Neutrinoless Double Beta Decay Searches

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The Neutrino Mass Scale and Hierarchy

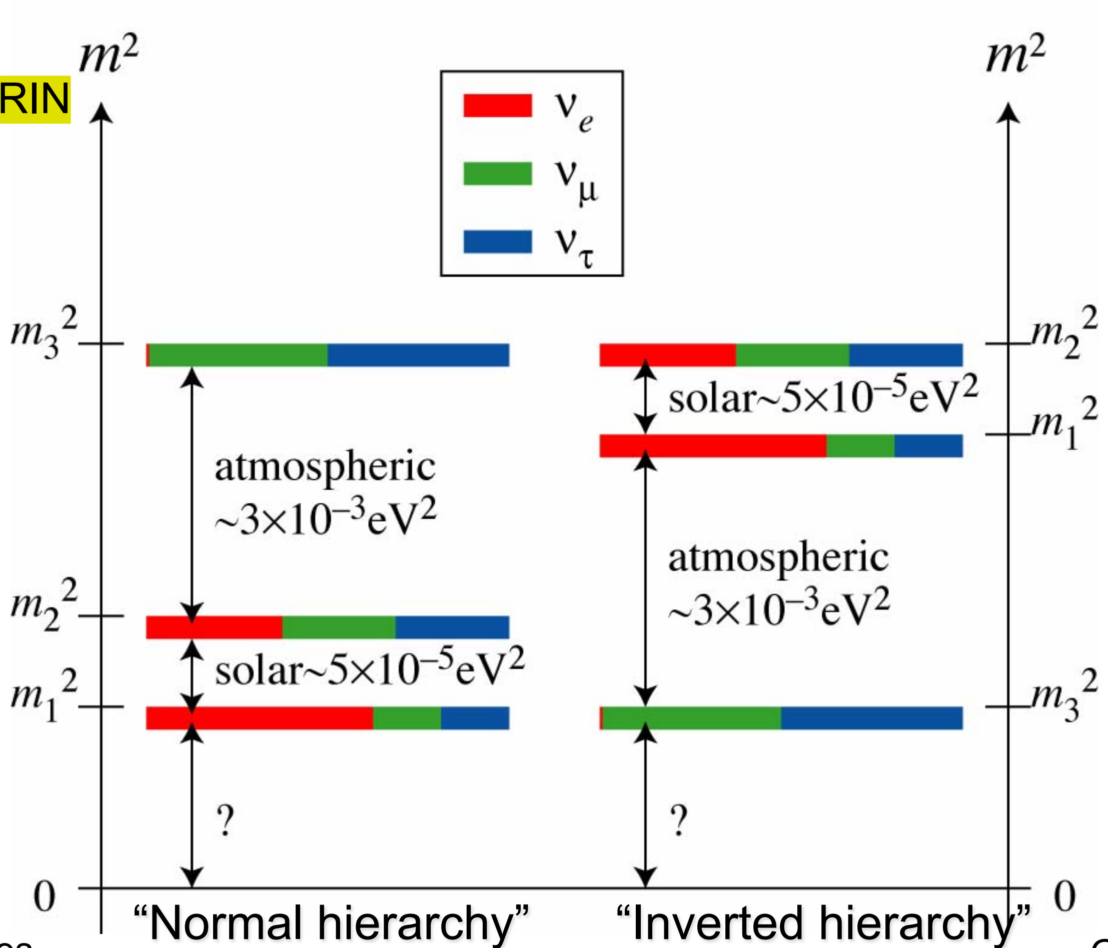
New result from KATRIN

<1.1 eV

<0.1 eV

From 0νββ, Majorana Neutrino

Tritium EndPoint



< 0.14 – 0.66 eV

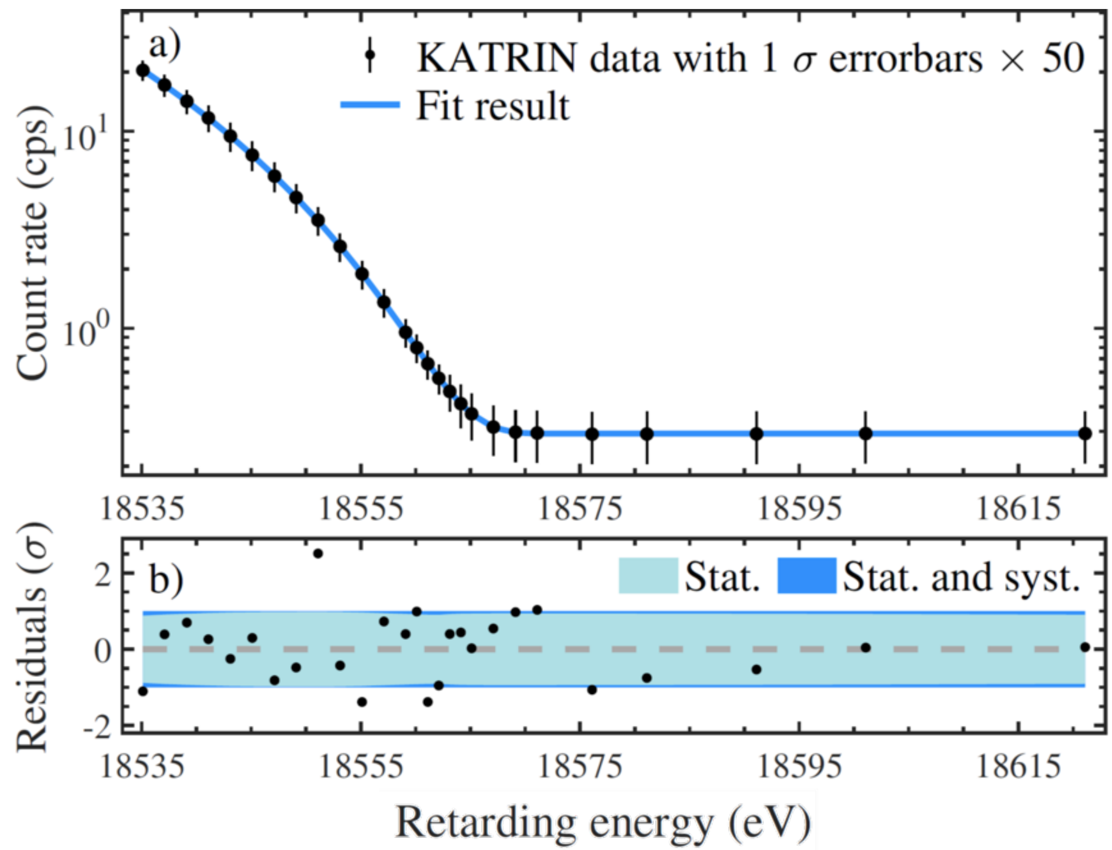
Cosmology

Measures effective Majorana neutrino mass

Measures electron neutrino mass

Cosmology WMAP + SN + Galaxy clustering (measures sum of neutrino mass)

First Result from KATRIN



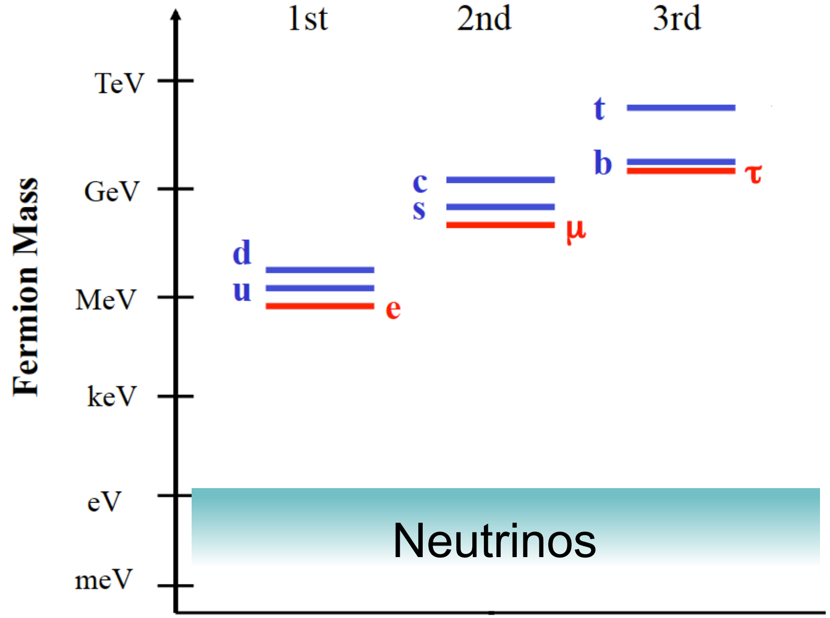
- 4-week long measuring campaign in spring 2019
- First ever large-scale throughput of high-purity tritium in closed loops
- High statistics β spectrum 2 million events in 90-eV-wide interval
- Data well modelled and systematics well understood.
- 1000 days of measurement can reach m_ν sensitivity of 0.2 eV

First neutrino mass result
m_ν < 1.1 eV (90 % CL)

G. Drexlin, “Direct Neutrino Mass Measurements”, TAUP conference 2019

Neutrino Mass Generation Mechanism

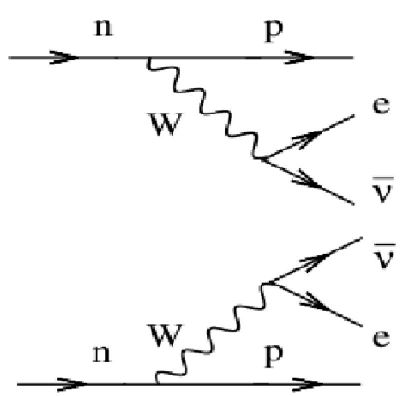
- Neutrino oscillation experiments demonstrate that neutrinos have tiny, but non-zero masses
- Neutrino mass is significantly smaller than other spin ½ leptons
- If neutrinos are Majorana particles, see-saw Mechanism provides a natural way to explain the smallness of the mass.
- It also predicts heavy GUT scale neutrinos (possible source of leptogenesis)



The best experimental probe for the Majorana Nature of the neutrinos is the search for neutrinoless double beta decay

Double Beta Decay

Maria Goeppert Mayer



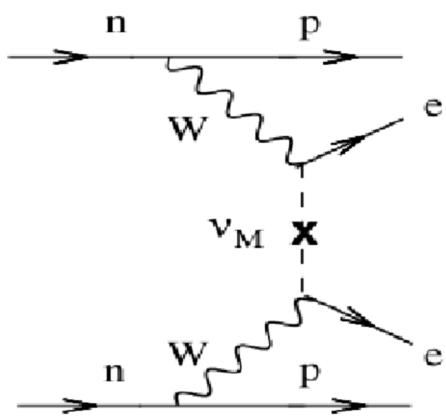
Two neutrino double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in ^{82}Se by M. Moe

Ettore Majorana



Neutrinoless double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1937 Ettore Majorana proposed the theory of Majorana fermions

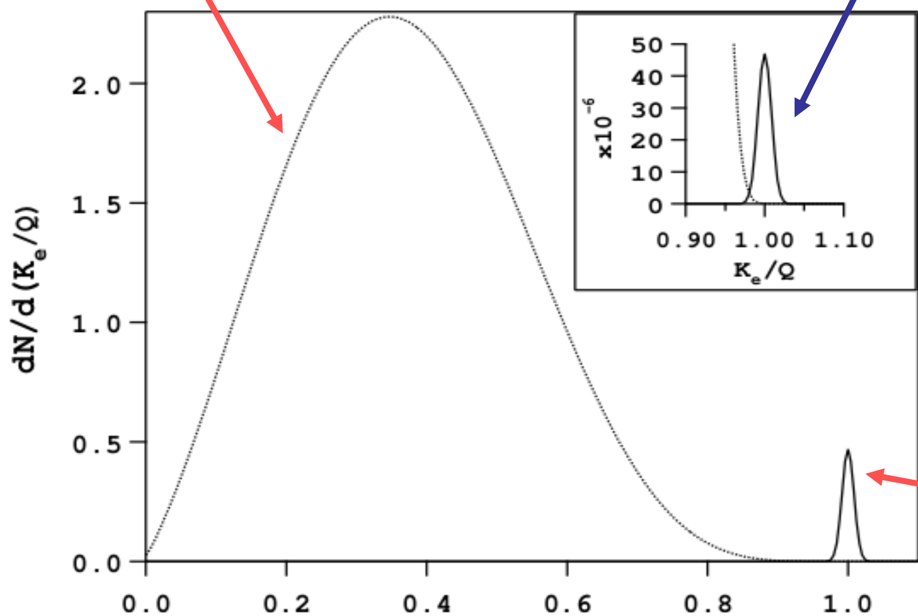
1939 Wendell Furry proposed neutrino less double beta decay

The search continues….

Observation of 0νββ:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Double Beta Decay Energy Spectrum



Summed electron energy in units of the kinematic endpoint (Q)

The two peaks can be separated in a detector with good energy resolution

[P. Vogel, arXiv:hep-ph/0611243]

If 0νββ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \, G_{0\nu\beta\beta}(E_0, Z) \, \left| M_{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_{0\nu\beta\beta}$ Nuclear matrix element

$G_{0\nu\beta\beta}$ Phase space factor

$T_{1/2}^{0\nu\beta\beta}$ Measured half-life

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \, \varepsilon_i \right|$$

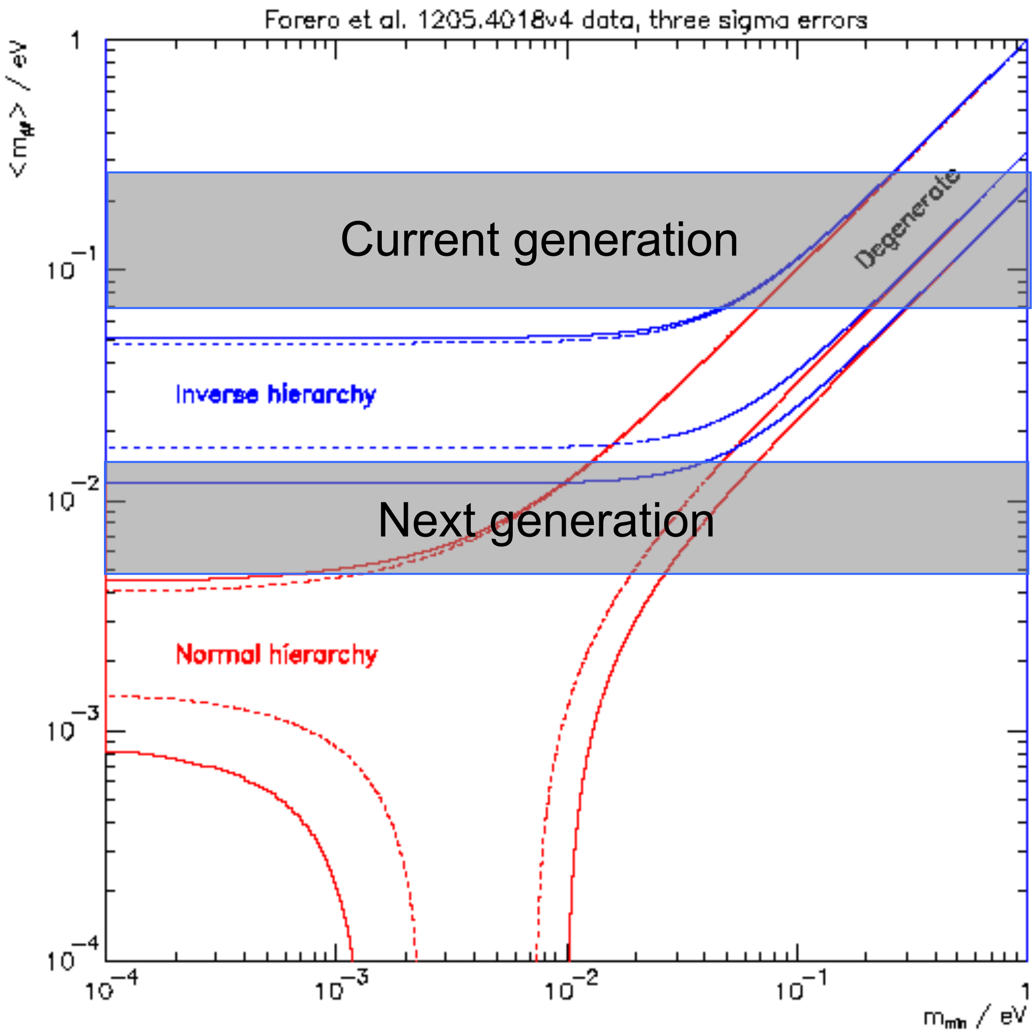
effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

$0\nu\beta\beta$ as a probe for Majorana Neutrino Mass

Isotope Mass

10-100 kg
e.g. EXO-200

1-10 ton
e.g. nEXO



Background

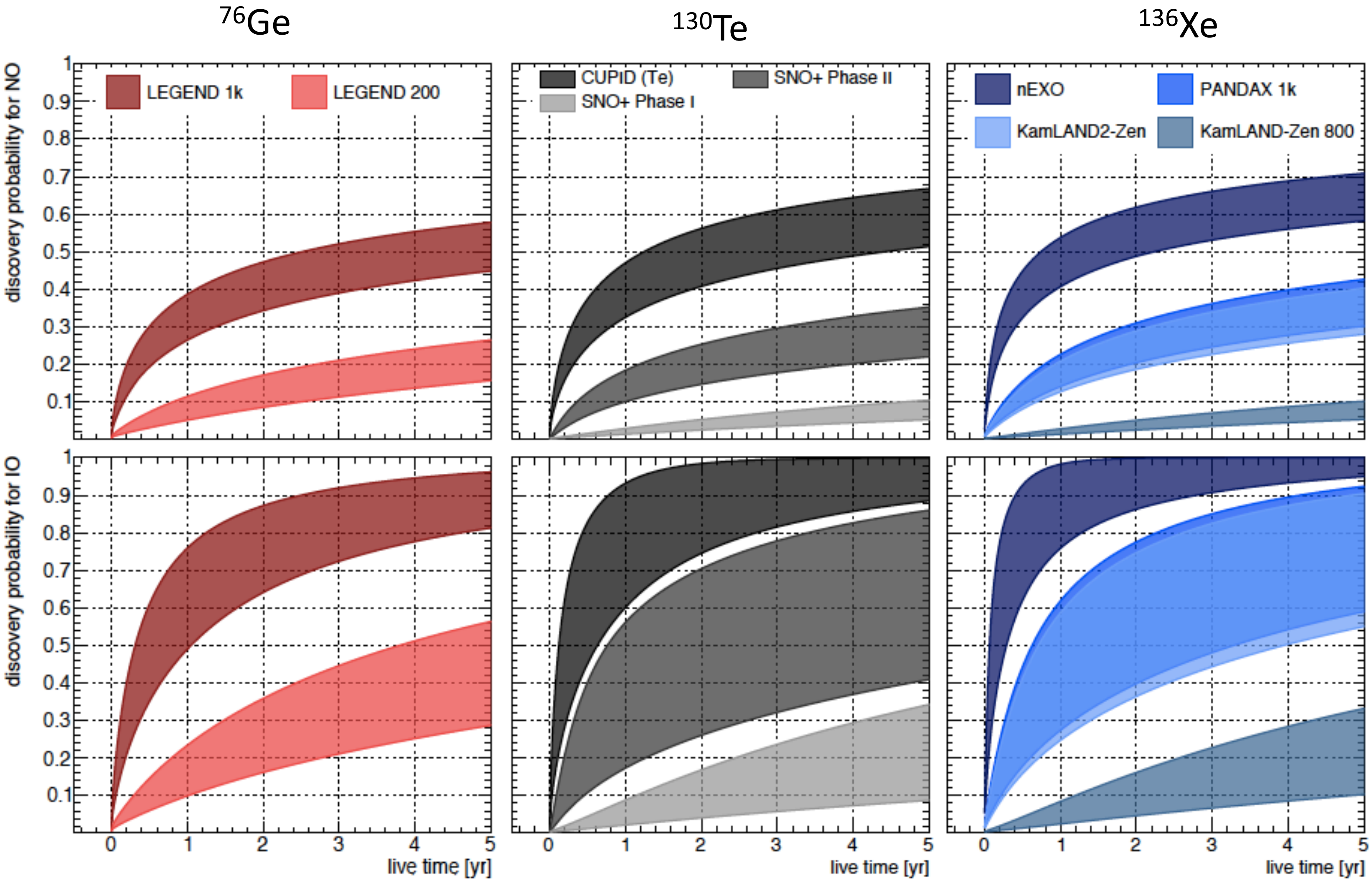
10-100cts/yr/ton

0.1-1cts/yr/ton

Plot courtesy Andreas Piepke

Modern experiments use multiple parameters for analysis, not simple event counting.

Discovery potential



Analysis assumes free value of g_A and uses a Bayesian analysis with flatly distributed priors.

Observation in more than one isotope needed to understand underlying physics mechanism

Agostini, Benato, Detwiler, *PRD* 96 (2017) 053001
See also A. Caldwell et al., *PRD* 96 (2017) 073001

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	M. Agostini et al., Science, (2019)
	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)

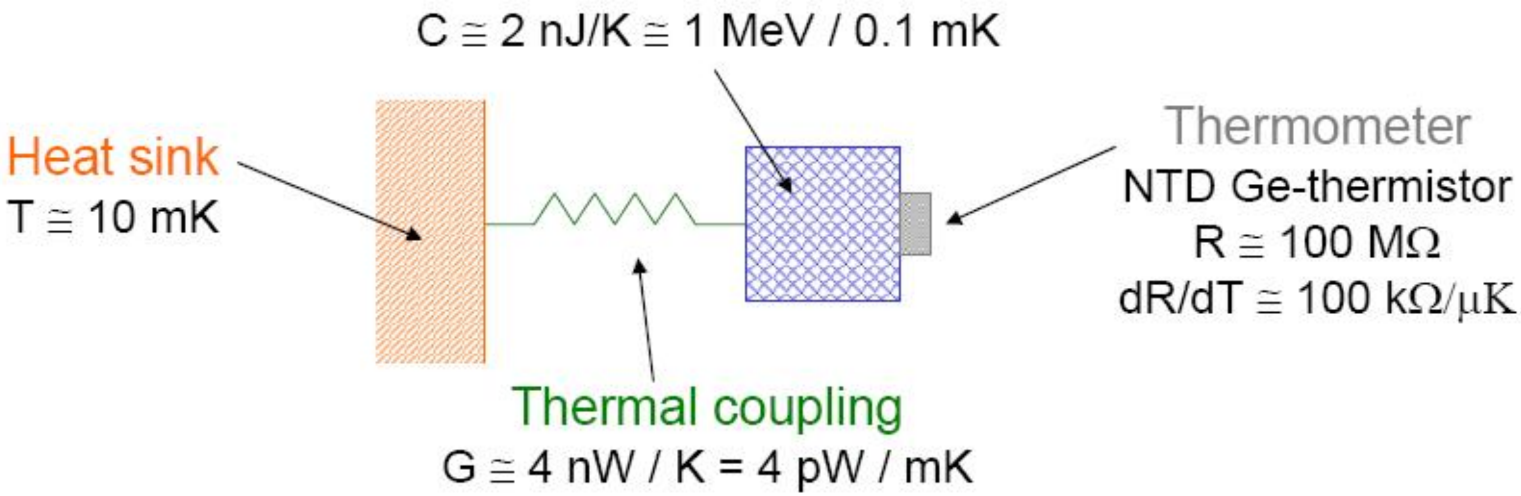
*Note that the range of NME is chosen by the experiments, and uncertainties related to g_A are not included.

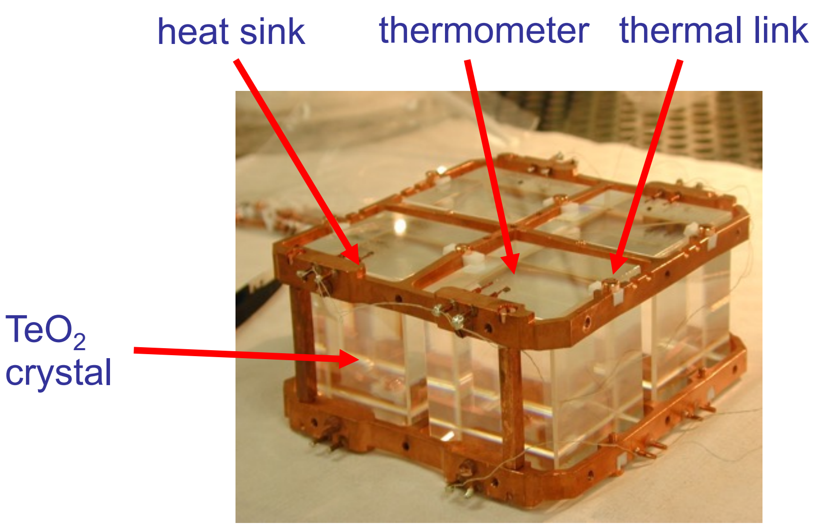
- A variety of experimental methods and isotopes are used with different pros and cons.
- Since it is not possible to discuss all experiments, I will focus on the leading experiments in this talk and how they can scale to a tonne scale experiments.

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

Not covered in the talk: SNO+, superNEMO, NEXT, PANDAX-III, AMORE, CANDLE….

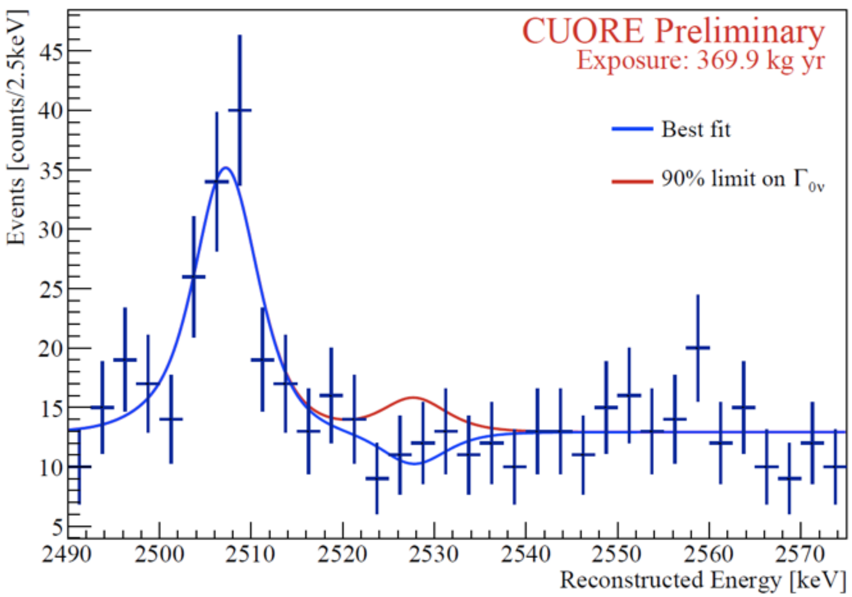
Cryogenic Bolometer: ^{130}Te

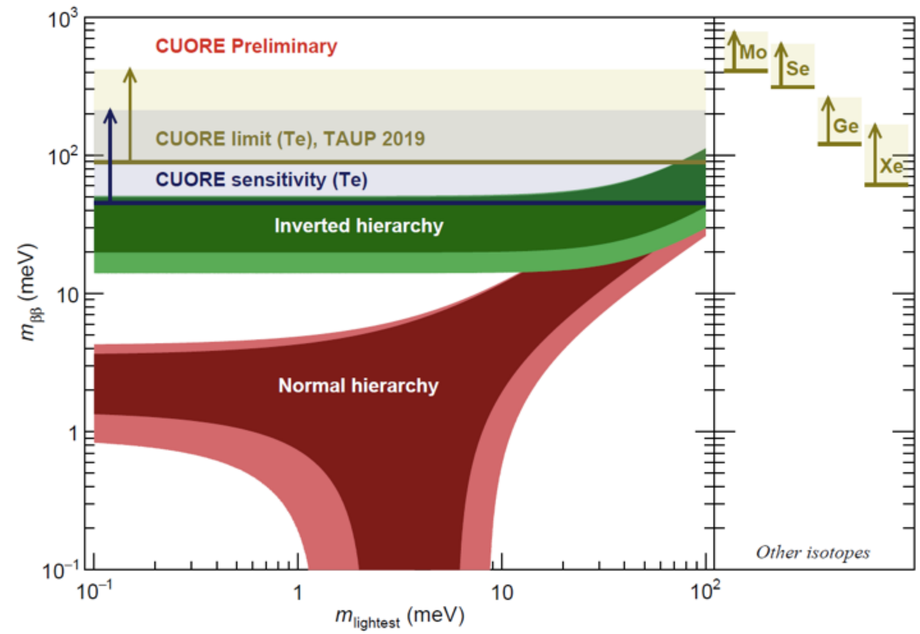




- Measure total energy deposited in the crystal.
- Techniques applicable to many isotopes. Te has the highest natural abundance.
- High energy resolution, 7-9 keV FWHM @ 2530keV.
- No information about the particle ID, external γ and surface degraded *α* are major background concerns.

CUORE recent results





- Exposure: 369.9 kg yr
- Bayesian fit on the region of interest (2490-2575 keV)
- Free parameters: ^{60}Co rate and position, background, $\Gamma_{0\nu}$
- Bkg : (1.37 ± 0.07) x 10^{-2} ckky

Limit on 0νββ half life computed on physical range:

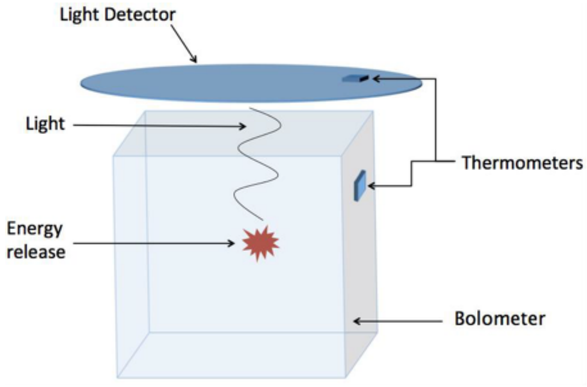
$T_{1/2} > 2.3 \times 10^{25}$ y (90% C.I.) (PRELIMINARY)

$m_{\beta\beta} < 0.09\text{-}0.42$ eV (90% C.I.)

S. Pozzi, "New Results from the CUORE Experiment", TAUP conference 2019

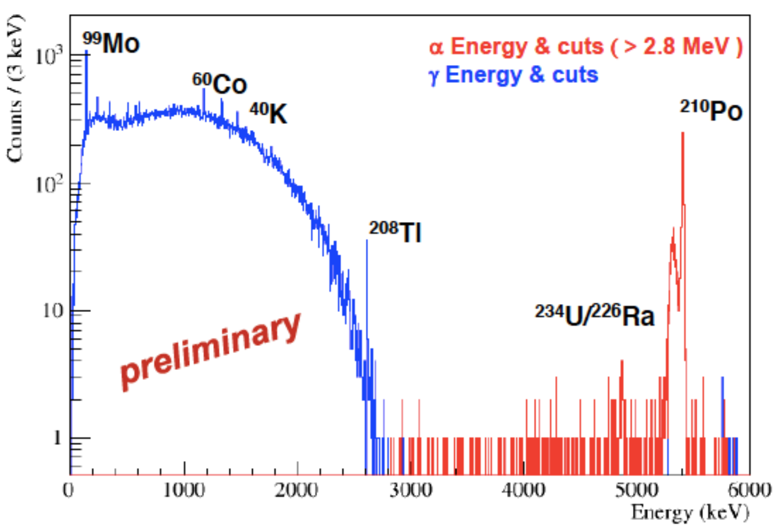
CUPID: CUORE Upgrade with Particle IDentification

Use Cherenkov or scintillation light information to suppress background

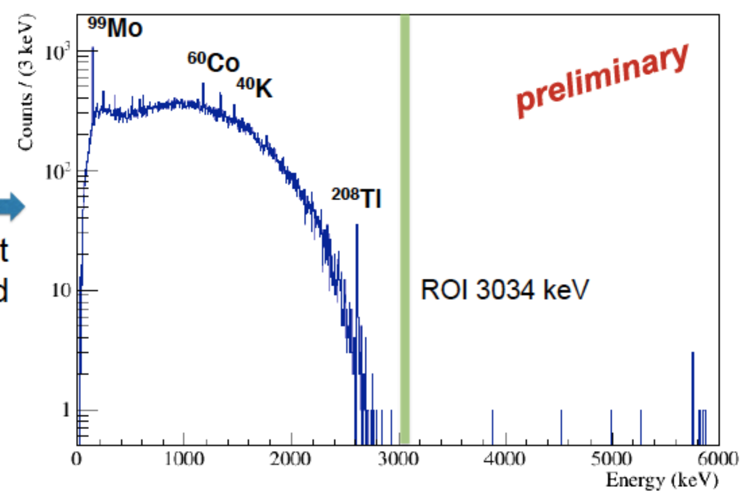


CUPID ^{100}Mo (heat + light)
Scintillating bolometer

- Pre-Conceptual Design: 250 kg of $Li_2{}^{100}MoO_4$ scintillating crystals, enriched to > 95%
- $0\nu\beta\beta$ sensitivity $t_{1/2}$~ 10^{27} y → $m_{\beta\beta}$ 12-20 meV
- CUPID1–ton will use 1 ton of larger crystals with lower background
- In case of discovery, can explore multiple targets: TeO_2 - ZnSe – Li_2MoO_4 – $CdWO_4$

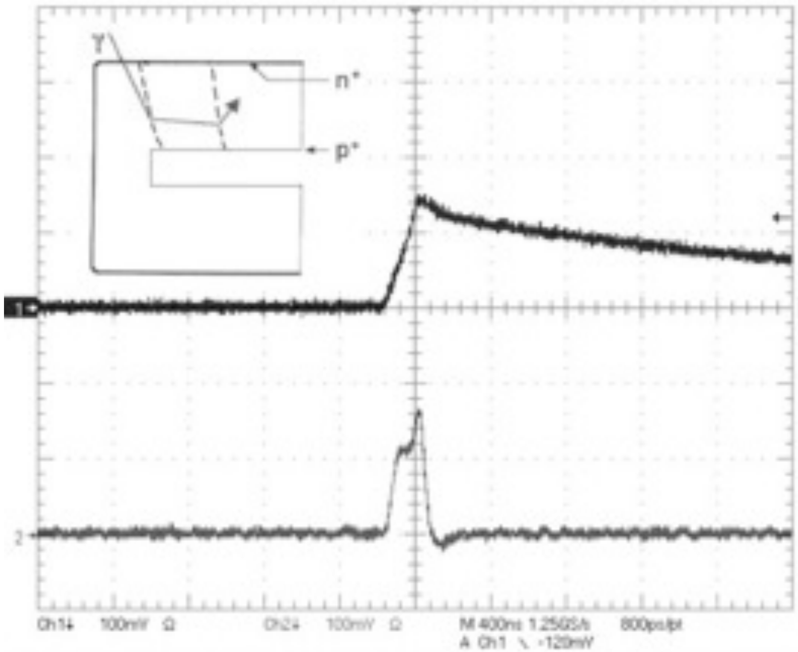


Light Yield cut

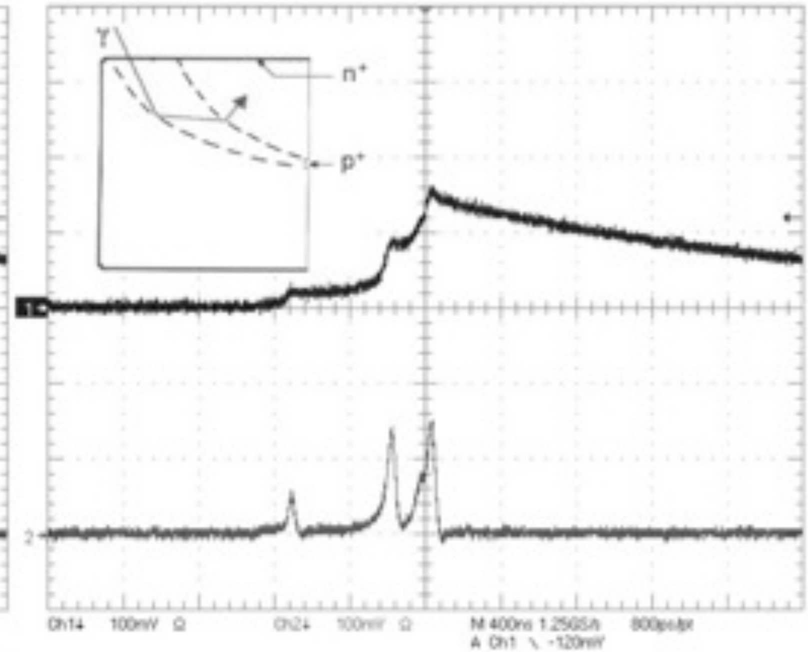


P. Pavan, "CUPID", B. Schmidt, "First data from the CUPID-Mo neutrinoless double beta decay experiment", TAUP conference 2019

Semiconductor Detector: ^{76}Ge



P-type semi-coaxial Detector



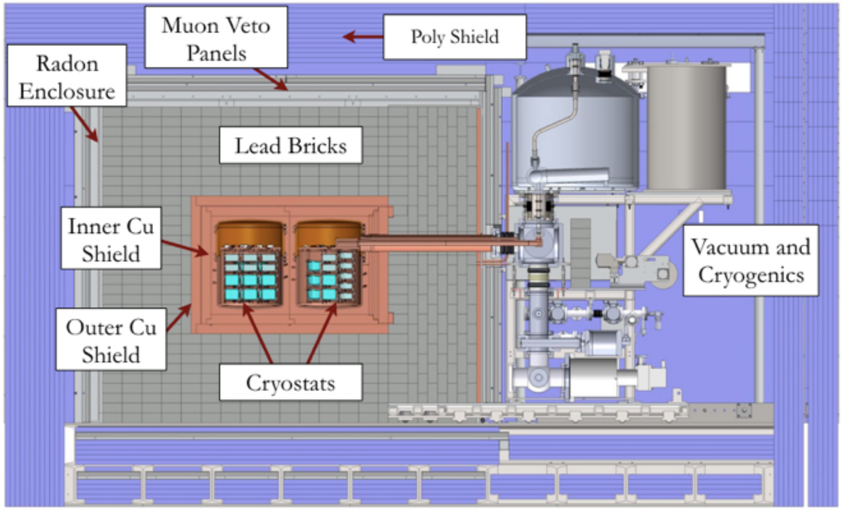
P-type point contact Detector*

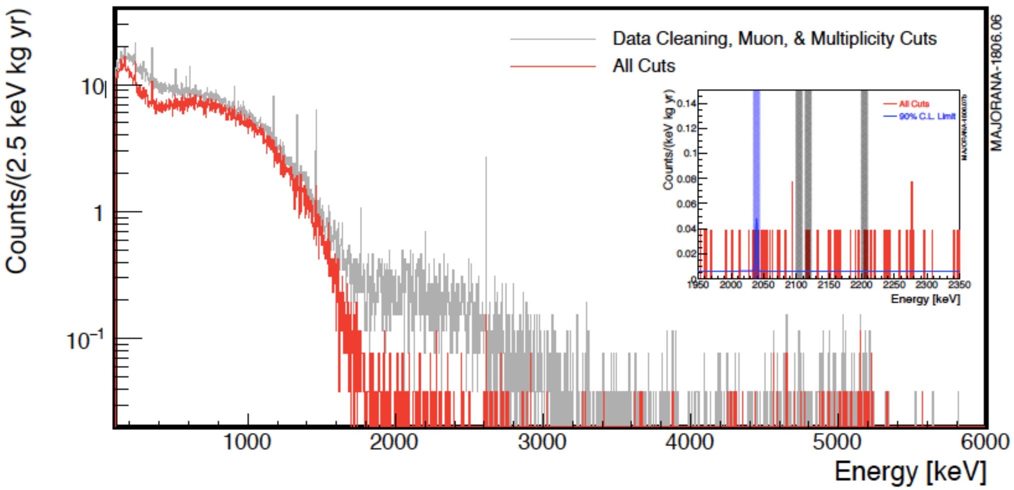
Barbeau et al., JACP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36, 926 (1989).

- Excellent energy resolution (4keV FWHM at Q value)
- Pulse shape analysis rejects multiple site events within a single crystal.
- P-type point contact crystal has superior single vs. multi-site rejection capability.
- Modest Q value (2039 keV), cosmogenic activation of Ge and Cu cryostat

*Also called Broad Energy Ge (BEGe) Detector.

MAJORANA Demonstrator



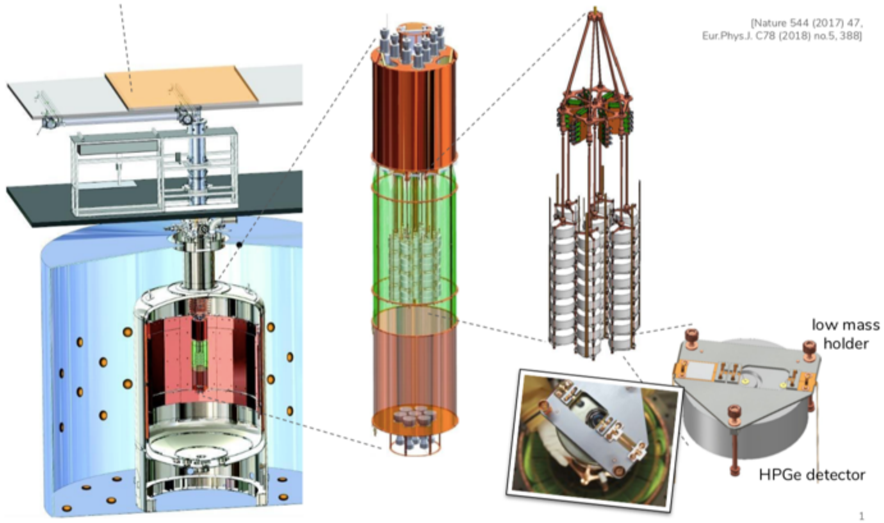


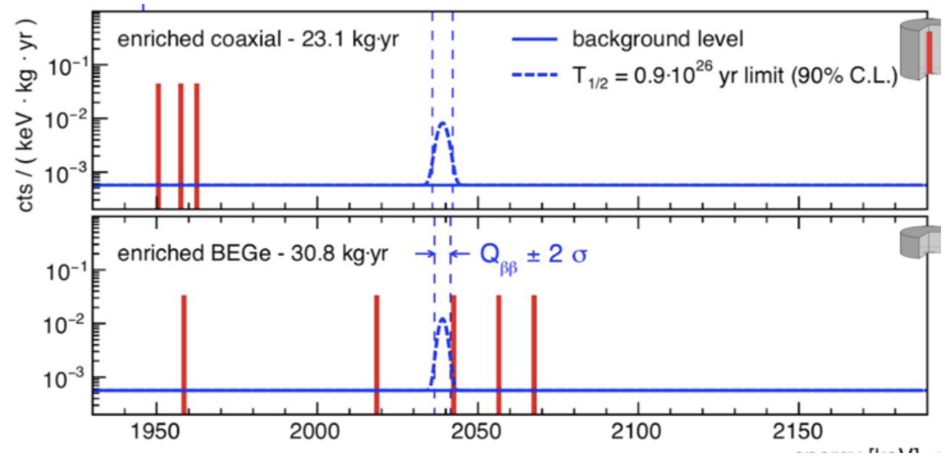
- Source & Detector: Array of p-type, point contact detectors, 29.7 kg of 88% enriched ^{76}Ge crystals
- Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
- Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials
- Total exposure: 26 kg-yr exposure
- Median $T_{1/2}$ Sensitivity: 4.8 x 10^{25} yr
- Limit: $T_{1/2}$ > 2.7 x 10^{25} yr (90% CL)
- Background Index at 2039 keV in lowest bkg config: 11.9 ± 2.0 cts/(FWHM t yr)

[PRL 120 132502 (2018), PRC 100 025501 (2019)]

M. Green, "MAJORANA DEMONSTRATOR Status and Background Characterization", TAUP conference 2019

GERDA Phase-II





- Used several types of HP Ge detectors including coaxial, BEGe and inverted coaxial
- Excellent Energy Resolution: Coaxial: 3.6 keV and BEGe 3.0 keV FWHM @ 2039 keV
- Use active LAr veto for additional background rejection

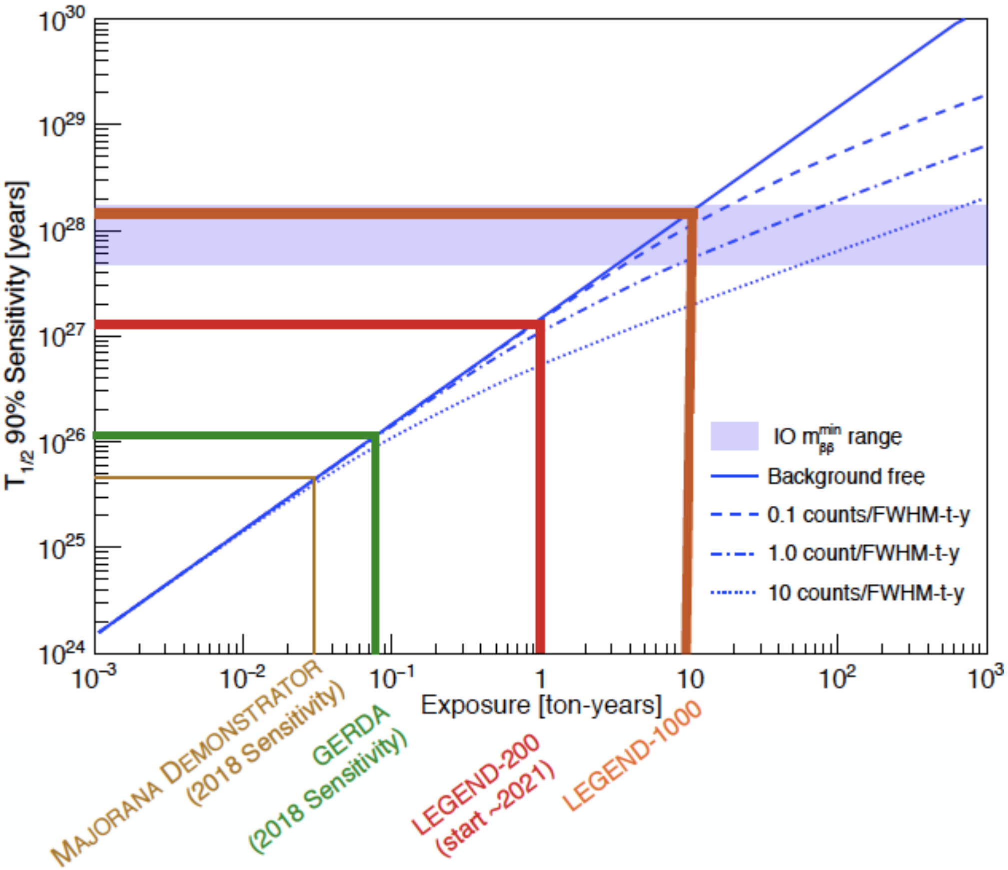
- combined (+ Phase I) unbinned maximum likelihood analysis
- Median $T_{1/2}$ Sensitivity: 1.1 x 10^{26} yr
- Limit: $T_{1/2}$ > 0.9 x 10^{26} yr (90% CL)
- Background Index:
  ~ 0.6 x 10^{-3} cts/(keV kg yr)

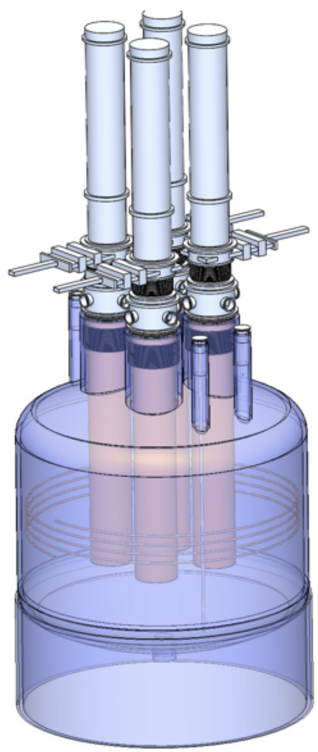
[Nature 544 (2017) 47, DOI: 10.1126/science.aav8613]

C. Wiesinger, “Results and post-upgrade performance of GERDA Phase II”, TAUP conference 2019

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

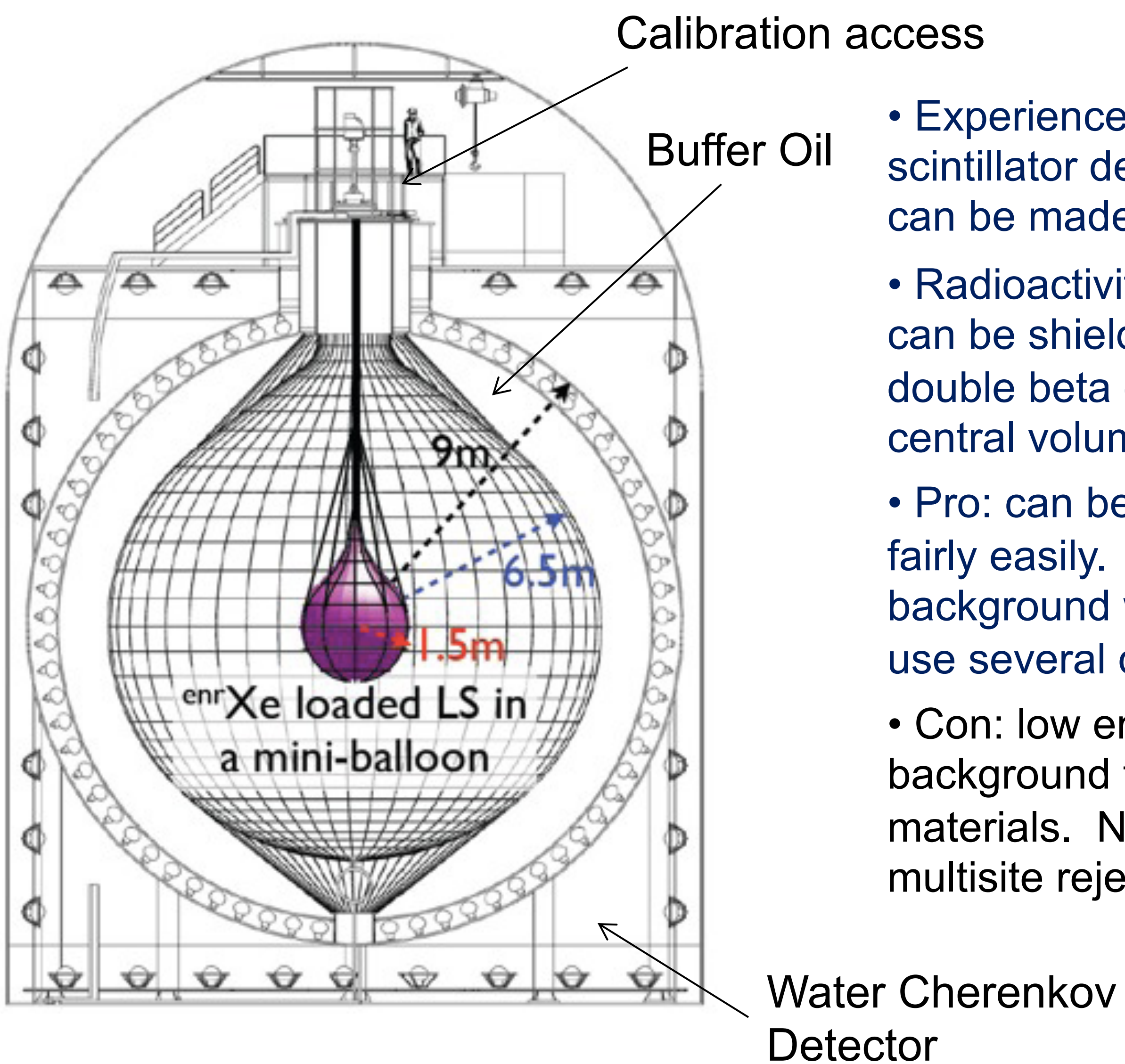
- Build on the experience of GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Design sensitivity of ~1x10^{28} y with a background of 0.1 cnt/tonne-yr in the region of interest (background reduction of ~6-20 relative to existing)





LEGEND

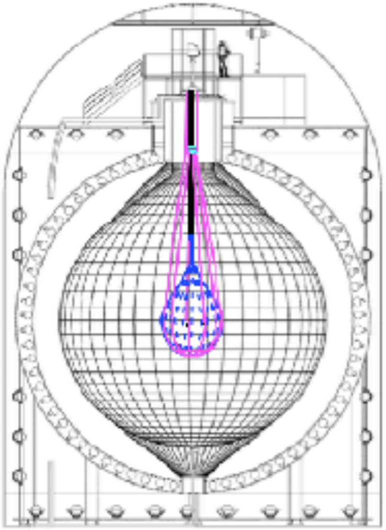
Scintillation Detector: KamLAND-Zen



- Experience with large liquid scintillator detectors show that LS can be made extremely pure.
- Radioactivity from PMTs and vessel can be shielded by LS and confining double beta decay isotopes inside a central volume.
- Pro: can be scale to large mass fairly easily. Most detector background well understood. Can use several different isotopes.
- Con: low energy resolution, background from $2\nu\beta\beta$ and balloon materials. No single site and multisite rejection.

KamLAND-Zen series

<u>Past</u>



KamLAND-Zen 400

R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

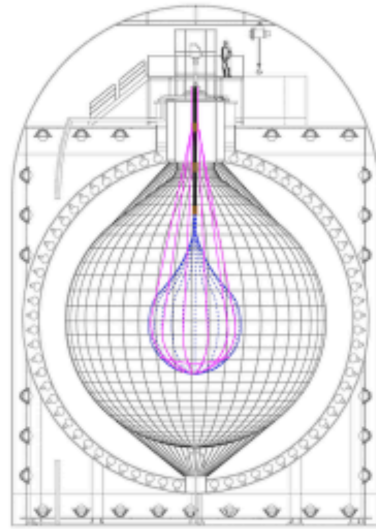
2011 ~ 2015

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

$\langle m_{\beta\beta} \rangle$ **< 61 – 165 meV**

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

<u>Ongoing</u>



KamLAND-Zen 800

R = 1.90m mini-balloon

Xenon 745 kg

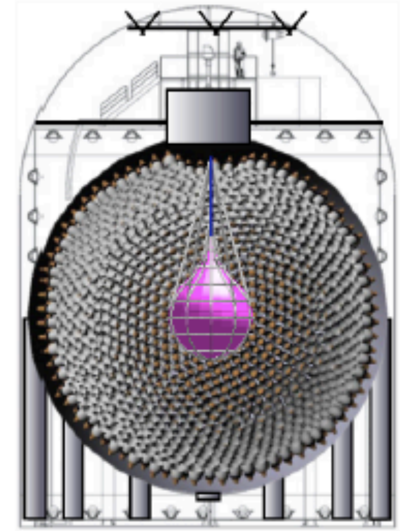
Jan. 22, 2019 ~

Preliminary result with 132.7-days live-time

$T^{0\nu}_{1/2} > 4 \times 10^{25}$ year (90% C.L.)

Y. Gando, "First results of KamLAND-Zen 800", TAUP conference 2019

<u>Future</u>



KamLAND2-Zen

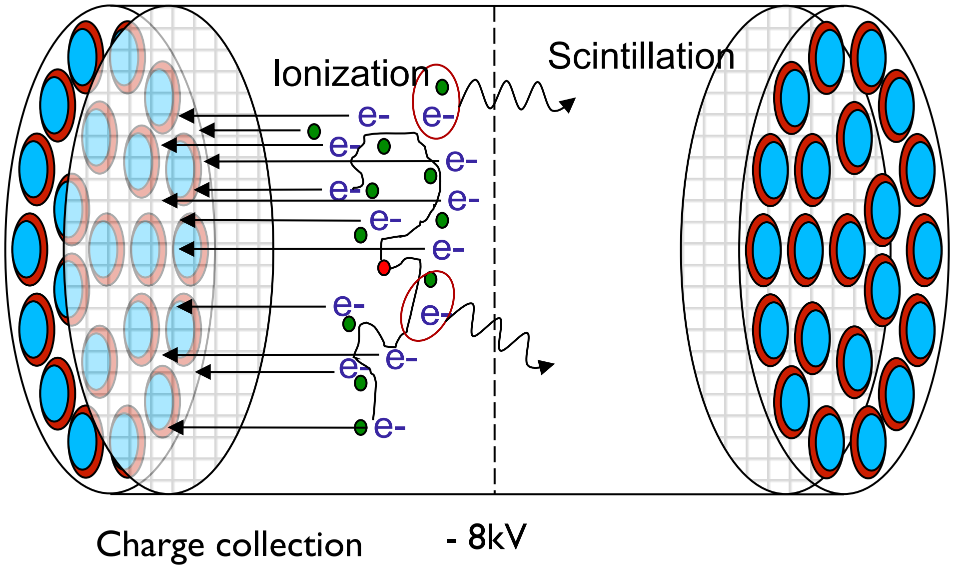
Xenon ~ 1 ton

Increase energy resolution through better light detection efficiency.

target sensitivity 20 meV

Use Liquid Xenon Time Projection Chambers (TPC) to Search for 0νββ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.

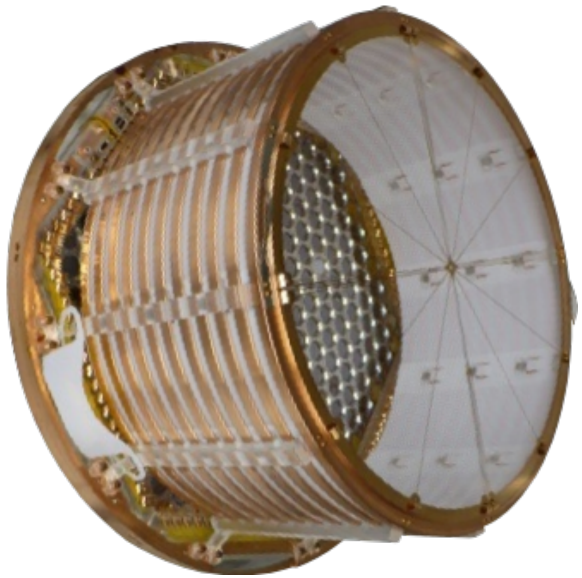


Example of TPC schematics (EXO-200)

EXO-200 is a LXe detector with ~110 kg active volume, operated from 2011-2018. It has demonstrated key performance parameters for 0νββ search, and has set a lower limit on the 0νββ half-life at 3.5x10^{25} yrs with its entire dataset.

nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach 0νββ half-life sensitivity of ~ 10^{28} yrs.

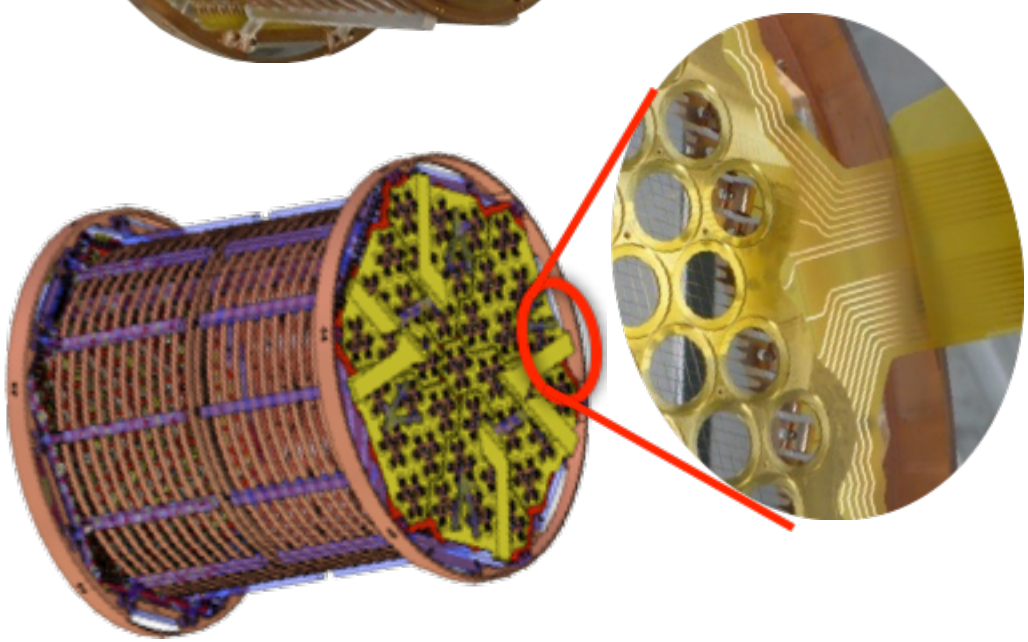
The EXO-200 TPC



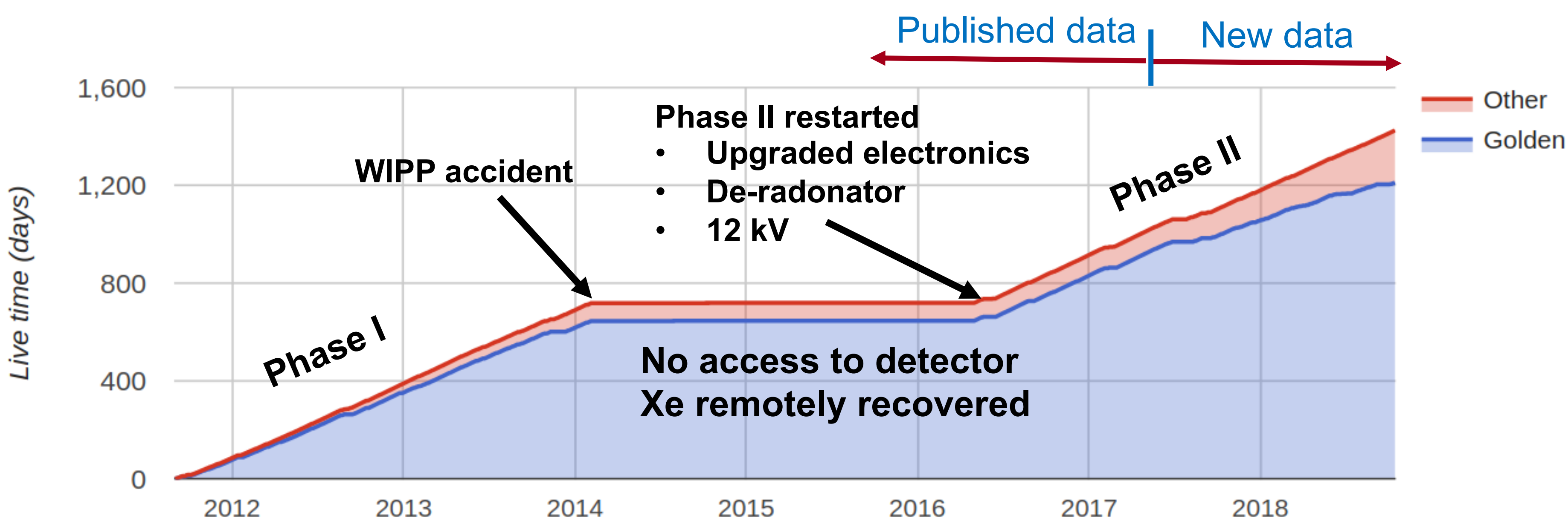
Two almost identical halves reading

ionization and 178 nm **scintillation**, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60^{o} (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- All signals digitized at 1 MHz, ±1024 μs around trigger (2 ms total)
- Drift field 376 V/cm
- TPC housed in a copper vessel with 1.37 mm wall thickness



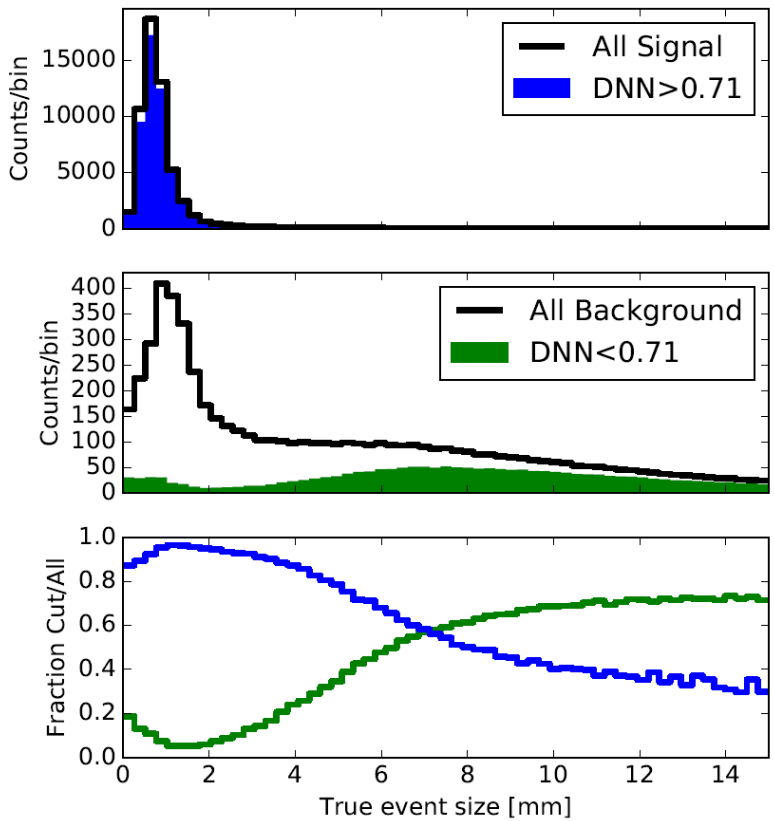
EXO-200 Timeline

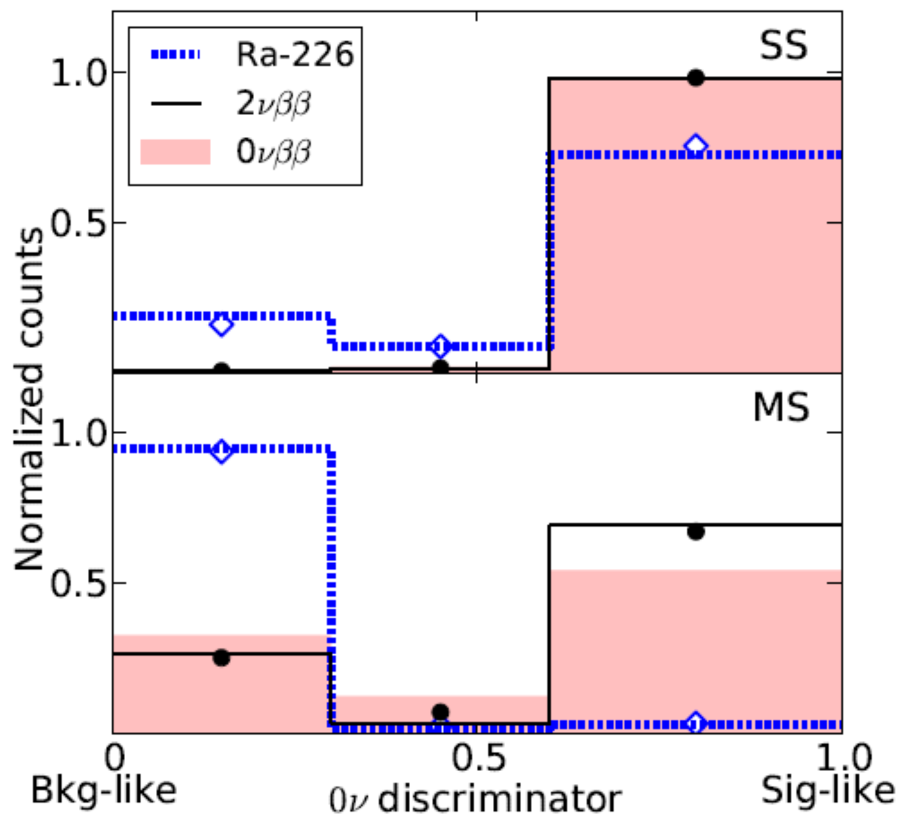


- **Operation concluded in Dec 2018, with 234.1 kg·yr total exposure of ^{136}Xe**
- Phase I from Sep 2011 to Feb 2014
  - Most precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510****, 229 (2014)*
- Phase II operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data from upgraded detector, *Phys. Rev. Lett.* ***120****, 072701 (2018)*
  - **New result with the Complete data set posted on arXiv 1906.02723**

Using Deep Learning for 0νββ Search

Use Deep neural network (DNN) bases to $0\nu\beta\beta$ discriminator, more powerful to boosted decision tree (BDT) based ones

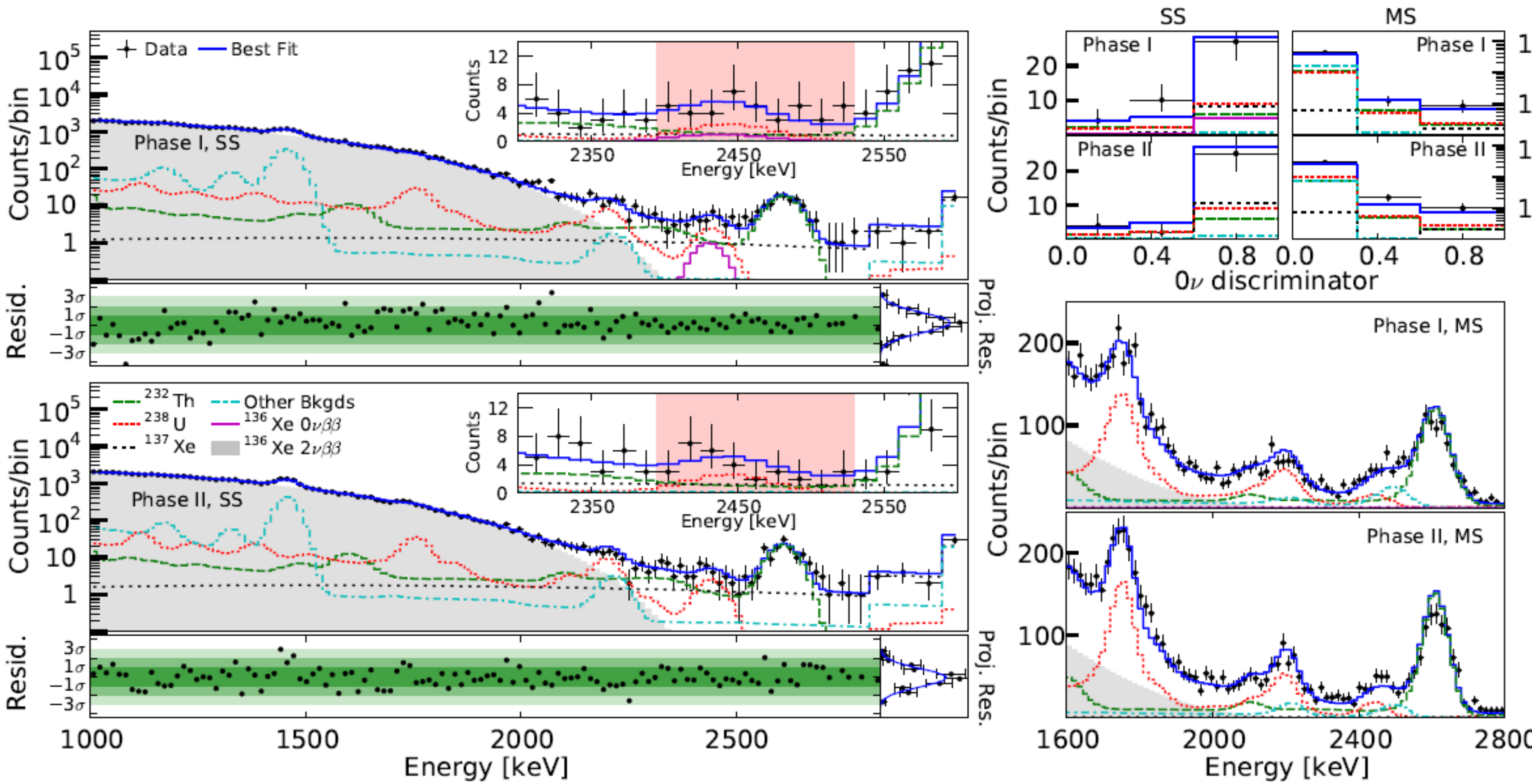




- DNN trained on images built from U-wire waveforms
- Signal/background identification efficiency clearly correlates with the true event size

- 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

EXO-200 0νββ search with complete dataset



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

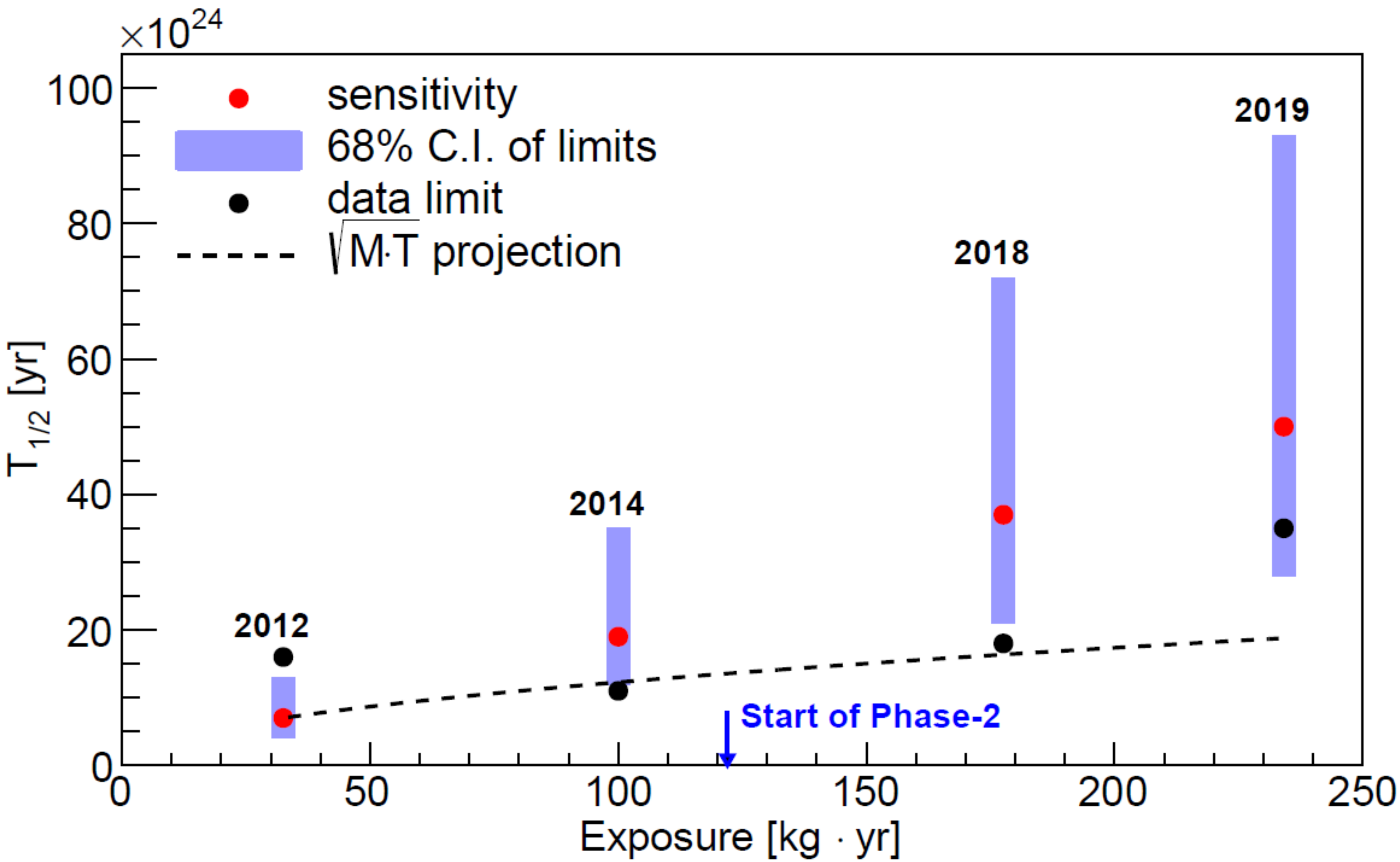
[arXiv:1906.02723]

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

Evolution of EXO-200 0νββ Results

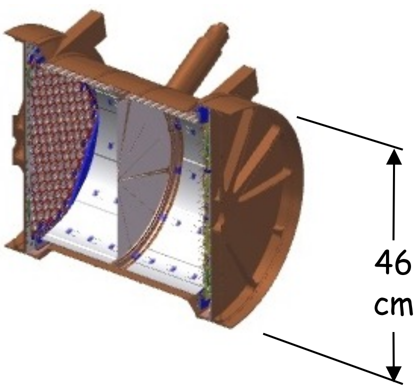


The sensitivity gains continue to improve faster than statistics due to improvements in hardware and analysis.

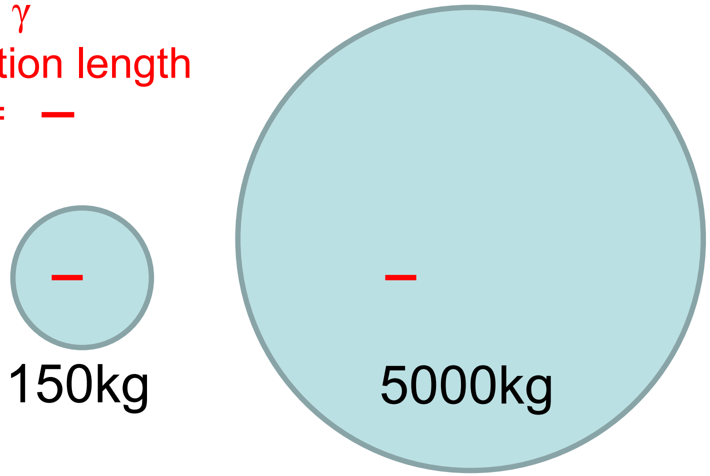
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: arXiv 1906.02723

From EXO-200 to nEXO

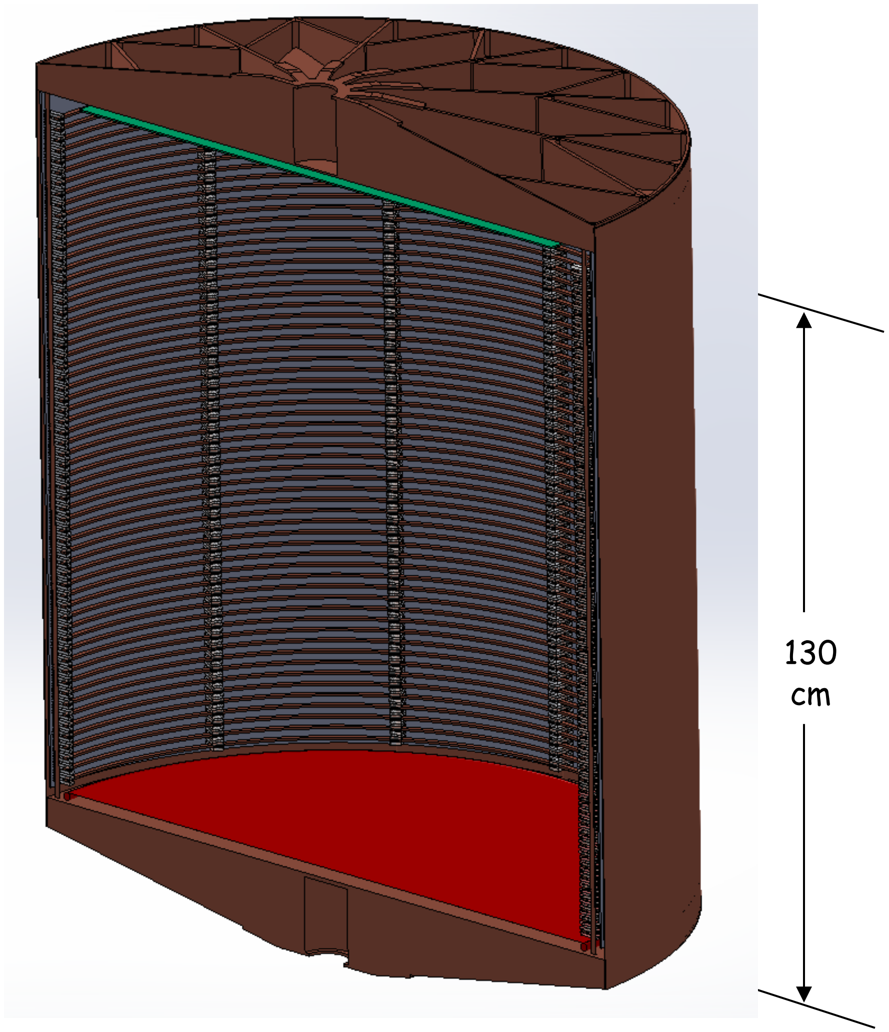
EXO-200 as a technology demonstrator



2.5MeV γ
attenuation length
8.5cm = –



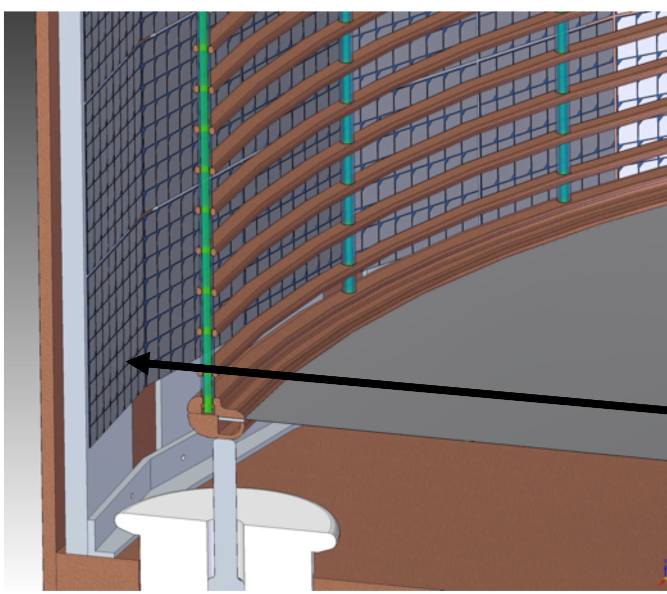
nEXO: a 5000 kg enriched LXe TPC

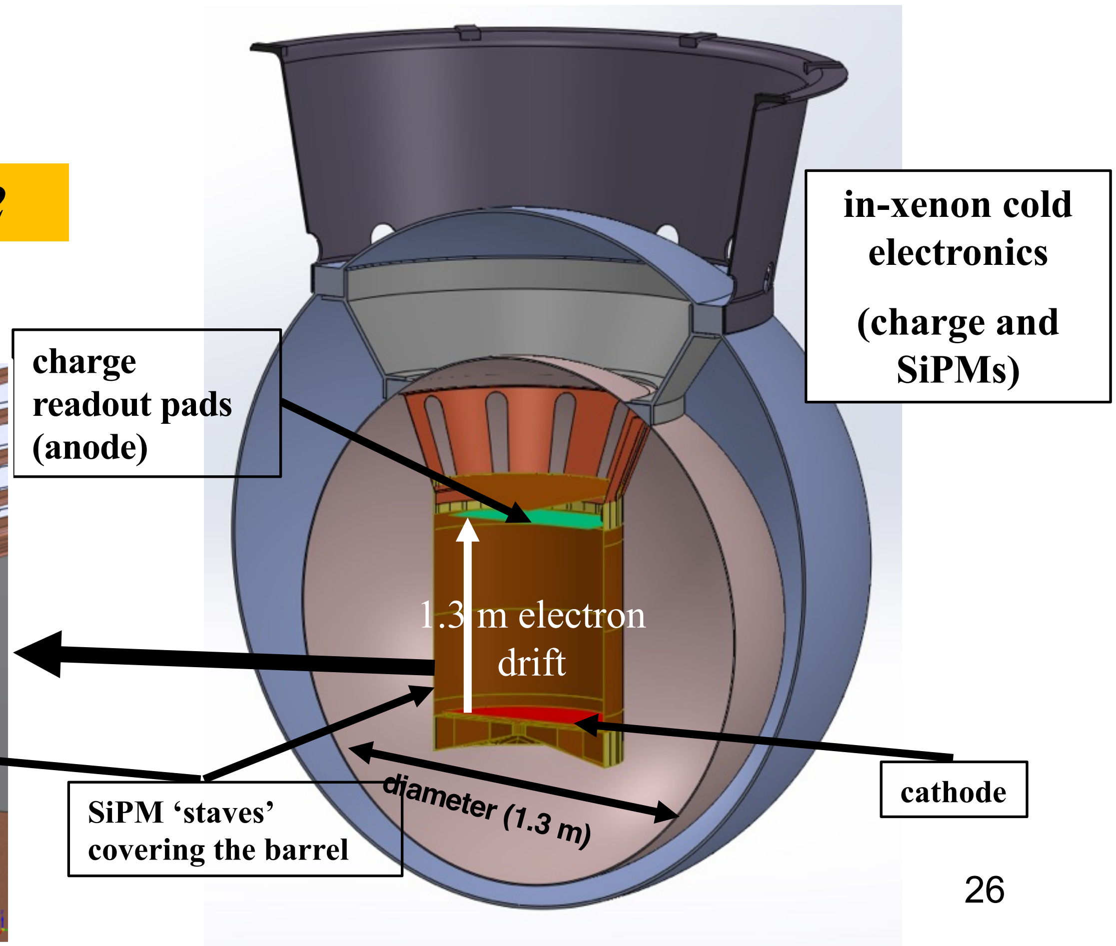


Pre-Conceptual Design of nEXO

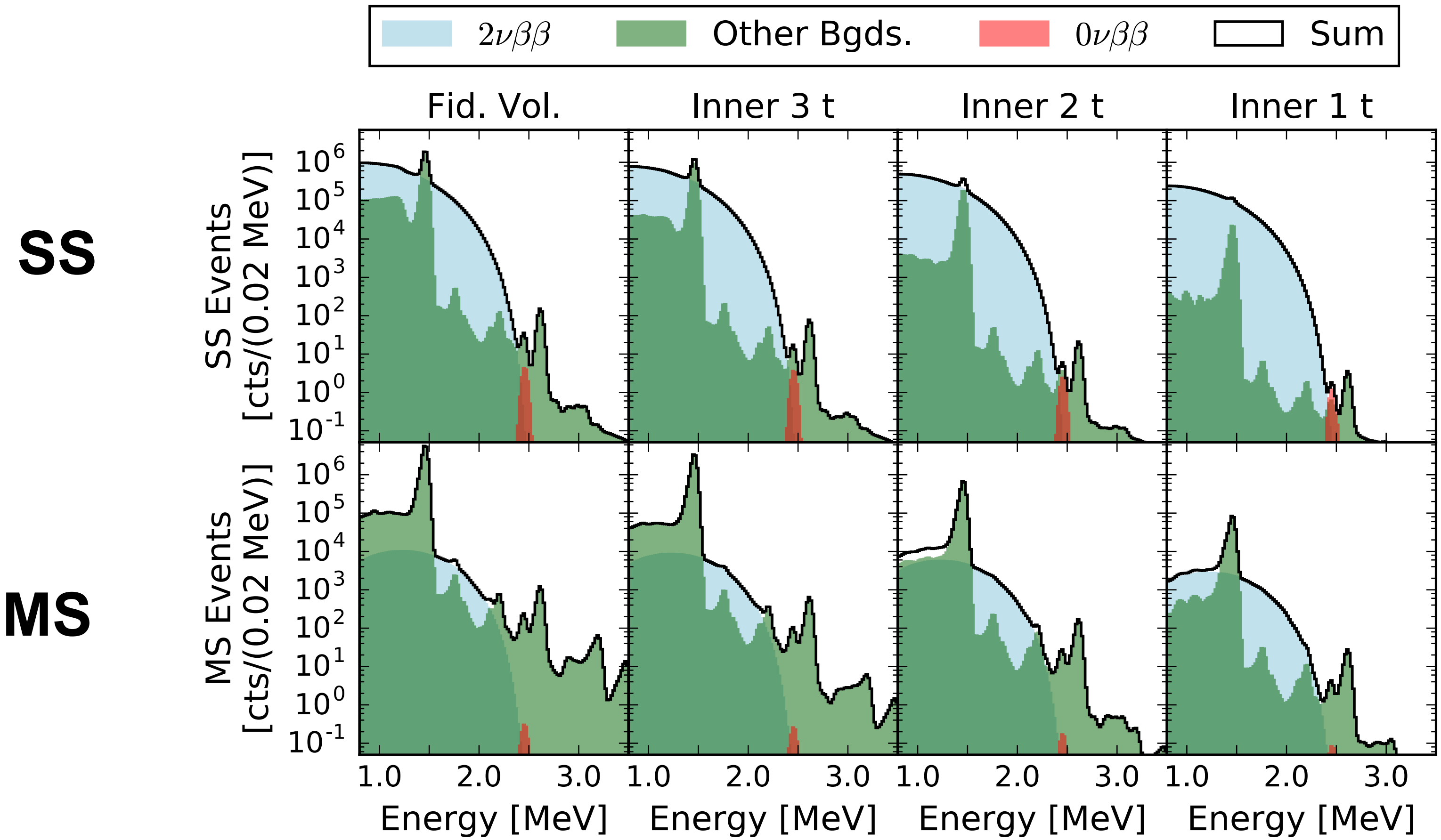
- **5 tones of single phase LXe TPC.**
- **Ionization charge collected by anode.**
- **178nm lights detected by ~4 m^2 SiPM array behind field shaping rings.**
- **Combining light and charge to enhance the energy resolution.**

nEXO pre-CDR, arXiv:1805.11142





nEXO as a Discovery Tool

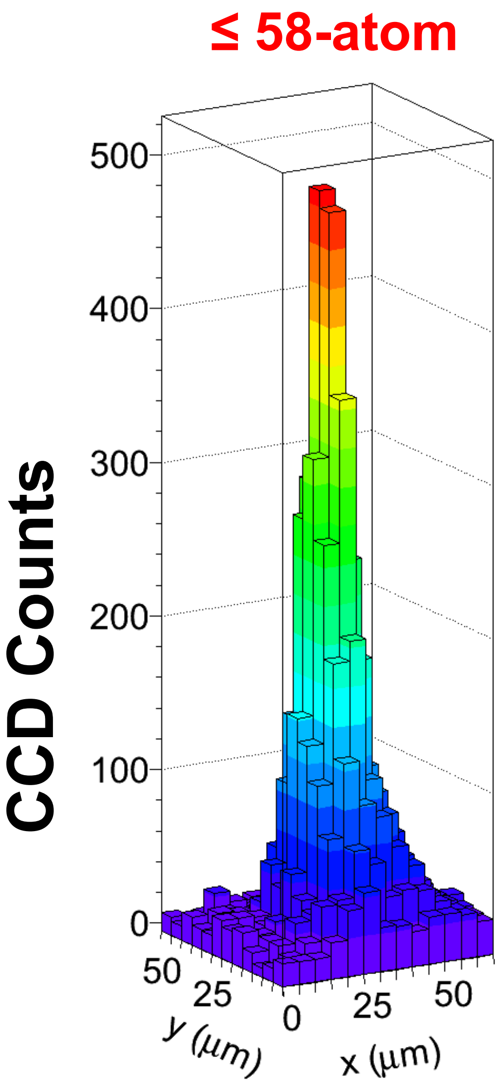


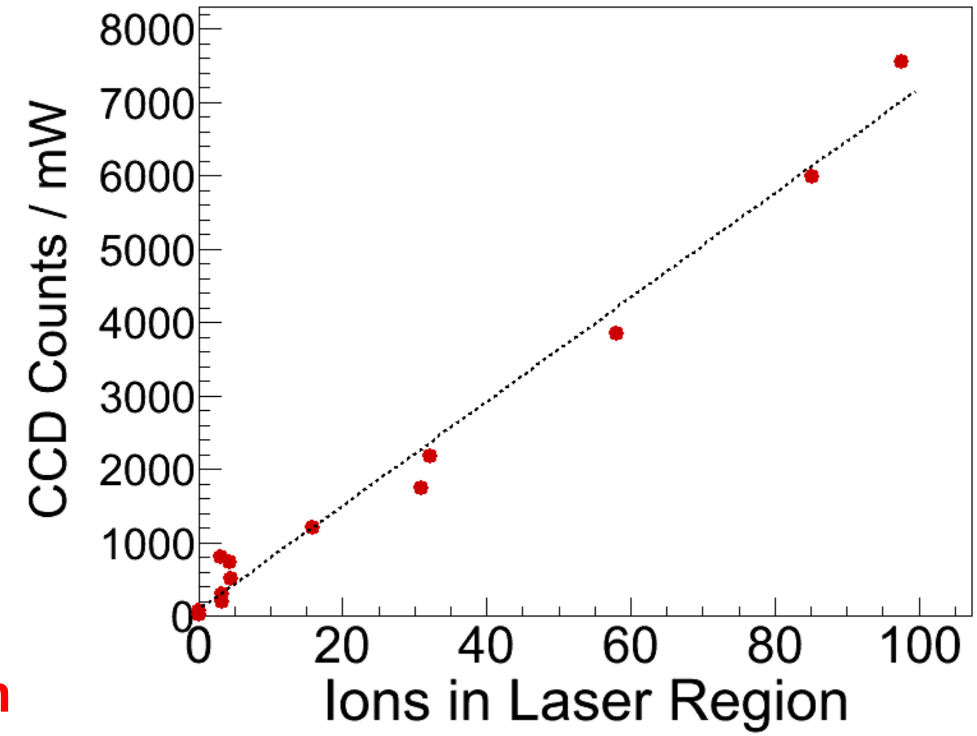
10 yr data, $0\nu\beta\beta$ corresponding to $T^{1/2} = 5.5\times10^{27}$ yr

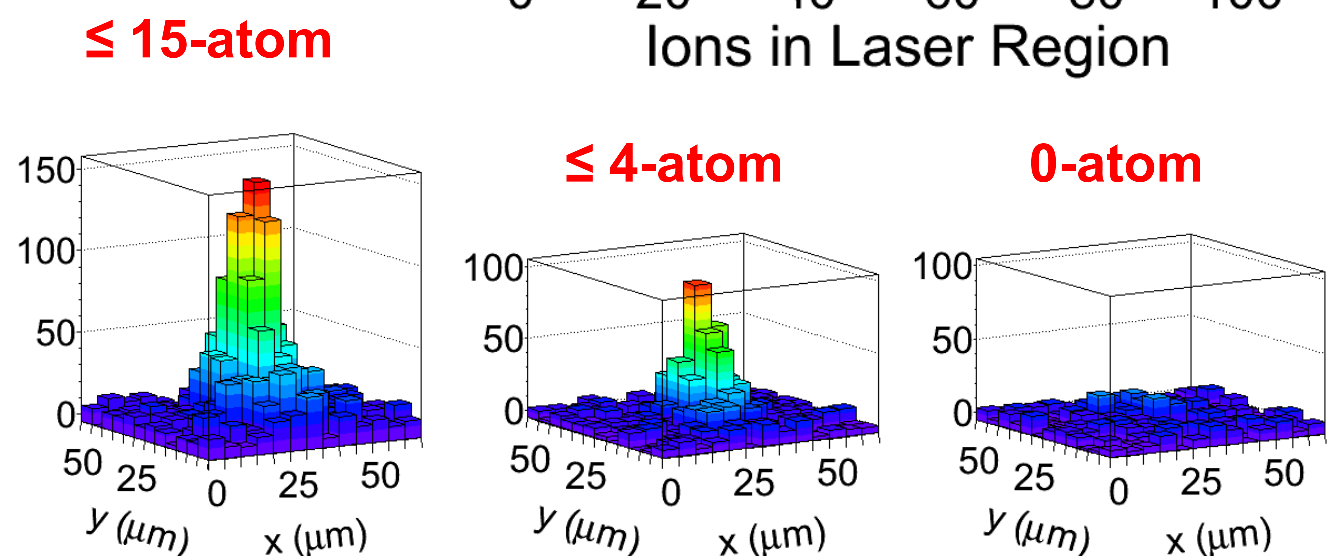
In nEXO, background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position. ➔ ***The power of the homogeneous detector***

Tagging ββ decay daughter Ba

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

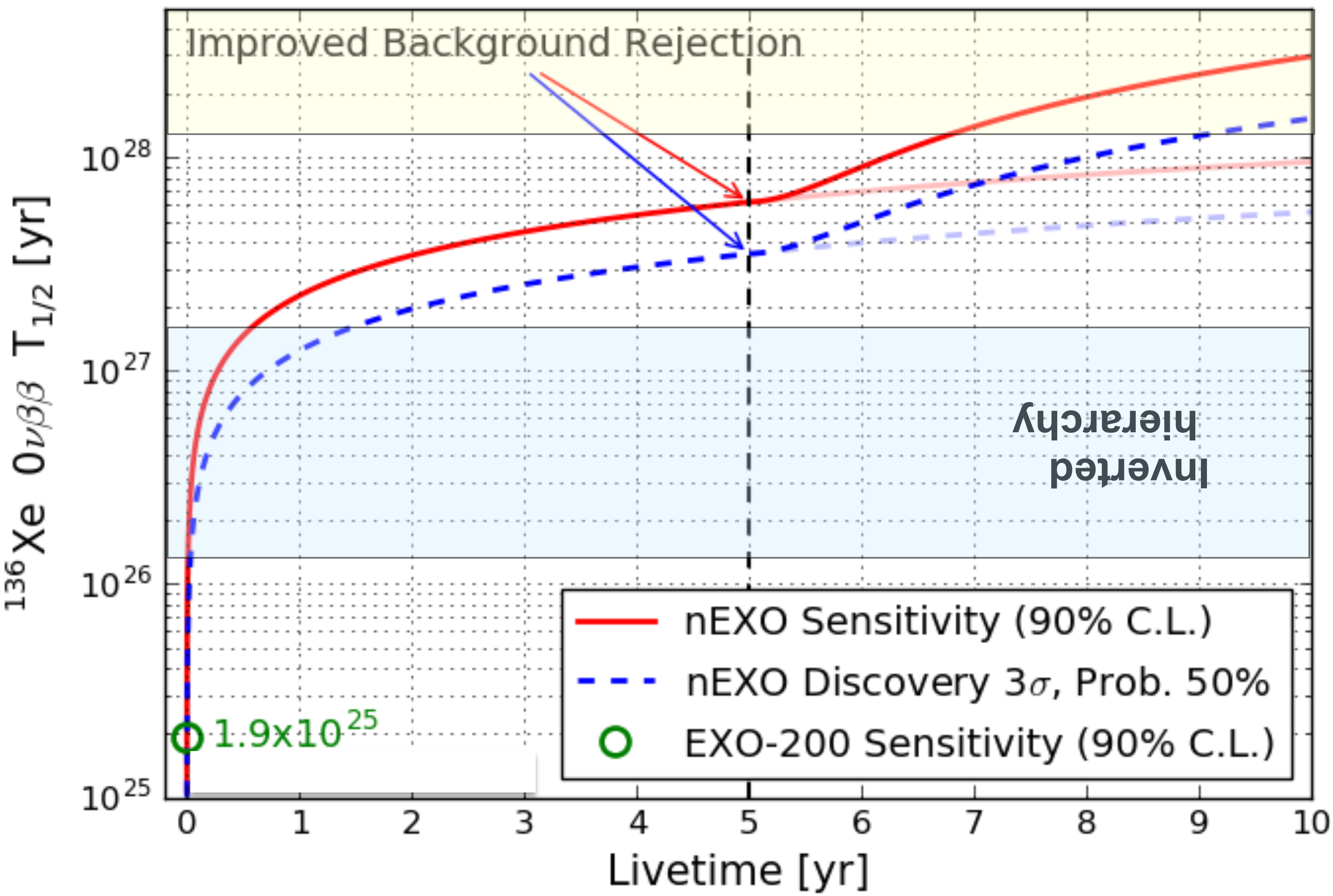






C. Chambers et al., Nature, **569**, 203–207 (2019)

nEXO Sensitivity (with Ba tagging)



Normal hierarchy

GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

nEXO Sensitivity Paper: arXiv:1710.05075

Discovery potential of next gen experiments

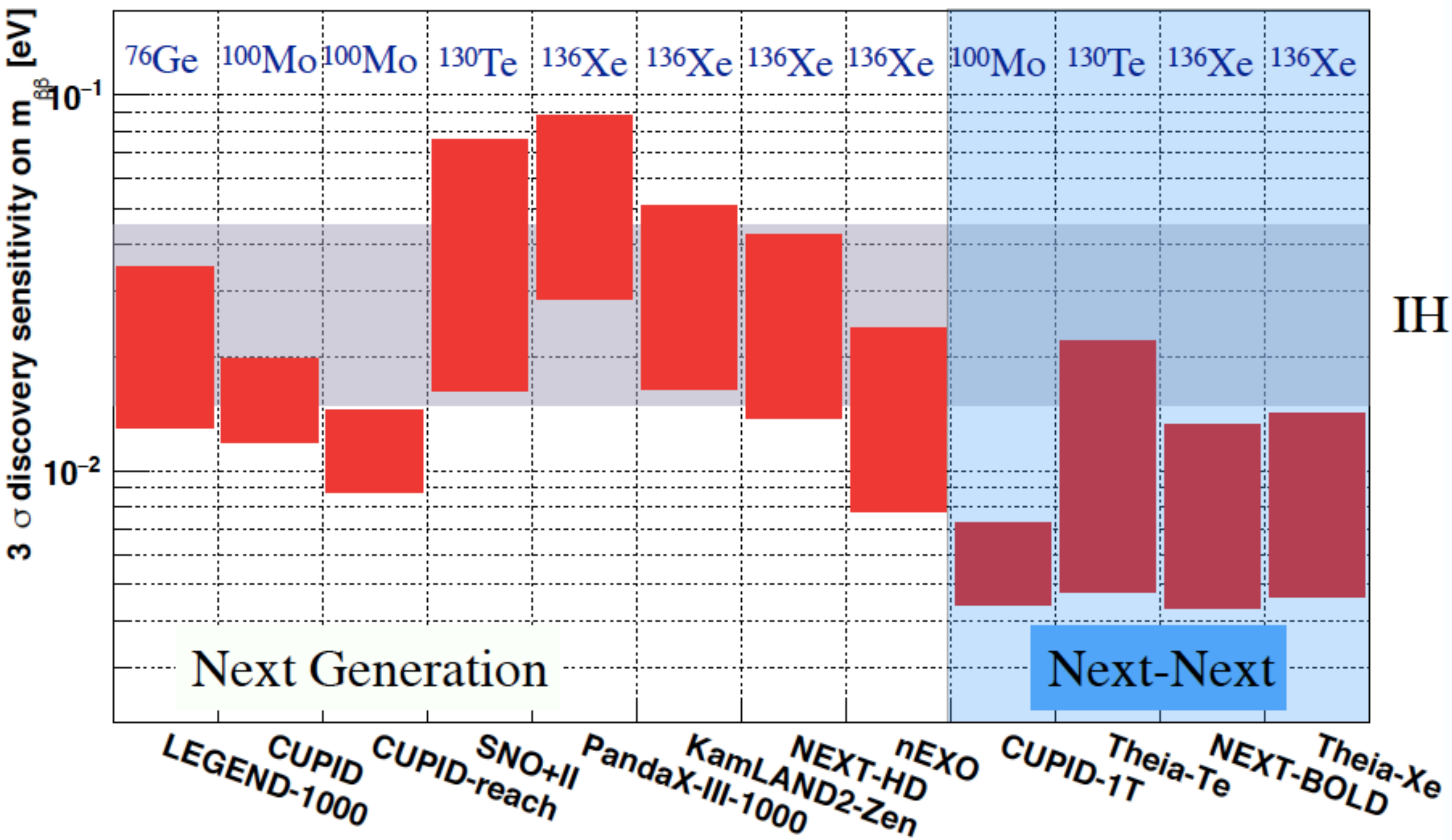


Figure from G. Benato, Y.G. Kolomensky
Methodology from Phys. Rev. D96, 053001 (2017)

Summary and Outlook

- If neutrinos are Majorana fermions, their small masses can rise naturally from the “see-saw” mechanism.

- Neutrinoless double beta decay search is the most sensitivity probe for Majorana neutrinos.

- Results from ~100 kg yr searches (KamLAND-Zen, EXO-200, CUORE, GERDA, and MAJORANA) are here with sensitivities to half-lives > 10^{25} yr! No discovery yet…

- Tonne-scale searches for $0\nu\beta\beta$ can explore the inverted hierarchy region, and are complementary to other searches for new physics in the particle physics community.