Physics in Collision 2016, Quy Nhon, Vietnam

Searches for double beta decay

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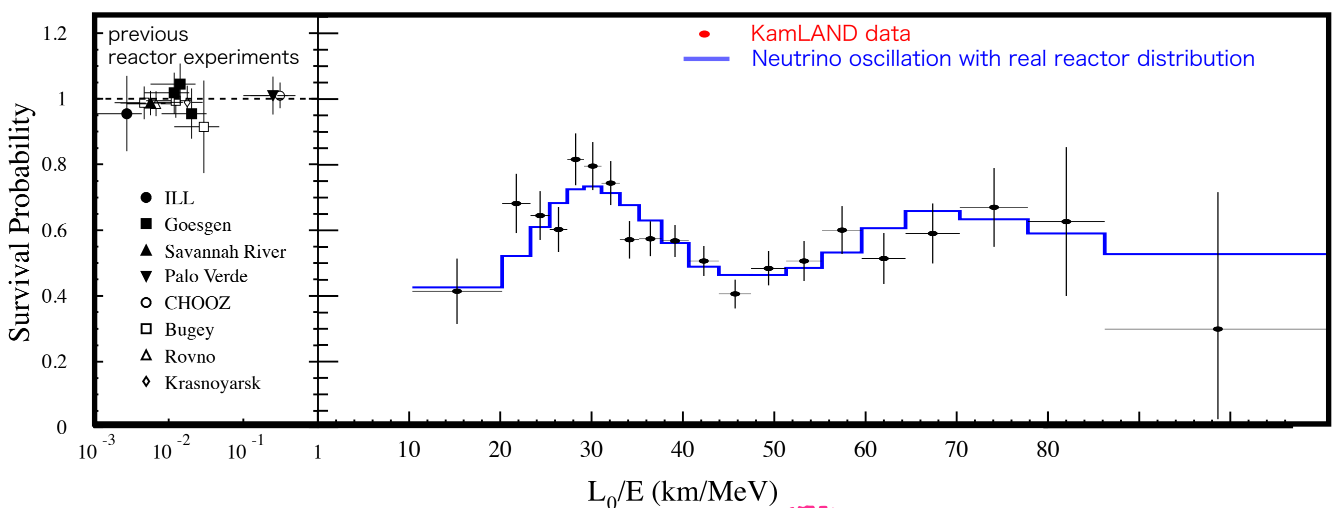
Contents

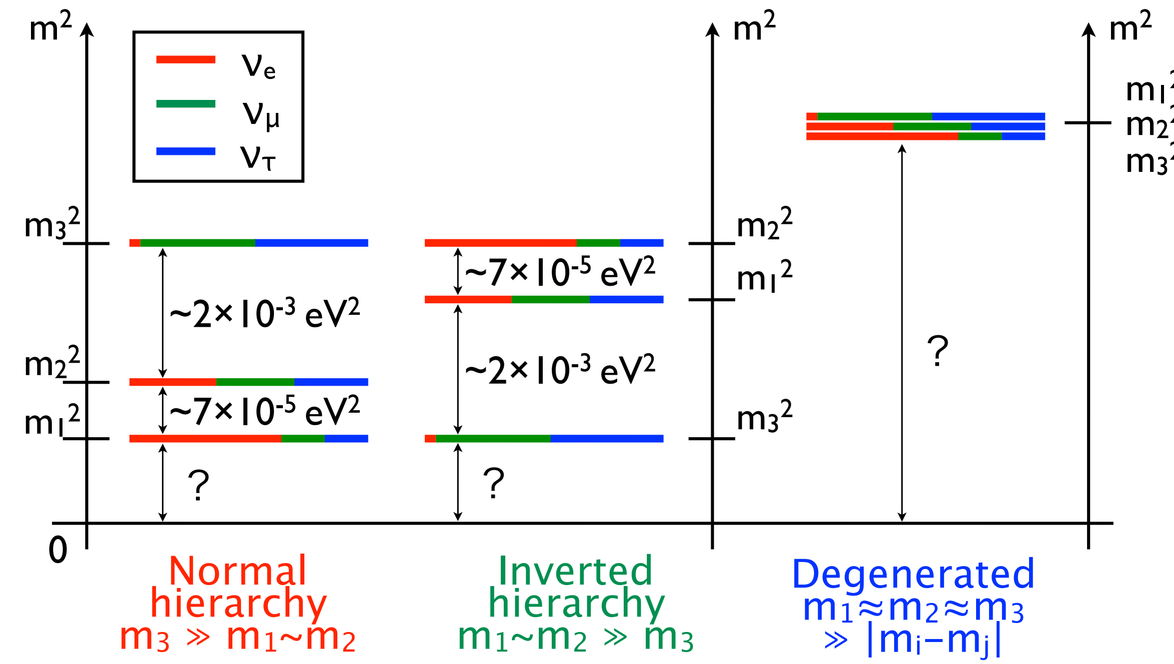
Neutrino

- Originally m_ν=0 in standard model
- **$m_\nu \neq 0$** from oscillation experiment



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right), \quad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

Q. Absolute mass scale?
Mass hierarchy ?



Q. Dirac or Majorana particle?

Dirac neutrino

$$\nu \neq \bar{\nu}$$

Same mass for right and left-handed
All leptons except for neutrino is Dirac type

Majorana neutrino

$$\nu = \bar{\nu}$$

Lepton number violation (ΔL = 2)
Can be different mass for right and left-handed neutrino

Experiment Search for neutrinoless double beta ($0\nu\beta\beta$) decay

Double beta decay

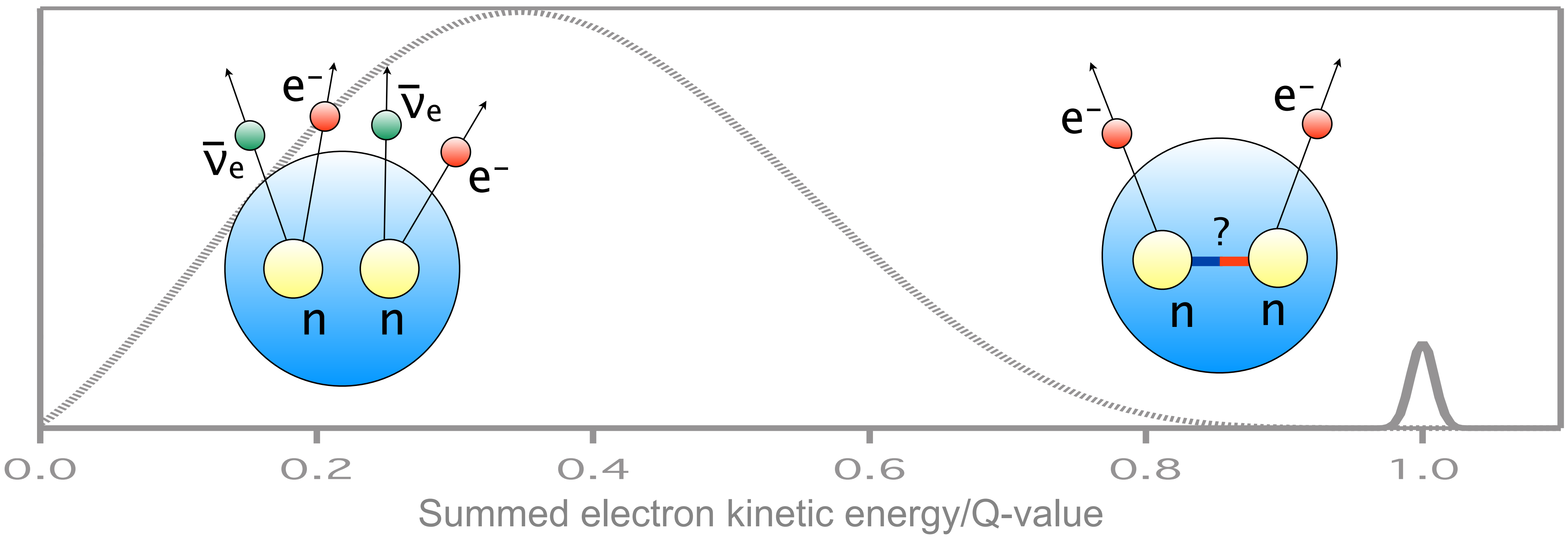
- Two decay modes

2νββ decay

(A,Z)→(A,Z+2) + 2e⁻ + 2$\bar{\nu}_e$

0νββ decay

(A,Z)→(A,Z+2) + 2e⁻



- Second order weak process
- Continuous spectrum
- Occurs on tens of isotopes
- Observed half-life $T_{1/2} \sim 10^{19\text{-}24}$ yr

$$\left(T^{2\nu}_{1/2}\right)^{-1} = G^{2\nu}|M^{2\nu}|^2$$

phase space factor → $G^{2\nu}$; Nuclear matrix element → $M^{2\nu}$

- Massive majorana neutrino
- Lepton number violation
- Mono-energetic peak at Q value (widen by the energy resolution)
- It has never been observed
- Limit on half-life $T_{1/2} \sim 10^{24\text{-}25}$ yr

Neutrinoless double beta decay

In the framework of light Majorana neutrino exchange…

Decay rate of 0νββ ⟺ Effective neutrino mass

→ Hint for absolute mass scale

→ Neutrino mass hierarchy

Observation $$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu \rangle^2$$

Phase space factor

Calculable

phase space ∝ Q^5

Nuclear matrix element

Theoretical calculation.

Biggest uncertainty

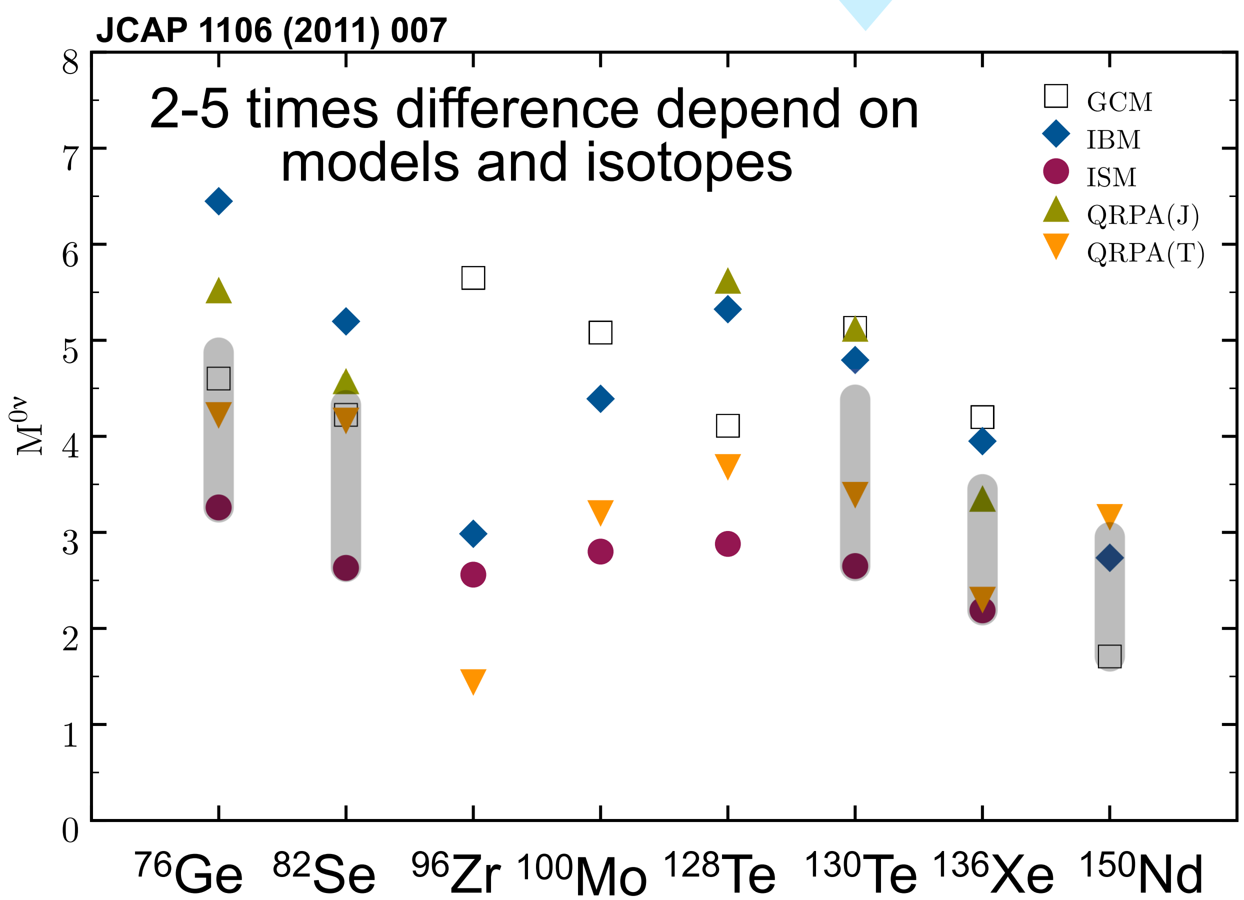
to estimate effective

neutrino mass.

Effective neutrino mass

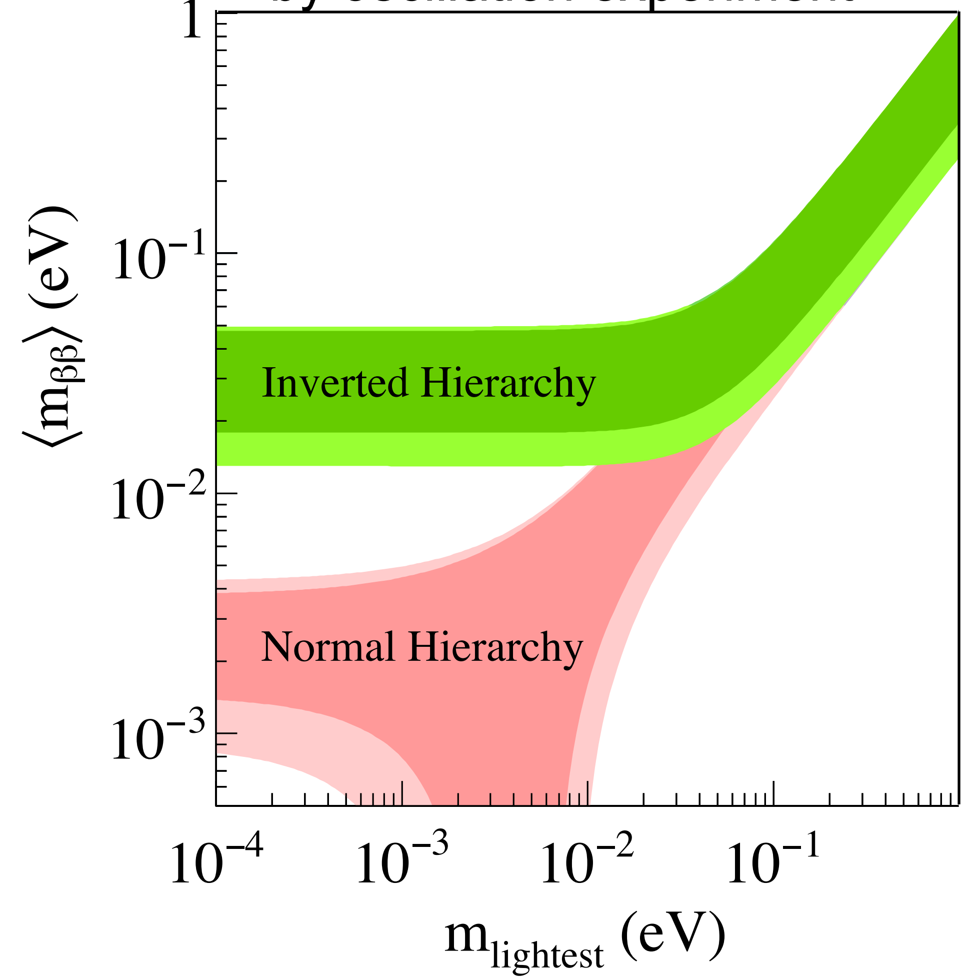
$$\langle m_\nu \rangle \equiv \left| |U_{e1}^L|^2 m_1 + |U_{e2}^L|^2 m_2 e^{i\phi_2} + |U_{e3}^L|^2 m_3 e^{i\phi_3} \right|$$

U: PMNS matrix, m_i: neutrino mass, φ: Majorana phase



Allowed region of $\langle m_\nu \rangle$

by oscillation experiment

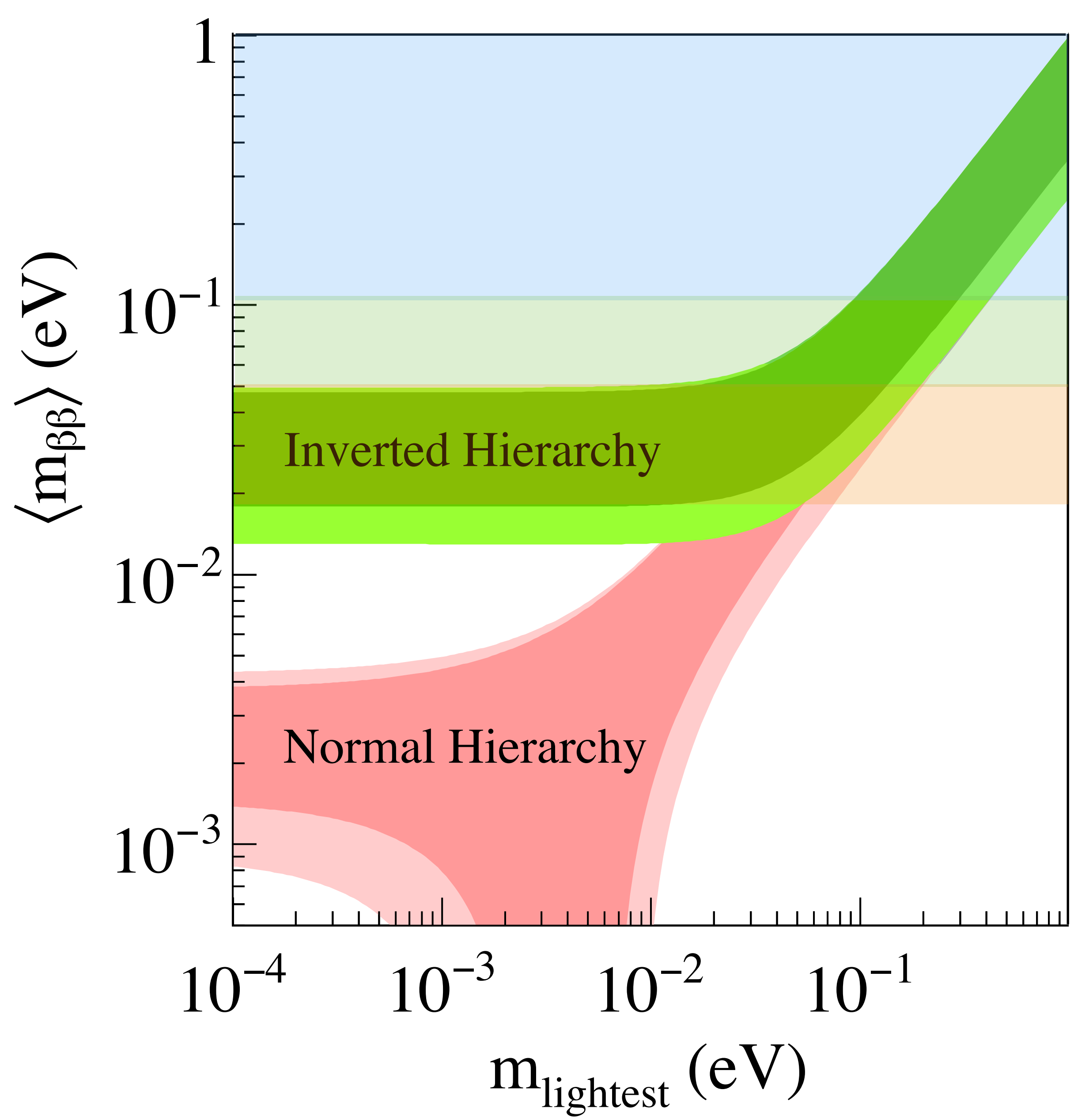


Experimental sensitivity

Decay rate of 0vββ ⟺ Effective neutrino mass

Observation $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$

→ Hint for absolute mass scale
→ Neutrino mass hierarchy



		Half life	Mass of isotopes
Past & present	~100meV →	10^{25}~10^{26}y	10~10^2kg
Near future	~60meV →	10^{26}~10^{27}y	10^2~10^3kg
Future	~20meV →	10^{27}~10^{28}y	10^3 kg~

Experiment needs
- capacity of large isotope mass
- low background
- high efficiency
- good energy resolution

Isotopes for double beta decay (Q-value > 2MeV)

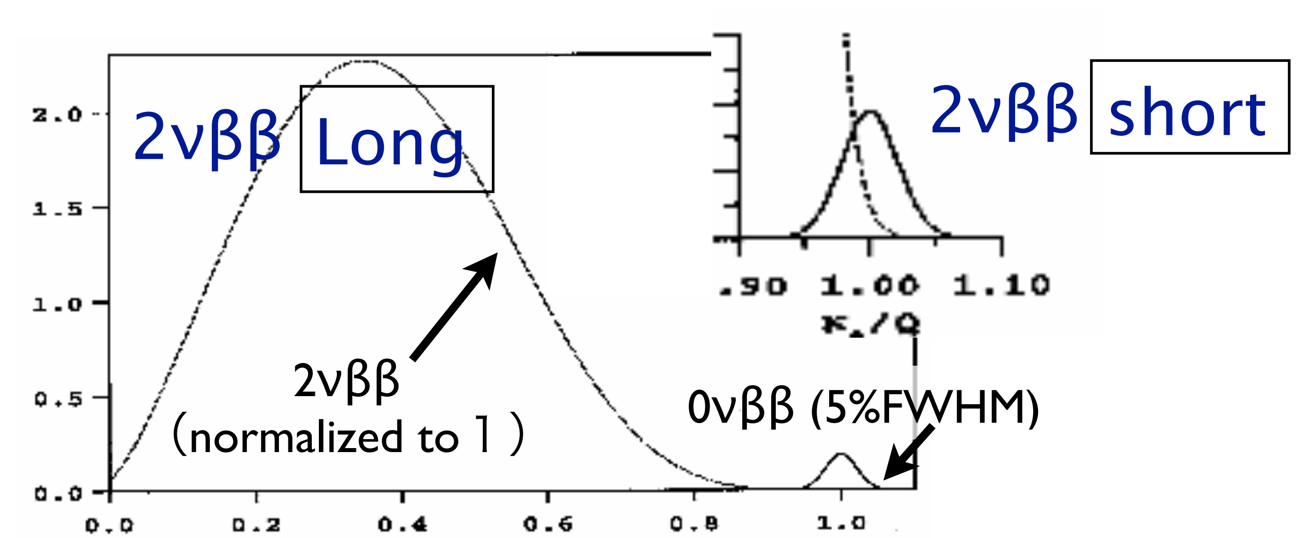
- No perfect isotope for double beta decay

Isotopes	Q-value (keV)	N.A. (%)	$T^{2\nu}_{1/2}$ (year) measurement PDG2015, no error included	$T^{0\nu}_{1/2}(50\,\mathrm{meV})$ calculation PRC 79, 055501 (2009), (R)QRPA (CCM SRC)	Pros & Cons
^{48}Ca	4273.6 ± 4	0.19	4.4×10^{19}	-	Q-value **biggest**, N.A. **small**, enrichment **difficult**
^{76}Ge	2039.006 ± 0.050	7.6	1.84×10^{21}	$(2.99\text{-}7.95)\times10^{26}$	2v **long**, enrichment **~90%**
^{82}Se	2995.50 ± 1.87	8.7	9.6×10^{19}	$(0.85\text{-}2.38)\times10^{26}$	enrichment **>90%**
^{96}Zr	3347.7 ± 2.2	2.8	2.35×10^{19}	$(3.16\text{-}6.94)\times10^{26}$	
^{100}Mo	3034.40 ± 0.17	9.4	7.11×10^{18}	$(0.59\text{-}2.15)\times10^{26}$	2v**short**, enrichment **>90%**
^{110}Pd	2017.85 ± 0.64	7.5	-	-	
^{116}Cd	2813.50 ± 0.13	7.5	2.8×10^{19}	$(0.98\text{-}3.17)\times10^{26}$	enrichment **80~90%**
^{124}Sn	2287.80 ± 1.52	5.8	-	-	
^{130}Te	2527.01 ± 0.32	34.1	7.0×10^{20}	$(7.42\text{-}2.21)\times10^{26}$	N.A. **high**
^{136}Xe	2457.83 ± 0.37	8.9	2.165×10^{21}	$(1.68\text{-}7.17)\times10^{26}$	2v **long**, enrichment **~90%**
^{150}Nd	3317.38 ± 0.20	5.7	9.11×10^{18}	-	2v **short**, enrichment **difficult**

2νββ → Background of 0νββ

$$T^{0\nu}/T^{2\nu}$$

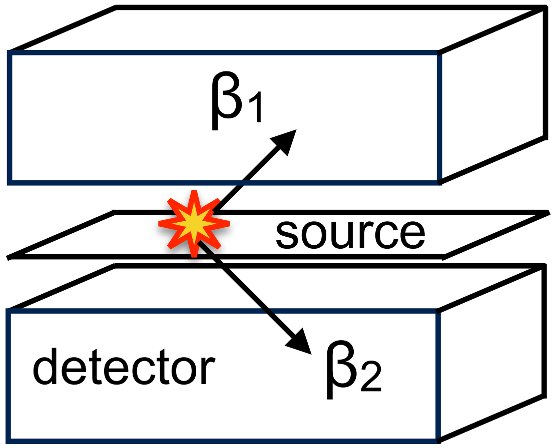
If ratio is big
→ Energy resolution is important



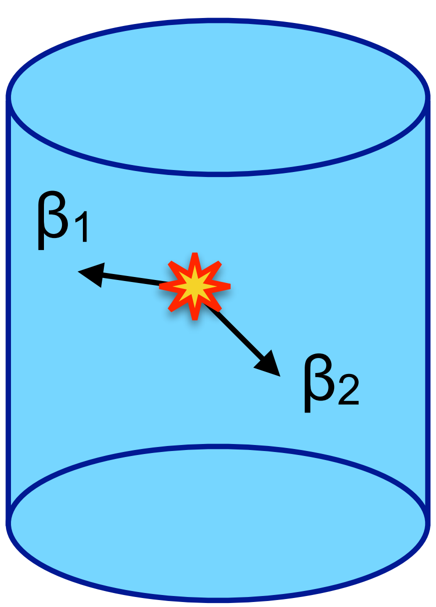
Techniques for double beta decay

- No perfect detection techniques for double beta decay

source ≠ detector

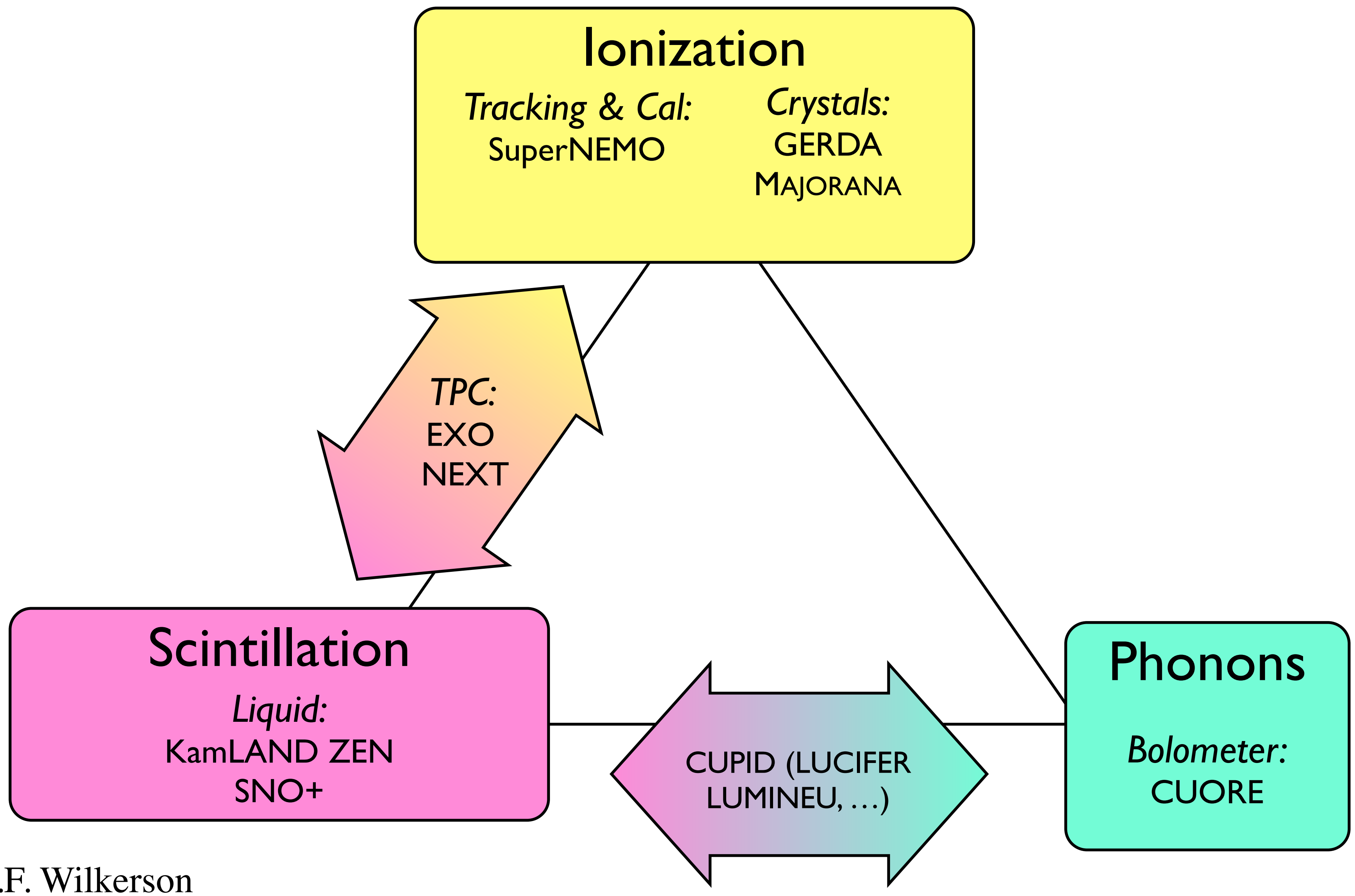


source = detector



Experiment needs
- capacity of large isotope mass
- low background
- high efficiency
- good energy resolution

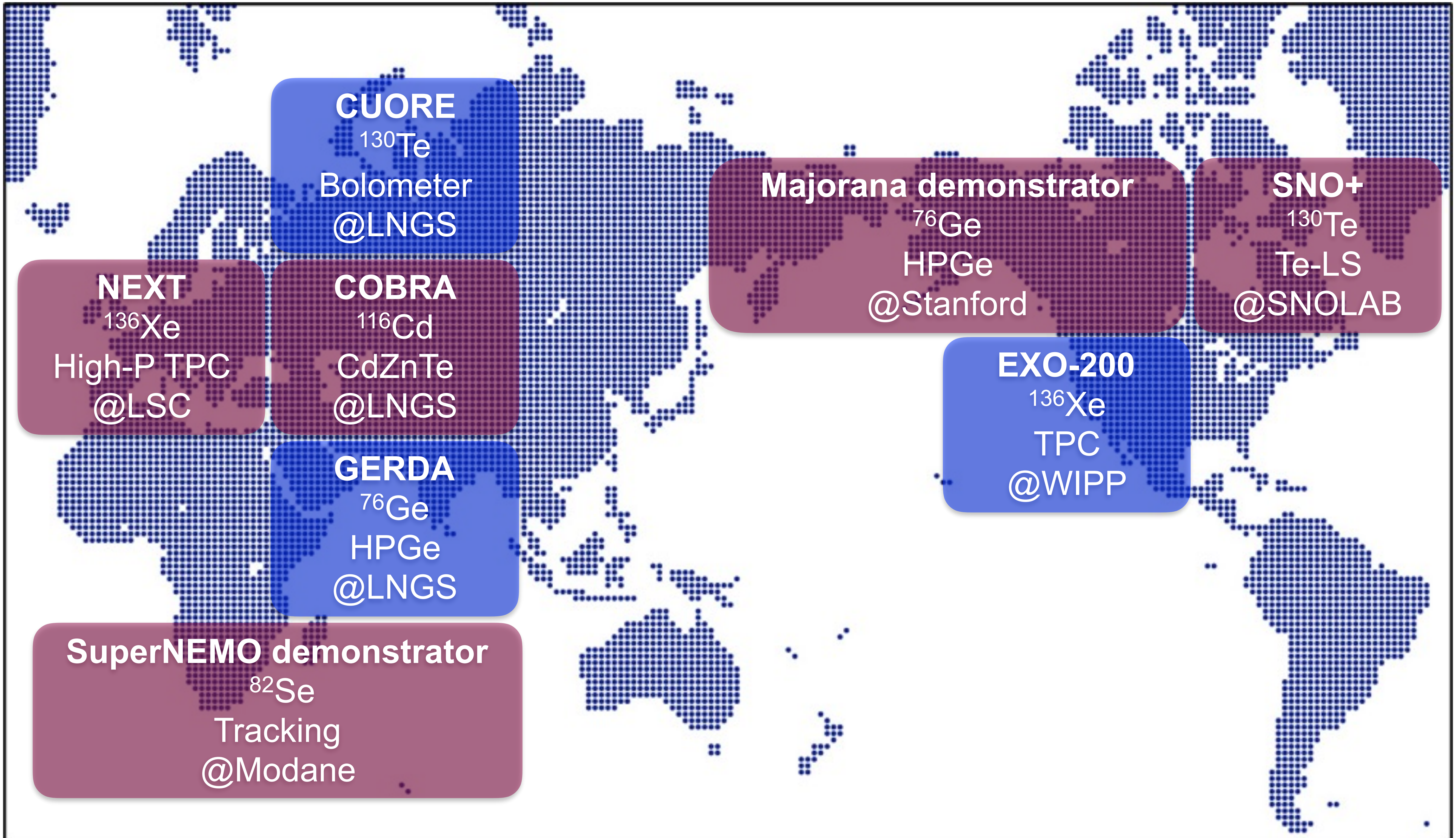
Location
- Underground is better



J.F. Wilkerson

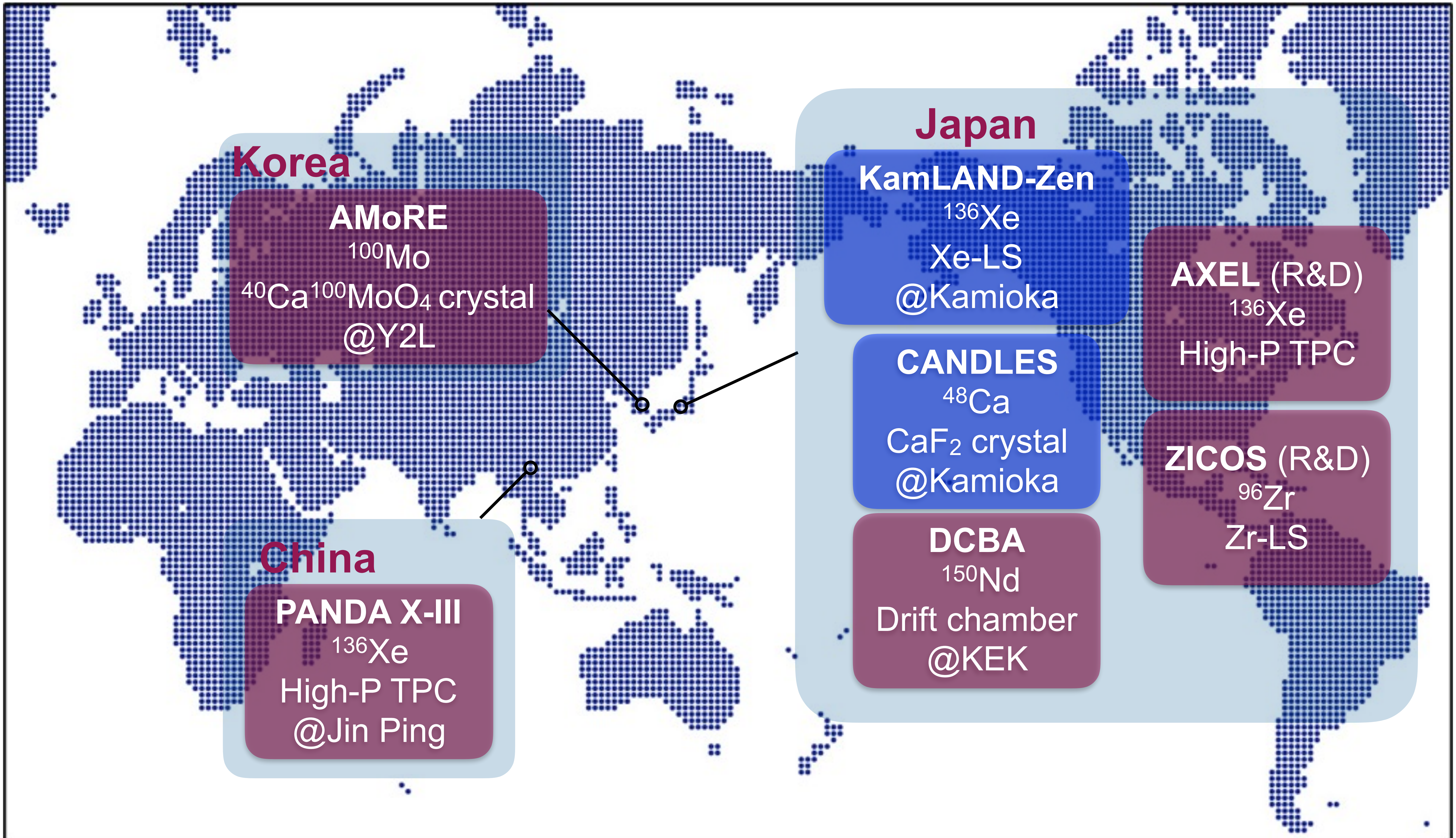
isotopes × detection techniques = different approaches

Experiments in Europe and America



I am focus on experiments colored with blue

Experiments in Asia

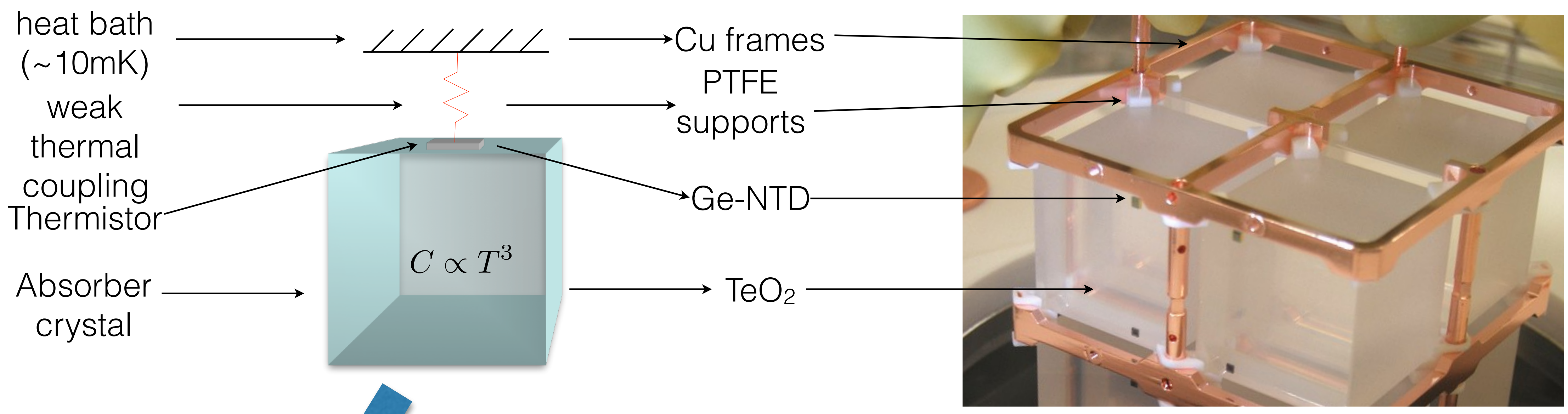


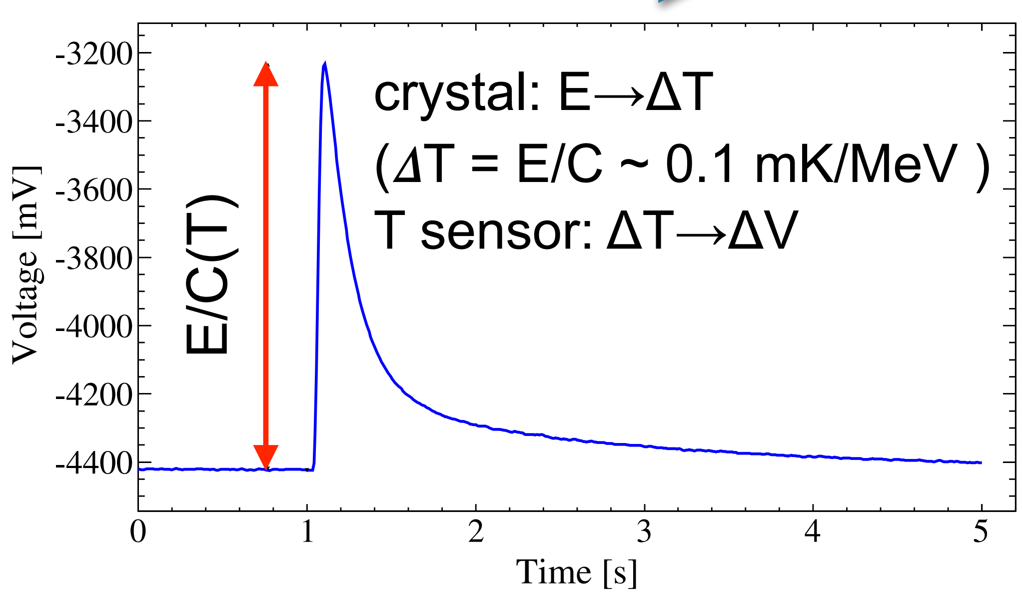
I am focus on experiments colored with blue

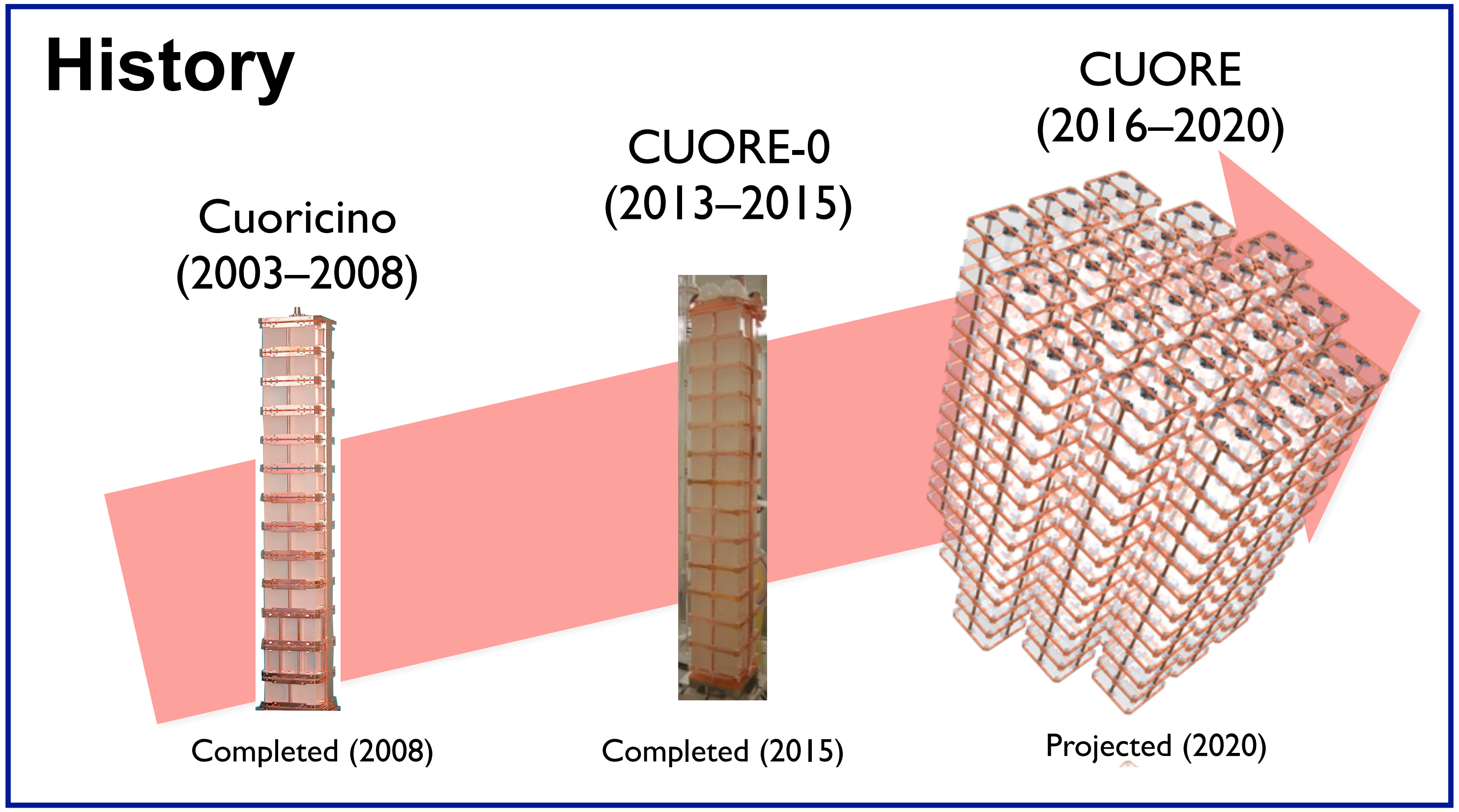
CUORE (^{130}Te)

Detector: CUORE

- 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



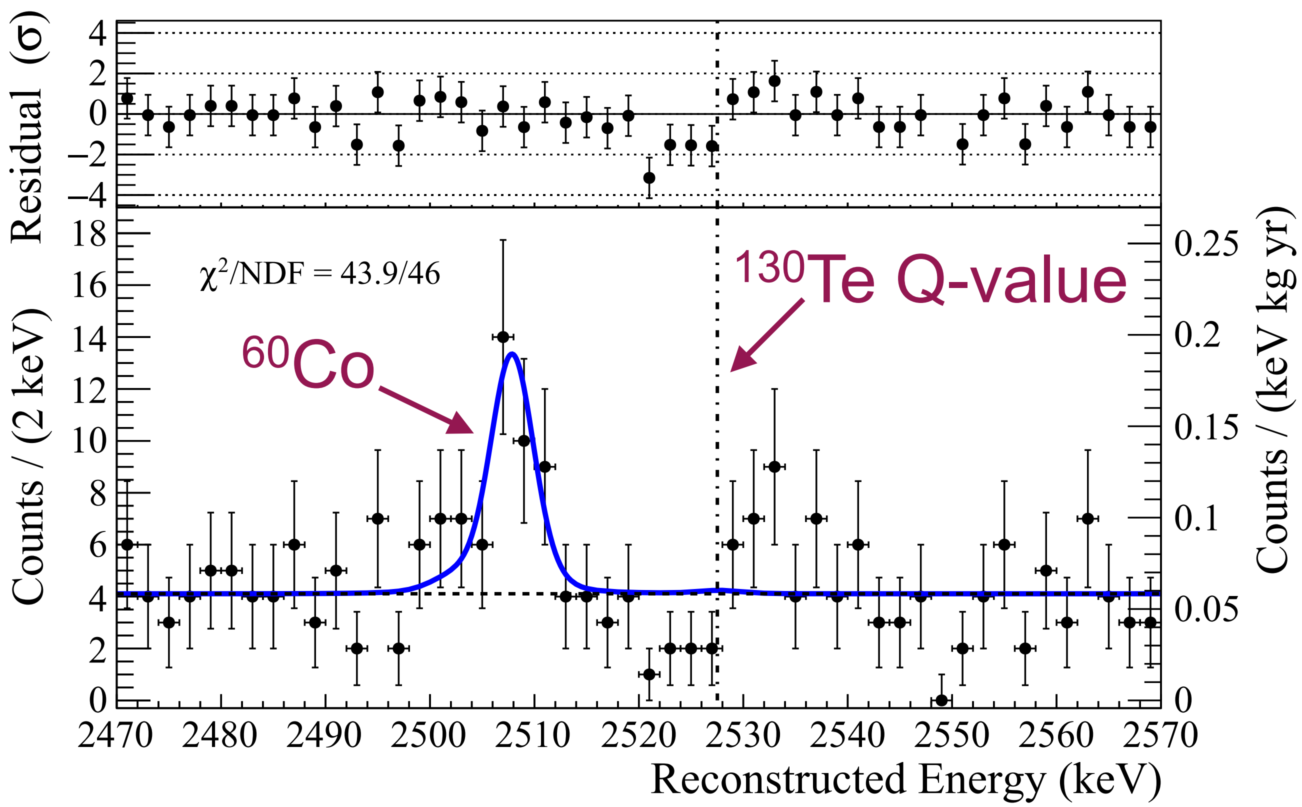


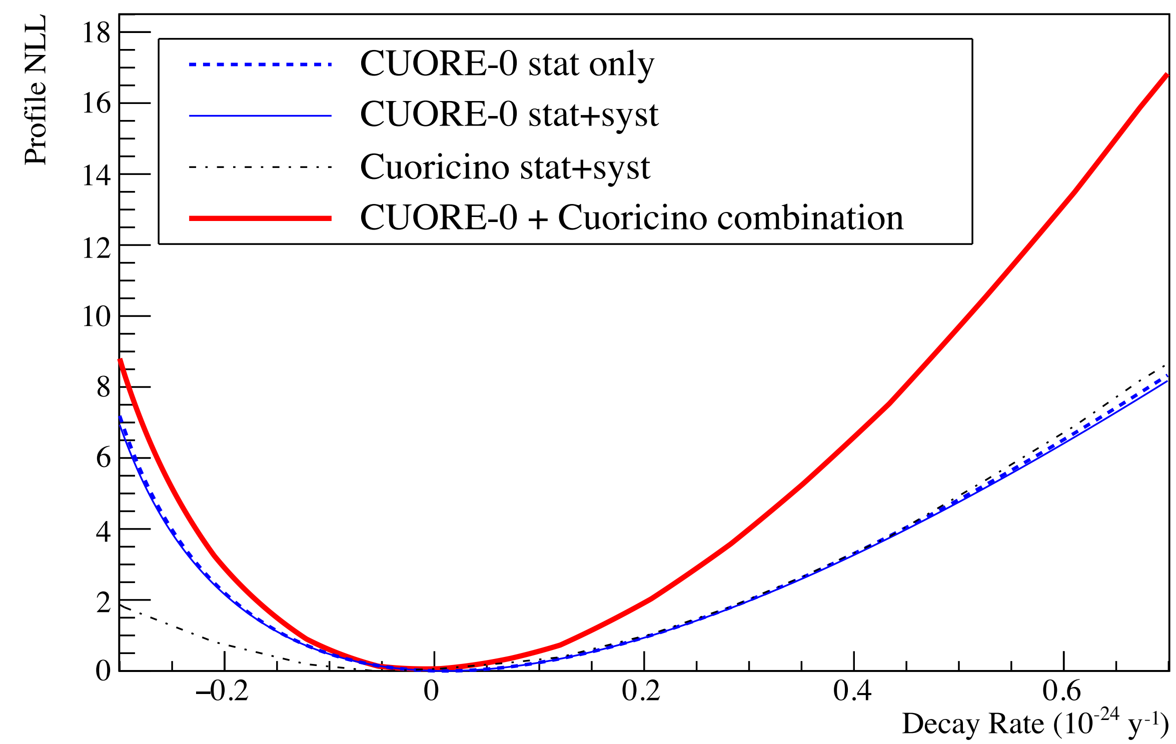


CUORE-0 Result of 0νββ decay

- CUORE-0: The first tower produced out of the CUORE assembly line
- Operated between 2013 and 2015
- 52 TeO_2 crystals (5×5×5 cm^3, ~750 g each)
- Total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)
- ^{130}Te exposure: 9.8 kg·yr

Phys. Rev. Lett. **115**, 102502
Phys. Rev. C 93, 045503 (2016)





CUORE-0 Final Limit

$T^{1/2} > 2.7 \times 10^{24}$ yr (90% C.L.)

Combining the limit
with Cuoricino experiment

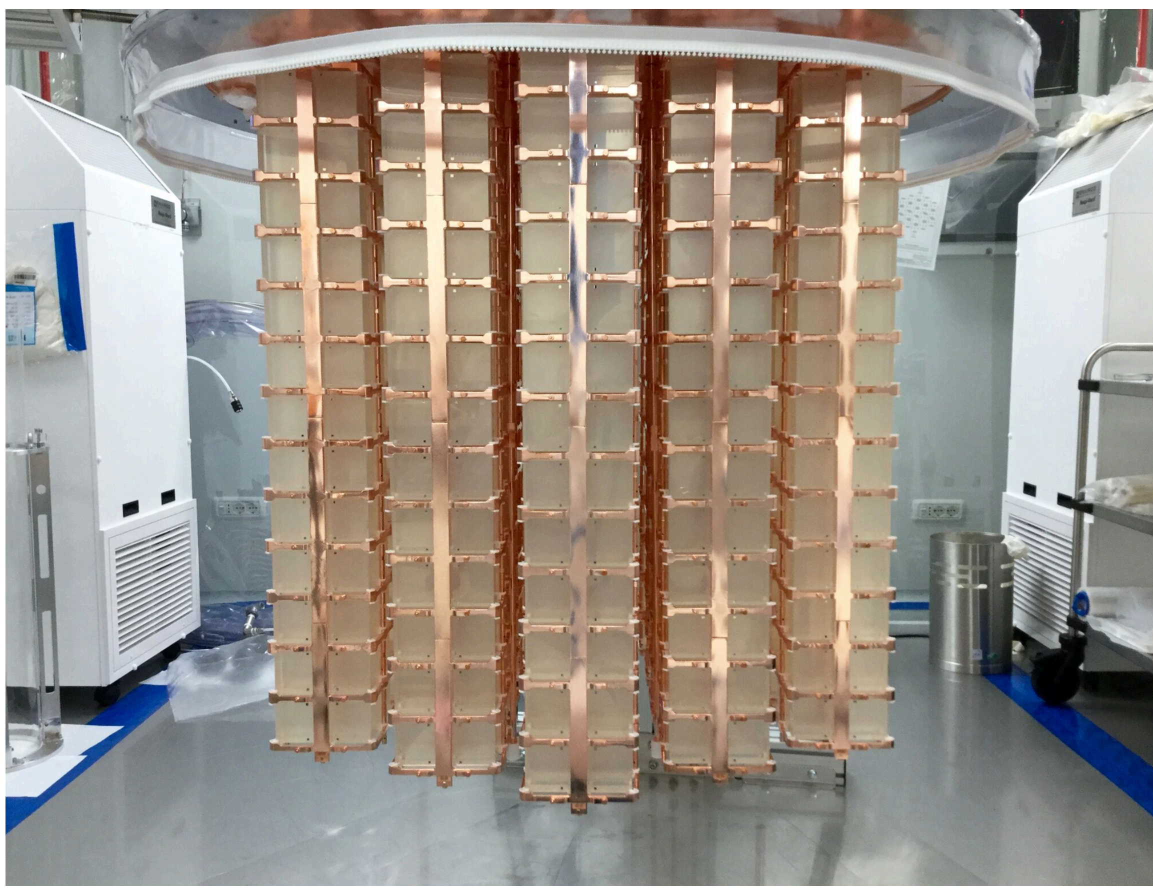
$T^{1/2} > 4.0 \times 10^{24}$ yr (90% C.L.)

$m_{\beta\beta} < 270 - 670$ meV

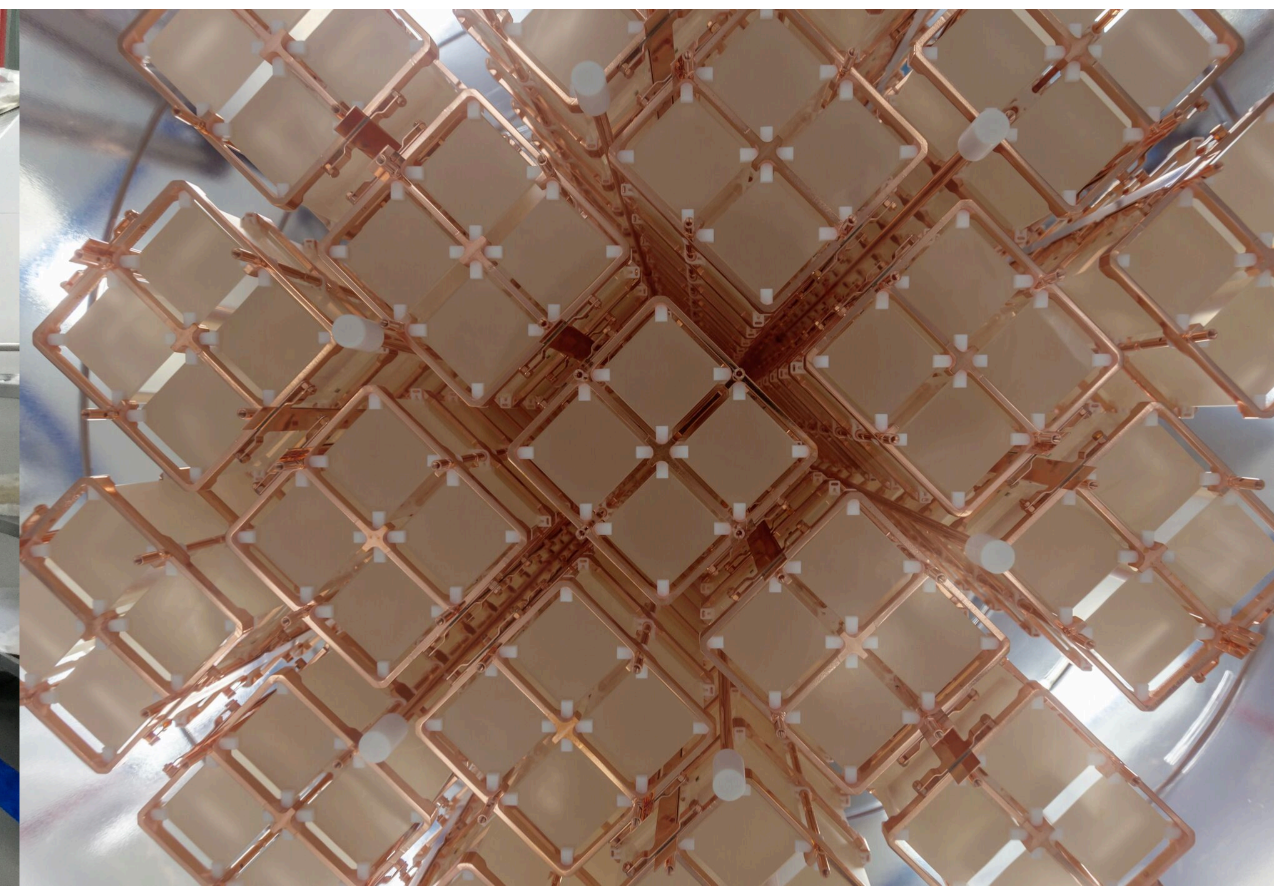
B.Fujikawa

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



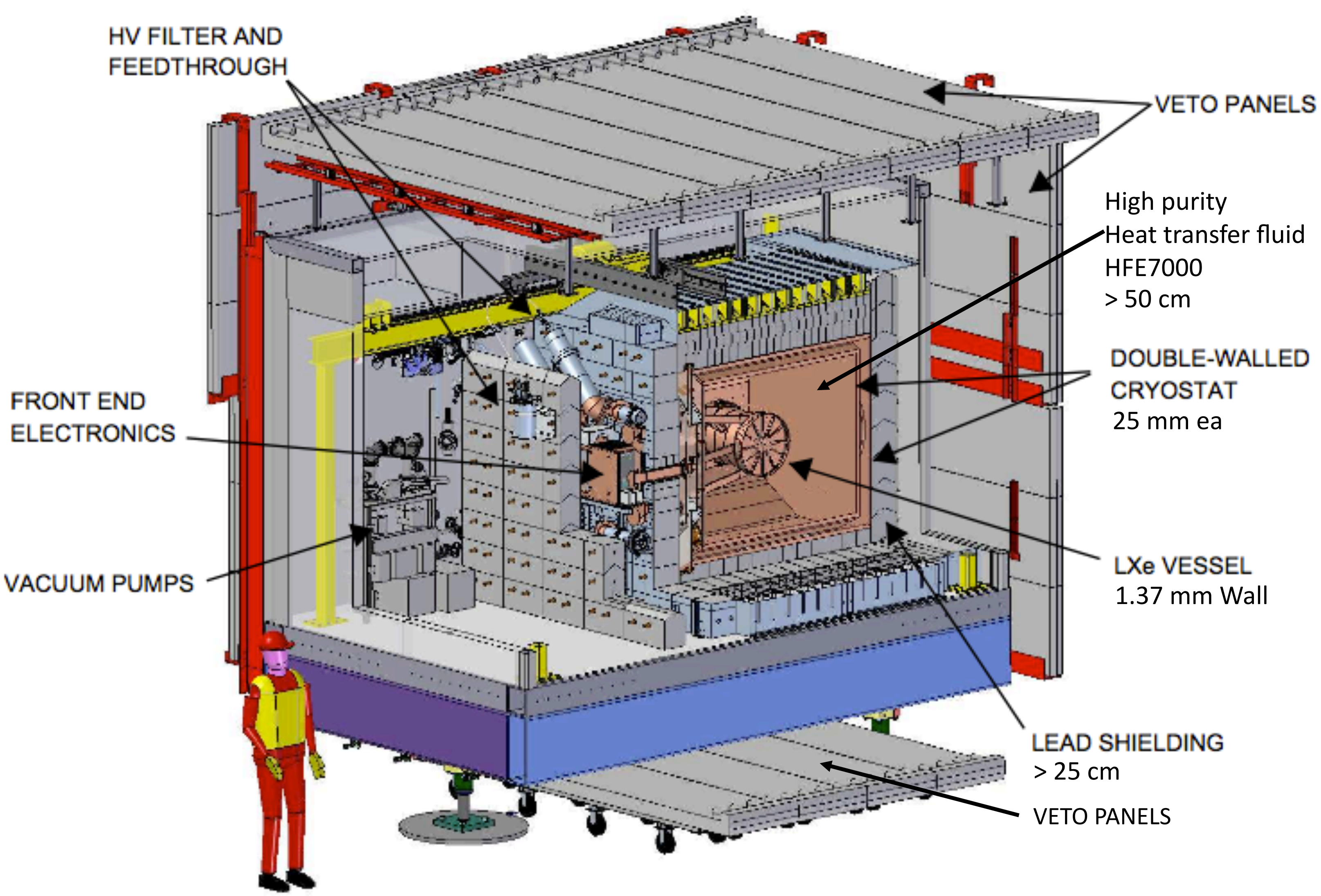
Bottom view of the towers

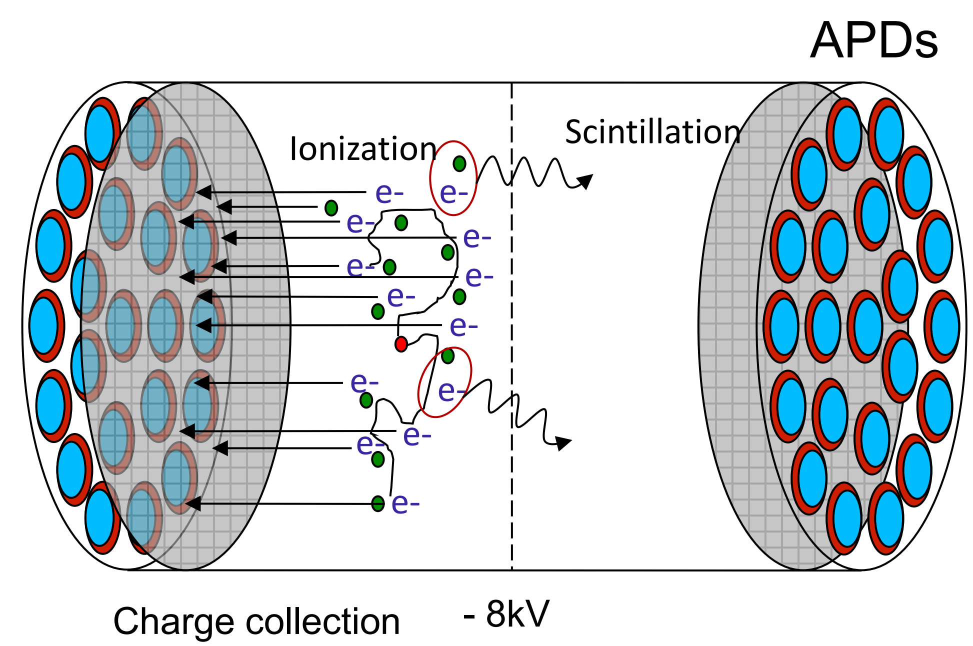
5-year sensitivity: $T_{1/2}(^{130}Te) > 9.5\times10^{25}$ years, $m_{\beta\beta} < 50\text{-}130$ meV (90% C.L.)

EXO-200 (^{136}Xe)

Detector: EXO-200

- Located at WIPP (U.S.), ~1600 m.w.e.
- 80.6% enriched liquid Xe in a time projection chamber
- Operation started in 2011
- Latest result (2014)
  - $T^{0\nu}_{1/2} > 1.1\times10^{25}$ yr (90% C.L.) with 100 kg·yr of ^{136}Xe exposure





Example of TPC schematics (EXO-200)

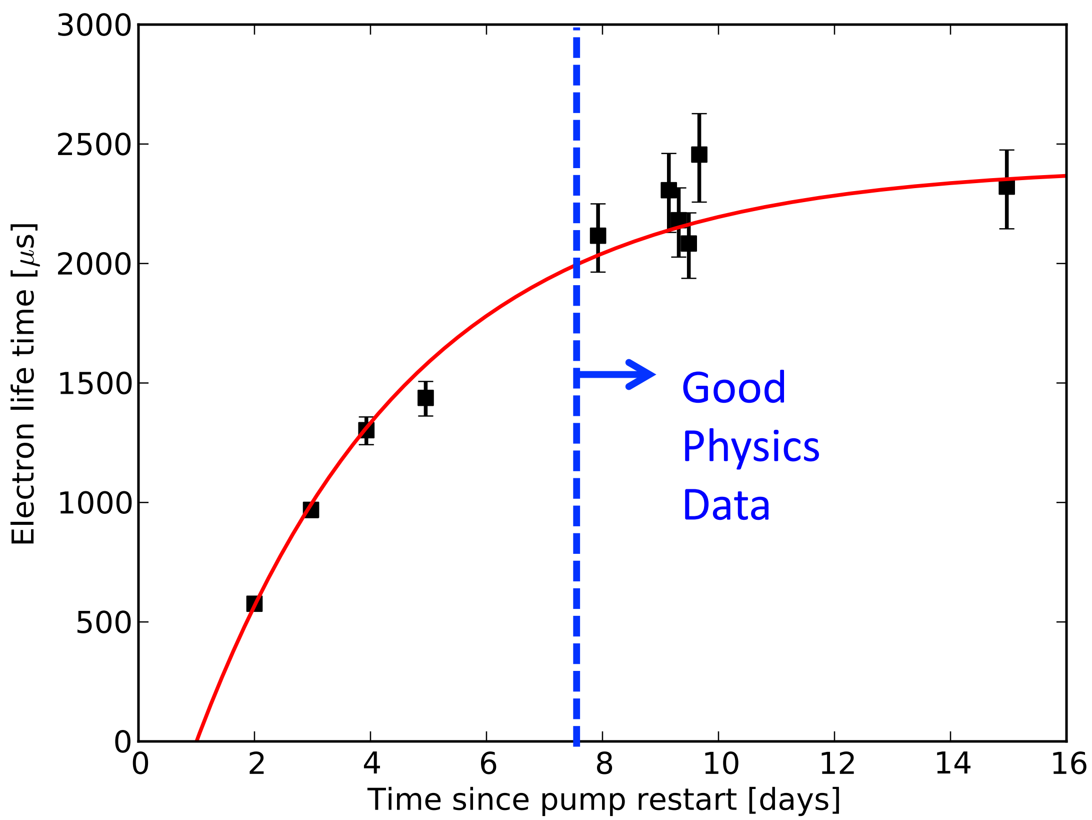
- Scintillation collected by APDs
- Charge collected by 2 wire grids

EXO-200 Phase-II Operation

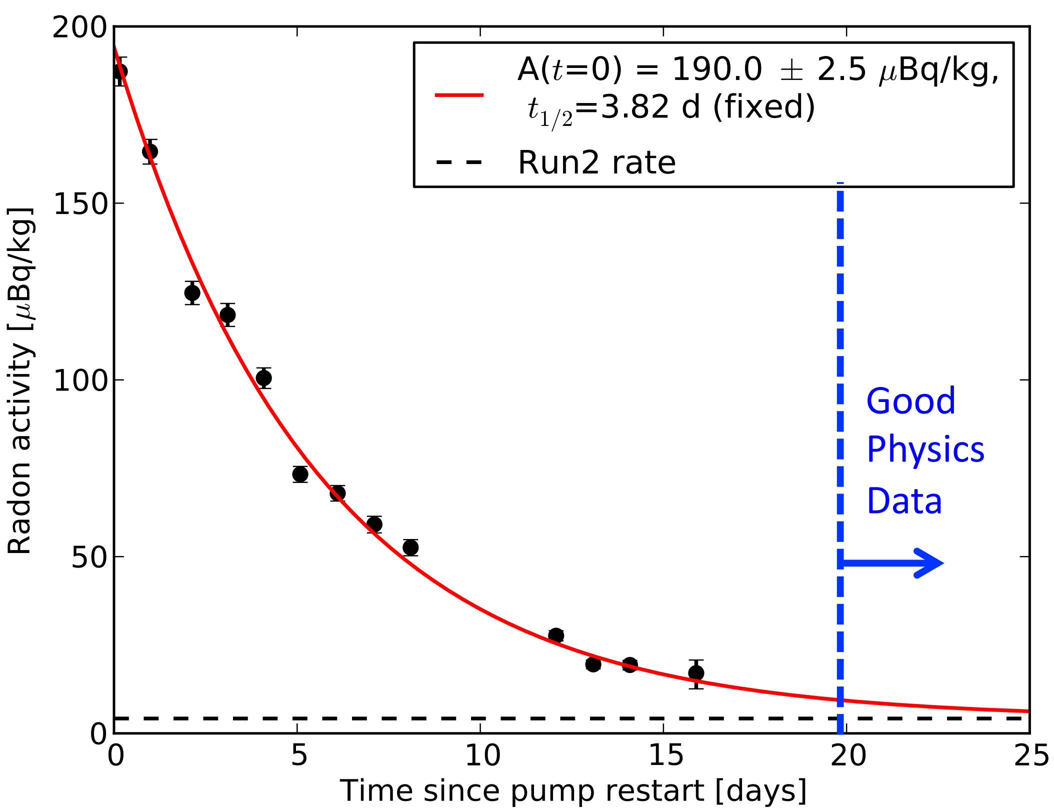
After a two year hiatus due to he February 2014 fire and radioactivity leak at the WIPP site, EXO-200 has successfully re-commissioned its major systems and started its Phase-II Operation.

- Enriched liquid xenon fill completed on 1/31/2016.

- Initial data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.



Xenon purity since Jan. 31, 2016



Rn level in TPC since Jan. 31, 2016

A. Piepke

- Energy resolution improved due to Front End Read Upgrade
  Phase I: 1.58% in SS at 0νββ Q-value ⟶ Phase II: (initial) 1.28% in SS at 0νββ Q-value

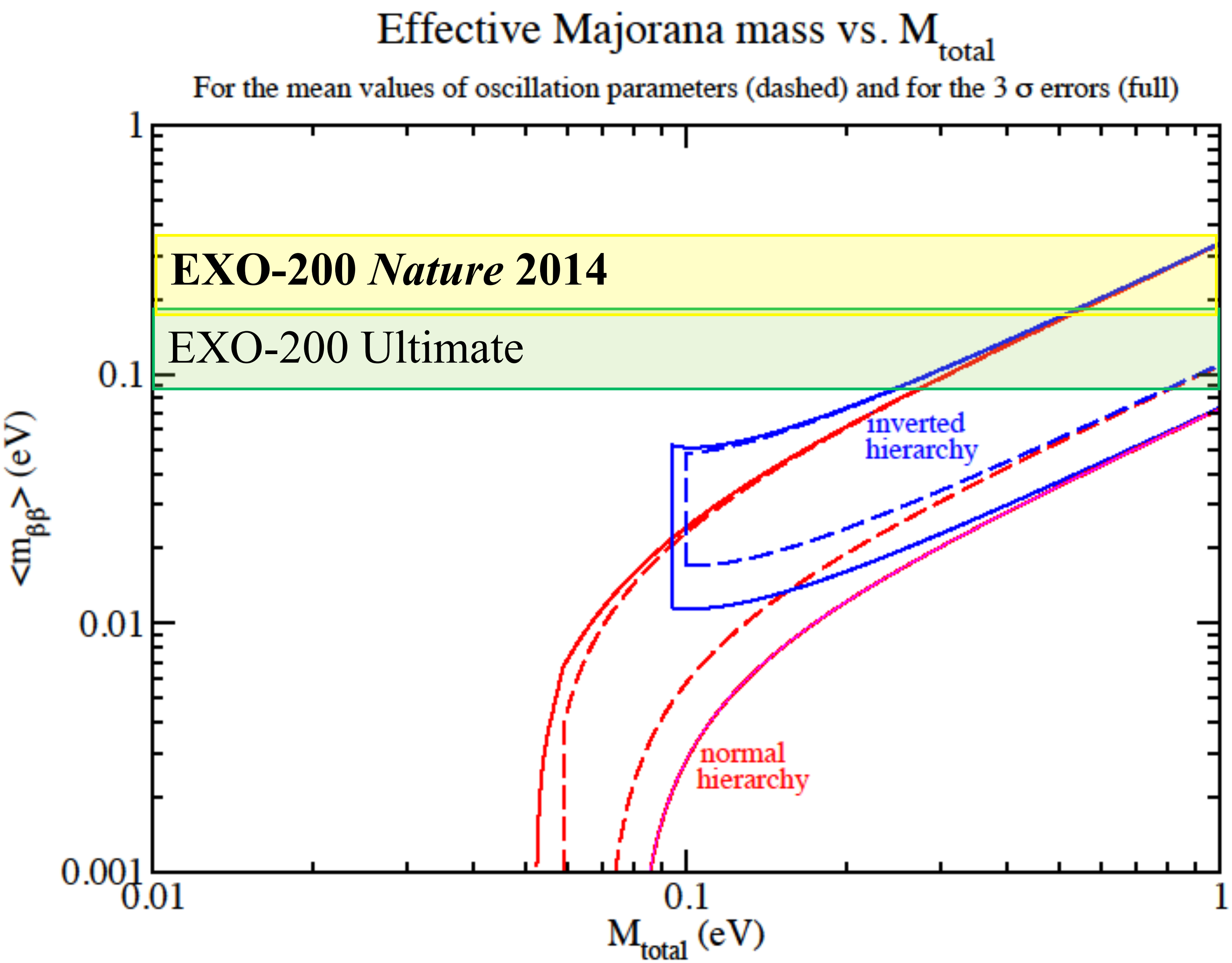
EXO-200 Status and Outlook

Two detector upgrades have been implemented for Phase-II:

• Upgraded front end readout system to enhance detector energy resolution.

• A radon purge system to remove background from external Rn.

Low background physics data ~~is expected to~~ begin in April, 2016.



EXO-200 current sensitivity (90%CL):

1.9 x 10^{25} yr

EXO-200 ultimate sensitivity (90%CL):

5.7 x 10^{25} yr

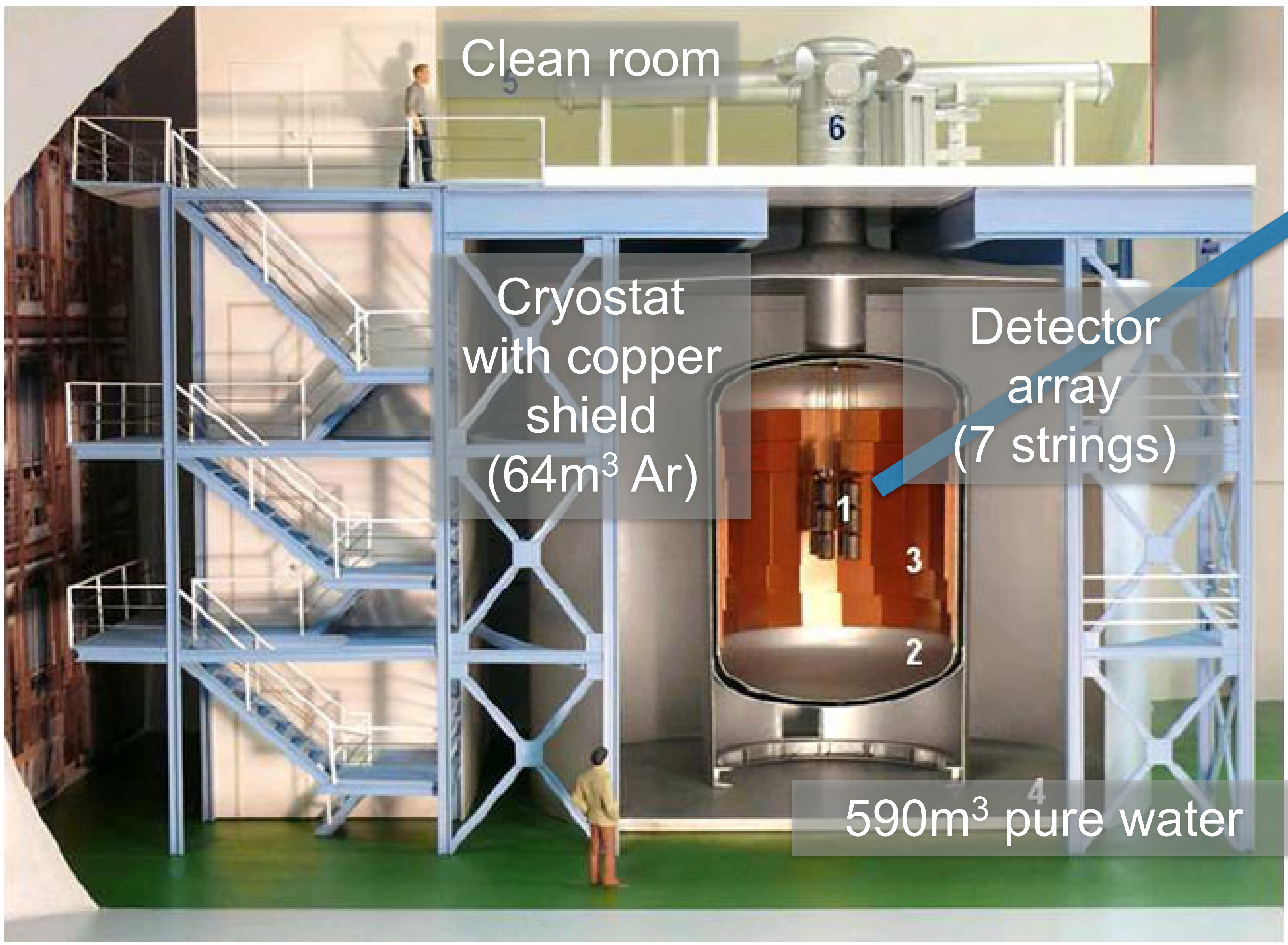
3 years additional running with detector upgrades and analysis improvements

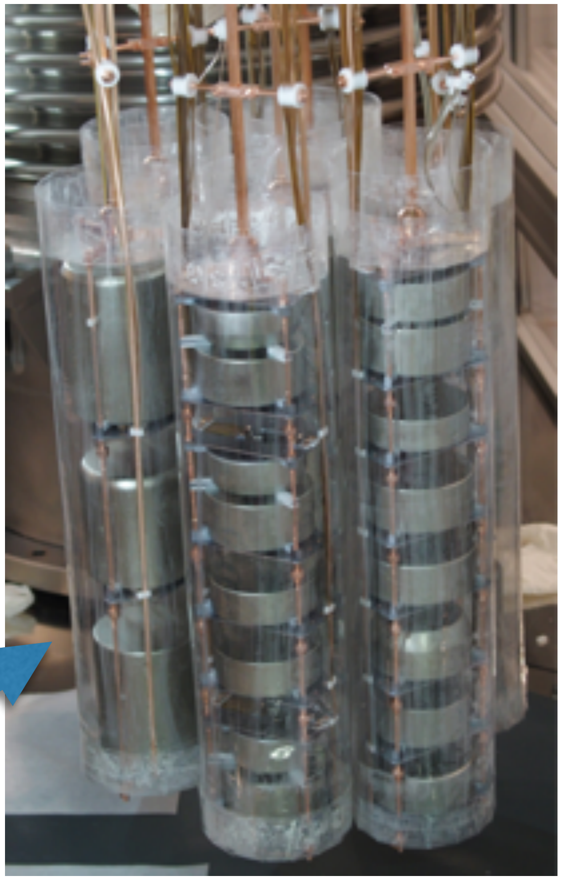
A. Piepke

GERDA (^{76}Ge)

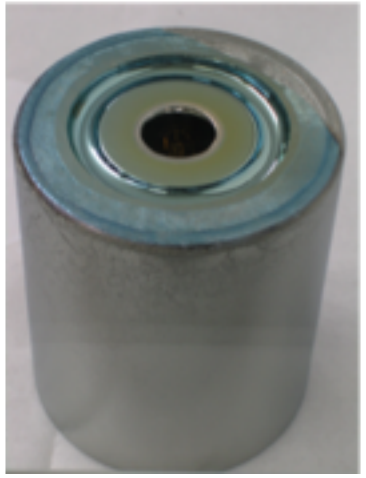
Detector: GERDA

- Located at LNGS (Italy), ~3600 m.w.e.
- HPGe detector array in copper shielding filled with LAr
- Phase I: Nov. 2011 - June 2013
  - 21.6 kg·yr exposure
  - Result $T^{0\nu}_{1/2} > 2.1\times10^{25}$ yr (90% C.L.)
- Phase II: Started in Dec. 2015. First data release on June 2016





Coaxial



Enriched × 7
15.8 kg
Natural × 3
7.6 kg

+

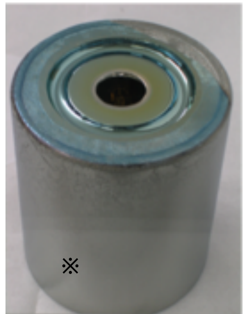
BEGe

Enriched × 30
20.0 kg

GERDA phase-II Result of 0νββ decay

- Doubled target mass & reduced background by factor ~10

Coaxial

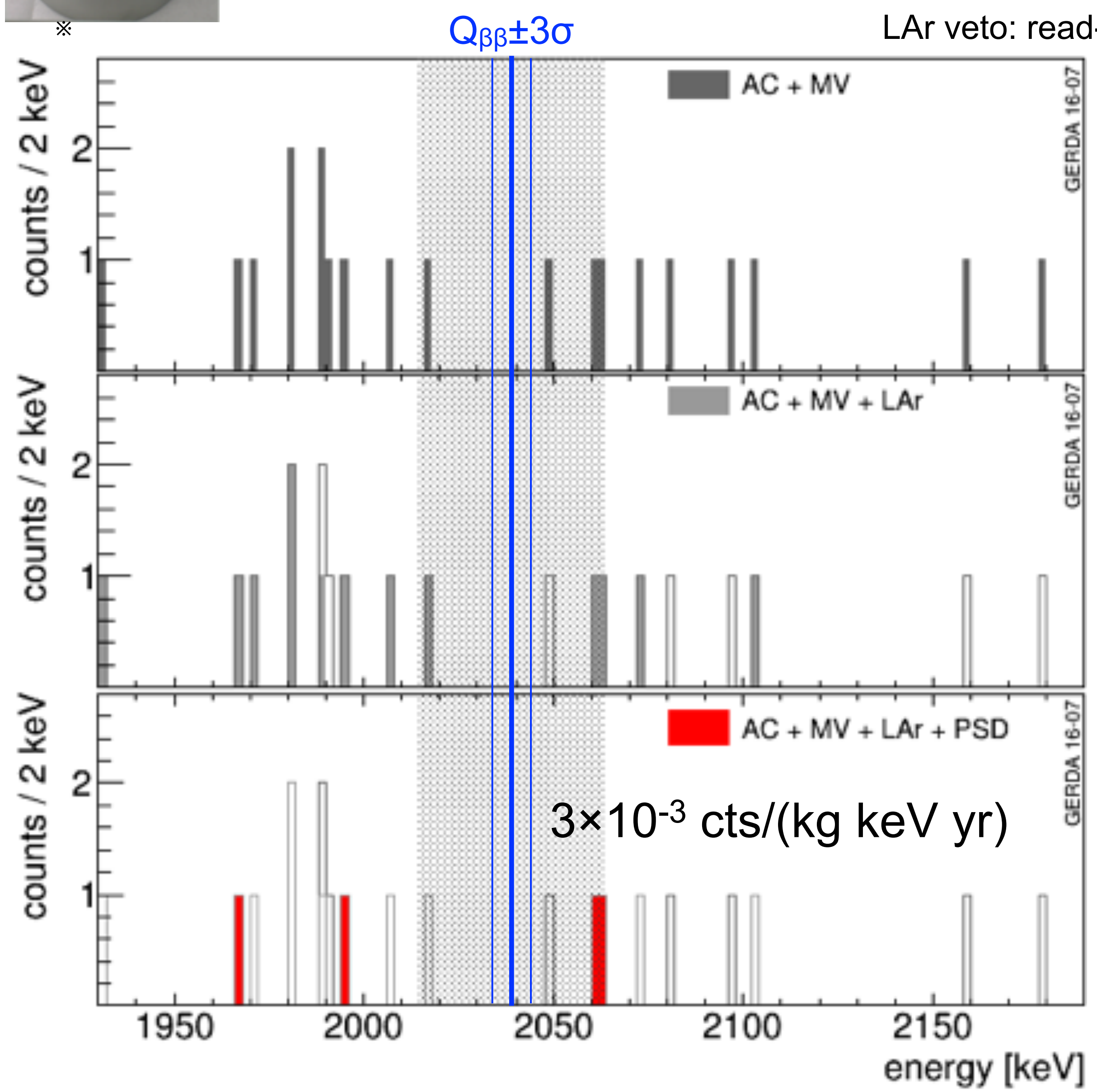


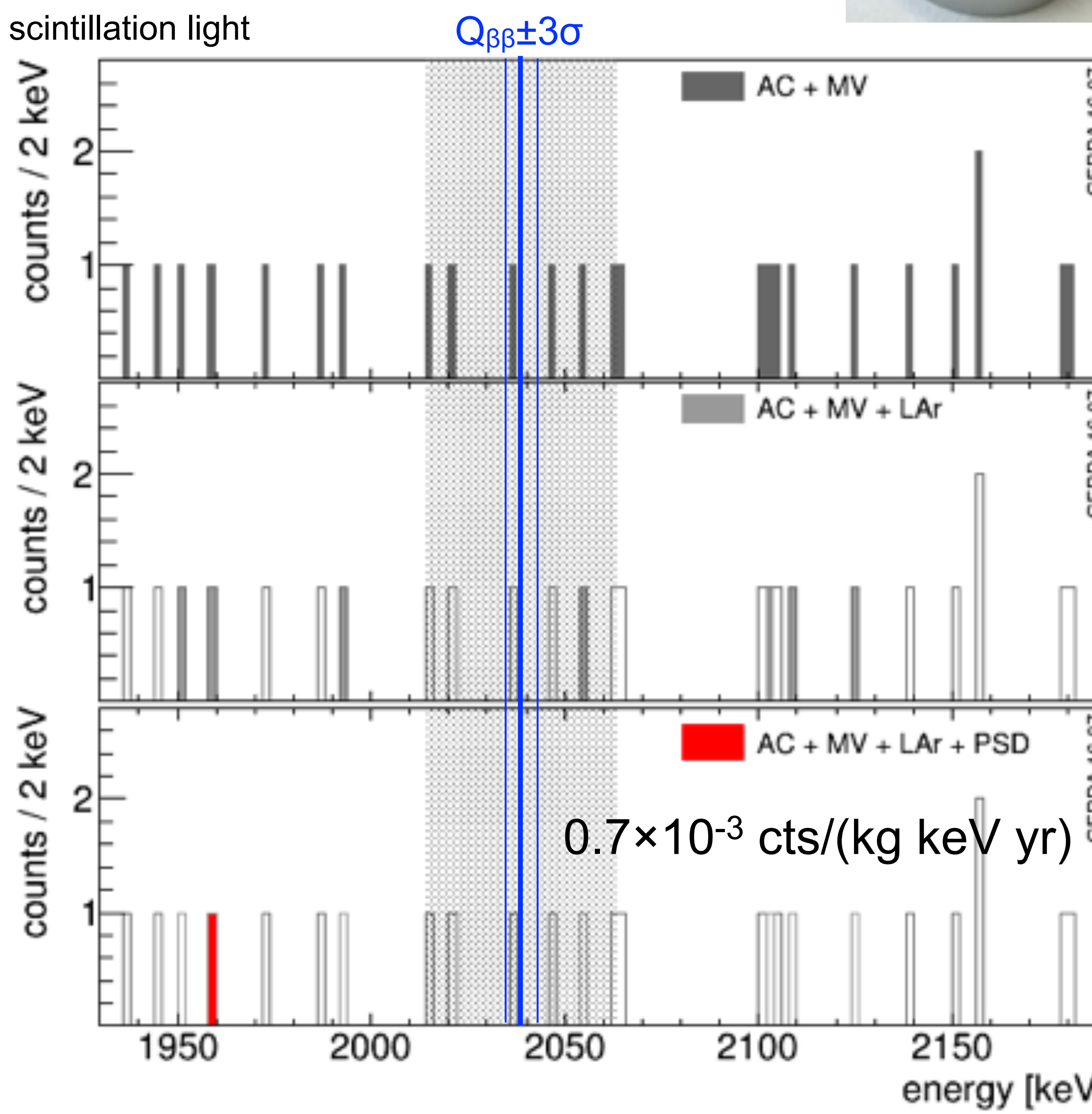
- 5.0 kg·yr exposure
- Resolution(FWHM) 4.0 keV

- 5.8 kg·yr exposure
- Resolution(FWHM) 3.0 keV

BEGe

AC: anti-coincidence cut, MV: muon veto, PSD: pulse shape discrimination,
LAr veto: read-out LAr scintillation light

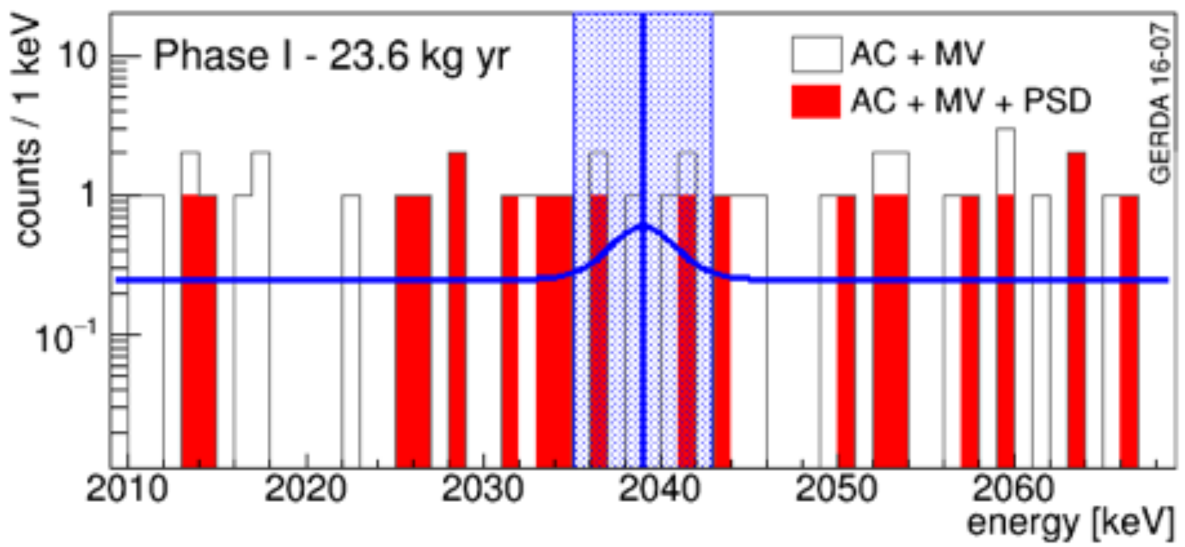




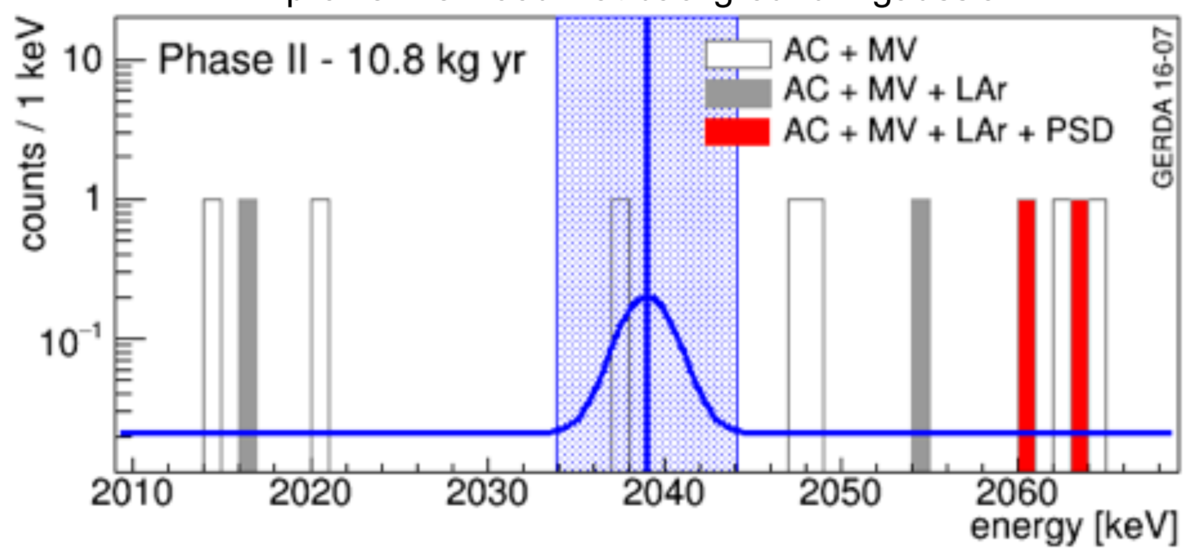
GERDA Phase II reached it’s background goal

GERDA phase-II Result of 0νββ decay

- Doubled target mass & reduced background by factor ~10



profile likelihood: flat background + gaussian



preliminary

	profile likelihood 2-side test-stat	Bayesian flat prior on cts
Best fit value of 0νββ [cts]	0	0
$T^{1/2}$ lower limit [yr] (90% C.L.)	**$> 5.2 \times 10^{25}$**	$> 3.5 \times 10^{25}$
$T^{1/2}$ median sensitivity [yr] (90% C.L.)	$> 4.0 \times 10^{25}$	$> 3.0 \times 10^{25}$

$m_{\beta\beta}$ < 160 – 260 meV (90% C.L.)

Sensitivity with a total 100 kg yr exposure: 10^{26} years (90% C.L.)

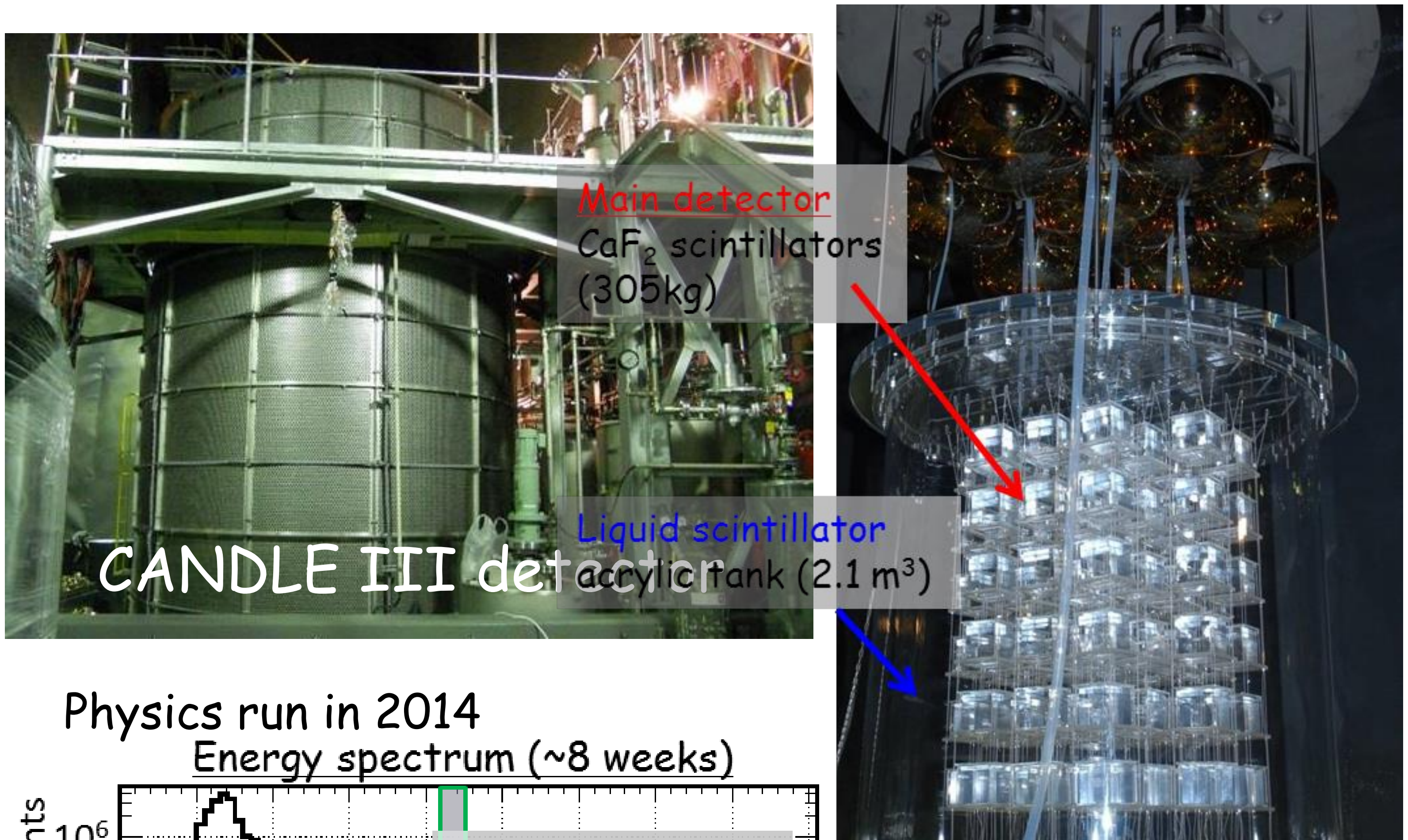
CANDLES (^{48}Ca)

S.Yoshida

CANDLES Experiment

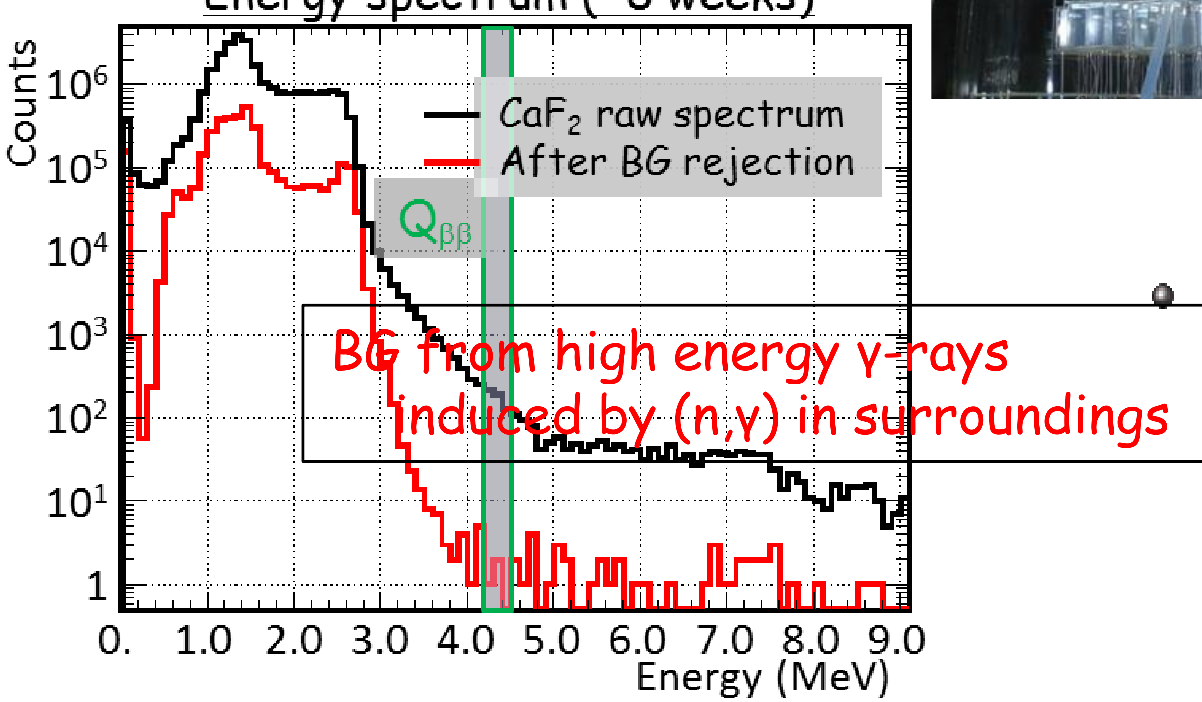
Highest Q-valued

- **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

Energy spectrum (~8 weeks)



- **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 m³ (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

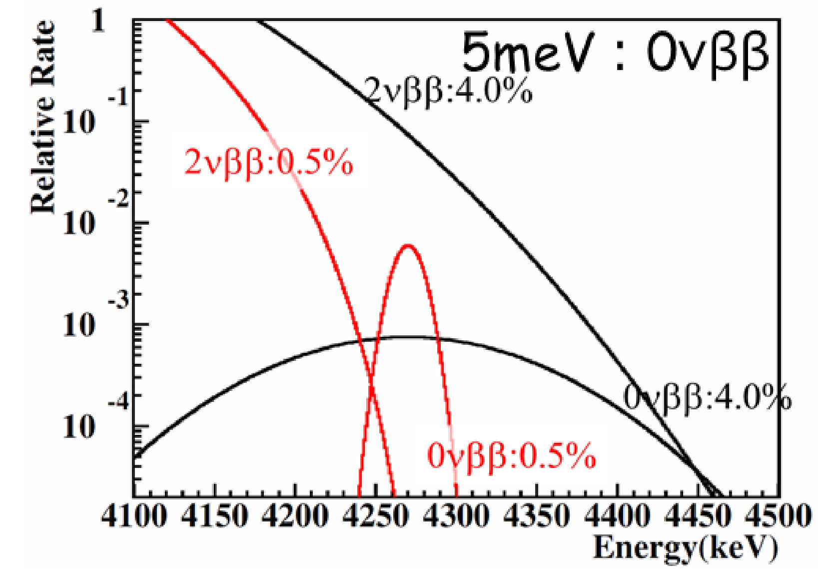
Installed in 2016

S.Yoshida

Development in Future

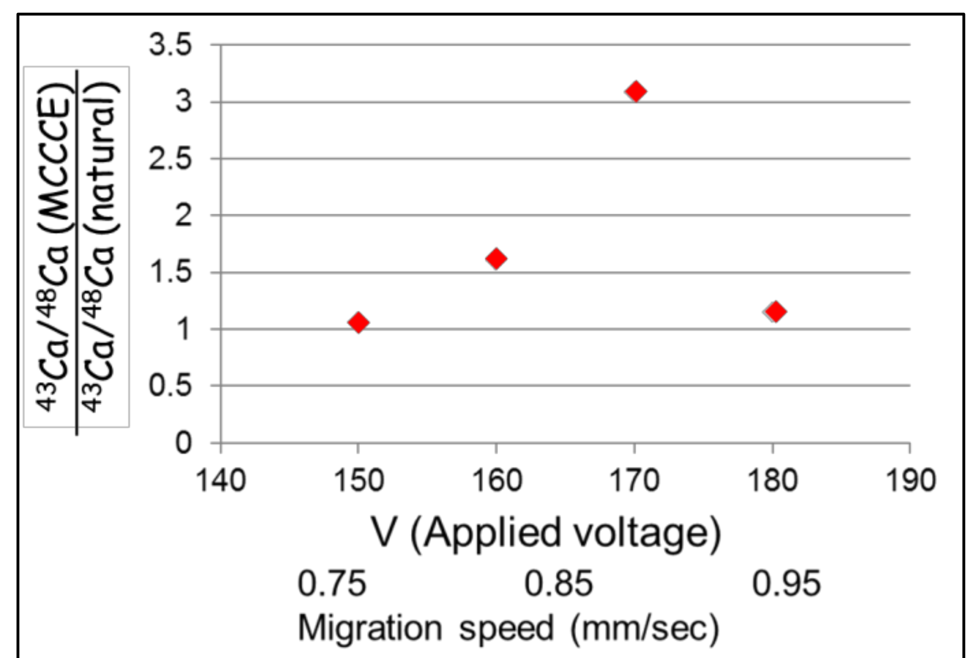
- Exploring Inverted hierarchy → Normal hierarchy region

	CANDLES III	Next CANDLES		
Crystal	3.2kg × 96 crystals	2% ^{48}Ca		50% ^{48}Ca
Total Mass	305kg (350g)	2 ton (25kg)		2 ton(610kg)
Energy Resolution	(4.0%)	2.8%(Req.)	⇨	0.5%(Req.)
$2\nu\beta\beta$	0.01	0.1		0.01
^{212}Bi, ^{208}Tl	0.26	~0.1		~0.01
Expected BG	0.27/year	< 0.7/3year		< 0.2/9year
$\langle m_\nu \rangle$	0.5 eV	0.08		0.009
	Current system	~2% enriched ^{48}Ca and cooling system		



- Development 1 : ^{48}Ca Enrichment, to increase the ββ source amount
  - Difficulties of ^{48}Ca enrichment
    - Centrifugal method is not possible due to unavailability of gas compounds.
    - Commercial → expensive (~ M$/10g), too small amount for ton-scale.
  - Challenges in CANDLES: cost effective
    - Multi-channel counter current electrophoresis

      Achieved (43/40): 3.08 ≒ (48/40): ~ 6
    - Crown ether resin + chromatography
    - Crown ether liquid + micro reactor
    - Laser: recoil by laser light momentum



The enrichment techniques were established for the small amount of Calcium. The techniques are promising, we are on the stage of stable driving.

S.Yoshida

Development in Future

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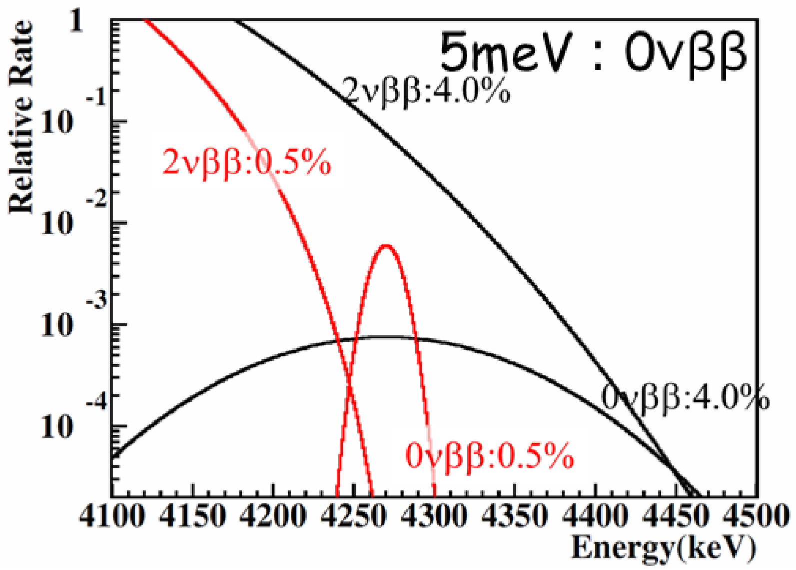
$\langle m_\nu \rangle$	0.5 eV	0.08		0.009
	Current system	~2% enriched ^{48}Ca and cooling system		



- Developent2 : Improving Energy Resolution
  - <u>Unavoidable BG of 2νββ tail events</u>
    - Impossible to further improve the energy resolution of CaF_2 <u>scintillator</u>
    ➔ Development of ^{48}CaXX (scintillating) bolometer
  - <u>Development in CANDLES</u>
    - Bolometer → expect much improving energy resolution.
    - Scintillating → to avoid BG of ^{238}U (α) by α/β particle ID
    - CaF_2 crystal → Highly radio-pure CaF_2 scintillator is already developed in CANDLES !
      (less than a few μBq/kg of U/Th chain impurity)

The cooling operation is in progress. We will soon achieve the temperature at 10mK, and detect the heat signal from CaF_2 crystal through NTD-Ge thermistor.

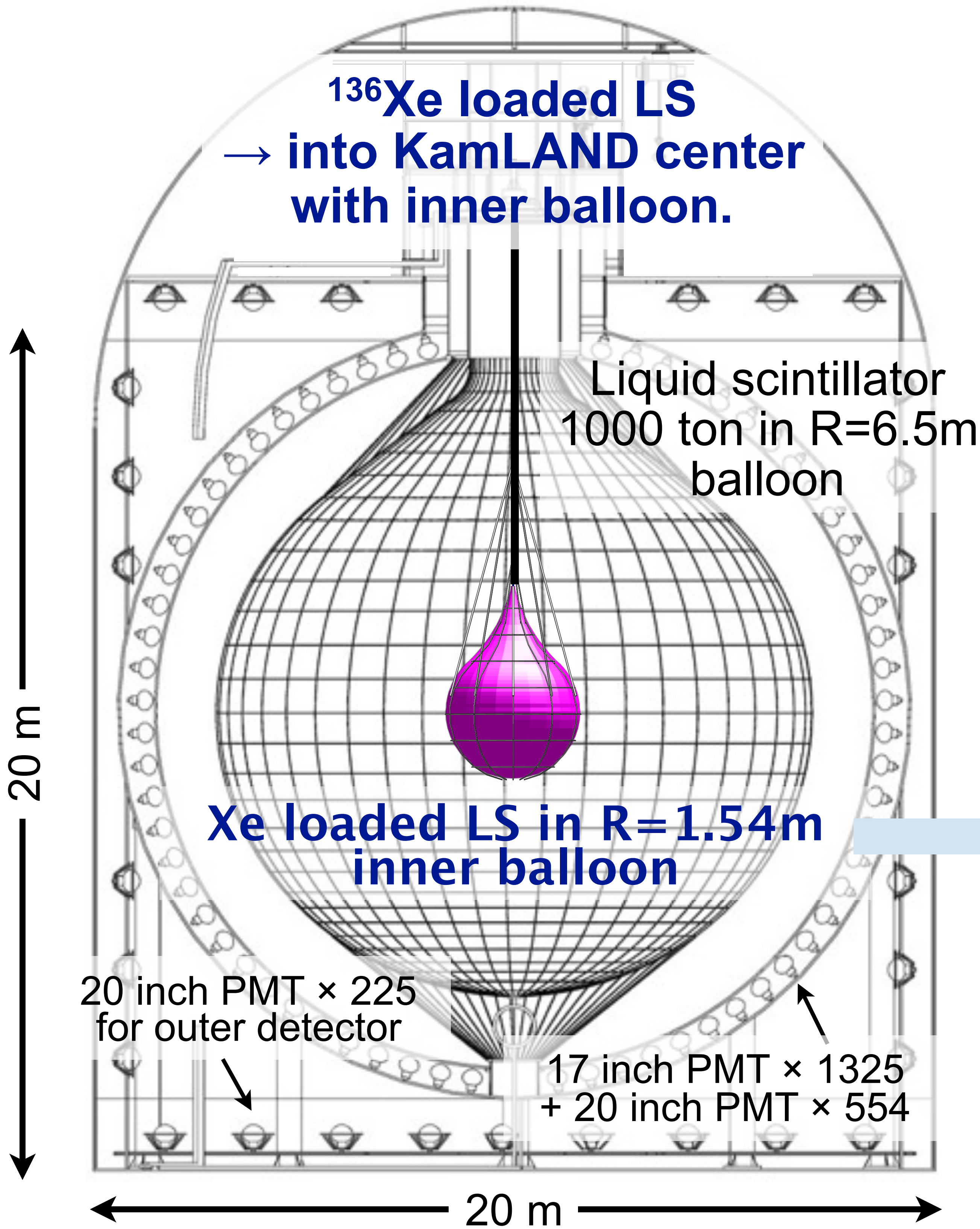


Dilution refrig. & detector for this study, developed by Minowa-group

KamLAND-Zen (^{136}Xe)

Detector: KamLAND-Zen

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

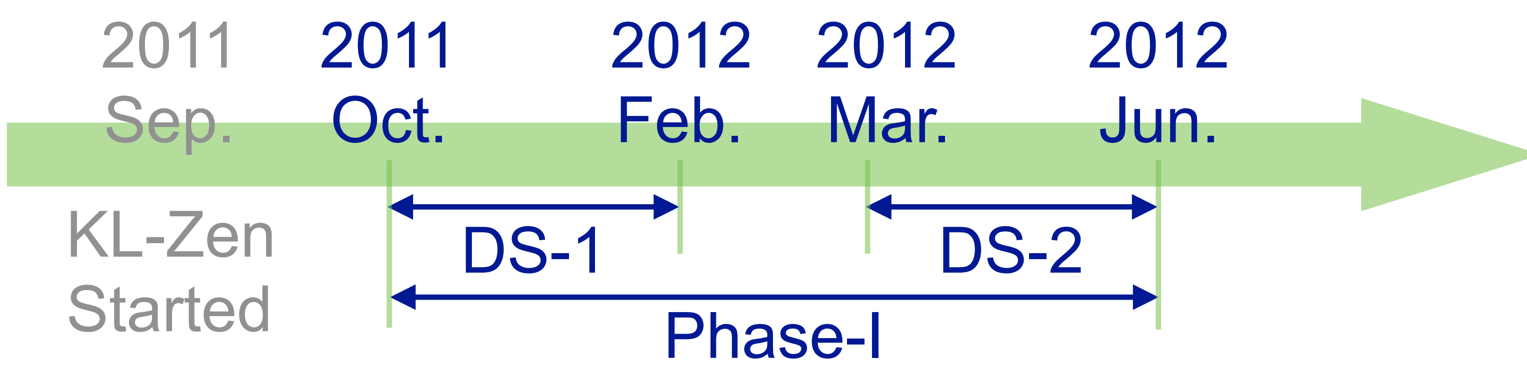


Advantage

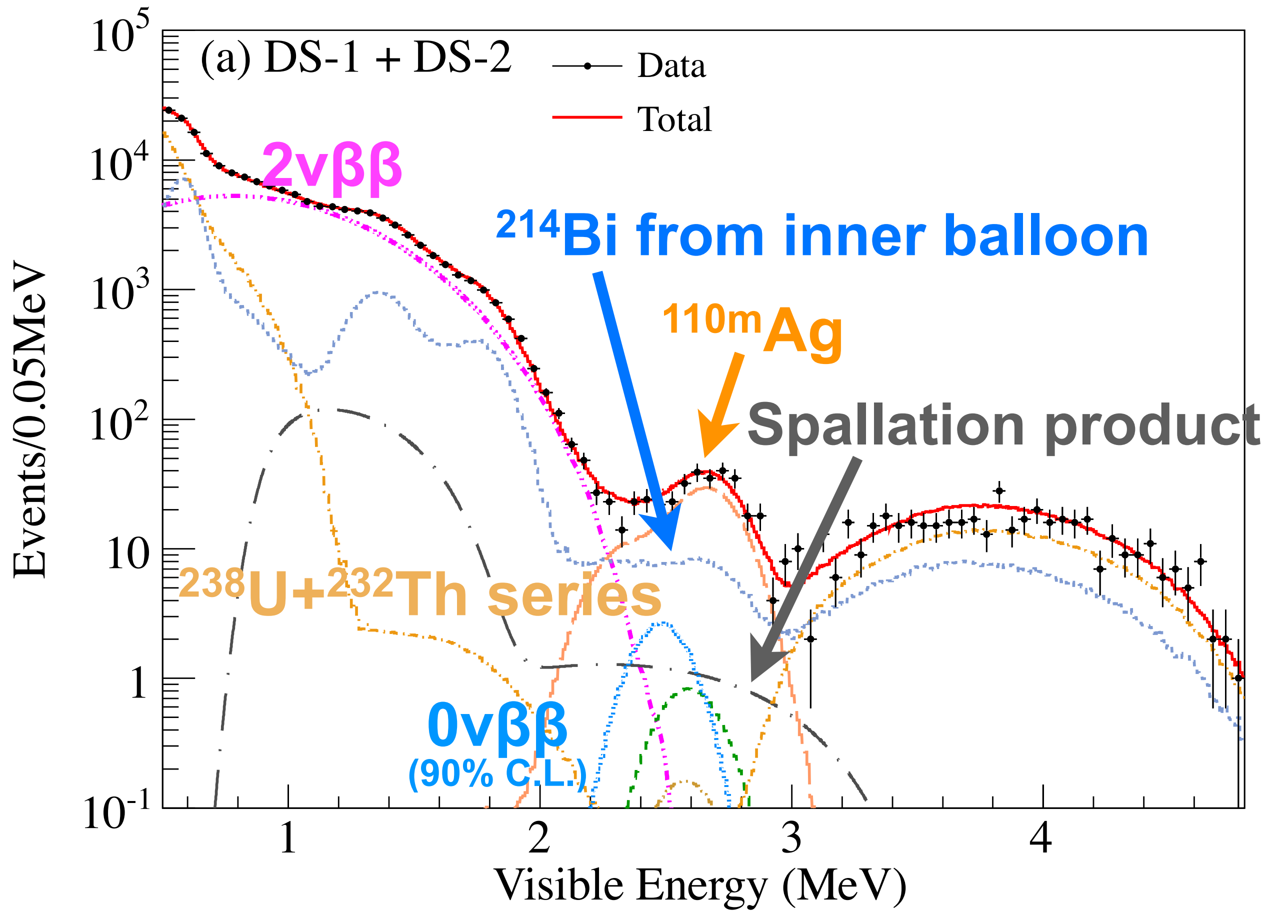
- Running detector
  Well known detector response
- Low background
  U, Th are at $10^{-17 \sim -18}$ g/g level
- Big detector → high scalability
  Ton order isotopes

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



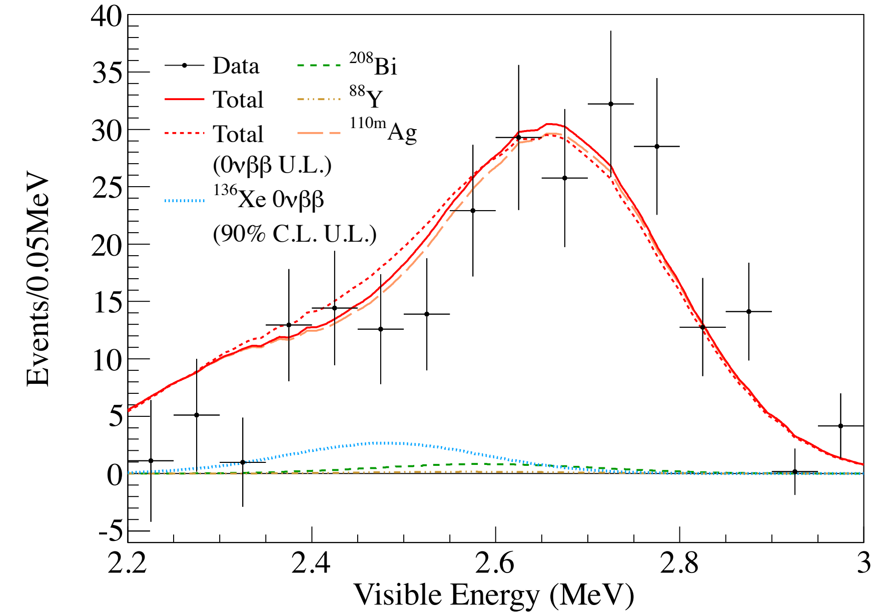
Lower limit of 0νββ decay half-life

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

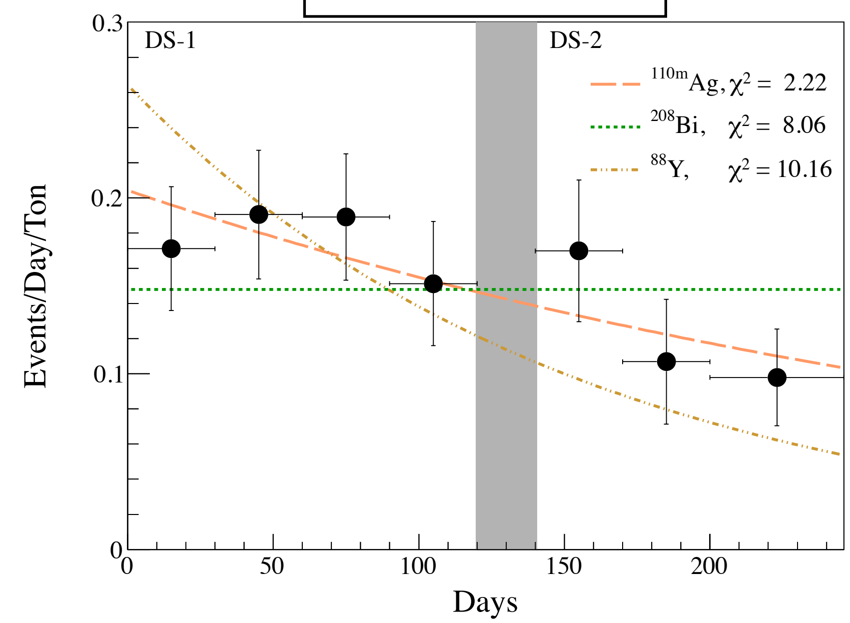
- Most stringent limit at that time.
- But many background at ROI. It is ^{110m}Ag (Q value of ^{136}Xe : 2.458 MeV)

Event in 2.2<E<3.0 MeV

Energy spectrum (linear, known BG subtracted)

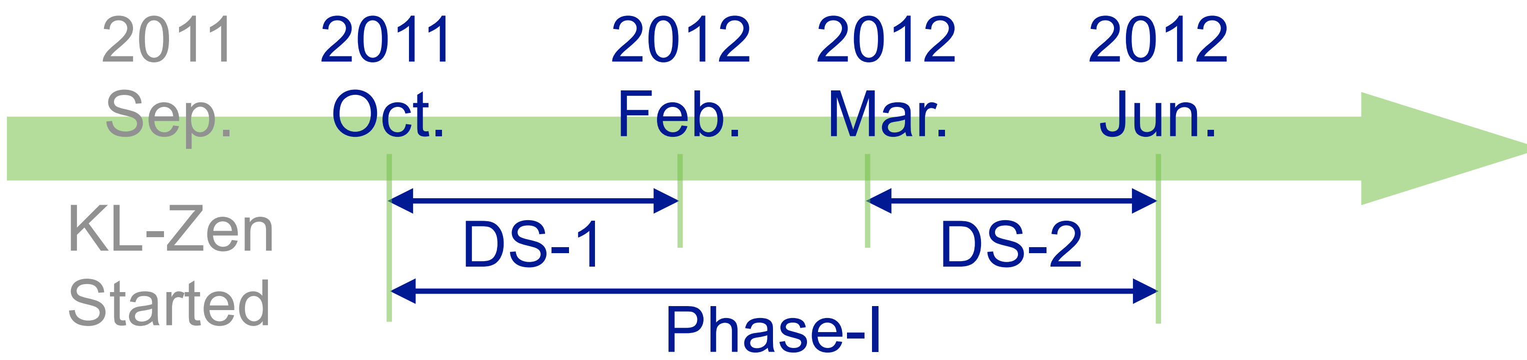


Time variation

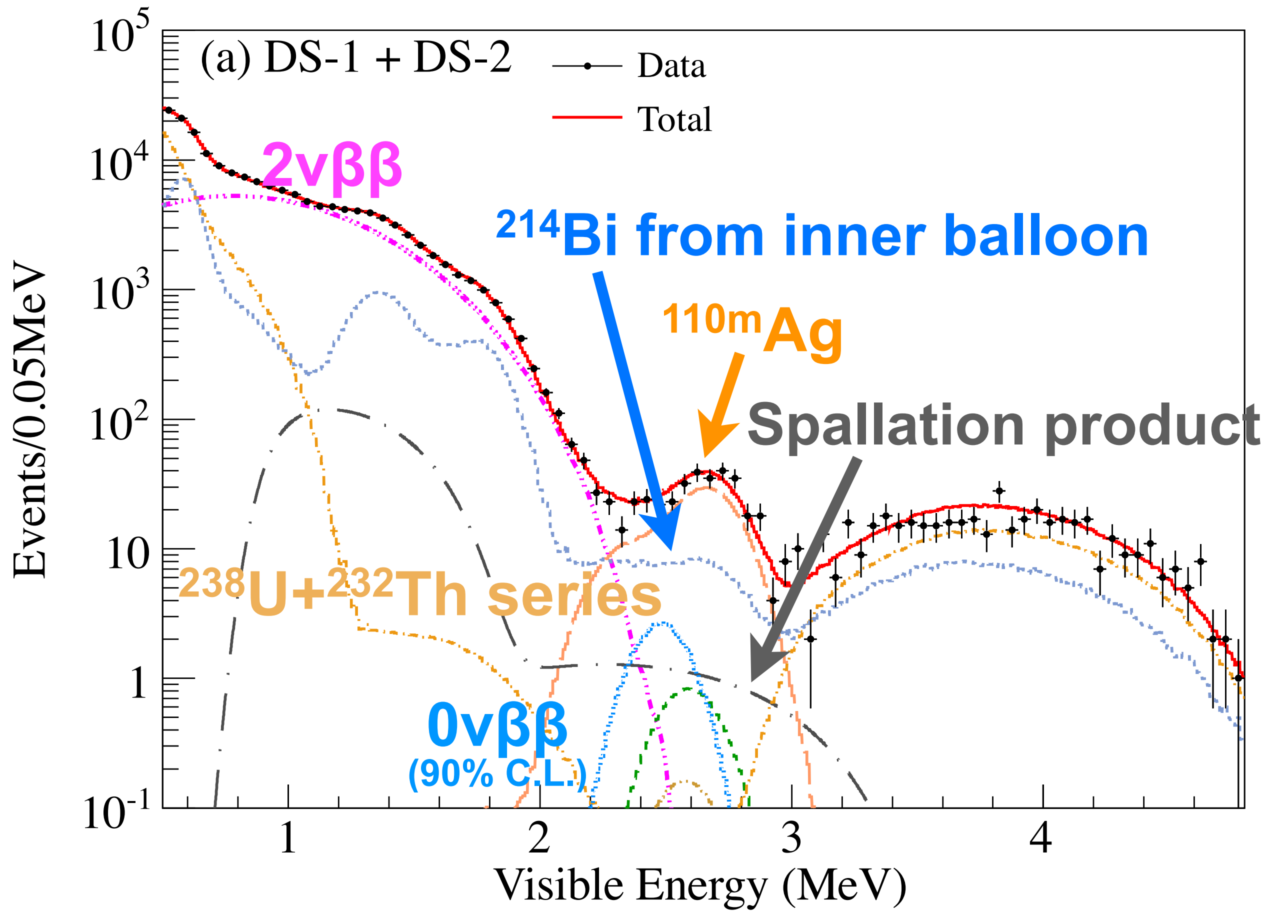


Unexpected peak → ^{110m}Ag

History



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



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

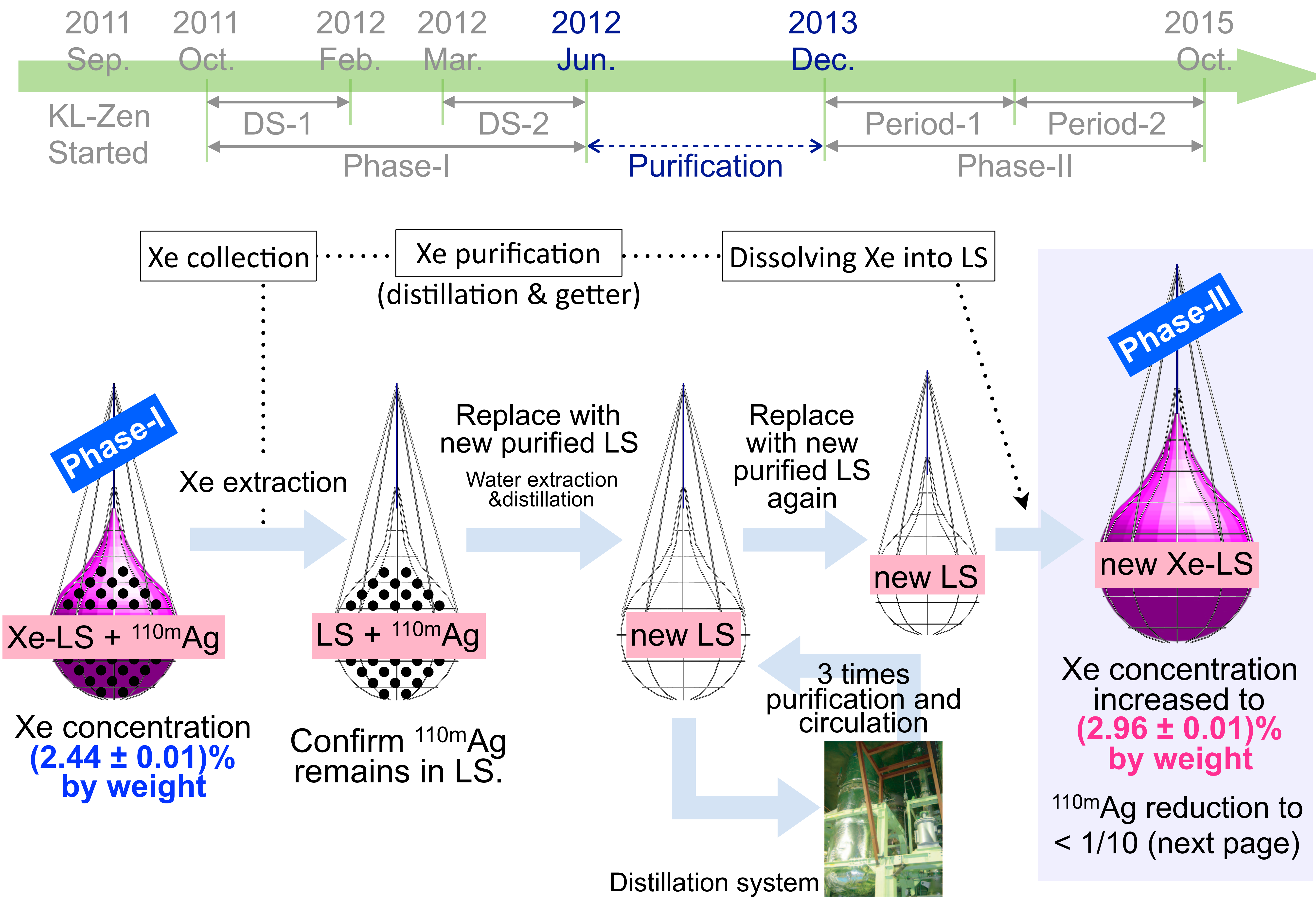
Large amount
Small amount

Lower limit of 0νββ decay half-life

$T^{1/2} > 1.9\times10^{25}$ 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)

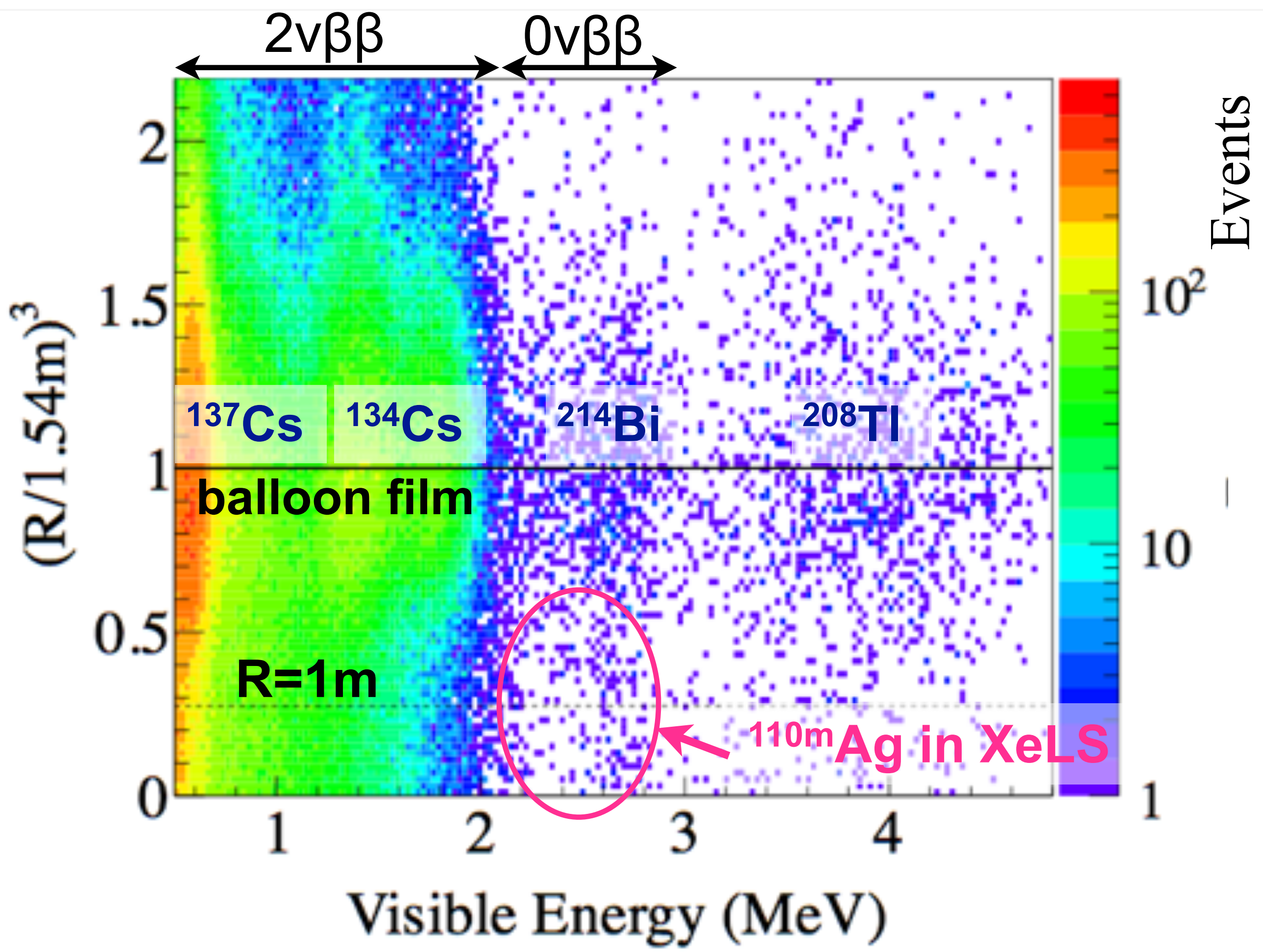
History



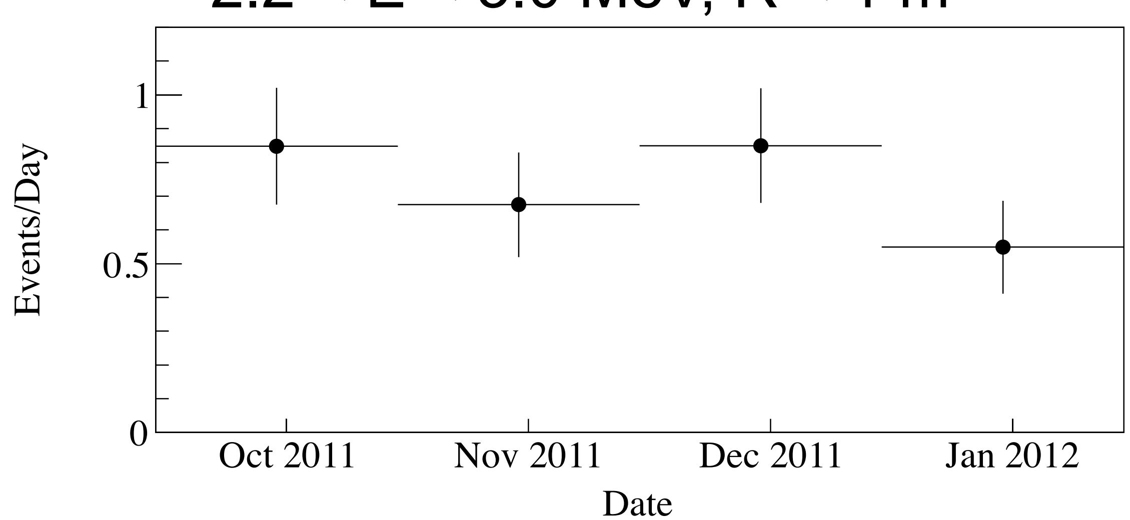
2011 Sep.
2011 Oct.
2012 Feb.
2012 Mar.
2012 Jun.
2013 Dec.
2015 Oct.
KL-Zen Started
DS-1
DS-2
Phase-I
Purification
Period-1
Period-2
Phase-II
Xe collection
Xe purification
(distillation & getter)
Dissolving Xe into LS
Phase-I
Xe extraction
Replace with new purified LS
Water extraction &distillation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

^{110m}Ag background reduction

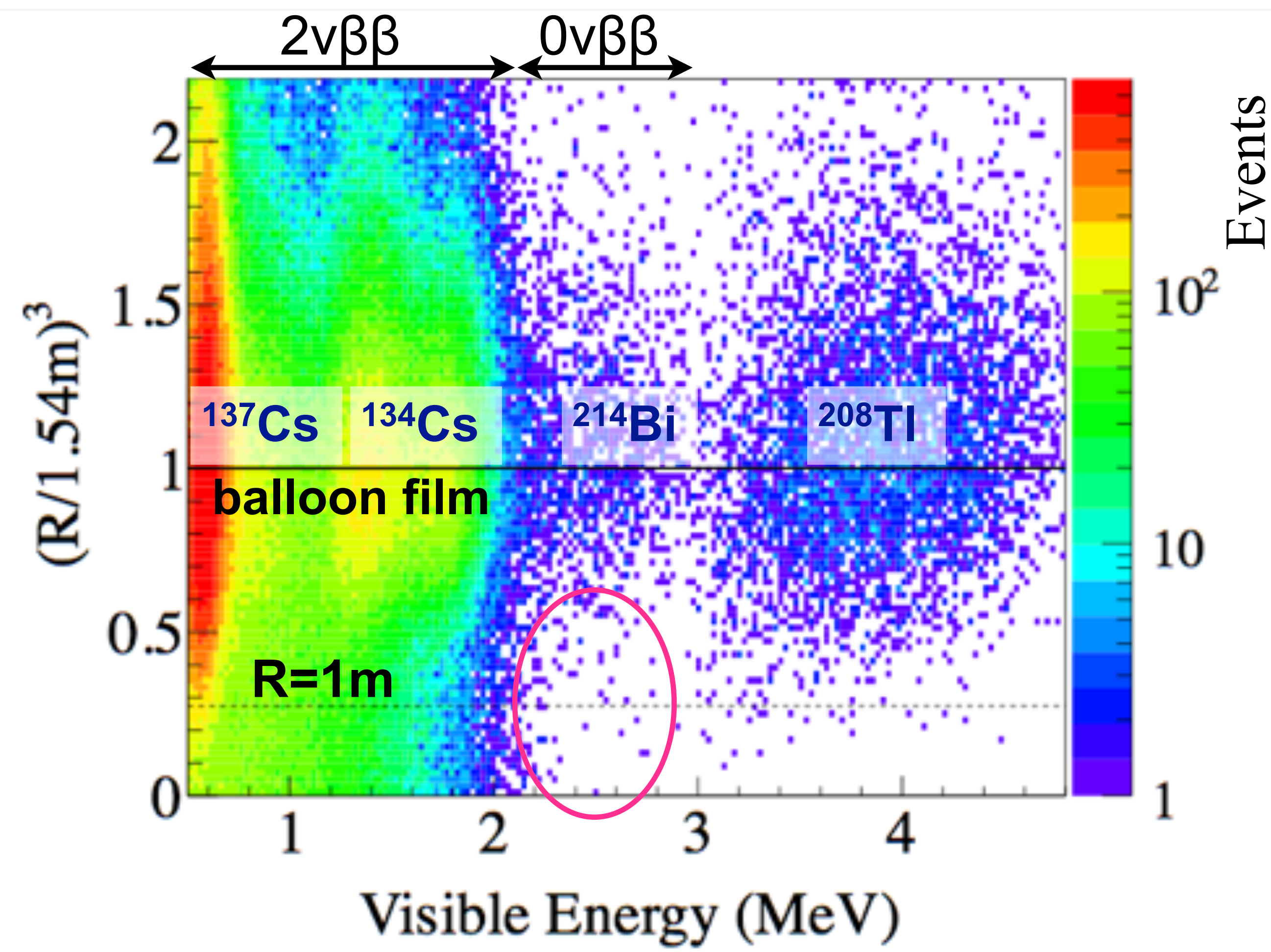
Phase-I (first 112.3 days)



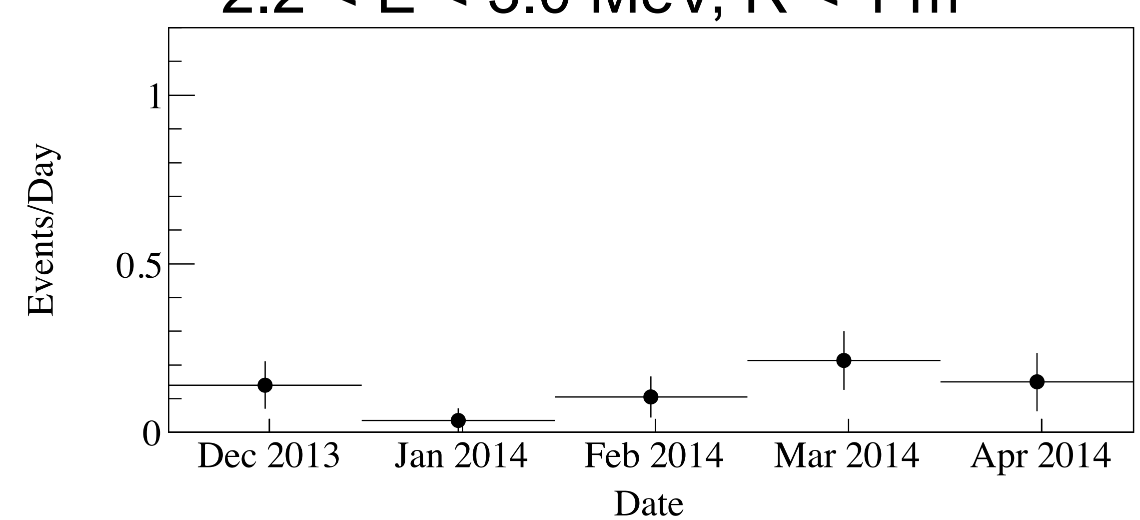
2.2 < E < 3.0 MeV, R < 1 m



Phase-II (first 114.8 days)



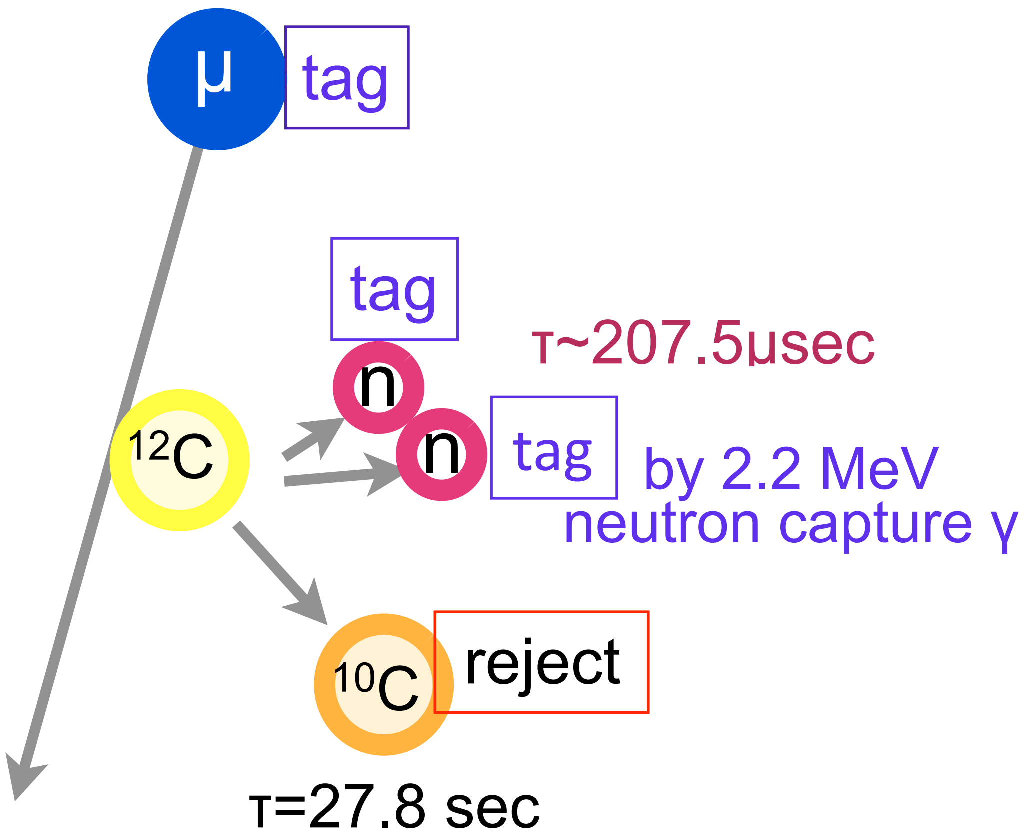
2.2 < E < 3.0 MeV, R < 1 m



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

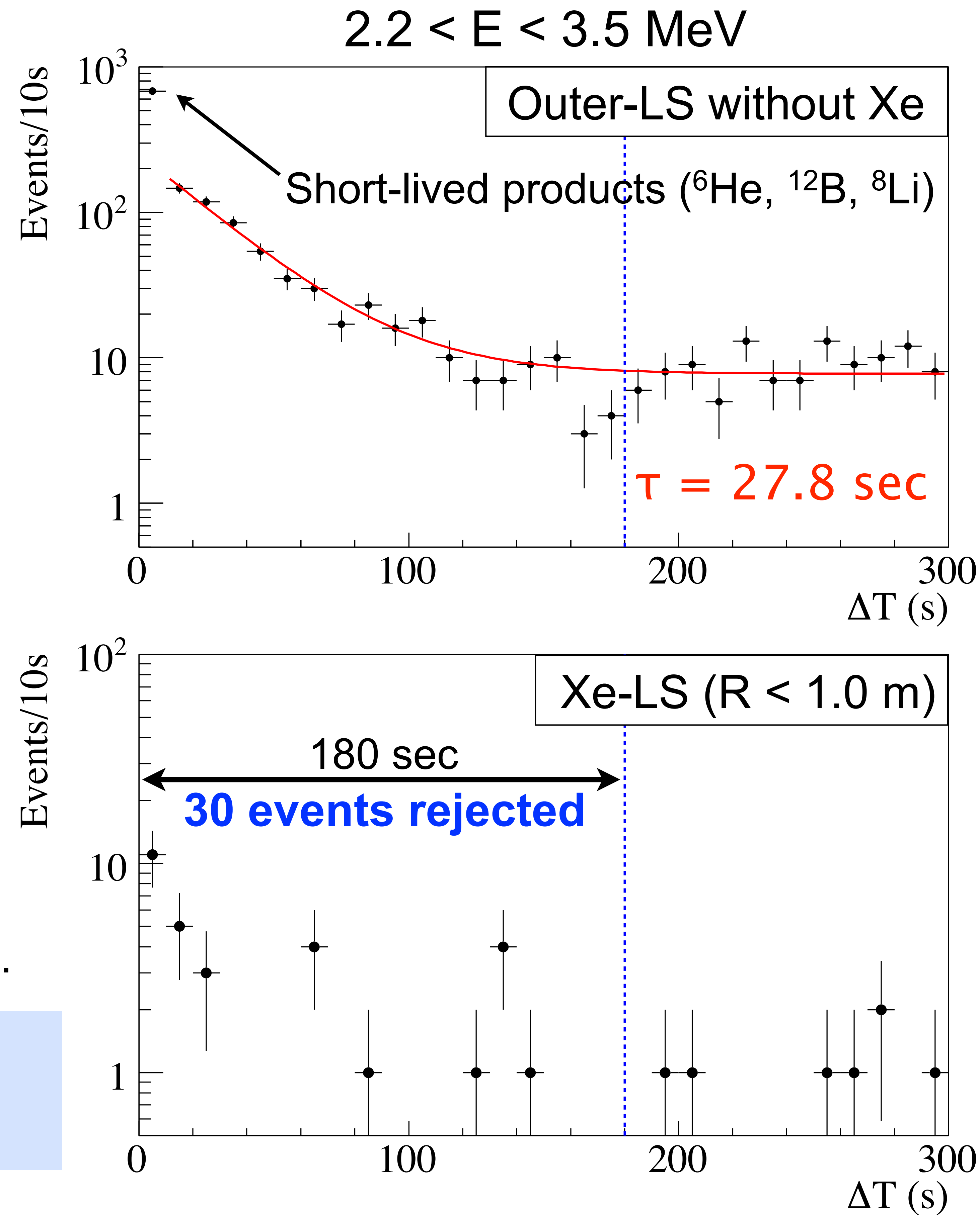
Spallation cut

- Main target is ^{10}C
- Triple coincidence with muon, neutron and ^{10}C

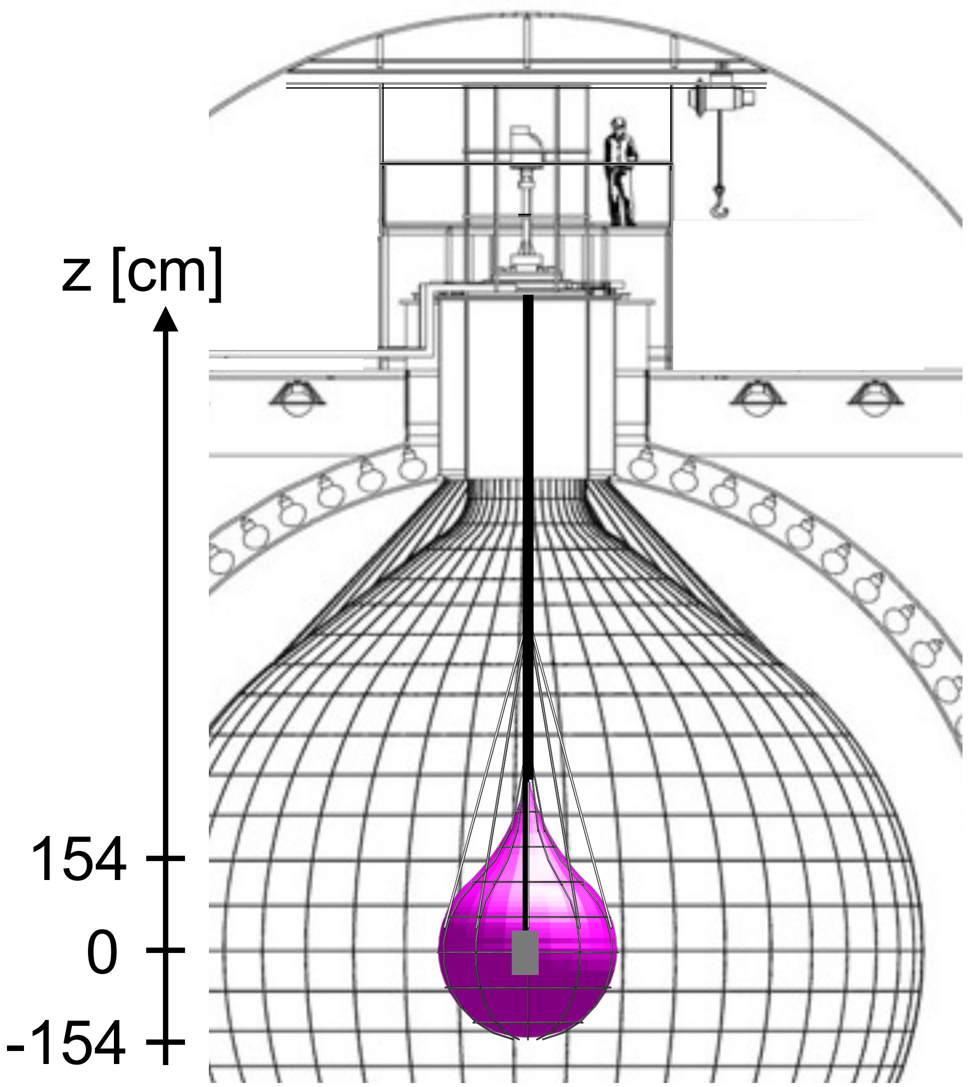


Thanks to dead time free electronics, neutron tagging efficiency is improved.

BG rejection efficiency (^{10}C) 64 ± 4%
signal inefficiency 7%



Source calibration



Composite source

^{60}Co (1.173 + 1.333 MeV)

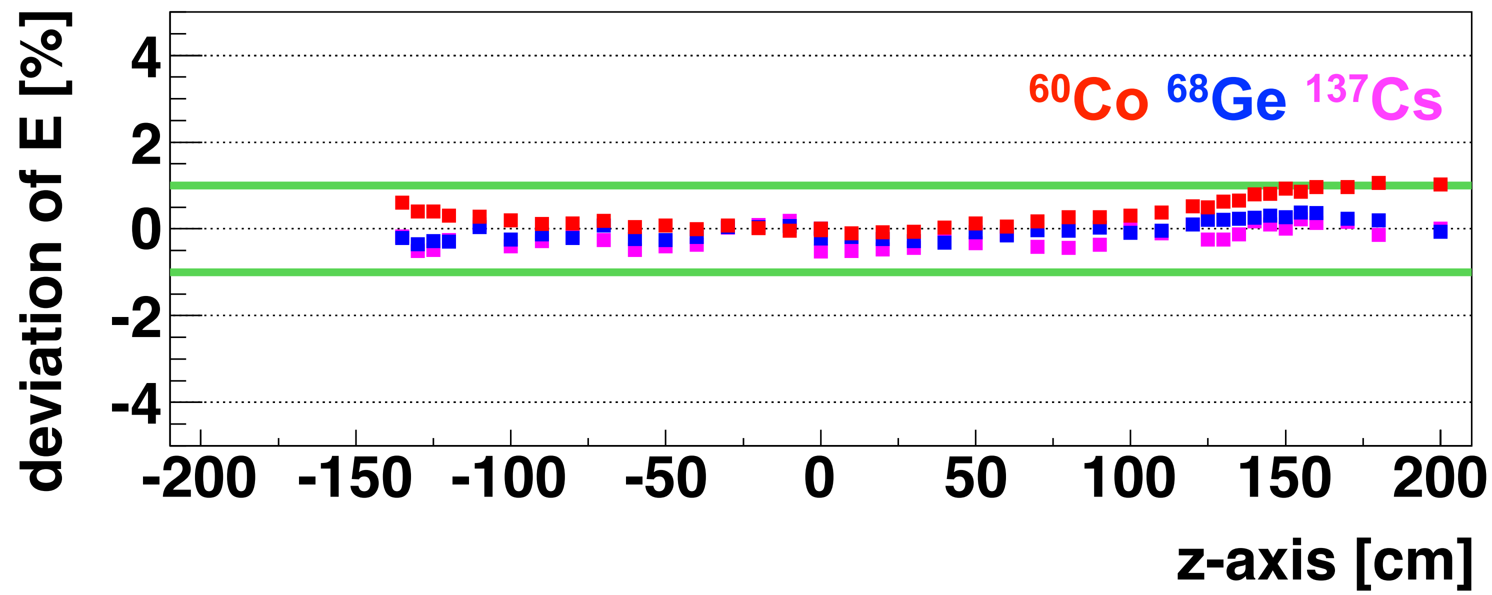
^{68}Ge (0.511 × 2 MeV)

^{137}Cs (0.662 MeV)

$\sigma \sim 7.3\%/\sqrt{E(\mathrm{MeV})}$

z-dependence of energy

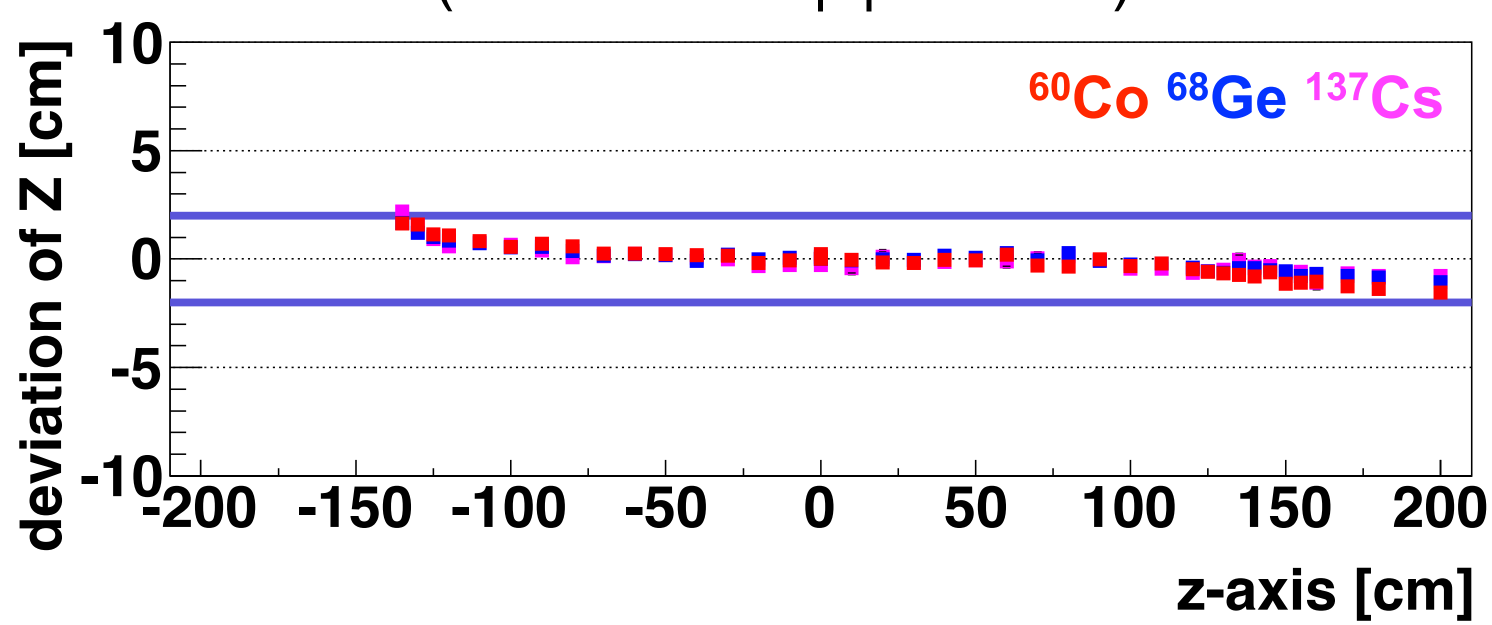
Position dependent bias < 1.0%



z-dependence of vertex

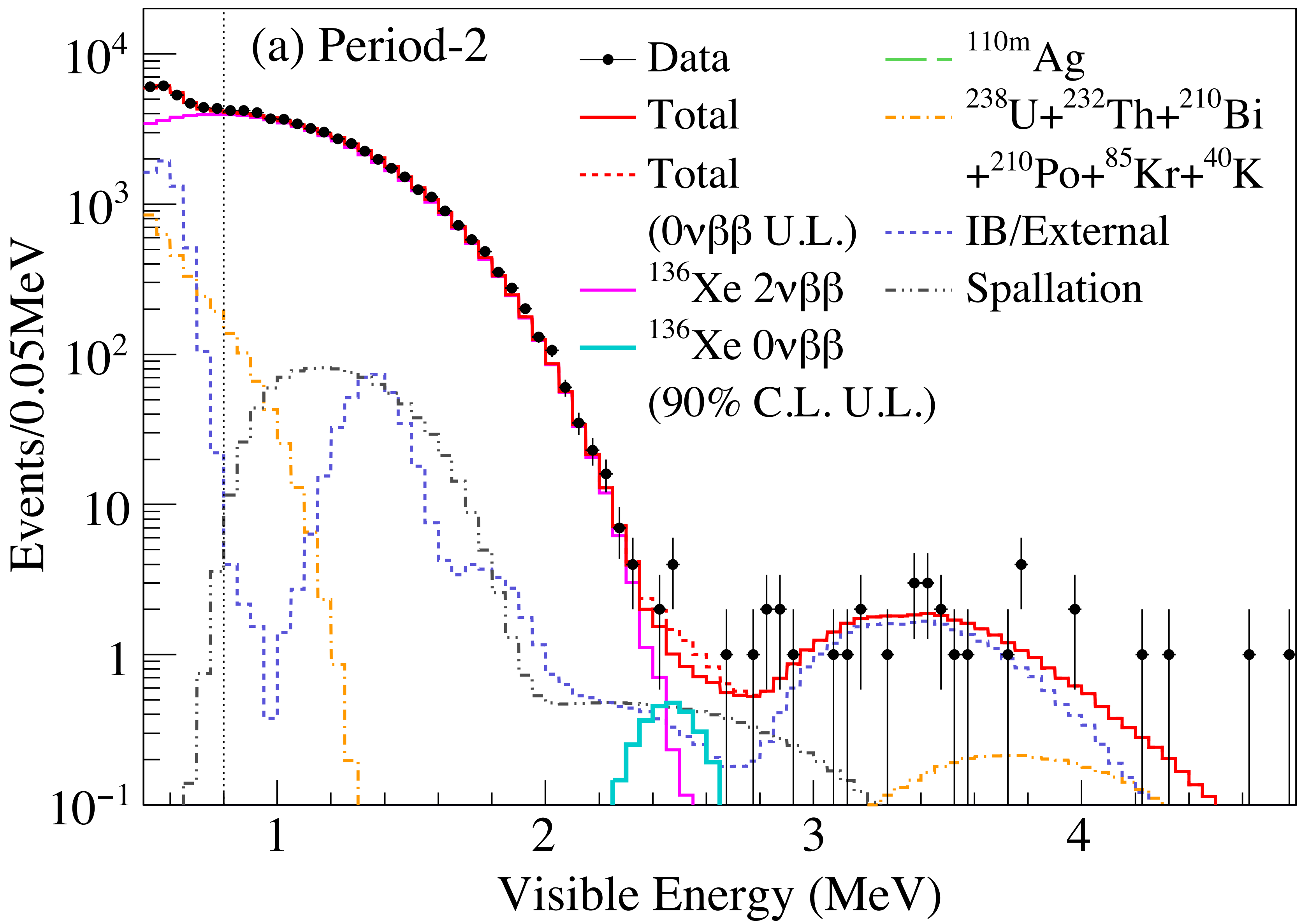
position dependent bias < 2.0 cm

(< 1.0 cm for |z| < 1.0 m)



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

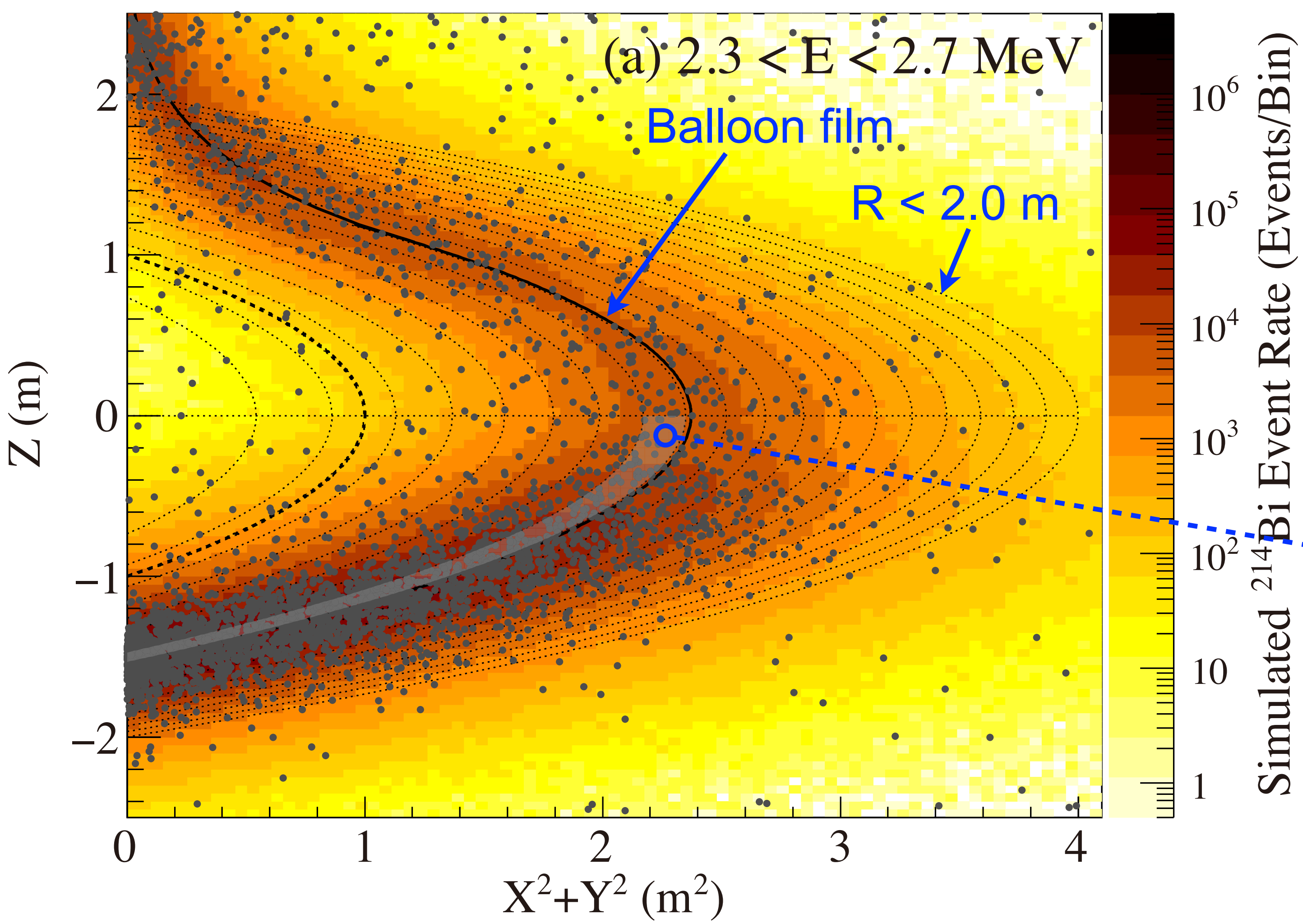
$T^{1/2}(2\nu) = 2.21 \pm 0.02(\text{stat}) \pm 0.07(\text{syst}) \times 10^{21}$ yr

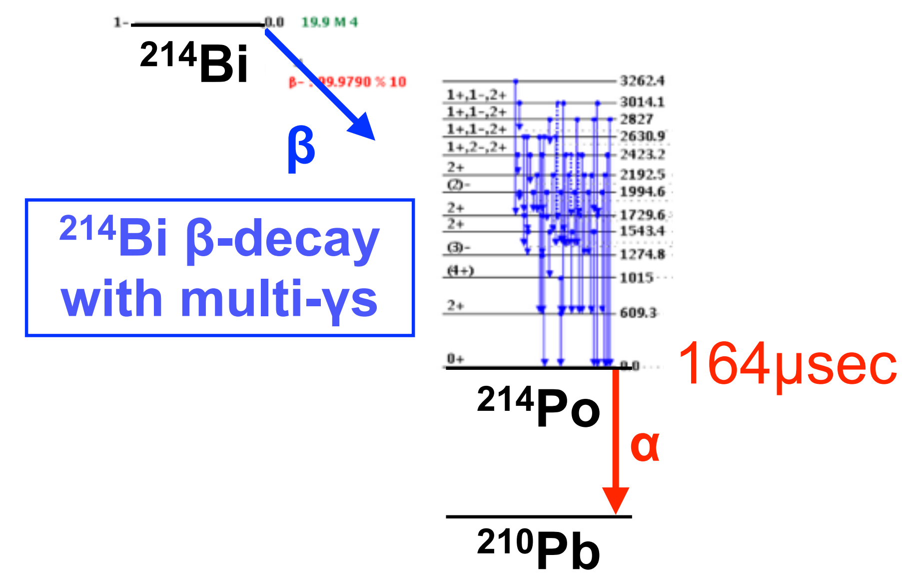
- Total ^{136}Xe exposure = 126 kg yr
- Consistent with previous KamLAND-Zen results and EXO-200 results

Fiducial volume selection for $0\nu\beta\beta$ analysis

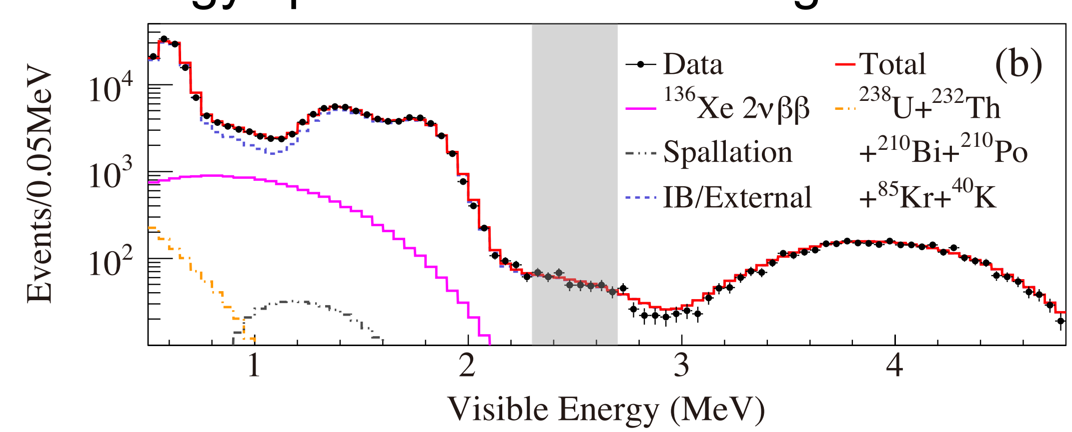
Distribution of ^{214}Bi background from IB film is asymmetry.
Larger background at the bottom → Effected to fiducial volume selection.

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





Energy spectrum of shaded region



Multi-volume selection for analysis optimization

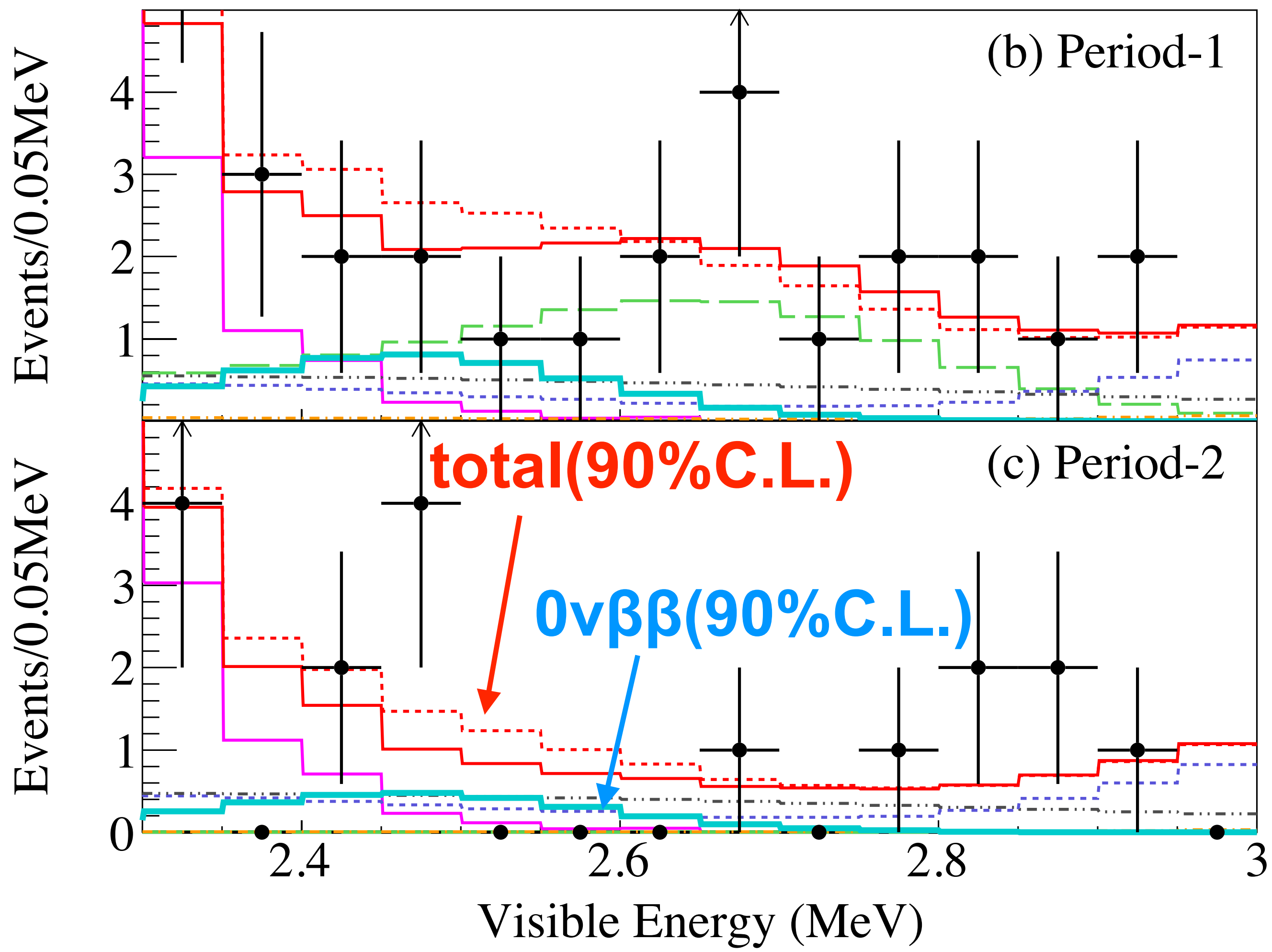
Target volume for spectral fit : R < 2.0 m

lower / upper hemisphere

R 20bin (same volume in each radius bin)× Theta 2bin ($-1<\cos\theta<0$, $0<\cos\theta<1$)

Result of 0νββ decay

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



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

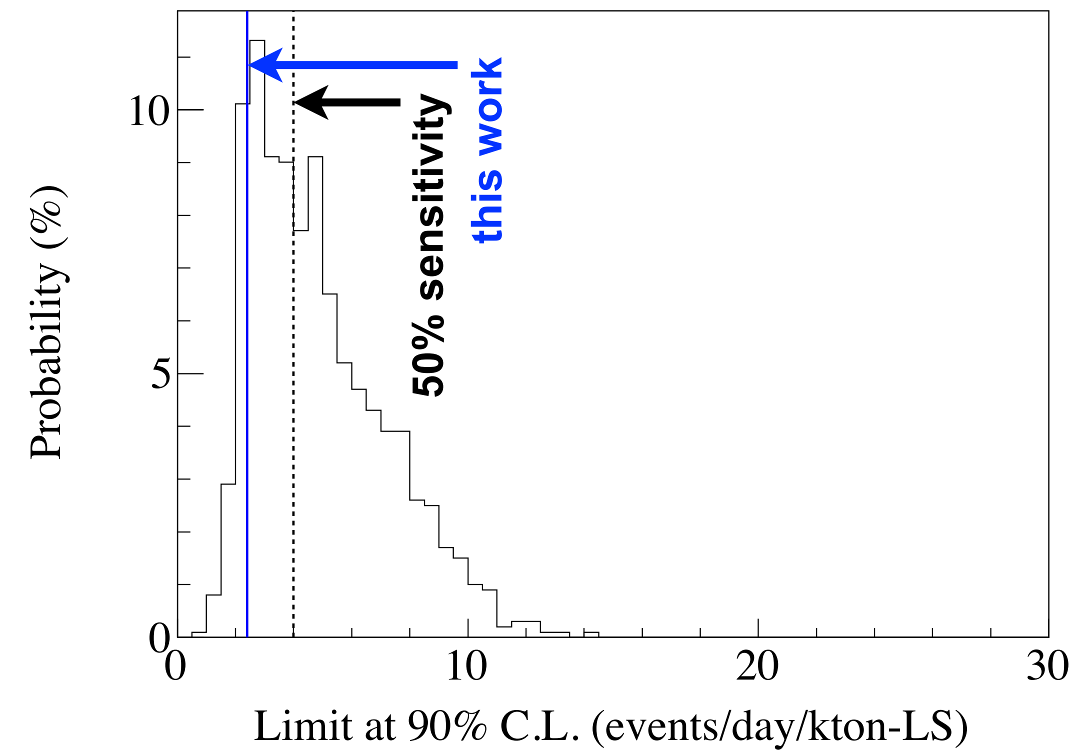
Period-1: < 3.4 events/day/kton-LS
Period-2: < 5.5 events/day/kton-LS
→ combined: < 2.4 events/day/kton-LS

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

Upper Limits from Toy MC

Distribution of 0νββ limits from Toy MC

(no 0νββ signal, best-fit BG rate)



MC : 4.0 < events/day/kton-LS

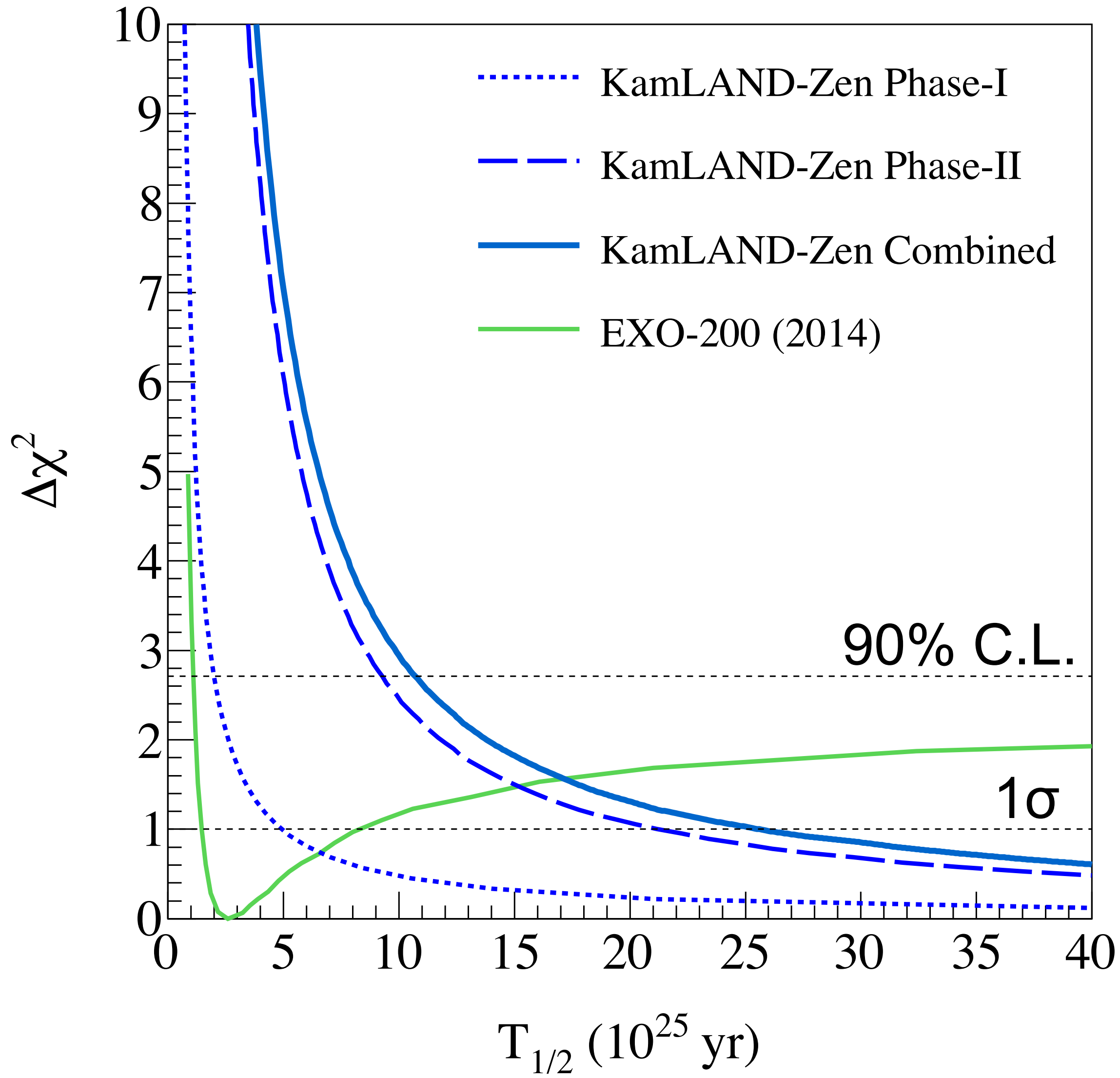
$T^{1/2}(0\nu) > 4.9 \times 10^{25}$ yr
(50% of the time)

this work :
2.4 < events/day/kton-LS
(12% of the time)

Result of 0νββ decay

PRL 117, 082503 (2016)

^{136}Xe Half-life limit

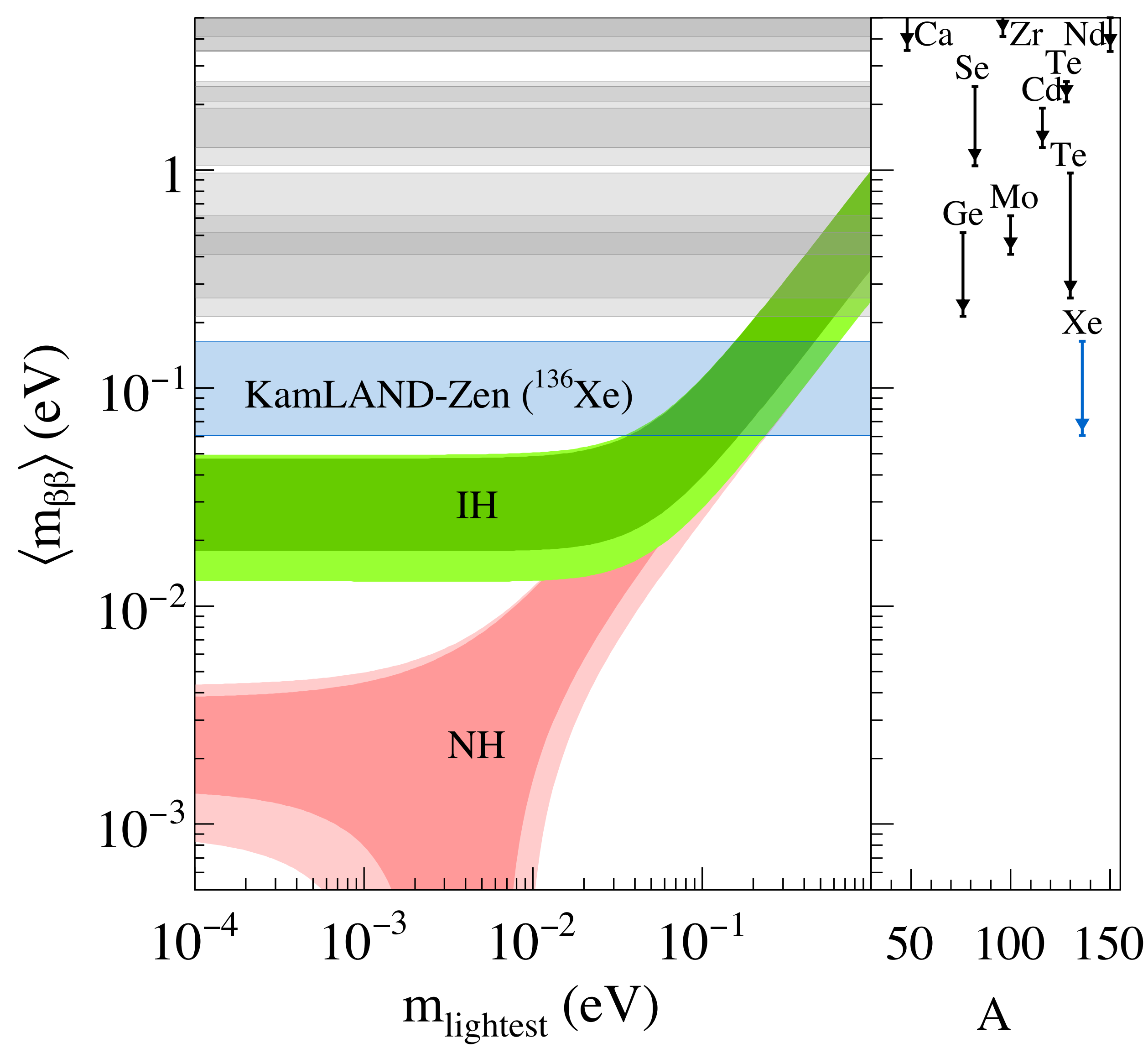


Combined result

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

Phase-1: $T^{1/2} > 1.9 \times 10^{25}$ yr
Phase-2: $T^{1/2} > 9.2 \times 10^{25}$ yr

Limit for effective neutrino mass

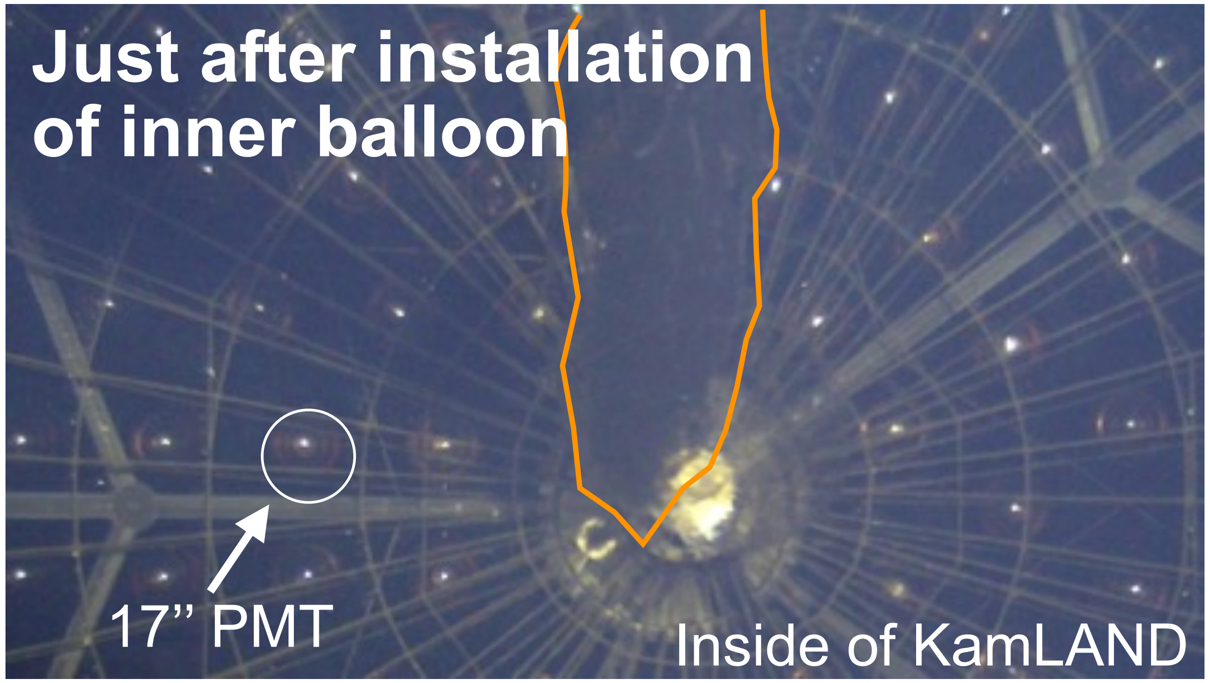


$\langle m_{\beta\beta} \rangle$ < 61-165 meV

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 to KamLAND.
- Expected sensitivity is below 50 meV



Summary

Neutrinoless double beta decay is a key to search for physics beyond the Standard Model.

Recent status of 5 experiments were reviewed.

New results from KamLAND-Zen were presented.

KamLAND-Zen limits on 0νββ at 90% C.L.

Lower limit of half-life (90% C.L.)

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

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

Combined : $T^{1/2} > 1.07\times10^{26}$ yr

Effective neutrino mass **$\langle m_{\beta\beta} \rangle < 61\text{-}165$ meV**

- First experiment to reach below 100 meV

Many thanks to: Brian Kurt Fujikawa, Peter Grabmayr, Joseph Janicsko, Andreas Piepke and Sei Yoshida