Double Beta Decay Experiments with ^{136}Xe + …

Sei Yoshida
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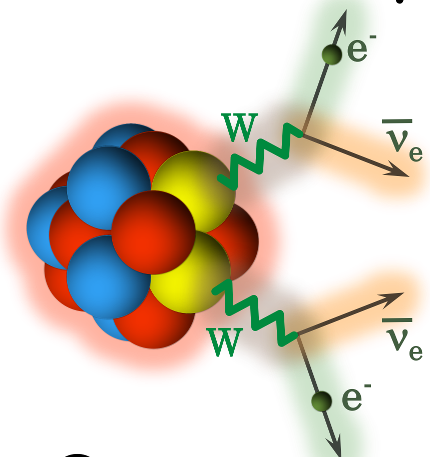
on behalf of KamLAND-Zen

ββ Decay

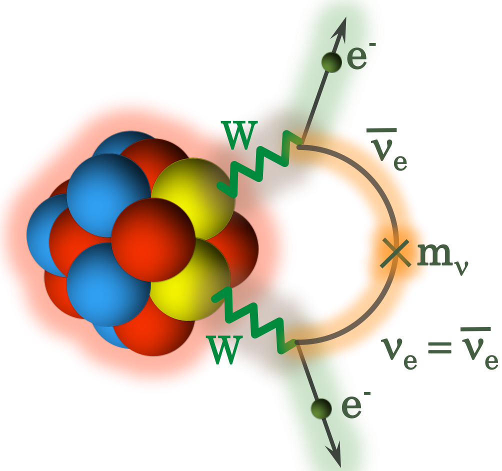
- Two decay modes are usually discussed for ββ decay:

<u>① 2νββ decay</u> : (A,Z) → (A,Z+2) + 2e⁻ + $2\bar{\nu}_e$



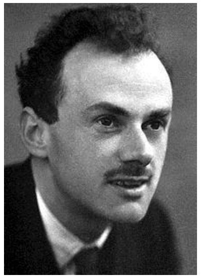
- allowed by the Standard Model.
- already observed in more than 10 isotopes.
- Lifetimes ; $\tau = 10^{18} \sim 10^{21}$ yr

<u>② 0νββ decay</u> : (A,Z) → (A,Z+2) + 2e⁻



- process beyond the Standard Model.
  - Lepton number violation
  - non-zero neutrino mass
  - **<u>Majorana particle</u>**
- not observed yet.
  except for the KKDC claim, still alive ?
- predicted lifetimes ; $\tau > 10^{26}$ yr

Physics of 0νββ Decay



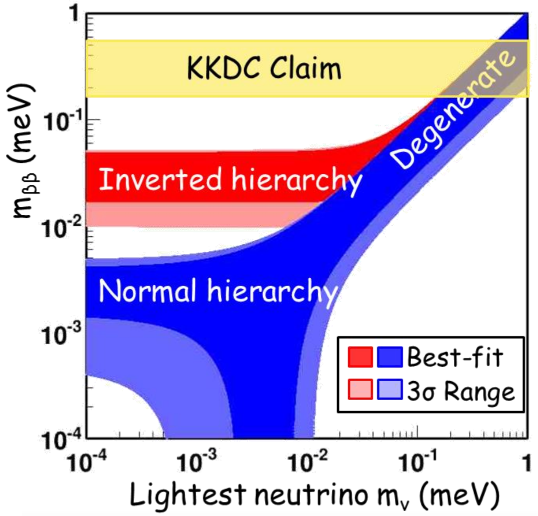
- 0νββ search is the useful tools to explore unknown neutrino properties,
  - Origin of neutrino mass, **Dirac or Majorana ?**

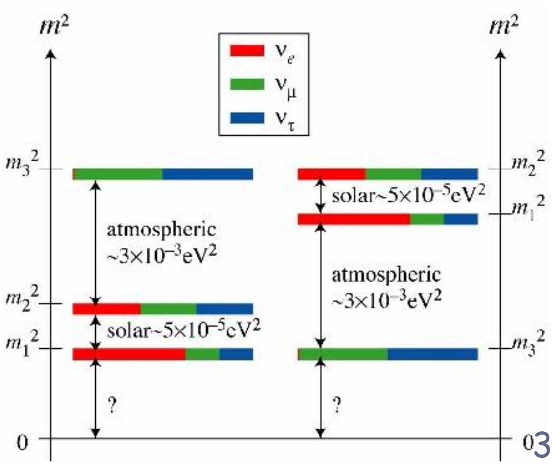
    If neutrino is Majorana, 0νββ will be observed !
  - Absolute mass scale ?

    The effective Majorana mass is calculated by

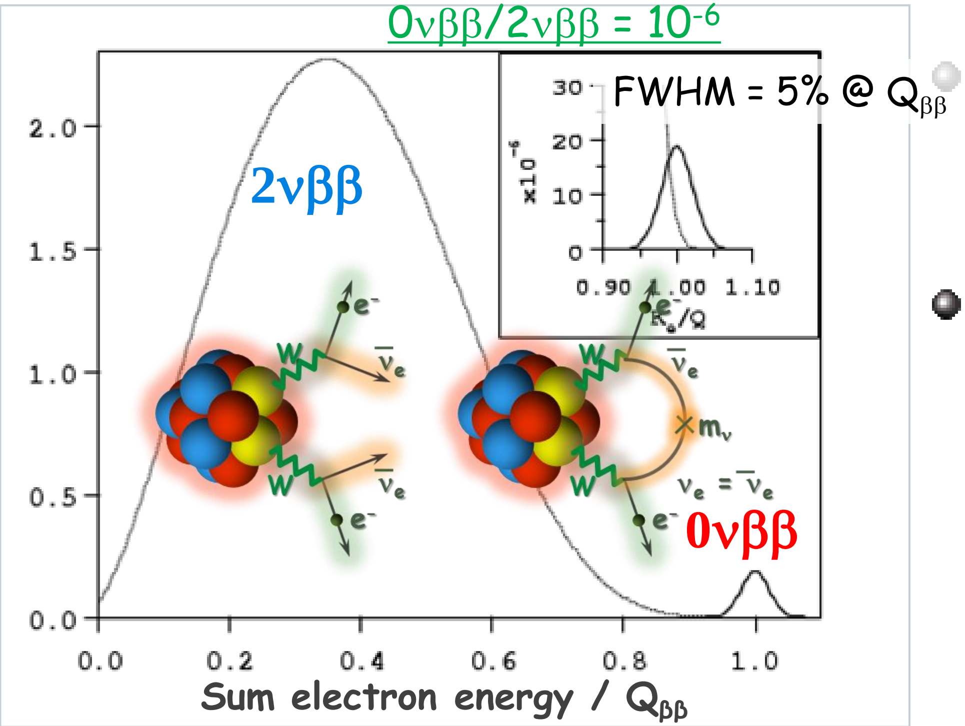
    $$T_{0\nu}^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\ |M_{0\nu}|^2\ \langle m_\nu \rangle^2 \ \text{(mass term)},$$
    $$\langle m_\nu \rangle = |\Sigma U_{ei}^2\ m_i|$$
  - Mass hierarchy

    (normal, inverted or degenerate) ?
  - CP Phase in the neutrino mixing matrix ?
  - Sterile neutrino ?
  - ……
- Neutrino is Majorana particle, ➔
  - ΔL ≠ 0 (Lepton number violation) → Leptogenesis ?
  - See-Saw mechanism ?
    - It can explain tiny neutrino masses.





Signature of 0νββ



S.R.Elliot and P.Vogel, Ann. Rev.Nucl.Part.Sci.52(2002)115.

- $0\nu\beta\beta$ decay ;
  - peak at $Q_{\beta\beta}$
- $2\nu\beta\beta$;
  - continuum to $Q_{\beta\beta}$ end point
  - two electrons from vertex
  - production of daughter isotope

- The shape of the two electron sum energy spectrum enables to distinguish the two different decay modes. ← Good energy resolution.

- The predicted $T_{1/2}$ is long (~ 10^{26}yr) . ← **Low BG condition**

0νββ and Neutrino Mass

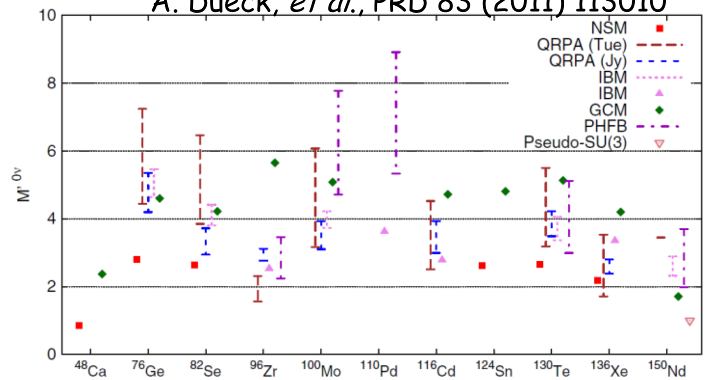
- Decay rate (observable quantity) ;

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

assuming light neutrino exchange **(Mass term)**

- $G_{0\nu}$: phase-space factor
- $|M_{0\nu}|^2$: Nuclear matrix element
  - only theoretically calculate with nuclear models
  - Uncertainty ; factor of ~2

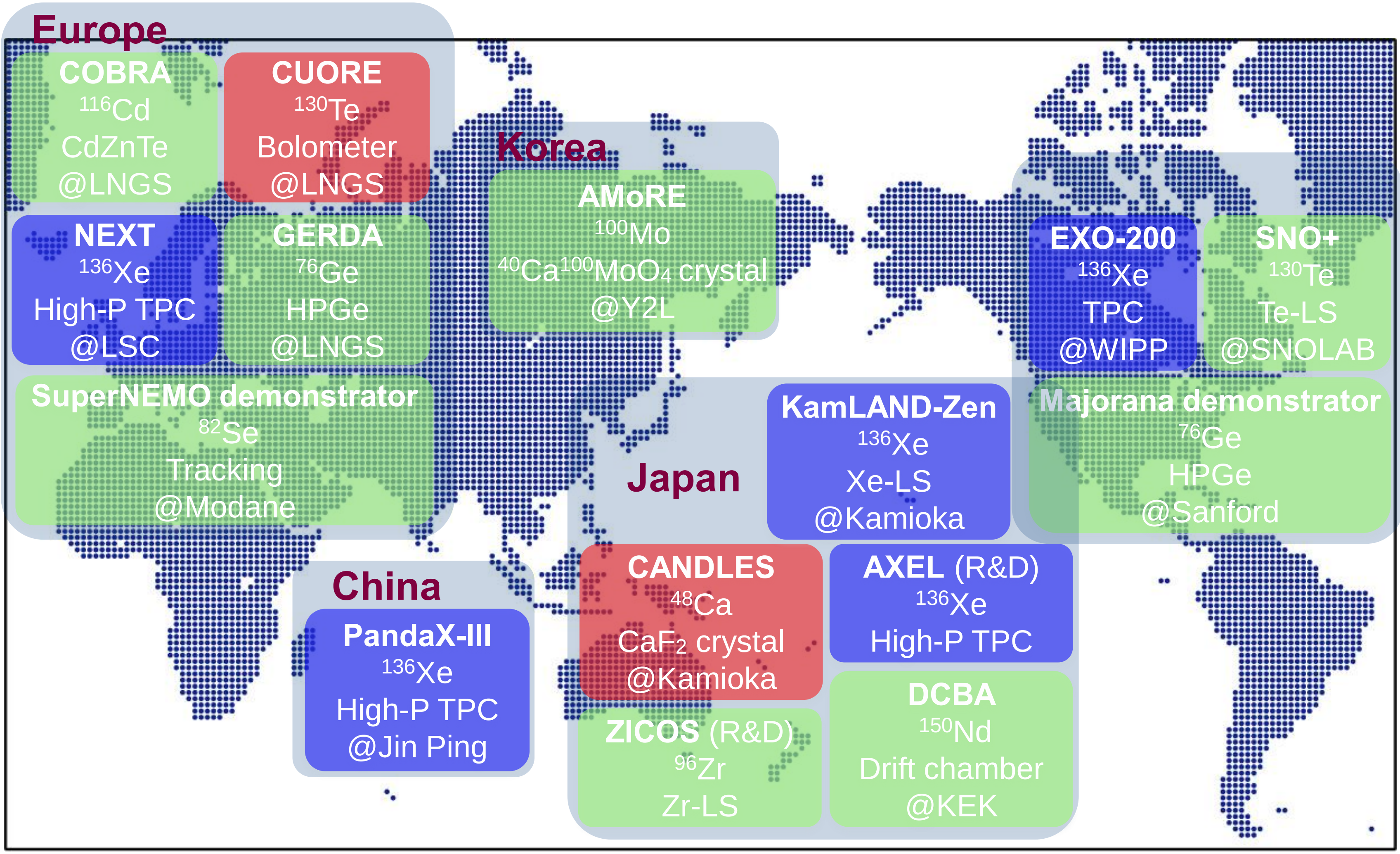
A. Dueck, *et al.*, PRD 83 (2011) 113010



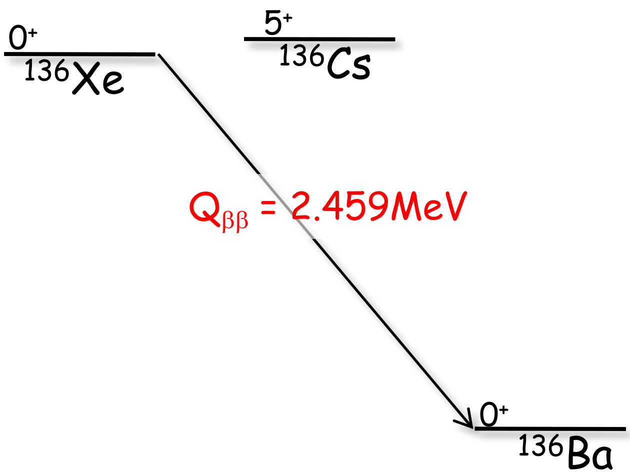
Important to observe 0νββ by several isotopes !

- $\langle m_\nu \rangle$: (effective) Majorana mass
  - $\langle m_\nu \rangle = |\sum U_{ei}^2\ m_i|$
  - U_{ei} ; (complex) neutrino mixing matrix

Experiments using ^{136}Xe



^{136}Xe for ββ isotope



- Advantages of ^{136}Xe
  - Q-value ; valley of natural RI background
    - 2.6MeV γ-ray from ^{208}Tl
  - Easy to enrich
    - More than 90% enriched gas is available with reasonable cost
  - Gaseous isotope can be purified during the experiment
    - Filter, getter, distillation etc.
  - Long 2νββ half-life → Require modest energy resolution
    - ~2 x 10^{21} yr
  - No long lived unstable Xe isotopes

KamLAND-Zen Experiment

Slides from Azusa Gando

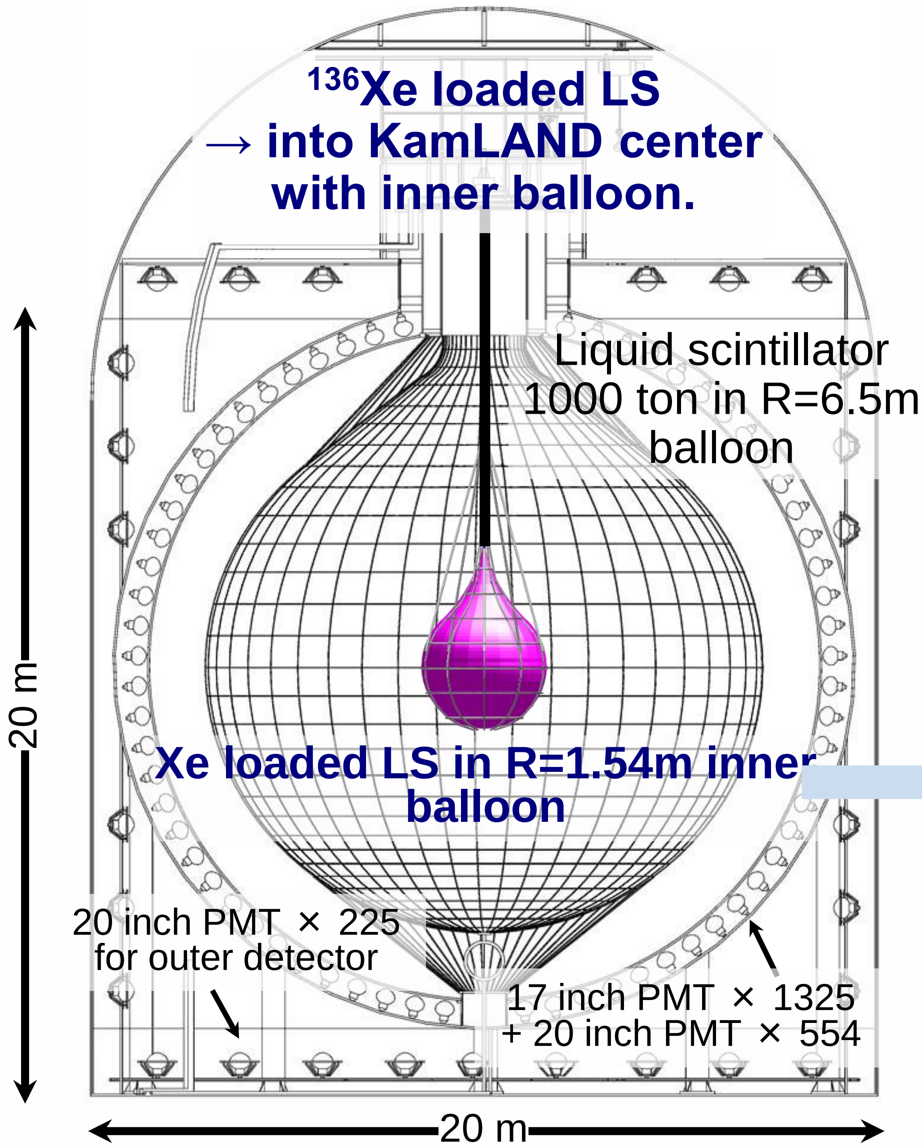
^{136}Xe in KamLAND

- Easy to dissolve ; more than 3 wt%
- Easy to extract

High sensitivity with low cost

Detector: KamLAND-Zen

- Located in Kamioka (Japan), 2700 m.w.e.
- Modification of KamLAND (ν detector)

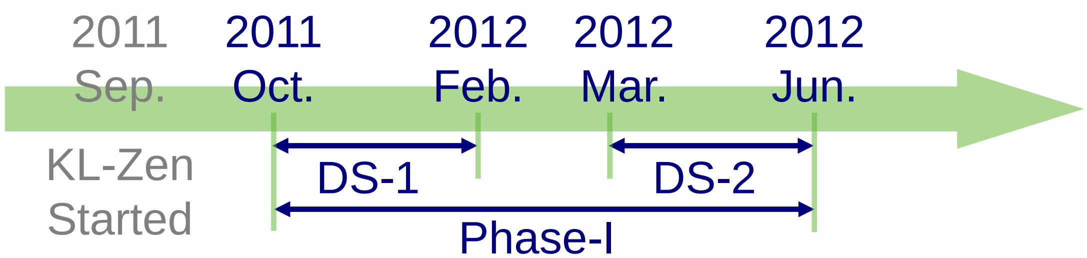


Advantage

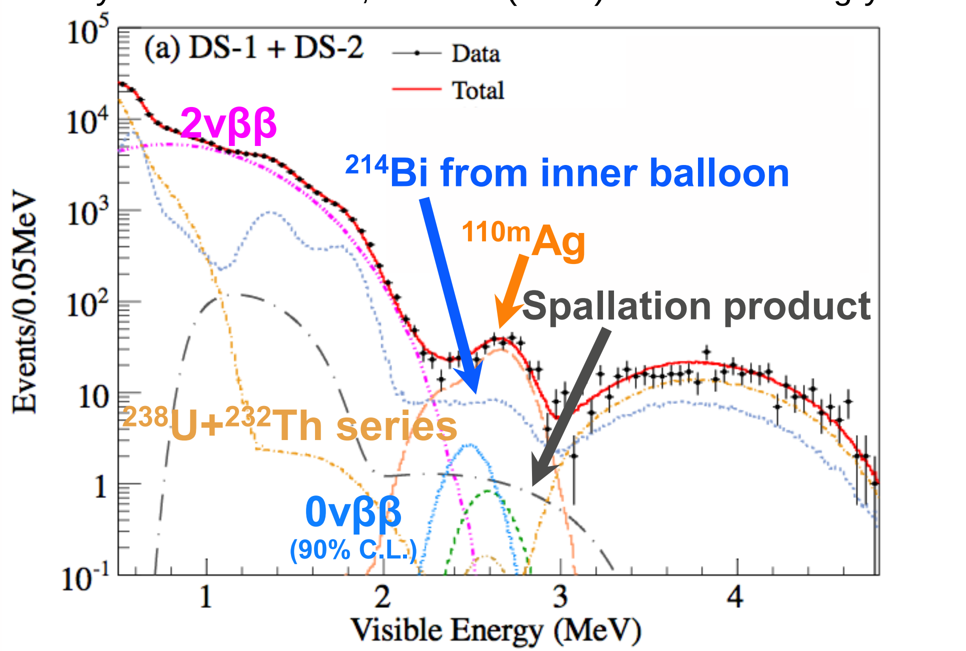
- Running detector
  Well known detector response
- Low background
  U, Th are at $10^{-17\sim-18}$ g/g level
- Big detector → high scalability
  Ton order isotopes

Made of 25-um-thick clean nylon by welding (no glue) at class-1 clean room

History



Phys. Rev. Lett. 110, 062502 (2013) ^{136}Xe 89.5 kg-yr



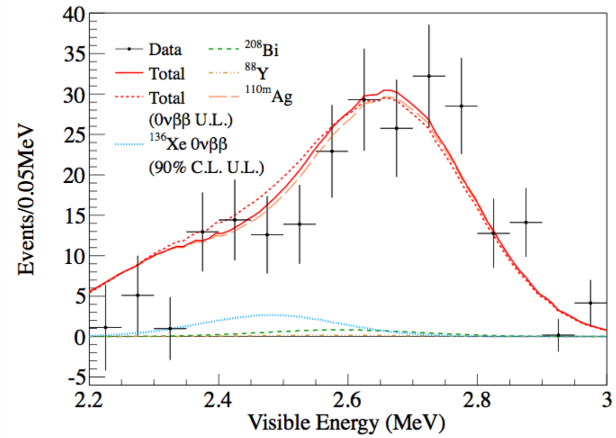
Lower limit of 0νββ decay half-life

$T^{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)

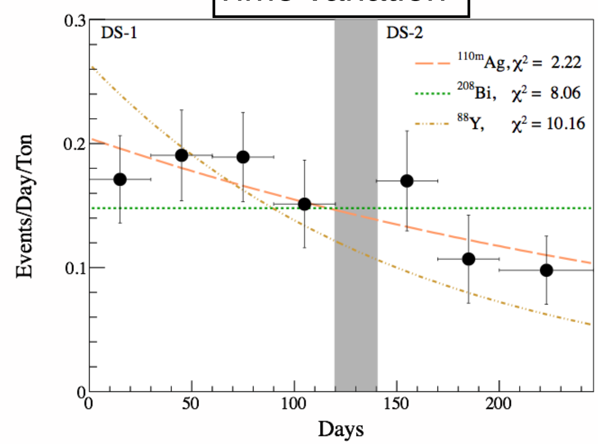
- Most stringent limit at that time.
- But many background at ROI. It is ^{110m}Ag (Q value of ^{136}Xe : 2.458 MeV)

Event in 2.2<E<3.0 MeV

Energy spectrum (linear, known BG subtracted)

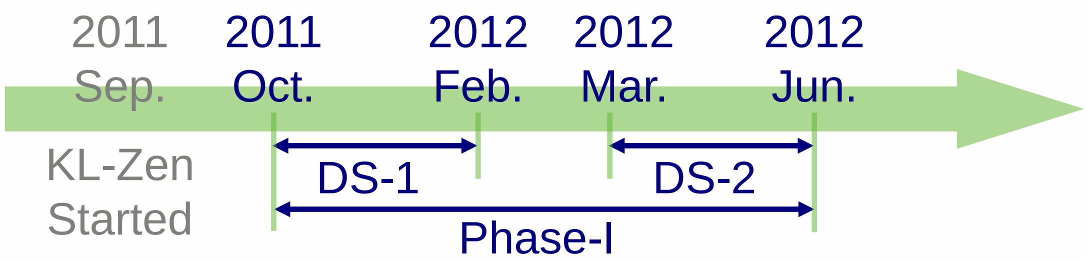


Time variation



Unexpected peak → ^{110m}Ag

History



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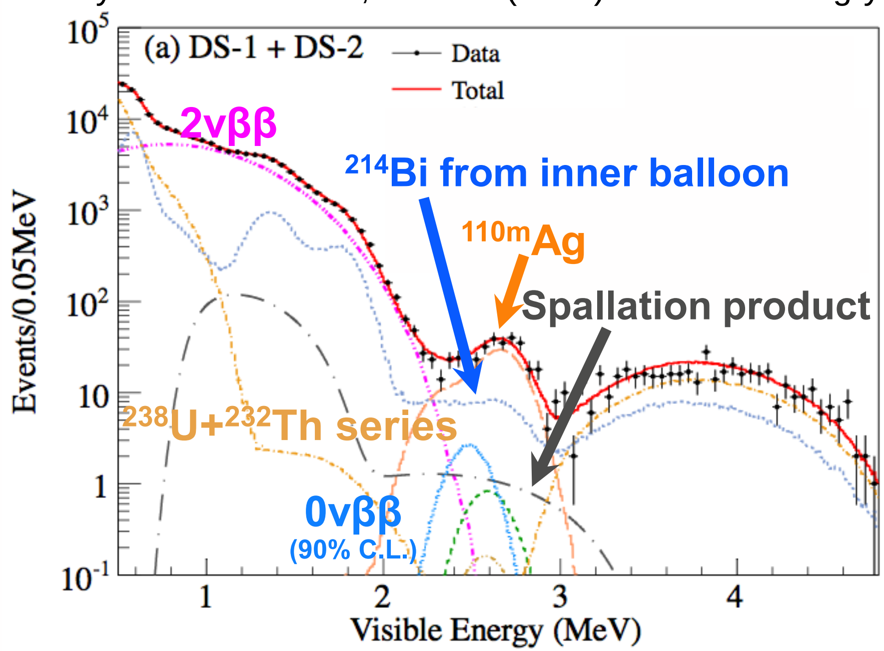


Backgrounds in 0νββ region:

(1)Unexpected peak around 2.6MeV

→ All nuclei were checked. 4 possible isotopes (lifetime longer than 30 days)

^{110m}Ag (250d), ^{208}Bi (3.7×10^{5}y), ^{60}Co (5.27y), ^{88}Y (107d)

(2) ^{214}Bi from inner balloon

(3) Spallation product ^{10}C

(4) ^{136}Xe 2νββ decay

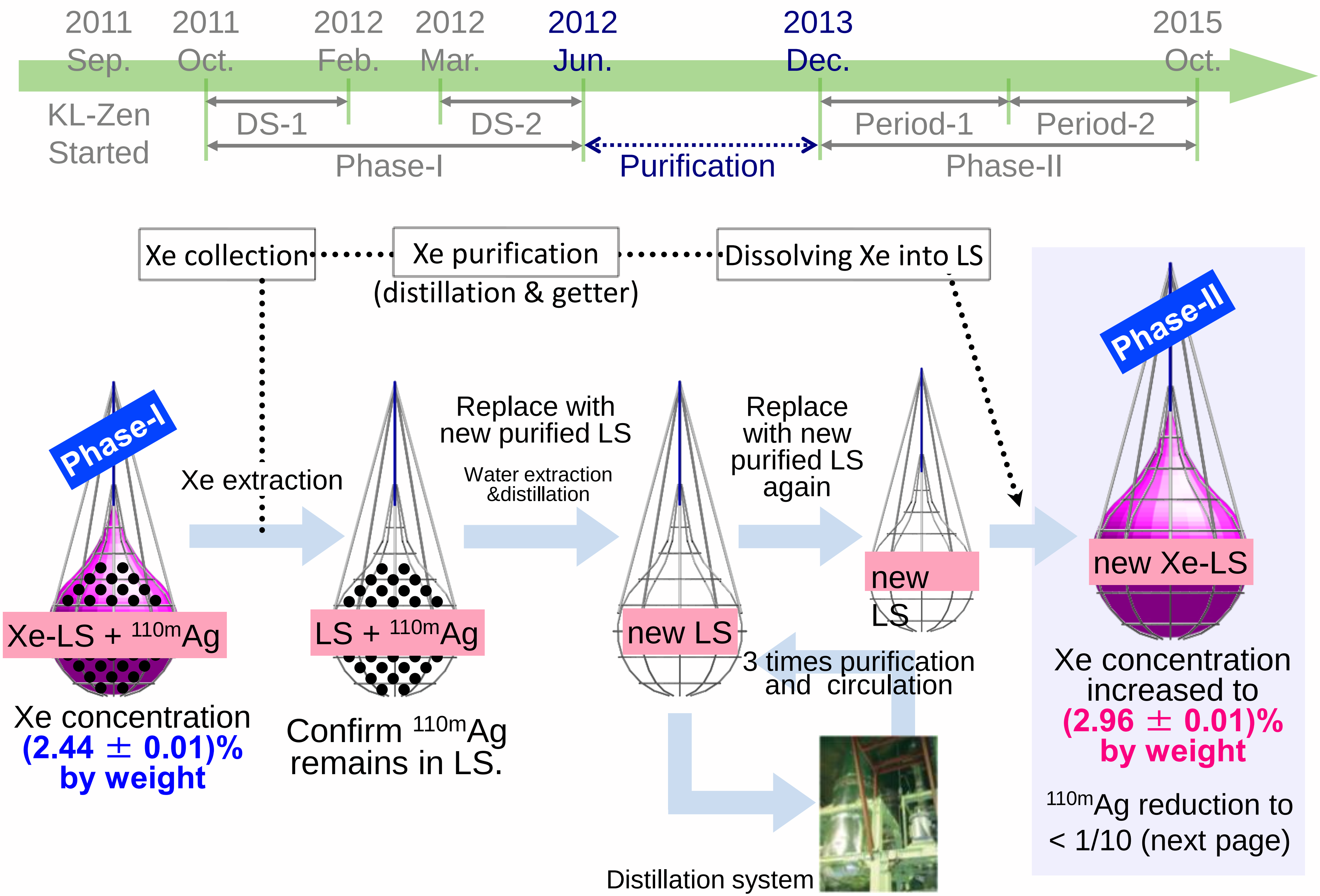
Large amount ↕ **Small amount**

Lower limit of 0νββ decay half-life

$$T^{1/2} > 1.9\times10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- Most stringent limit at that time.
- But many background at ROI. It is ^{110m}Ag (Q value of ^{136}Xe : 2.458 MeV)

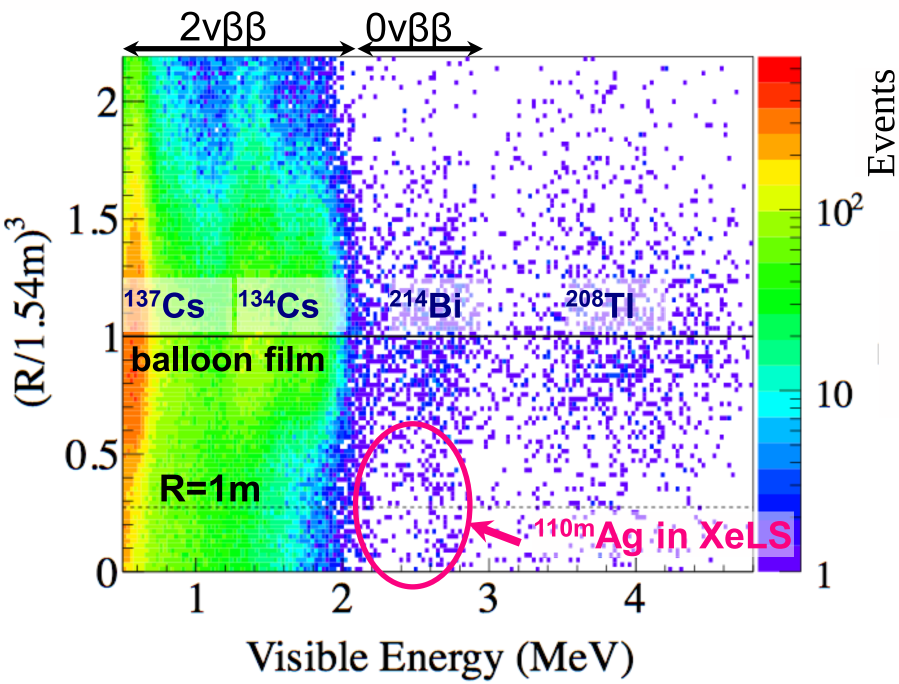
History



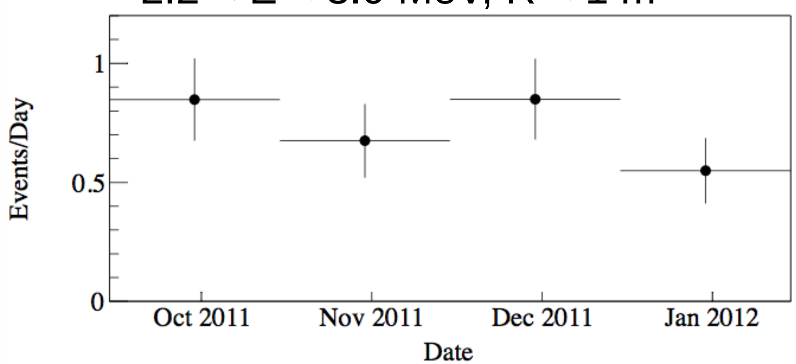
2011 Sep.
2011 Oct.
2012 Feb.
2012 Mar.
2012 Jun.
2013 Dec.
2015 Oct.
KL-Zen Started
DS-1
DS-2
Phase-I
Purification
Period-1
Period-2
Phase-II
Xe collection
Xe purification
(distillation & getter)
Dissolving Xe into LS
Phase-I
Xe extraction
Replace with new purified LS
Water extraction &distillation
Replace with new purified LS again
Phase-II
Xe-LS + ^{110m}Ag
LS + ^{110m}Ag
new LS
new LS
new Xe-LS
3 times purification and circulation
Xe concentration (2.44 ± 0.01)% by weight
Confirm ^{110m}Ag remains in LS.
Distillation system
Xe concentration increased to (2.96 ± 0.01)% by weight
^{110m}Ag reduction to < 1/10 (next page)

^{110m}Ag background reduction

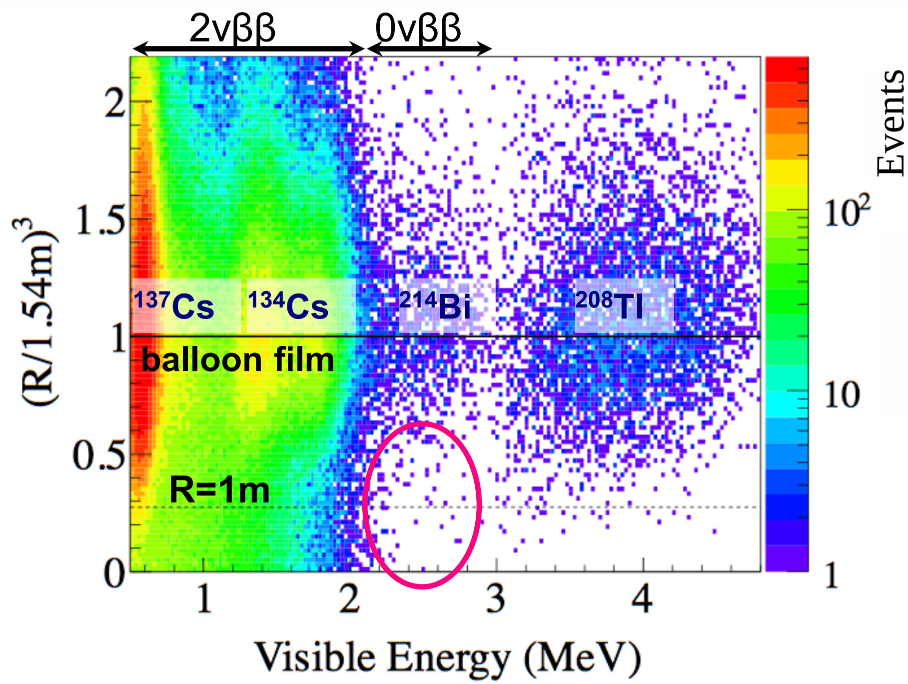
Phase-I (first 112.3 days)



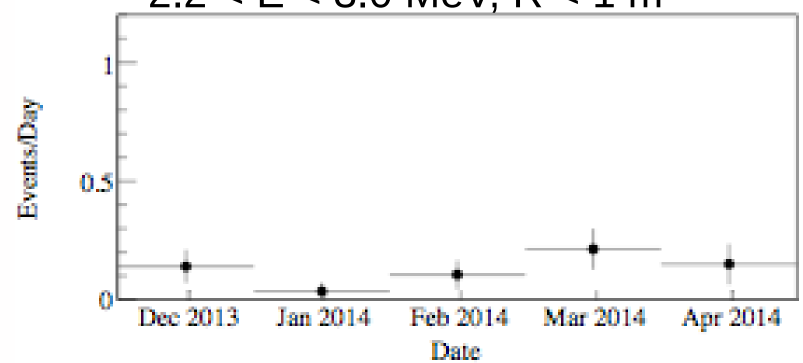
2.2 < E < 3.0 MeV, R < 1 m



Phase-II (first 114.8 days)



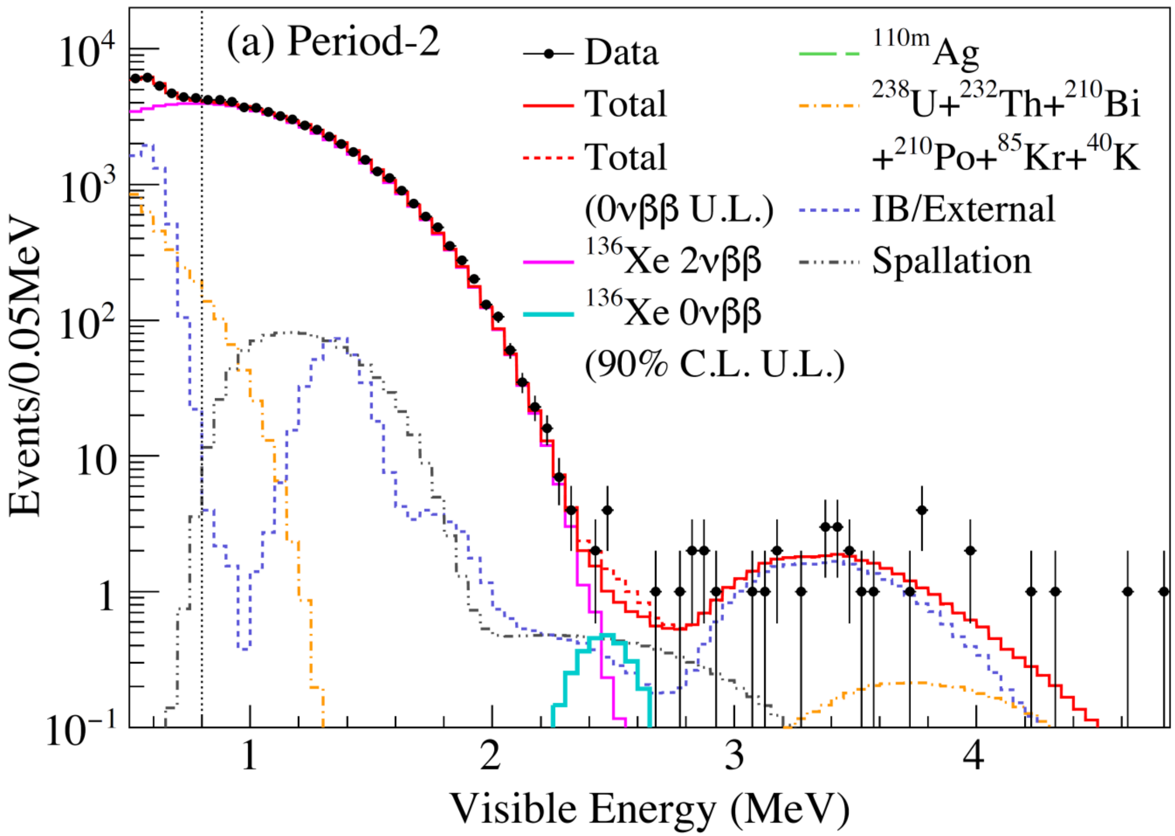
2.2 < E < 3.0 MeV, R < 1 m



^{110m}Ag BG reduction to < 1/10

Result of 2νββ decay

Phase-II, R<1m fiducial volume



Systematic uncertainty (%)	
Fiducial volume	3.0
Xenon mass	0.8
Detector energy scale	0.3
Efficiency	0.2
^{136}Xe enrichment	0.09
Total	3.1

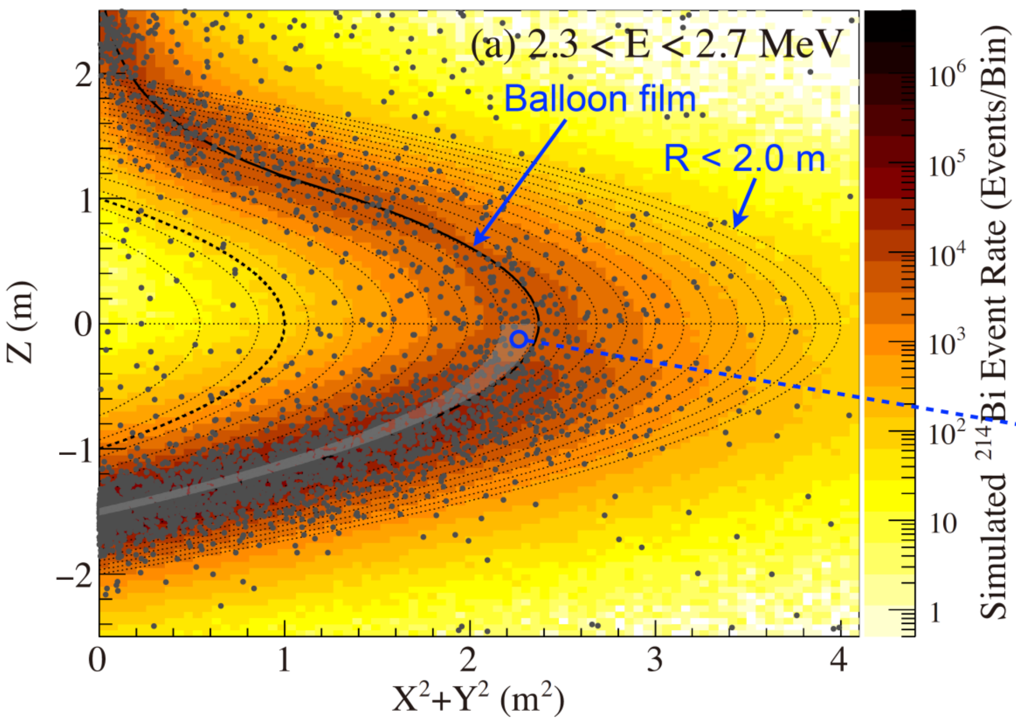
$T^{1/2}(2\nu) = 2.21 \pm 0.02(\text{stat}) \pm 0.07(\text{syst}) \times 10^{21}$ yr

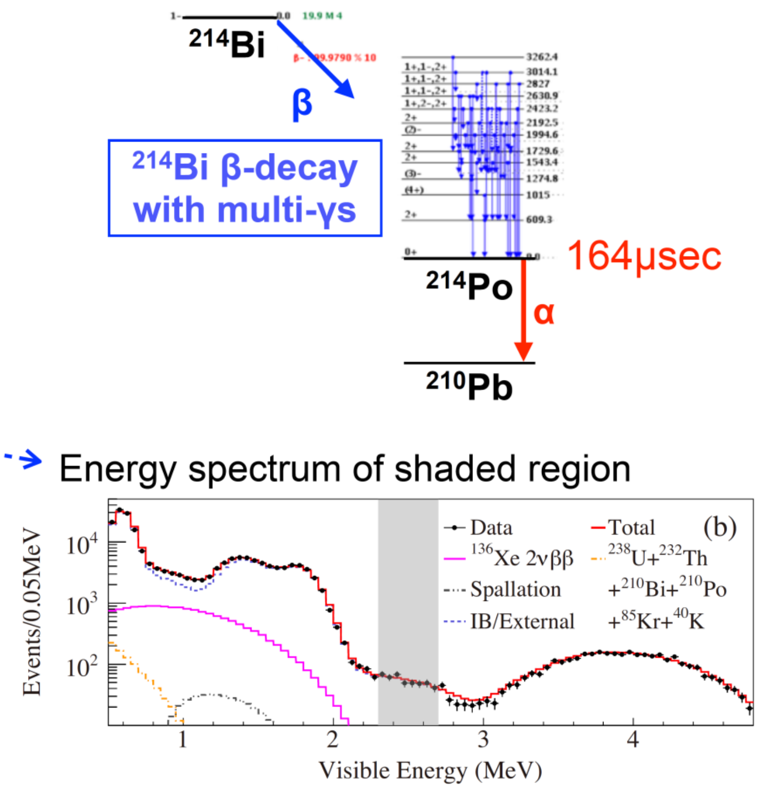
- Total ^{136}Xe exposure = 126 kg yr
- Consistent with previous KamLAND-Zen results and EXO-200 results

Fiducial volume selection for 0νββ analysis

Distribution of ^{214}Bi background from IB film is asymmetry.
Larger background at the bottom → Effected to fiducial volume selection.

Data (black dots) & ^{214}Bi sim (color)





Multi-volume selection for analysis optimization

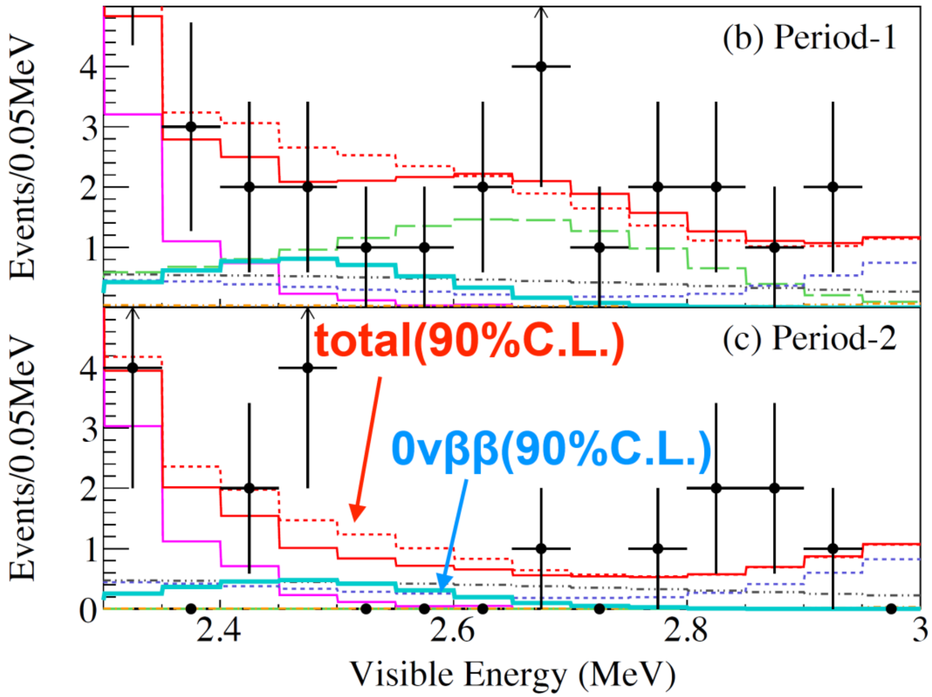
Target volume for spectral fit : R < 2.0 m

lower / upper hemisphere

R 20bin (same volume in each radius bin)× Theta 2bin (-1<cosθ<0, 0<cosθ<1)

Result of 0νββ decay

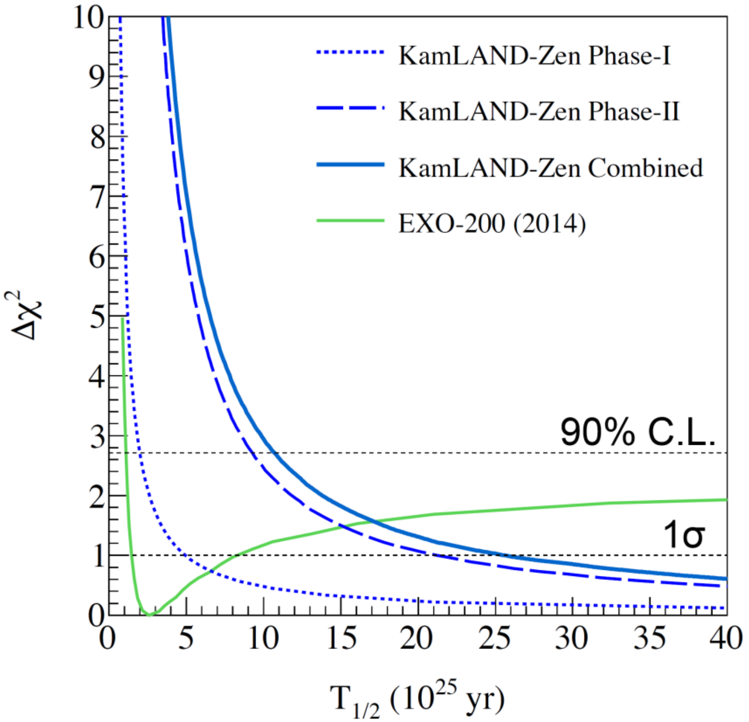
Energy spectrum
$2.3 < E < 3.0$ MeV, $R < 1.0$ m



0nu limit of Phase-2 (90%C.L.)

Period-1: < 3.4 events/day/kton-LS
Period-2: < 5.5 events/day/kton-LS
→ combined: < 2.4 events/day/kton-LS

$T^{1/2} > 9.2\times10^{25}$ yr (90% C.L.)



Combined result

$T^{1/2} > 1.07\times10^{26}$ yr (90% C.L.)

Phase-1: $T^{1/2} > 1.9\times10^{25}$ yr
Phase-2: $T^{1/2} > 9.2\times10^{25}$ yr

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

It reaches below 100 meV!

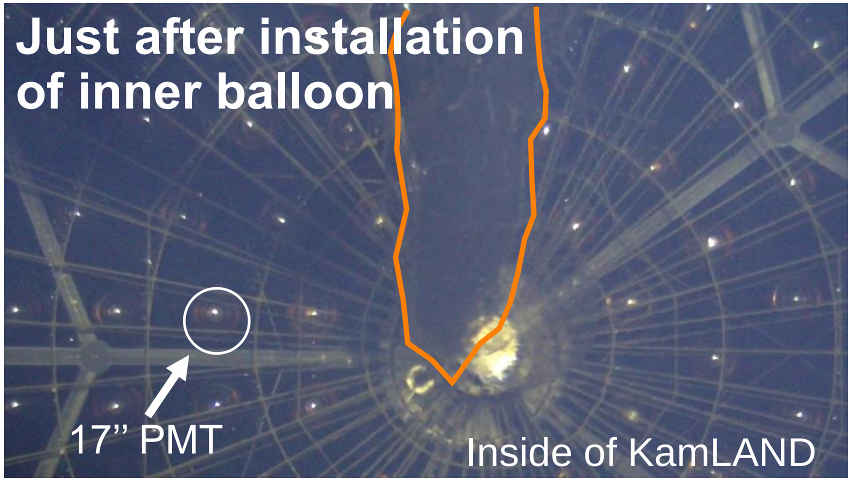
Current status

KamLAND-Zen 800 in preparation

750 kg of Xenon

-New clean inner balloon (radius 1.54 m → 1.92 m) installed in KamLAND.

-Expected sensitivity is below 50 meV.

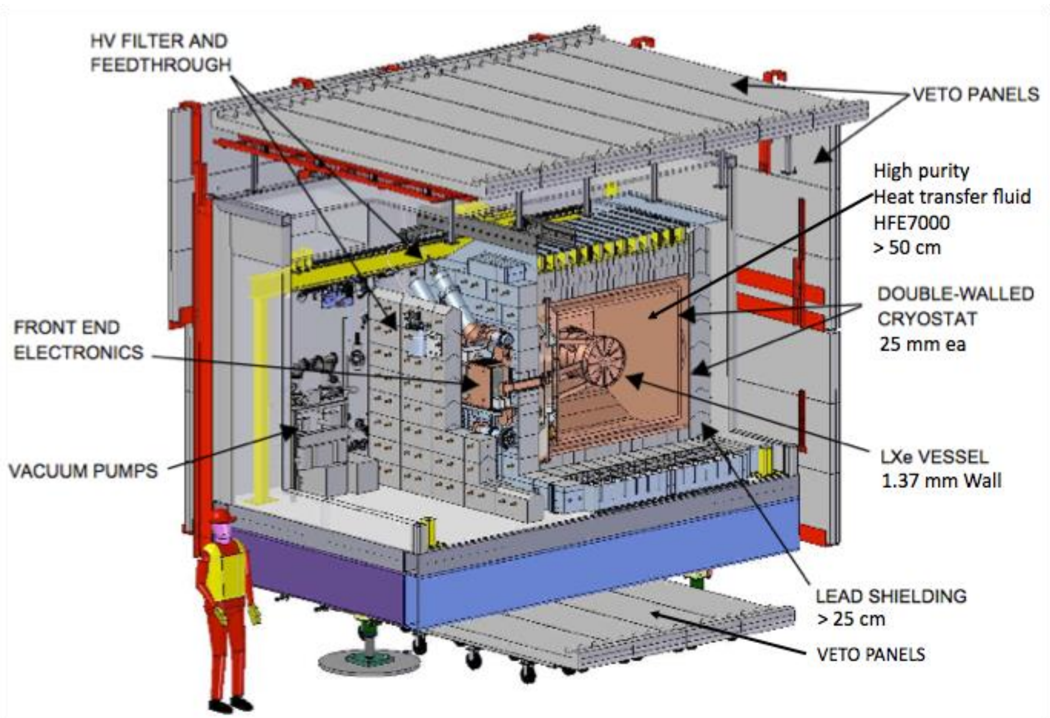


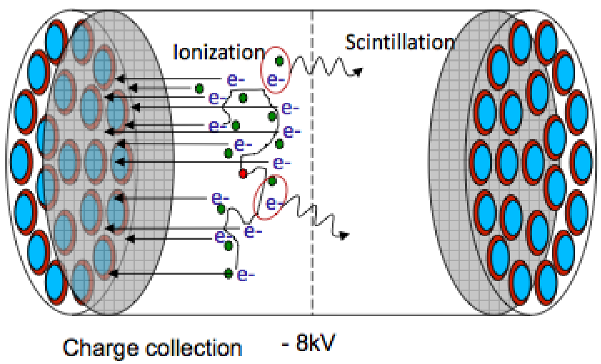
EXO Experiment

Pictures from slides in Neutrino2016

EXO Detector

- Located at WIPP (U.S.), ~ 1600 m.w.e.
- 80.6% enriched liquid Xe in TPC
- Operation started in 2011
- $T^{0\nu}_{1/2} > 1.1\times10^{25}$ yr (90% C.L.) with 100 kg·yr of ^{136}Xe exposure

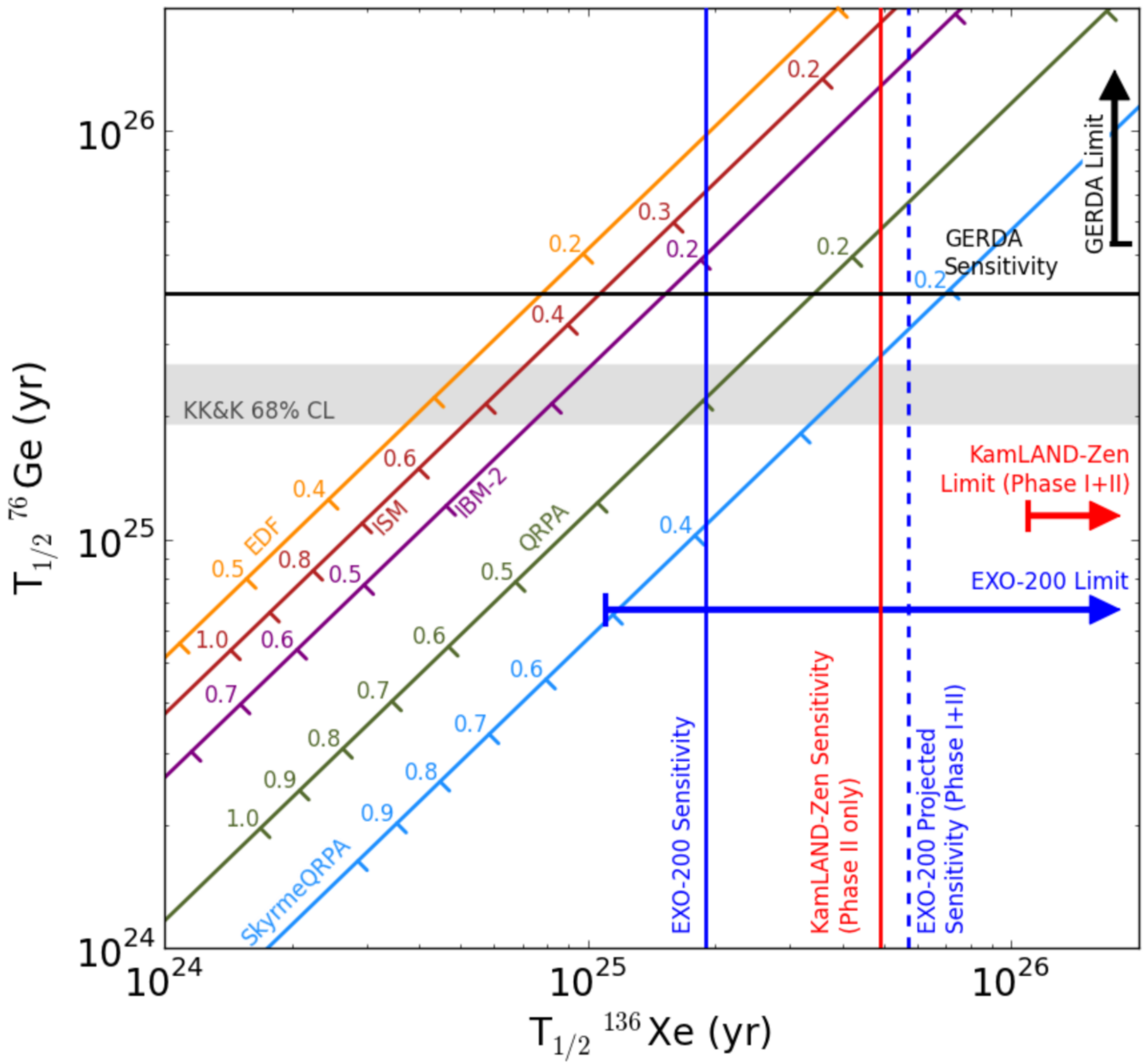




Example of TPC schematics (EXO-200)

- Simultaneous collection of both ionization and scintillation signals.
  - Scintillation viewed by APDs
  - Charge collected by 2 wire grids
- Full 3-D reconstruction
- Excellent background rejection capabilities (Single/Multi-site events)

EXO-200 Sensitivity



EXO-200 can reach $0\nu\beta\beta$ **half-life sensitivity of** 5.7×10^{25} **ys.**

With lower threshold, EXO-200 can improve measurement of ^{136}**Xe** $2\nu\beta\beta$ **and searches in other physics channels.**

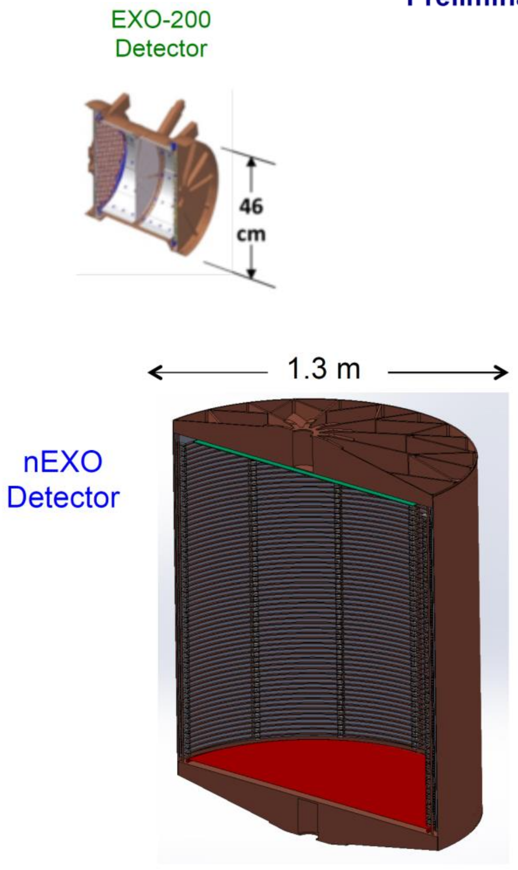
EXO-200:
Nature (2014),
doi:10.1038/nature13432

GERDA Phase 2:
Public released result. June, 2016
(frequentist limit)

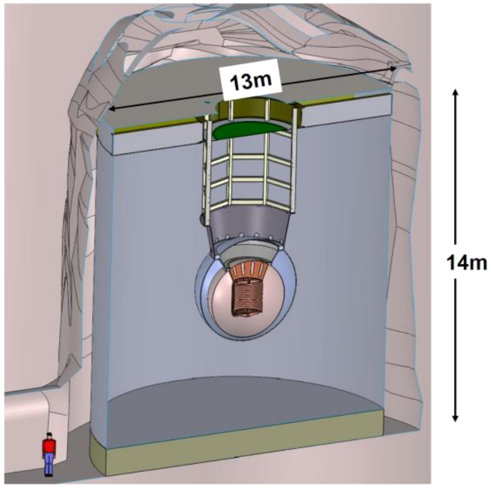
KamLAND-Zen:
arXiv:1605.02889 (2016)

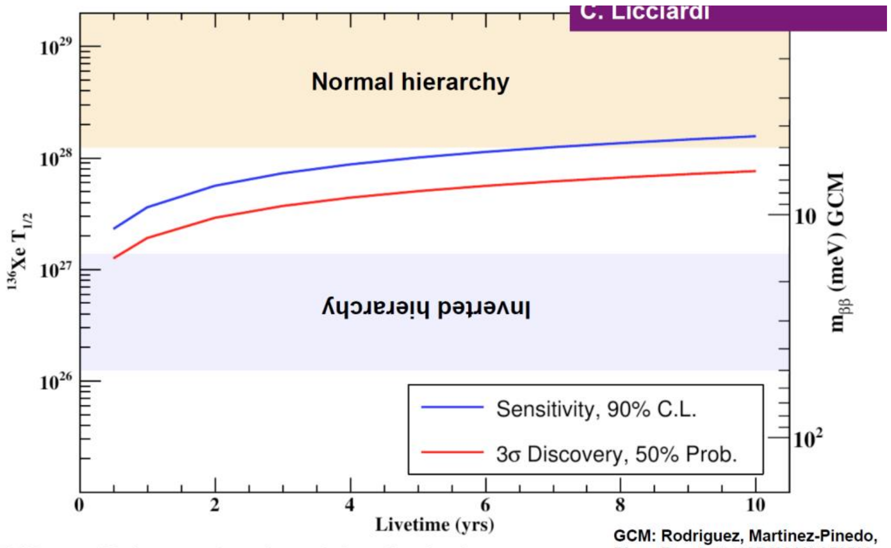
From EXO-200 to nEXO

- EXO-200 has surpassed design energy resolution and SS/MS rejection capability, and is expected to surpassed the design background goals.
- nEXO is a proposed ~ 5 tonne detector.
- 4.7 tons of active $^{enr.}Xe$ (90% or higher), < 1.0% (σ/E) energy resolution.
- Its design can reach $0\nu\beta\beta$ half-life sensitivity of ~ 10^{28} yrs



Preliminary artist view of nEXO in the SNOlab Cryopit





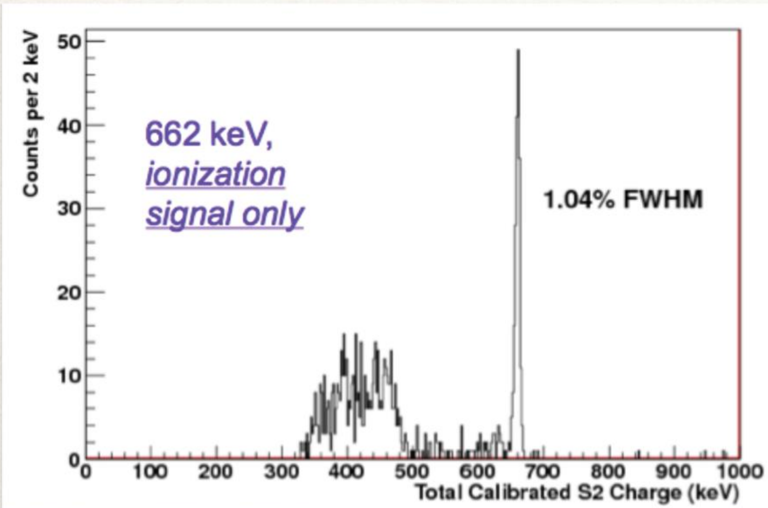
nEXO sensitivity as a function of time for the best-case nuclear matrix element (GCM).

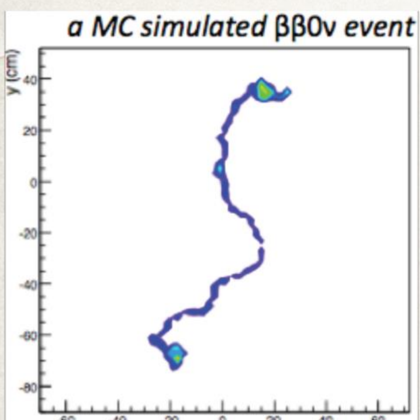
GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

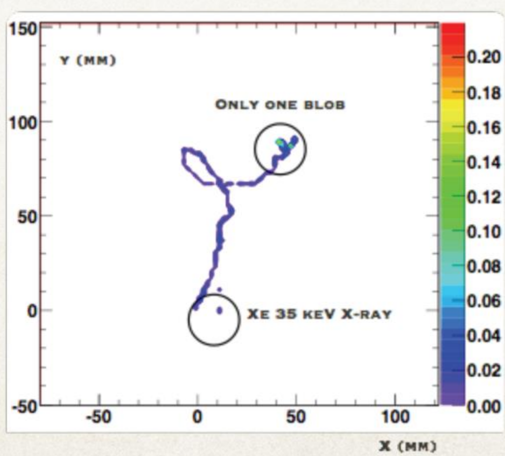
NEXT Experiment

All slides from Francesc Monrabal

NEXT: Salient features

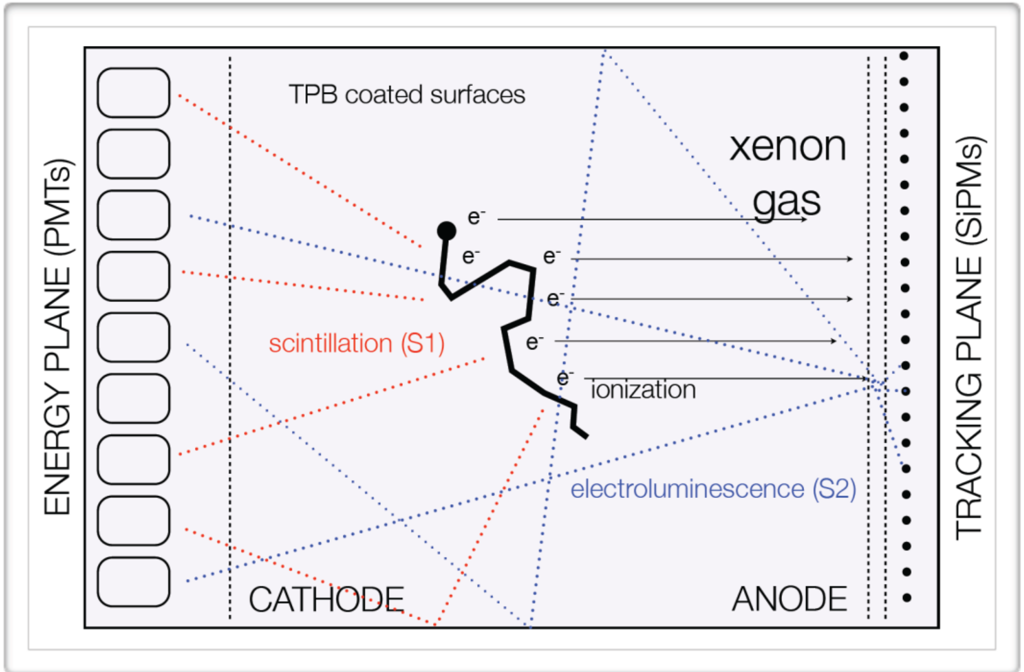






- Excellent resolution: 1% FWHM measured at 662 keV by NEXT prototypes, extrapolates to 0.5 % FWHM at Qbb.
- Topological signature (TPS), e.g. the ability to distinguish between signal ("double electrons") and background ("single electrons").
- Target = source. Fiducial region away from surfaces.
- Detector = Monolithic active mass.
- TPC: scalable. Economy of scale (S/N increases linearly with L)
- Xenon: the cheapest isotope to enrich in the market (NEXT owns 100 kg of enriched xenon).

NEXT: A light TPC



EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with Xenon enriched at 90% in Xe-136 (100 kg in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t_0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

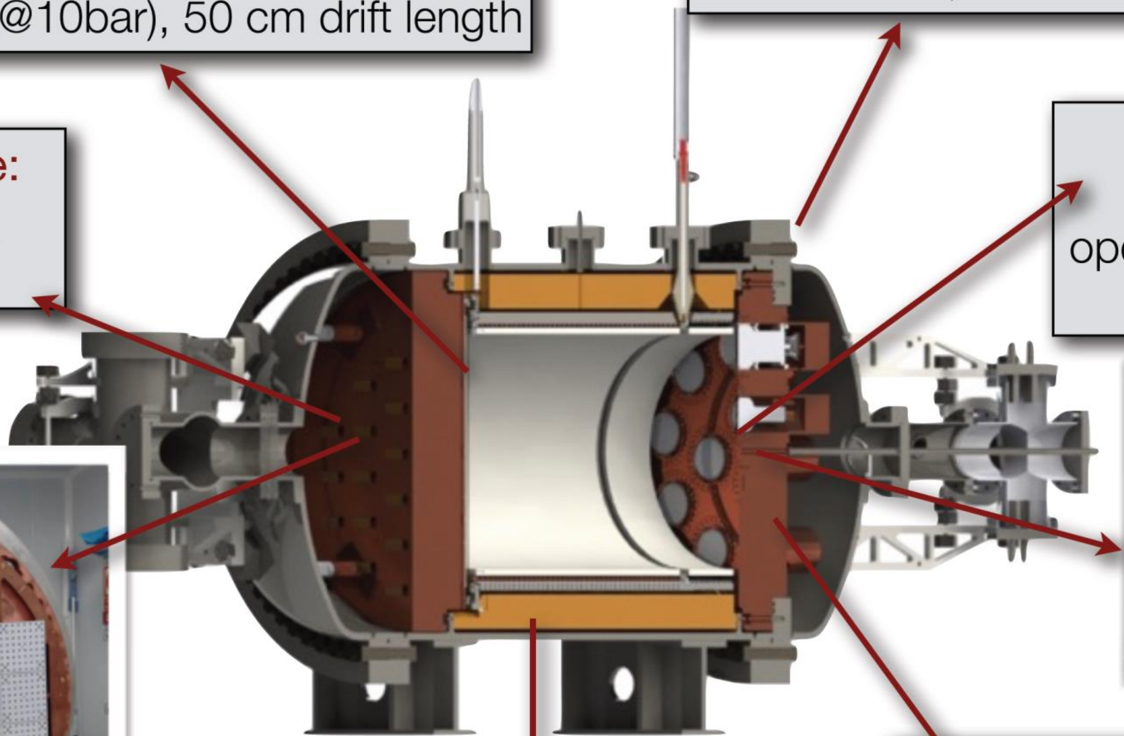
NEW (NEXT-WHITE) Running in 2016

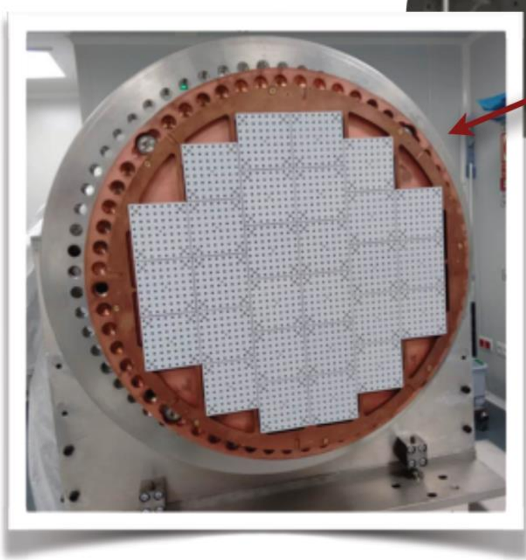
Time Projection Chamber:
10 kg active region(@10bar), 50 cm drift length

Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch

Energy plane:
12 PMTs,
operating at vacuum.
30% coverage

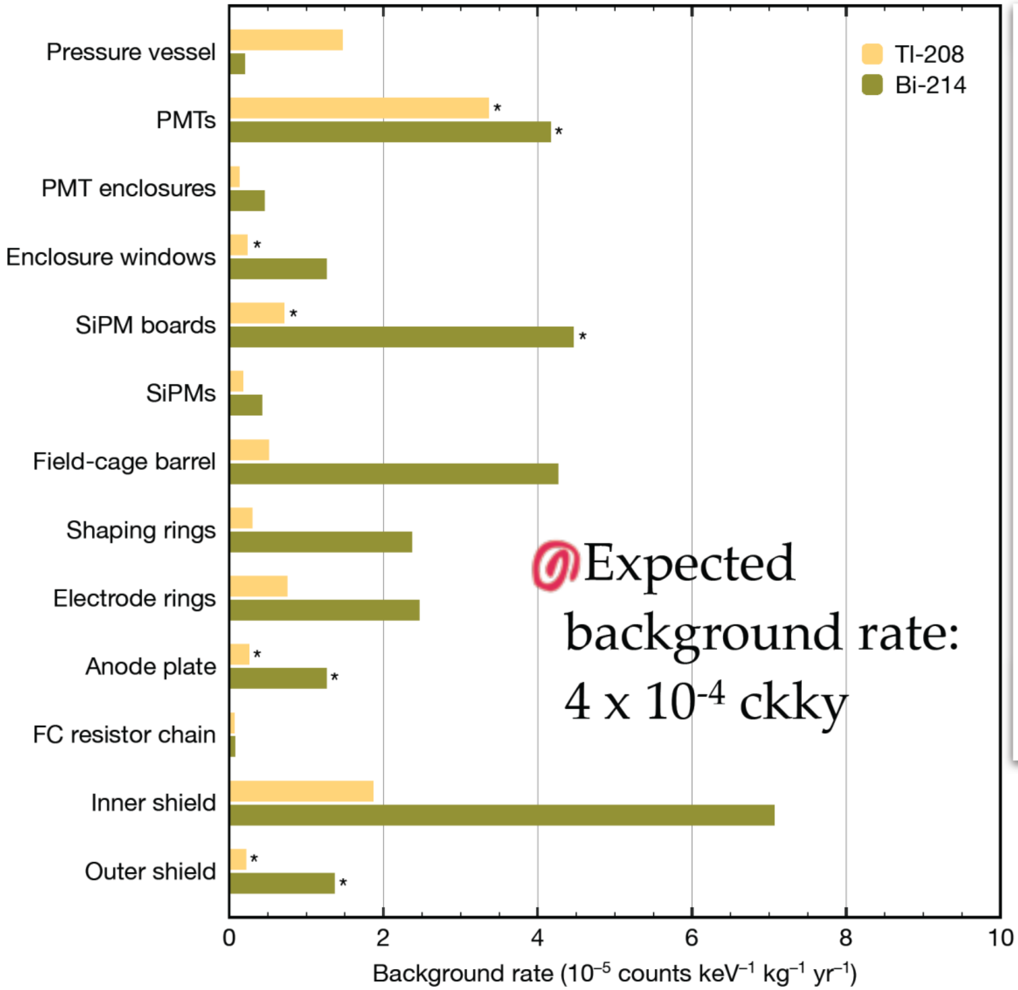




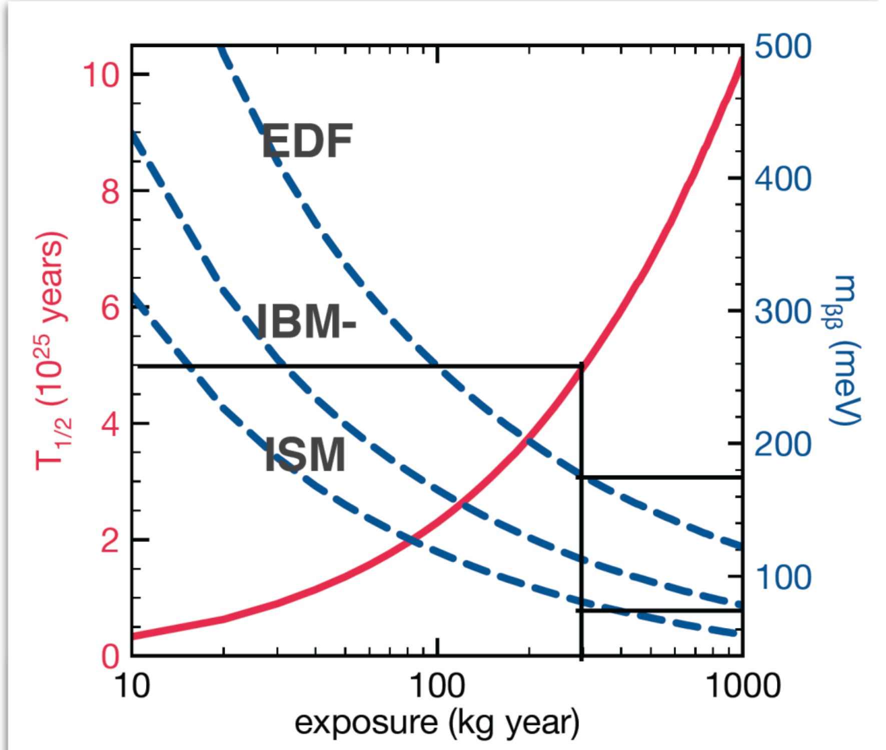
Mother can:
12 cm copper plate that separates pressure from vacuum and ads shielding.

Inner shield:
copper, 6 cm thick

Background and sensitivity



- Expected background rate: 4×10^{-4} ckky



- Expect 5×10^{25} y in 3 years run (2018-2020).
- mbb ~[90-180] meV depending on NME

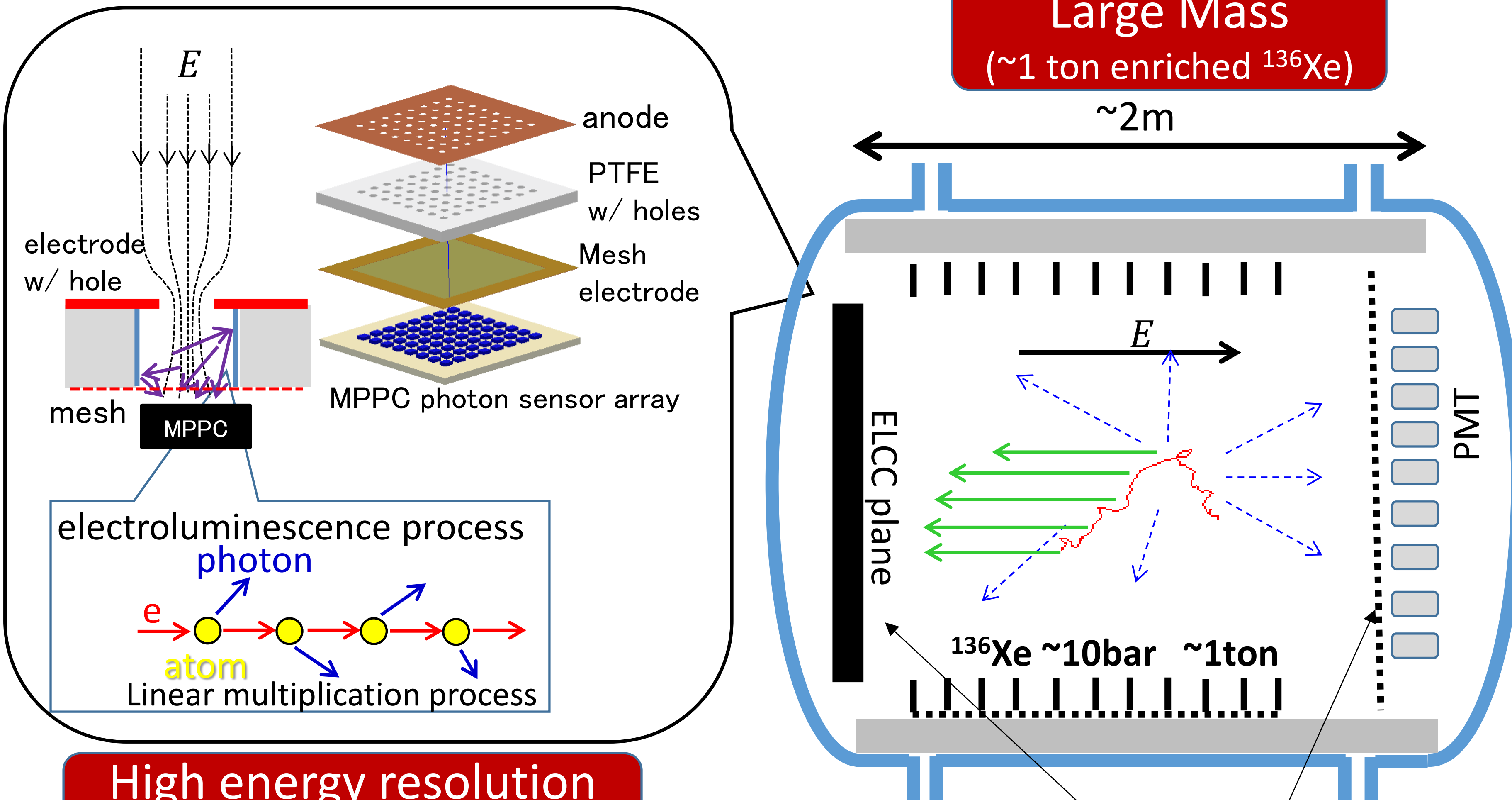
https://inspirehep.net/record/1407146

AXEL Experiment

All slides from Atsuko Ichikawa

- Developed in Kyoto U.

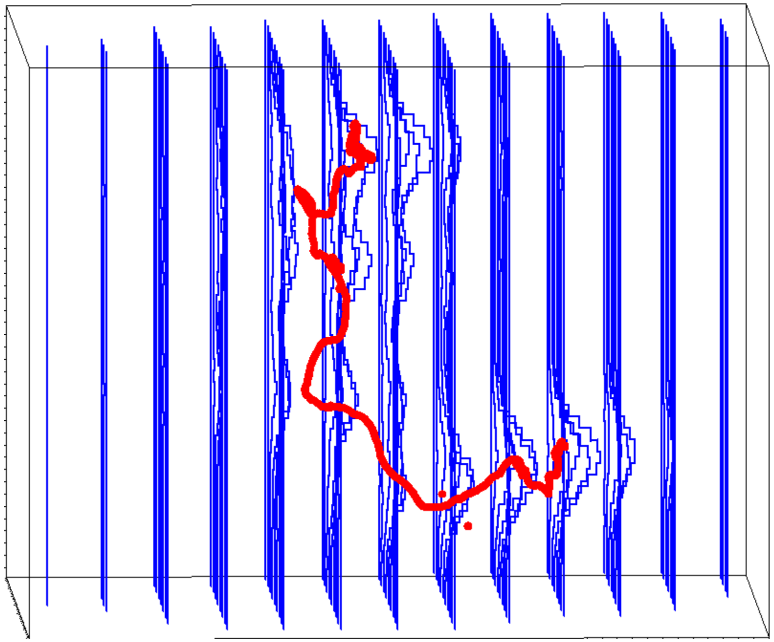
AXEL –A Xenon ElectroLuminescence detector to search for neutrinoless double-beta decay -



Large Mass
(~1 ton enriched ^{136}Xe)

High energy resolution
(goal: <0.5%(FWHM))

Background rejection by event topology

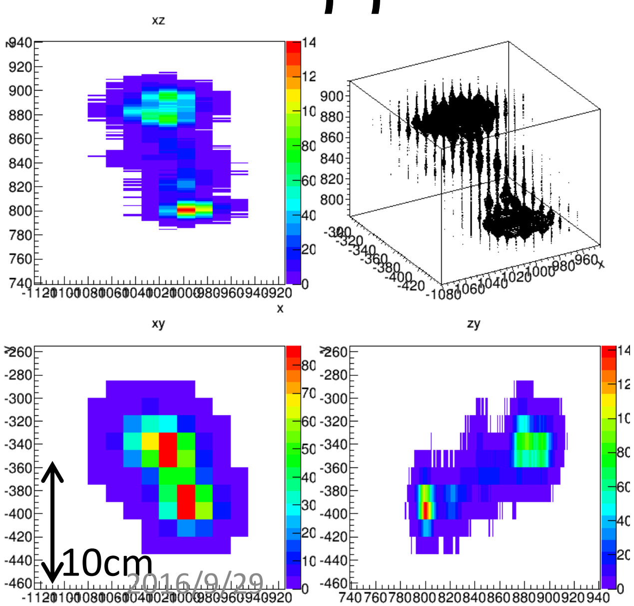


AXEL

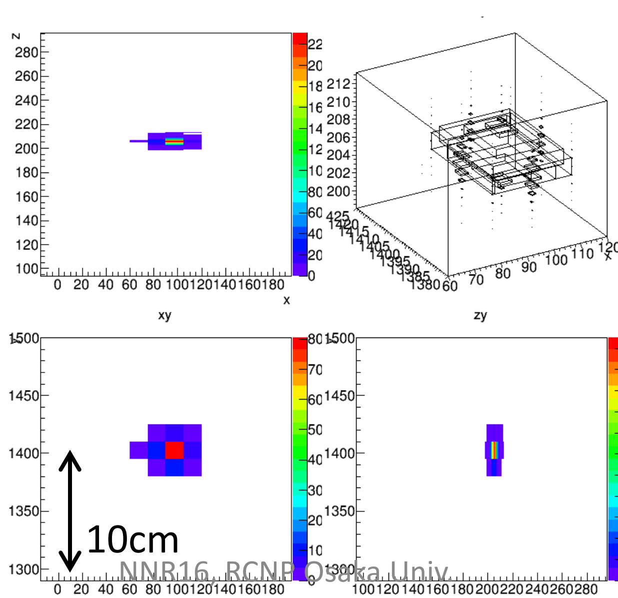
-Expected event topologies-

simulation

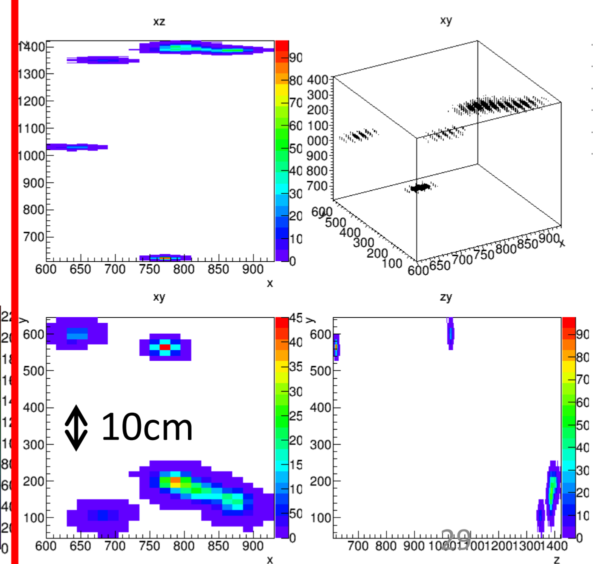
0νββ



α

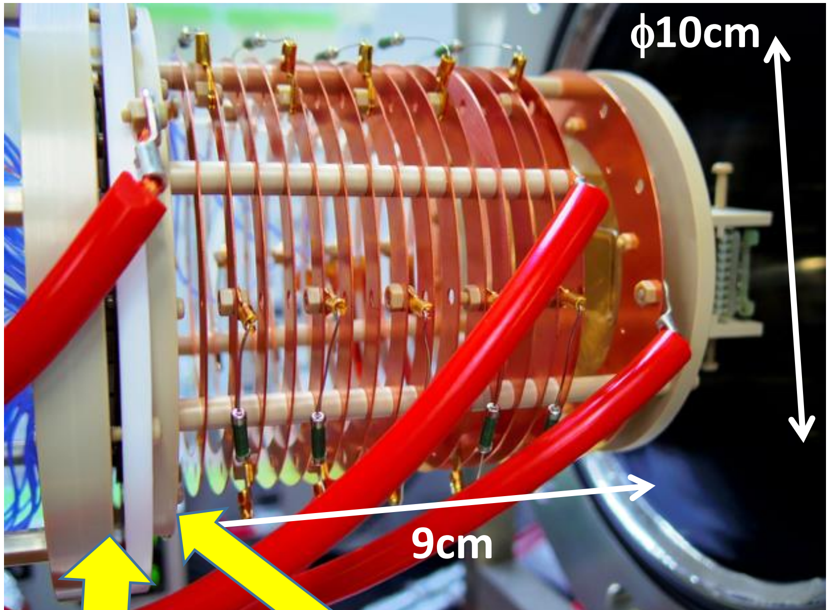


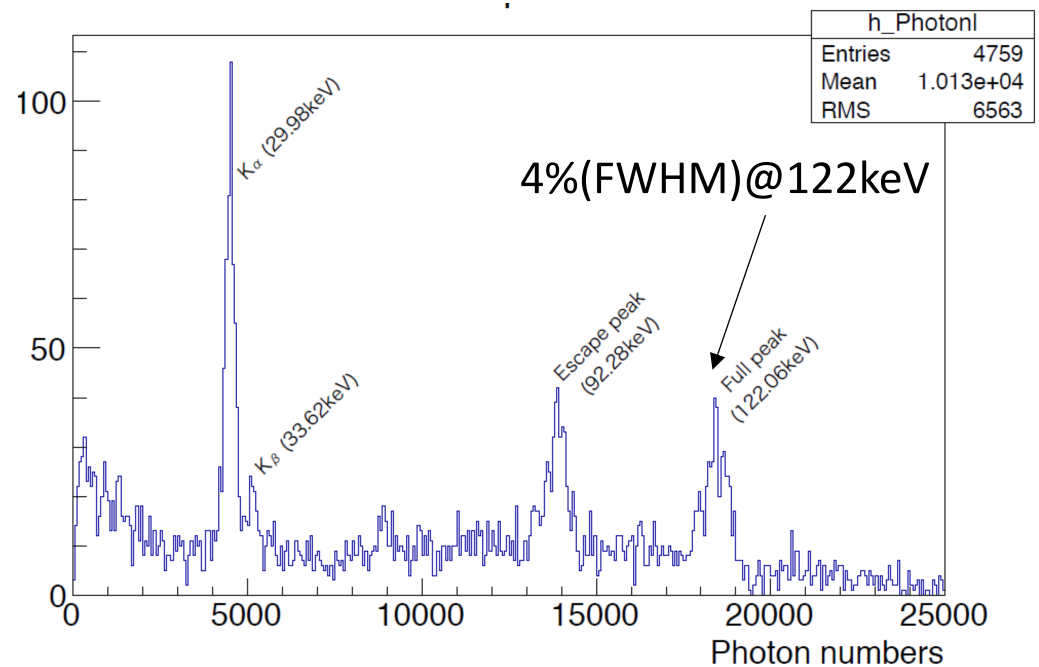
γ

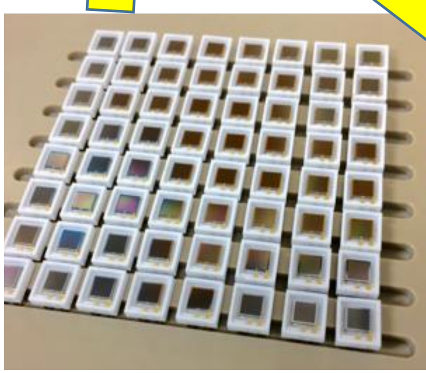


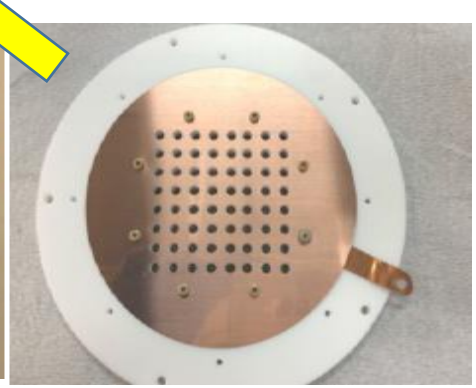
AXEL -Prototype Detector-

10L prototype









Next prototype in 2016~2017

- ~120L (7.5kg)
- ~1,600ch
- demonstration at ~Q-value(2.5MeV)

64ch VUV-sensitive MPPC

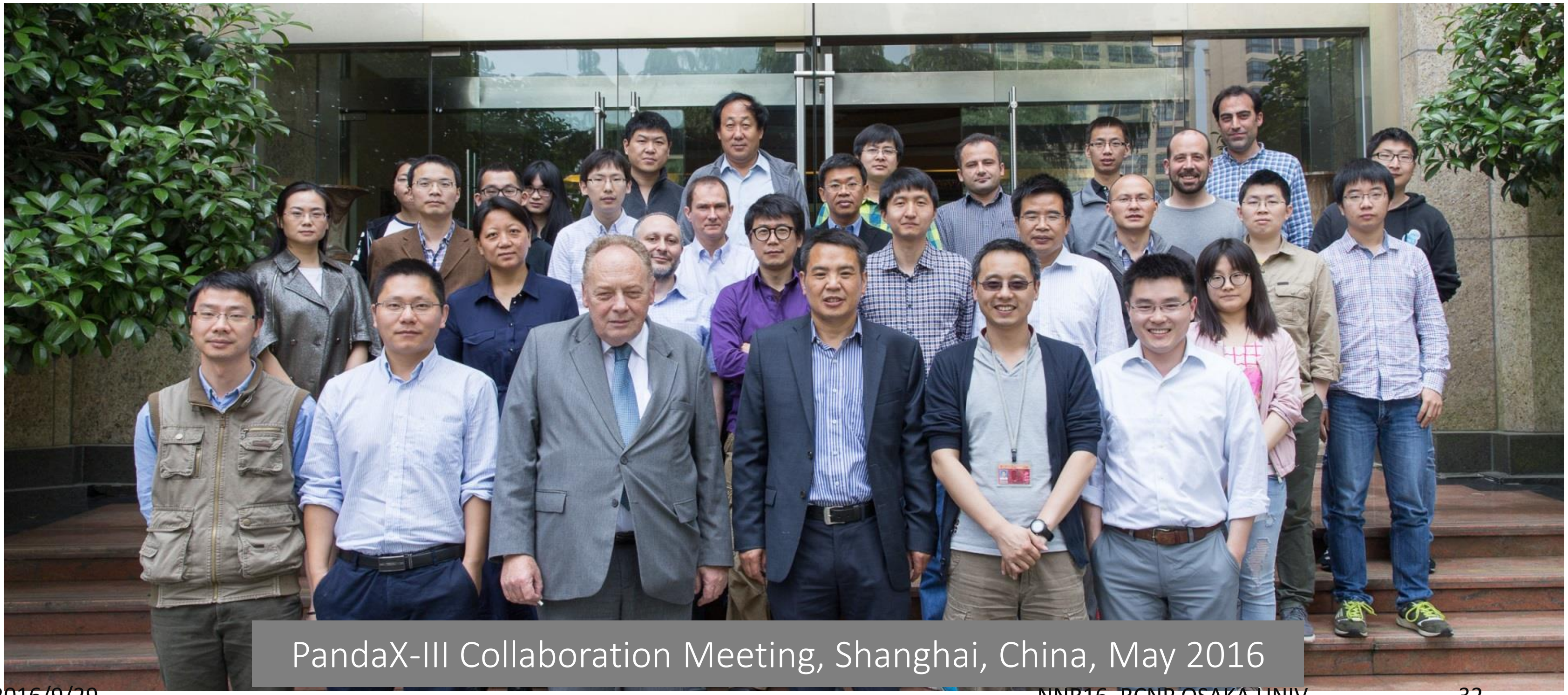
PandaX III Experiment

All slides from Ke Han

- Initial phase of PandaX experiment to search for cosmic dark matter using Xe TPC
- The detector is installed in JinPing underground

Collaboration

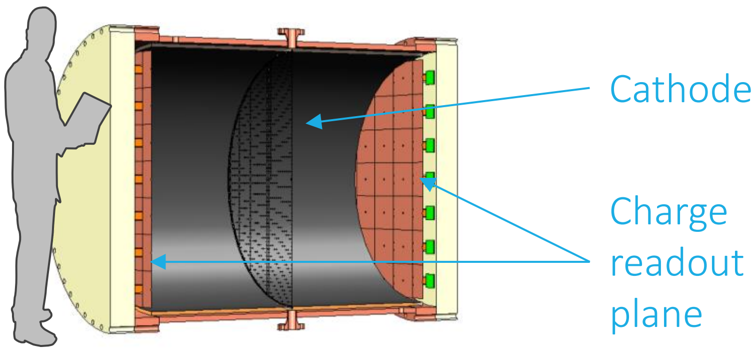
- China: Shanghai Jiao Tong University, University of Science and Technology of China, Peking University, China Institute of Atomic Energy, Shandong University, Sun Yat-Sen University, Central China Normal University
- Spain: Universidad de Zaragoza
- France: CEA Saclay
- US: University of Maryland, Lawrence Berkeley National Laboratory
- Thailand: Suranaree University of Technology



PandaX-III Collaboration Meeting, Shanghai, China, May 2016

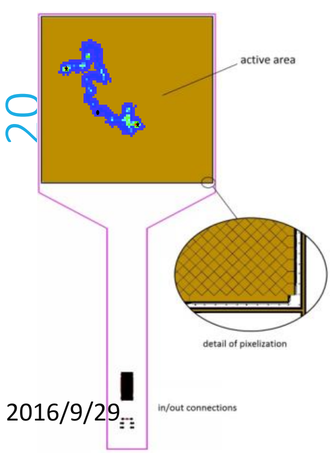
PandaX-III: high pressure gas TPC for neutrinoless double beta decay of ^{136}Xe

TPC: 200 kg scale, symmetric, double-ended charge readout with cathode in the middle

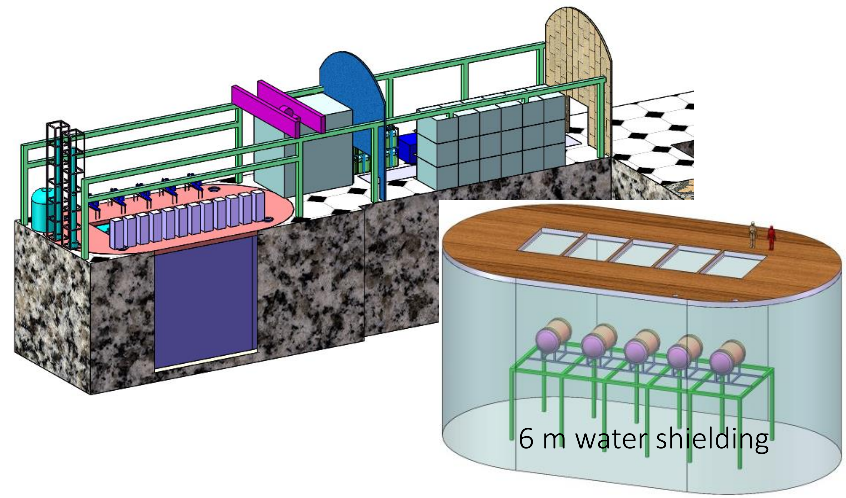


Charge readout plane: tiles of square Microbulk Micromegas (MM) modules with X, Y strips

- 3% energy FWHM and topological info from MM



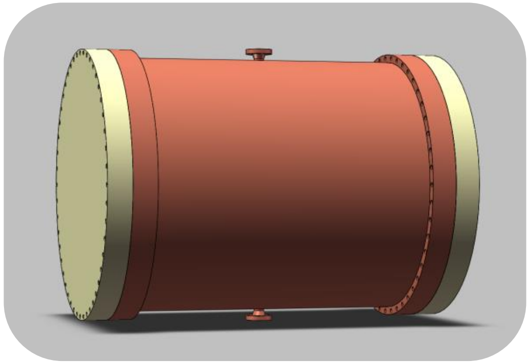
PandaX-III will be located at Hall #B4 at China Jin Ping underground Laboratory (CJPL-II).



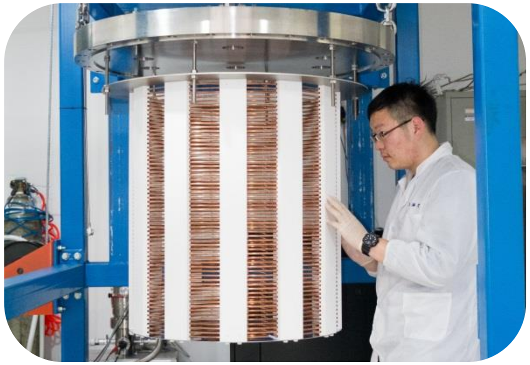
- 150 kg enriched ^{136}Xe purchased
- Prototype TPC commissioned at SJTU
- First TPC will be deployed in 2017 at CJPL
- Expected half-life sensitivity at 10^{26} year (90% CL) with background rate of 10^{-4} c/keV/kg/yr in the ROI
- Four more upgraded TPC modules for a ton scale experiment

Status

150 kg of 90% enriched ^{136}Xe purchased

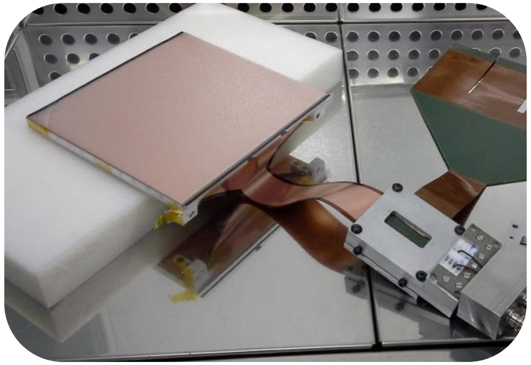


High pressure vessel made of OFHC copper designed



20 kg scale prototype TPC made and taking data with MicroMegas

Front end electronics are being designed and tested

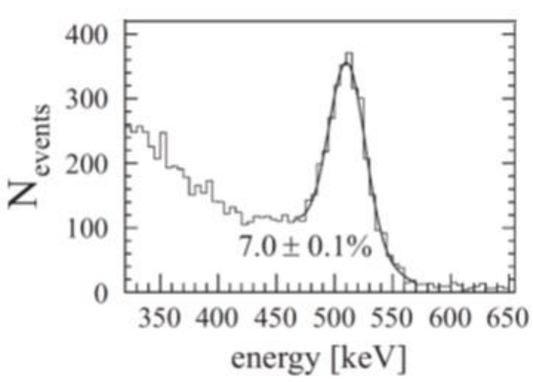


First batch of 20 cm square MicroMegas modules made and commissioned

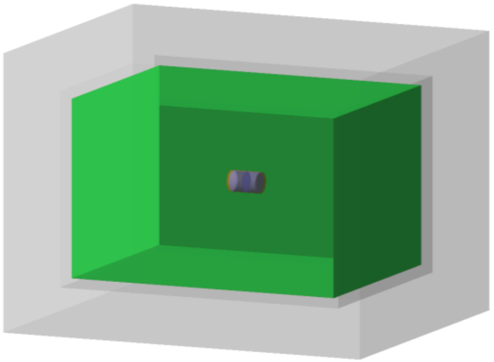
Excavation of water pit finished. Finalizing the layout of Hall B4 at CJPL-II

Sensitivity

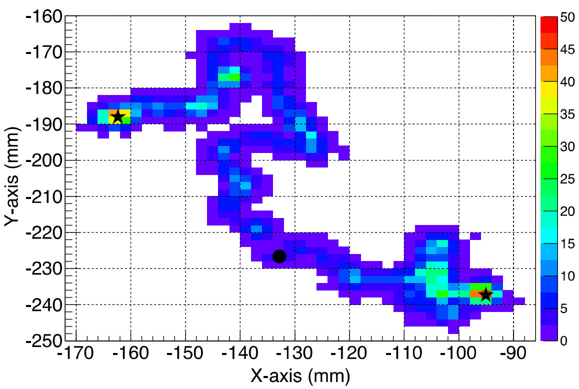
- Expected ^{136}Xe $0\nu\beta\beta$ half-life sensitivity (90% CL) reaches 10^{26} year after 3 years of live time
  - 3% FWHM energy resolution at Q-value
  - 35% $0\nu\beta\beta$ signal efficiency
  - 6 m of ultra-pure water shielding of all directions.
  - Baseline background rate 10^{-4} c/keV/kg/y at ROI, achieved with carefully material screening as well as energy and topological cuts.



Measured energy resolution at 7% at 511 keV. 3% at 2.5 MeV from extrapolation



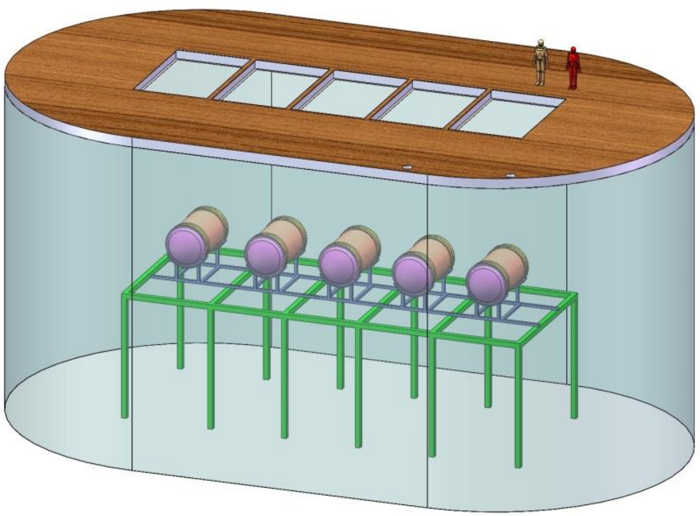
Water shielding and underground lab environment in simulation



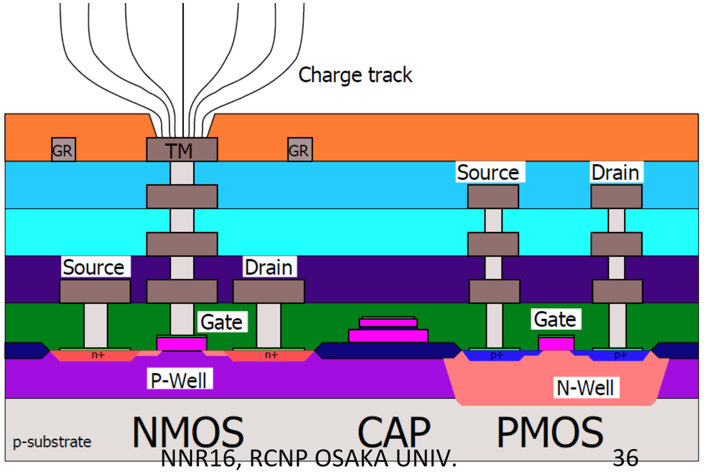
Simulated $0\nu\beta\beta$ event in high pressure Xe+TMA gas mixture, readout with MicroMegas

Future Plans

- Additional modules with upgraded options will be installed in the same water shielding pit.
  - 1% energy resolution to approach the intrinsic resolution of high pressure xenon gas with TMA
  - Better material screening
- Reaches ton-scale in 2022.



- Alternative vessel for even better background rate
  - Thinner Cu vessel with pressurized shield
  - Composite design with carbon fiber/Kevlar with copper to balance vessel mechanical strength and mass.
- TopMetal Direct Charge Sensor
  - Direct pixel readout without gas amplification
  - Low electronics noise to reach 1% energy resolution at ROI



CANDLES
@Kamioka Observatory

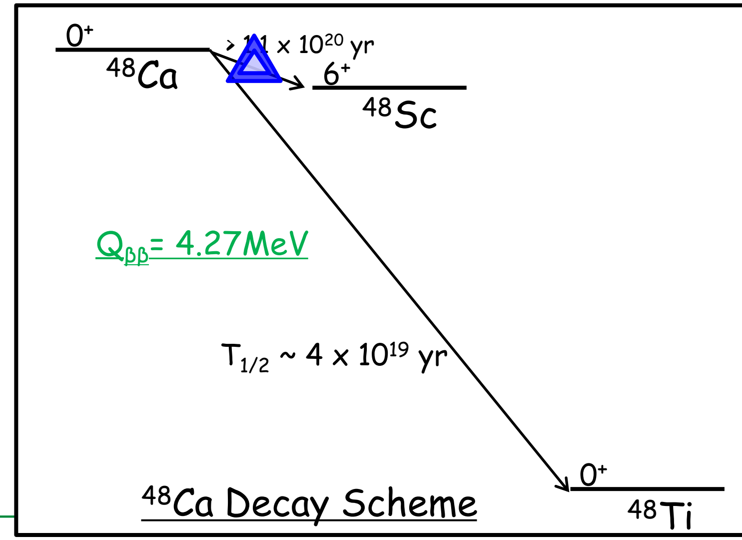
- **CANDLES is the project to search for 0νββ decay of ^{48}Ca.**
- **Detector (CANDLES-III)**
  - Main detector : CaF_2 scintillators(~300kg)
  - Liquid Scintillator : Active Veto (~ 2.1 m^3/1.7 tons)
  - PMTs : 13inch x 48 & 20inch x 14
  - Installed in $3m^{\phi} \times 4m^{h}$ (Water tank)
- **Site: Kamioka** (~1000 m depth)

^{48}Ca for ββ Isotope

- ^{48}Ca isotope
  - Highest Q-value (4.27MeV)
    - ➔ Large phase space factor
    - ➔ Low background

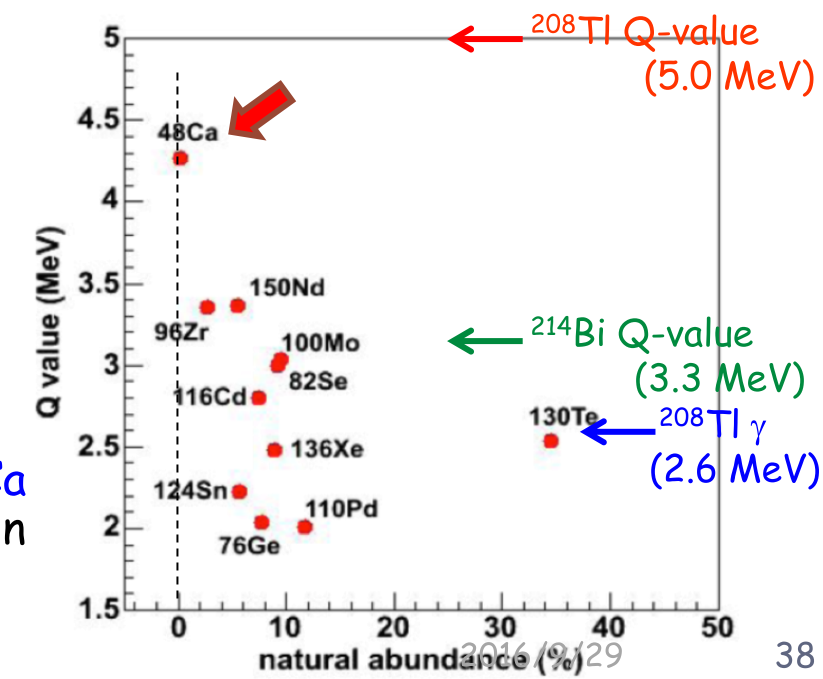
      γ-ray ; 2.6 MeV (^{208}Tl)

      β-ray ; 3.3 MeV (^{214}Bi)
  - Chance to realize the Background Free Measurement !



$$\boxed{\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (1/\, M \cdot T_{live})^{1/2}}$$

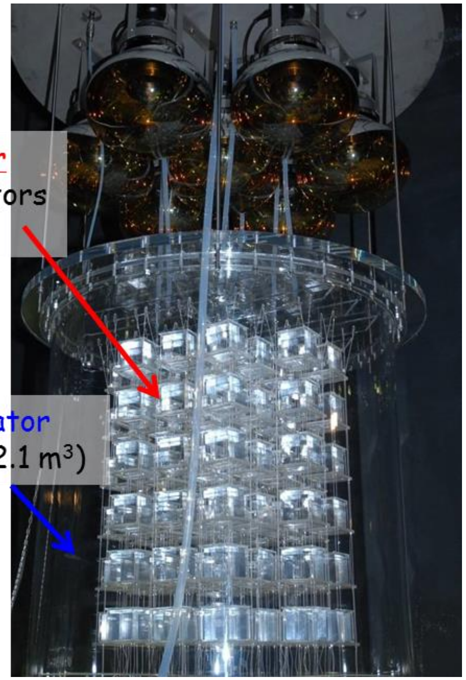
- Small natural abundance (0.187 %)
  - Chance to improve the sensitivity by the enrichment without scale-up.
  - Enrichment has low risk to increase BG origins
- Usually, β-decays of ββ isotopes are energetically forbidden, β-decay of ^{48}Ca is strongly suppressed by spin transition law, not forbidden.



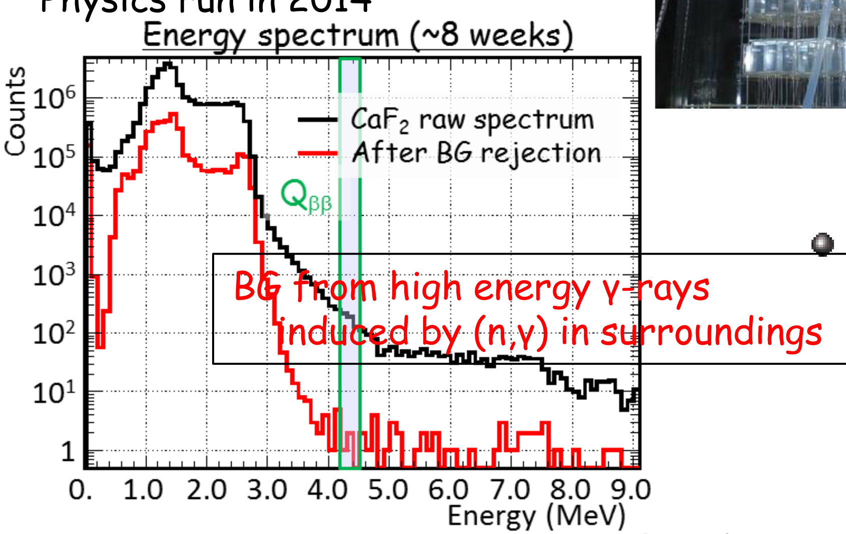
CANDLES Experiment

Highest Q-valued

- **CANDLES** is the project to search for $0\nu\beta\beta$ decay of **^{48}Ca ($Q_{\beta\beta}$ = 4.27 MeV)**
- The CANDLES-III detector is currently installed in Kamioka Underground.



Physics run in 2014



- CaF_2 Module
  - CaF_2(Pure) ; 96 Crystal → 305 kg
  - WLS Phase ; 280 nm → 420 nm
    - Thickness ; 5 mm
    - Mineral Oil+bis-MSB (0.1 g/L)

4π Active shield

- Liquid Scintillator (LS)
  - 1.37 m ϕ x 1.4 m height
  - Volume ; 2.1 m^3 (1.65 ton)
  - Composition
    - Solvent ; Mineral Oil(80%) + PC(20%)
    - WLS's ; PPO (1.0g/L) + bis-MSB (0.1g/L)
- PMTs + Light pipe
  - 13 inch (Side) ; x 48
  - 20 inch (Top and Bottom) ; x 14
  - Reflector Film : reflectivity ~93%

- Toward "Background Free Measurement"
  - Designed the shields → finished the construction
    - Lead Bricks (10 ~ 12 cm thick)
    - Boron loaded sheet
  - Number of BG after shield installation estimated
    - Rock : 0.34±0.14 event/year
    - Tank : 0.4±0.2 event/year

Installed in 2016

BG Spectrum after Shielding

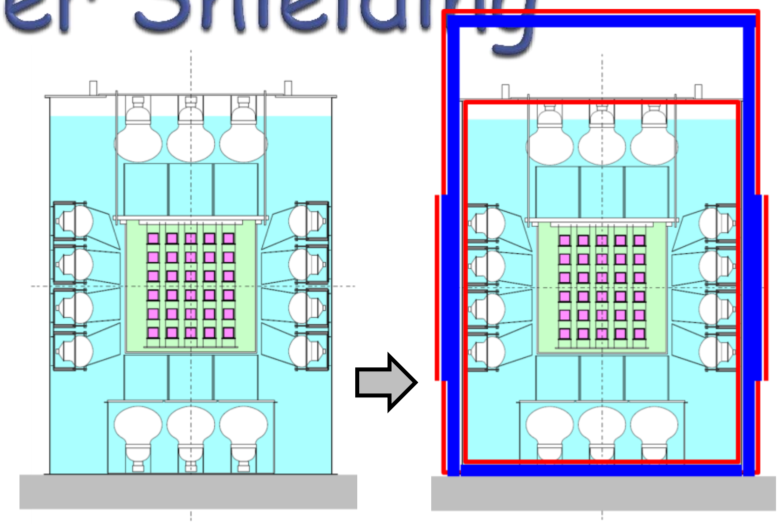
- Statistics
  - Before shielding: 60.3 days (2013 data)
  - After shielding: 8.3 days (July 2016)

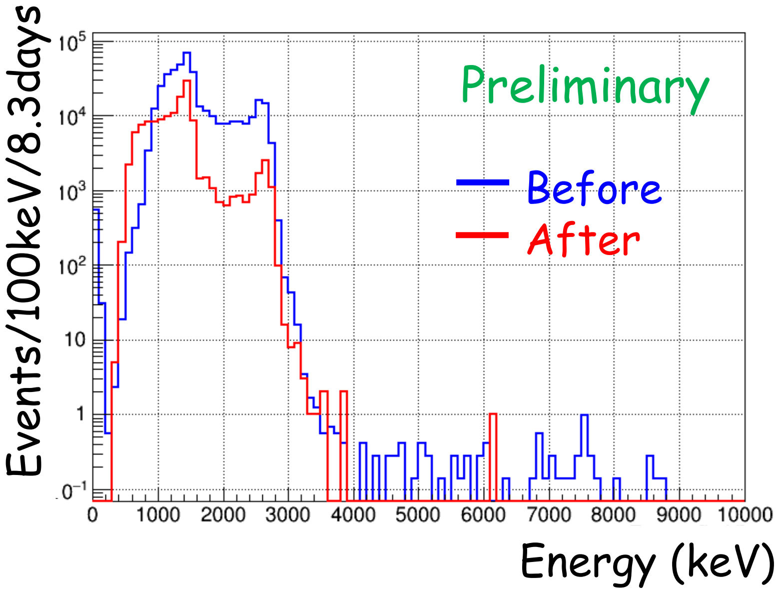
- $0\nu\beta\beta$ analysis
  - CaF_2 Crystal x 26
    - Th contents within crystal < 10 μBq/kg
  - All BG cut are applied, but cut condition is not optimized yet.
    - LS veto & β-events cut
    - ^{212}Bi-Po sequential decay cut
    - ^{208}Tl veto after ^{212}Po-decay

- Obtained spectrum
  - (n,γ)BG events above 5 MeV is much reduced, as expected.

    ➔ reduction factor will be estimated
  - ^{40}K, ^{208}Tl rates are also reduced.

    ➔ expect to improve ^{208}Tl veto efficiency



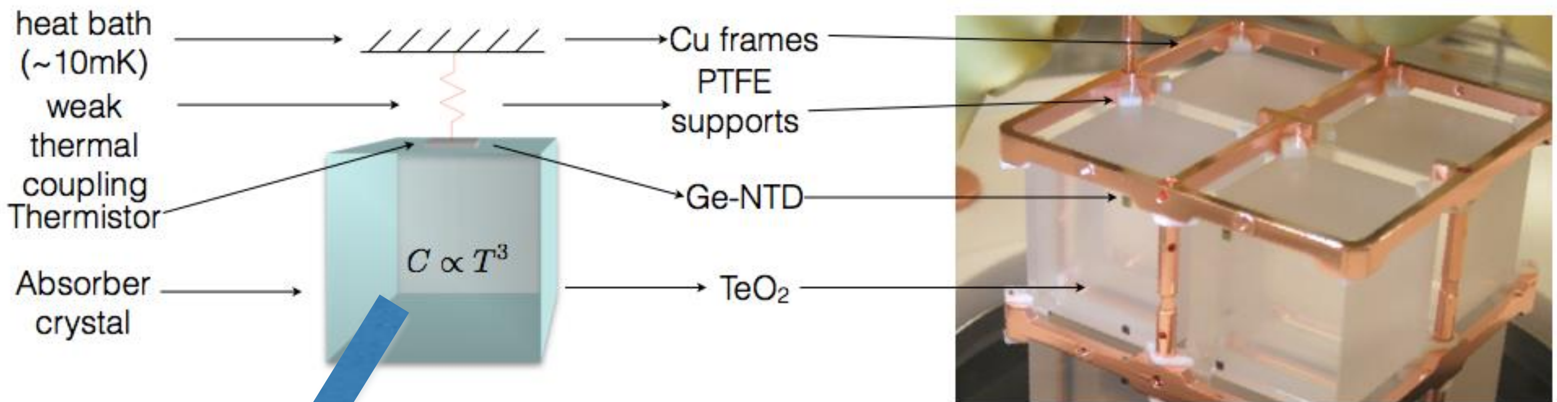


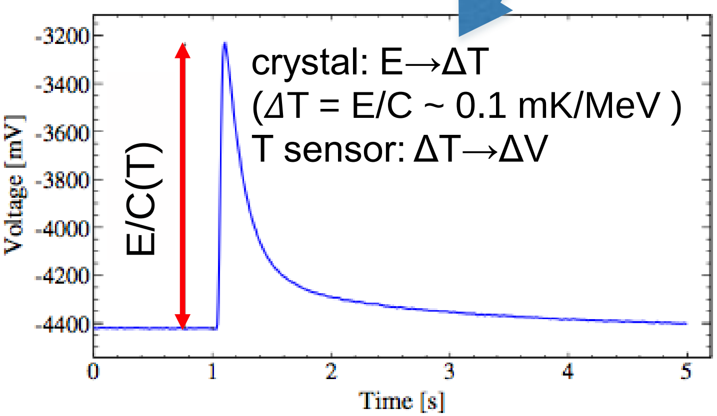
CUORE

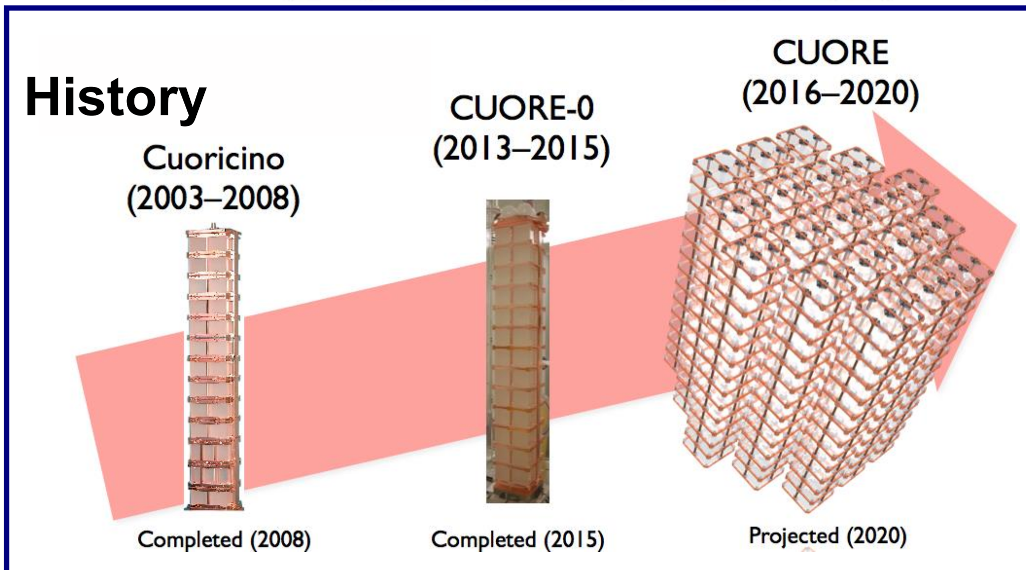
All slides from Brian Fujikawa

CUORE Detector

- Located at LNGS (Italy), ~3600 m.w.e.
- TeO_2 bolometers (988 crystals in 19 towers), a total mass of ^{130}Te 206 kg
- Operated at ~10mK. Energy resolution ~0.2% FWHM





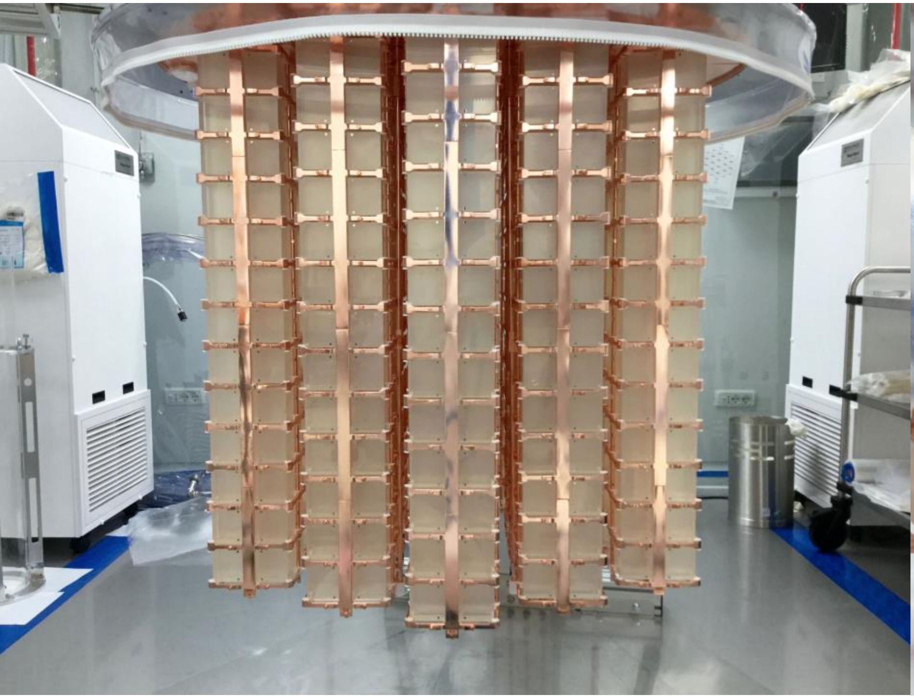


Combining the limit
with Cuoricino experiment

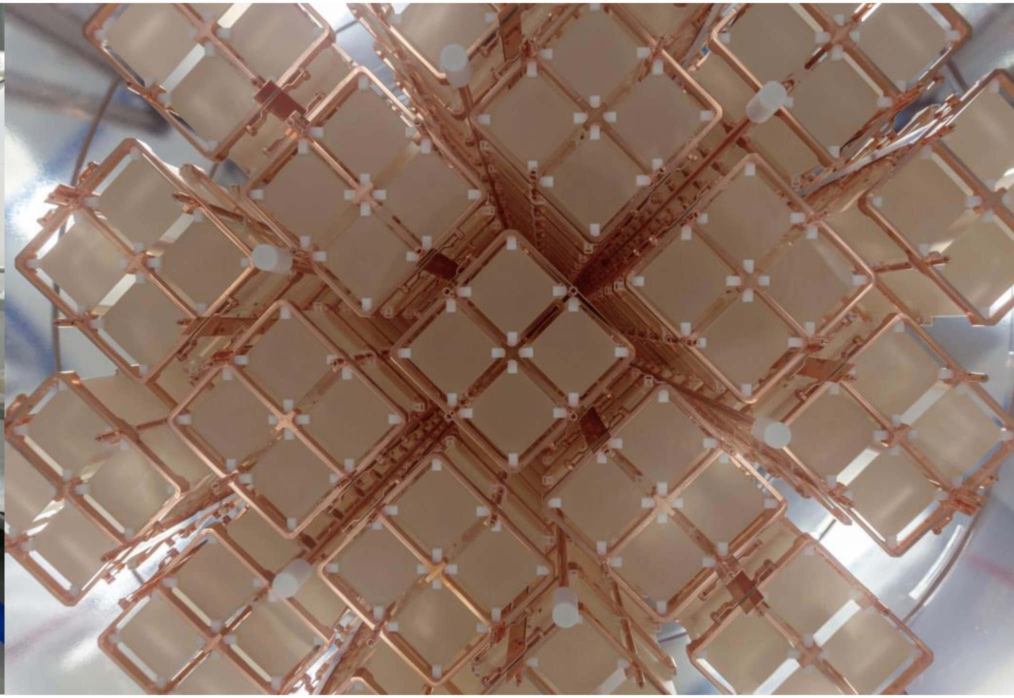
$T^{1/2} > 4.0 \times 10^{24}$ yr (90% C.L.) $m_{\beta\beta} < 270 – 670$ meV

CUORE tower installation completed!

On August 26, 2016, the CUORE Collaboration reached a major milestone: all 19 towers, consisting of 988 individual TeO_2 crystals and weighing almost 750 kg (1650 lbs), are now installed in the cryostat! Thanks to the dedicated efforts of specially trained teams of scientists, engineers, and technicians, and logistical support from the entire collaboration, the installation went smoothly over a period of about a month. We are now preparing to close the cryostat and start scientific operations in search for neutrinoless double beta decay, which may hold keys to our understanding of matter abundance in the Universe.



The detectors were installed in a specially constructed cleanroom to protect them from naturally occurring radioactivity, including air filtered to remove radon gas



Bottom view of the towers

5-year sensitivity: $T_{1/2}(^{130}Te) > 9.5 \times 10^{25}$ years, $m_{\beta\beta} < 50\text{-}130$ meV (90% C.L.)

Symmary

- KamLAND-Zen Eperiment
  - 400kg phase ; stringent limit was obtained T > 1.07 x 10^{26} yr
  - Preparing next phase ; KamLAND-Zen 800

- Another 4 experiments are briefly reviewed
  - EXO-200/nEXO ; liq-Xe TPC
  - NEXT and AXEL; high pressure Xe gas TPC, using electroluminescence
  - PandaX III; high pressure Xe gas TPC

- CANDLES, CUORE updates

- Special thanks to
  - Francesc Monrabal and Juan Jose Gomez-Cadenas (NEXT)
  - Atsuko Ichikawa (AXEL)
  - Ke Han (PandaX III)
  - Brian Fujikawa (CUORE)
  - Azusa Gando (KamLAND-Zen)