UC San Diego

Neutrinoless Double Beta Decay

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CCEPP summer school

Lecture II, 8/25/2013

Lecture Outlines

Lecture 1:

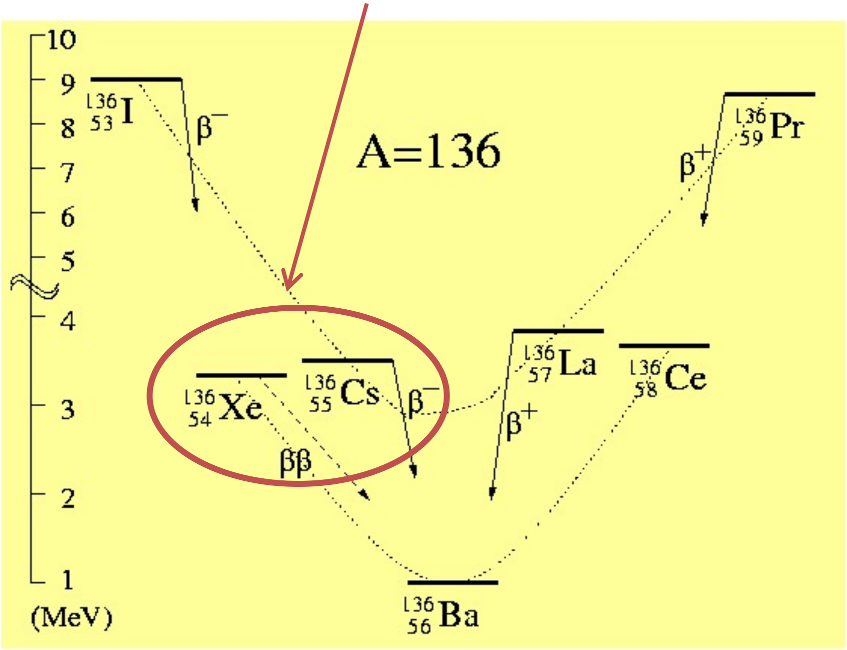
- Brief review of theory of neutrino mass
- Majorana vs. Dirac neutrinos
- Experimental ideas to test Majorana neutrinos
- Neutrinoless double beta decay experiment overview
- Experimental sensitivity and background sources

Lecture 2:

- **Tracking detectors**
- **Bolometers**
- **Semiconductor**
- **Liquid Scintillators**
- **TPCs**

Double Beta Decay

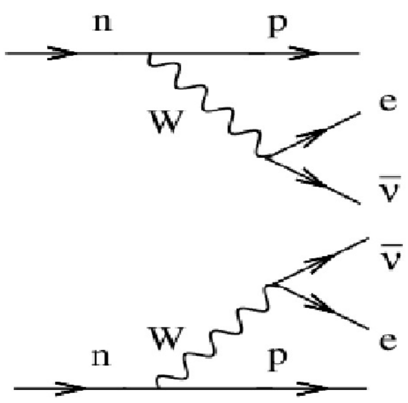
Observable if single beta decay is forbidden



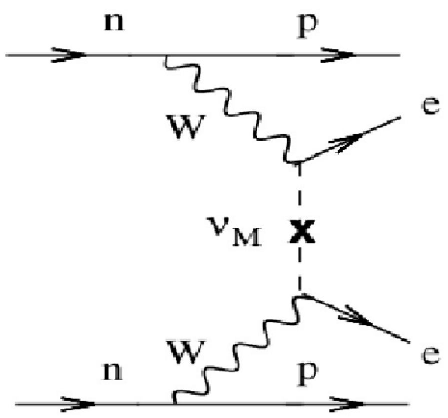
Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

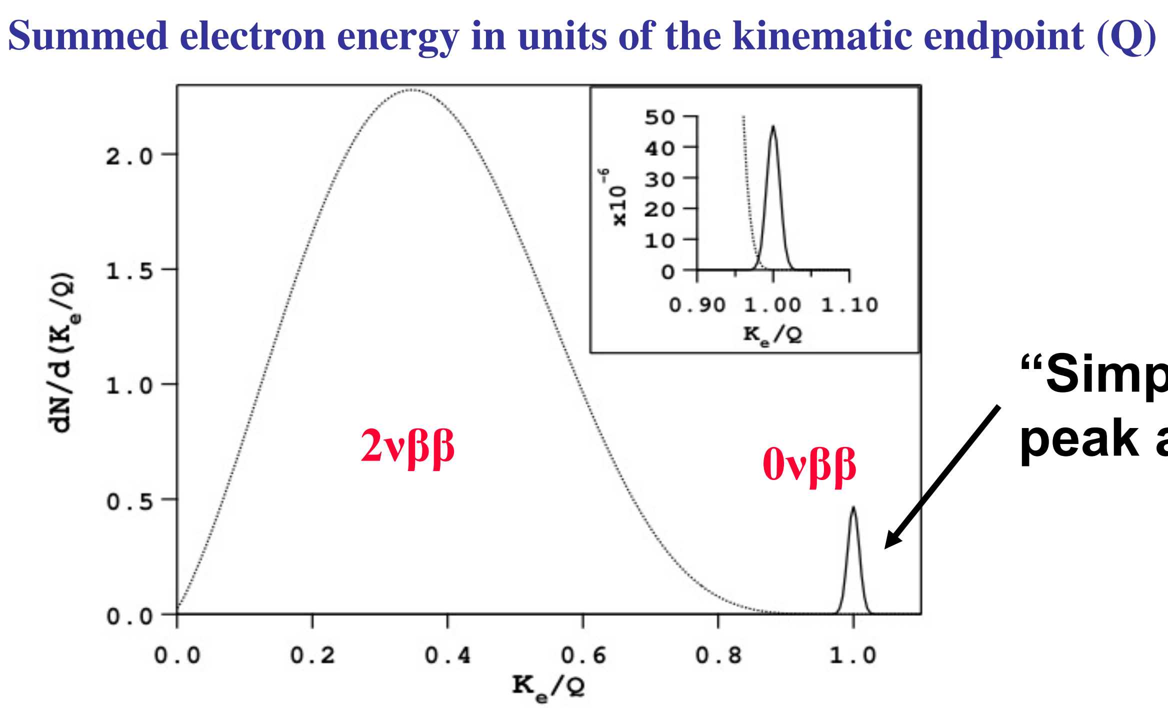
Two neutrino double beta decay



Neutrinoless double beta decay



Detecting $0\nu\beta\beta$

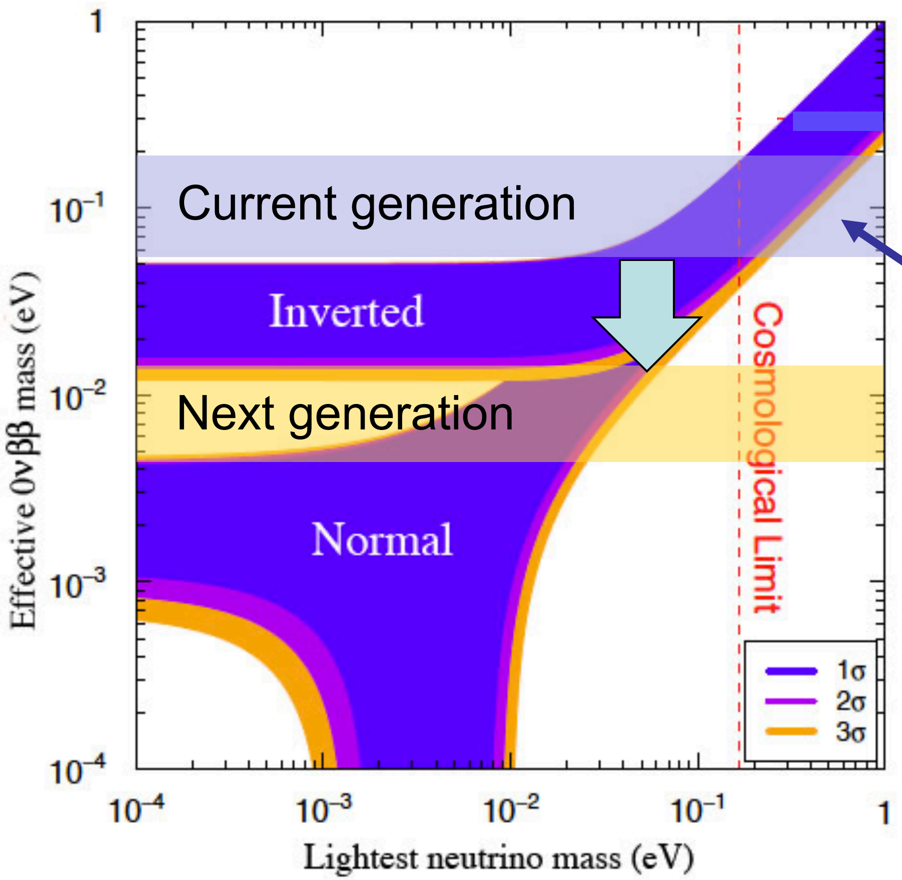


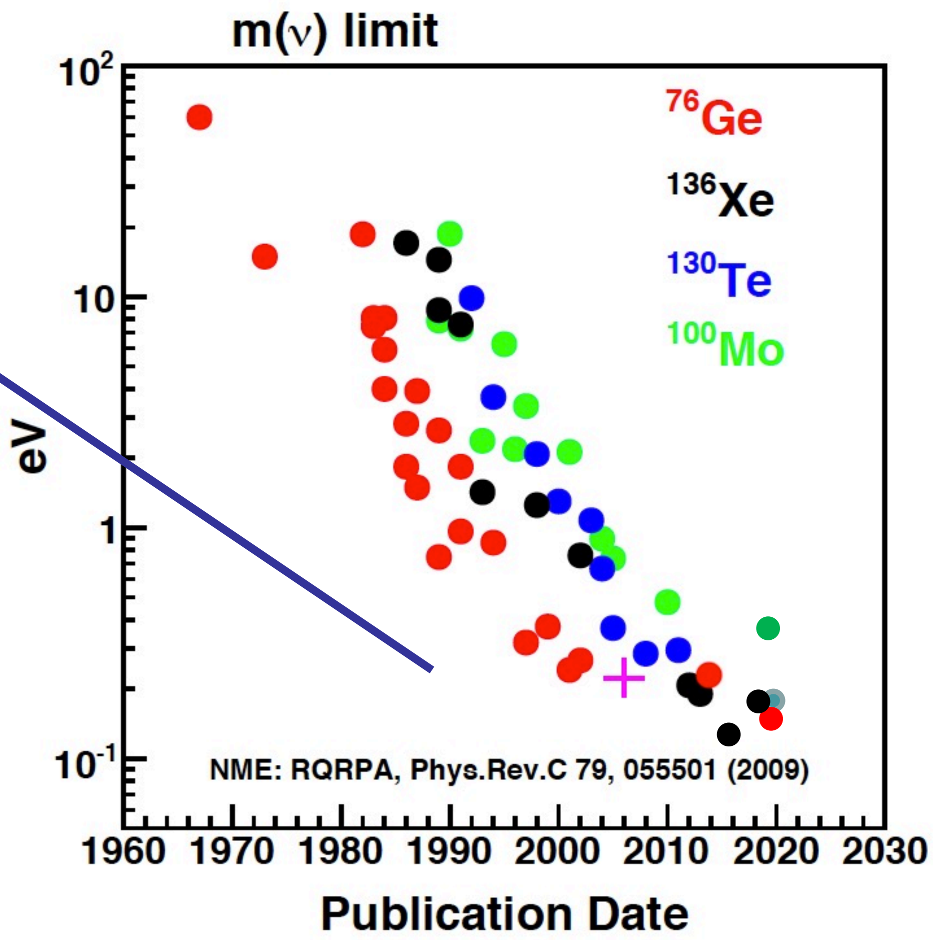
"Simple", Look for the peak at the end point!

But needs:

- Good Energy resolution
- Excellent background discrimination against gammas and alphas
- Low radioactive contamination for detector construction

$0\nu\beta\beta$ Historical Progress

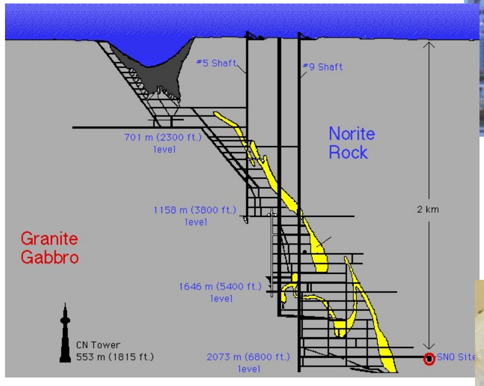




- Current generation experiments at 100 kg scale, has started to probe the inverted mass hierarchy region.
- Next generation tonne scale experiment aims to improve the neutrino mass sensitivity by another factor of 10.

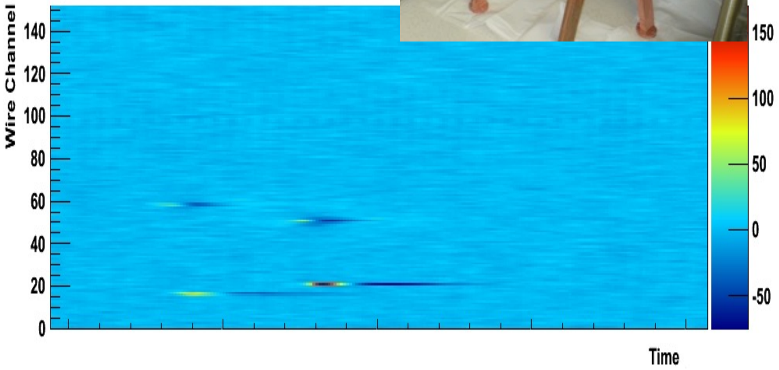
Four Pillars of Modern $0\nu\beta\beta$ Experiments

1) Isotopic enrichment of the source material
(that is generally also the detector)



2) Underground location to shield
cosmic-ray induced background

3) Ultra-low radioactive contamination for
detector construction components

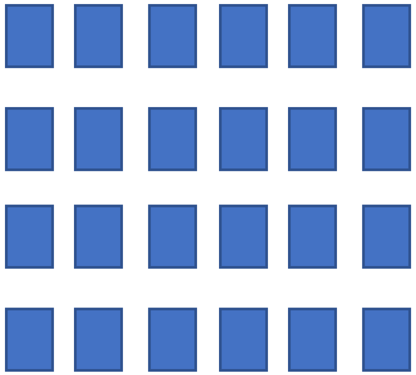


4) New detector techniques for
background discrimination

(This improves for large detectors)

$0\nu\beta\beta$ experiments

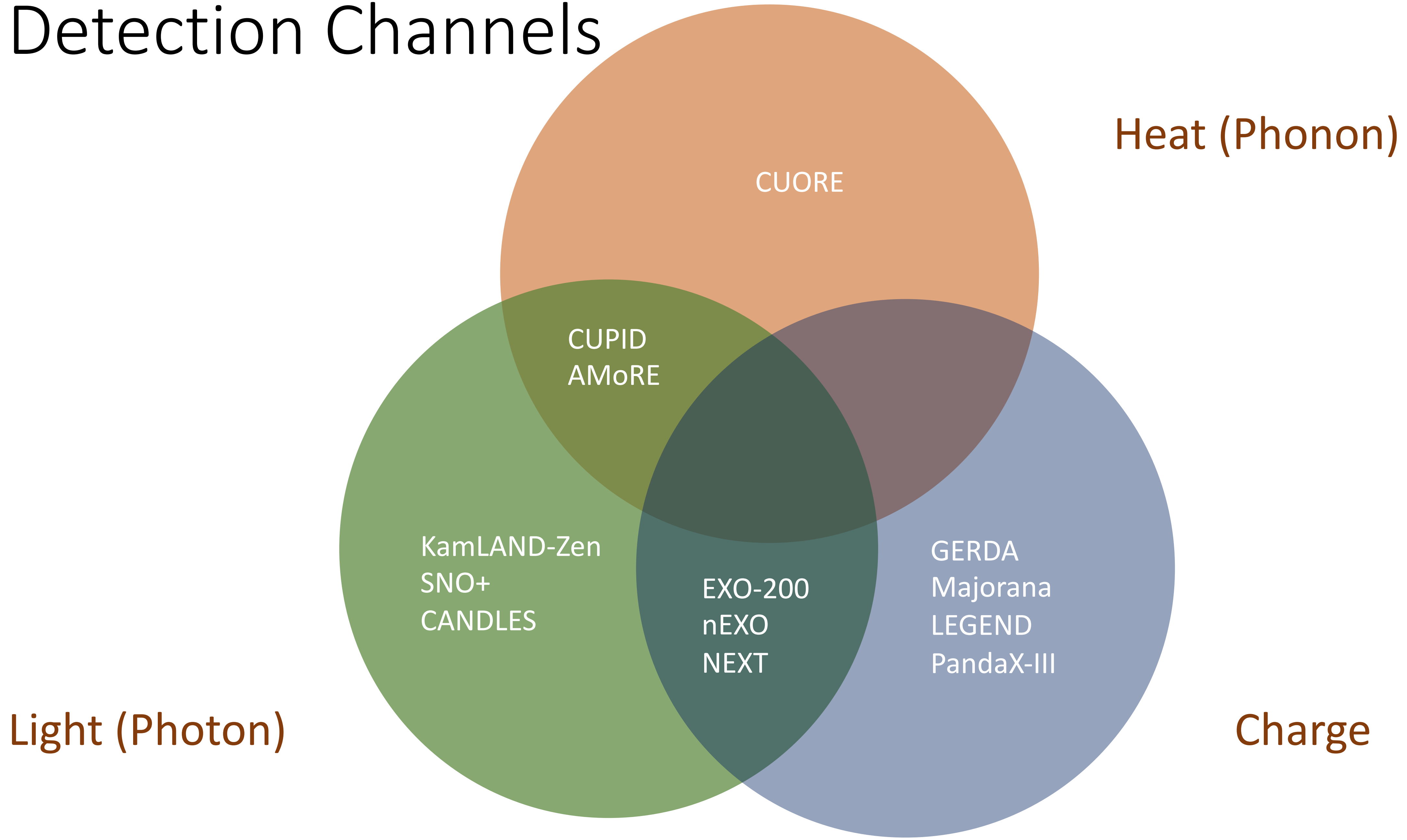
- Tracking detectors (superNEMO)
- Bolometers (CUORE, CUPID, AMoRE, CANDLE IV)
- Semiconductor (LEGEND)
- Liquid Scintillators (KamLAND2-Zen, SNO+, Theia)
- TPCs (NEXT, PandaX, nEXO)



modular

monolithic

Detection Channels



Background sources for $0\nu\beta\beta$ experiments

- α background
  - Short range (a few MeV), mostly surface events
- β background
  - Can be both external and internal, short range
- γ background
  - mostly external, difficult to shield
- n background
  - Can activate material and (n, α) reaction
- Cosmic muon
  - Cosmogenic background
- Neutrino background

Material Selection and Qualification

Experiments undergo massive effort on material radioactive qualification using:

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

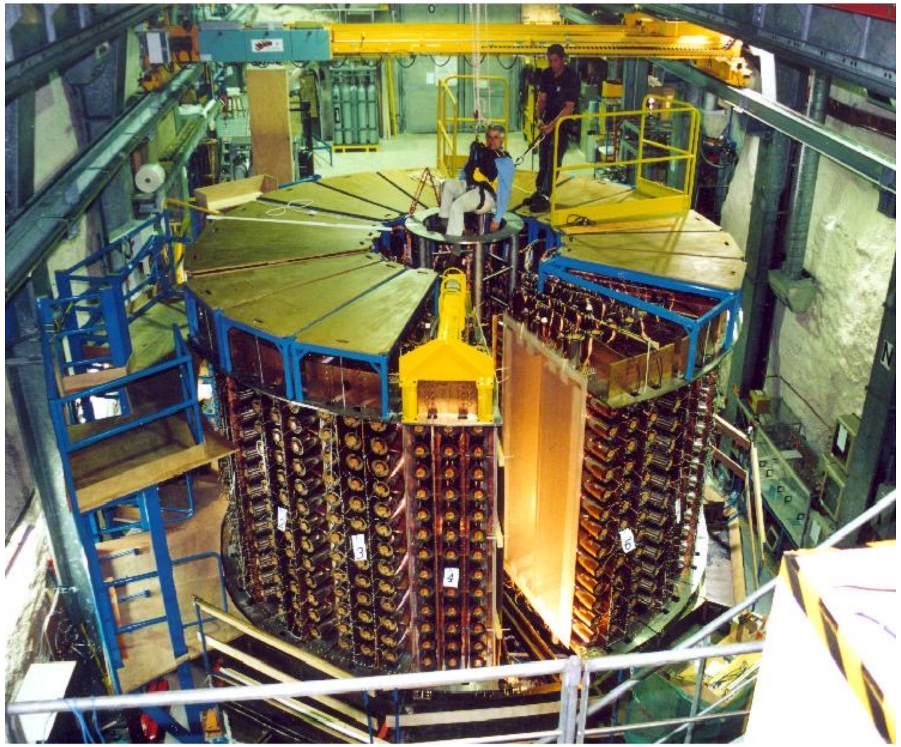
Background impact of each component is evaluated by MC simulation using the measured radioactive.

Background Suppression Techniques

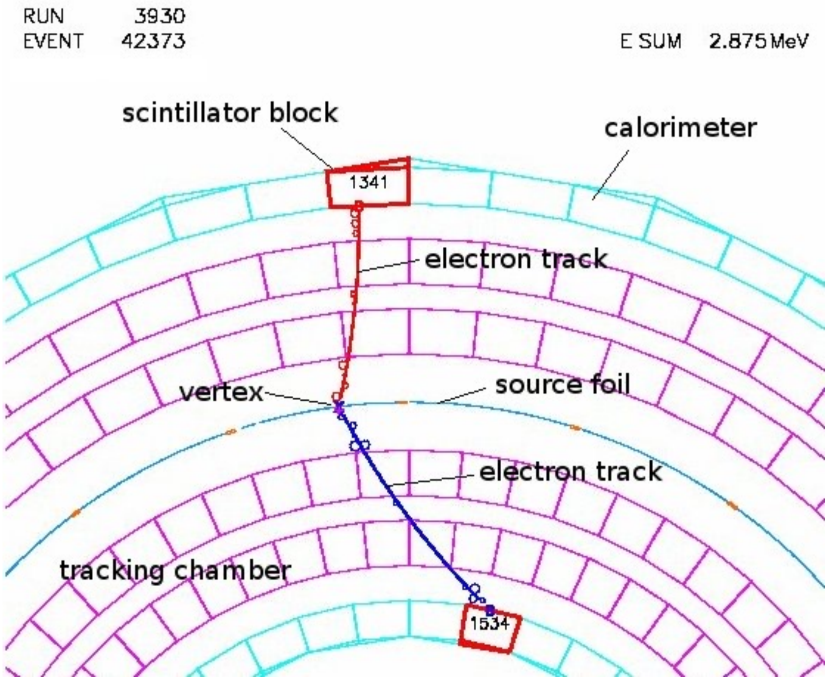
- Energy measurements
- Event multiplicity/ topology
- Event location (surface/bulk, distance to wall)
- Particle identification: separating α from e^- / γ
- Time coincident information and veto systems
- Tagging the daughter ions

Modern experiments uses a combination of the techniques.

Tracking Detector: NEMO-3 (2003 – 2011)



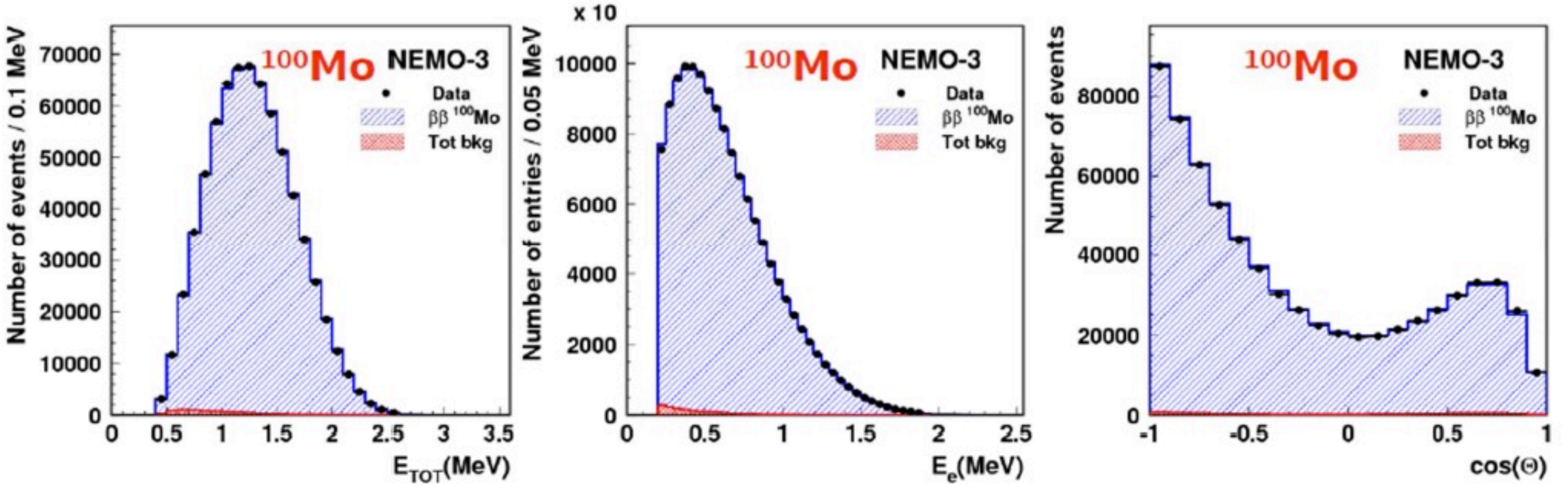
NEMO-3 detector



An ^{100}Mo $2\nu\beta\beta$ event

- Double beta decay isotope are in the form of thin foils ~ 60mg/cm^2.
- Decay electrons are tracked with Geiger mode drift tubes in modest magnetic field.
- The energy of the electrons are measured by plastic scintillators coupled to PMTs.

NEMO-3: 2νββ Results



Electron sum energy

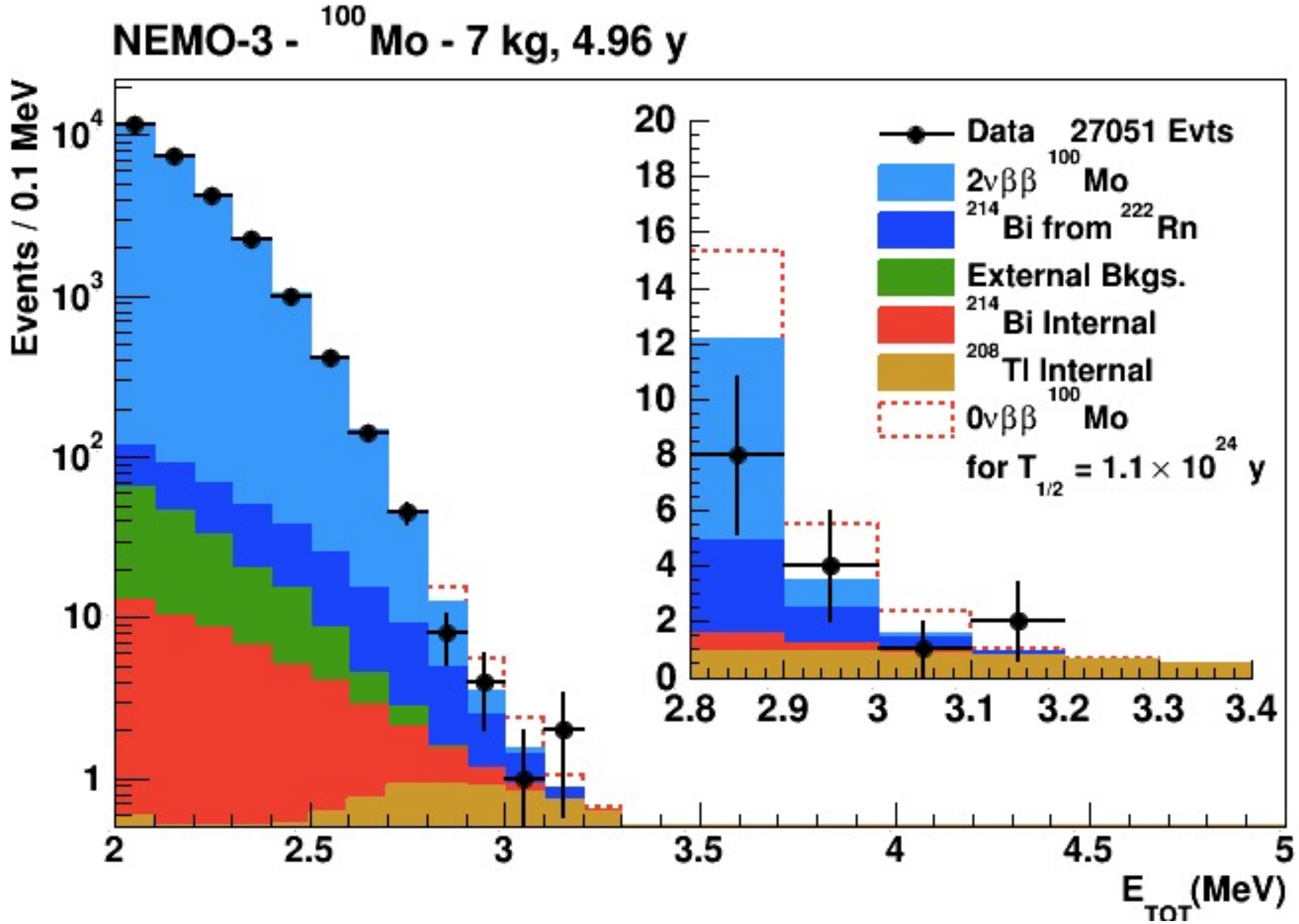
Single electron energy

Angular distribution

^{100}Mo $T_{1/2}^{2\nu\beta\beta}$:[7.16 ± 0.01 (stat) ± 0.54 (sys)] 10^{18} y

- Measured 2νββ half life for ^{100}Mo, ^{82}Se, ^{116}Cd, ^{130}Te, ^{150}Nd, ^{96}Zr and ^{48}Ca.
- Ratio of Signal/Background > 70, most halflife measurements are systematic limited
- Beautiful spectra of single electron energy and angular distribution between two decay electrons demonstrate the power of the tracking method.

NEMO-3: 0νββ Result (^{100}Mo)



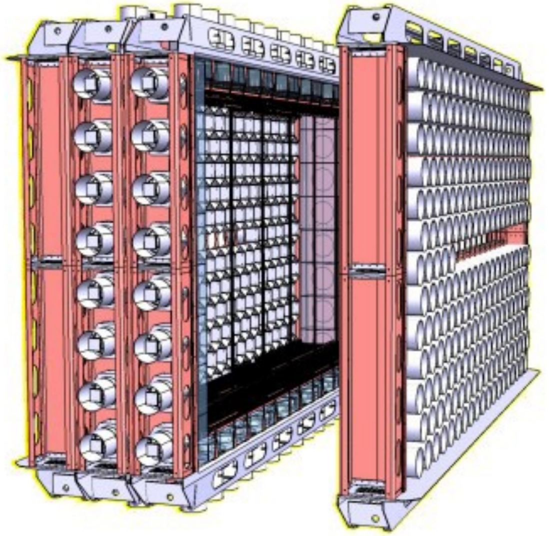
Exposure: 34.3 kg yrs

$T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ yrs (90%C.L.)

$m_{\beta\beta} < 0.33 - 0.62$ meV

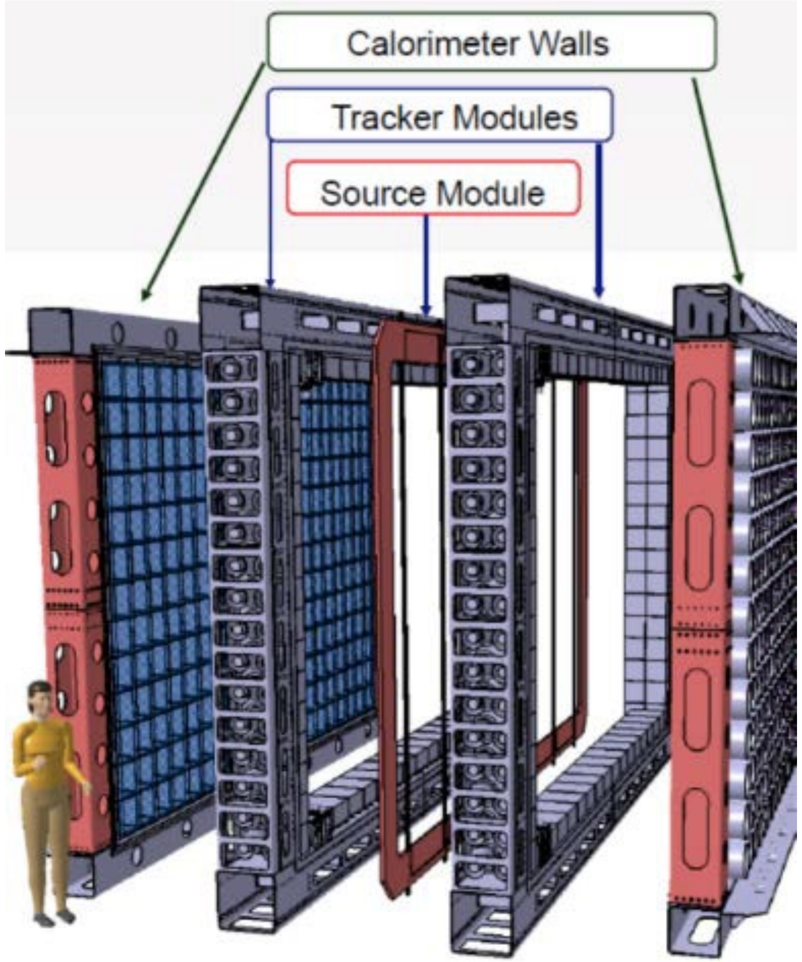
Physical Review D 92(2015) 072011

NEMO-3 → SuperNEMO



NEMO-3	Super-NEMO
1 cylindrical module	> 20 planar modules
7 kg ^{100}Mo	100 kg ^{82}Se (or ^{150}Nd, or ^{48}Ca) (longer $2\nu\beta\beta$ halflife)
8% FWHM @ 3MeV	4% FWHM @ 3MeV
~ 100 μBq/kg (^{208}Tl) < 300 μBq/kg (^{214}Bi) ~ 5.0 mBq/m^3 (^{222}Rn)	< 2 μBq/kg (^{208}Tl) < 10 μBq/kg (^{214}Bi) < 0.15 mBq/m^3 (^{222}Rn)
$T_{1/2}^{0\nu} > 10^{24}$ yrs	$T_{1/2}^{0\nu} > 10^{26}$ yrs

Tracking detector



SuperNEMO Demonstrator
assembled in November 2018

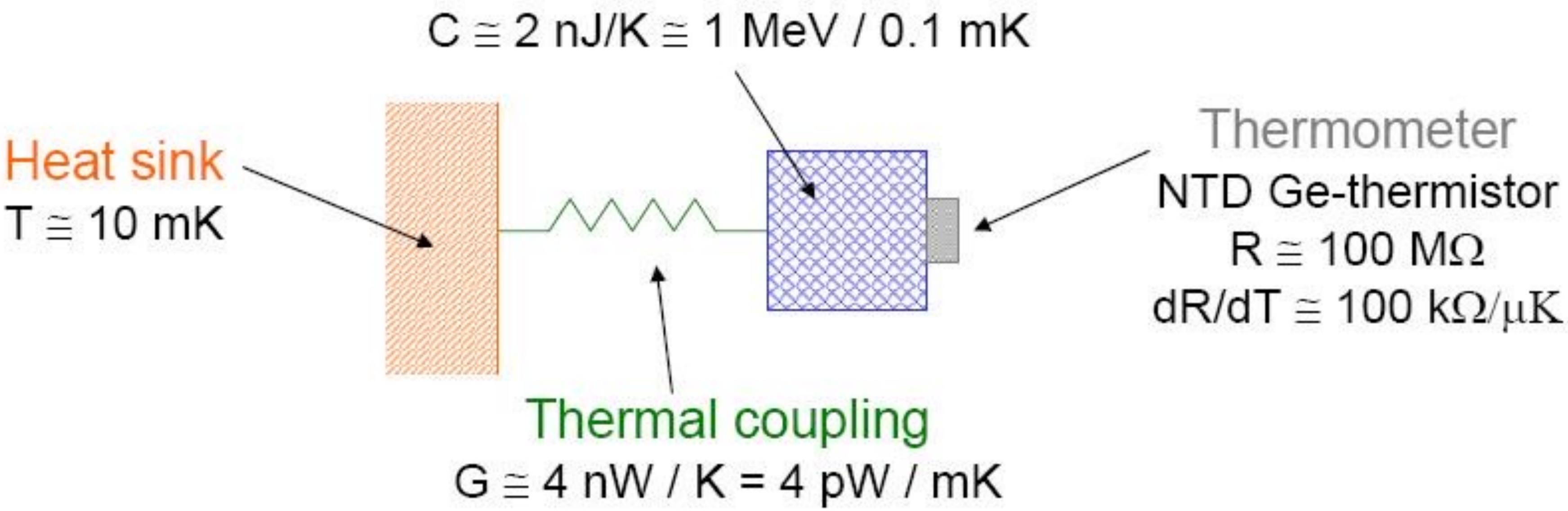
Strengths

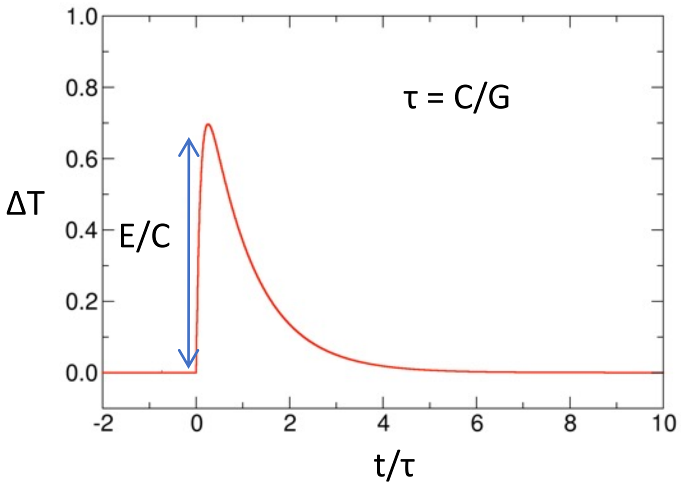
- Source decoupled from detector and can use any solid isotope
- Particle ID and background rejection with track and timing information
- Angular distribution and individual β energy can be used to study $\beta\beta$ mechanism

Weaknesses

- Poor energy resolution
- High cost in scaling up to large isotope mass

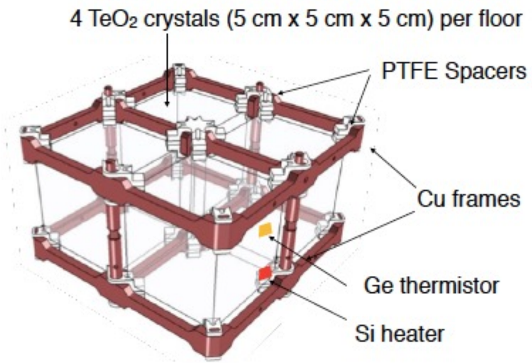
Cryogenic Bolometer: ^{130}Te

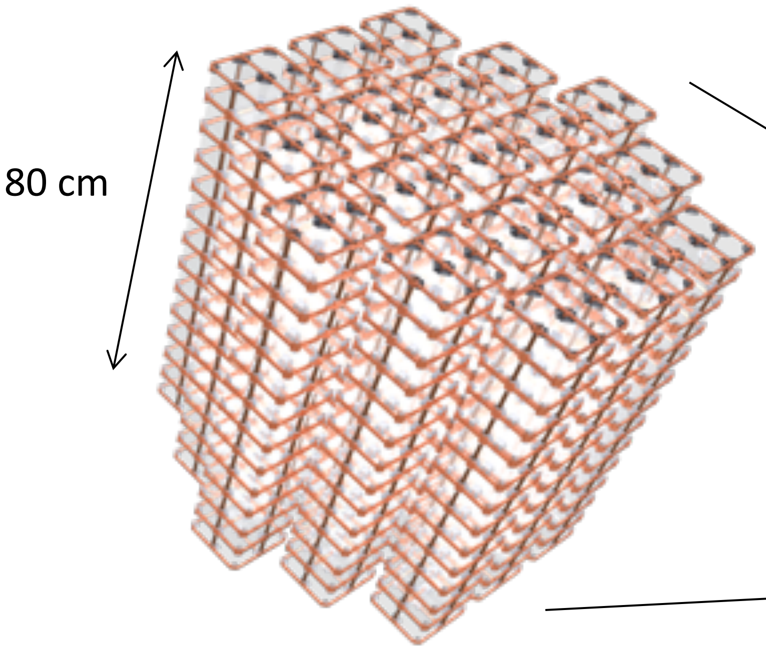


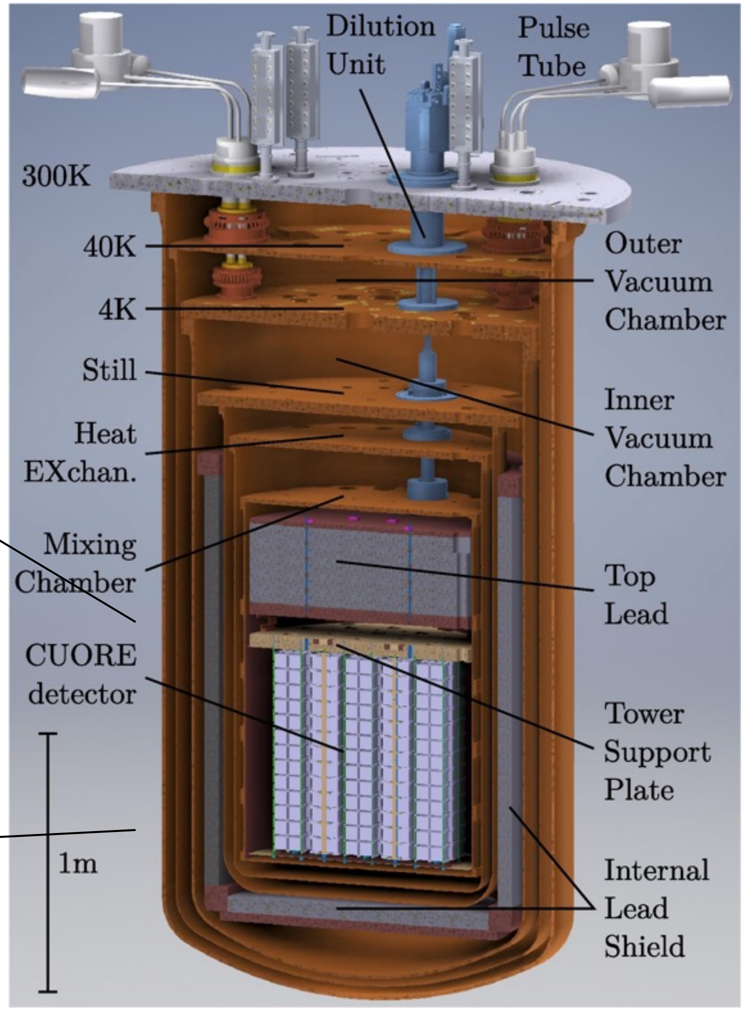


- Measure total energy deposited in the crystal.
- Techniques applicable to many isotopes. Te has the highest natural abundance.
- High energy resolution, 7-9 keV @ 2530keV.
- No information about the particle ID, external γ and surface degraded α are major background concerns.

CUORE: Cryogenic Underground Observatory for Rare Events

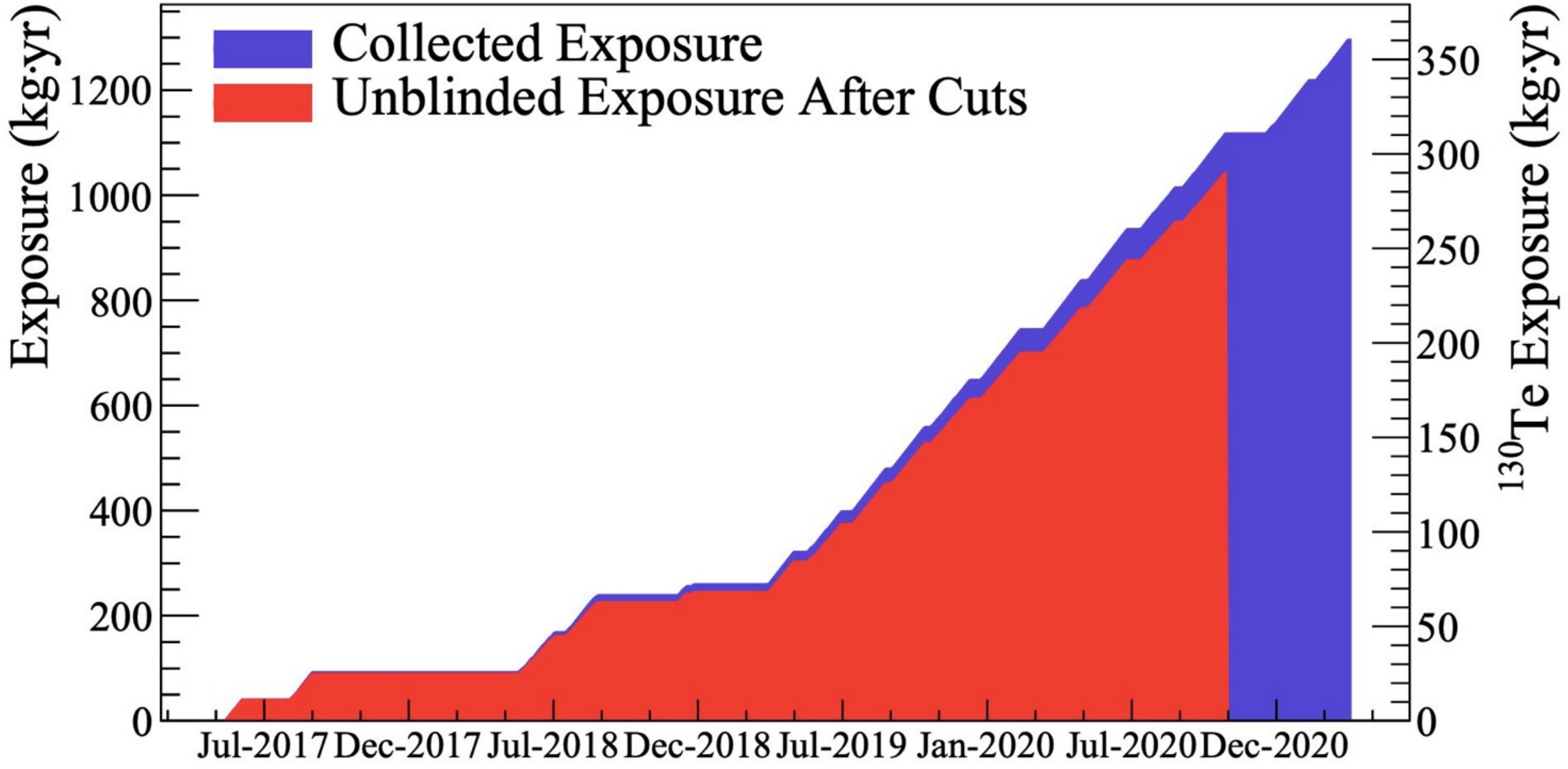






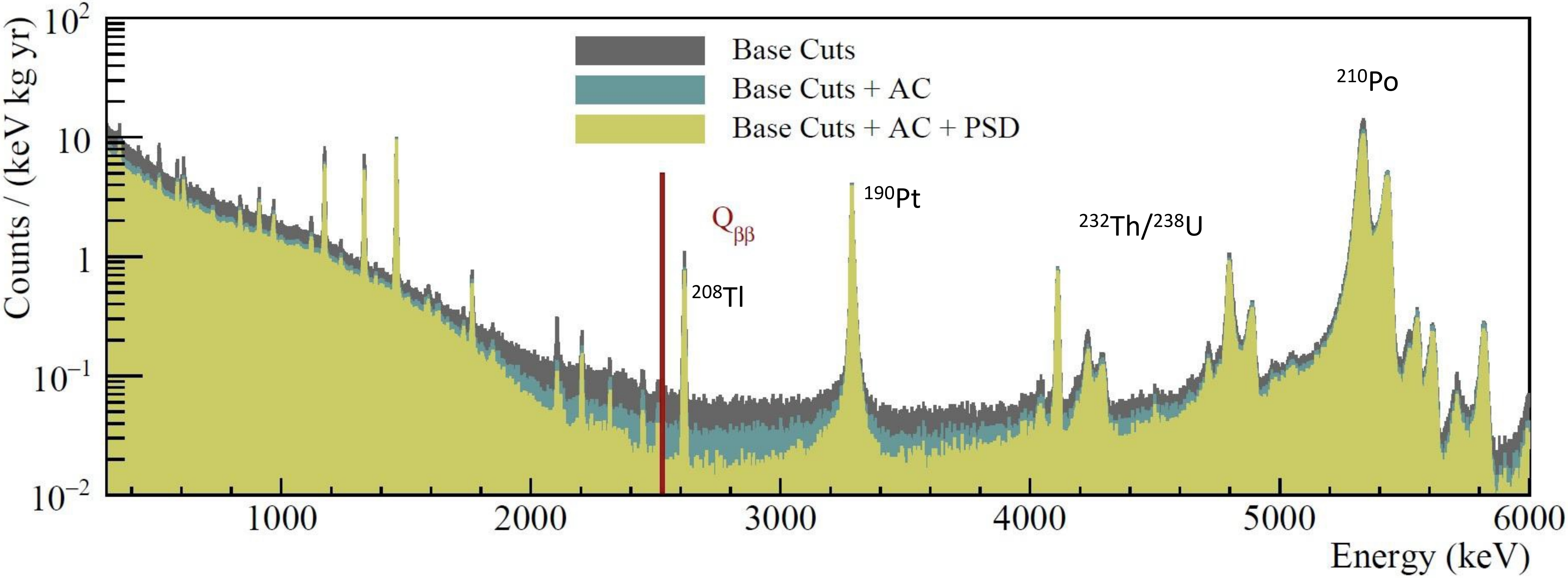
- 19 tower (13 floors per tower), 988 bolometers, ~ 206 kg ^{130}Te
- "Coldest cubic meter in the known Universe"

CUORE Exposure Accumulation



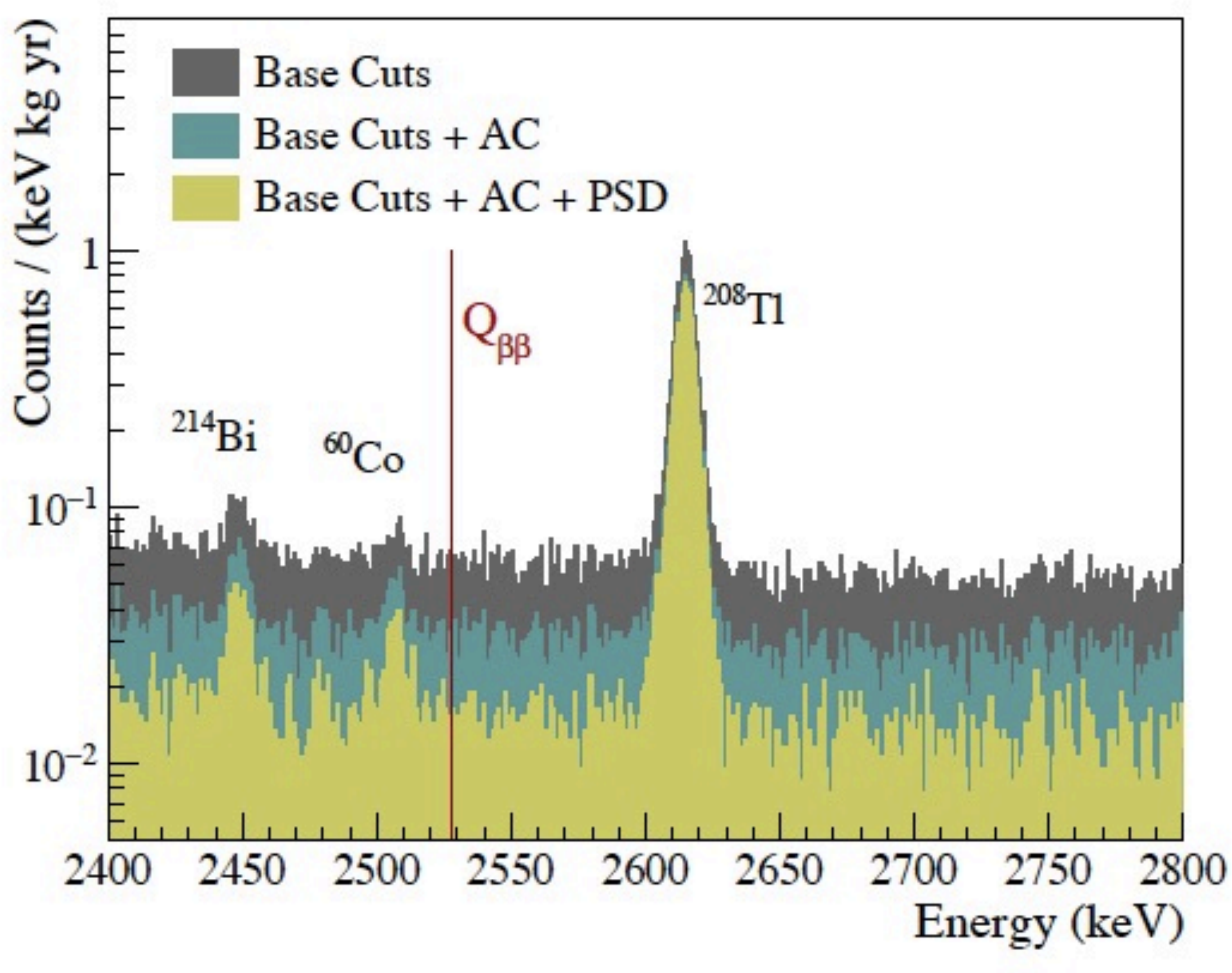
CUORE: 0νββ Result (2021)

Base cut: removing noise period
AC: anticoincidence cut
PSD: pulse shape discrimination cut



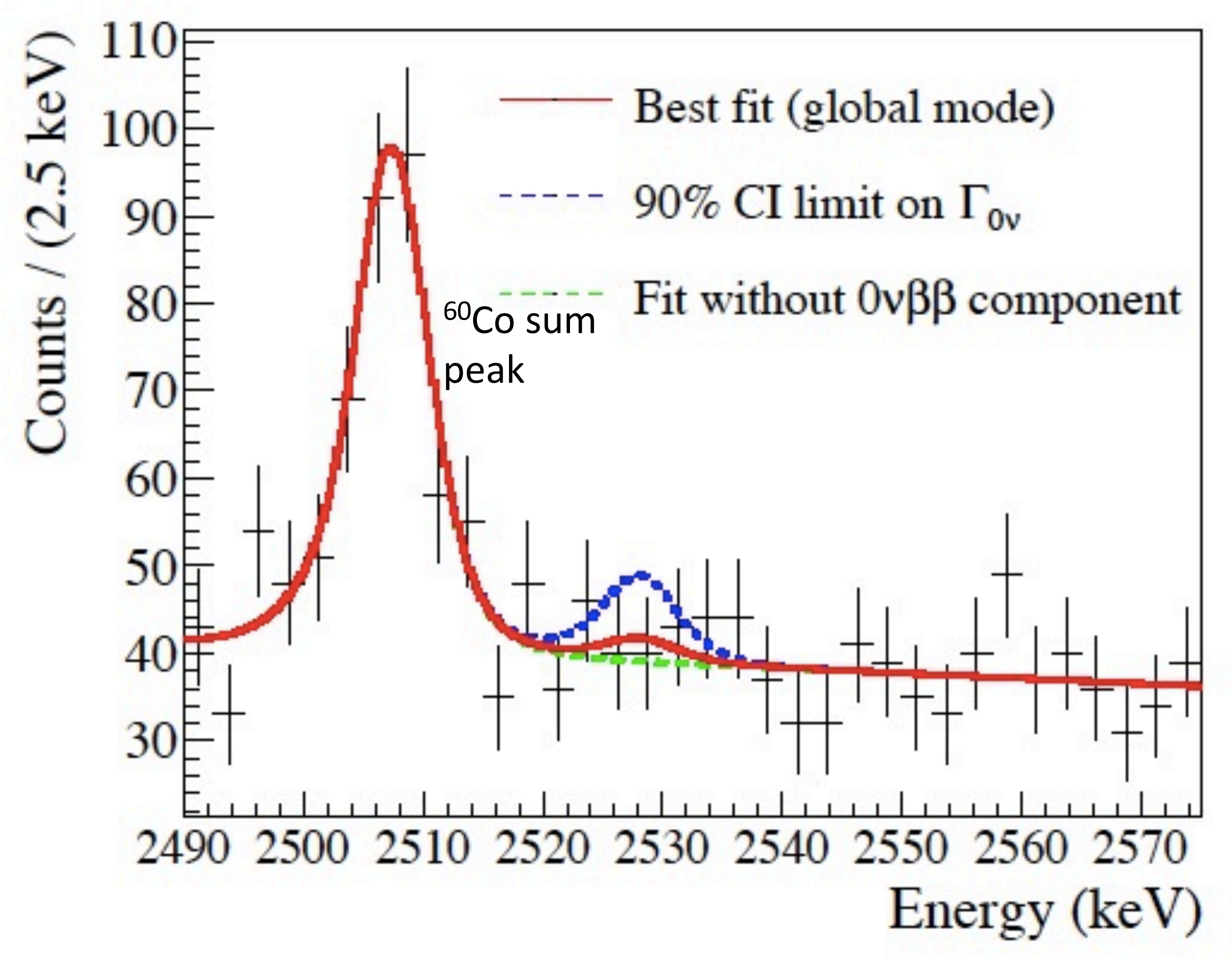
arXiv:2104.06906v1

CUORE background in the ROI



~ 90% of the background in ROI is due to degraded alpha interactions

CUORE: 0νββ Result (2021)



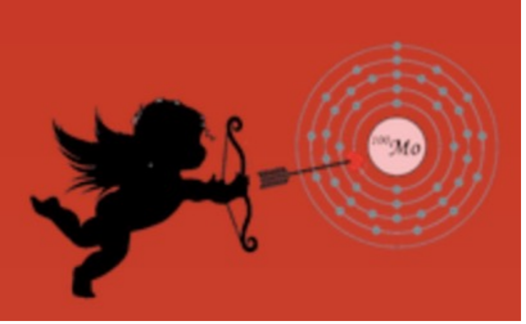
arXiv:2104.06906v1

$T_{1/2} > 2.2 \times 10^{25}$ yr

$m_{\beta\beta} < (90 – 305)$ meV

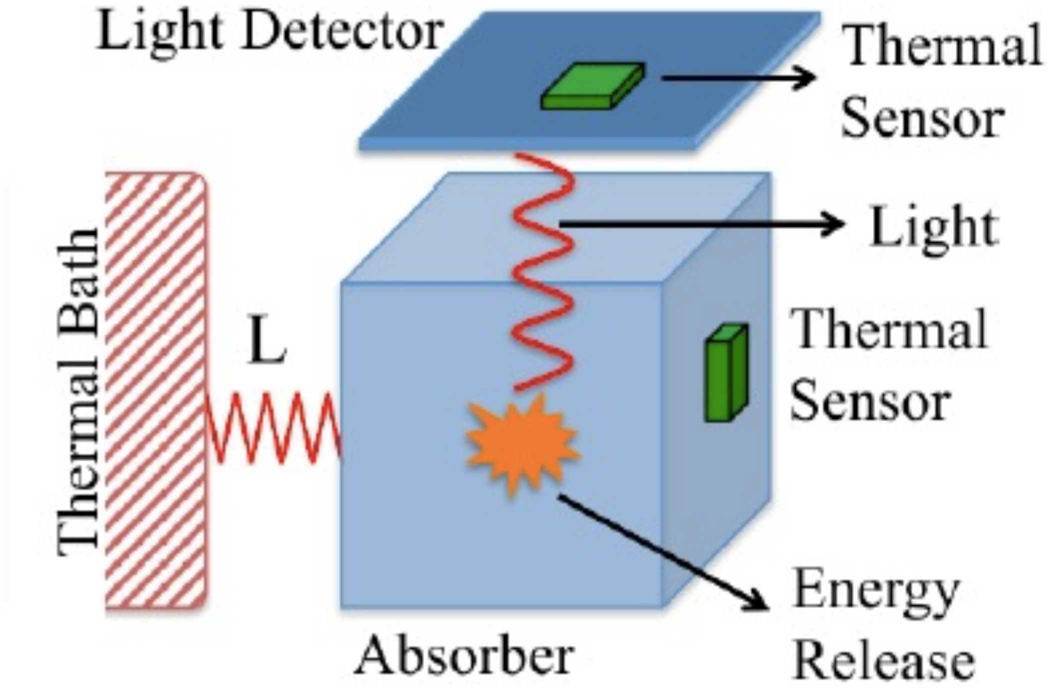
- Background index:
  $(1.49 \pm 0.04) \times 10^{-2}$ cnts/(keV kg yr)

- Characteristic FWHM E at $Q_{\beta\beta}$:
  7.0 ± 0.3 keV

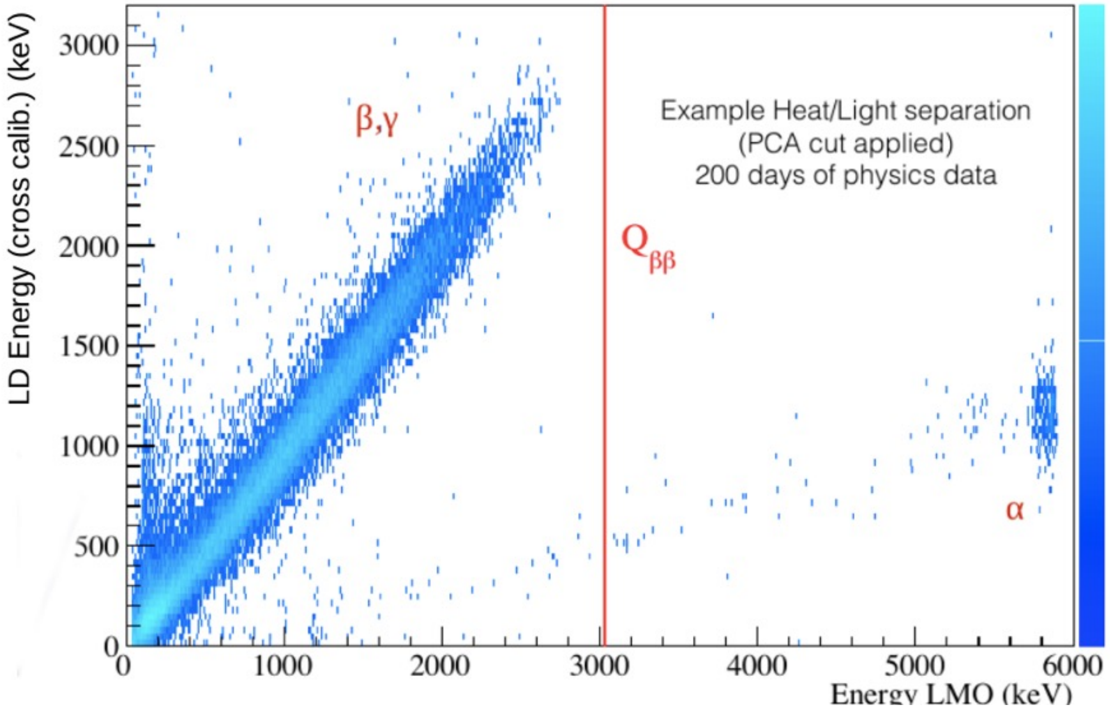


CUPID: CUORE Upgrade with Particle Identification

Scintillating Bolometer (Heat and Light)



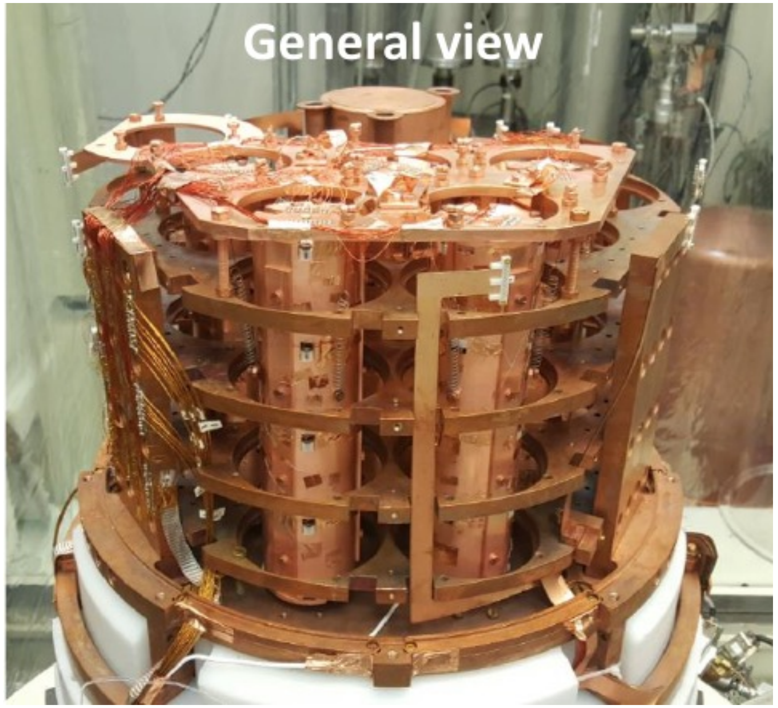
γ/β - α identification

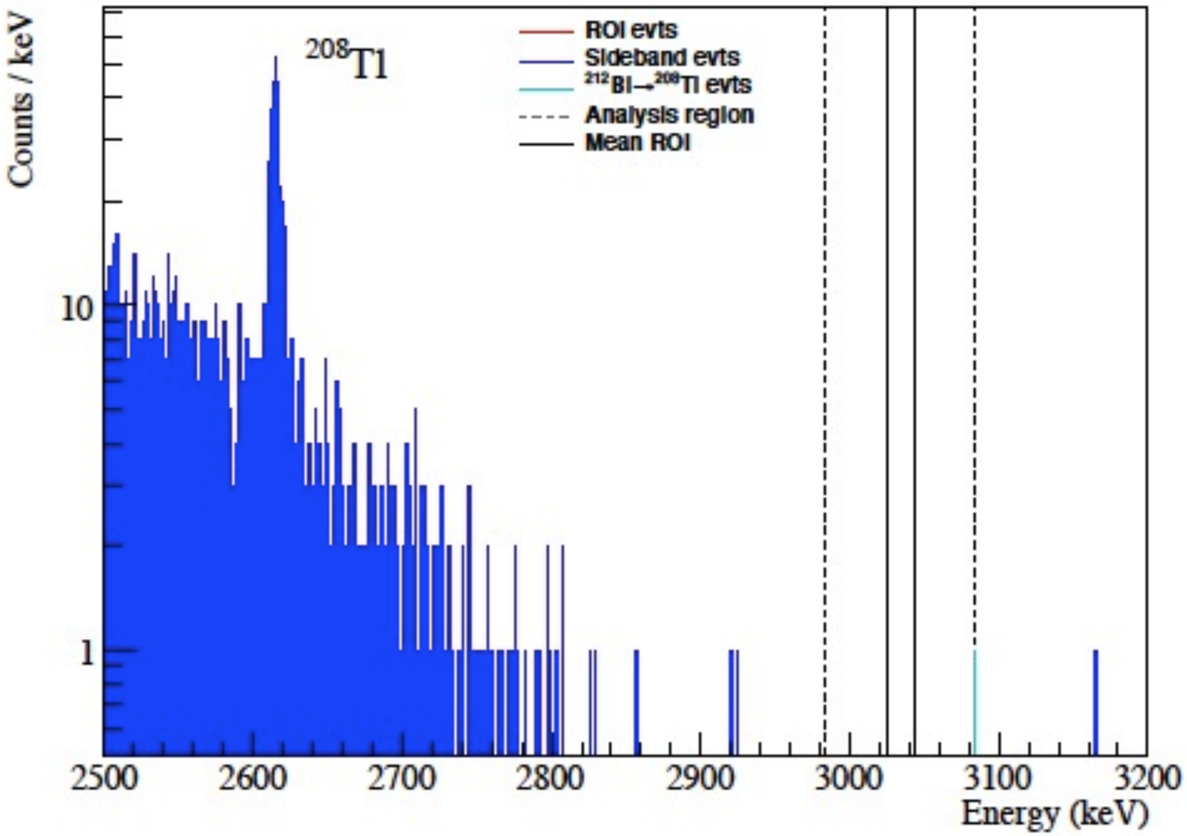


CUPID: CUORE Upgrade with Particle Identification

$Li_2{}^{100}MoO_4$ crystal selected in PCDR

CUPID-Mo set new limit for $0\nu\beta\beta$ ^{100}Mo (1.17 kg yr exposure)

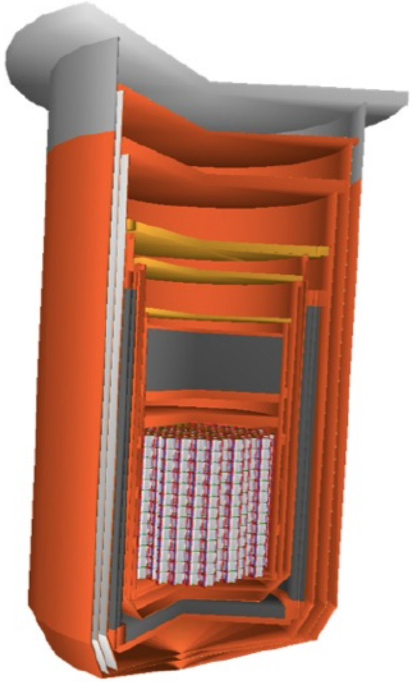


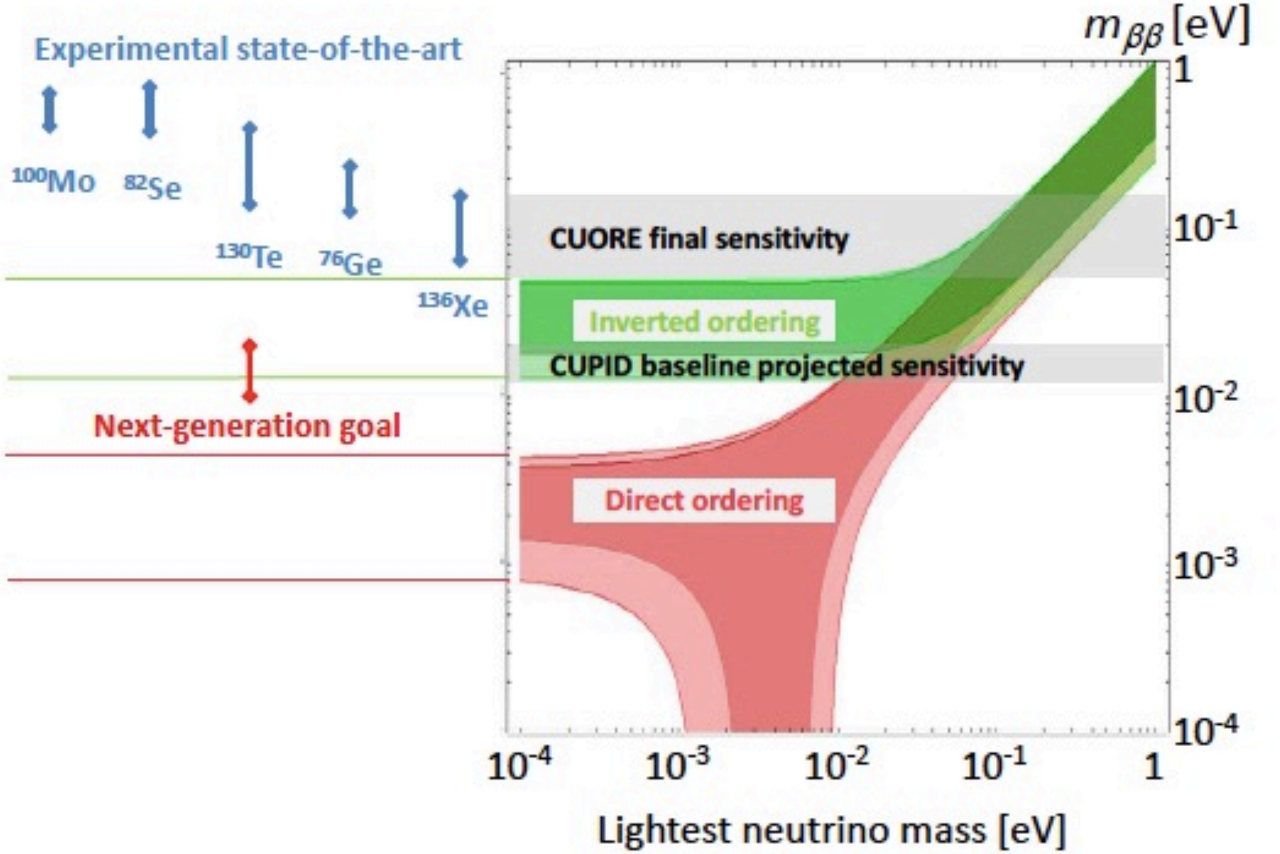


Phys. Rev. Lett. 126, 181802 (2021)

$T_{1/2} > 1.5 \times 10^{24}$ y (90% CI)

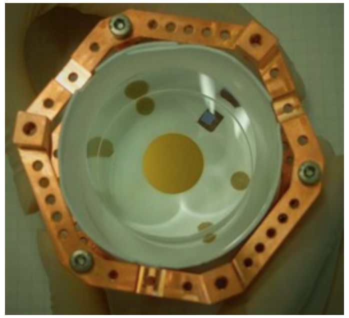
CUPID: CUORE Upgrade with Particle Identification





- Pre-Conceptual Design: 250 kg of ^{100}Mo in $Li_2{}^{100}MoO_4$ 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 isotope mass in larger crystals with lower background
- In case of discovery, can explore multiple targets: TeO_2 - ZnSe – Li_2MoO_4 – $CdWO_4$

AMoRE-I



CaF_2 crystal

Bolometer

Strengths

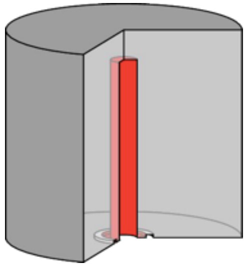
- Excellent energy resolution
- Scintillation bolometer provides effective way to reject surface alpha background
- Tonne scale detector operation demonstrated by CUORE

Weaknesses

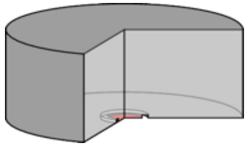
- Complex detector technology and low temperature operation
- Difficult to scale beyond 1 tonne isotope mass

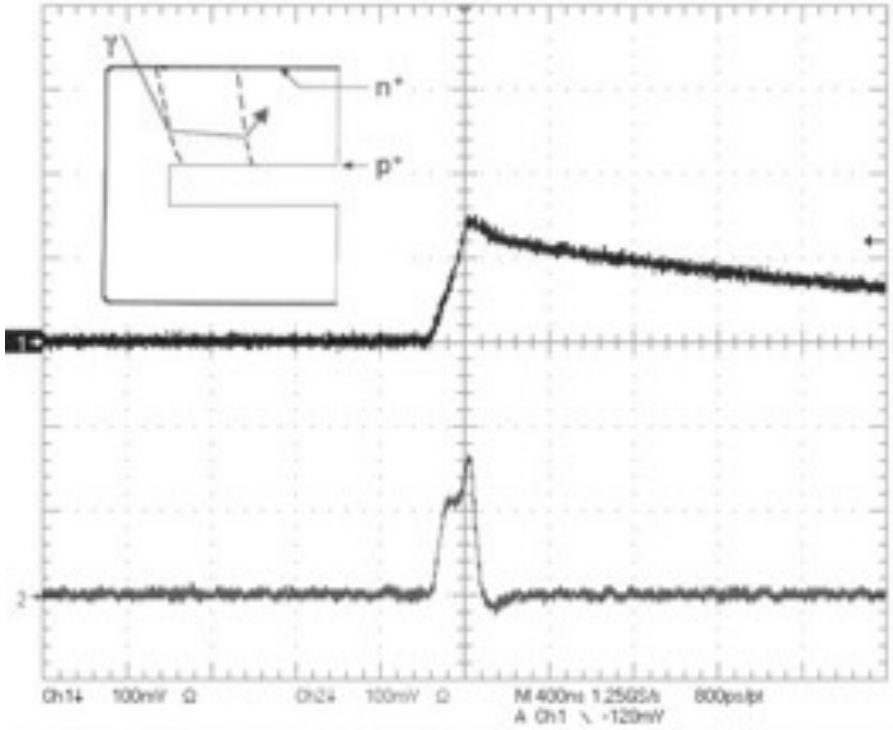
On-going projects:

- CUPID (Li_2MoO_4)
- AMoRE (Li_2MoO_4, $CaMoO_4$)
- CANDLEs (CaF_2)

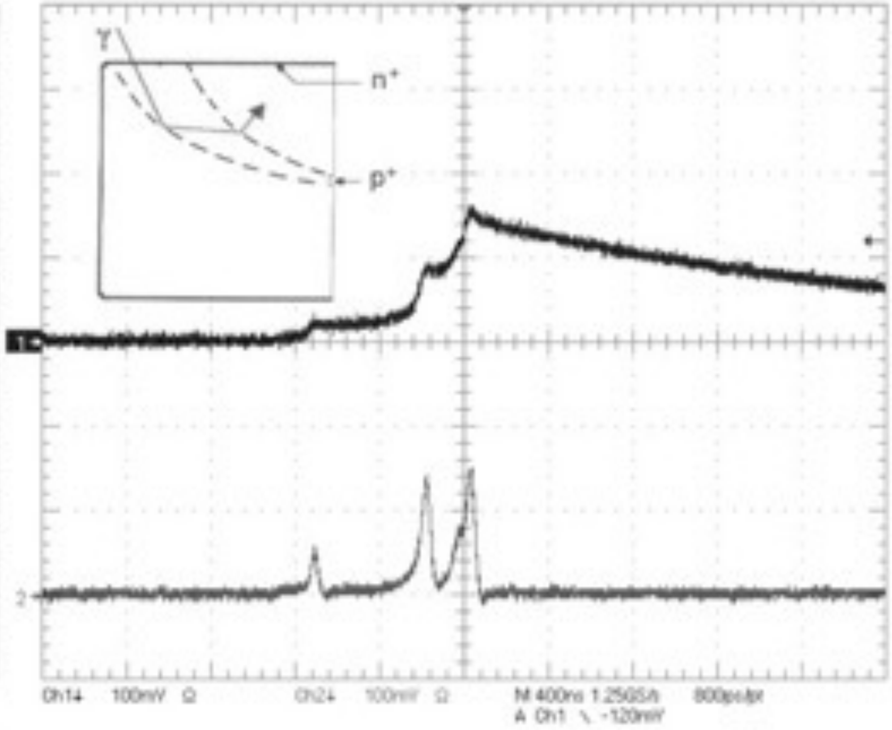


Semiconductor Detector: ^{76}Ge





P-type semi-coaxial Detector



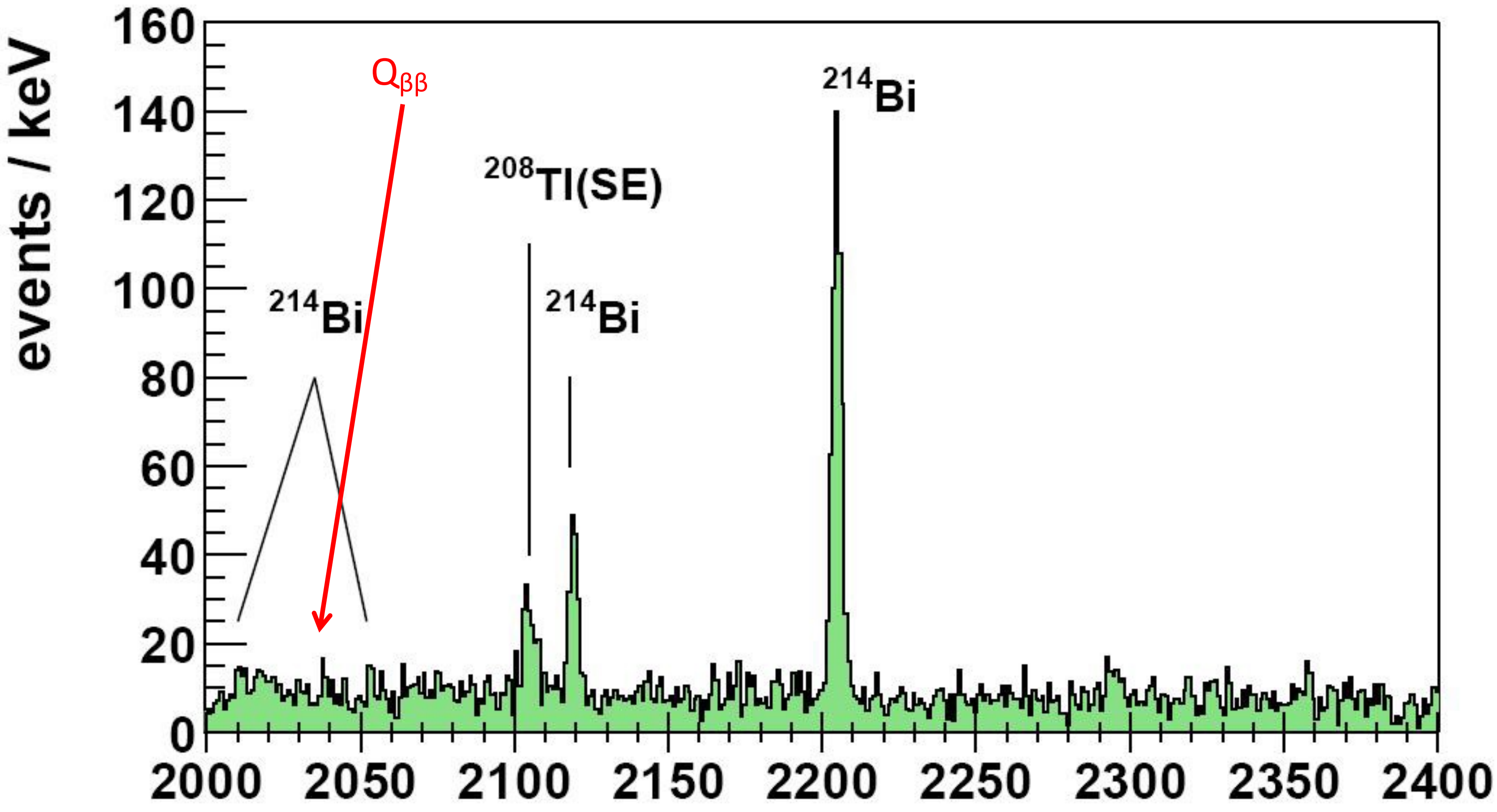
P-type point contact Detector*

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

*Also called Broad Energy Ge (BEGe) Detector.

- 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

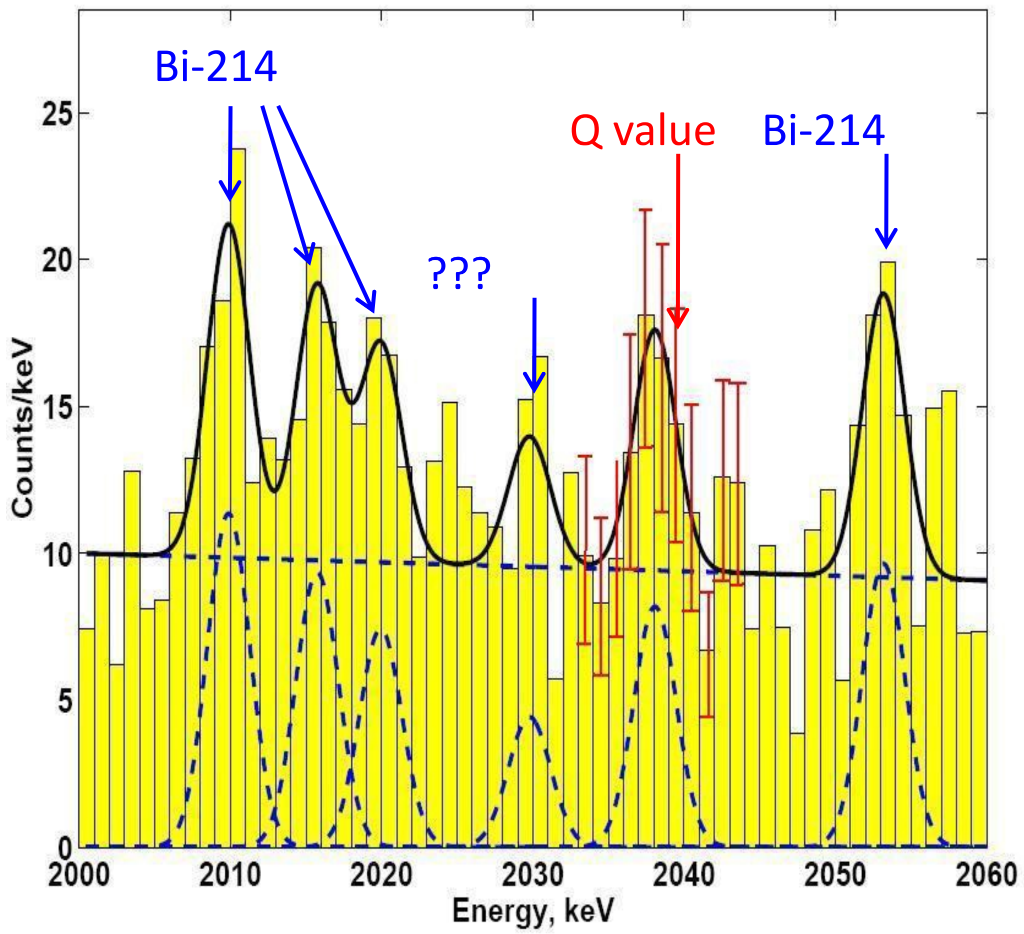
0νββ Discovery Claim



Publication by part of the Heidelberg-Moscow Collaboration, often referred to as the Klapdor's (or KKDC) claim.

HV. Klapdor-Kleingrothaus, et. al, Nucl. Instrum, and Meth, A 522 (2004) 371-406

$0\nu\beta\beta$ Discovery Claim – 2004



Spectrum near ROI

HV. Klapdor-Kleingrothaus, et. al, Nucl. Instrum, and Meth, A 522 (2004) 371-406

Fit model: 6 Gaussian + linear background

Four lines at 2010, 2016, 2022 and 2053 are consistent with γ from ^{214}Bi

^{214}Bi intensity from fit is 2 – 2.5 σ larger than MC prediction.

An unknown line at 2030, electron conversion of ^{214}Bi 2118 keV line?

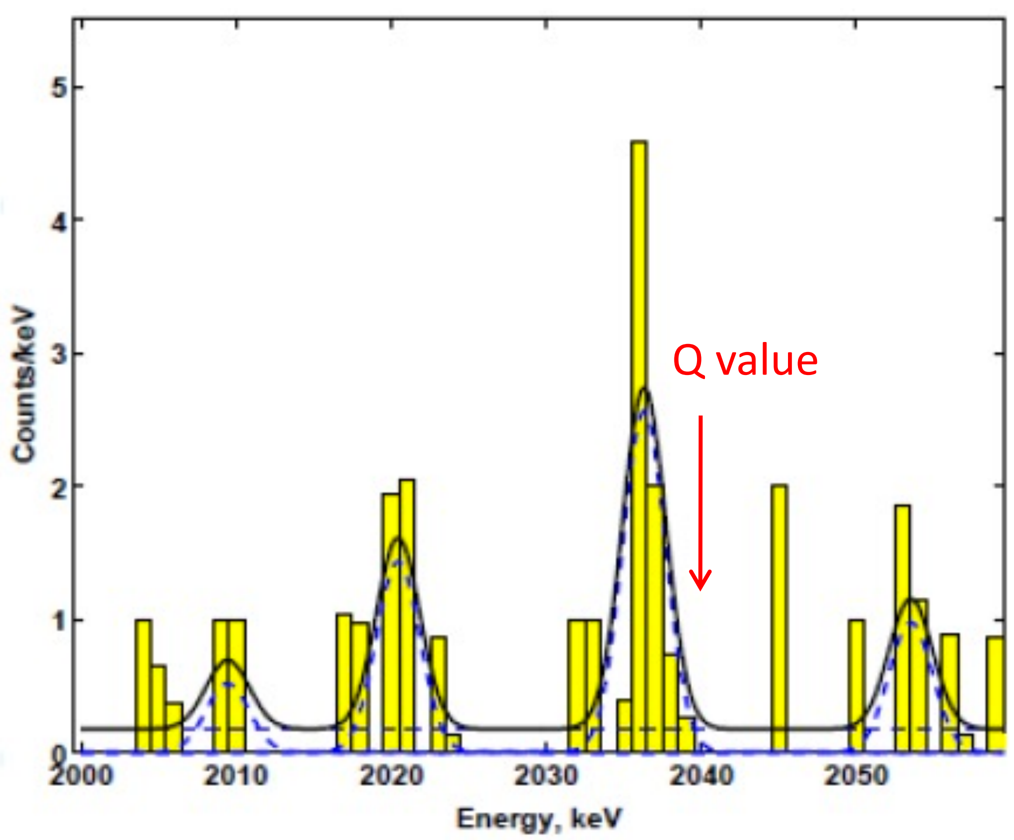
Total exposure: 71.7 kg•yr ^{76}Ge

Fit intensity @ $Q_{\beta\beta}$= 28.75 ± 6.86

Authors claim significance of 4.2 σ.

$T_{1/2}^{0\nu} = 1.19_{-0.23}^{+0.37} \times 10^{25}$ yr

$0\nu\beta\beta$ Discovery Claim (PSA) – 2006



Spectrum near ROI,
after pulse shape analysis

A special pulse shape analysis (PSA) is applied to the data which selects only $\beta\beta$ like events.

Background in ROI dropped from 0.17 cnts/(keV kg yr) to 0.015 cnts/(keV kg yr)

PSA efficiency not quoted in the paper, but a value of 100% is used.

Fit intensity @ $Q_{\beta\beta}$= 11.32 ± 1.75

Authors claim significance of 6.5 σ.

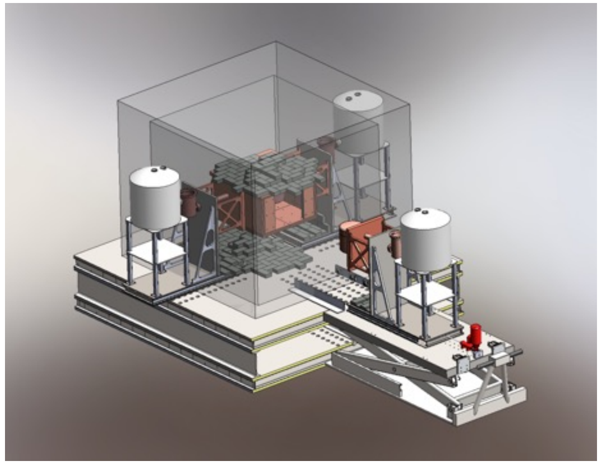
$T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ yr.

Mod. Phys. Lett., A 21, 1547 (2006)

Mod. Ge Exps: MAJORANA and GERDA

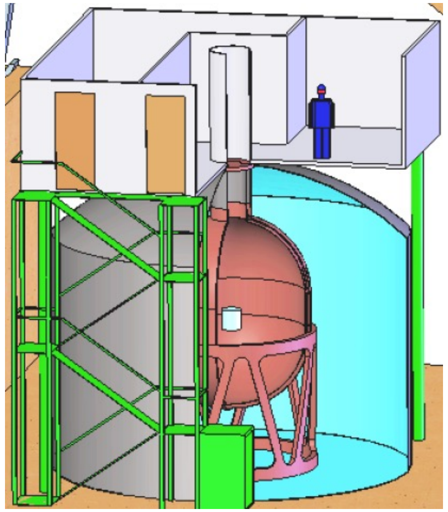
- ^{76}Ge experiments can check the Klapdor claim in a model independent way.
- More than ten times lower background.
- Superior detector technology, enriched BEGe, (MAJORANA and GERDA Phase II)

MAJORANA



- Use electroformed high purity Cu as shielding, Cu/Pd passive outer shielding
- 4π plastic scintillator veto.
- DEMONSTRATOR: 30 kg ^{enr}Ge, 10 kg ^{nat}Ge

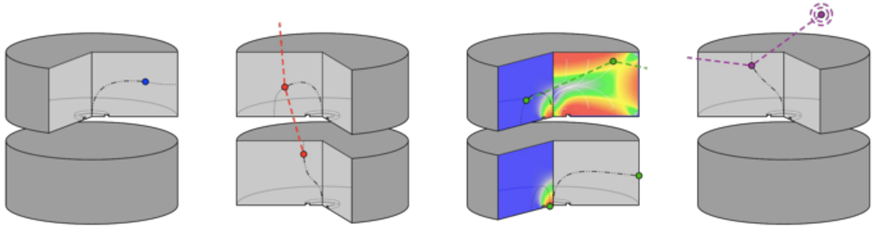
GERDA

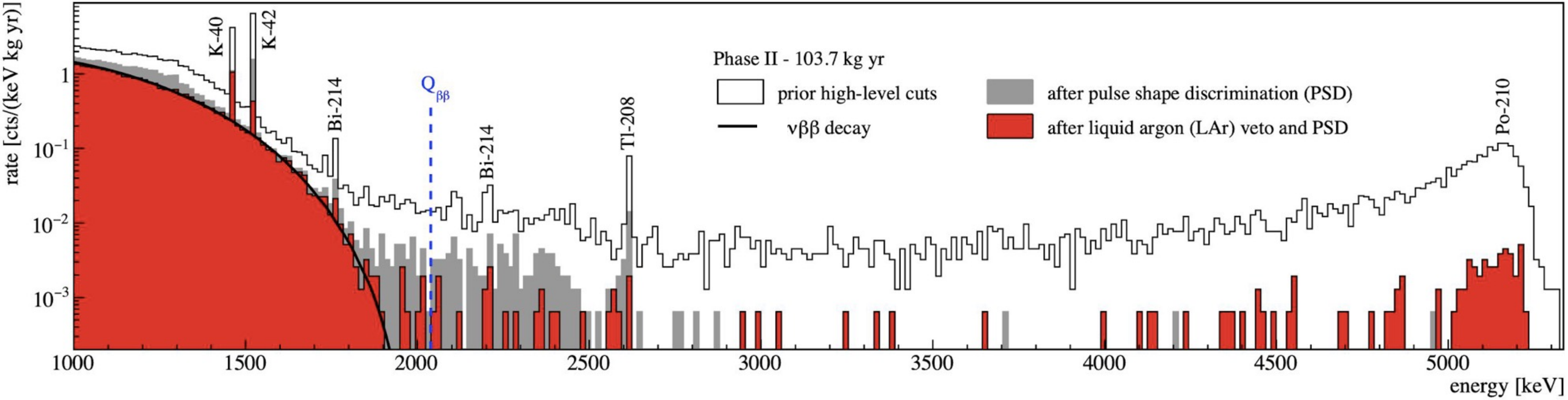


- Operate ‘bare’ Ge crystal in liquid Ar
- Liquid Ar can be used as active veto
- Water Cherenkov μ veto
- Phase I: ~ 18 kg, Phase II: + 20kg

Very different background reduction strategy.

GERDA Phase-II Results

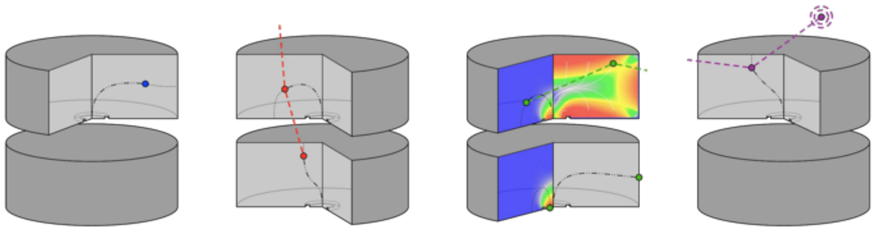


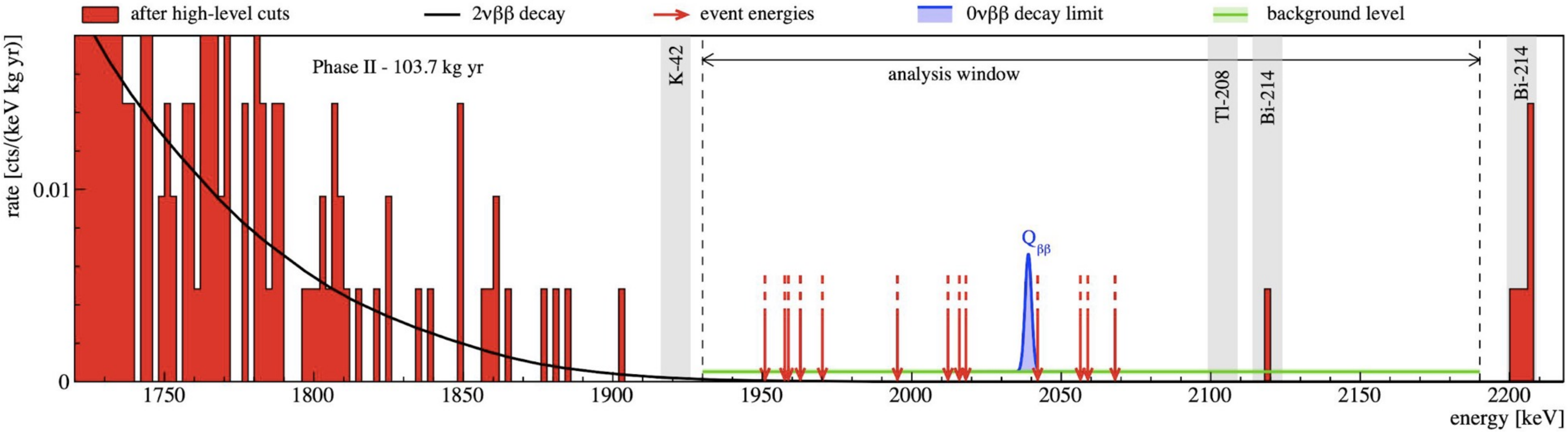


- 103.8 kg yr exposure
- PSD trained with ^{228}Th calibration data
- Liquid argon instrumented with WLS fiber and SiPM

C. Wiesinger, “WIN conference 2021

GERDA Phase-II Results





- Background index 5.2 x 10^{-4} cts/(keV kg yr), energy resolution ~3 keV (FWHM)
- $T_{1/2}$ > 1.8 x 10^{26} yr at 90% CL

C. Wiesinger, “WIN conference 2021

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

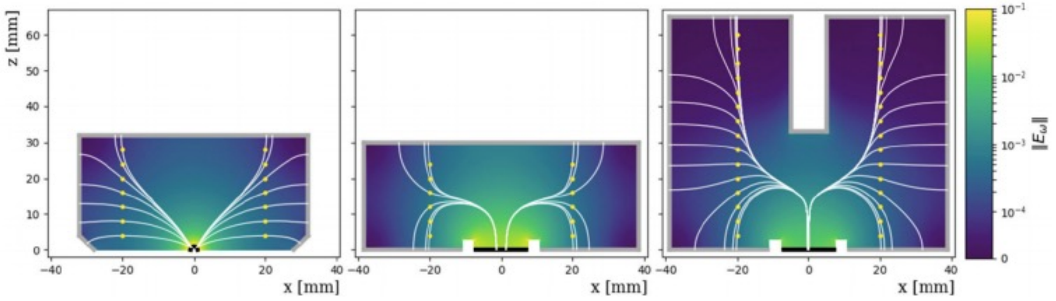
LEGEND-200:

- 200 kg in existing infrastructure at LNGS
- 14 string array, improved light collection and electronics

LEGEND-1000:

- 4 payloads with up to 300 kg in underground LAr containment

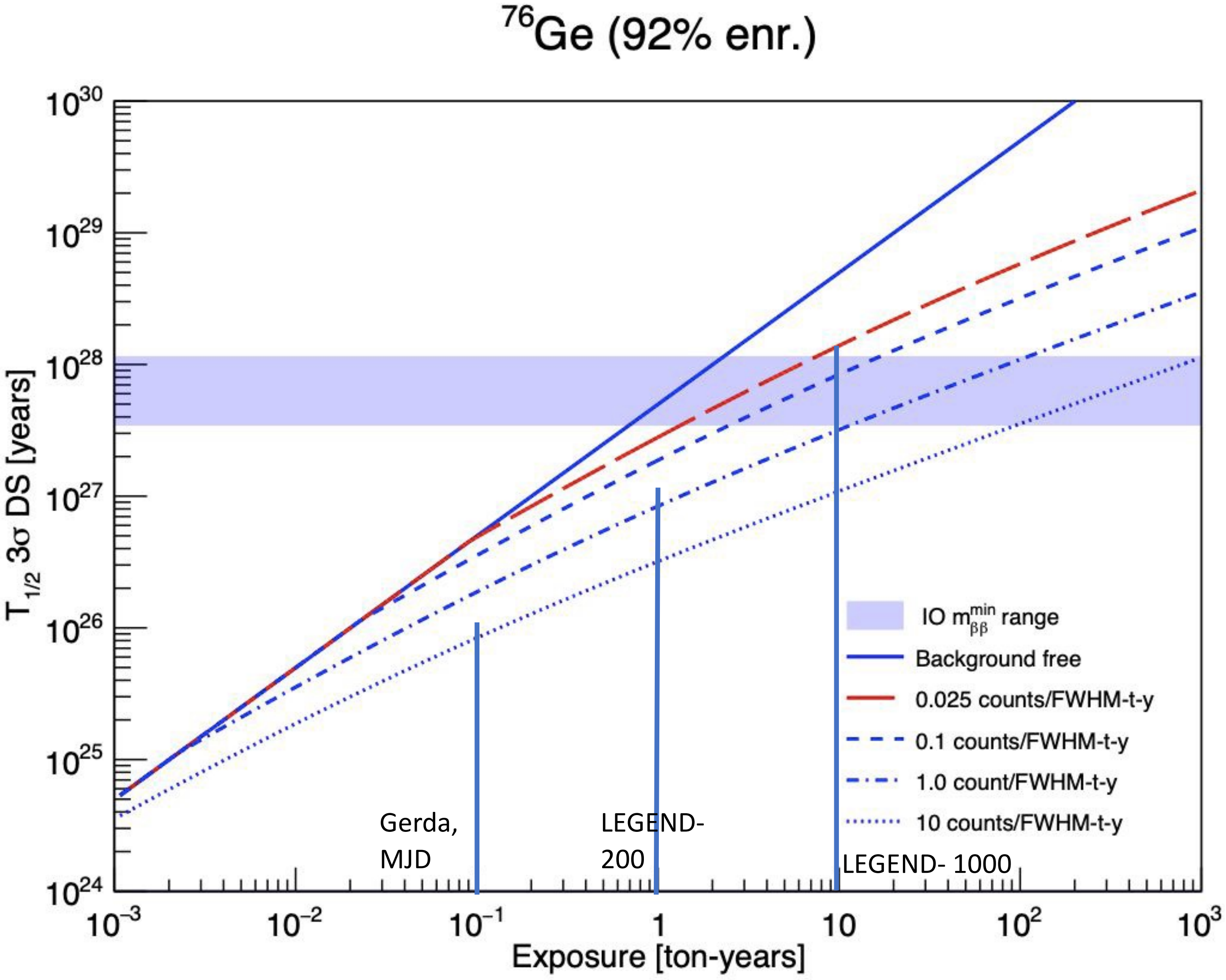
PPC (MJD) BEGe (Gerda) **ICPC (LEGEND)**

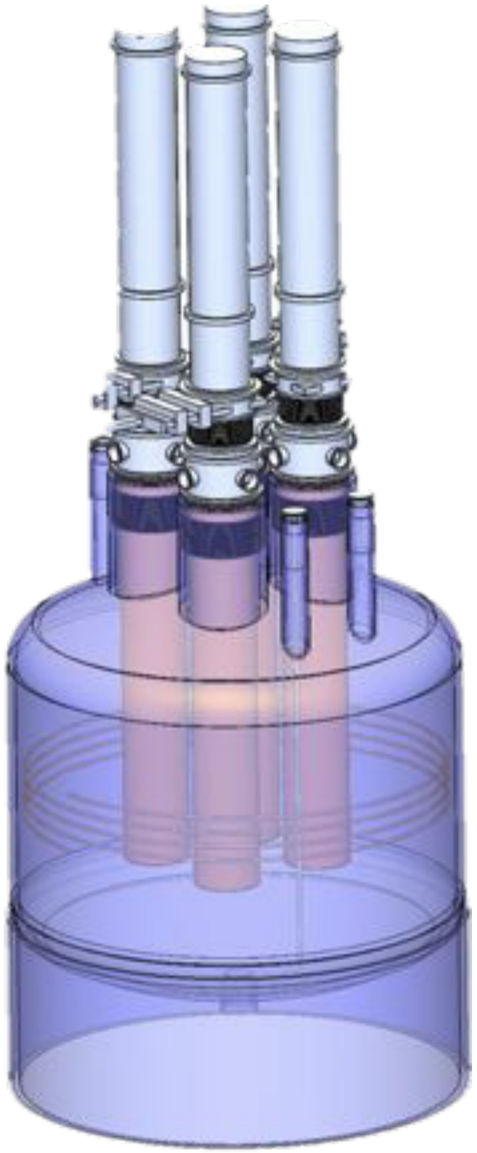


LEGEND-200 LEGEND-1000

C. Wiesinger, “WIN conference 2021

Discovery Sensitivity





Semiconductor (Ge)

Strengths

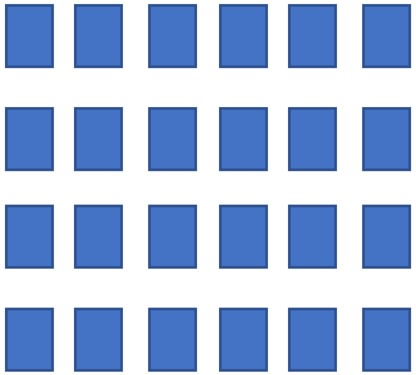
- Exquisite energy resolution
- New detector design increases module size to 2-3 kg
- Excellent background rejection with PSD and LAr veto
- Modularity facilitates phased deployment
- Lowest background demonstrated

Weaknesses

- Complex and expensive detector manufacturing process
- Difficult to scale beyond 1 tonne isotope mass

$0\nu\beta\beta$ experiments

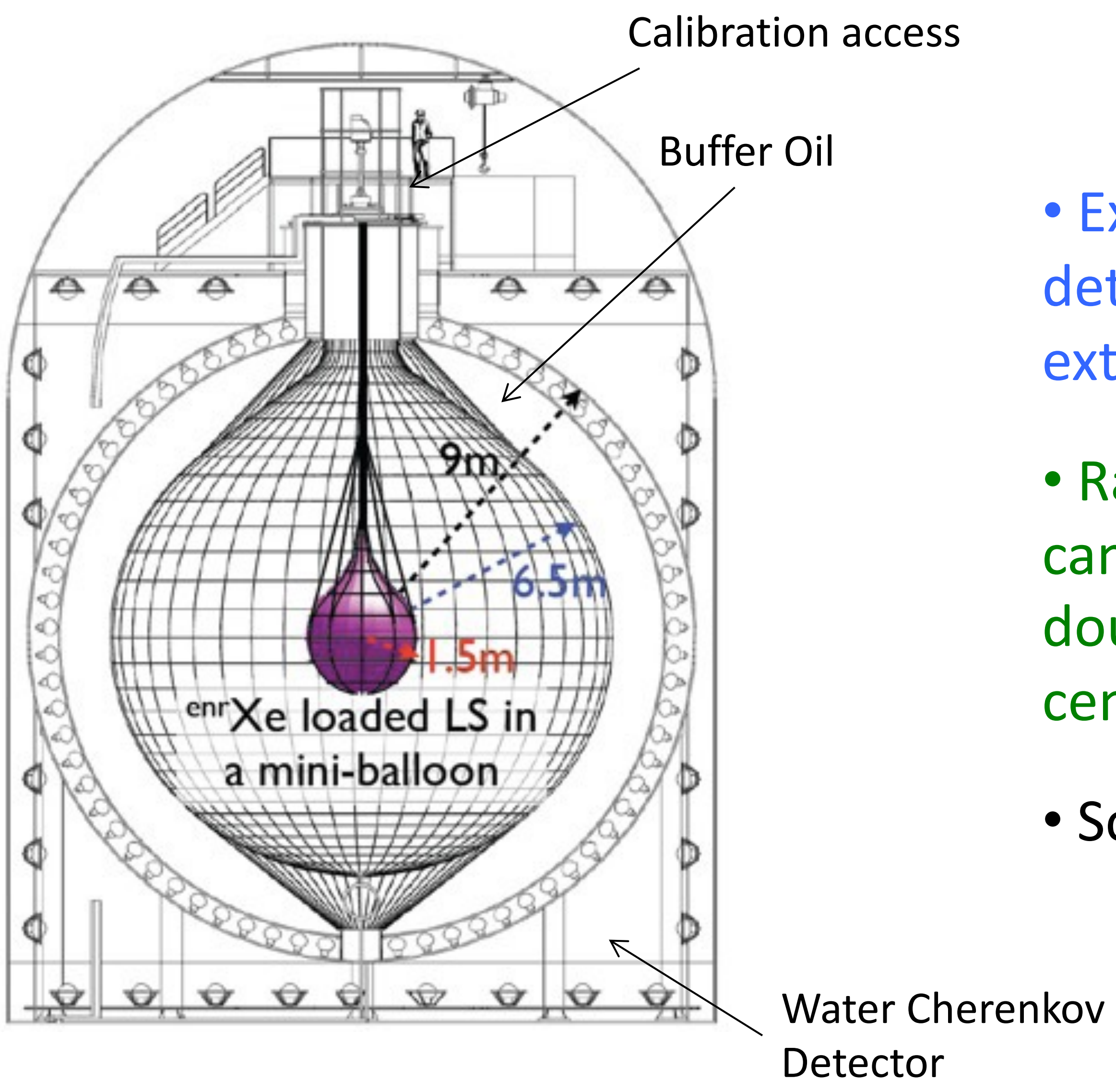
- Tracking detectors (superNEMO)
- Bolometers (CUORE, CUPID, AMoRE, CANDLE IV)
- Semiconductor (LEGEND, SELENA)
- Liquid Scintillators (KamLAND-Zen, SNO+, Theia)
- TPCs (NEXT, PandaX, nEXO)



modular

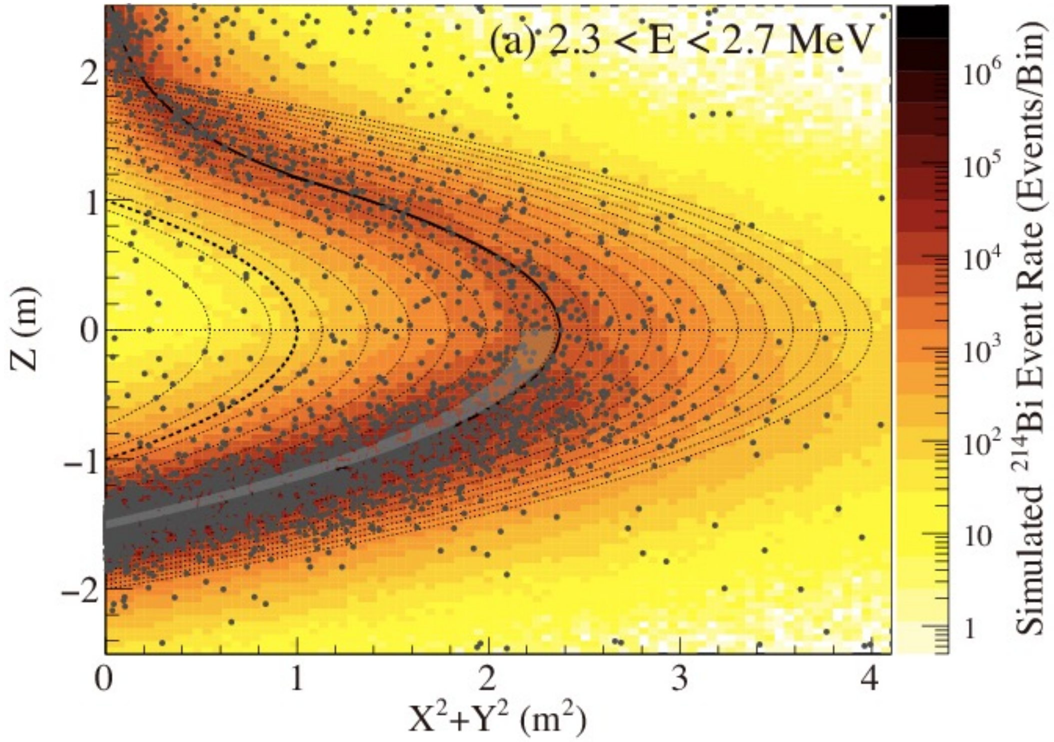
monolithic

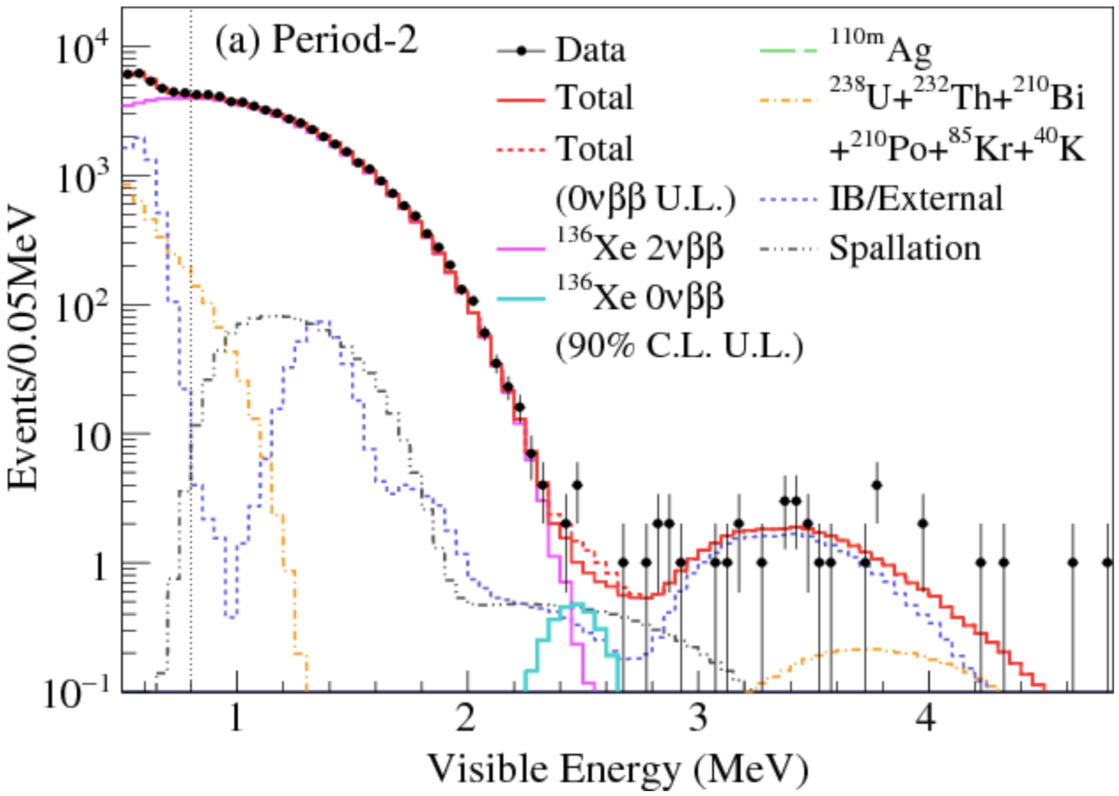
Scintillation Detector: KamLAND-Zen



- Experience with large liquid scintillator detectors shows 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.
- Solubility: Xe-LS ~ 3 wt%

KamLAND-Zen 400: ^{136}Xe Result





Largest backgrounds are on the inner balloon (IB) and from ^{10}C made in muon spallation.

(significant reduction of ^{110m}Ag background from previous searches)

$T_{1/2}(\beta\beta 0\nu) > 1.07 \times 10^{26}$ yr (90% C.L.)

$m_{\beta\beta} < 61 - 165$ meV

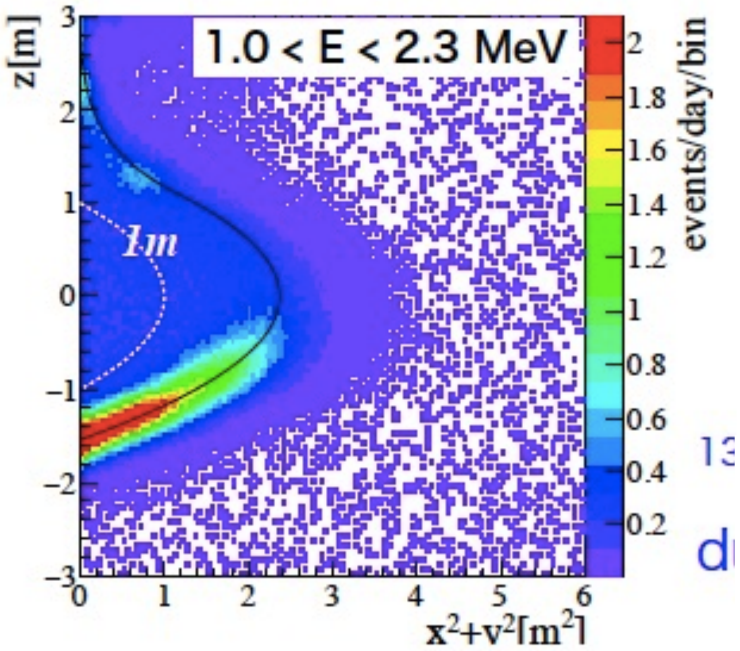
Exposure: 504 kg yr

Phys. Rev. Lett 117, 082503 (2016)

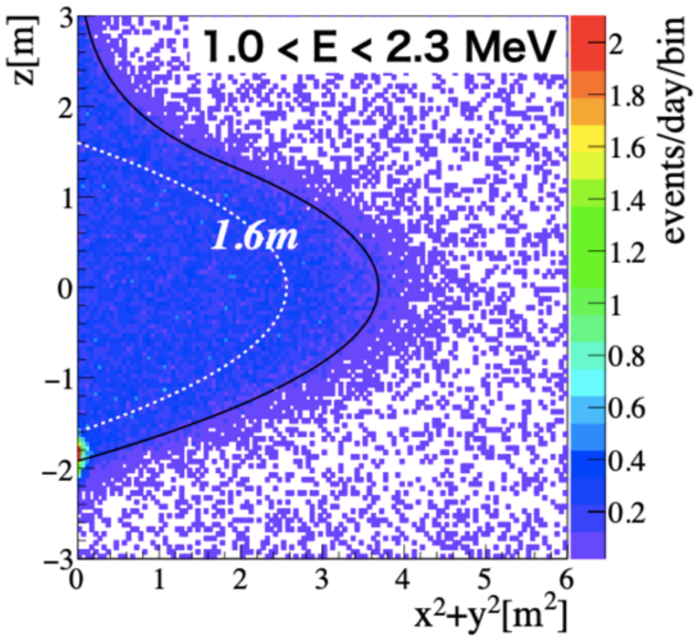
KamLAND-Zen 800

Mini-balloon installation (2018)

KamLAND-Zen 400 Phase II

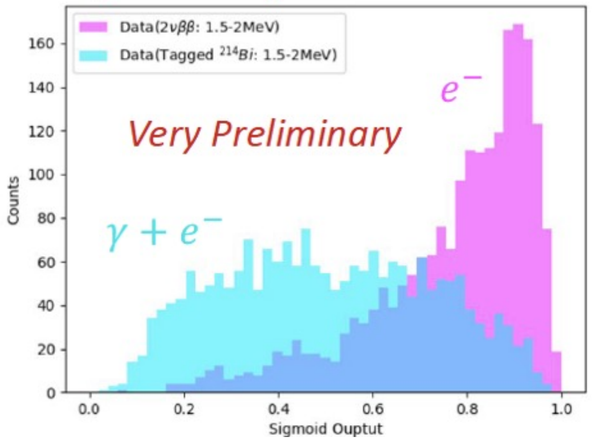


KamLAND-Zen 800



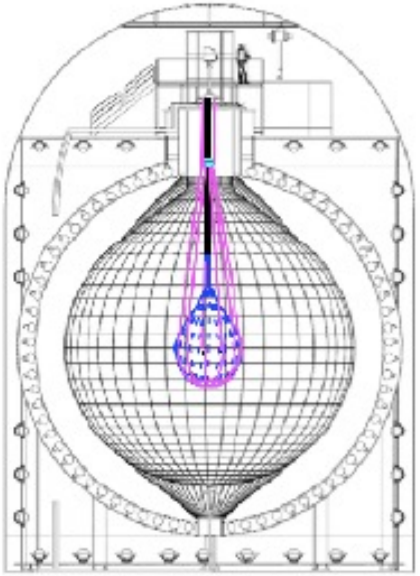
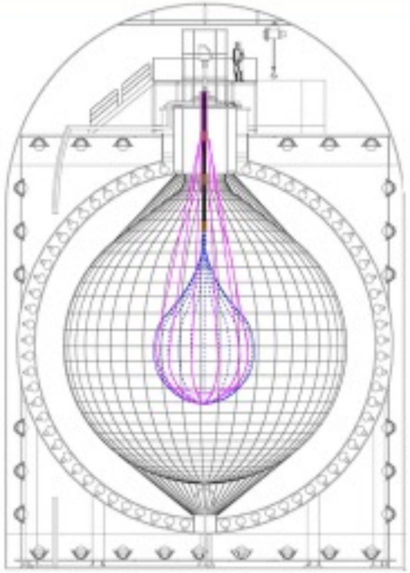
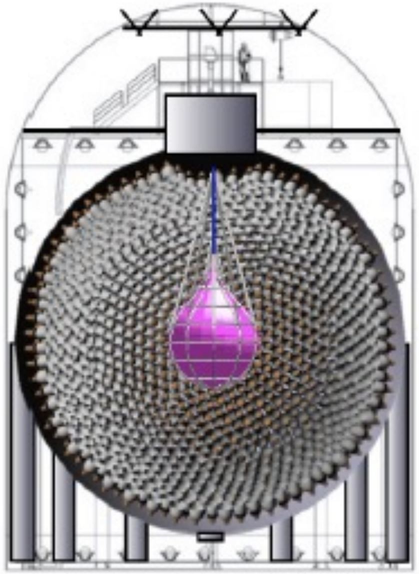
- Significant reduction in mini-balloon background, $2\nu\beta\beta$ dominate in all volume
- Photo coverage 34%, Energy resolution: $7\%/\sqrt{E(MeV)}$
- New electronics to collect all neutron captures
- ^{12}C-spallation background reduced with analysis

Spherical CNN applied to subset of KLZ data



Z. Fu, Neutrino 2020

KamLAND-Zen series

Past	Ongoing	Future
		
KamLAND-Zen 400	KamLAND-Zen 800	KamLAND2-Zen
R = 1.54m mini-balloon	R = 1.90m mini-balloon	
Xenon 320 ~ 380 kg	Xenon 745 kg	Xenon ~ 1 ton
2011 ~ 2015	Jan. 22, 2019 ~	

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

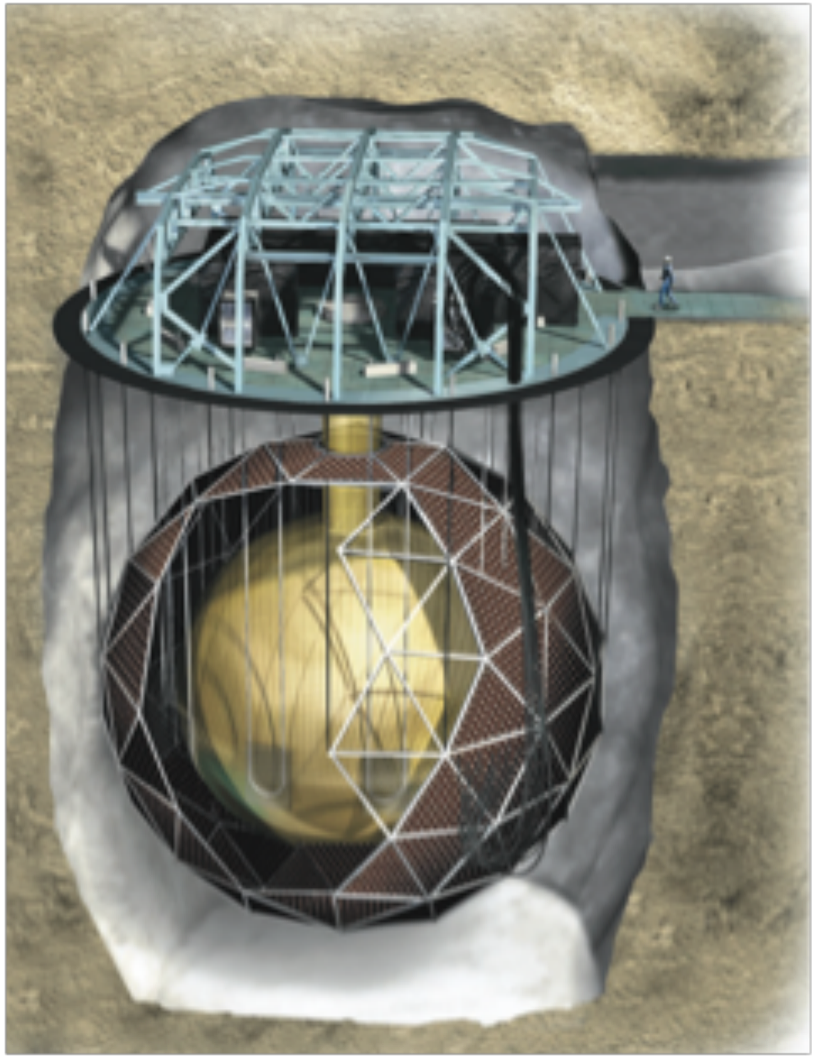
$\langle m_{\beta\beta} \rangle < 61 - 165$ meV

- **Target: $T_{1/2} > 5 \times 10^{26}$ yr**

- x 5 increase in light collection.
- Scintillation balloon film
- **Target: $T_{1/2} > 2 \times 10^{27}$ yr**

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

SNO+

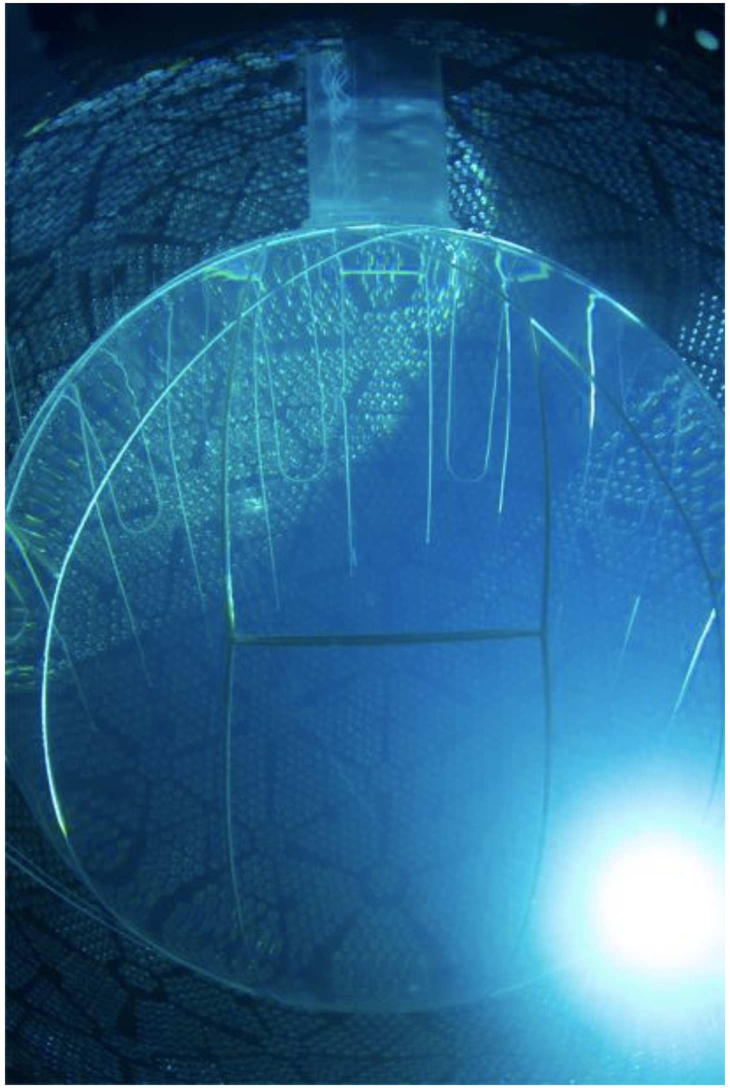


Reuse the SNO detector, replace D_2O with liquid scintillator doped with double beta decay isotope.

Addition of hold-down ropes to counter LS buoyancy

Upgrade electronics for higher data-taking rates

0.5% ^{nat}Te loading by weight
~ 460 p.e. / MeV

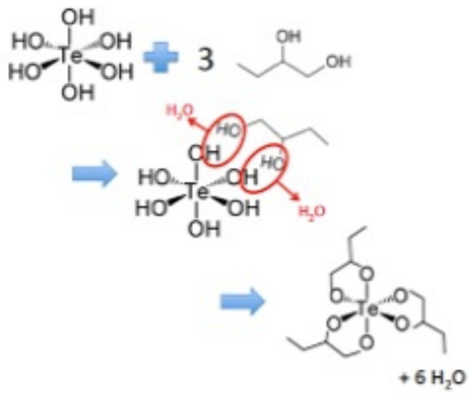


SNO+ Scintillator Phase

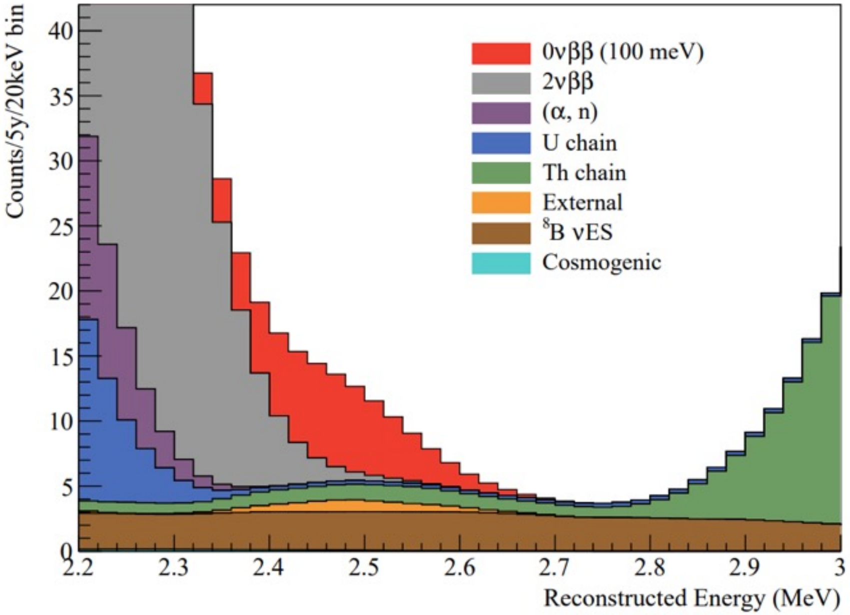
780 tonnesof LAB + 0.6-0.8g/L PPO
(Aug 2021)   PPO top-off ongoing

Te loading plant

$Te(OH)_6 \rightleftharpoons Te(OH)_5O^- + H^+$



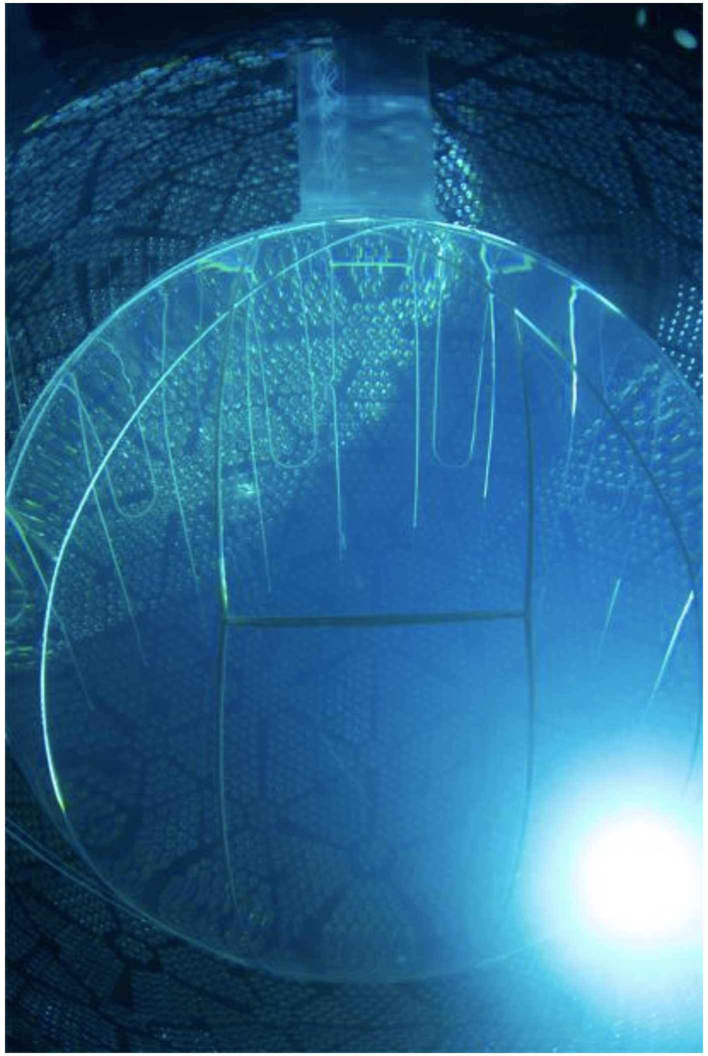
LAB + PPO (2 g/L) + bis-MSB + Tellurium
(0.5%)-ButaneDiol+ DDA
3.9 tonnes of ^{nat}Te – 1330 kg of ^{130}Te



0.5% Te loading
3 years

$T_{1/2} > 2 \times 10^{26}$ yrs (90% CL)

Sensitivity increase linearly
with increased loading



Loaded Liquid Scintillator (Xe, Te)

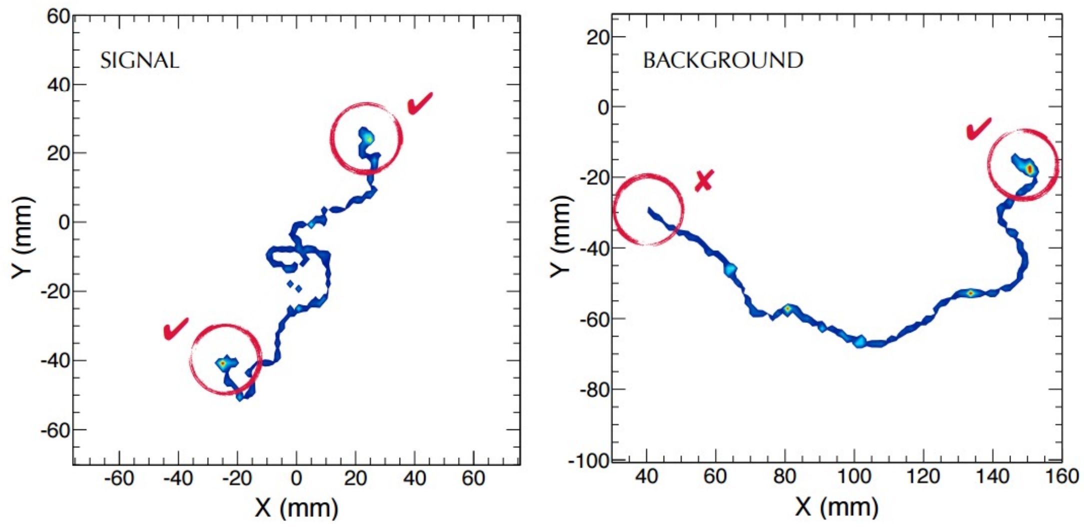
Strengths

- Scalability to multiple tonnes possible
- Well-understand detector technology and backgrounds
- Relatively low cost and ease of operation

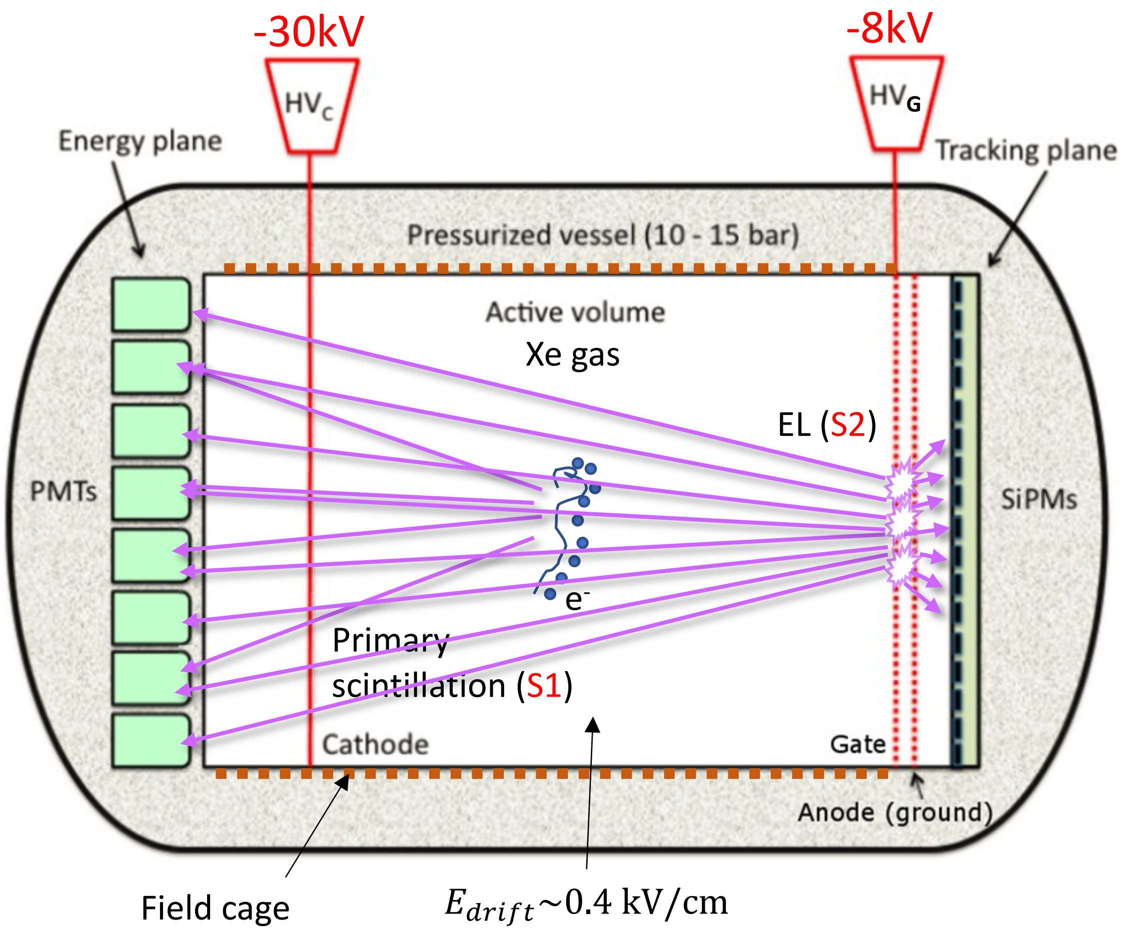
Weaknesses

- Low energy resolution
- Difficult to do particle ID
- solar ν, and cosmogenic spallation backgrounds

Time Projection Chamber (TPC): NEXT

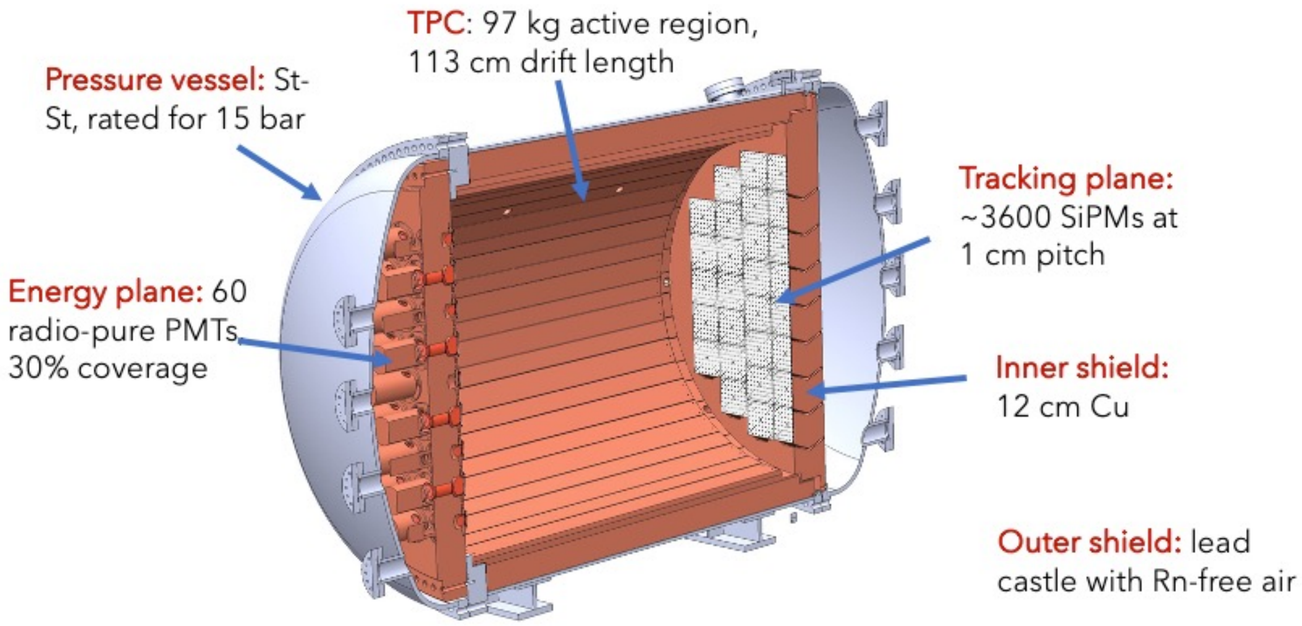


- Neutrino Experiment with a Xenon TPC (NEXT) is a high pressure (10 bar) gas ^{136}Xe experiment
- Energy resolution < 1% FWHM
- High gamma background rejection (~10^6) using event topology.



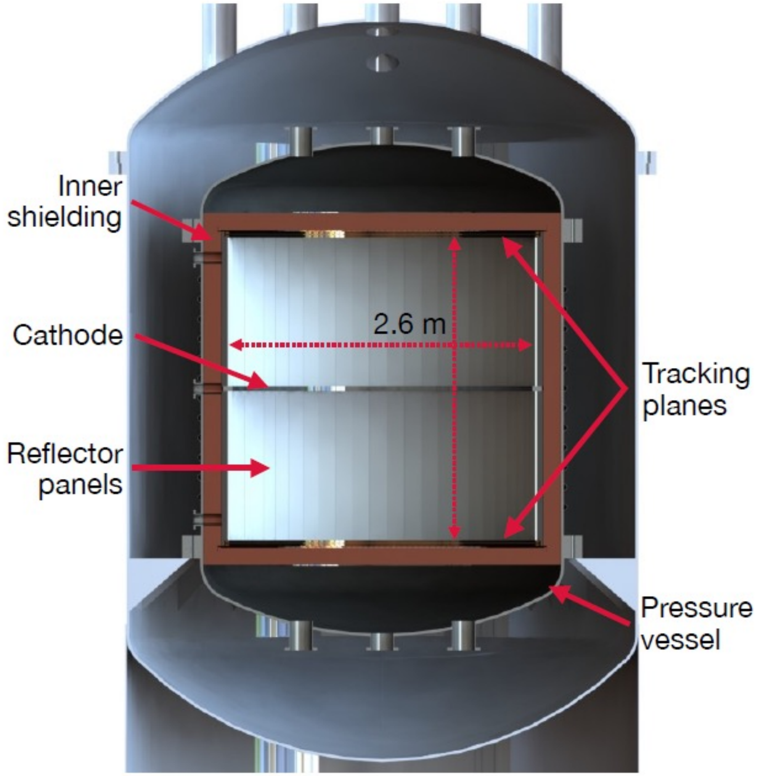
NEXT technical design report, arXiv:1202:0721

NEXT-100



- Technology demonstrator at 100 kg scale
- Expected sensitivity ~ 10 yr
- Background index 4×10^{-4} counts/keV/kg/yr.
- Construction planned for 2021

NEXT-Tonne

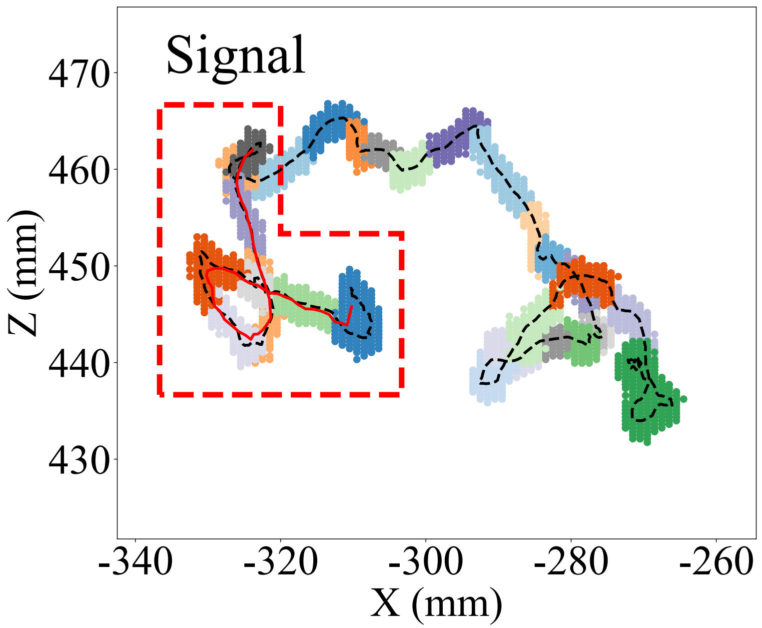


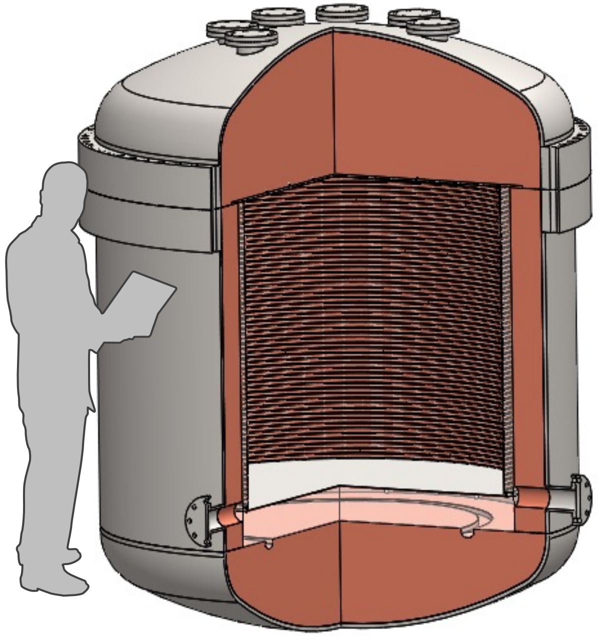
- 1000 kg enriched Xe
- Tracking + energy by radiopure SiPMs
- Low-diffusion gas mixture (e.g., Xe/He 85/15)
- Expected sensitivity at 3 tonne-yr: $T_{1/2}^{0\nu} \sim 1\times10^{27}$ y

L. Arazi, Neutrino Telescope 2021

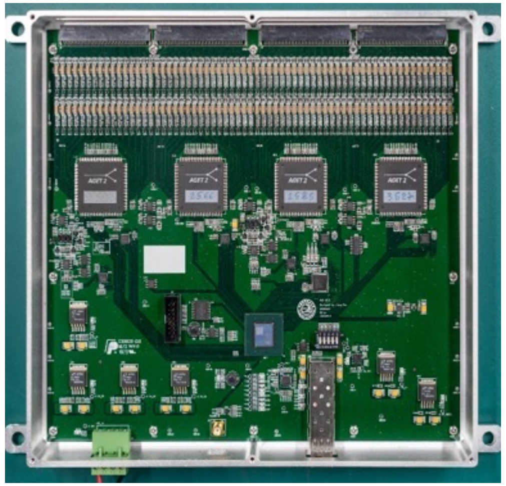
PandaX-III: high pressure gaseous TPC for $0\nu\beta\beta$ of ^{136}Xe

- TPC: 100 kg scale high pressure TPC at 10 bar operating pressure
- Charge only readout with Micromegas for a spatial resolution of mm
- Tracking capability for signal-background discrimination
  - Detailed topological analysis with simulation data (JPG, 47, 045108 (2020))
  - Kalman-filtered based track reconstruction (JHEP, 2021, 106 (2021))






Micromegas from USTC

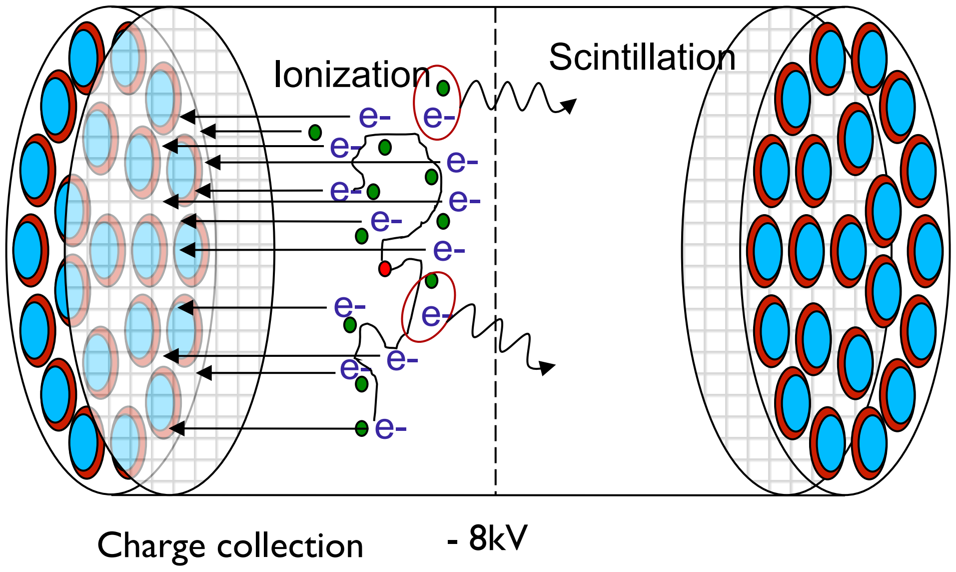

Kapton-based low-bkg front end electronics


Low-bkg SS vessel and fixture


PandaX-III clean room at CJPL

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.

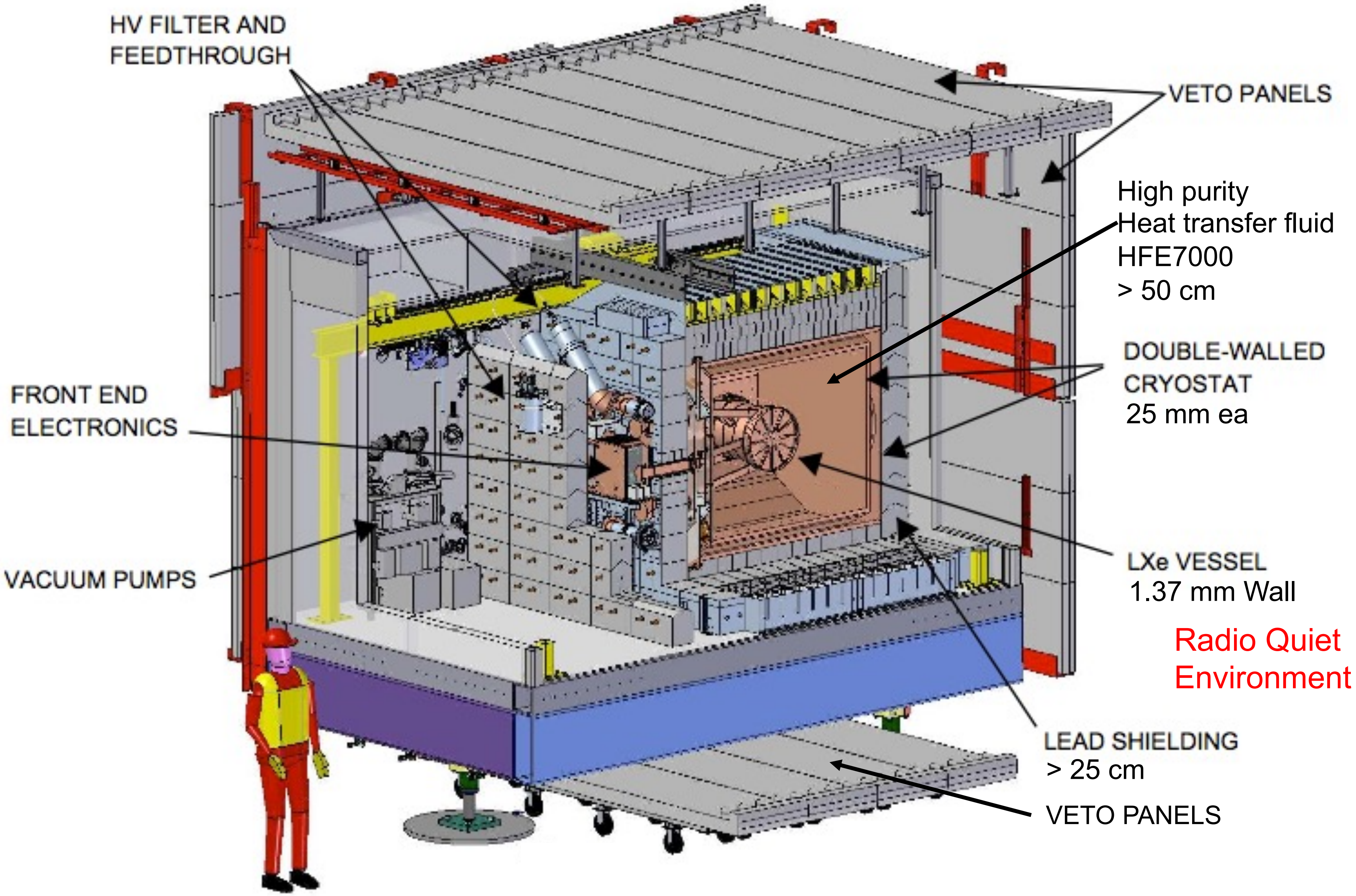


Example of TPC schematics (EXO-200)

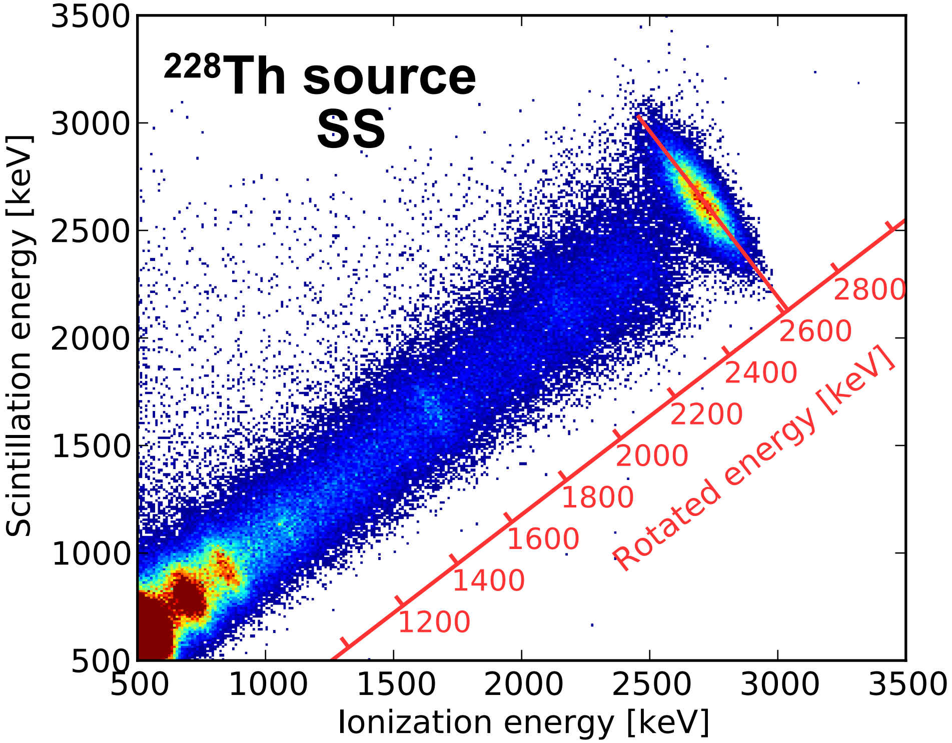
EXO-200 is a LXe detector with ~110 kg active volume, operated from 2011-2018. It has demonstrated key performance parameters for 0νββ search, and has set a lower limit on the 0νββ half-life at 3.5x10^{25} yrs with its entire dataset.

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 Detector



EXO-200 Energy Resolution

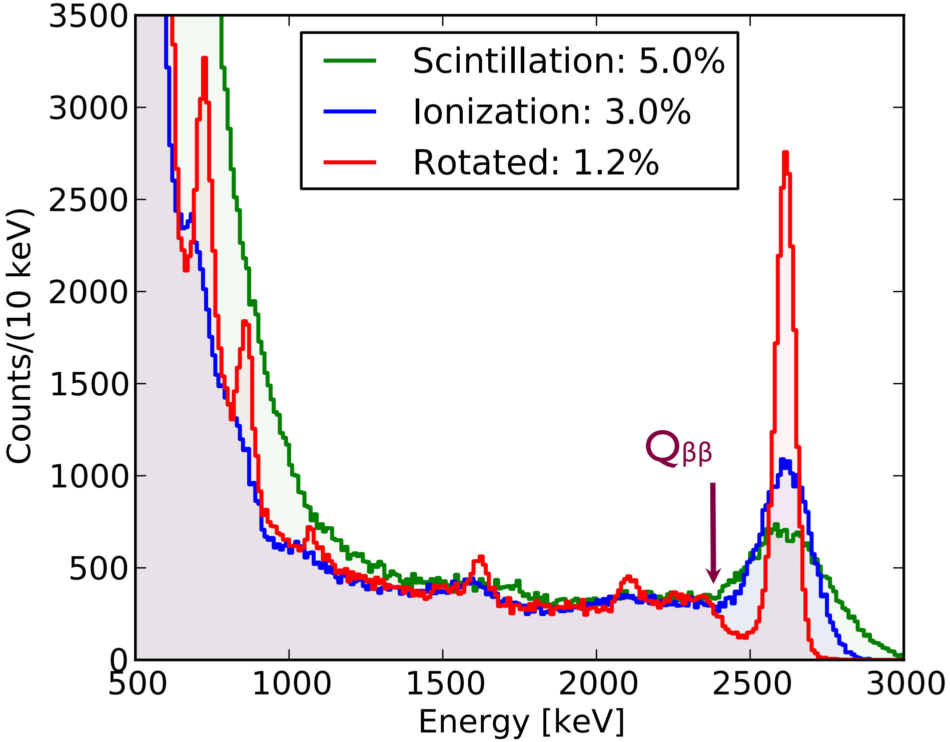


Combining Ionization and Scintillation energy to enhance energy resolution

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

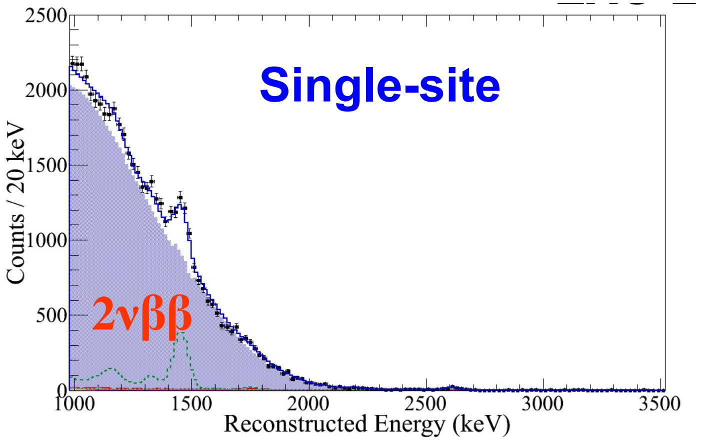
(E.Conti et al. Phys Rev B 68 (2003) 054201)

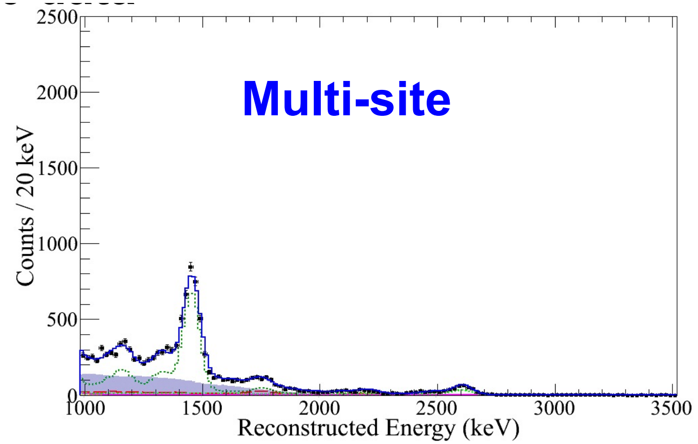
Rotation angle chosen to optimize energy resolution at 2615 keV



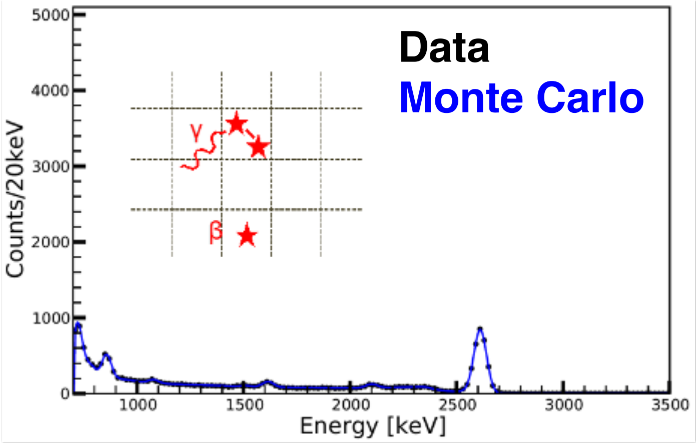
Topological Event Information in TPC

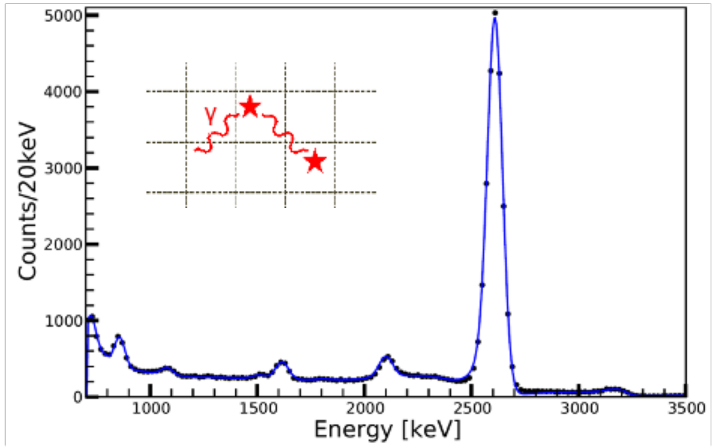
Low background data





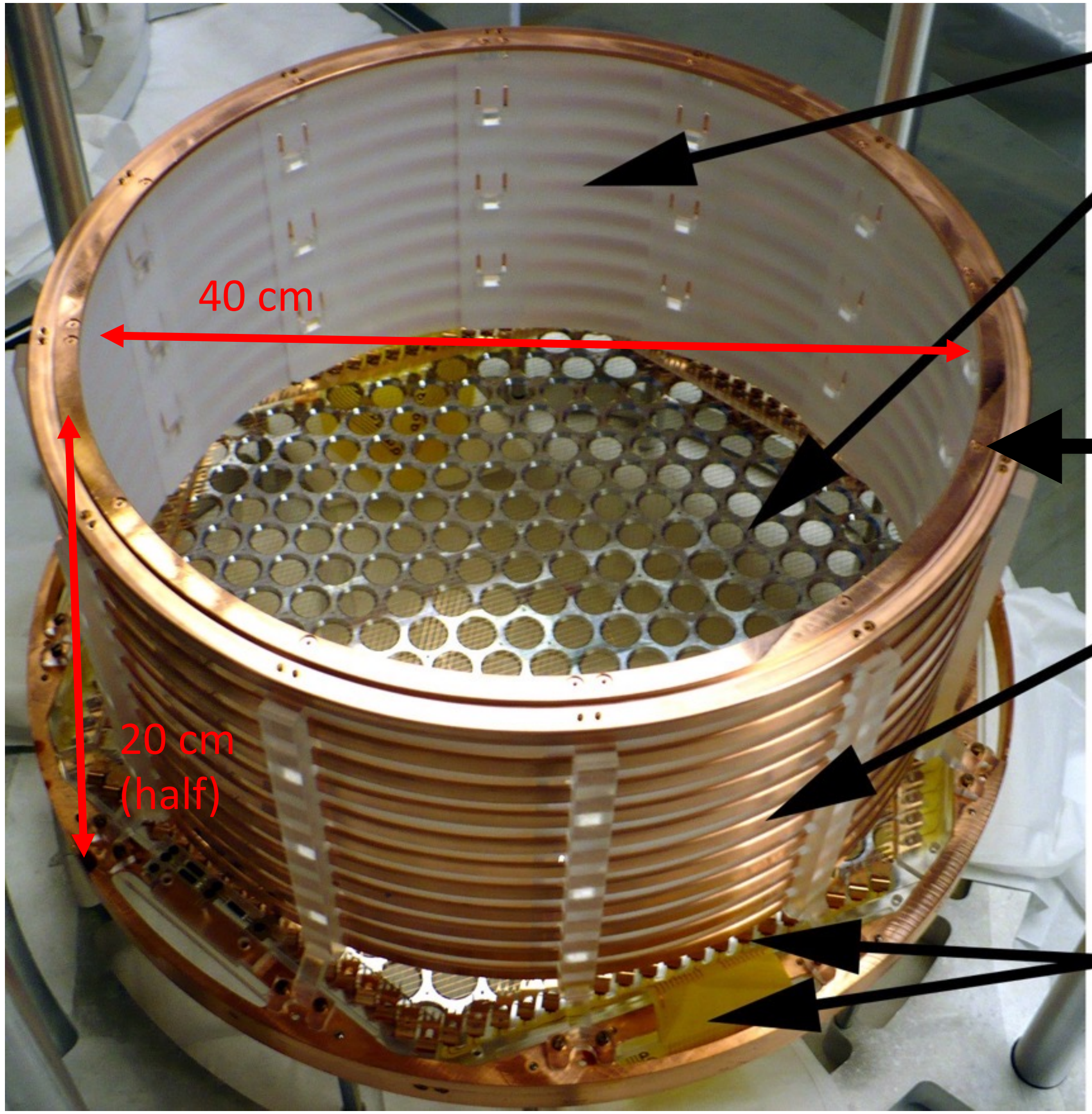
^{228}Th calibration source





- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

EXO-200 TPC



Teflon Reflectors
(increase light collection)

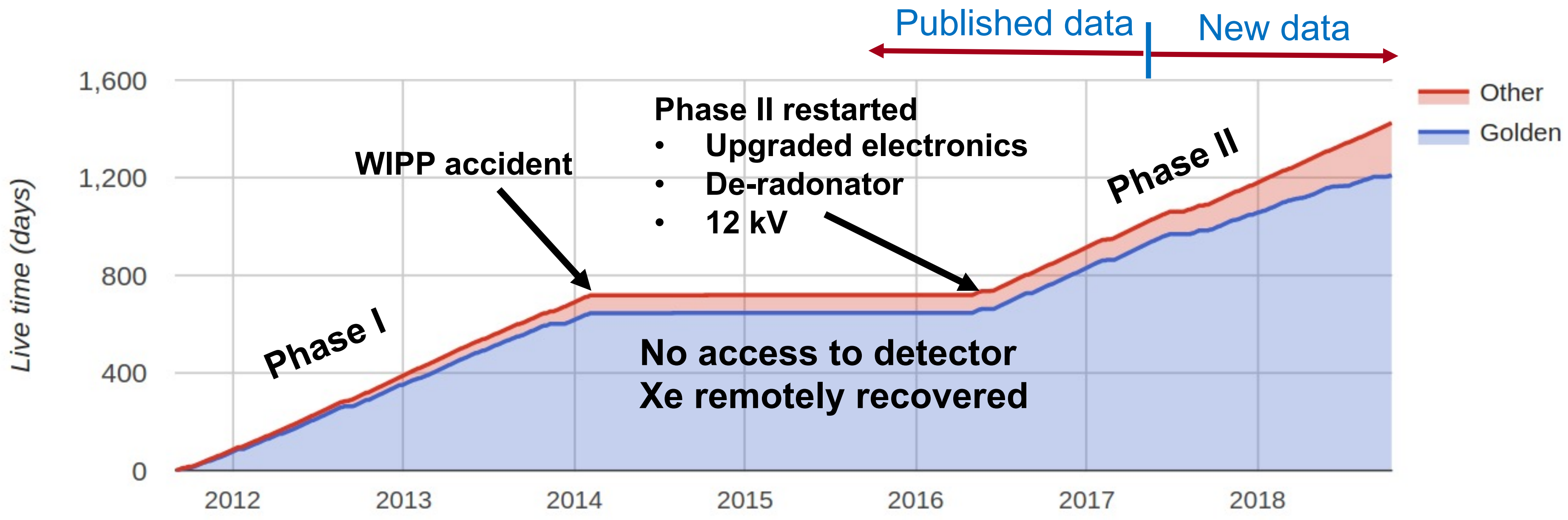
APD plane and wire planes
(wires are photo-etched)

Central HV plane
(photo-etched phosphor bronze)

Acrylic supports
and field shaping
rings

Kapton flex cables
(spring connections
eliminate solder joints
and glue)

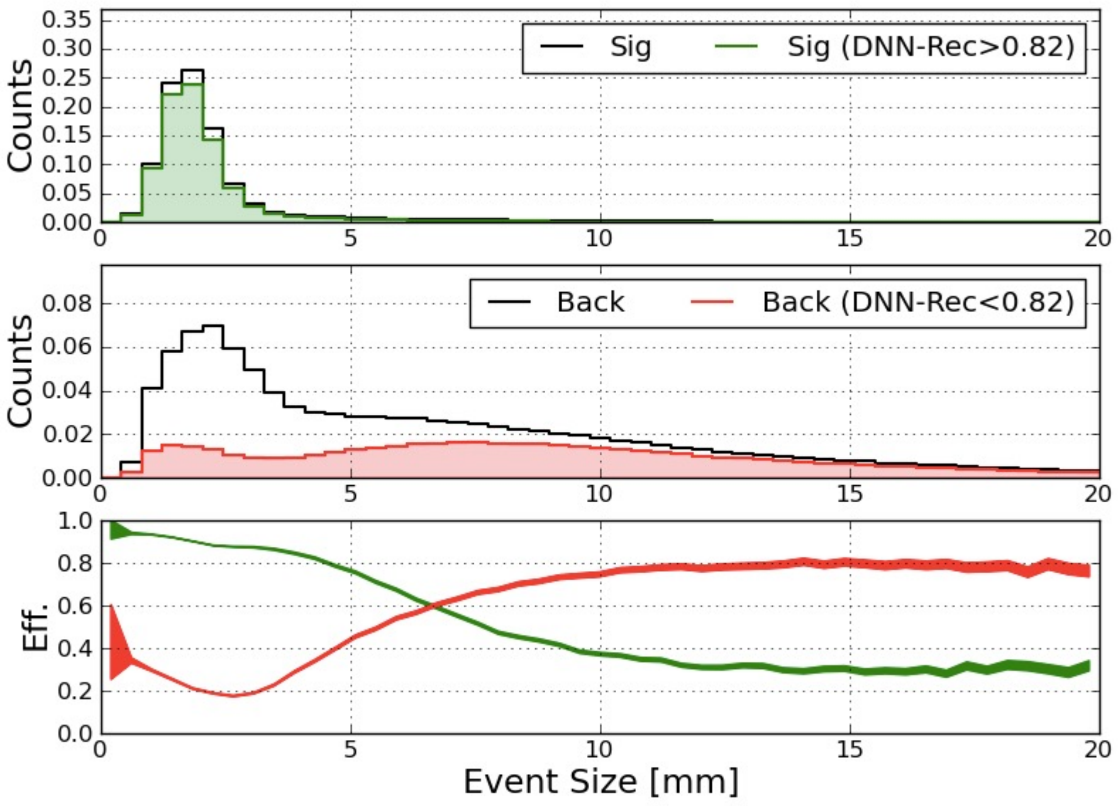
EXO-200 Timeline

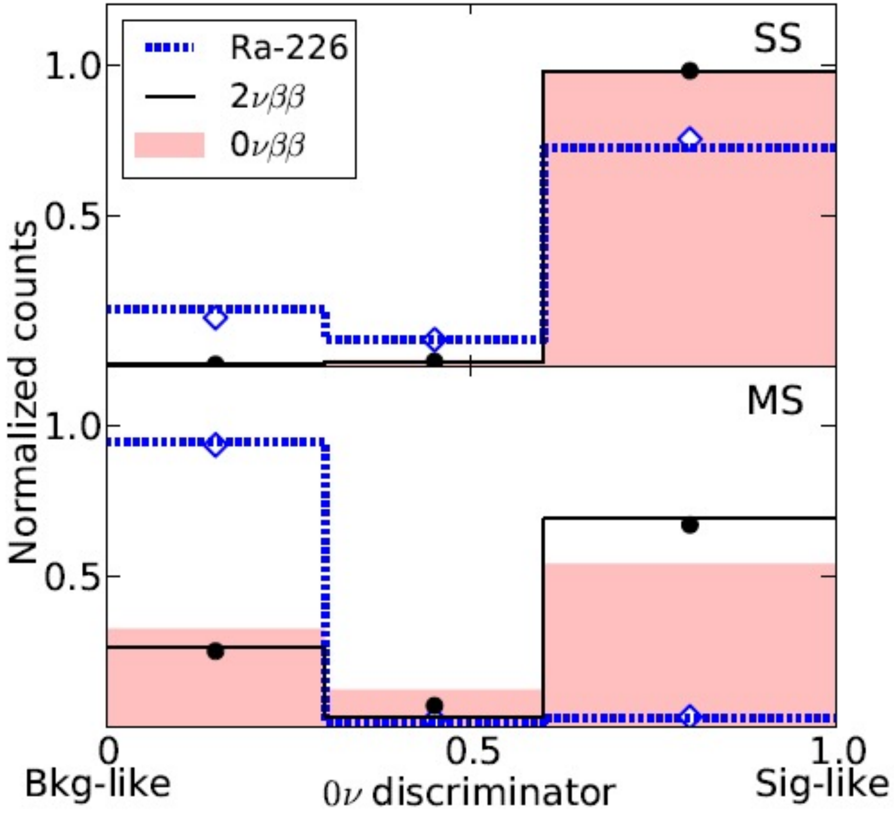


- **Operation concluded in Dec 2018, with 234.1 kg·yr total exposure of ^{136}Xe**
- Phase I from Sep 2011 to Feb 2014
  - Most precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510****, 229 (2014)*
- Phase II operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data from upgraded detector, *Phys. Rev. Lett.* ***120****, 072701 (2018)*
  - Results with the Complete data set published in Phys. Rev. Lett. 123, 161802 (2019)

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

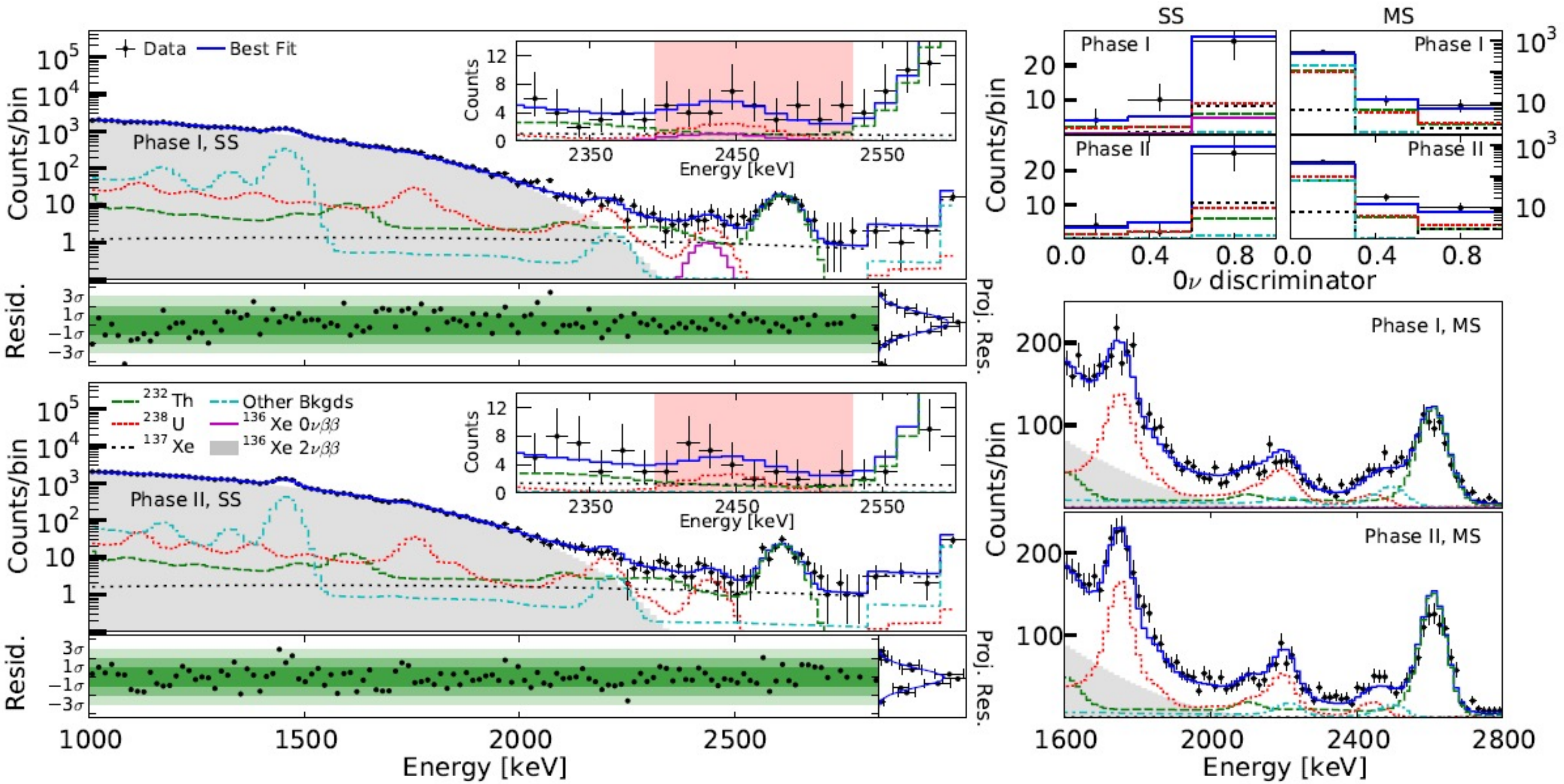




- DNN trained on images built from U-wire waveforms
- Signal/background identification efficiency clearly correlates with the true event size

- 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:

[PRL 123, 161802 (2019)]

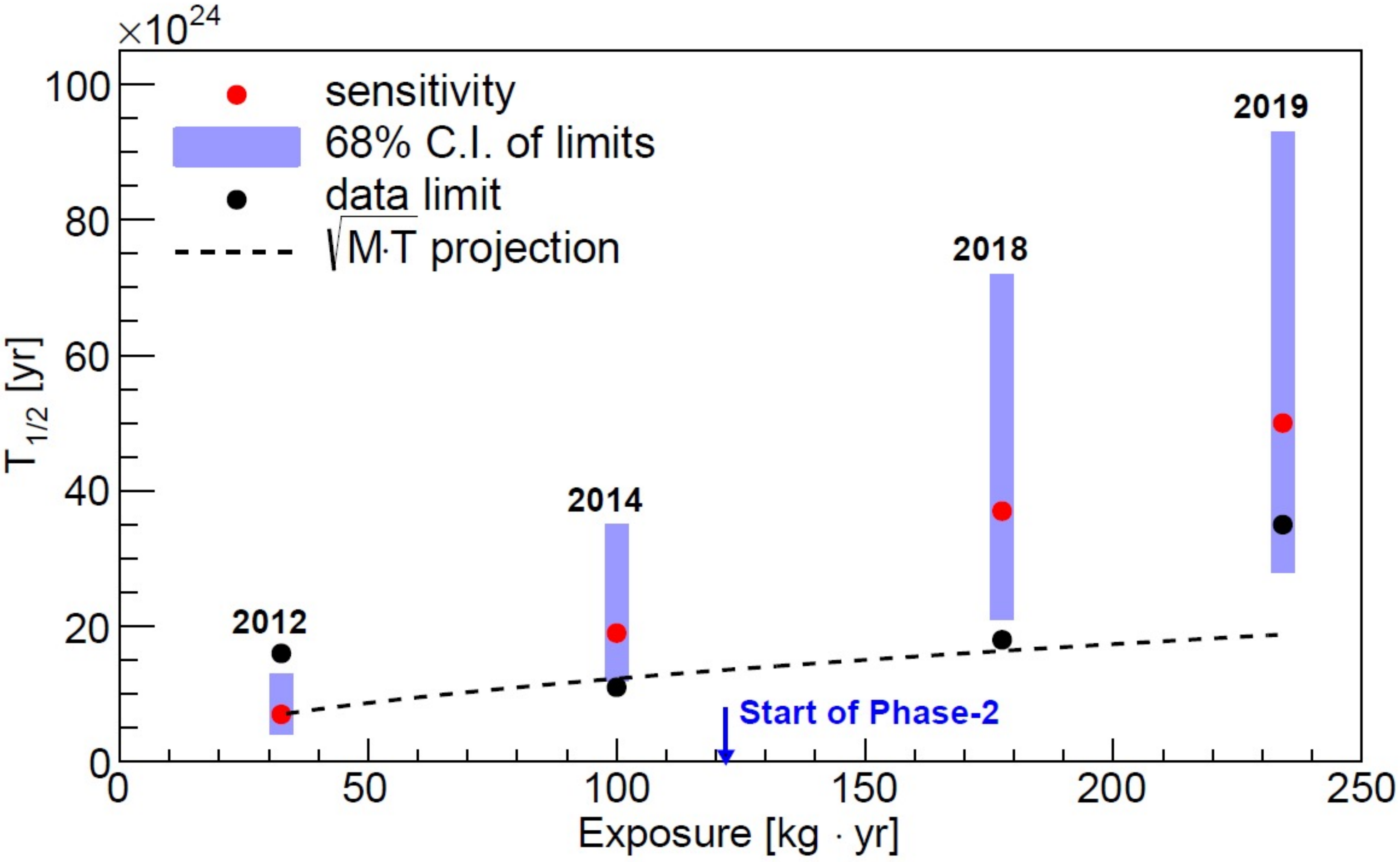
Total exposure = 234.1 kg.yr

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

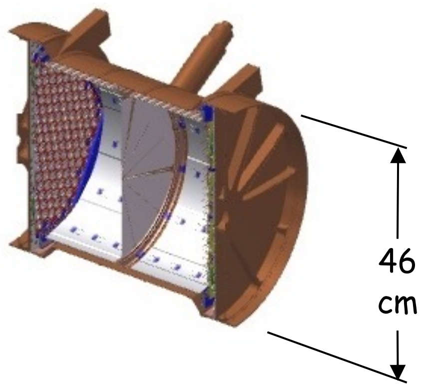


The sensitivity gains continue to improve faster than statistics due to improvements in hardware and analysis.

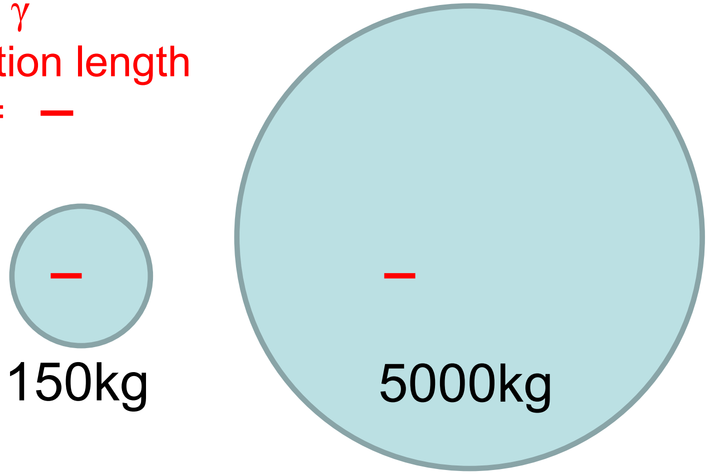
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: PRL 123, 161802 (2019)]

From EXO-200 to nEXO

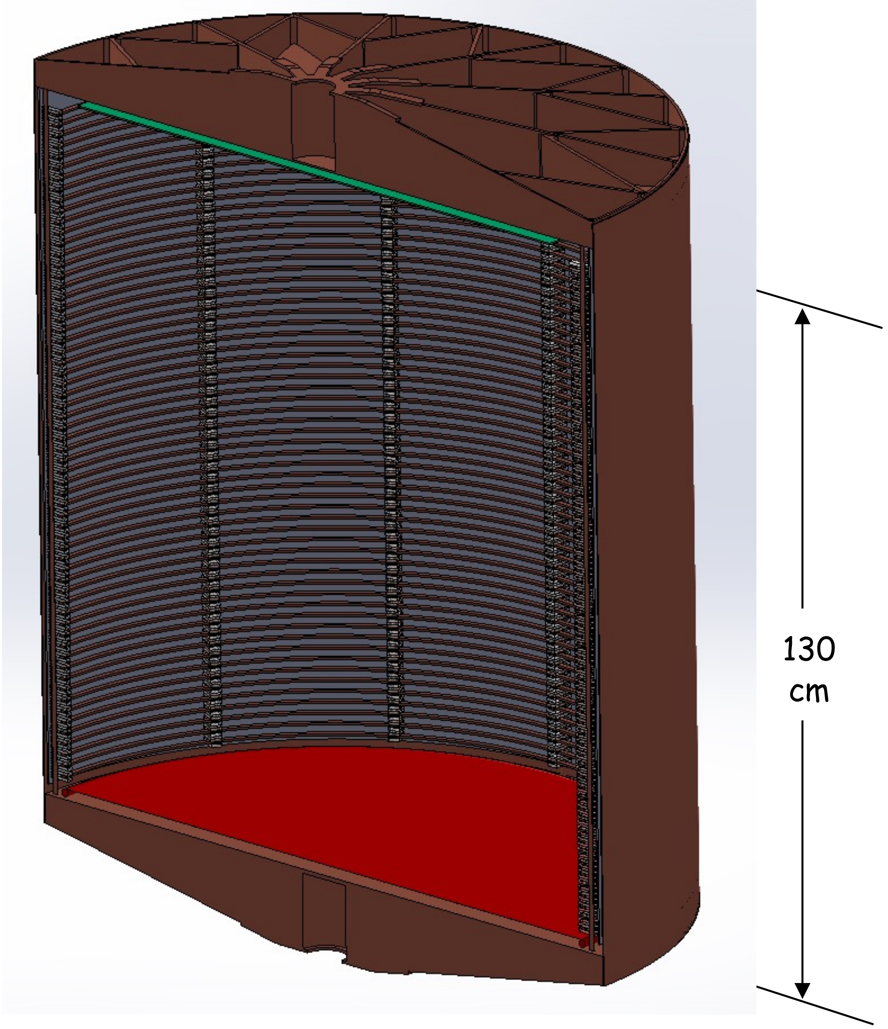
EXO-200 as a technology demonstrator



2.5MeV γ
attenuation length
8.5cm = –



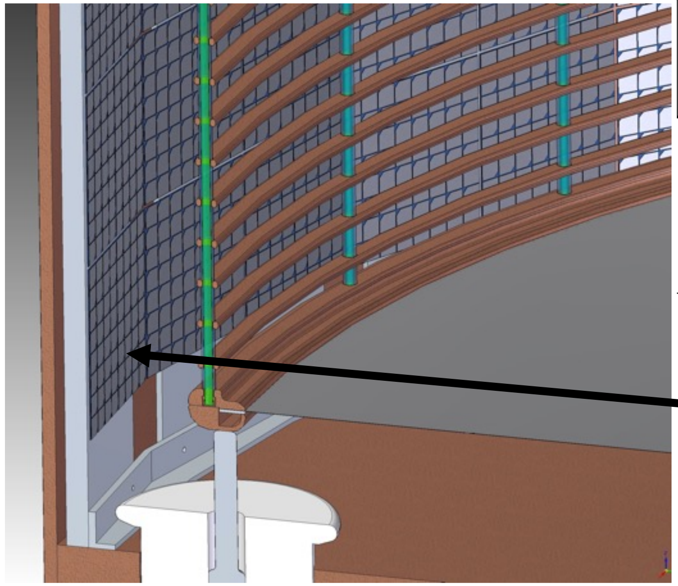
nEXO: a 5000 kg enriched LXe TPC

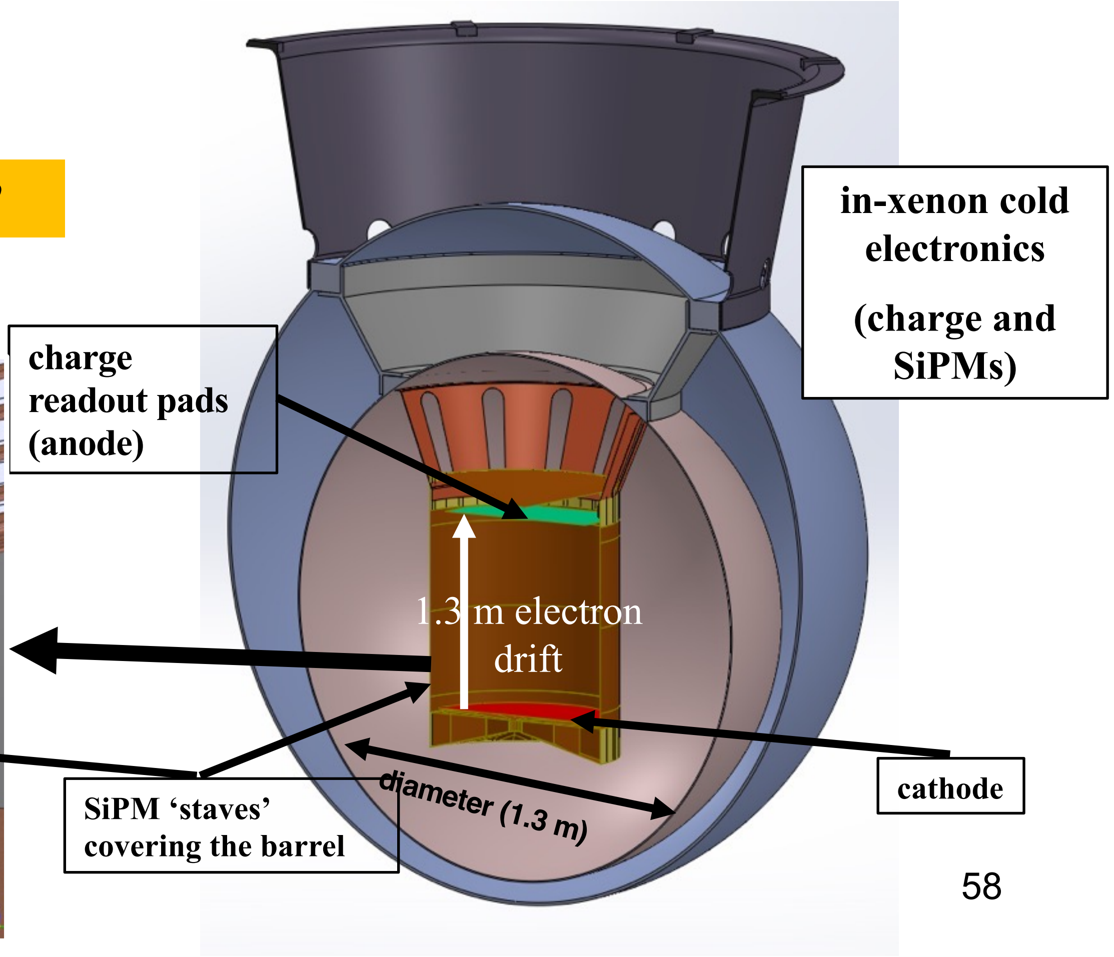


Pre-Conceptual Design of nEXO

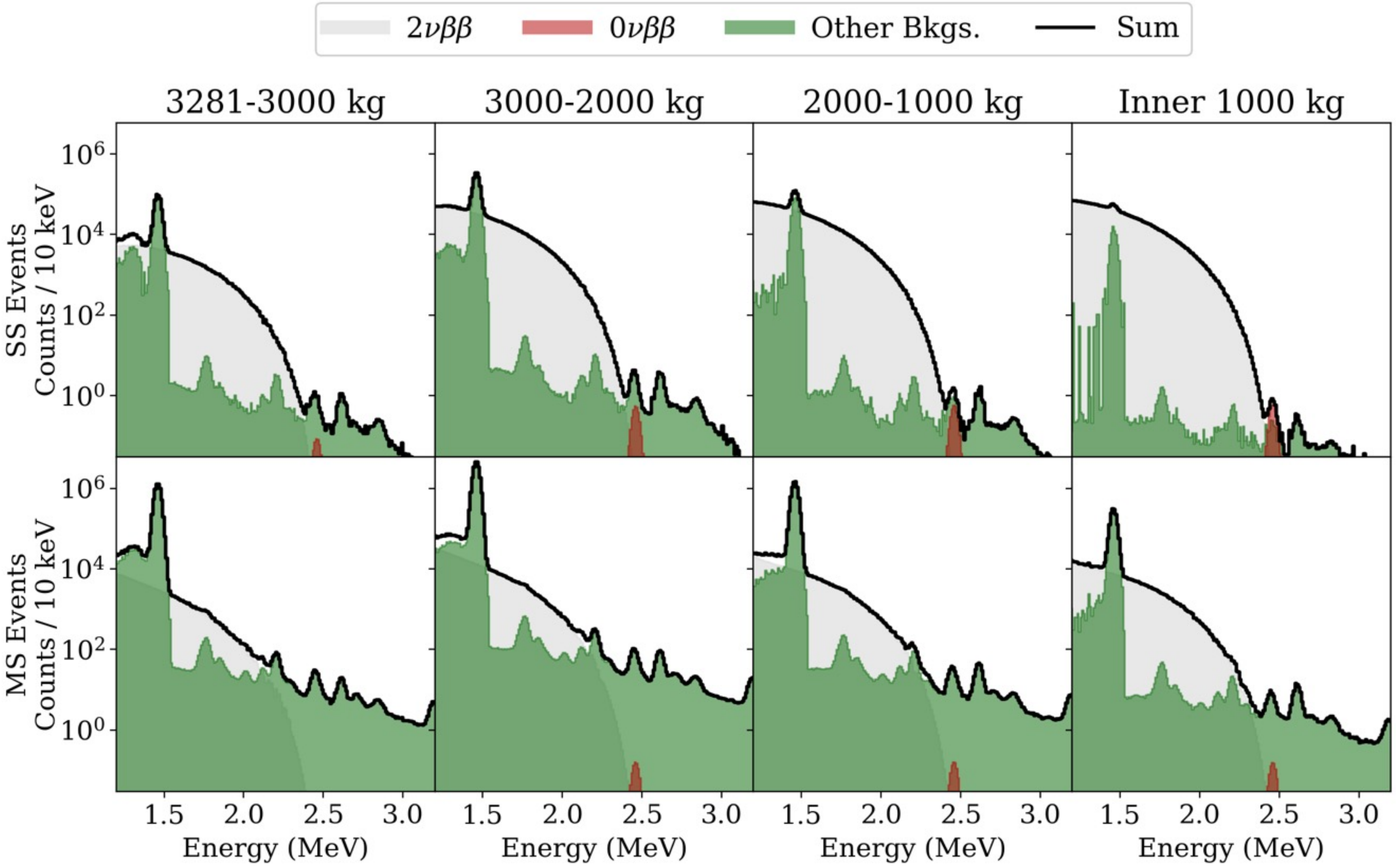
- 5 tones of single phase LXe TPC.
- Ionization charge collected by anode.
- 178nm lights detected by ~4 m^2 SiPM array behind field shaping rings.
- Combining light and charge to enhance the energy resolution.

nEXO pre-CDR, arXiv:1805.11142





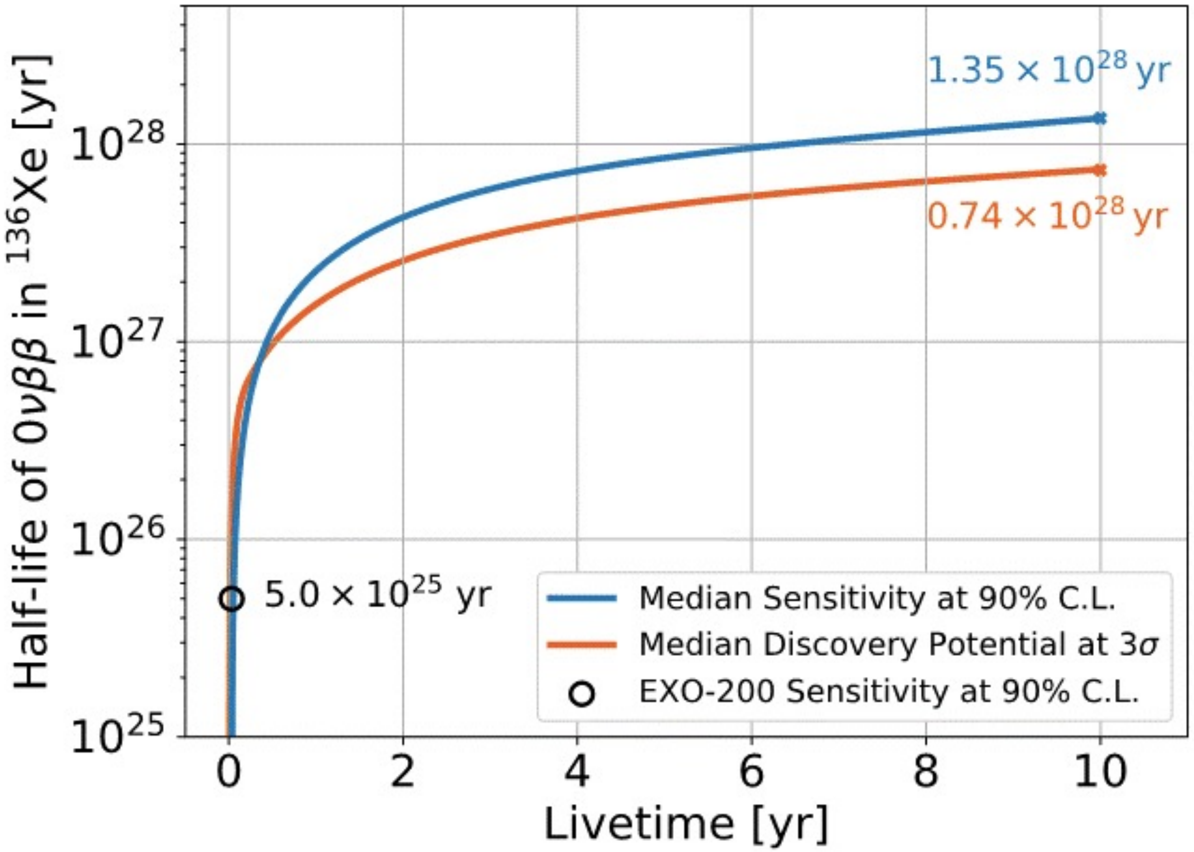
nEXO as a Discovery Tool

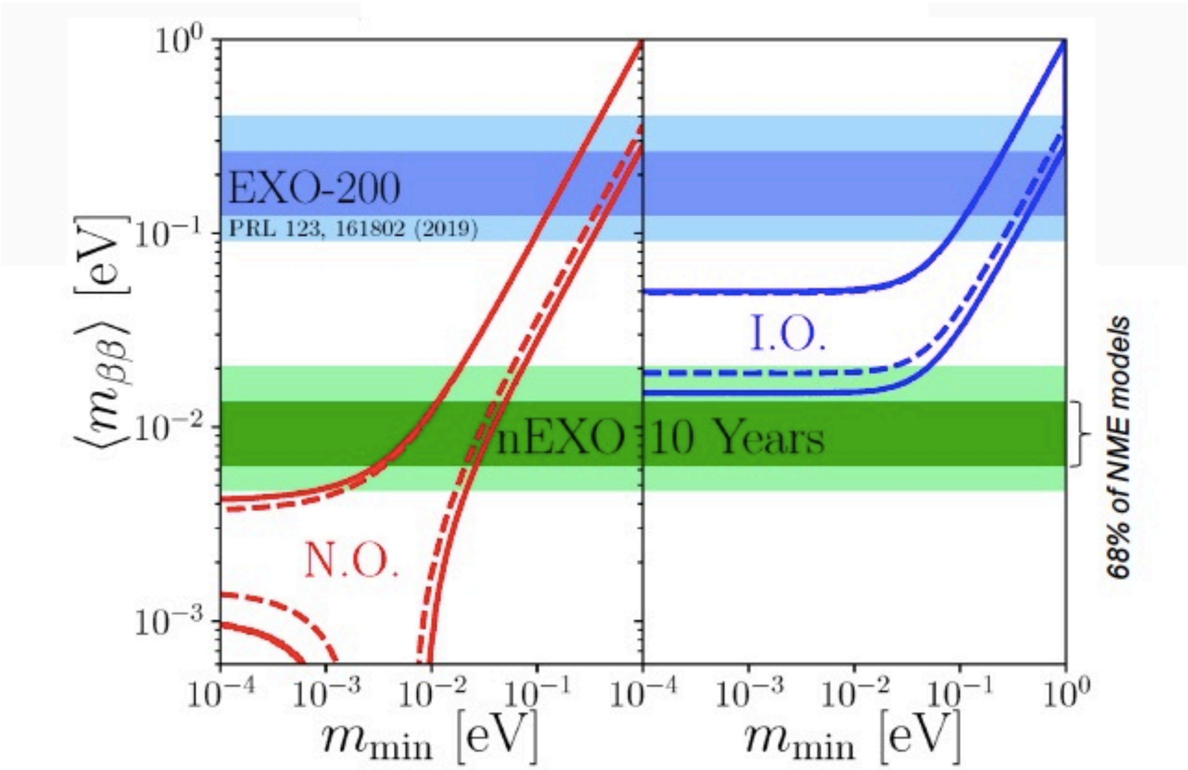


10 yr data,
0νββ corresponding to $T^{1/2} = 7.4 \times 10^{27}$ yr

Multi-parameter analysis is a powerful tool for background identification and rejection

nEXO Experimental Sensitivity

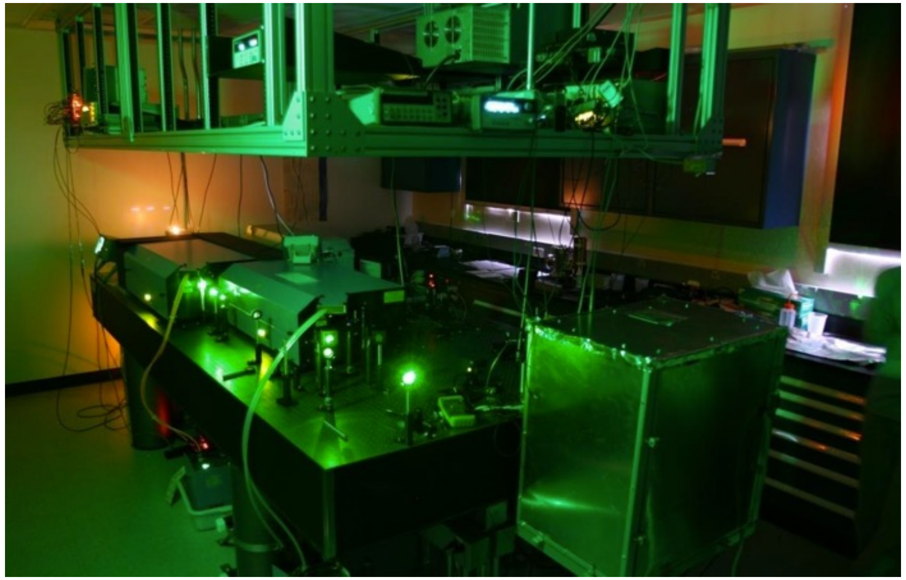


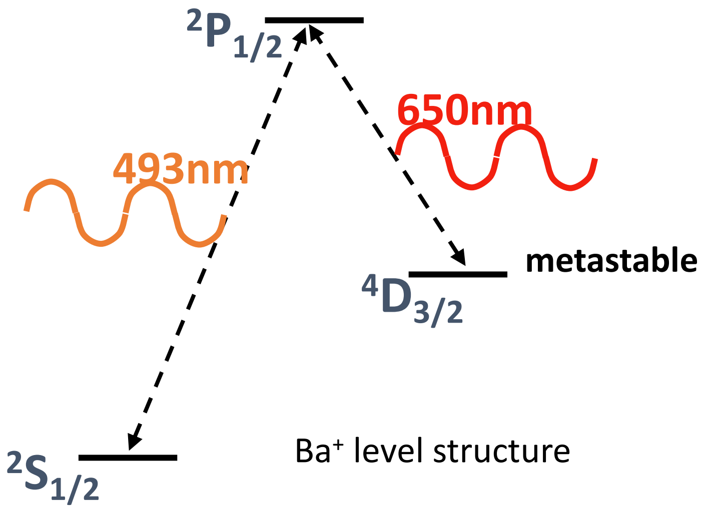


nEXO sensitivity reaches 10^{28} yrs in 6.5 yr data taking

Barium Tagging for Background Rejection

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

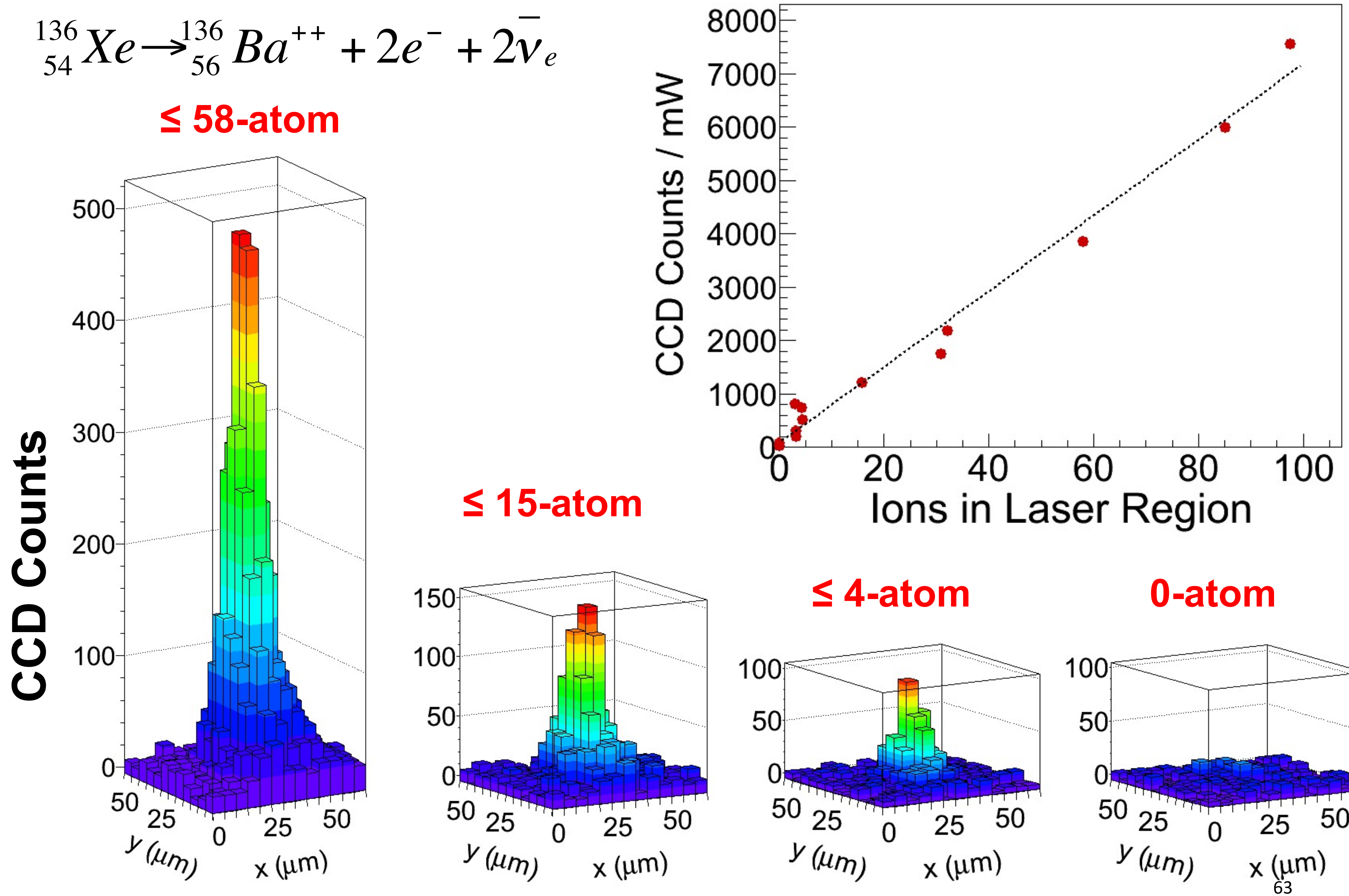




- In-situ identification of decay daughter nucleus Ba can be used to eliminate all radioactivity induced background.
- Ba ions have nice laser spectroscopy signatures.
- Difficult problem to detect a single ion inside few hundred kgs of xenon.

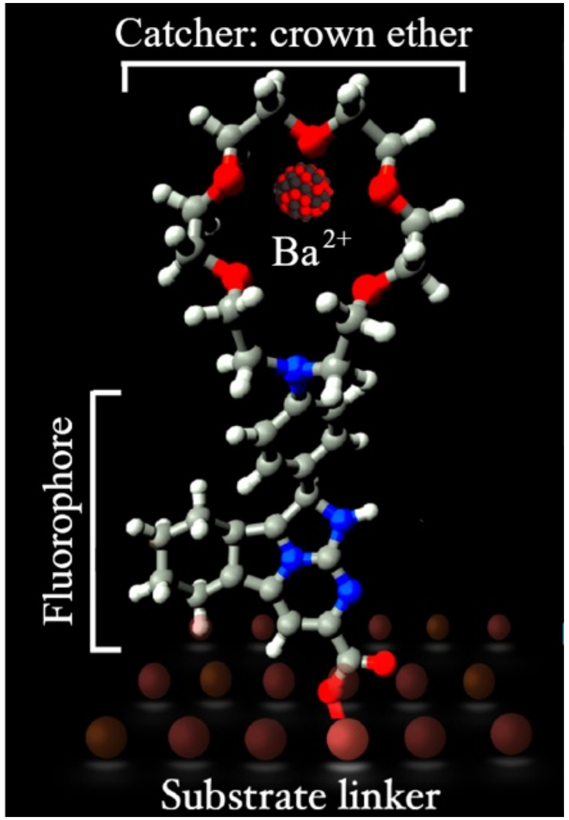
Tagging ββ decay daughter Ba in Solid Xe (nEXO)

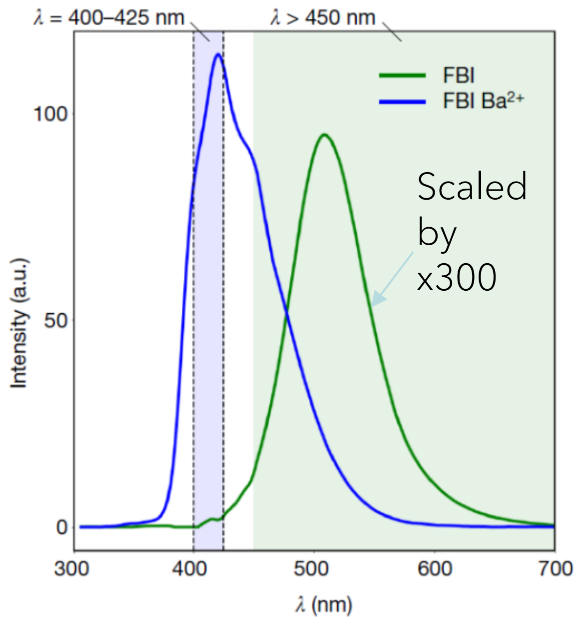
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$



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

Ba Tagging in Gas Xe (NEXT)





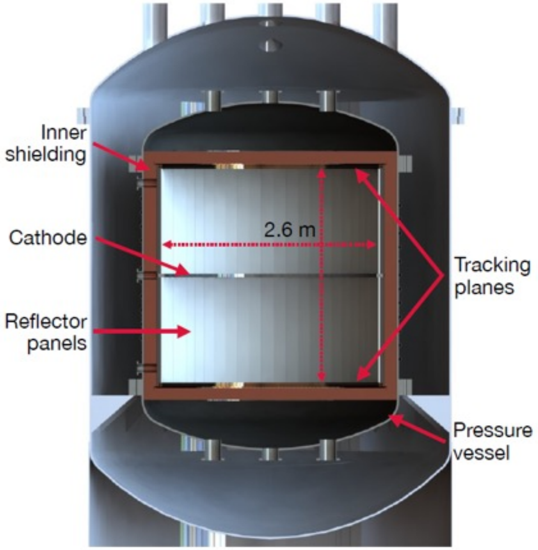
- Use single molecule fluorescent imaging to visualize (“tag”) a single Ba^{2+} ion as it arrives at the TPC cathode (D. Nygren)

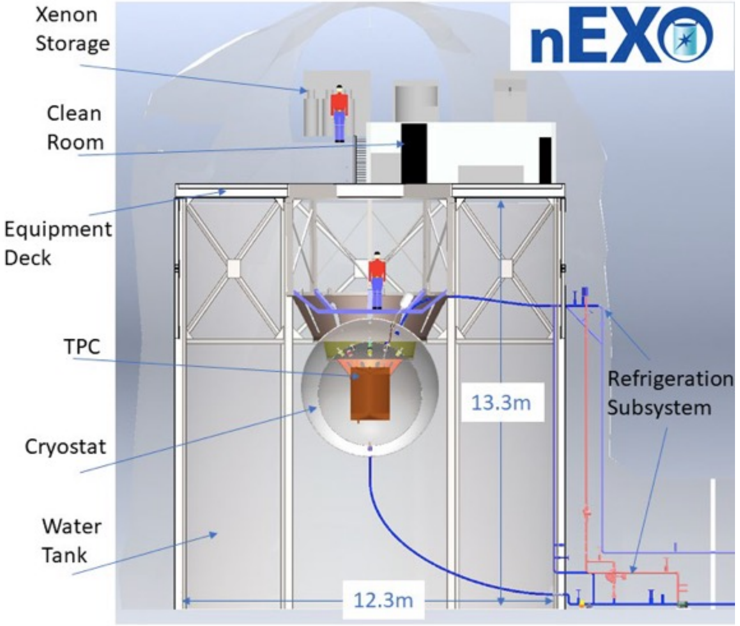
- Fluorescent Bicolor Indicators (FBI): enhanced fluorescence and spectral separation

- First demonstration of in-vacuo chelation

Nature 583 (2020) 48-54

ACS Sens 6 (2021) 192-202





Time Projection Chamber (TPC)

Strengths

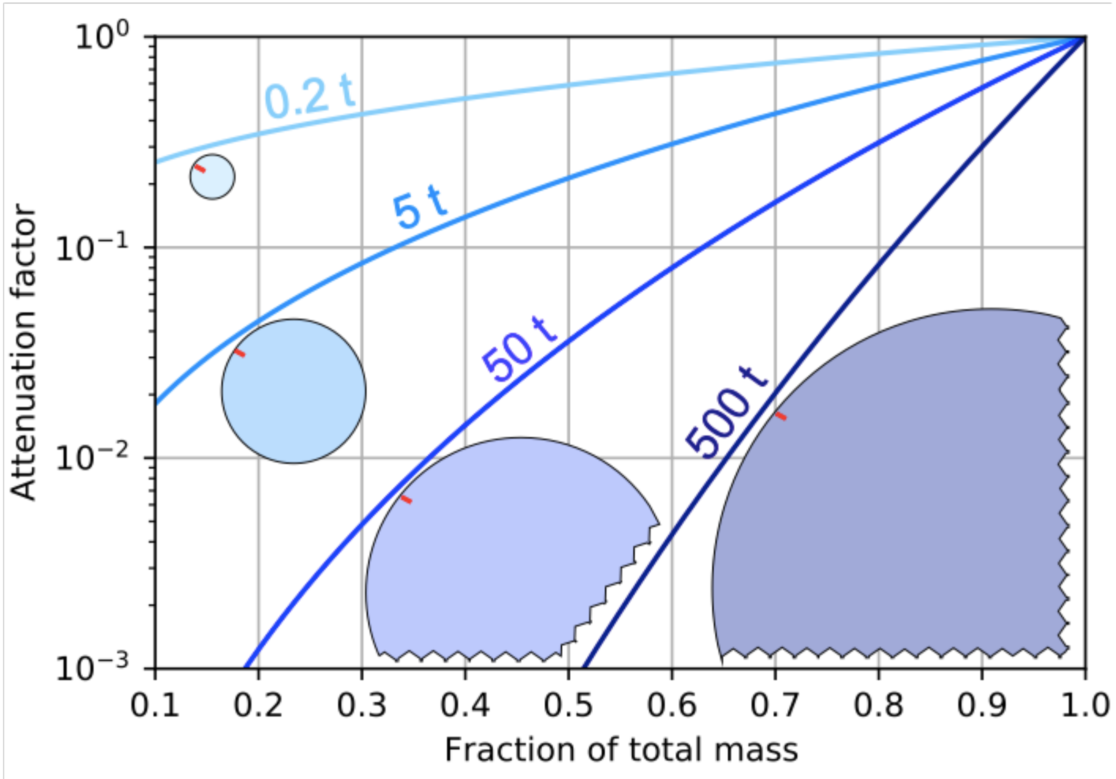
- Monolithic detector
- Good energy resolution
- Event topology measurements
- Excellent background rejection with multi-parameter analysis
- Isotope can be purified continuously and exchanged
- Tagging decay daughter possible for Xe

Weaknesses

- Worse energy resolution than Ge and Bolometer
- Detector more complex compared with LS
- Isotope availability

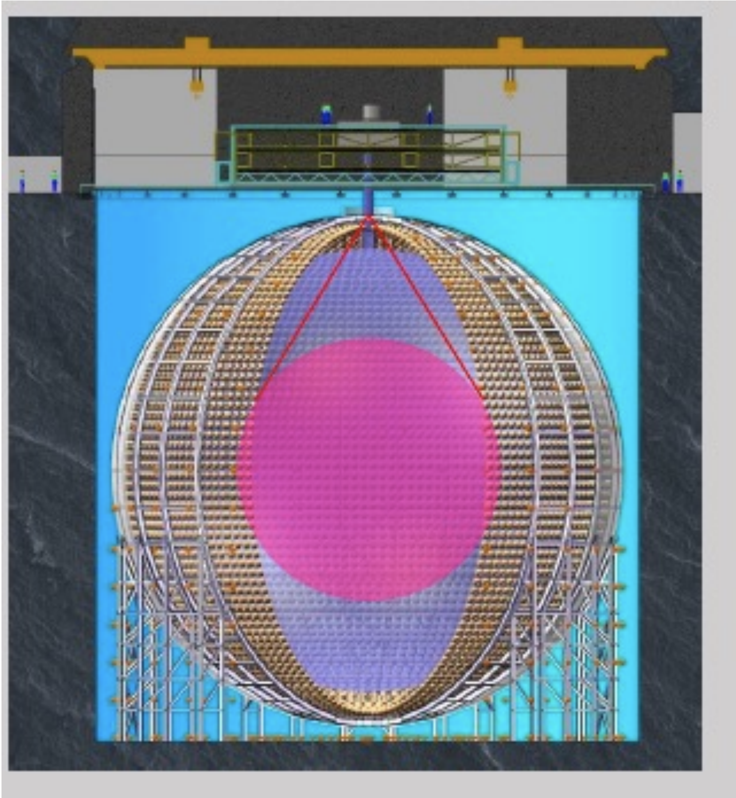
Beyond Tonne scale detectors (2030)

Large TPC



50 t scale LXe detector R&D underway for dark matter search. Some synergy with $0\nu\beta\beta$ searches

Loaded LS

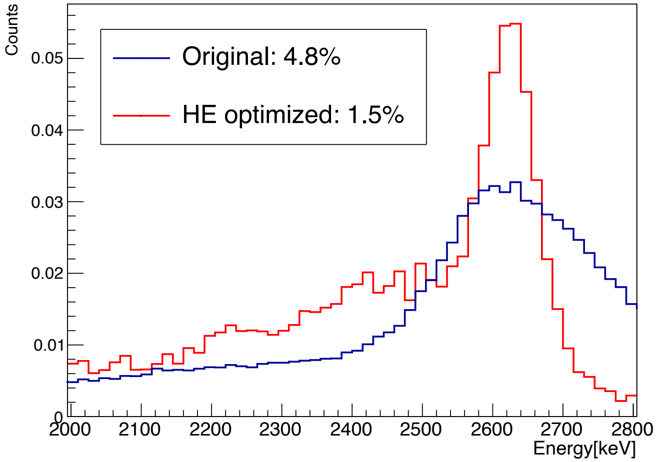


JUNO can be upgraded by loading $0\nu\beta\beta$ isotope in LS

Background sources will require careful study and control.

$0\nu\beta\beta$ search with PandaX-4T and beyond

- PandaX-4T multi-physics detector was commissioned in late 2020; first DM search results released
- 4T natural xenon→ ~350 kg of ^{136}Xe; 400 kg of ^{134}Xe; 4 kg of ^{124}Xe: ββ and ECEC searches in multiple isotopes possible
- Th and Co calibration runs for high energy ROI
- Compared to PandaX-II: much improved energy resolution (~4%→1.5%); cleaner detector; better self-shielding



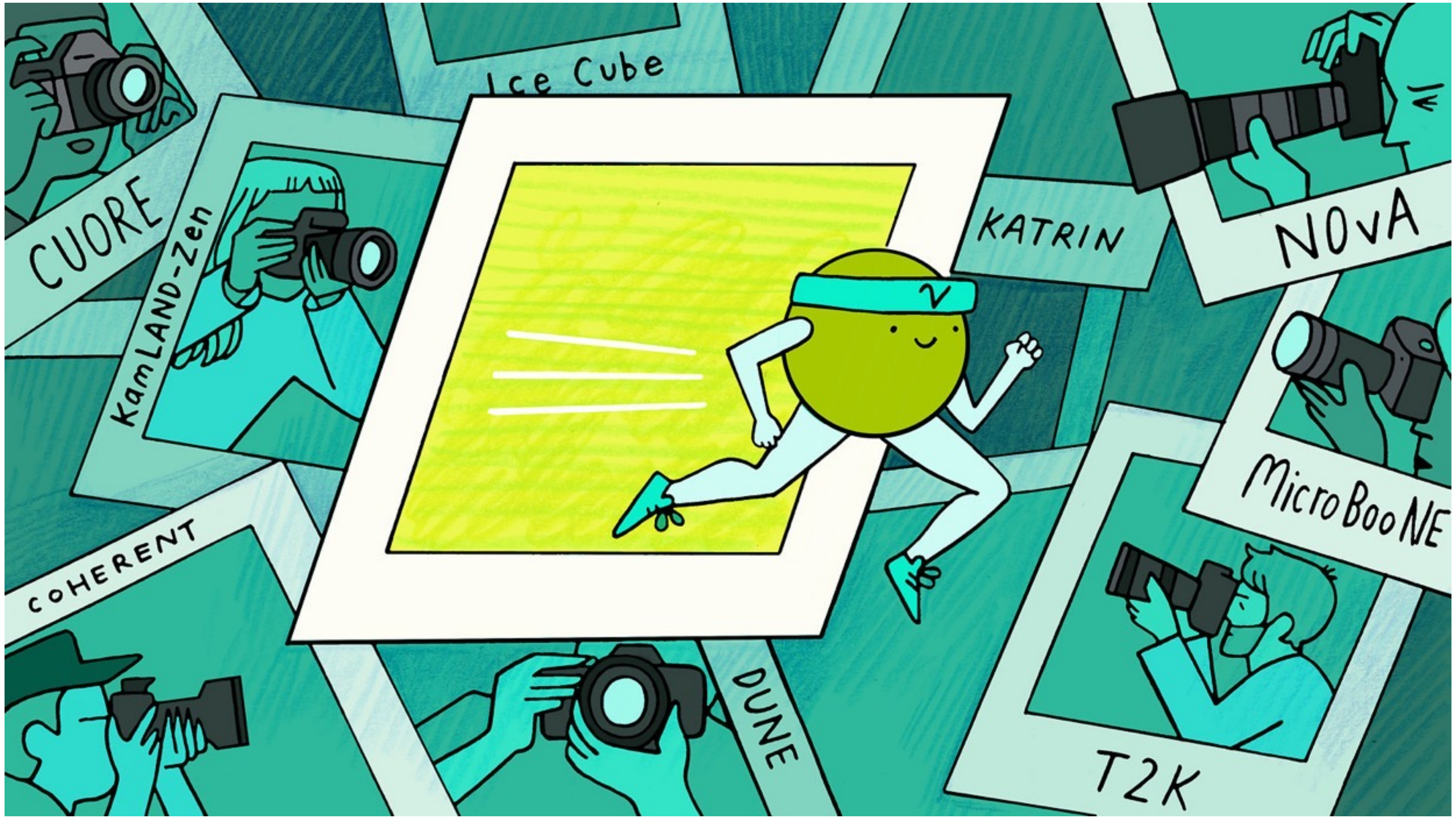
- Active R&D on new generation of liquid xenon TPC at CJPL
- Exploring options for better ββ physics:
  - New PMT for low radioactivity, better position recon, fast timing, no saturation
  - New vessel materials/designs for minimizing background
  - Enrichment with cryogenic distillation

Summary

• Neutrinoless double beta search is the most sensitive probe for the Majorana nature of neutrinos.

• After decades of research, physicists are ready to build “tonne-scale” experiments to probe the entire inverted hierarchy region.

• Probing the normal hierarchy will require continued development in new technology and ideas.



Hope you will join us for the adventure!