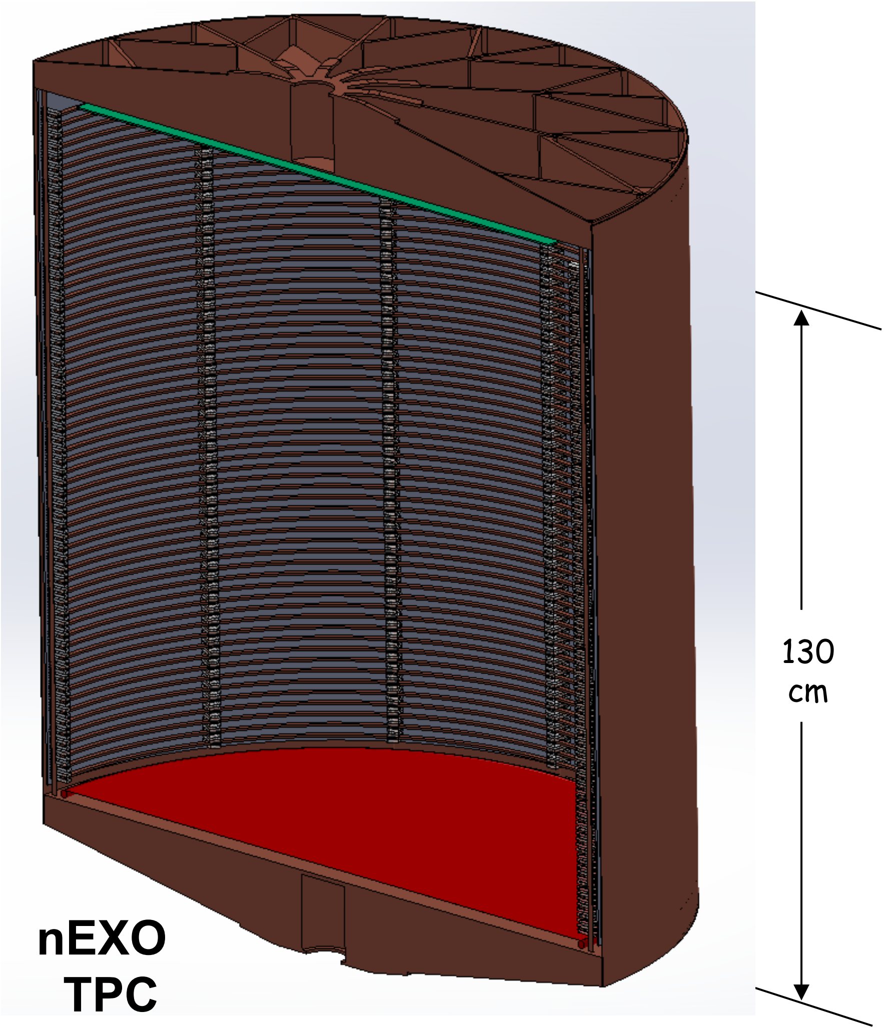
In general, detectors are optimized differently for dark matter and $0\nu\beta\beta$, but dark matter detectors also search for double beta decay.

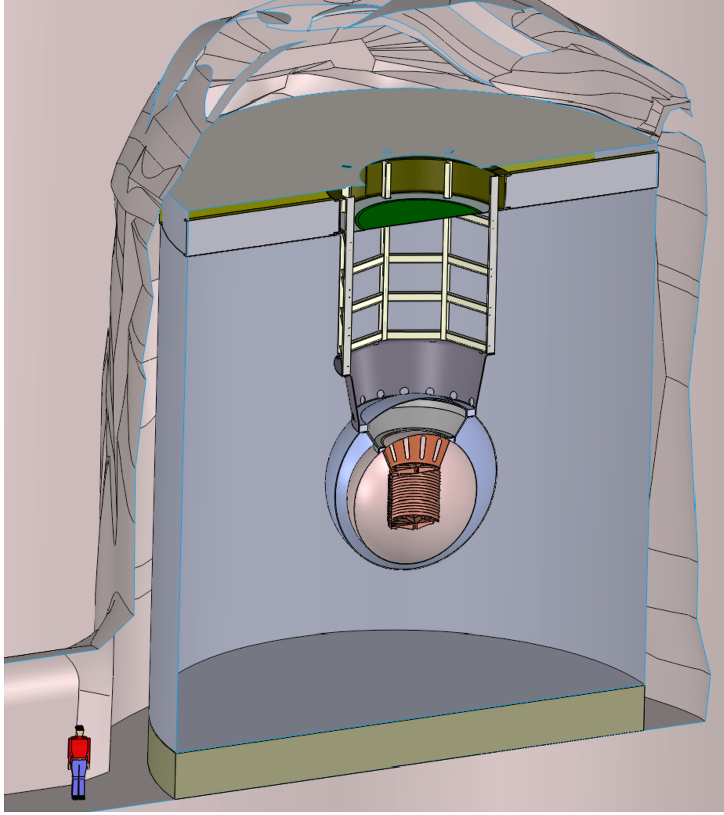


$$^{124}Xe\ T_{1/2}^{2\nu ECEC} = 1.8 \pm 0.5(\mathrm{stat}) \pm 0.1(\mathrm{sys}) \times 10^{22}\ \mathrm{yr}$$

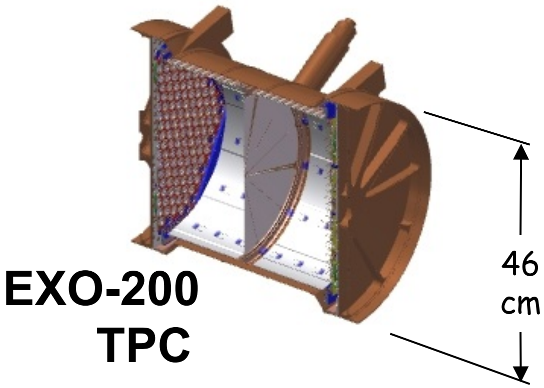
XENON Collaboration, *Nature* **568**, 532 (2019)

EXO-200 to nEXO



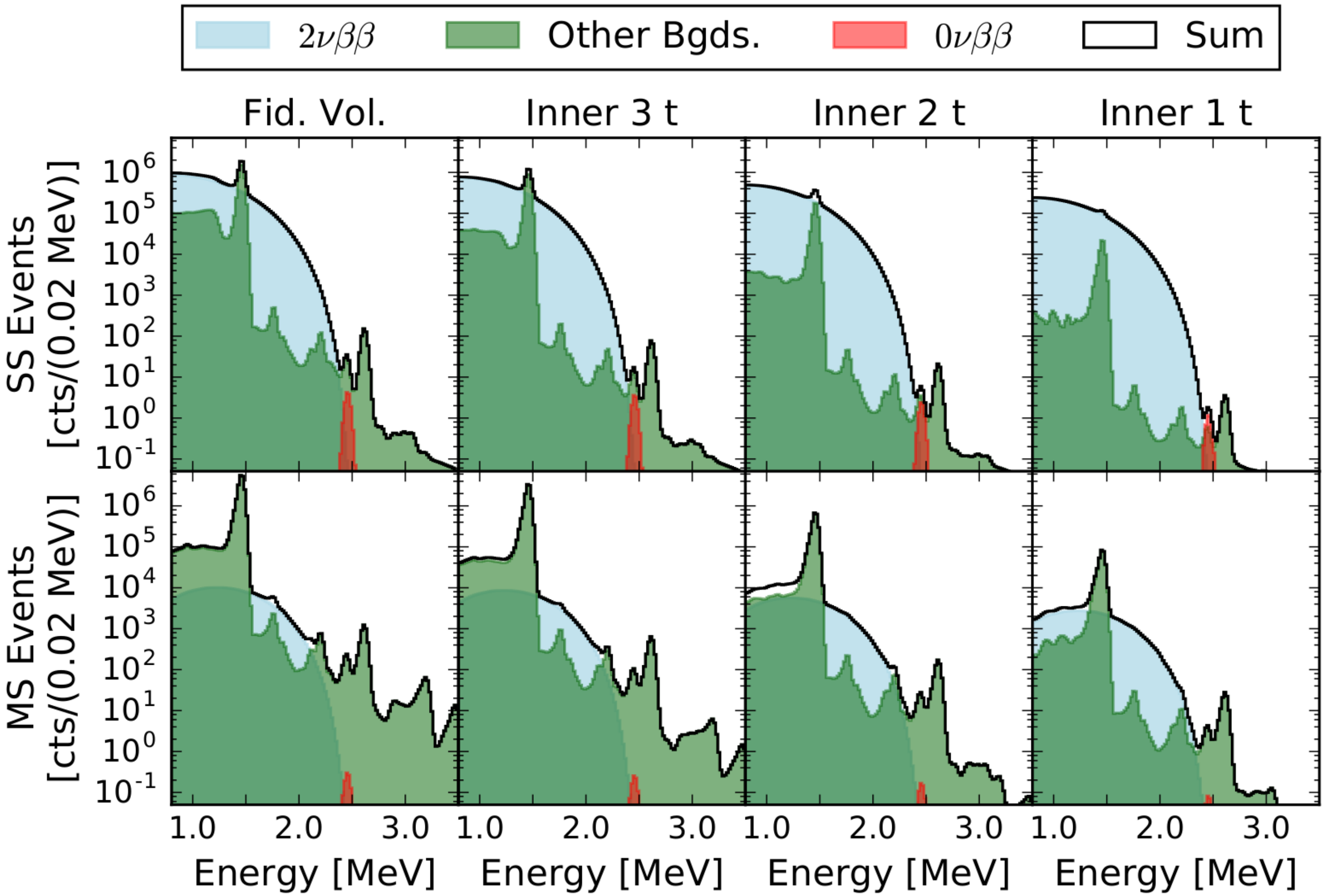


Preliminary artist view of nEXO in the SNOlab Cryopit



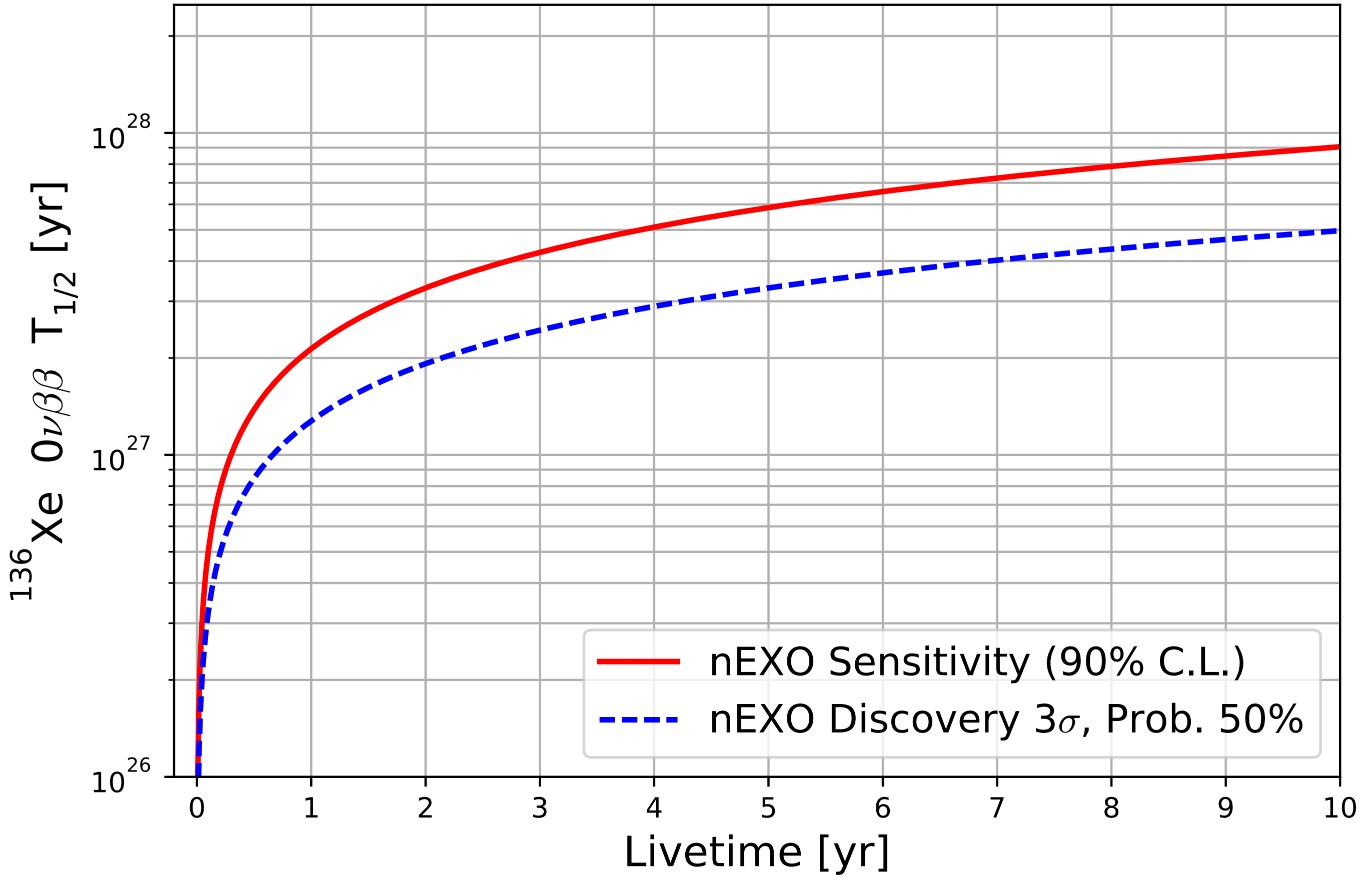
A 5000 kg enriched LXe TPC, based on success ofEXO-200

nEXO discovery potential



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

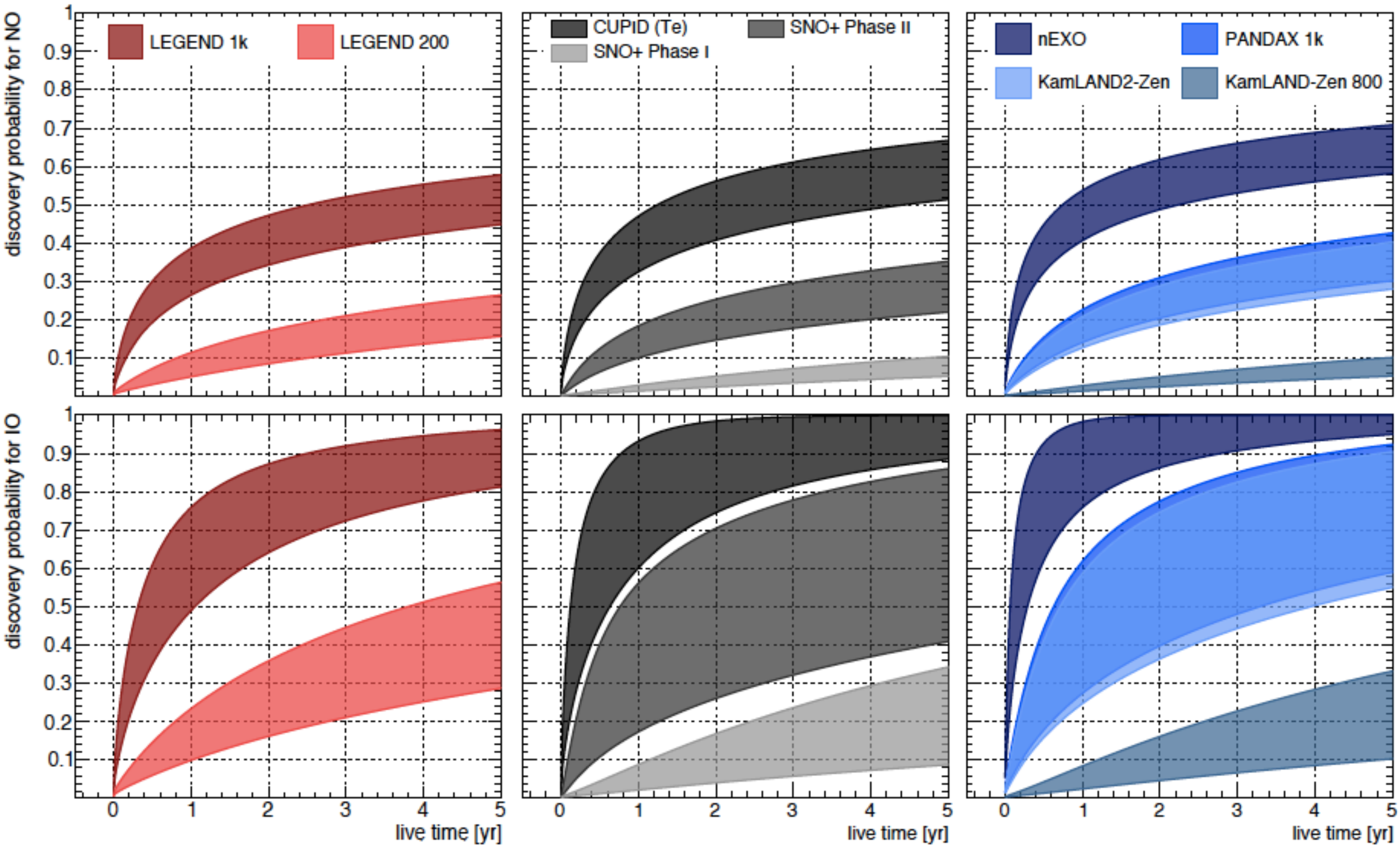
nEXO sensitivity



Baseline design assumes:

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

Discovery potential



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

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