Neutrinoless double beta decay searches: gearing up for the tonne-scale era

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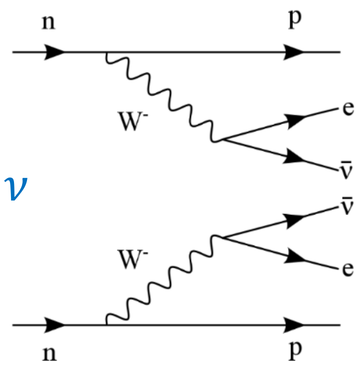
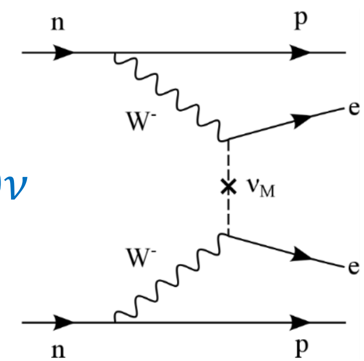
Neutrinoless double beta decay

- SM double beta decay $\beta\beta2\nu$: ${}^{A}_{Z}X \longrightarrow {}_{Z+2}^{A}X + 2e^{-} + 2\bar{\nu}_{e}$
- BSM neutrinoless double beta decay $\beta\beta0\nu$: ${}^{A}_{Z}X \longrightarrow {}_{Z+2}^{A}X + 2e^{-}$
- $\beta\beta0\nu$: violates lepton number by 2 units, neutrinos must be Majorana

$\beta\beta2\nu$



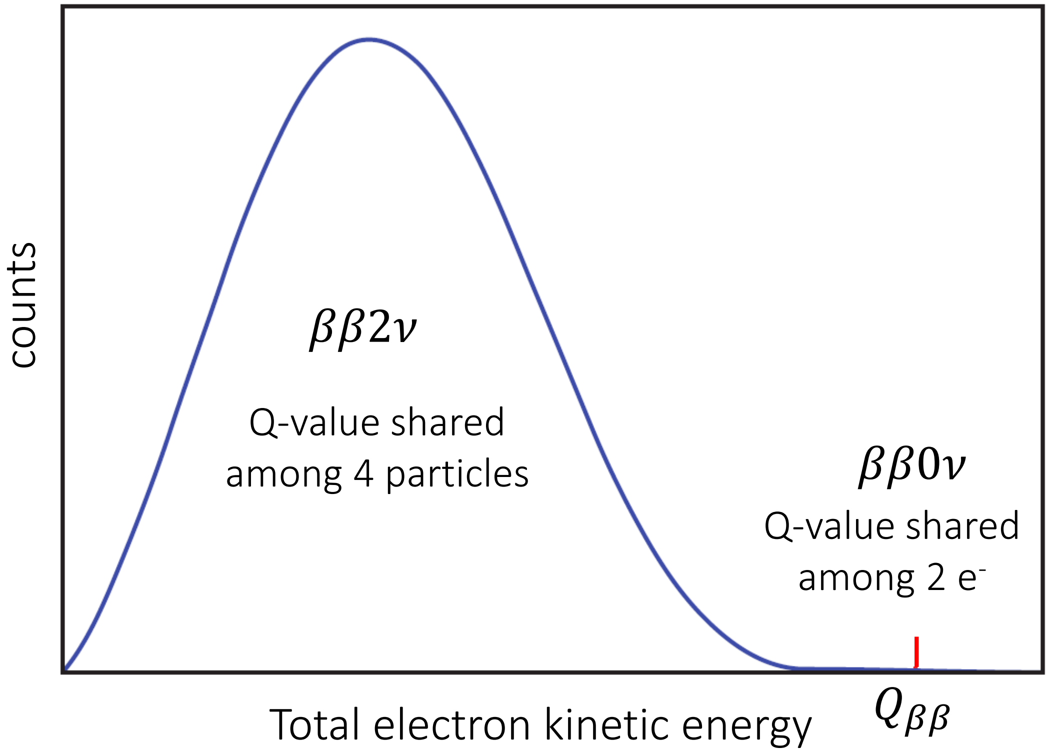
$\beta\beta0\nu$



Observed, $\Delta L = 0$, $T_{1/2} \sim 10^{19} - 10^{21}$ y

Unobserved, $\Delta L = 2$, $T_{1/2} > 10^{26}$ y

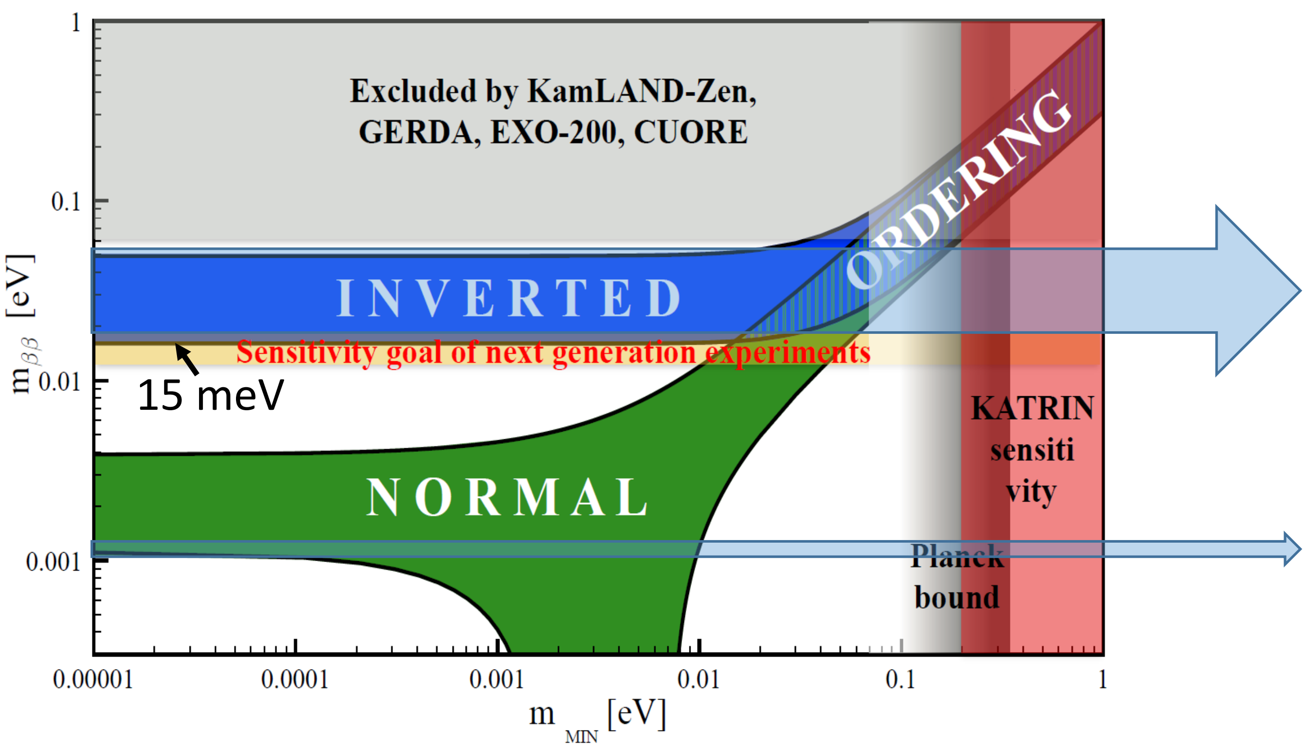
$\beta\beta 2\nu$ vs. $\beta\beta 0\nu$



$\beta\beta 0\nu$ can only occur in nuclei with $\beta\beta 2\nu$, with $< 10^{-5}$ relative rate

The Majorana neutrino challenge

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 m_{\beta\beta}^2$$



Lifetime ~10^{27}-10^{28} years. 1 signal event in a tonne of active volume per year

Lifetime ~10^{30} years. 1 signal event in 100 tonne of active volume per year

Backgrounds

- Natural radioactivity
- $\beta\beta 2\nu$ leakage into the ROI
- Cosmogenic activation
- Neutrinos

Background suppression requires excellent energy resolution + additional handles

$\beta\beta0\nu$ searches

- Germanium detectors
- Bolometers
- Loaded liquid scintillators
- Liquid xenon TPCs
- High-pressure gaseous xenon TPCs
- (Others)

All experiments give “forward-looking” MC-based predictions about their tonne-scale expected performance

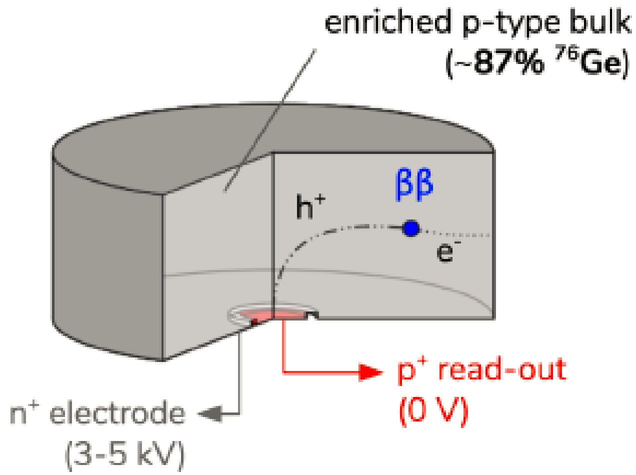
Germanium detectors

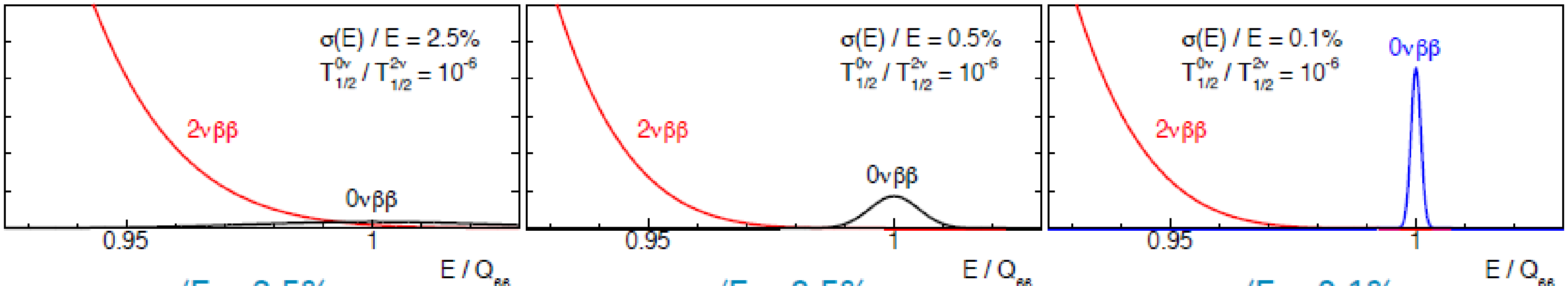
Majorana, GERDA, LEGEND

Ge diodes for $\beta\beta0\nu$ in ^{76}Ge

HPGe detectors enriched in >85% ^{76}Ge ($Q_{\beta\beta} = 2039$ keV)

- Superb energy resolution (0.13% FWHM at $Q_{\beta\beta}$)
- Diode geometry optimized for PSD
- High purity and radio-purity
- High detection efficiency



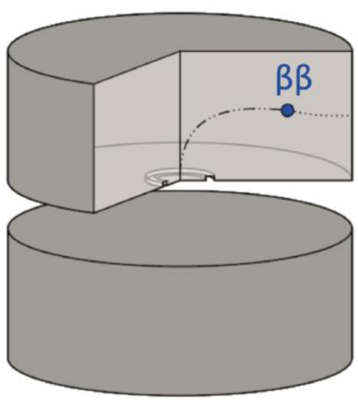


σ/E = 2.5% σ/E = 0.5% σ/E = 0.1%

Background suppression

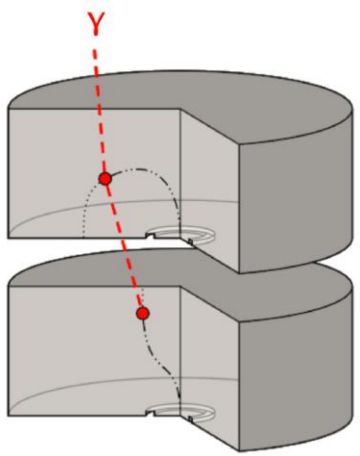
Event topology + anti-coincidence between HPGe detectors
+ pulse shape discrimination + liquid argon veto

Event topology



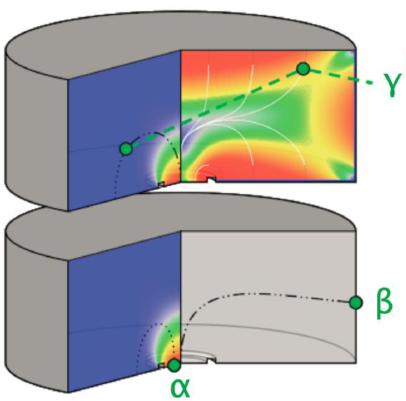
Differentiate point-like ββ topology from:

Detector anti-coincidence



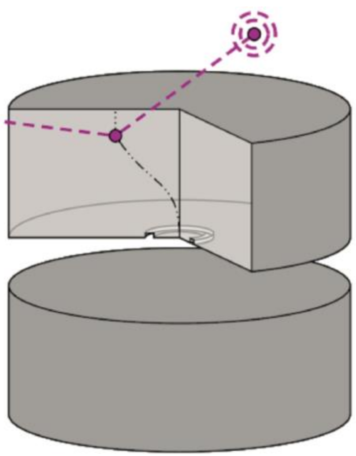
multi-detector interactions

Pulse shape discrimination



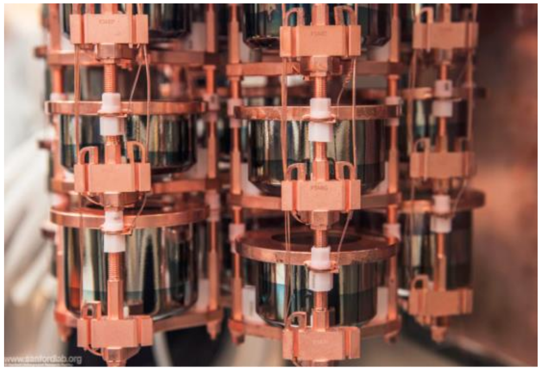
multi-site / surface interactions

Detector-LAr anti coincidence



interactions with coincident energy deposition in LAr

Existing and future Ge experiments



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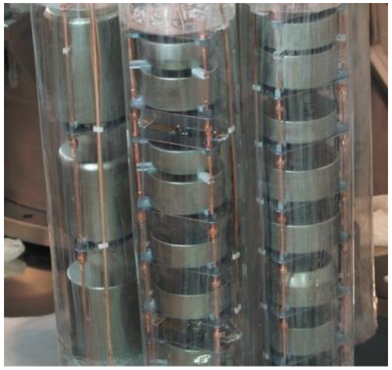
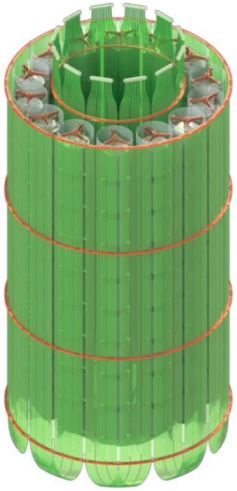




LEGEND-1t

Goal: $T_{1/2} \sim 1 \times 10^{28}$ y (90% CL)

Location: tbd

MAJORANA at SURF

29.7 kg of 88% enriched ^{76}Ge crystals

2.5 keV FWHM at 2039 keV

26 kg y exposure; PRL 120 (2018)

$T_{1/2} > 2.7 \times 10^{25}$ y (90% CL)

Continues taking data

GERDA at LNGS

35.6 kg of 86% enriched ^{76}Ge crystals

3.0 keV FWHM at 2039 keV

58.9 kg y exposure; published in Science 2019

$T_{1/2} > 0.9 \times 10^{26}$ y (90% CL)

LEGEND-200 at LNGS

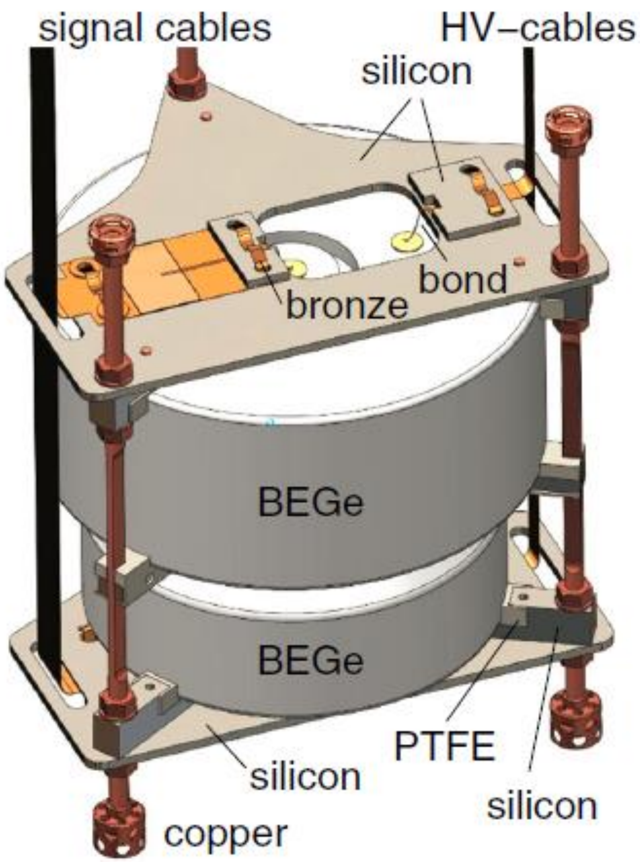
200 kg of ^{76}Ge crystals at LNGS

Goal: 1 tonne year exposure

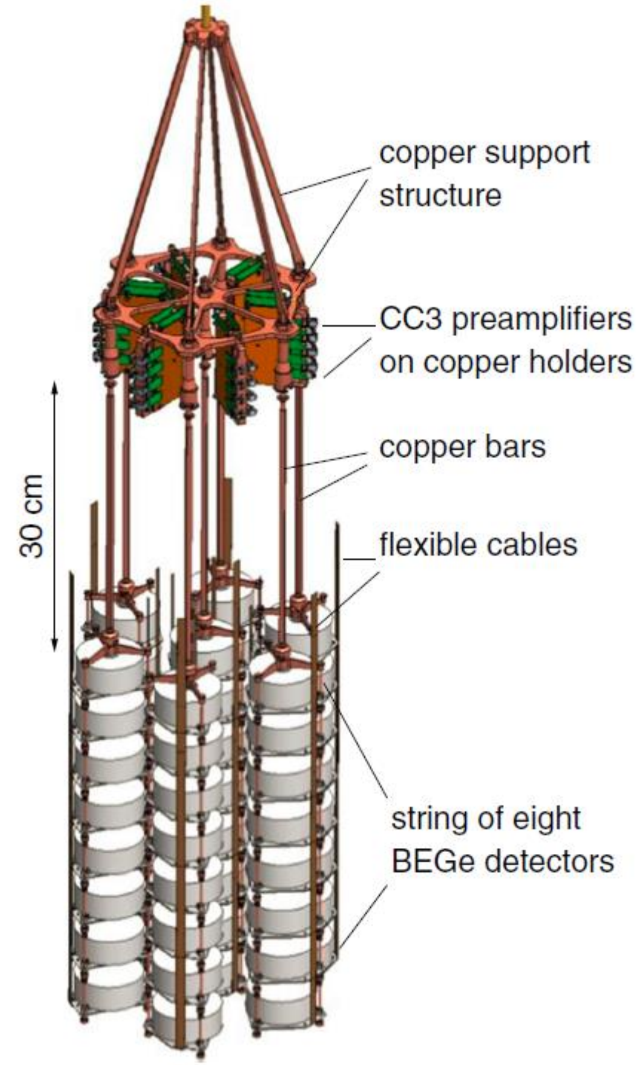
Goal: $T_{1/2} \sim 1 \times 10^{27}$ y (90% CL)

Start in 2021

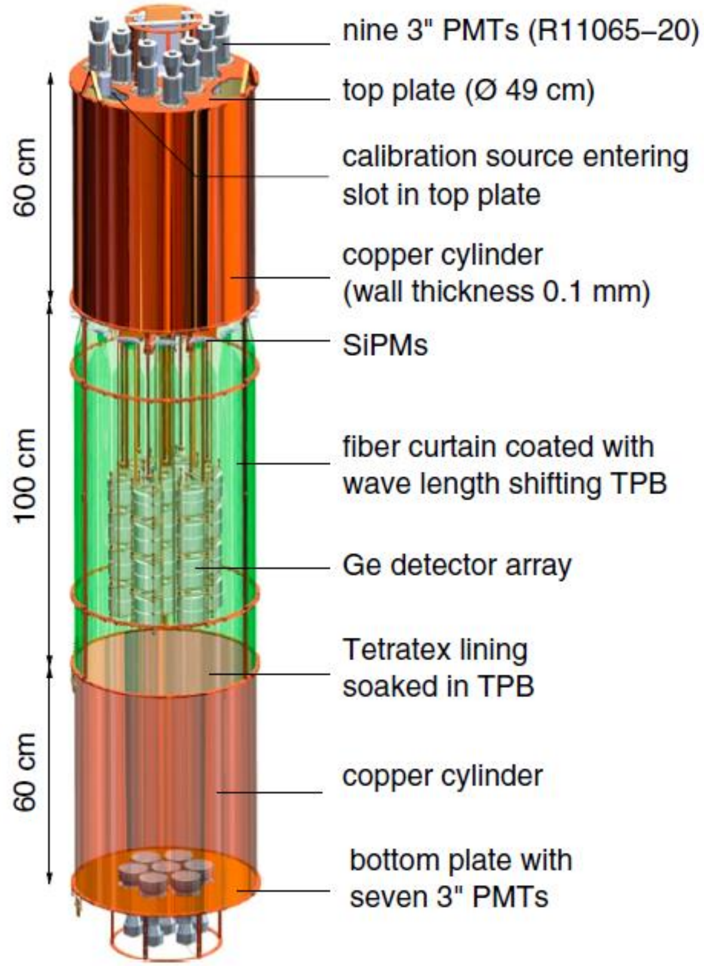
GERDA



Bare crystals

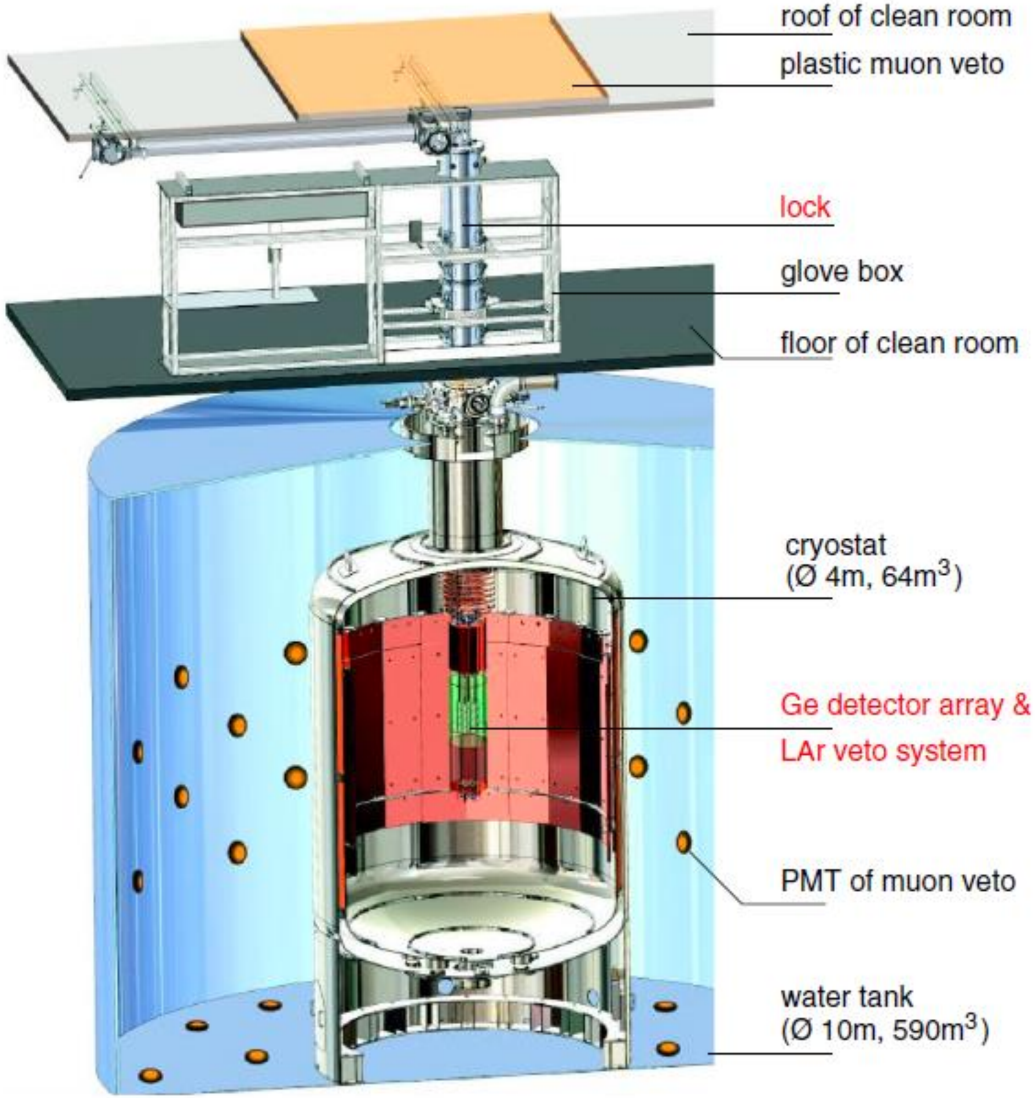


GERDA



LAr used for shielding, cooling + veto

GERDA

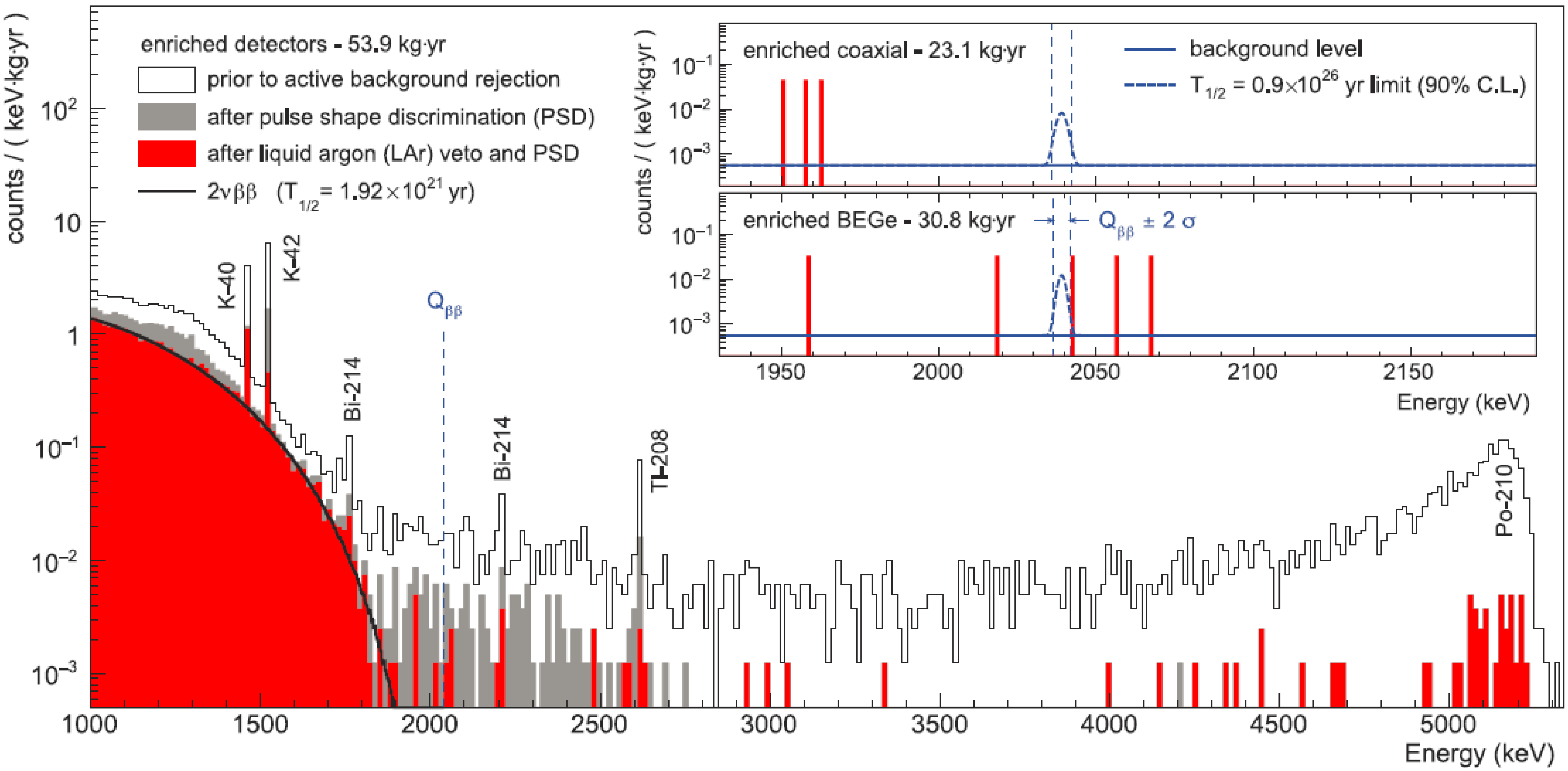


roof of clean room
plastic muon veto
lock
glove box
floor of clean room
cryostat
(Ø 4m, 64m³)
Ge detector array &
LAr veto system
PMT of muon veto
water tank
(Ø 10m, 590m³)

GERDA results

$T_{1/2}^{0\nu} > 0.9 \times\ 10^{26}\ \mathrm{y\ (90\%\ C.L.)}$

Background index = 5.6×10^{-4} counts/(keV kg y) at $Q_{\beta\beta}$ - practically background free!



Science 365 (2019) 1445

LEGEND-200

200 kg HPGe in existing (upgraded) infrastructure at LNGS

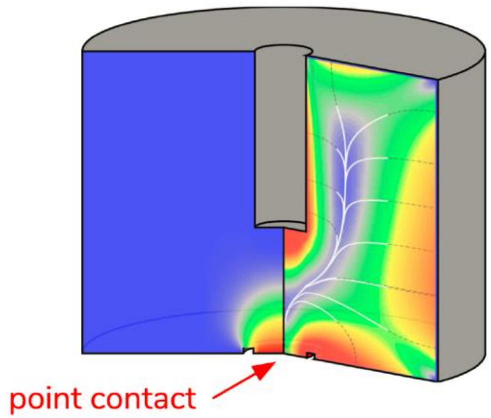
Ge detectors from Majorana and GERDA + new inverted coaxial detectors (larger mass)

Background reduction: factor 5 compared to GERDA (reduce ^{42}K, ^{214}Bi, ^{208}Tl)

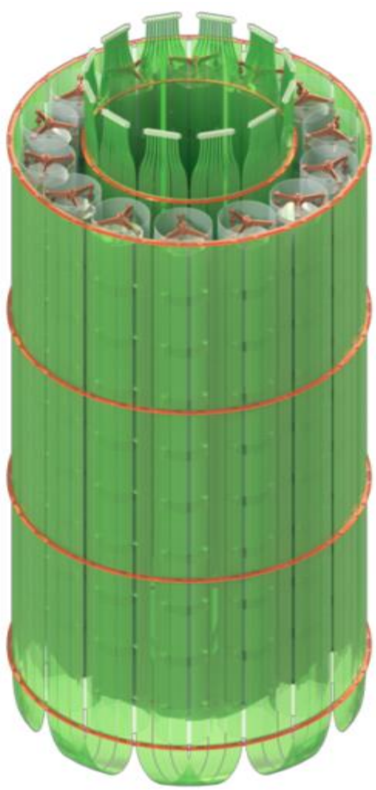
Discovery sensitivity (10 y):

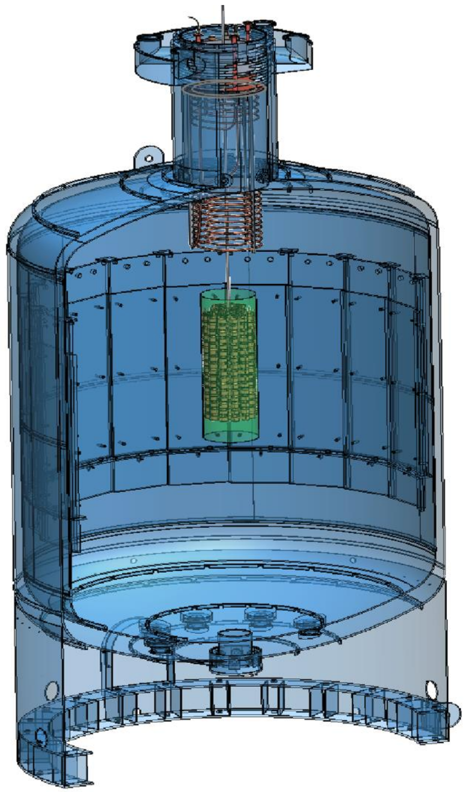
$T^{0\nu}_{1/2} \sim 1 \times 10^{27}$ y $(34 - 90 \text{ meV})$

(inside the IO band)



R.J Cooper et al.,
NIM A 665 (2011) 25

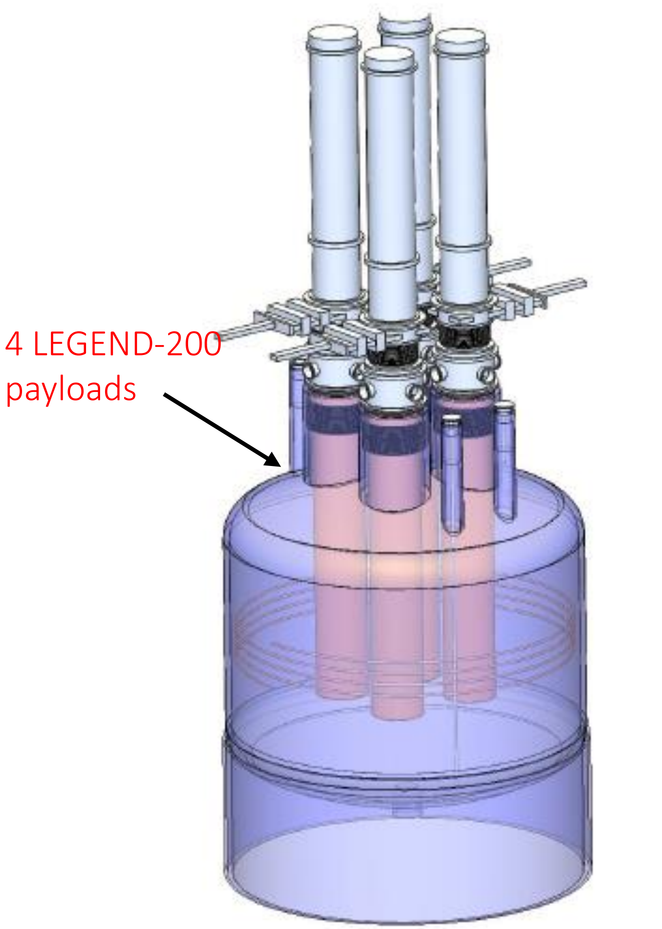




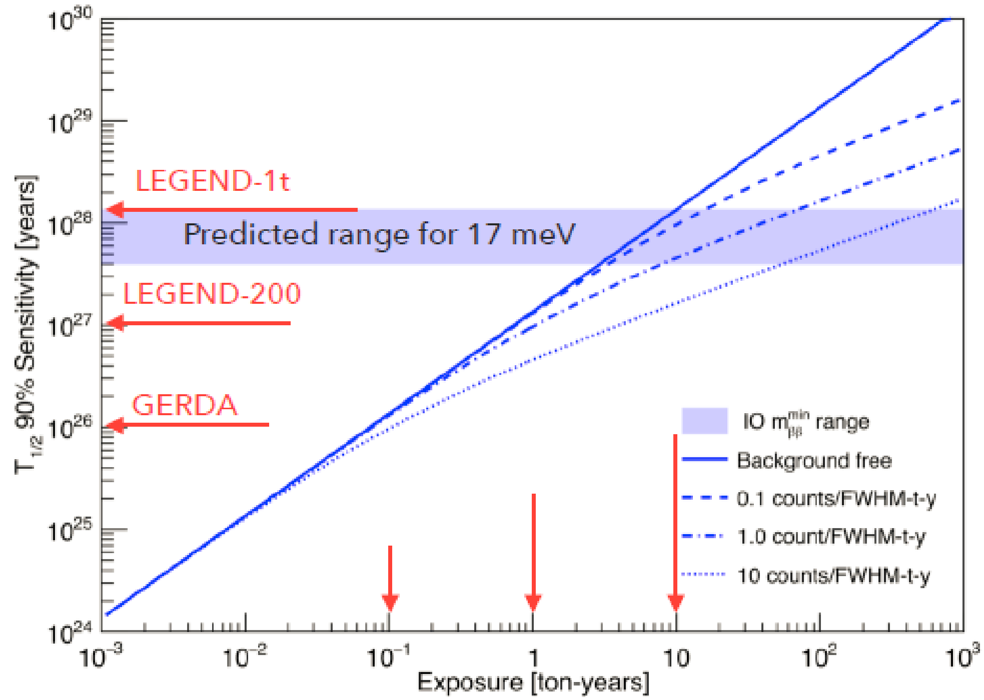
arXiv:1709.01980

LEGEND-1t

Discovery sensitivity (10 y): $T_{1/2}^{0\nu} \sim 1 \times 10^{28}$ y $(11 - 28\ \mathrm{meV})$ - cover IO band



LEGEND-1t baseline design



Background

GERDA: 3 events/(ROI t y)

LEGEND-200: 0.6 events/(ROI t y)

LEGEND-1t: $\boxed{0.1/(\mathrm{ROI\ t\ y})}$ challenging

Bolometers

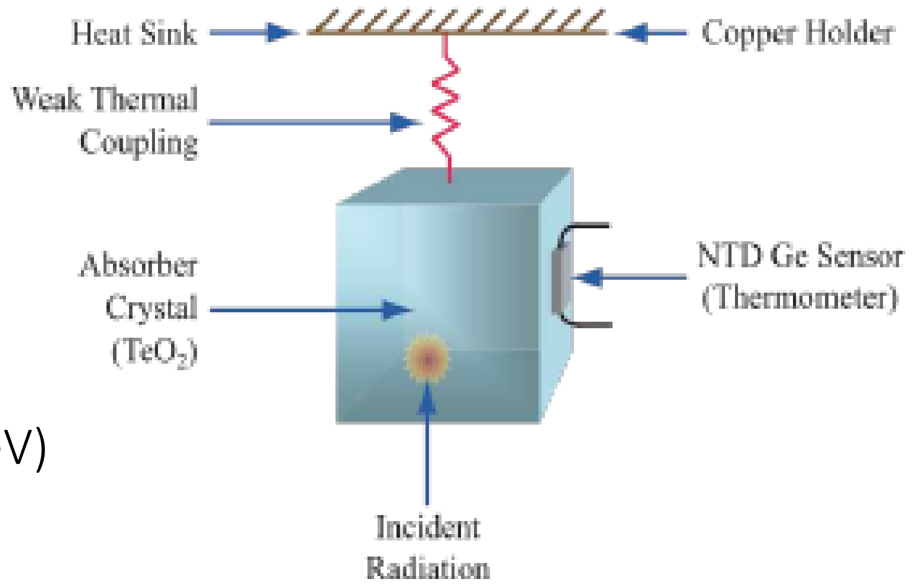
CUORE, CUPID, AMoRE

What is a bolometer?

- absorber + thermometer
  @ 10-20 mK
- Detects particle energy in the form of heat

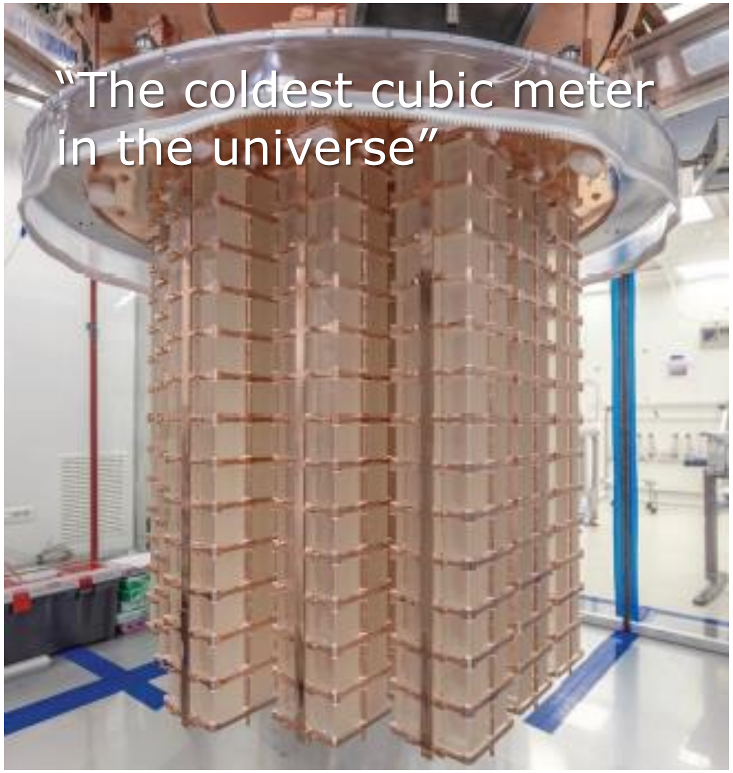
Key features for $\beta\beta0\nu$

- High energy resolution (few keV)
- Versatility in the choice of $\beta\beta0\nu$ materials

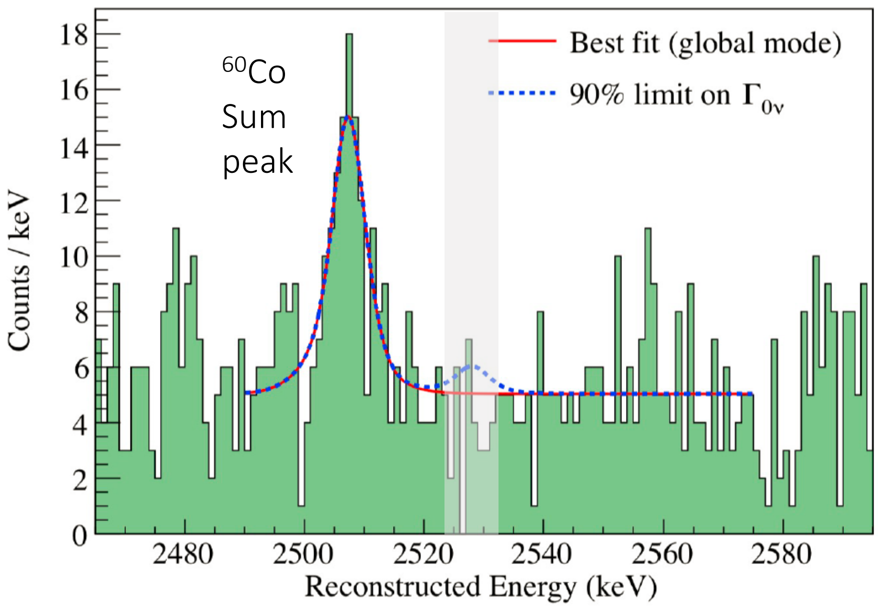


CUORE: $\beta\beta0\nu$ in ^{130}Te

988 $^{nat}TeO_2$ (34% ^{130}Te) crystals @ 10-15 mK @ LNGS



ΔE/E~8.7 keV FWHM (0.34%)

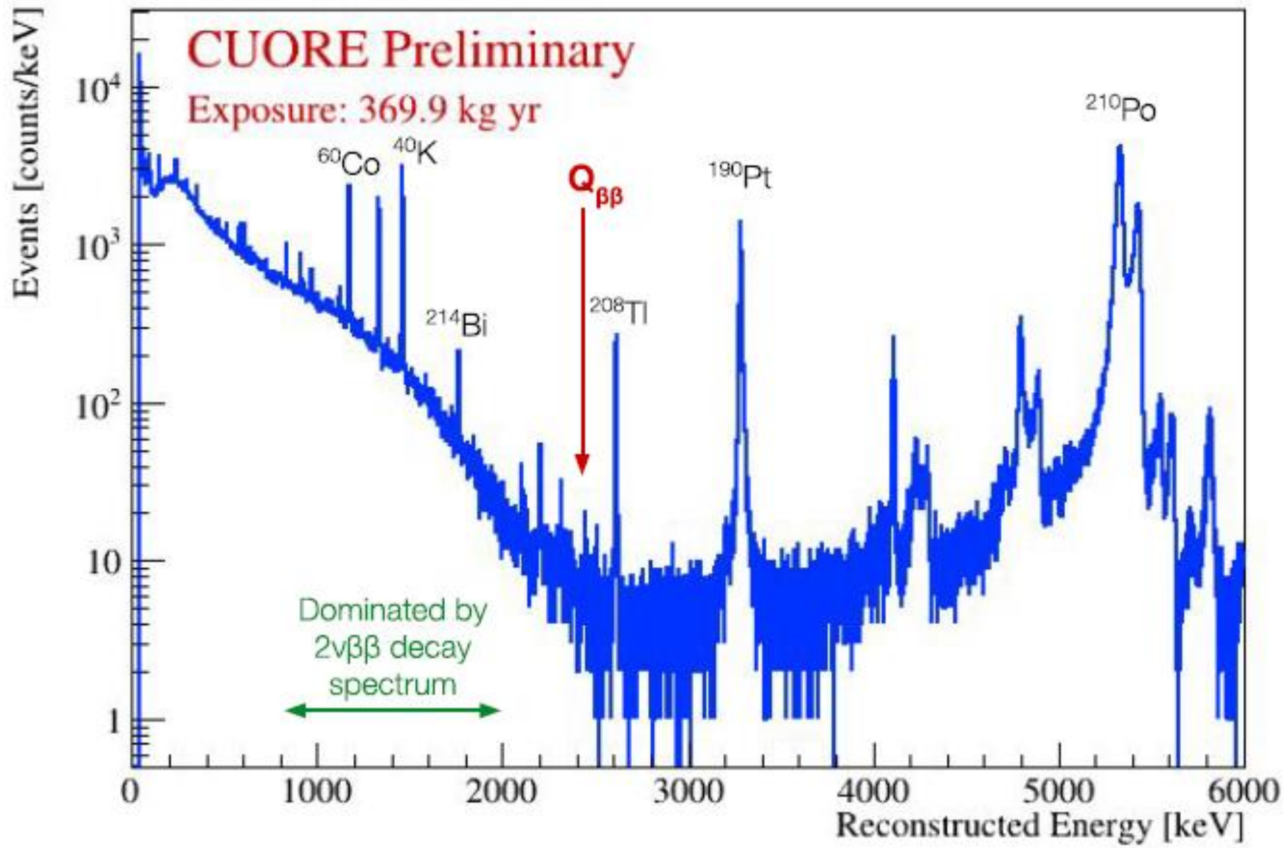


$$T_{1/2}^{0\nu} > 3.2 \times 10^{25}\ \mathrm{y}$$

$$m_{\beta\beta} = 75 - 350\ meV$$

arXiv:1912.10966

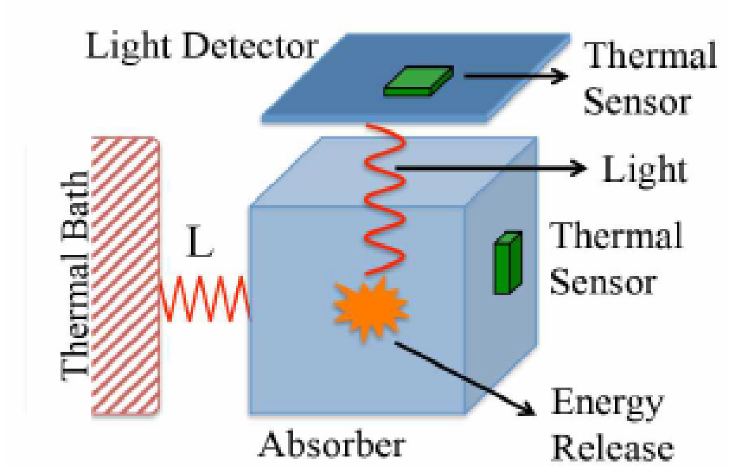
CUORE



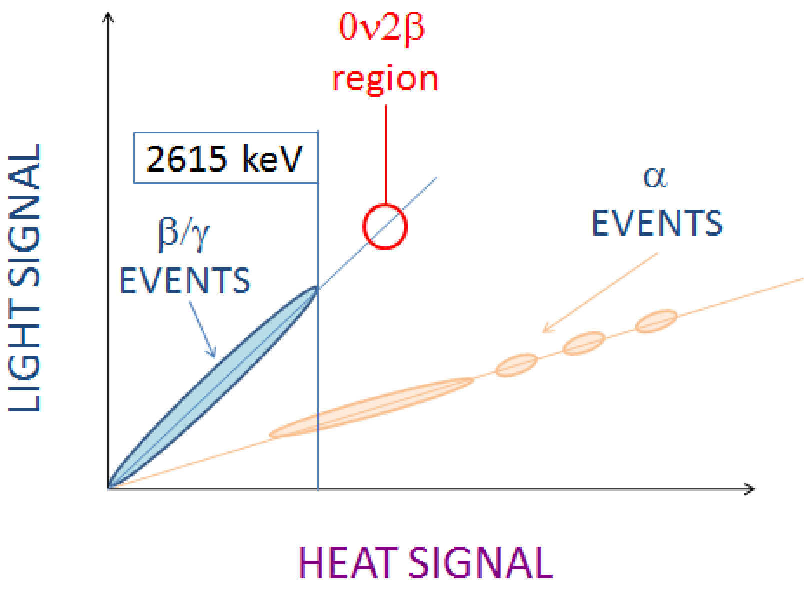
- Background dominated by α particles, 1.38×10^{-2} c/(keV·kg·yr)
- External γ background 10^{-3} c/(keV·kg·yr)

Reduction of α background: *scintillating bolometers*

Same as a bolometer + detector for scintillation



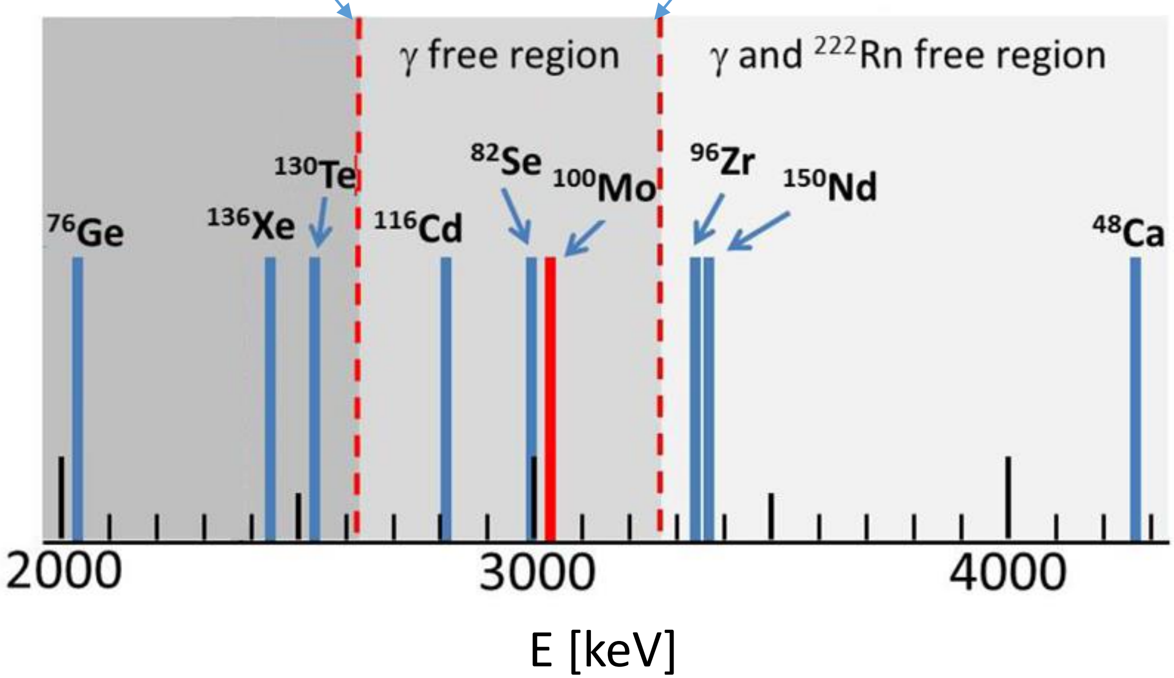
Particle ID by light/heat ratio → rejection of α particles



Reduction of γ background: *isotopes with large* $Q_{\beta\beta}$

End point of ^{232}Th γ radioactivity 2615 keV

End point of ^{238}U β radioactivity 3270 keV



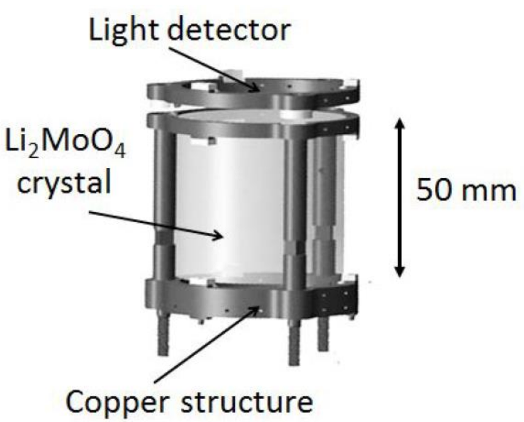
Isotope	abundance
^{116}Cd	7.5%
^{82}Se	9.2%
^{100}Mo	9.6%
^{96}Zr	2.8%
^{150}Nd	5.6%
^{48}Ca	0.19%

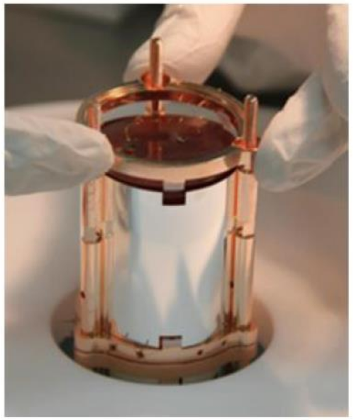
Expensive enrichment

Preferred

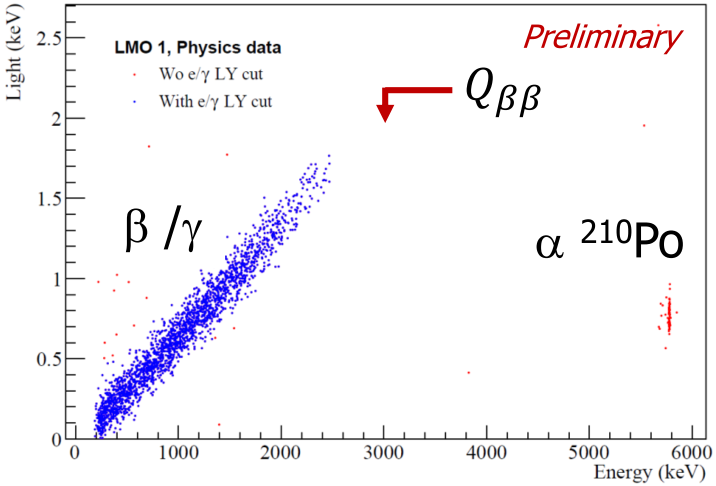
CUPID: CUORE Upgrade with Particle IDentification

- Scintillating bolometers with ^{100}Mo, $Q_{\beta\beta} = 3034\ \mathrm{keV}$
- Crystals: $Li_2{}^{100}MoO_4$
- Sensors (baseline): neutron-transmutation-doped (NTD) germanium thermistors, for both heat and light
- Current status: CUPID-Mo, 20 crystal demonstrator taking data (LSM, France)





ΔE=5 keV FWHM, high radiopurity



α/γ(β) separation ~15σ

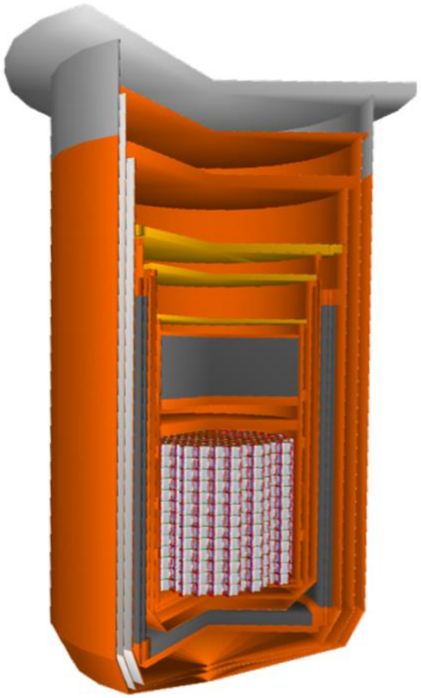
arXiv:1907.09376

CUPID: proposed plan

- Install 1534 $Li_2{}^{100}MoO_4$ crystals in the CUORE cryostat (250 kg ^{100}Mo, >95% enrichment)
- Expected background index: b ~ 10^{-4} counts/(keV kg yr)
- Expected sensitivity after 10 years: $T^{0\nu}_{1/2} = 1.5 \times 10^{27}$ y ($m_{\beta\beta} = 10 - 17$ meV – **enough to cover the IO band**)

Future potential:

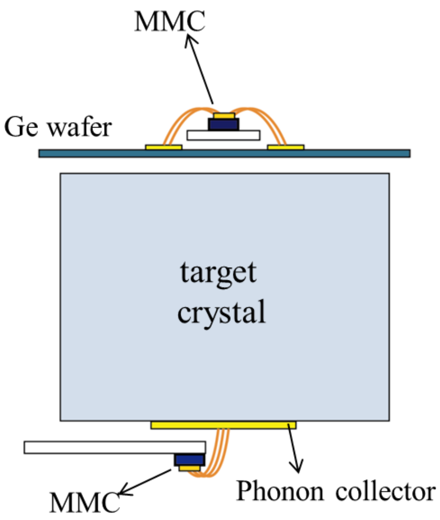
- “CUPID-1T”, $T^{0\nu}_{1/2} = 0.9 \times 10^{28}$ y after 10 years, requires a new cryostat and *20-fold improvement in background*



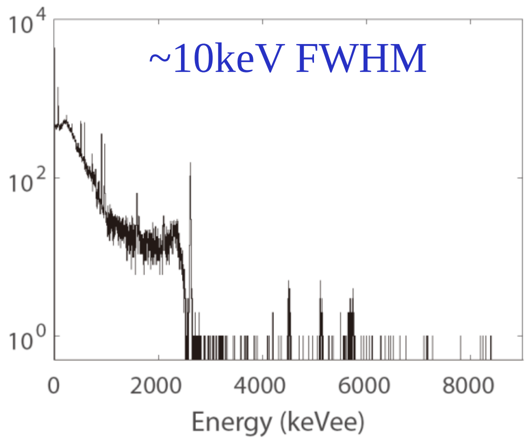
arXiv:1907.09376

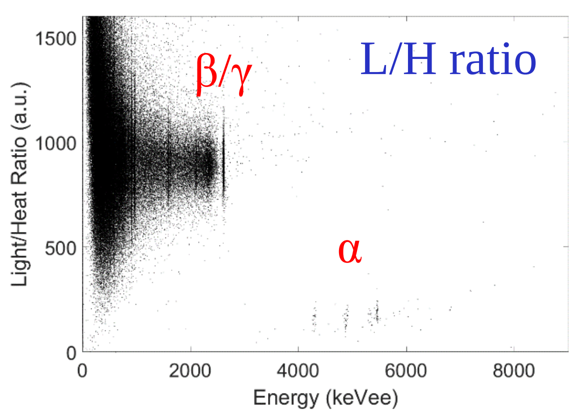
AMoRE: Advanced Mo-based Rare process Experiment

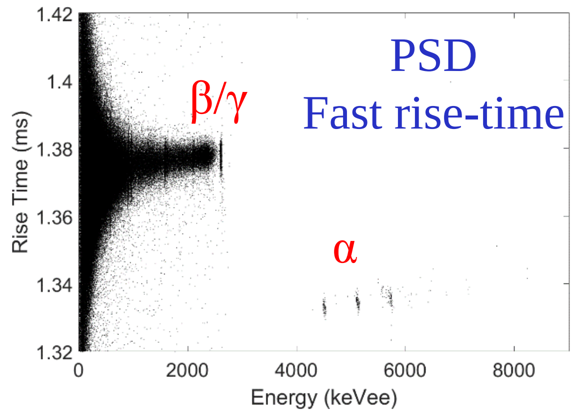
$^{40}Ca^{100}MoO_4$ ($X^{100}MoO_4$) + **Metallic Magnetic Calorimeters (MMC)**



- MMC: superconducting sensor with fast response time (~200 μs)
- Main advantage: better rejection of $\beta\beta 2\nu$ pileup (considerable background in large ^{100}Mo crystals)



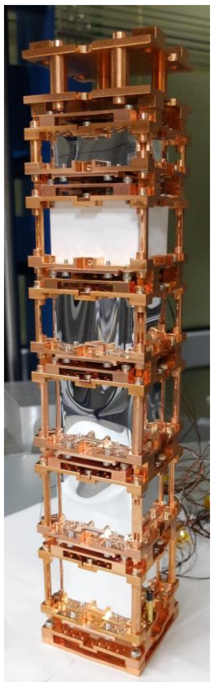




AMoRE-Pilot

MMC proof of principle

Completed



Six $^{48dep}Ca^{100}MoO_4$ crystals, ~1 kg ^{100}Mo

Y2L, Korea

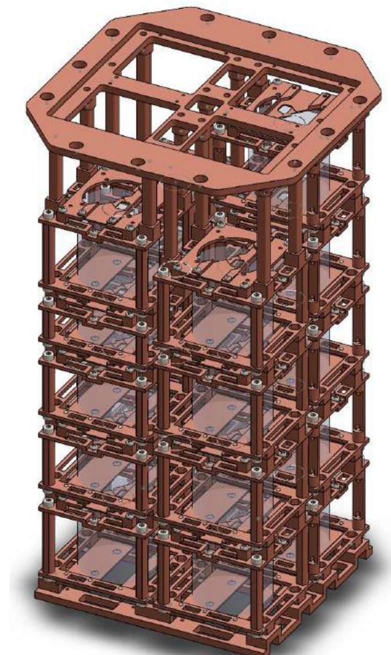
EPJC 79 (2019) 791

AMoRE-I

~$1.5x10^{-3}$ ckky

$T_{1/2}$: 10^{25} y

2020



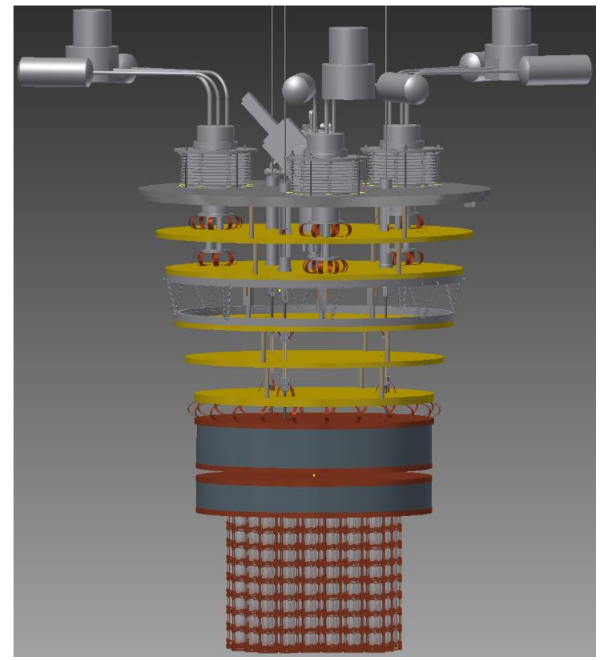
13 $^{48dep}Ca^{100}MoO_4$ crystals + 5 $Li_2{}^{100}MoO_4$, ~3 kg ^{100}Mo

AMoRE-II

~10^{-4} ckky

$T_{1/2}$: $5x10^{26}$ y, **$m_{\beta\beta}$: 17-29 meV**

Phased 2022-2024, fully funded



Favored $Li_2{}^{100}MoO_4$, ~100 kg ^{100}Mo

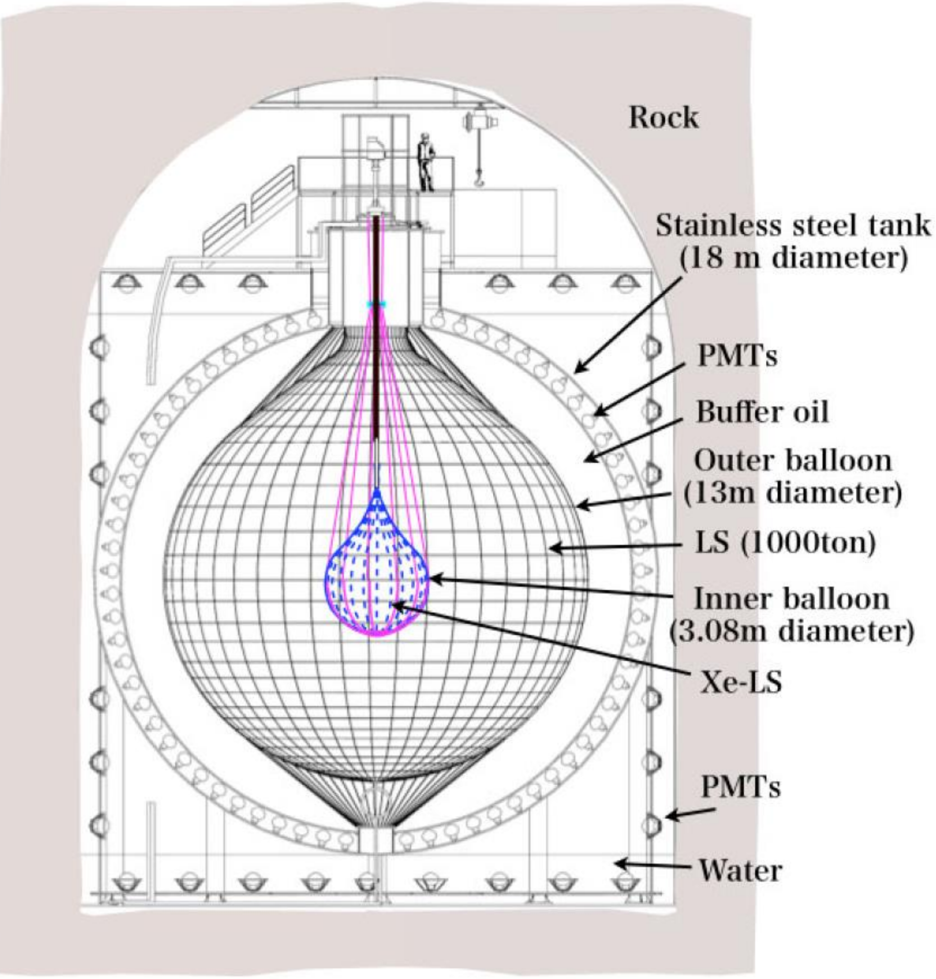
Yemilab (new), Korea

Loaded liquid scintillators

KamLAND-Zen, SNO+

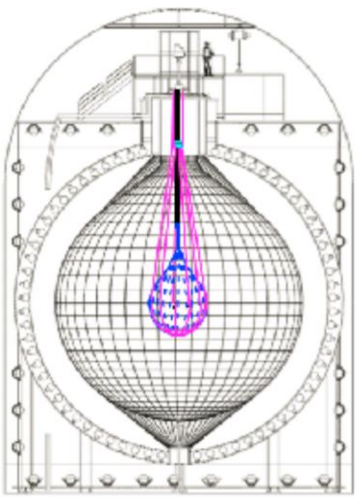
KamLAND-Zen: $\beta\beta0\nu$ in ^{136}Xe

- KamLAND neutrino detector + inner balloon, filled with liquid scintillator loaded with Xe (91% ^{136}Xe) at 3 wt%, ~25 tonnes total
- 1879 PMTs (17", 20"), photo-coverage 34%
- Inner balloon: 25 μm-thick nylon film
- Event location determined by photon time-of-arrival pattern (7.7 cm rms at $Q_{\beta\beta}$)
- E-res: 11% FWHM → $\beta\beta2\nu$ major background



KamLAND-Zen series

PAST



KamLAND-Zen 400

R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

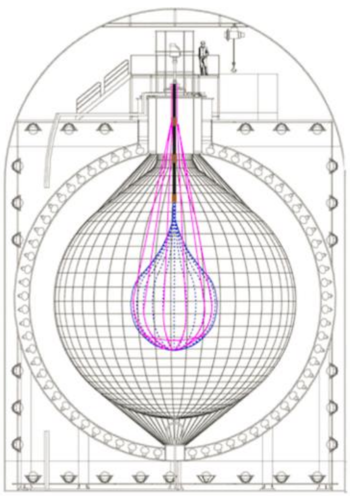
2011 ~ 2015

Published (90% C.L.):

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

PRL 117, 082503 (2016)

ONGOING



KamLAND-Zen 800

R = 1.90m mini-balloon

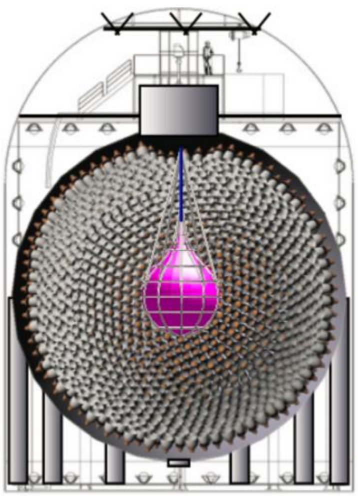
Xenon 745 kg

Jan. 22, 2019 ~

Expected sensitivity 5y:

$T_{1/2}^{0\nu} = 5 \times\ 10^{26}$ y

FUTURE



KamLAND2-Zen

Xenon ~ 1 ton

Expected sensitivity 5y:

$T_{1/2}^{0\nu} = 2 \times\ 10^{27}$ y

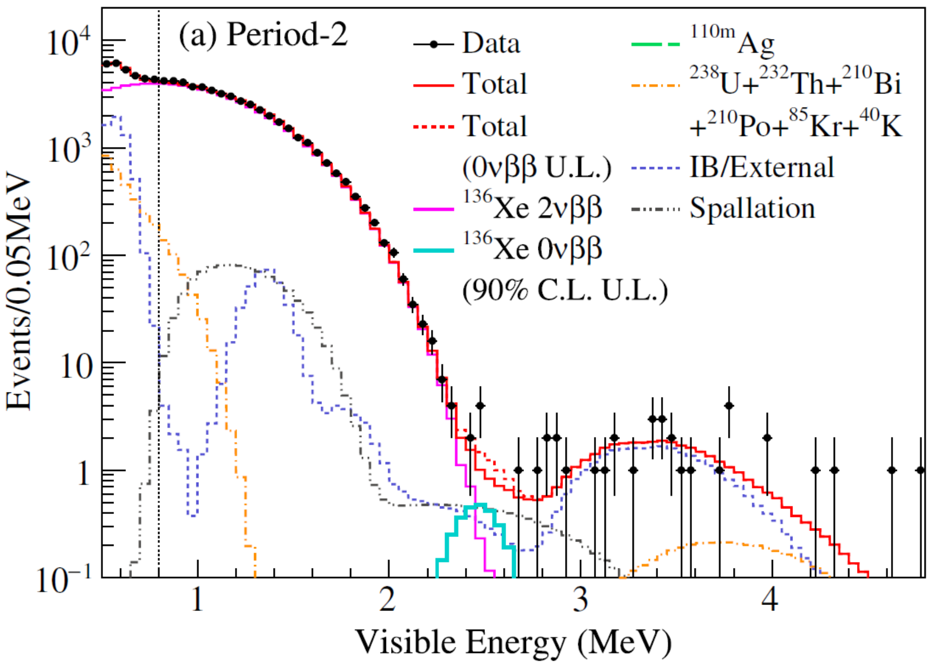
KamLAND-Zen series

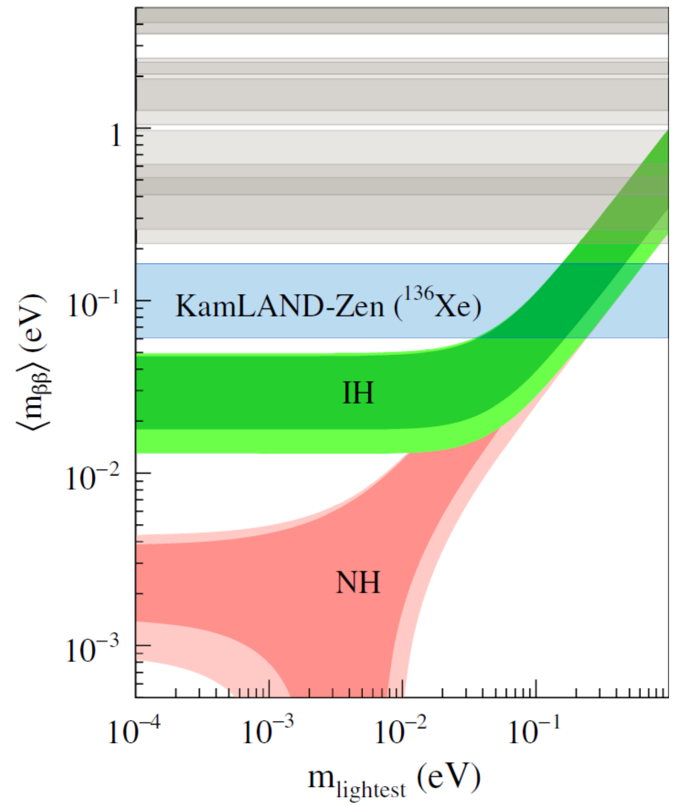
- E-resolution: 11% FWHM
- Main backgrounds in ROI: $2\nu\beta\beta$ (47%), ^{214}Bi (23%), Spallation products (30%)

Strongest limit to date:

$$T_{1/2}^{0\nu} > 1.07 \times\ 10^{26}\ \mathrm{y}\ (90\%\ \mathrm{CL})$$

$$m_{\beta\beta} = 61 - 165\ \mathrm{meV}$$

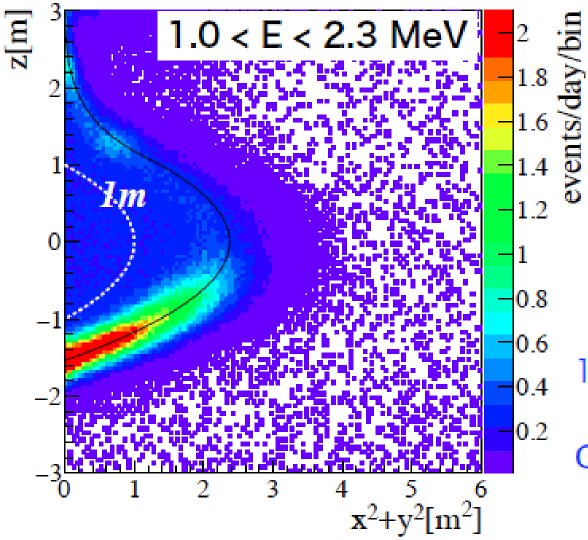




PRL 117, 082503 (2016)

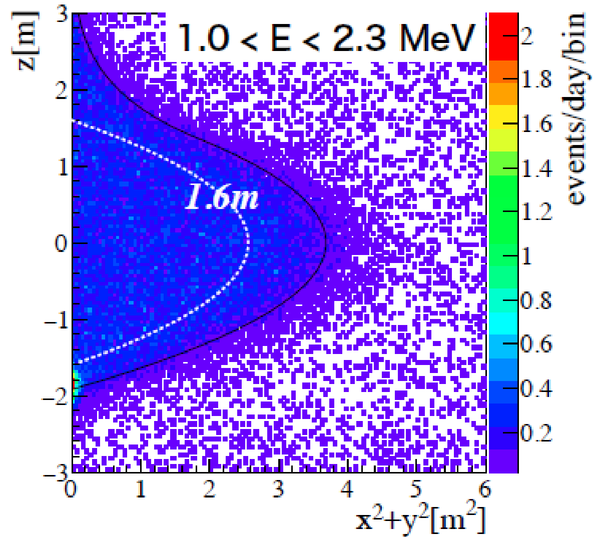
KamLAND-Zen 800 first results (132.7 live days)

KamLAND-Zen 400 phaseII



^{134}Cs,
dust sank

KamLAND-Zen 800



$2\nu\beta\beta$
dominates
in all volume

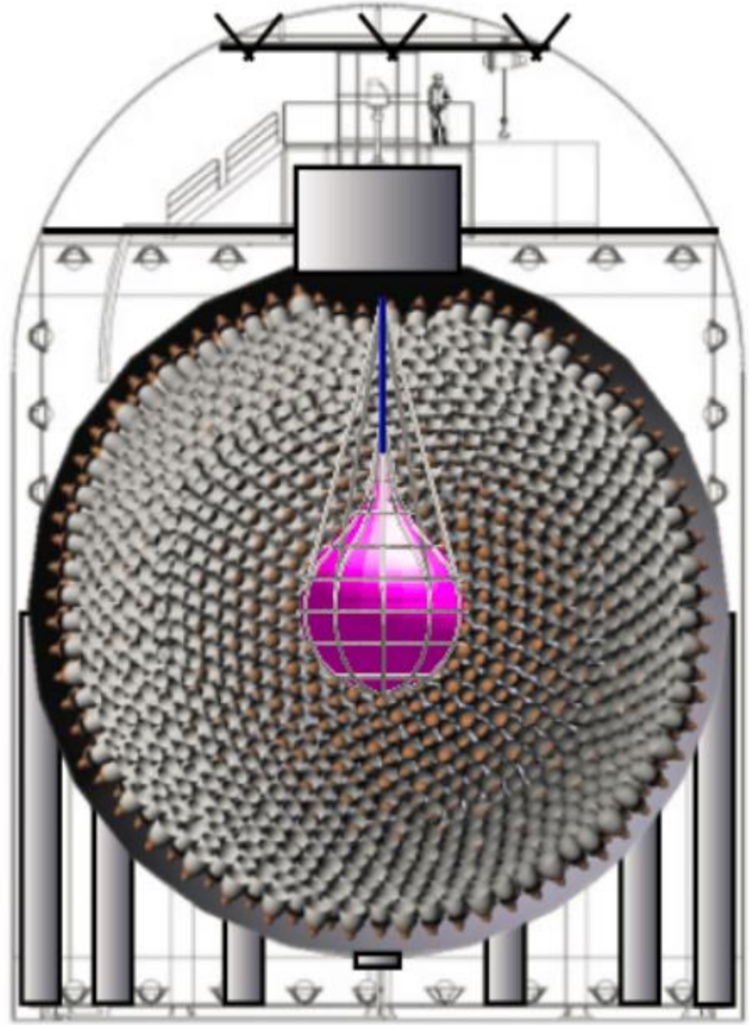
^{238}U and ^{232}Th background reduction by factor ~10

Towards 5×10^{26} y in 5 years (28-76 meV)

TAUP 2019

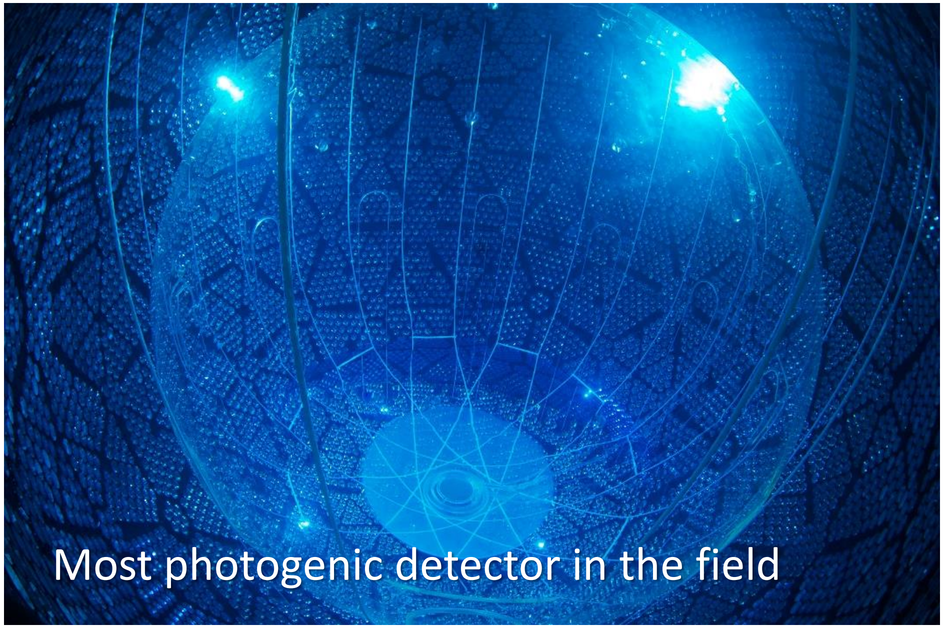
KamLAND2-Zen (future)

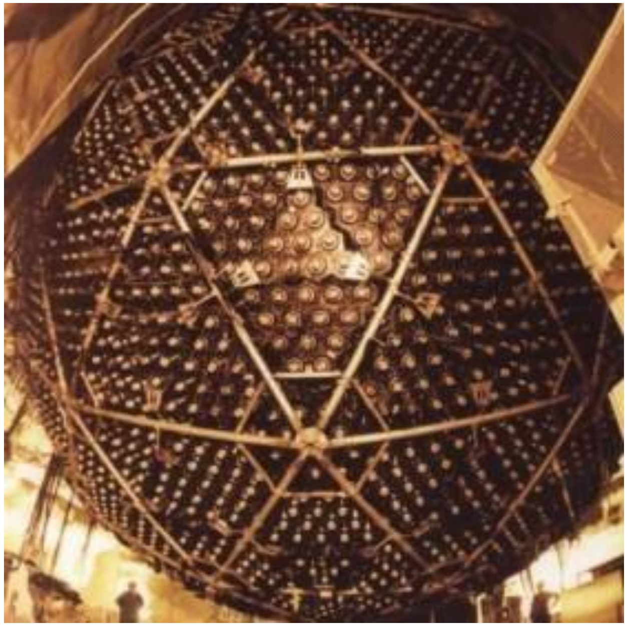
- Add Winston cones for all PMTs (×1.8 increased light collection)
- Replace PMTs (current QE~22% → >30%)
- Replace LS (8,000 photons/MeV → 12,000 photons/MeV)
- Expected increase in energy resolution 11% → < 6% FWHM
- ~1000 kg ^{136}Xe
- Expected sensitivity 2×10^{27} y in 5 years (14-38 meV)



SNO+: $\beta\beta0\nu$ in ^{130}Te

- Successor of the SNO experiment at SNOLAB, Canada
- Primary goal: $\beta\beta0\nu$ in ^{130}Te ($Q_{\beta\beta} = 2527\ \mathrm{keV}$)
- Secondary goals: measurements of solar, reactor and geo neutrinos + nucleon decay



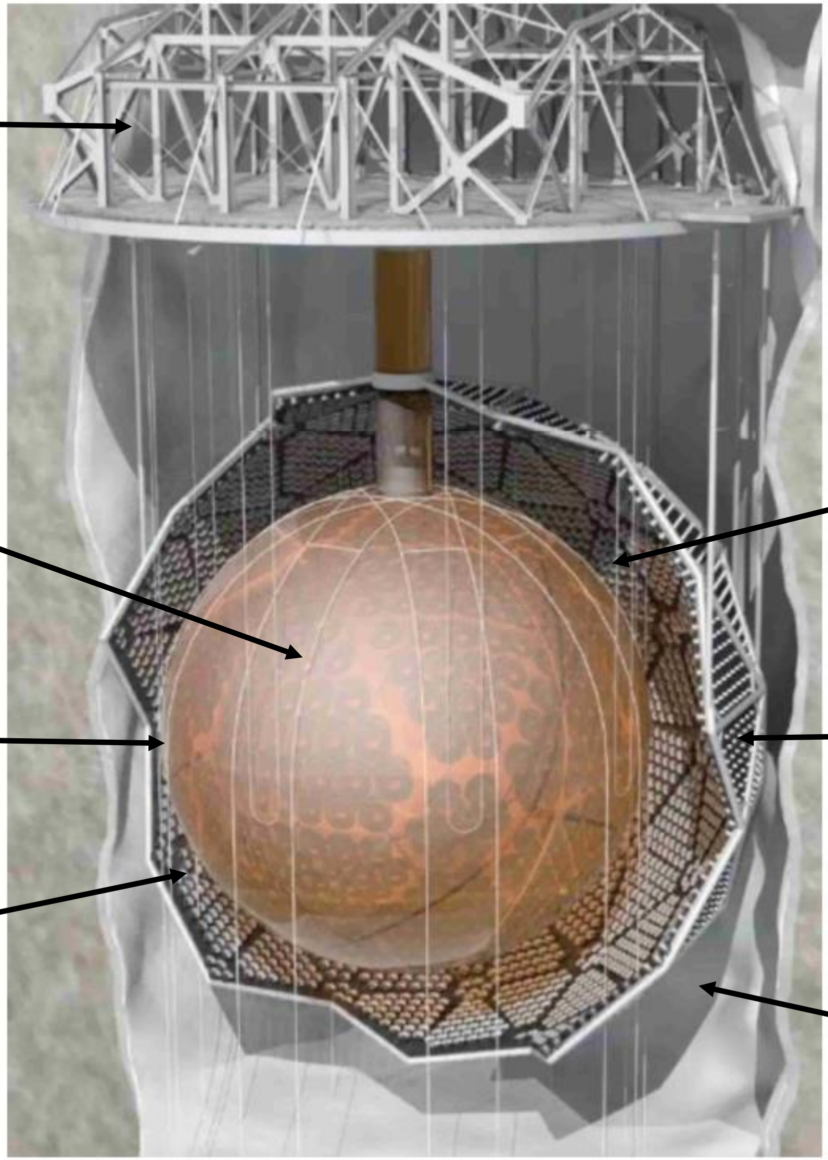


Electronics
and DAQ

~780 t of LABPPO
scintillator + ~4 t
of natural tellurium
(34% ^{130}Te)

Acrylic vessel
6 m radius,
10 cm thick

Inner water
shield (~1700 t)



~2 km depth,
~6 km.w.e.,
~3 muons/hour

Holding ropes

~9300 PMTs,
53% optical
coverage, on
St.St. support

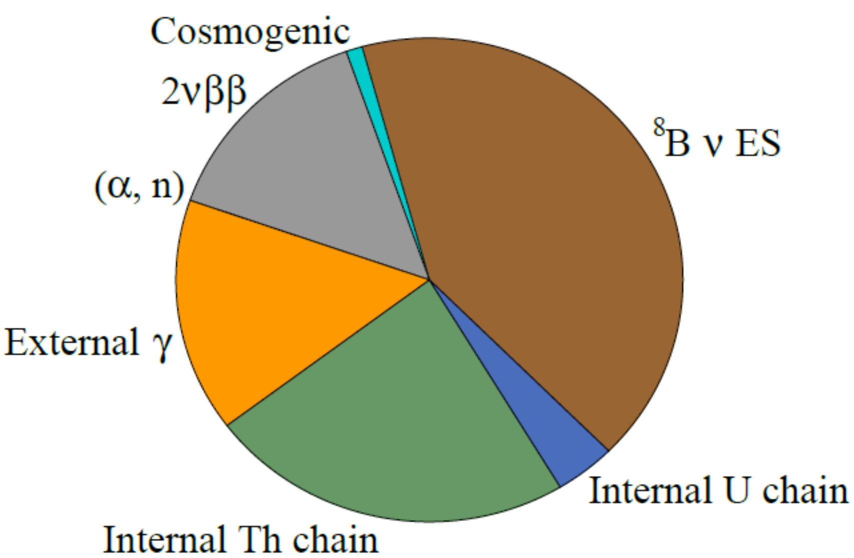
Outer shield:
cavity in rock
~5400 t
ultrapure water


SNO+
TIMELINE
~780 tonnes of LABPPO scintillator
+ ~4 tonnes natural tellurium (34% ^{130}Te)
SOLAR NEUTRINOS
NUCLEON DECAY
0νββ milestone: measure external backgrounds
SOLAR NEUTRINOS
GEO & REACTOR NEUTRINOS
0νββ milestone: measure internal backgrounds
0νββ
We are here
May 2017 → Water phase started
2019 → Scintillator fill starts
Dec. 2016 Started taking commissioning data
2016
2017
WATER PHASE
2019
PARTIAL PHASE
SCINTILLATOR PHASE
~2020
TELLURIUM PHASE

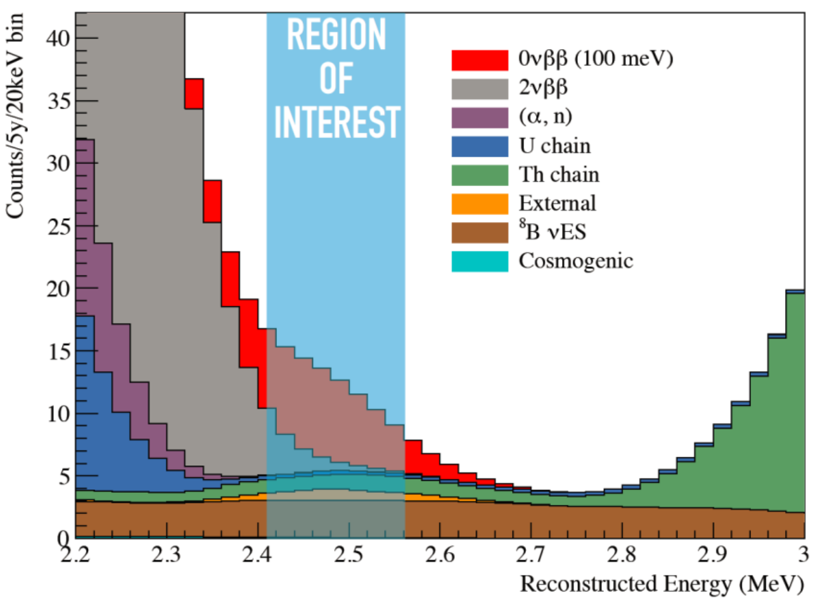
SNO+ expected performance

Expected energy resolution with 0.5% Te: 7.5% FWHM (188 keV)

ROI: 2.49 - 2.65 MeV [-0.5σ - 1.5σ]
Counts/Year: 12.4



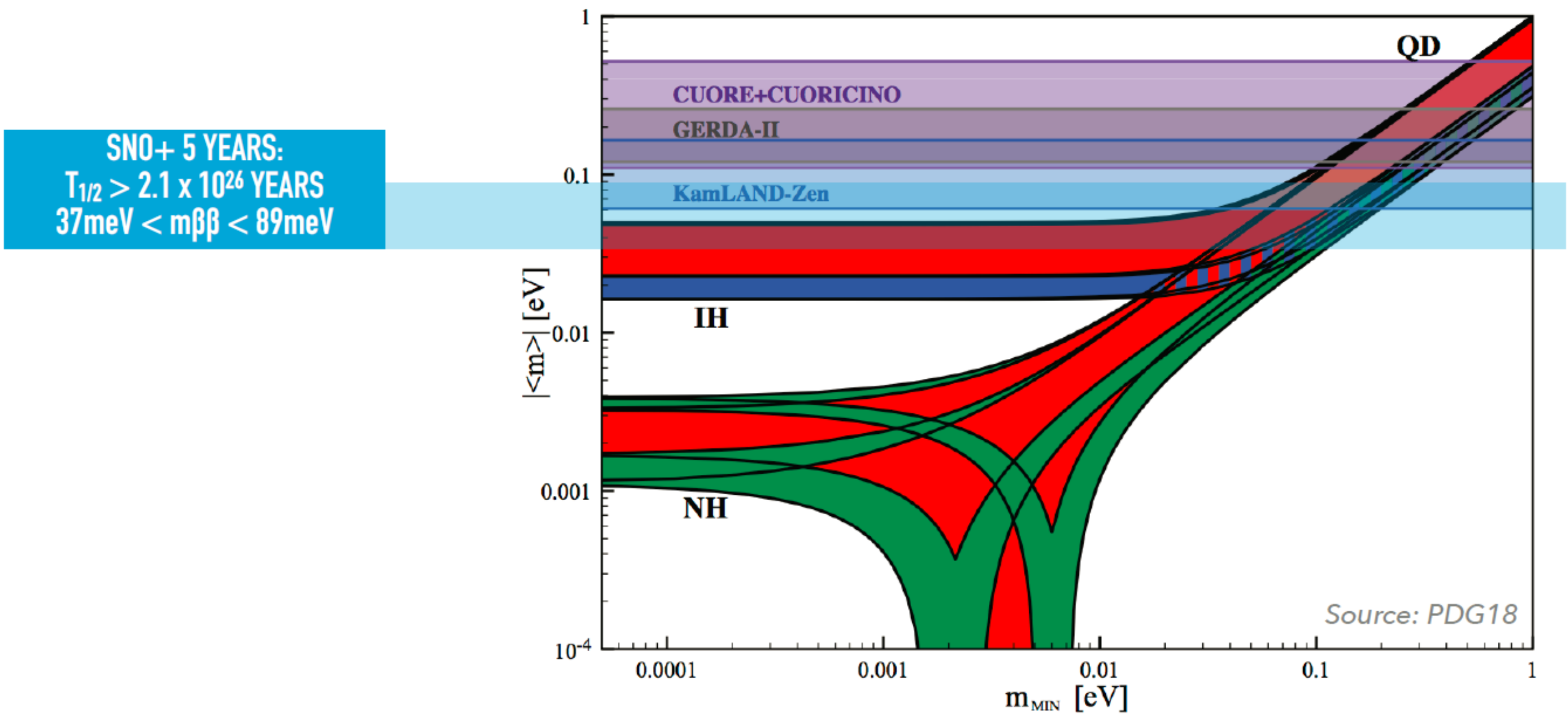
Expected energy distribution with nominal backgrounds



arXiv:1809.05986

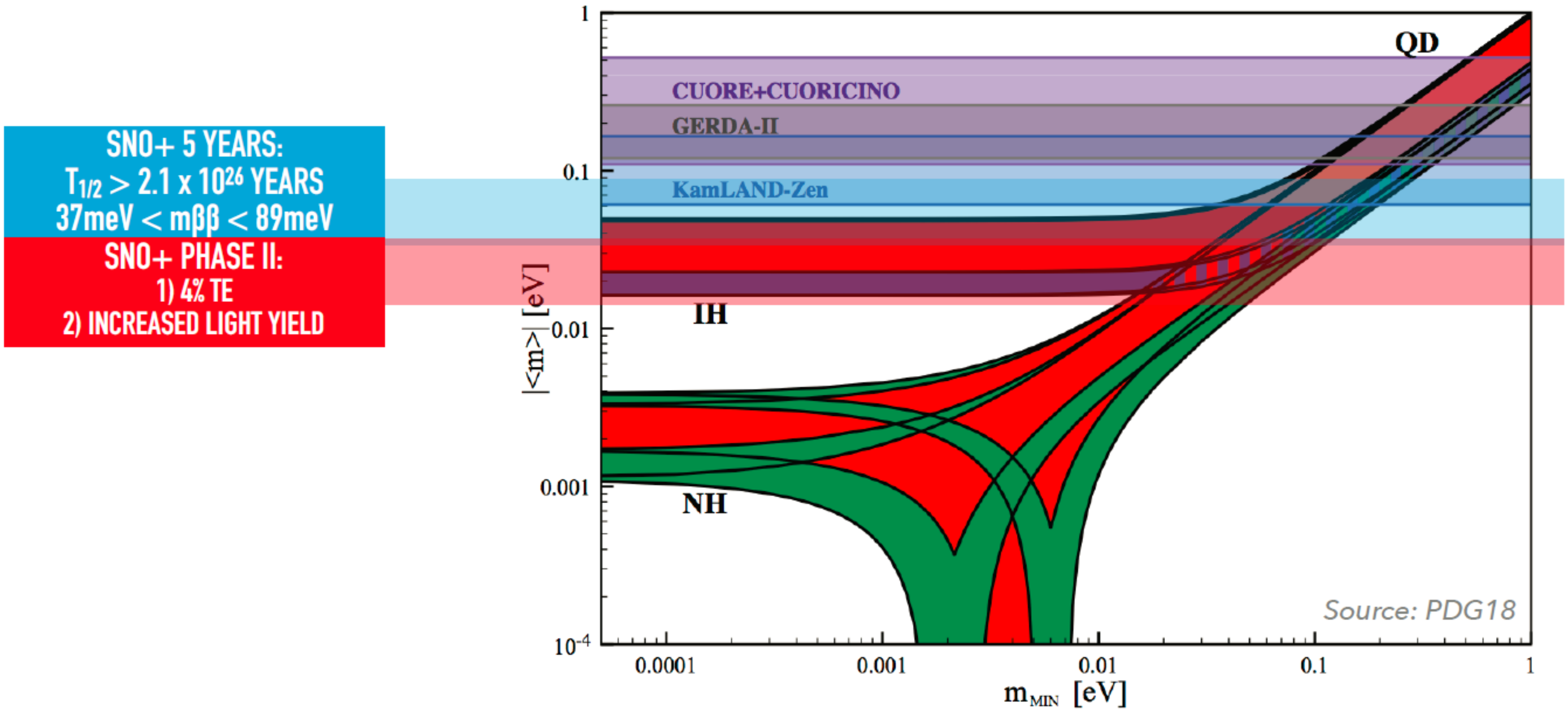
SNO+ expected sensitivity

90% confidence limit after 5 years with 0.5% tellurium (6.8 tonne-year exposure): $T_{1/2}^{0\nu} > 2.1 \times 10^{26}$ y ($m_{\beta\beta} = 50.6$ meV)



SNO+ future sensitivity

Phase II (4% Te + increased light yield):



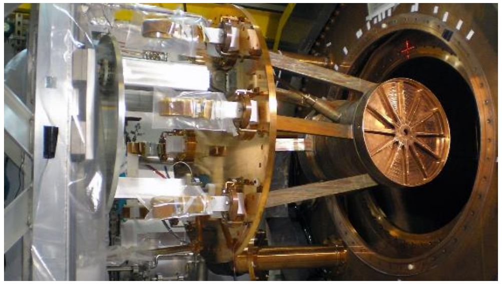
Liquid xenon TPCs

nEXO (EXO-200), DARWIN

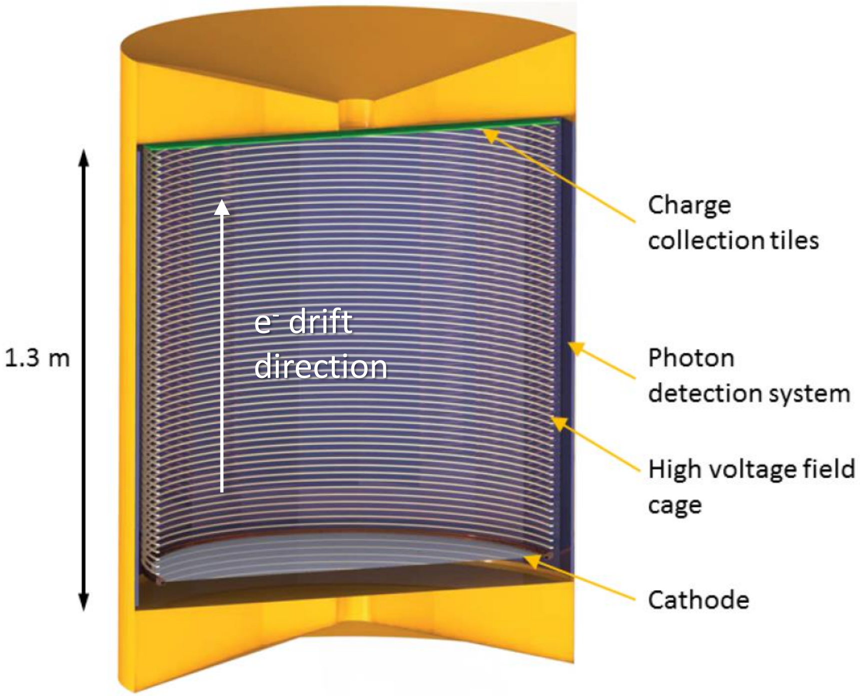
nEXO: LXe TPC for $\beta\beta 0\nu$ in ^{136}Xe

- Builds on experience gained in EXO-200 (110 kg LXe active mass, $T_{1/2}^{0\nu} > 1.8 \times 10^{25}$ y)
- Single-phase LXe TPC: 1.16 m inner diameter, 1.25 m drift height (single drift direction)
- 5.1 t LXe (90% ^{136}Xe) in total (4.0 in the TPC)
- Charge readout by induced current on charge collection tiles (top)
- Light readout by SiPM tiles (4.5 m^2 total) on barrel behind the field cage

arXiv:1710.05075, 1805.11142



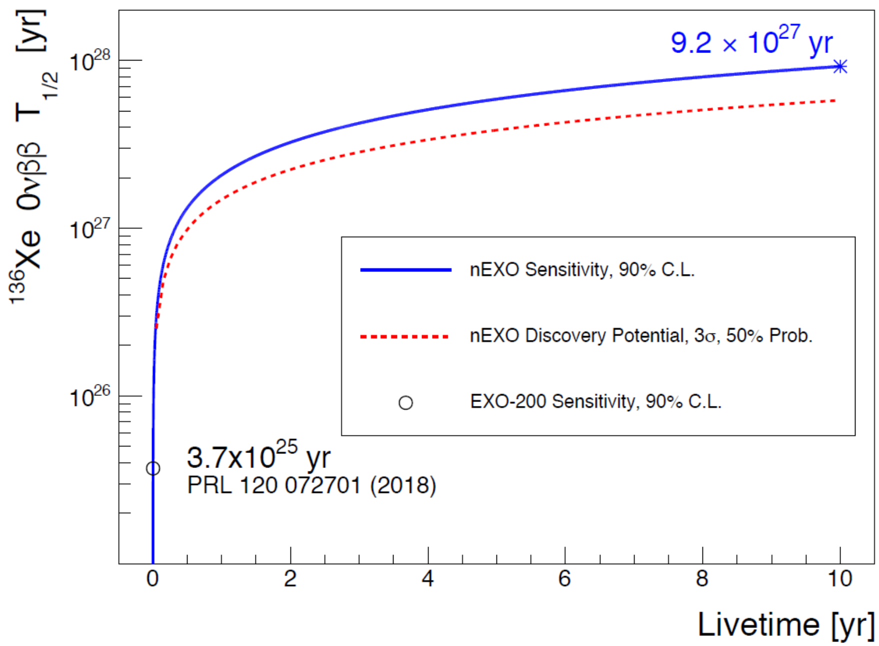
EXO-200 mounted in cryostat

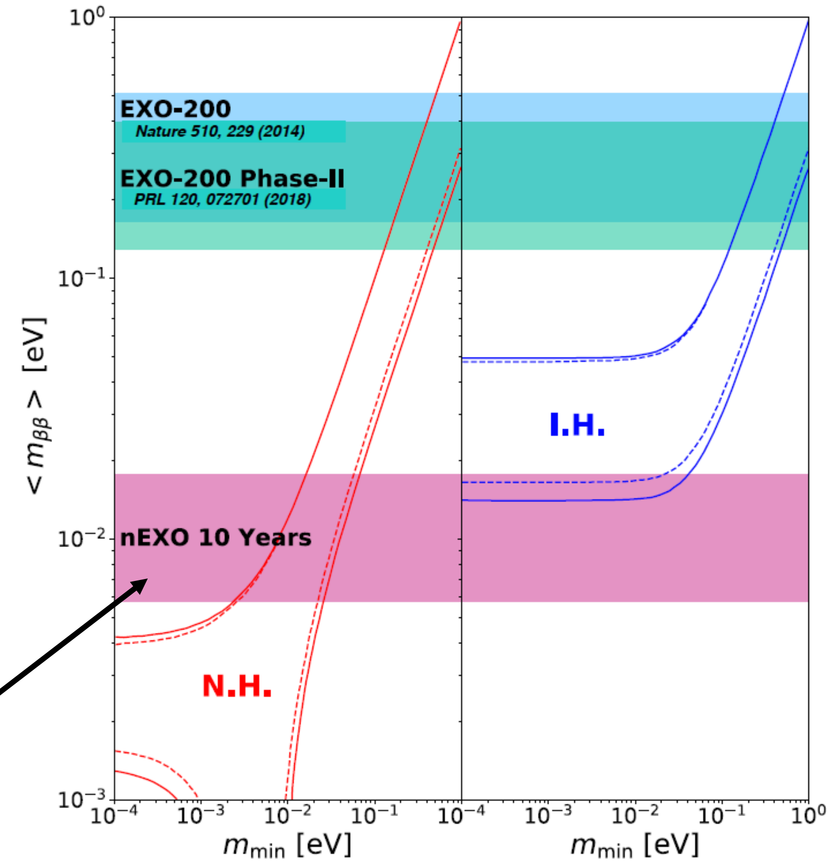


nEXO – background suppression

- 2.5 MeV γ attenuation length 8.5 cm – take $\beta\beta0\nu$ data away from wall
- Double-beta events are mostly single-site, while γs Compton-scatter → resolve multi-site events in space and time
- Optimize energy resolution (EXO-200 achieved 2.7% FWHM, expect 2.5% FWHM in nEXO)
- Cosmogenic production of ^{137}Xe by muon-induced neutron capture in ^{136}Xe (^{137}Xe beta decays with Q=4173 keV) → deep underground lab + active veto
- ^{214}Bi decays inside LXe active volume (from ^{222}Rn) tagged by subsequent ^{214}Po α decay
- Use entire active volume to establish background model
- Background index < 10^{-3} counts/(kev kg y)
- Parallel R&D on barium tagging – currently not the baseline option

nEXO – expected sensitivity

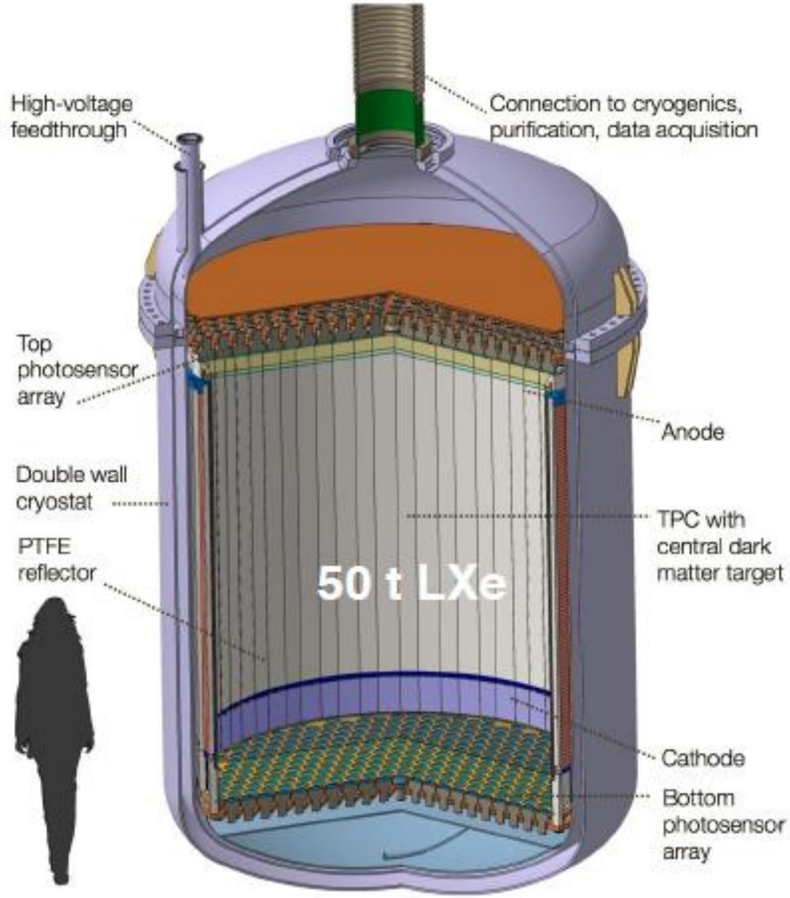




Similar half-life sensitivity as LEGEND-1000, but better mass sensitivity because of Xe's larger phase space factor

DARWIN

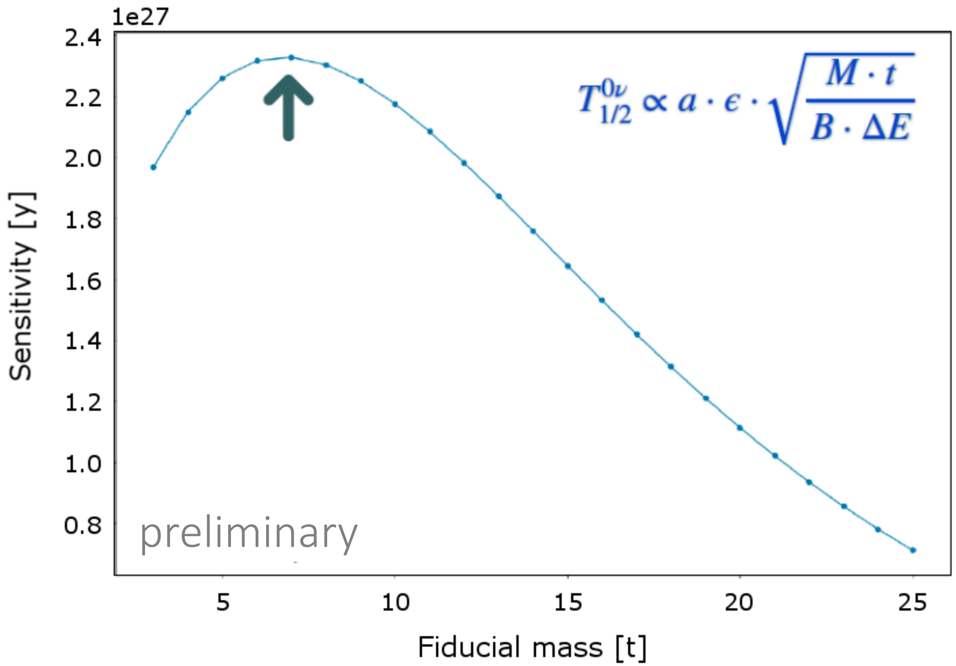
- Two-phase TPC: 2.6 m diameter, 2.6 m height
- 50 t LXe in total (40 in the TPC)
- Primary goal: WIMP search down to the "neutrino floor"
- Secondary goal: $\beta\beta0\nu$ in ^{136}Xe
- If natural Xe: 3.5 ton ^{136}Xe in the TPC!
- XENON1T E-res 1.9% FWHM → same expected in DARWIN



DARWIN collaboration, JCAP 1611 (2016) 017

DARWIN: expected background and sensitivity

Sensitivity sweep through different fiducial masses



Contributions in
ROI 2435-2481 keV*:

Background	Events/(t y keV)
^{8}B	2.4×10^{-4}
^{137}Xe	1.4×10^{-3}
^{136}Xe	3.7×10^{-7}
^{222}Rn	3.0×10^{-4}
Materials	$1.3 \pm 0.2 \times 10^{-3}$

* FWHM, PMT for both arrays scenario

Discovery sensitivity (10 y): $T^{0\nu}_{1/2} \sim 2.3 \times 10^{27}$ y (13 – 36 meV) - cover IO band

(Significant improvement possible in deeper site than LNGS and enhanced radiopurity)

TAUP 2019

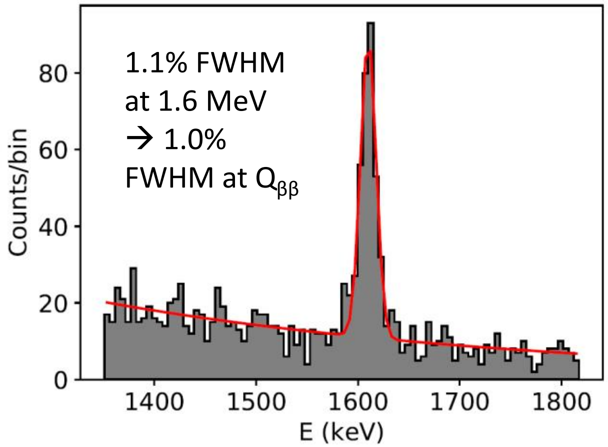
High-pressure gaseous xenon TPCs

NEXT, PandaX-III, AXEL

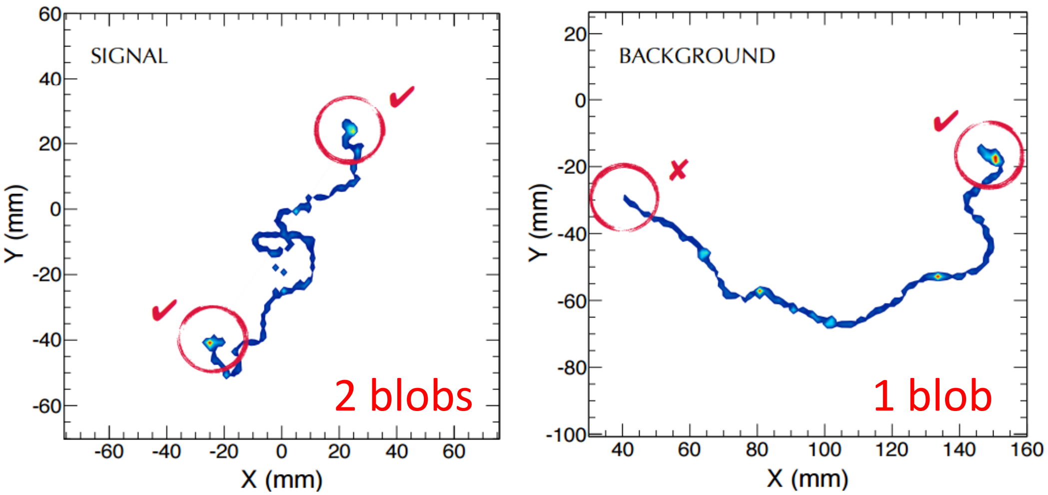
NEXT: High-pressure Xe gas TPC - $\beta\beta 0\nu$ in ^{136}Xe

Working in high-pressure (10-15 bar) gas rather than liquid allows:

Excellent energy resolution by proportional electroluminescence (demonstrated 1% FWHM at $Q_{\beta\beta}$, aim at 0.5%)



Reconstruction of track topology to discriminate between background and signal

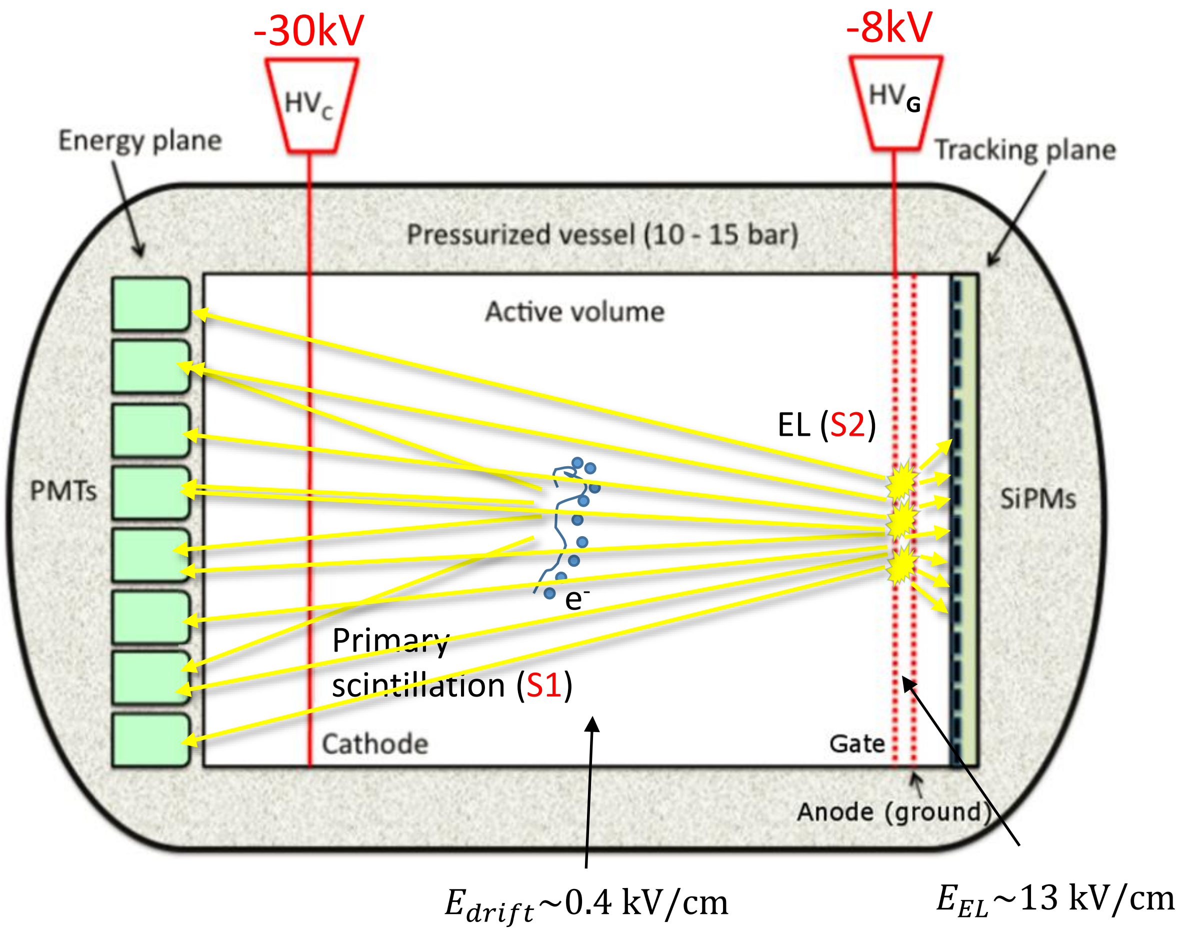


NEXT: Mode of operation

S1 (PMTs) gives t_0

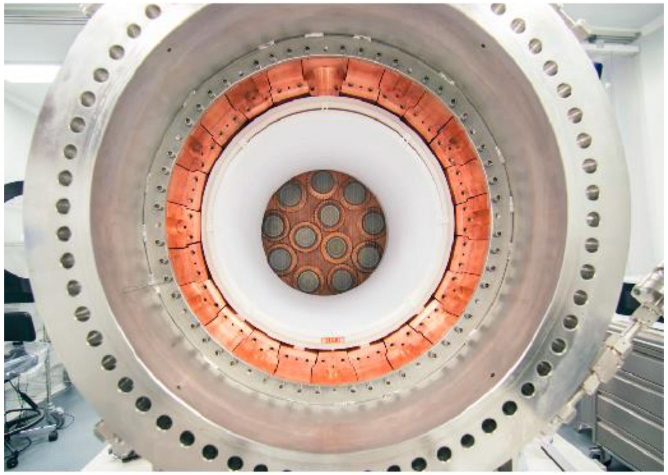
S2 magnitude by proportional EL (PMTs) gives the event energy

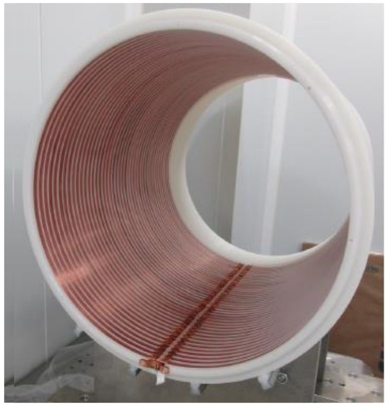
S2 time-slice images (SiPMs) give the event topology

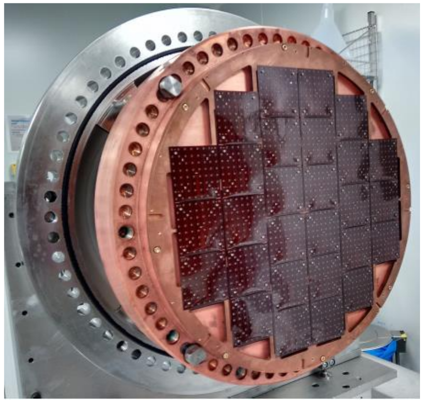


NEXT-White (now)

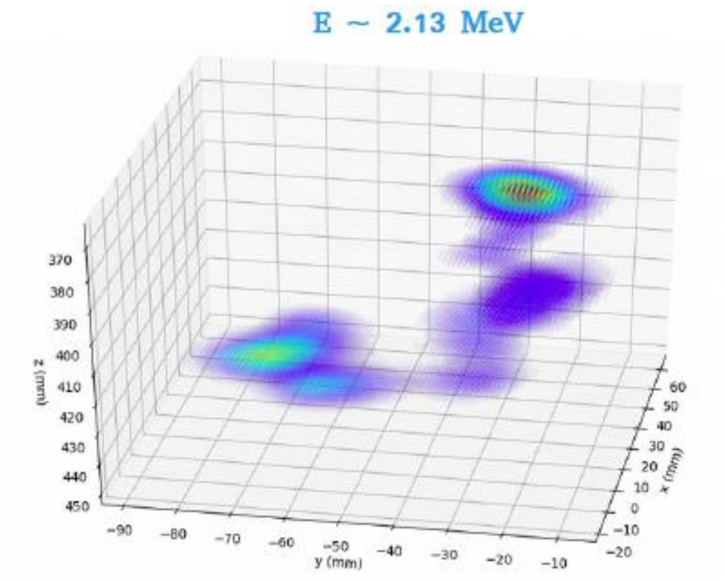
TPC inner diameter 45 cm, drift length 53 cm, 5 kg fiducial mass at 15 bar

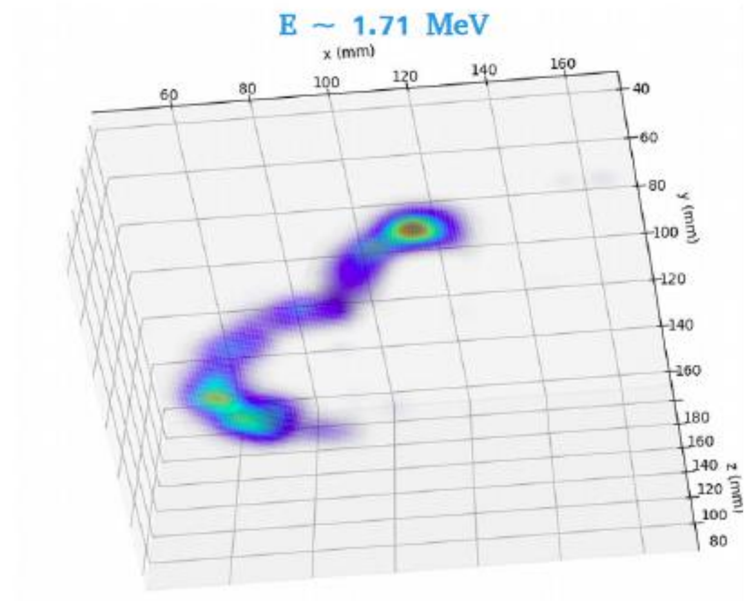






NEXT-White: $\beta\beta 2\nu$ events in data

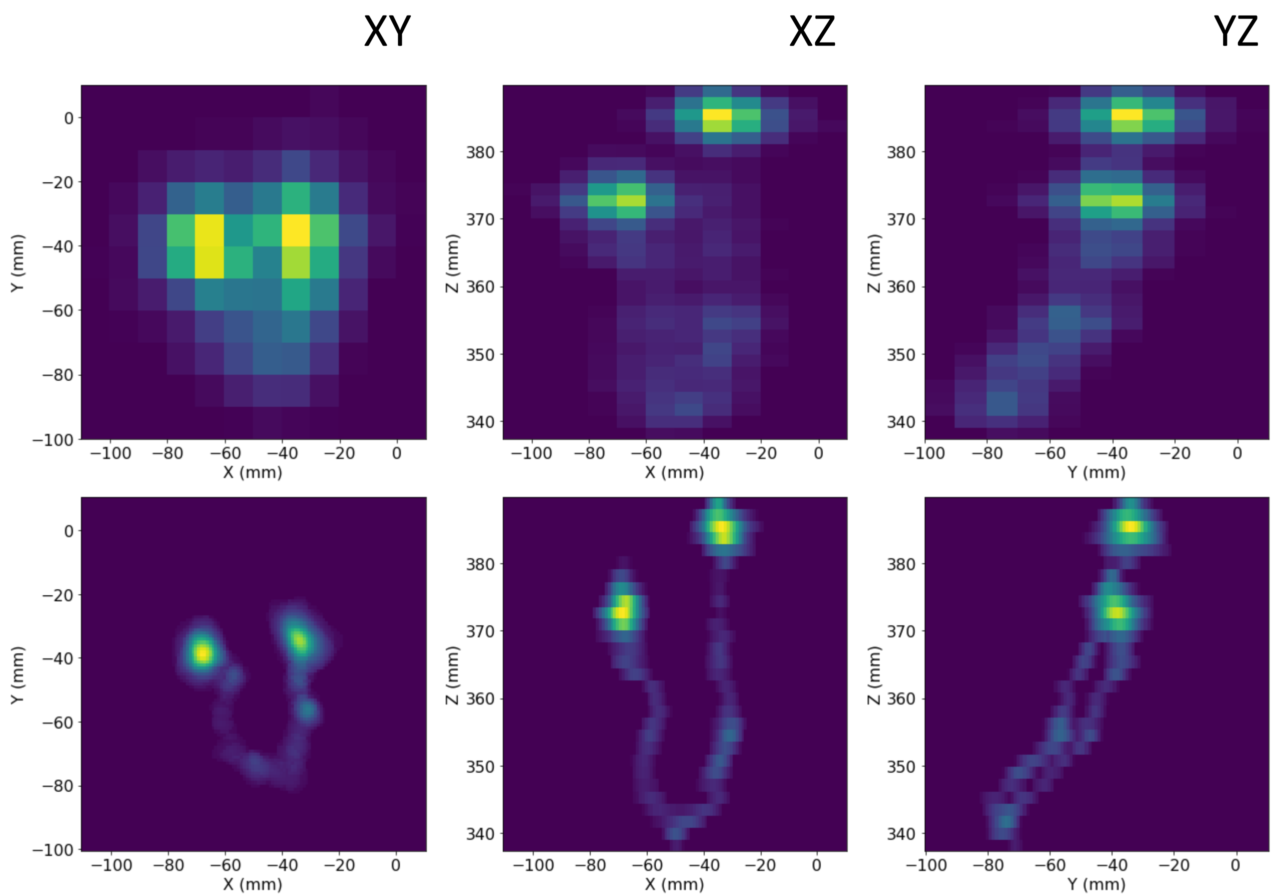




NEXT-White: $\beta\beta2\nu$ events in data

Sensor response

Deconvolution



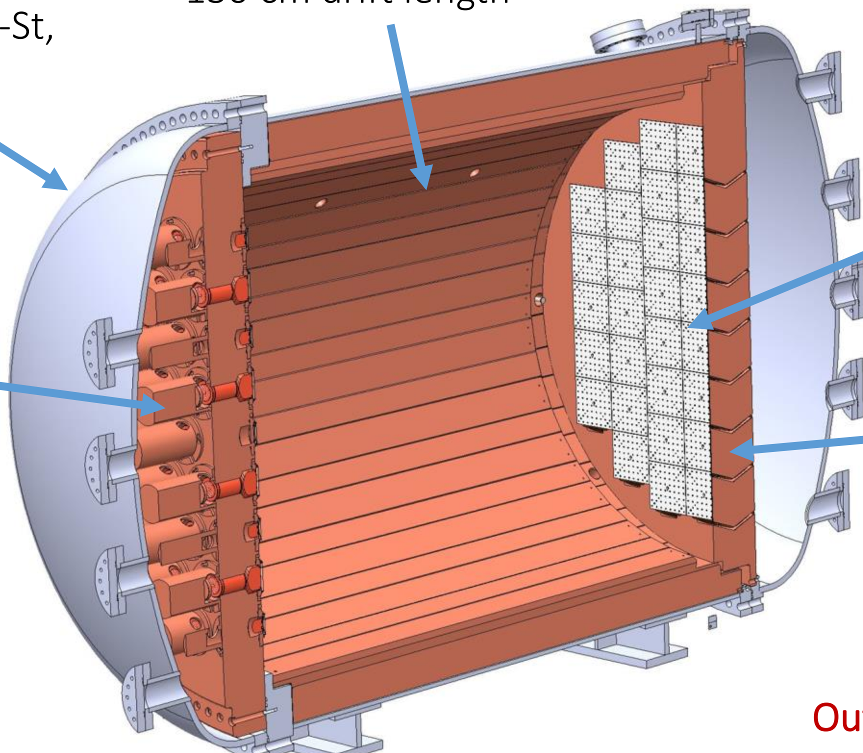
2.19 MeV

NEXT-100 (assembly in 2020)

Main goal: technology demonstrator on the 100 kg scale

TPC: 97 kg active region, 130 cm drift length

Pressure vessel: St-St, rated for 15 bar



Tracking plane: 5600 SiPMs at 1 cm pitch

Energy plane: 60 radio-pure PMTs, 30% coverage

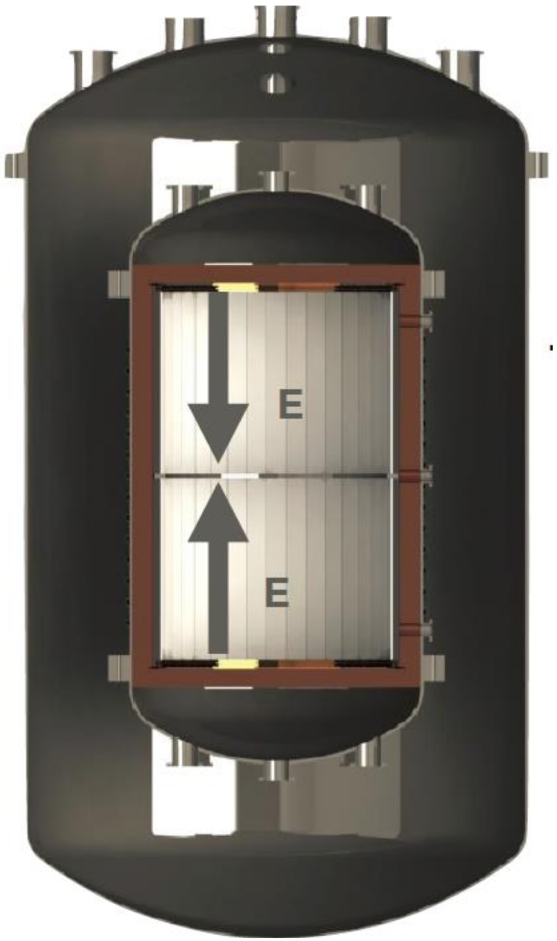
Inner shield: 12 cm Cu

Outer shield: lead castle with Rn-free air

Expected background index 4×10^{-4} counts/(keV kg y)

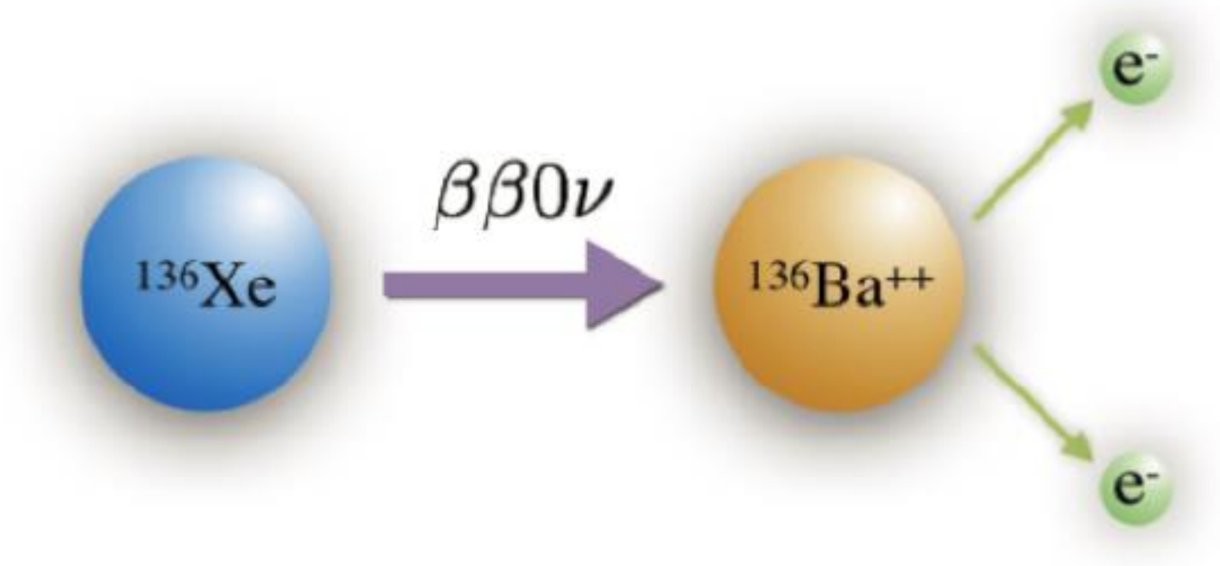
NEXT-HD (future)

- 1000 kg enriched Xe
- Bi-directional symmetric TPC
- Tracking + energy by radiopure SiPMs
- Operated at low temperature (to reduce SiPM dark count rate)
- Low-diffusion gas mixture (e.g., Xe/He 85/15) to further improve topology
- Expected sensitivity after 10 years:
  $T_{1/2}^{0\nu} \sim 3 \times 10^{27}\ \mathrm{y}\ (\sim 10 - 30\ \mathrm{meV})$



arXiv:1906.01743

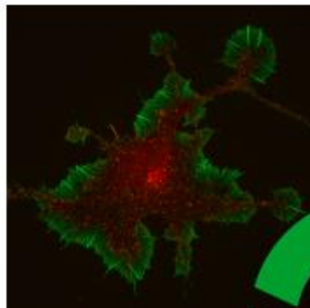
The aggressive approach: NEXT-BOLD

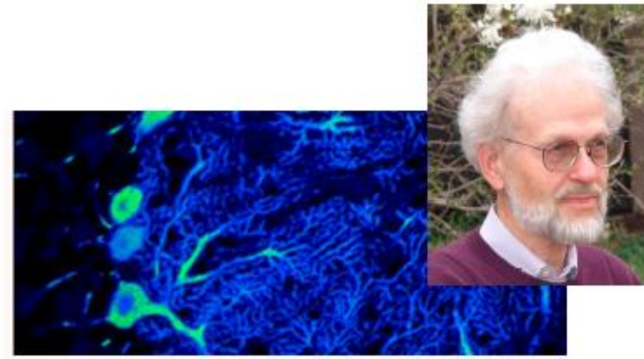


Tagging the barium daughter in a $\beta\beta0\nu$ candidate event can lead to a background-free experiment

Single Molecule Fluorescent Imaging comes back to physics!

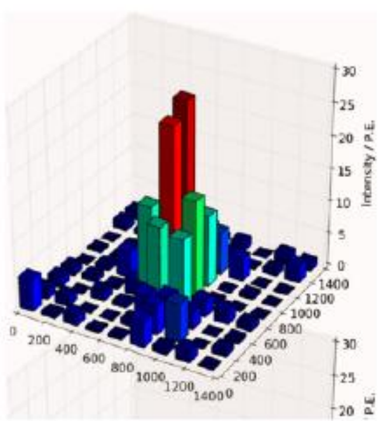
Noble price in Chemistry 2014:
Development of super-resolved fluorescence microscopy





A bright idea by D. Nygren

J.Phys.Conf.Ser. 650 (2015) no.1, 012002

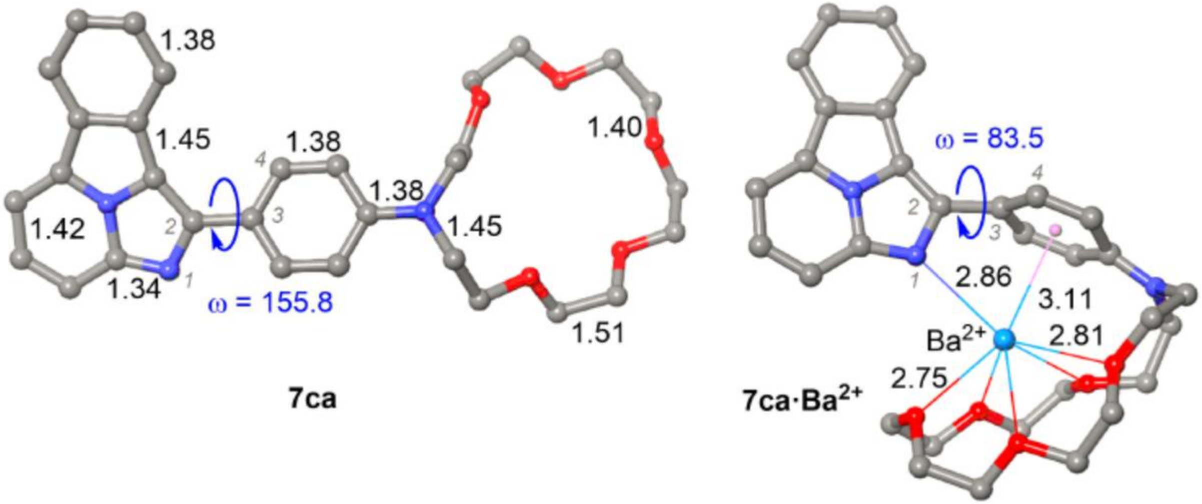


Demonstration of Single-Barium-Ion Sensitivity for Neutrinoless Double-Beta Decay Using Single-Molecule Fluorescence Imaging

A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. **120**, 132504

SMFI barium tagging in NEXT

- Coat cathode plane with chelating molecules that selectively catch barium ions (not Xe).
- The molecules are non fluorescent in isolation and become fluorescent upon chelation (or alternatively – change fluorescence color when containing barium).
- Following a trigger on the event energy, scan cathode with a laser. A single molecule holding Ba appears as a bright spot.

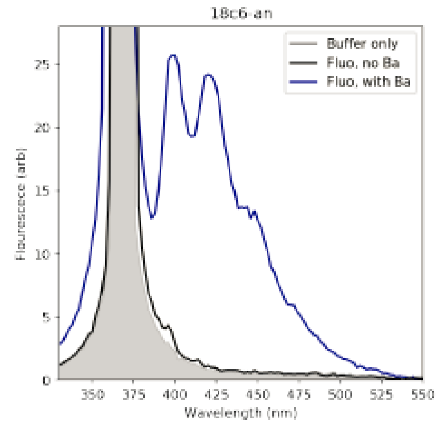


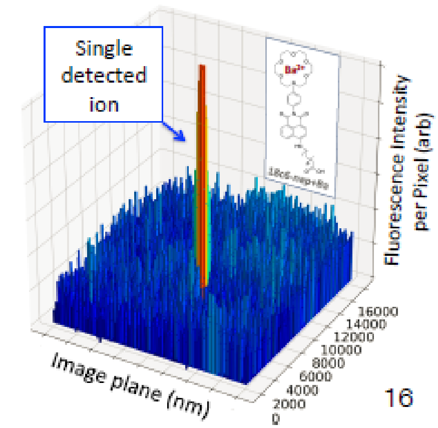
Bicolor molecule developed at DIPC/EHU by the F. Cossio group

arXiv:1909.02782

SMFI barium tagging in NEXT

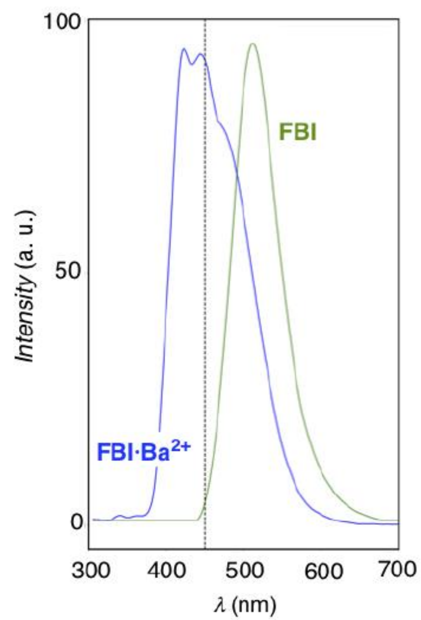
- Development at UTA based on monocolor molecules: on/off
- Enhanced fluorescence when "on"

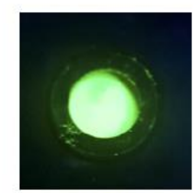




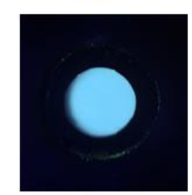
16

- Development at DIPC based on bicolor molecules (FBI)
- Enhanced fluorescence and spectral separation



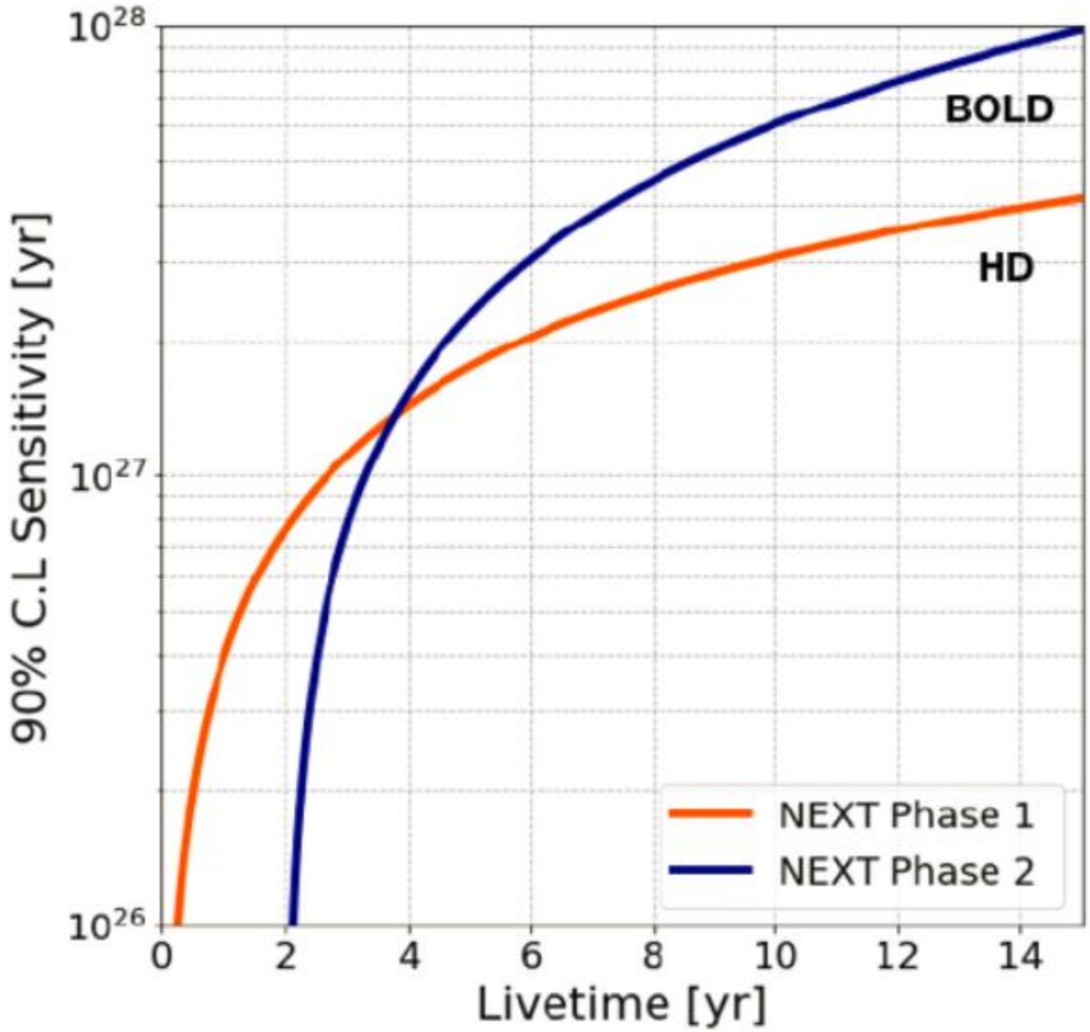


FBI



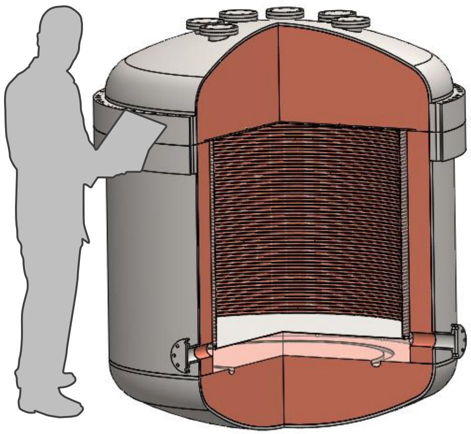
FBI·Ba^{2+}

NEXT-BOLD sensitivity

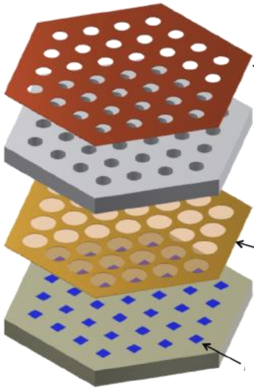


Additional projects (details in backup slides)

- PandaX-III: High-pressure Xe gas TPC - $\beta\beta 0\nu$ in ^{136}Xe
  - Multi-module approach (each ~100 kg) in CJPL China
  - Xe-TMA – favor topology over energy resolution
  - Readout by mosaic of bulk MicroMegas
  - First 100 kg module to be commissioned in 2020

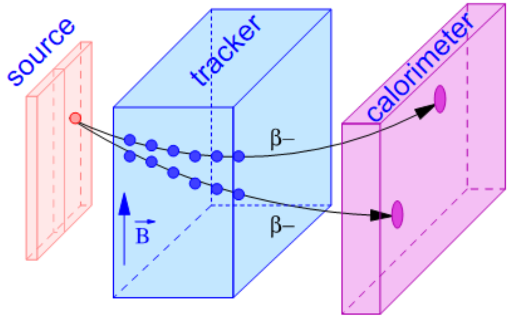


- AXEL High-pressure Xe gas TPC - $\beta\beta 0\nu$ in ^{136}Xe
  - EL in perforated PTFE structure, with SiPM readout for individual holes
  - Now operating a 4.5 kg Xe prototype with 168 channels
  - To be followed by a 40 kg module

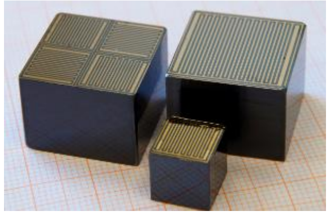


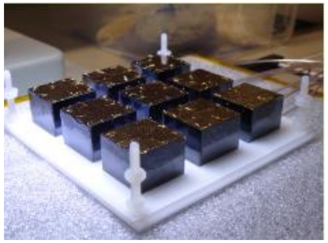
Additional projects (details in backup slides)

- SuperNEMO - $\beta\beta 0\nu$ in multi isotopes
  - Successor of NEMO-3
  - Isotope contained in a thin foil, with the outgoing $\beta\beta$ electrons passing through a gas tracker and a calorimeter
  - Ideal for characterizing the $\beta\beta 0\nu$ mechanism once a discovery is made by other experiments



- COBRA
  - Array of CdZnTe crystals, containing five $\beta^-\beta^-$ and four $\beta^+\beta^+$ isotopes, including ^{116}Cd and ^{130}Tl
  - Crystals serve as both source and detector
  - Background suppression by multi-crystal hits and PSD
  - Room temperature operation with ~35 keV FHWM
  - Two demonstrators with different crystal sizes taking data at LNGS (total masses 300 and 400 g).

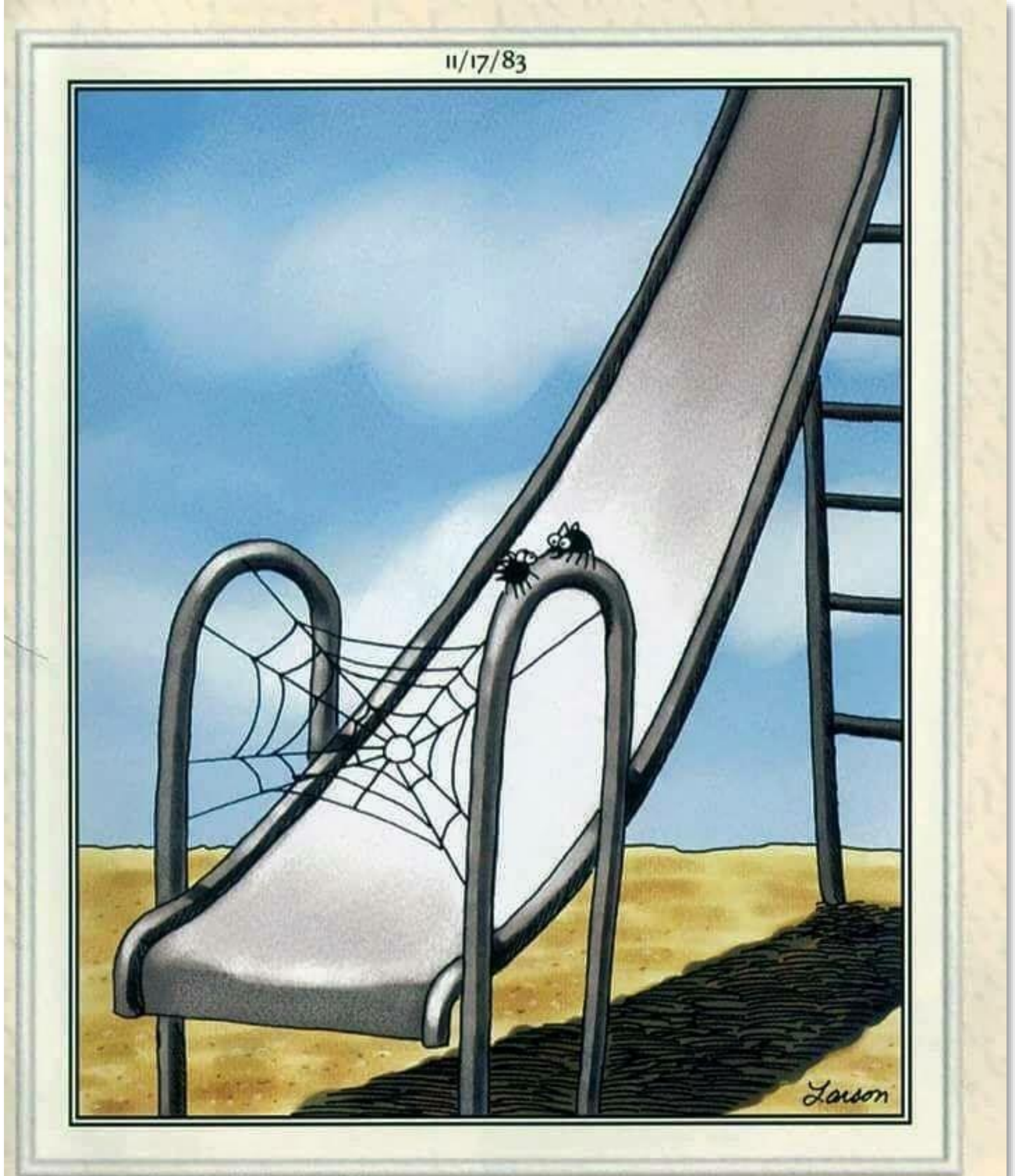




PRC 94, 024603 (2016), NIM A 807 (2016) 114

Summary

- The importance of $\beta\beta0\nu$ detection justifies a multi-isotope approach
- Several major players, but funding for the tonne-scale is still uncertain
- Tonne-scale experiments will require many tens of M€, clearly not all will make it
- GERDA and Majorana demonstrated a successful merger. Can this model apply to others?
- Normal-ordering appears favored by oscillation experiments, but other effects beyond light Majorana neutrinos exchange may contribute to $m_{\beta\beta}$
- g_A quenching lurks in the dark, but advanced nuclear matrix element calculations may save the day

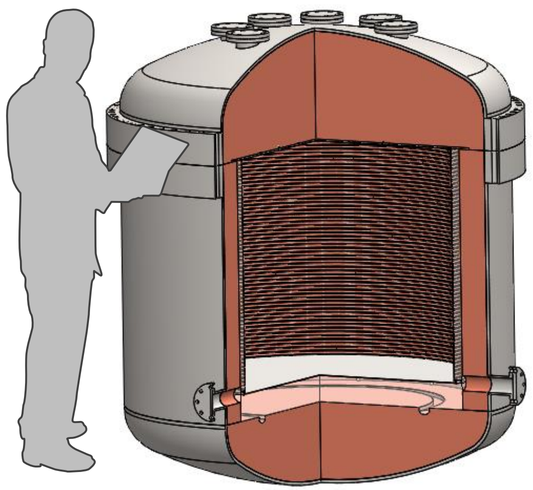


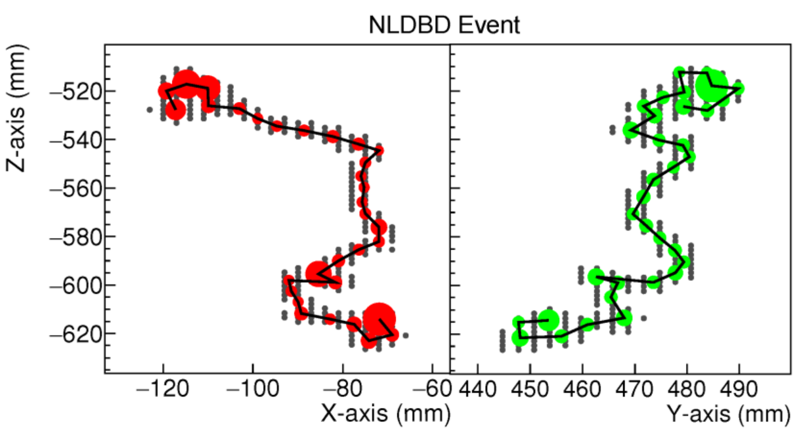
"If we pull this off, we'll eat like kings."

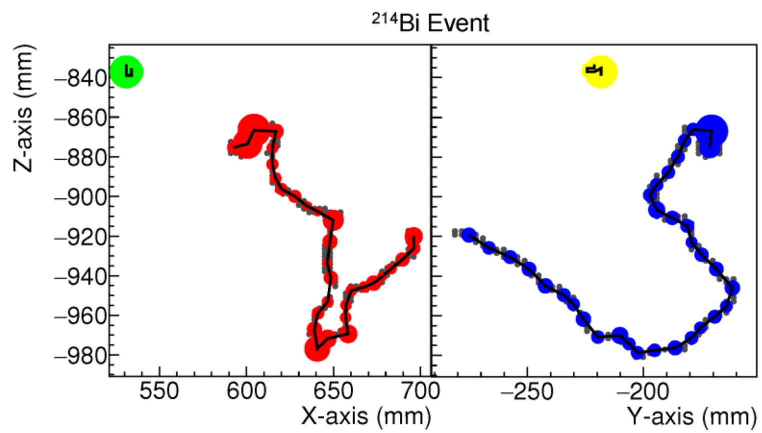
Backup slides

PandaX-III: High-pressure Xe gas TPC - $\beta\beta0\nu$ in ^{136}Xe

- TPC: 100 kg scale high pressure TPC with charge readout
- Main design features: good energy resolution and tracking capability
- Traditional cuts and neural network topological studies (arXiv:1903.03979 ;1802.03489)

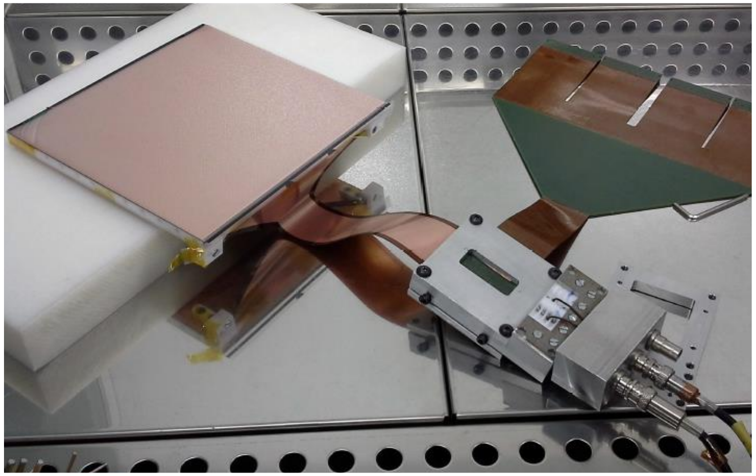


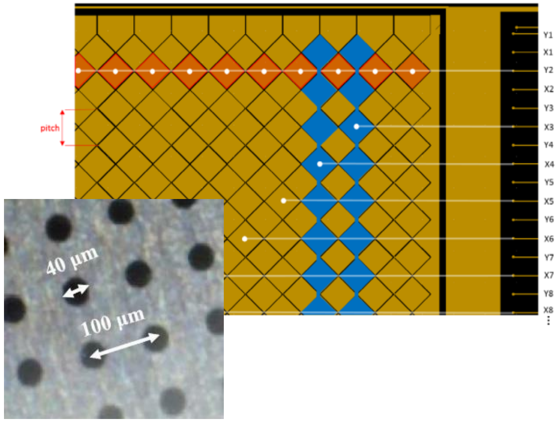


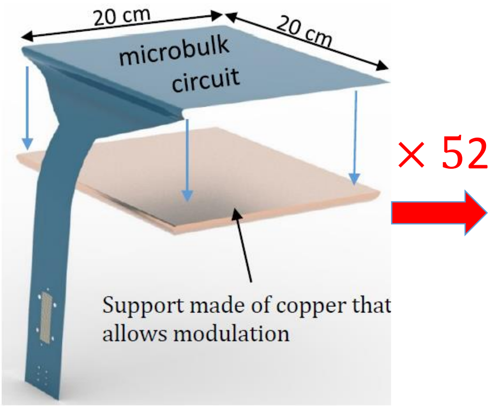


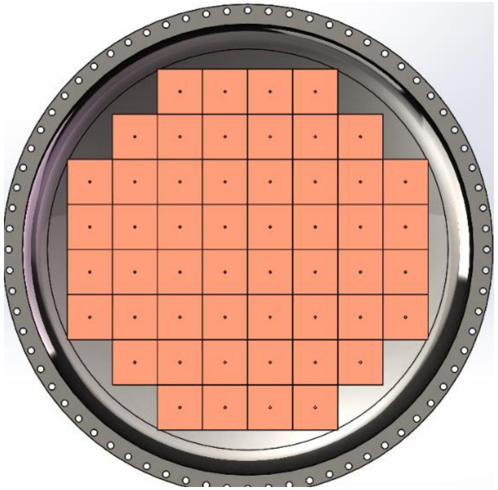
PandaX-III: readout plane

- Microbulk MicroMegas films made of Copper and Kapton only
  - Perfect for radio-purity purpose
  - 20 by 20 cm
  - 3 mm pitch size, 128 strip readouts
- Mosaic layout to cover readout planes



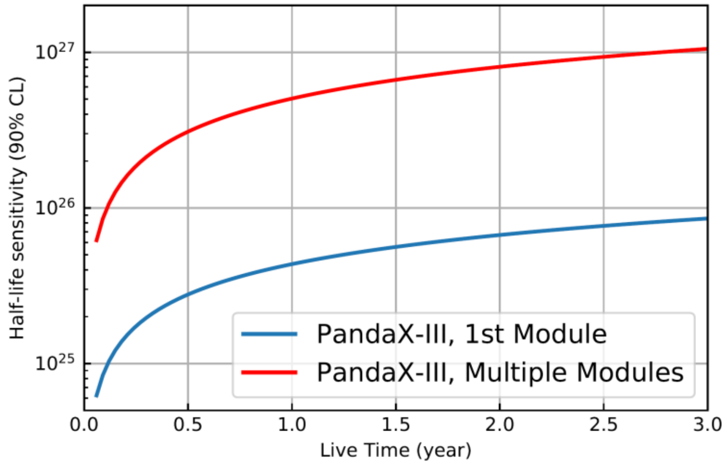


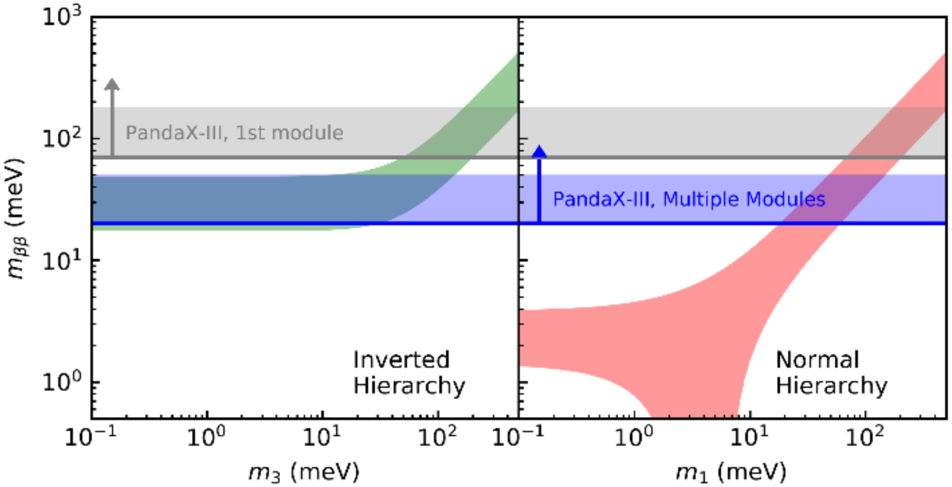




PandaX-III: status and sensitivity

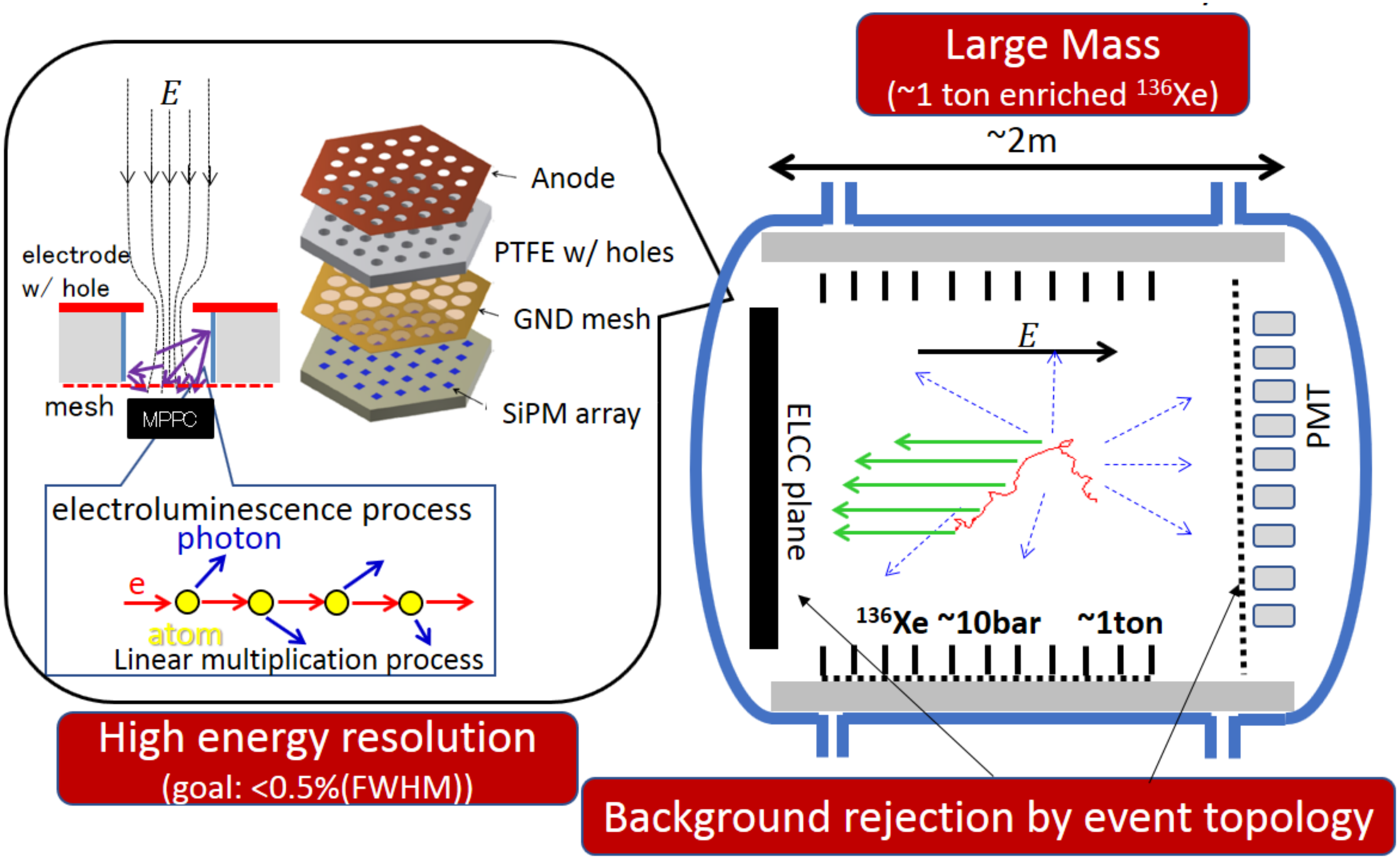
- A 20-kg scale prototype TPC is running (arXiv:1804.02863)
- 1st 100-kg scale module to commission in 2020
- Half-life sensitivity with 3 years of data: 9×10^{25} yr (90% CL)





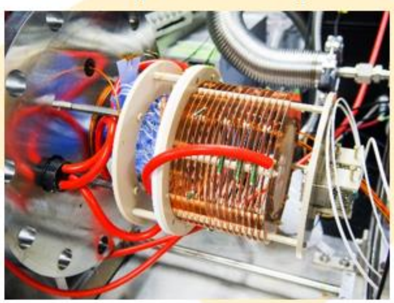
AXEL: High-pressure Xe gas TPC - $\beta\beta0\nu$ in ^{136}Xe

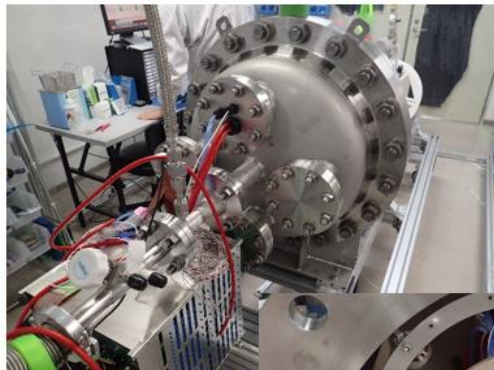
AXEL: A Xenon ElectroLuminescence detector to search for neutrinoless double-beta decay

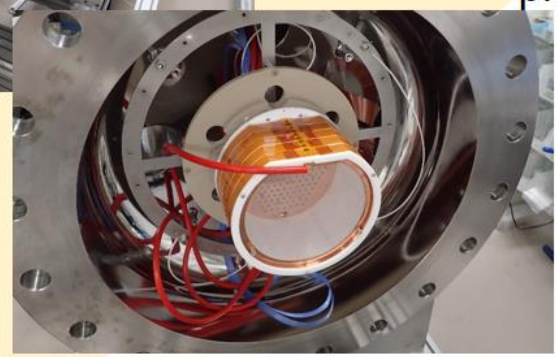


AXEL road map

10-L prototype
2014–2018
- ~0.05kg @8bar
- ELCC proof of principle







180-L prototype
2018–2020
- ~4.5kg @8bar

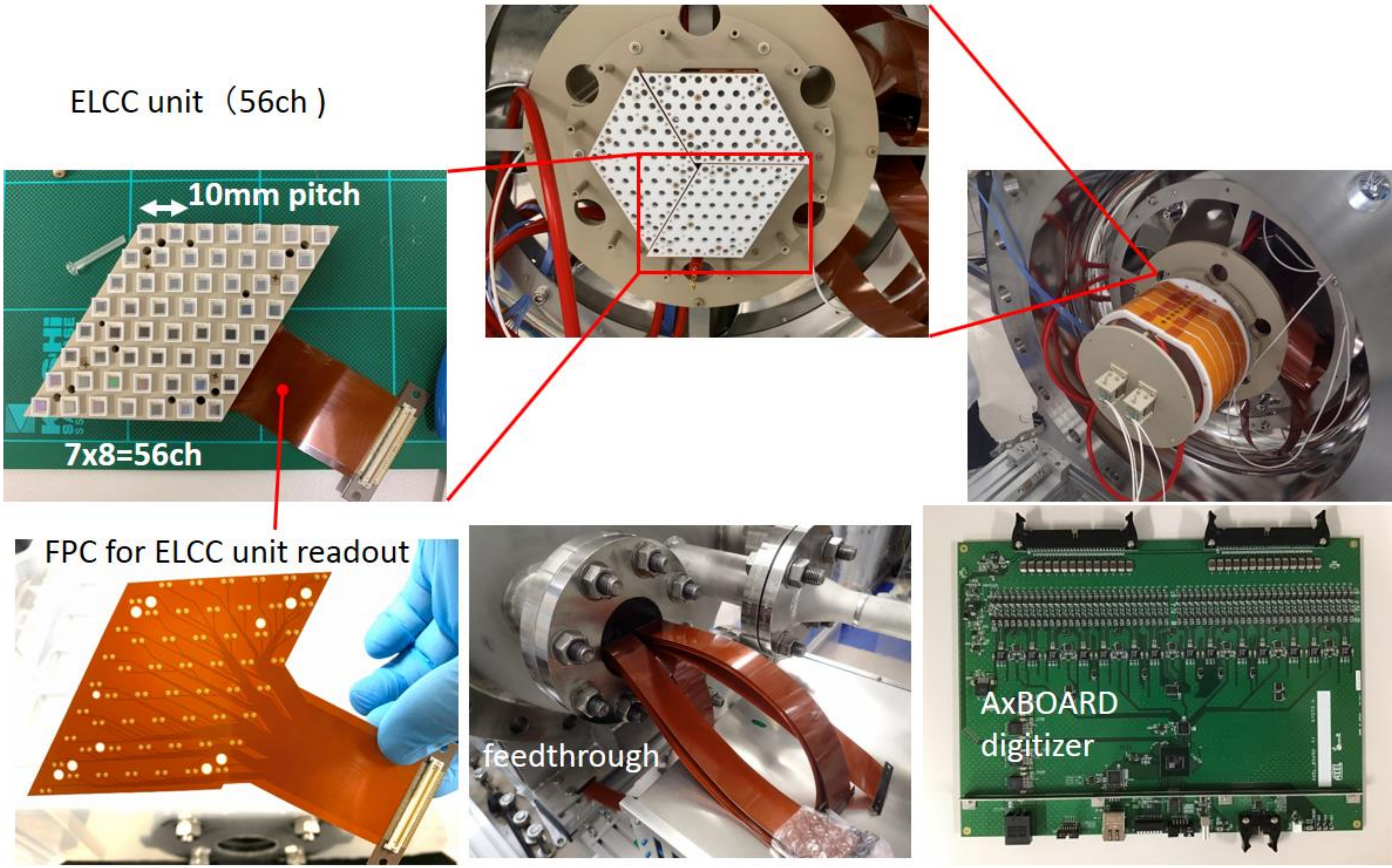
phase-1 : 168 ch
phase-2 : 672ch
phase-3 : 1,512 ch

1000L(40 kg) scale

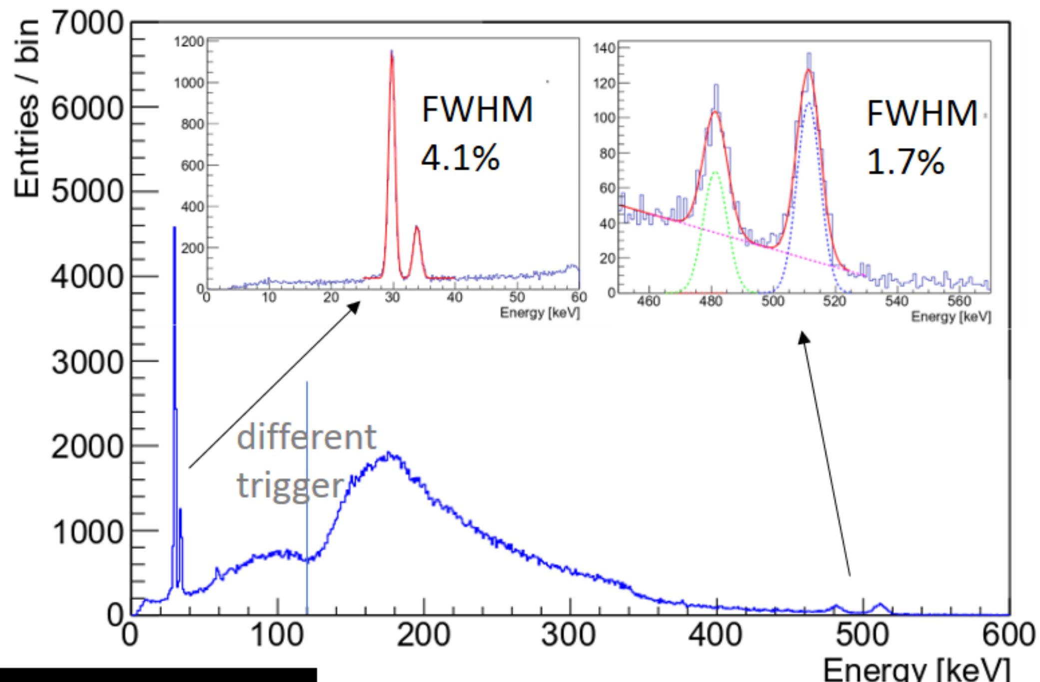
1 ton scale

202?–
physics data taking

AXEL: 180L phase 1



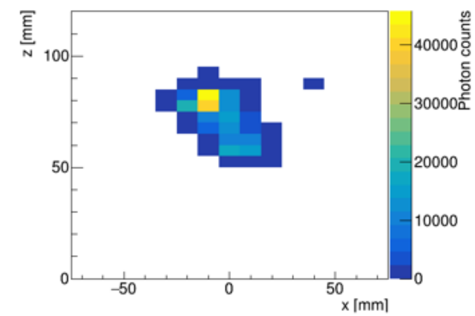
AXEL: 180L phase 1 performance

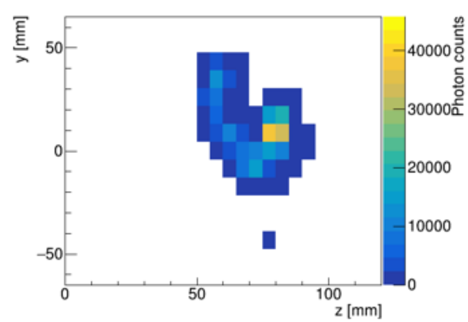


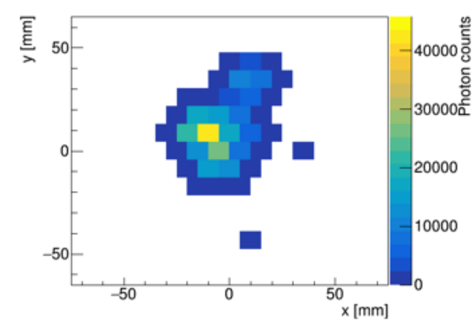
Energy spectrum

arXiv:2001.03281

511 keV event

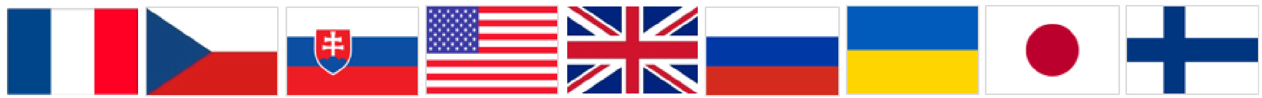






SuperNEMO: overview

supernemo collaboration



CENBG (Bordeaux), CPPM (Marseille), Charles U. (Prague), Comenius U. (Bratislava), CTU (Prague), INL (Idaho Falls), Imperial College (London), ITEP (Moscow), JINR (Dubna), LSM (Modane), LPC (Caen), LAL (Orsay), LAPP (Annecy), INR (Kiev), Osaka U. (Osaka), Manchester U. (Manchester), Texas U. (Austin), UCL (London), Jyväskylä U. (Jyväskylä), Warwick U. (Warwick), Werc (Fukui)

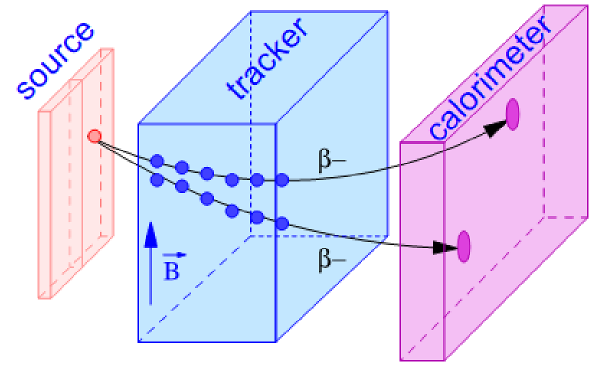
9 countries, 21 Laboratories

The goals of SuperNEMO :

1. Build on the experience of the extremely successful NEMO-3 experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (Demonstrator Module) phase.
3. Prove that a 100 kg scale experiment can reach the inverted mass hierarchy (~50 meV) domain.
4. In the event of a discovery by any of the next-generation experiments, demonstrate that the tracking-calorimeter approach is by far the best one for characterising the mechanism of $0\nu\beta\beta$ decay.

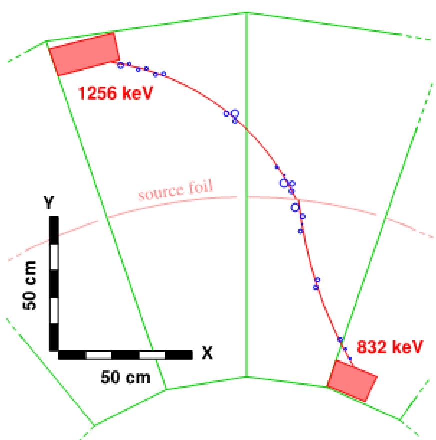
SuperNEMO: the tracker-calorimeter technique

- Source separated from detector: (almost) any solid isotope can be hosted.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification ➜ strong background control & mechanism probe.
- Successfully exploited by **NEMO-3** experiment: $0\nu\beta\beta$ limits and $2\nu\beta\beta$ $T_{1/2}$ for several isotopes.



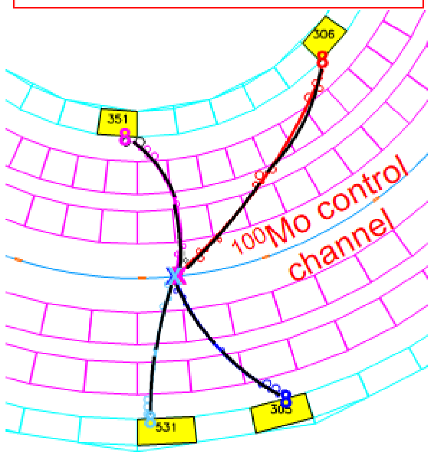
10^{24} year limit with just 7kg of ^{100}Mo

PRD 92, 072011 (2015)



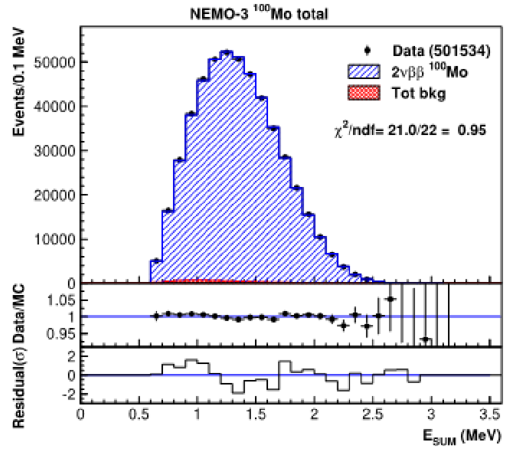
Access unique signatures, e.g. $0\nu4\beta$

PRL 119, 041801 (2017)

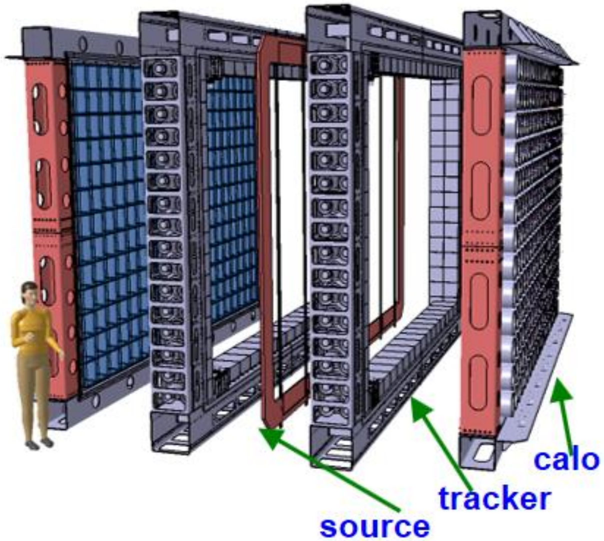


Kinematic probes of DBD mechanism (SSD/HSD)

EPJ C79, 440 (2019)



SuperNEMO: demonstrator



Demonstrator Module (2.5 year run)

17.5 kg × yr initial exposure :

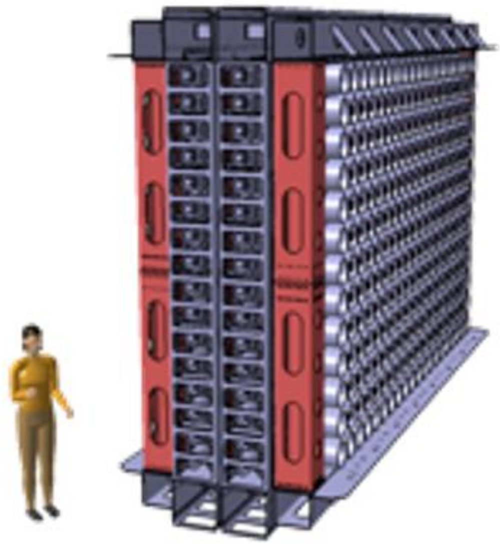
$$T^{0\nu}_{1/2} > 6.5 \times 10^{24}\ \mathrm{yr}$$

$$\langle m_\nu \rangle < 0.20 - 0.40\ \mathrm{eV}$$

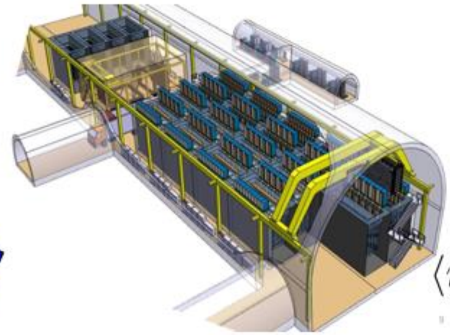
SuperNEMO Demonstrator Module : final commissioning in progress

- Experience from the Demonstrator Module suggests a 100 kg, 10^{26} yr class experiment ("full SuperNEMO") would be possible.
- Full event reconstruction of 2νββ **gives unique precision measurements** and access to nuclear physics : g_A analysis in preparation.
- Can the technique be extended to **confirm a signal anywhere in the IH region ? R&D and isotope developments** can point the way.

SuperNEMO: future directions



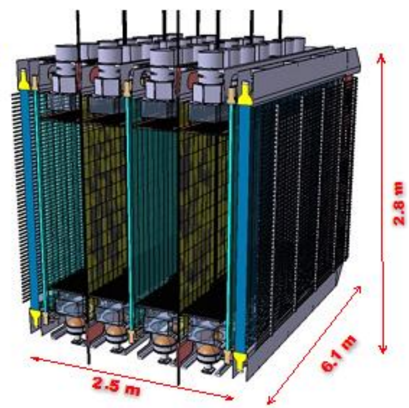
- A **unique approach** with access to fundamental nuclear physics.
- The best technique for **exploring a signal.**
- Continued R&D is essential.



Full SuperNEMO

500 kg × yr :

$$T^{0\nu}_{1/2} > 10^{26}\ \mathrm{yr}$$
$$\langle m_\nu \rangle < 50 - 100\ \mathrm{meV}$$



Alternative Designs

Largest source of uncertainty: the size of axial coupling g_A

$g_A = 1.269$ for weak interaction and decays of nucleons

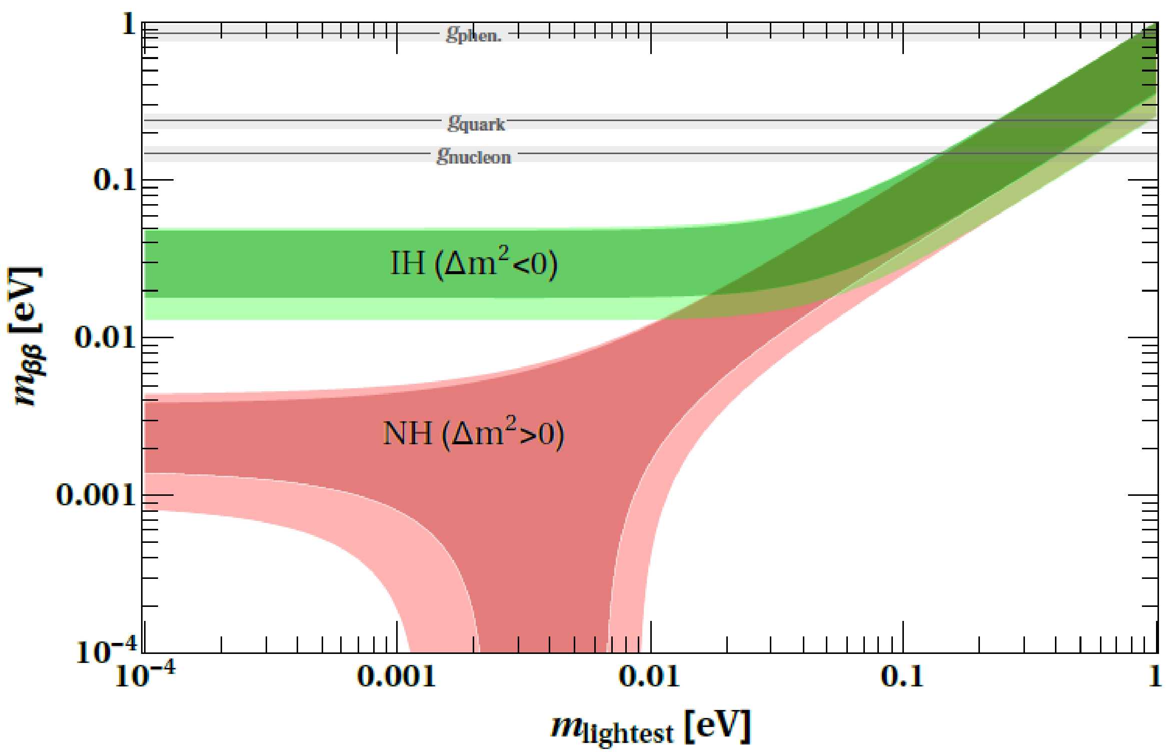
Quenching effects inside the nucleus *may* considerably reduce g_A

Conservatively one should consider several options:

$$g_A = \begin{cases} g_{nucleon} & = & 1.269 \\ g_{quark} & = & 1 \\ g_{phen.} & = & g_{nucleon} \cdot A^{-0.18} \end{cases}$$

The degree of g_A quenching is unknown. The expression for $g_{phen.}$ is based on $2\nu\beta\beta$ half-lives and may be different for $0\nu\beta\beta$

Effect of uncertainty in g_A



$g_A = g_{phen} = \ 0.52$

$g_A = 1$

$g_A = 1.269$

KamLand-Zen + EXO-200
2015 data

For ^{136}Xe taking $g_A = g_{phen}$ pushes up the limit on $m_{\beta\beta}$ by a factor of $\gtrsim 5$