Neutrino Mass Measurements Asia

Second International Meeting for Large Neutrino Infrastructures

Apr. 21, 2015

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Neutrino Mass

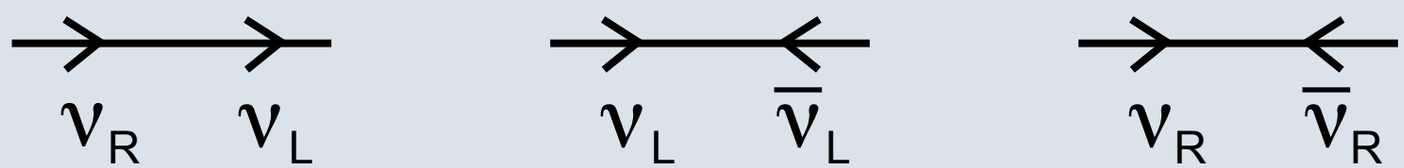
Neutrino oscillation $\longrightarrow$ finite small masses and mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \qquad (\alpha = e, \mu, \tau) \qquad m_i > 0$$

Possible mass terms

neutrino has no electric charge

$$L_{mass} = \overline{\psi_R} m_D \psi_L + \frac{1}{2}\overline{(\psi_L)^C} m_L \psi_L + \frac{1}{2}\overline{\psi_R} m_R (\psi_R)^C$$



$\Delta L = 0$ $\qquad$ $\Delta L = 2$ $\qquad$ $\Delta L = 2$

lepton number violation

Majorana particle $\nu = \bar{\nu}$

- Heavy neutrino (just below GUT scale) naturally explains
  "finite but light neutrino mass" $\quad m \sim \frac{m_D^2}{M_R}$ (Seesaw mechanism)
- CP violating decay of heavy neutrino explains
  "matter dominance in the universe" (Leptogenesis theory)

Neutrinoless Double-Beta Decay

Nucleus ββ-decay emitting two electrons

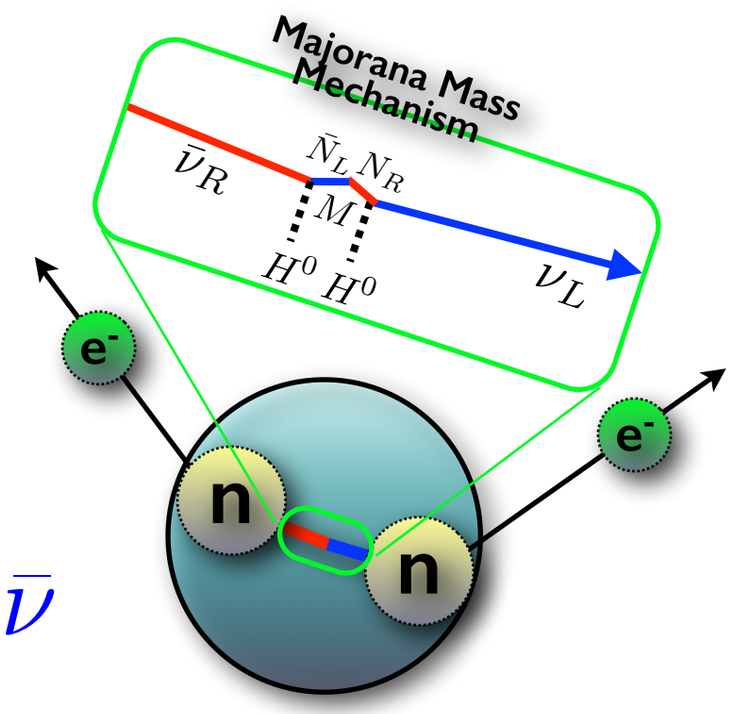
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

lepton number violation

$\Delta L = 2$

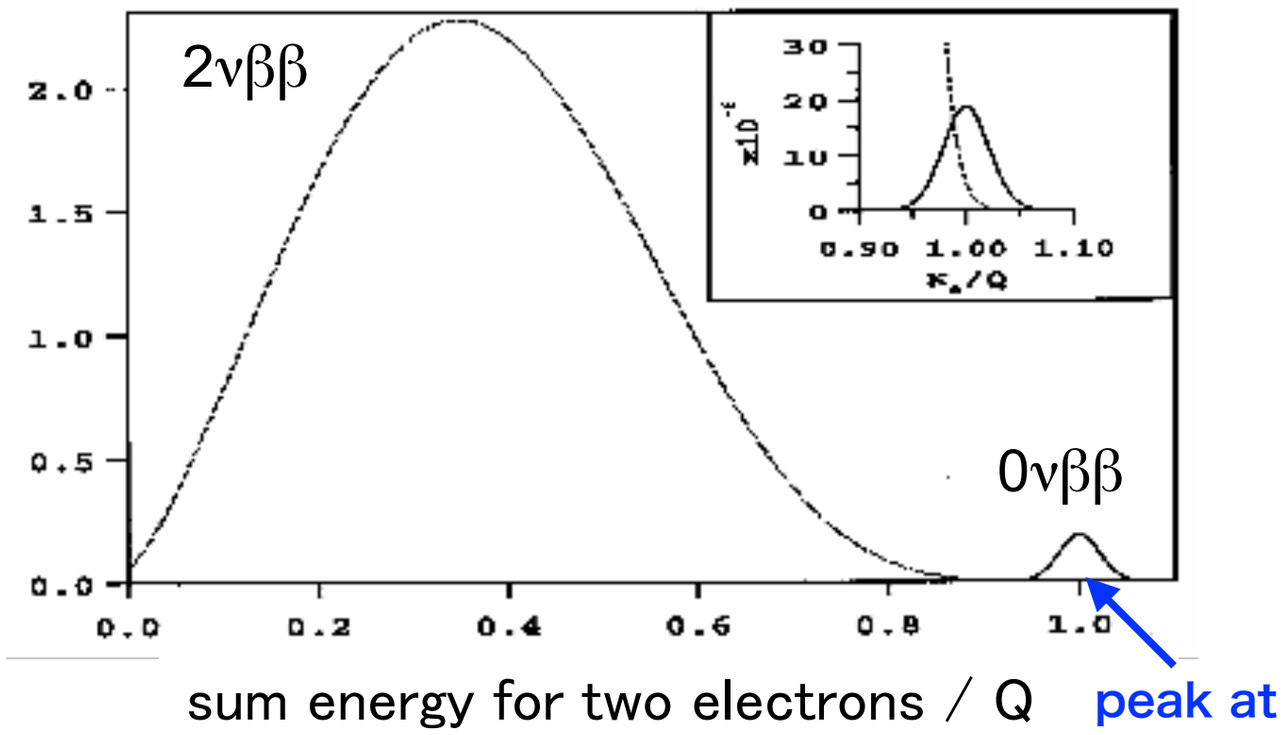
0νββ

neutrinoless double beta-decay



$\nu = \bar{\nu}$

Require the neutrino **Majorana nature**



sum energy for two electrons / Q

peak at Q-value

amplitude ~ $\langle m_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$

effective neutrino mass

decay rate

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

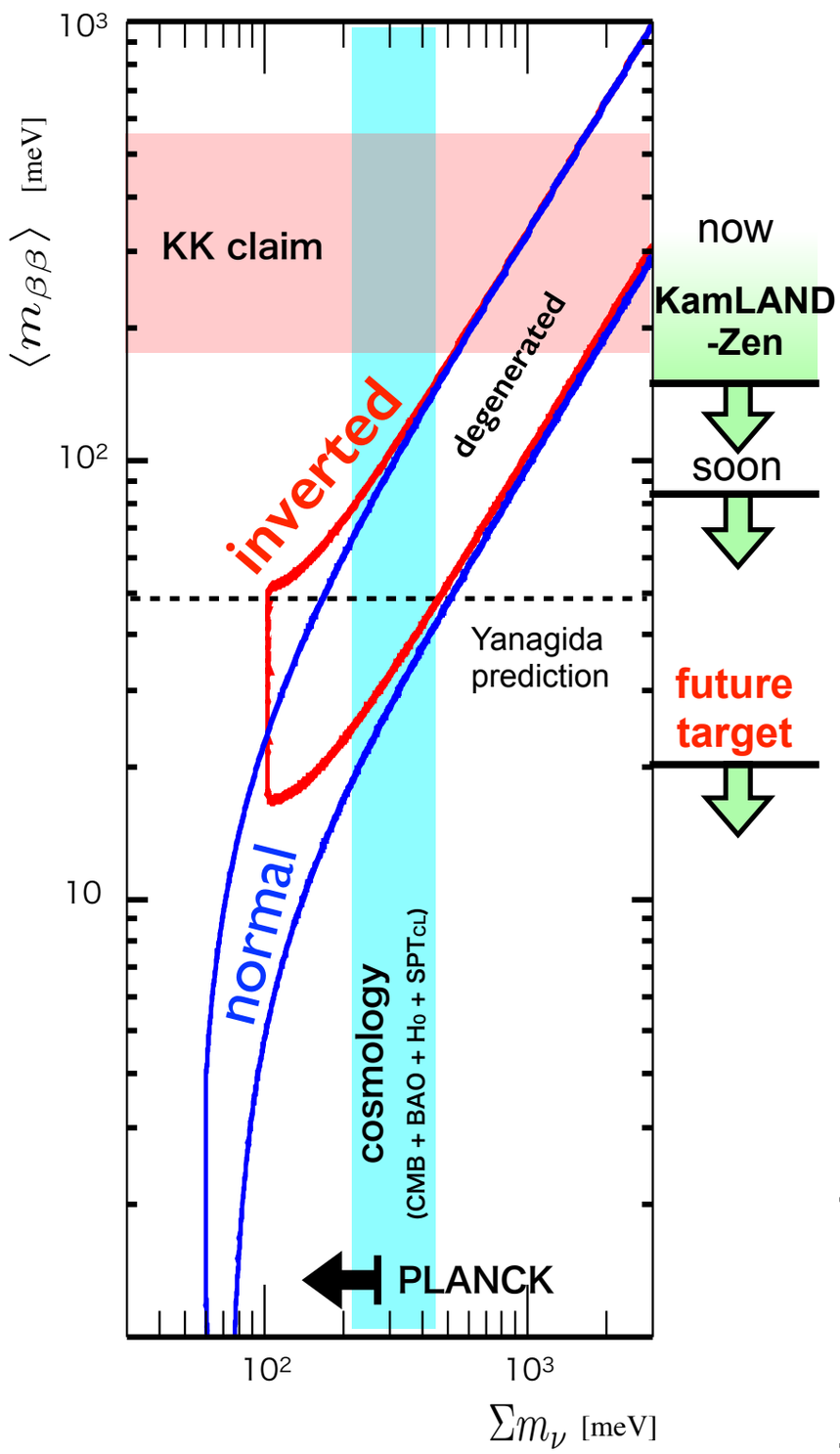
nuclear matrix element (nuclear physics)

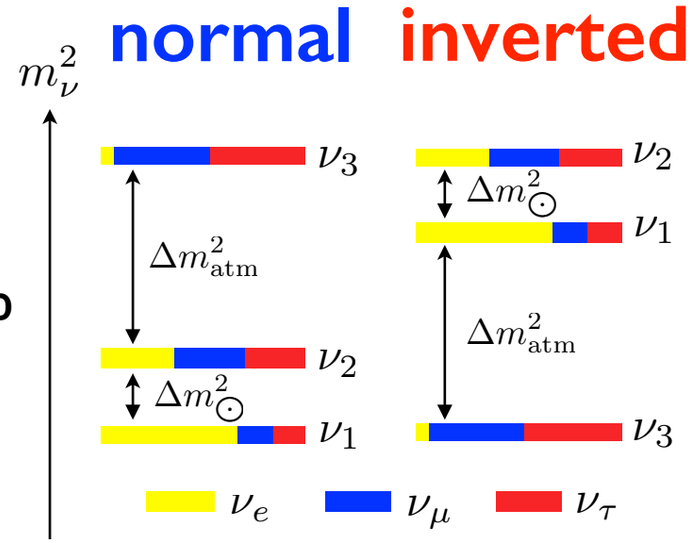
phase space factor

effective neutrino mass (particle physics)

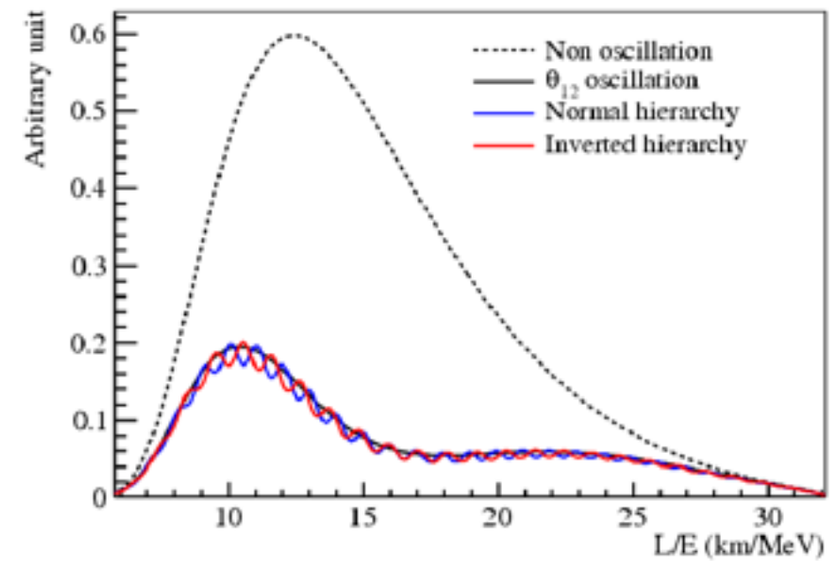
Possible contributions also from Majoron, SUSY, right-handed current, ...

Neutrino Mass Hierarchy



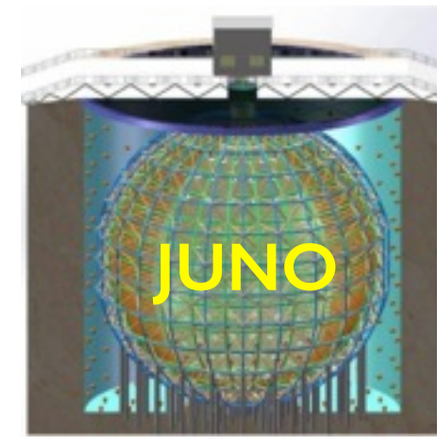


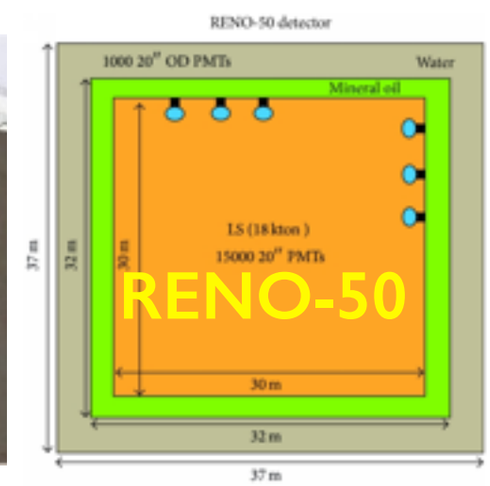
Reactor neutrino oscillation



<u>Mass hierarchy (MH) determination</u>

reactor neutrino experiments in China and Korea are competitive with other MH projects (atmospheric / accelerator neutrinos)





<u>(a) inverted hierarchy case</u>

find 0νββ signal in the next generation experiments! ☺

If we don't find the signal, "Majorana neutrino" will be rejected

<u>(b) normal hierarchy case</u>

need to set the next target down to 1-5 meV ... ☹

Double Beta Decay Experiments

Asia

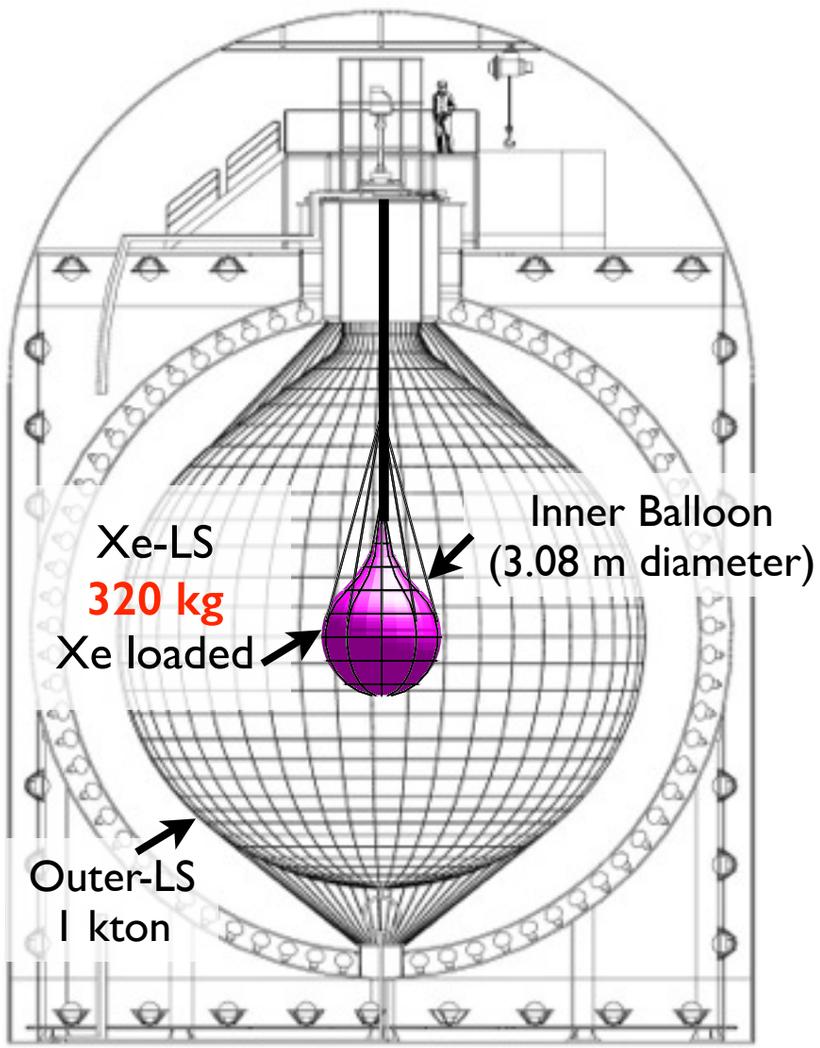
Experiment	ββ candidate	Q-value[keV]	Enrichm.	$N_{\beta\beta}$ x10^{26}	Start [y]	$<m_{ee}>$[meV]@5y
GERDA	^{76}Ge	2039	yes	3.2	2013	73-203
Majorana	^{76}Ge	2039	yes	2.4	2014	106-295
MaGe	^{76}Ge	2039	yes	68	2020	43-120
CUORE	^{130}Te	2527.5	no	9.6	2014	40-94
Lucifer	^{82}Se	2995	yes	1.3	2014	35-94
AMore	^{100}Mo	3034	yes	3	?	27-63
SNO+	^{150}Nd	3370	no	1.8	2014	172-180
Kamland-Zen	^{136}Xe	2476	yes	4	2013-2015	25
Candles	^{48}Ca	4270	no	0.04	2011	500
Candles-enr	^{48}Ca	4270	yes	1	?	IH
Exo-200	^{136}Xe	2476	yes	2.3	2011	87-221 @2y
Exo-Full	^{136}Xe	2476	yes	20	?	16-40
Next-100	^{136}Xe	2476	yes	4	2015	90 @6y
Next-1t	^{136}Xe	2476	yes	30	?	38 @(3+3)y
COBRA	^{116}Cd	2809	yes	nd	?	50
SuperNemo	^{82}Se	2995	yes	7.3	2014	40-105
Moon	^{82}Se/^{100}Mo	2995/3134	yes	30	?	IH
DCBA	^{150}Nd	3370	yes	10	?	30

KamLAND-Zen

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen Phase I



Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$\sigma_E(2.5\text{MeV}) = 4\%$

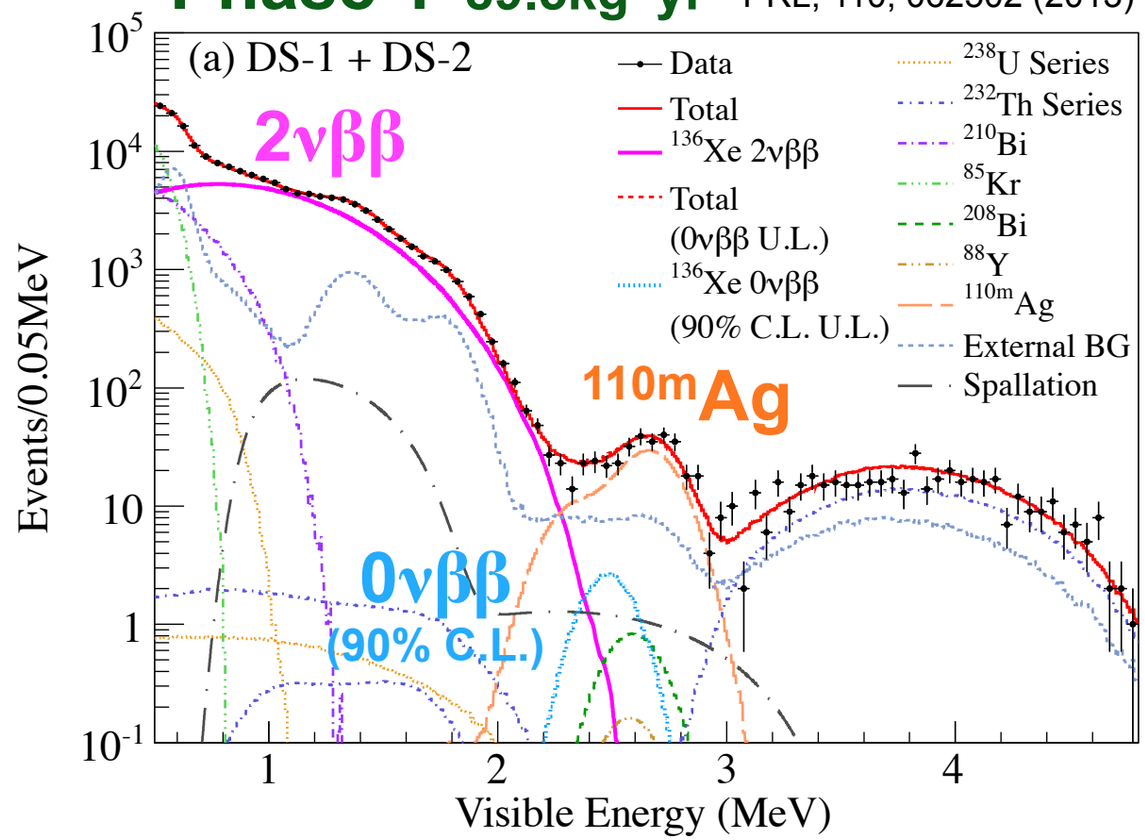
Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

→ **high scalability** (a few ton of Xe)

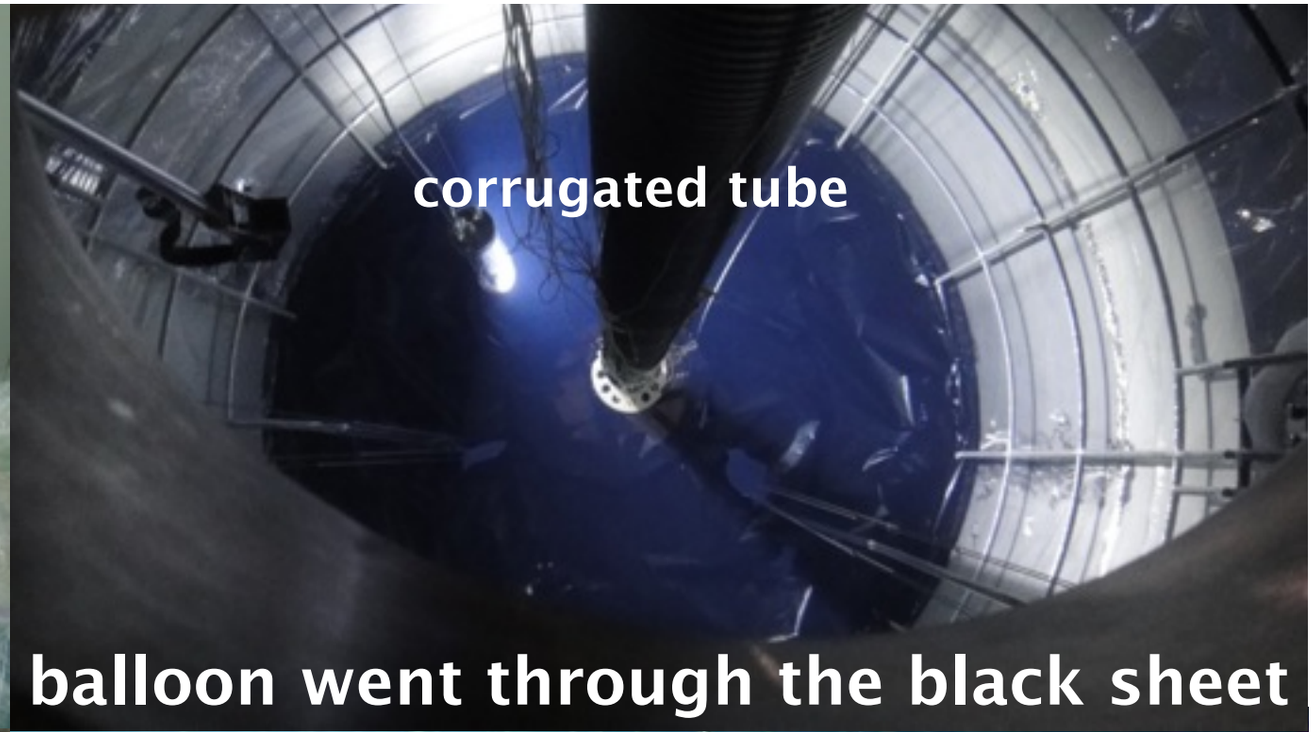
realize double beta-decay search with **low background**

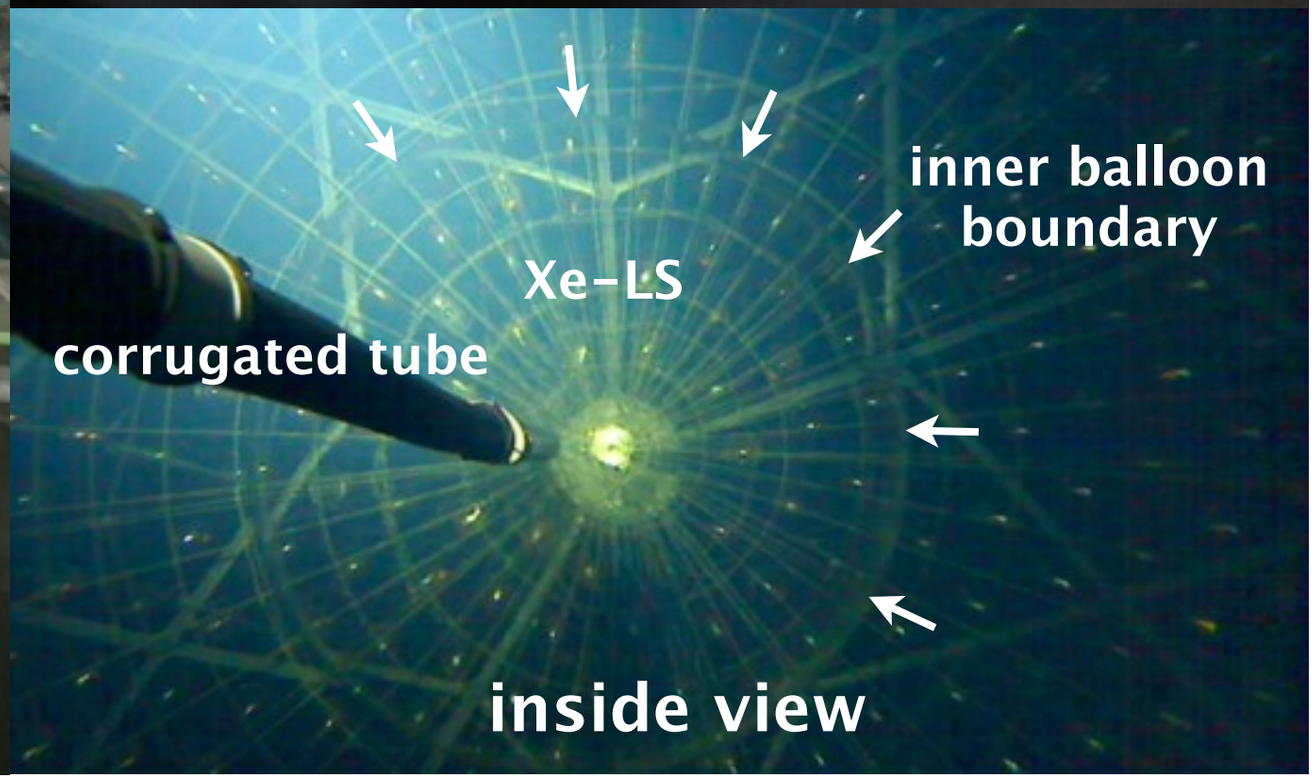
Phase 1 **89.5kg•yr** PRL, 110, 062502 (2013)



$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)

Construction in 2011





Improvement Efforts after Phase 1

1. Remove radioactive impurities by Xe-LS purification

candidates of ~2.6 MeV peak

⟶ only 4 nuclei ^{110m}Ag (250 d), ^{208}Bi (3.68x10^5 yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)

lifetime longer than 30 days

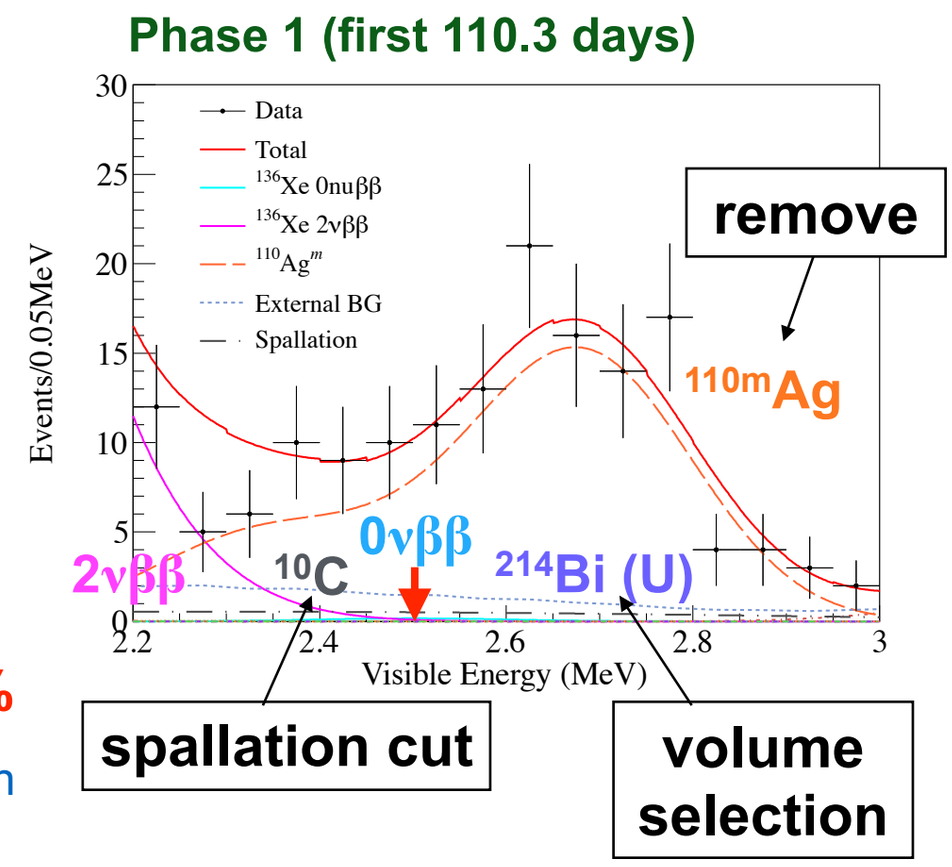
detected in Fukushima fallout

Two possible sources:

(1) contamination by Fukushima-I reactor fallout

(2) cosmogenic Xe spallation while above ground

"primary" background source (^{110m}Ag) can be removed by Xe-LS purification



2. Increase amount of Xenon

	phase 1		phase 2
Xe concentration	(2.44 ± 0.01) wt%	⟶	(2.96 ± 0.01) wt%

increase of S/N ~ 1.2 Xe-pressurized phase is a future option

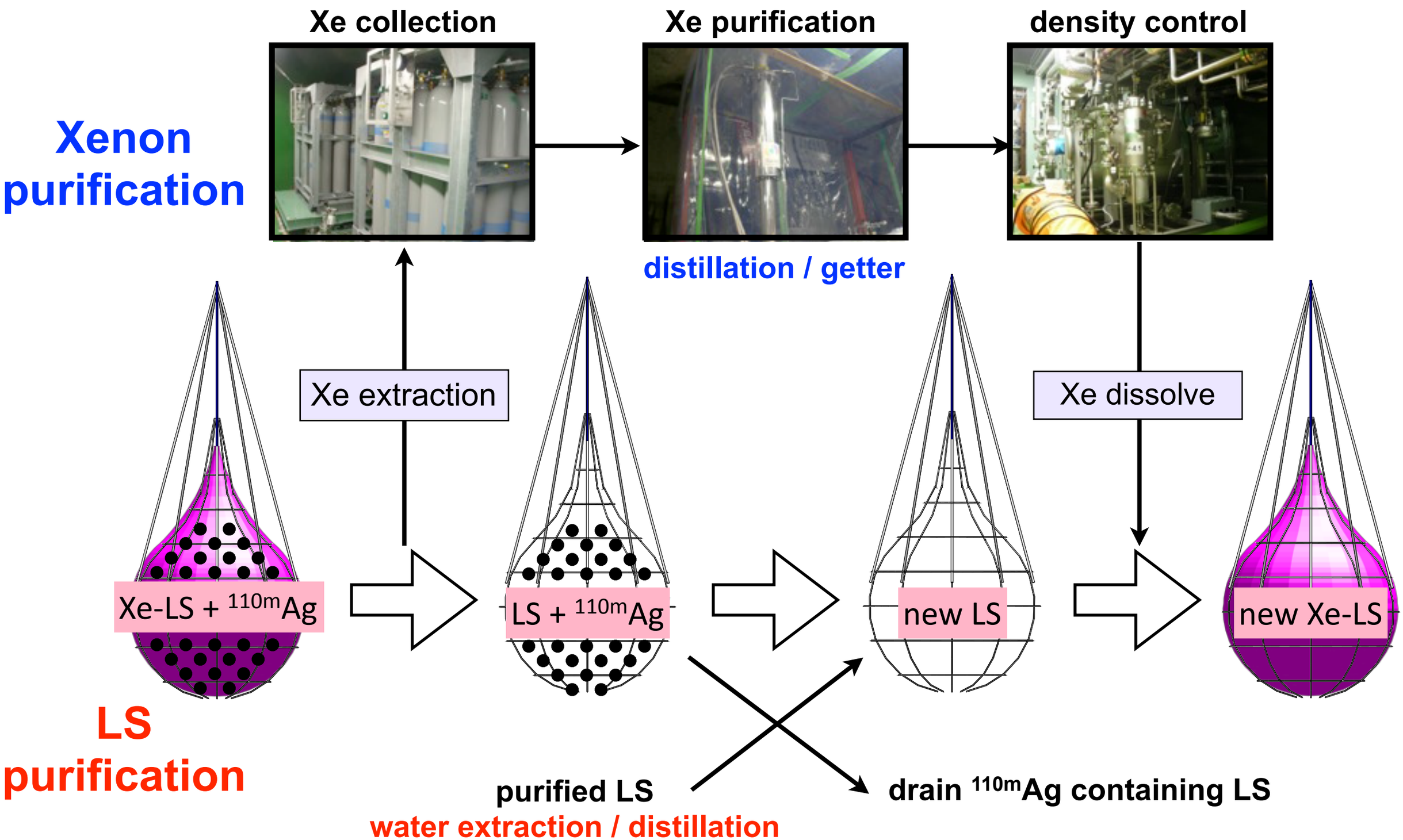
3. Spallation cut after muon

muon-neutron-^{10}C (τ = 27.8 s) triple coincidence ⟶ **^{10}C background rejection**

4. Optimization of volume selection

fiducial volume limitation by ^{214}Bi (U) on the balloon film ⟶ **multi-volume selection**

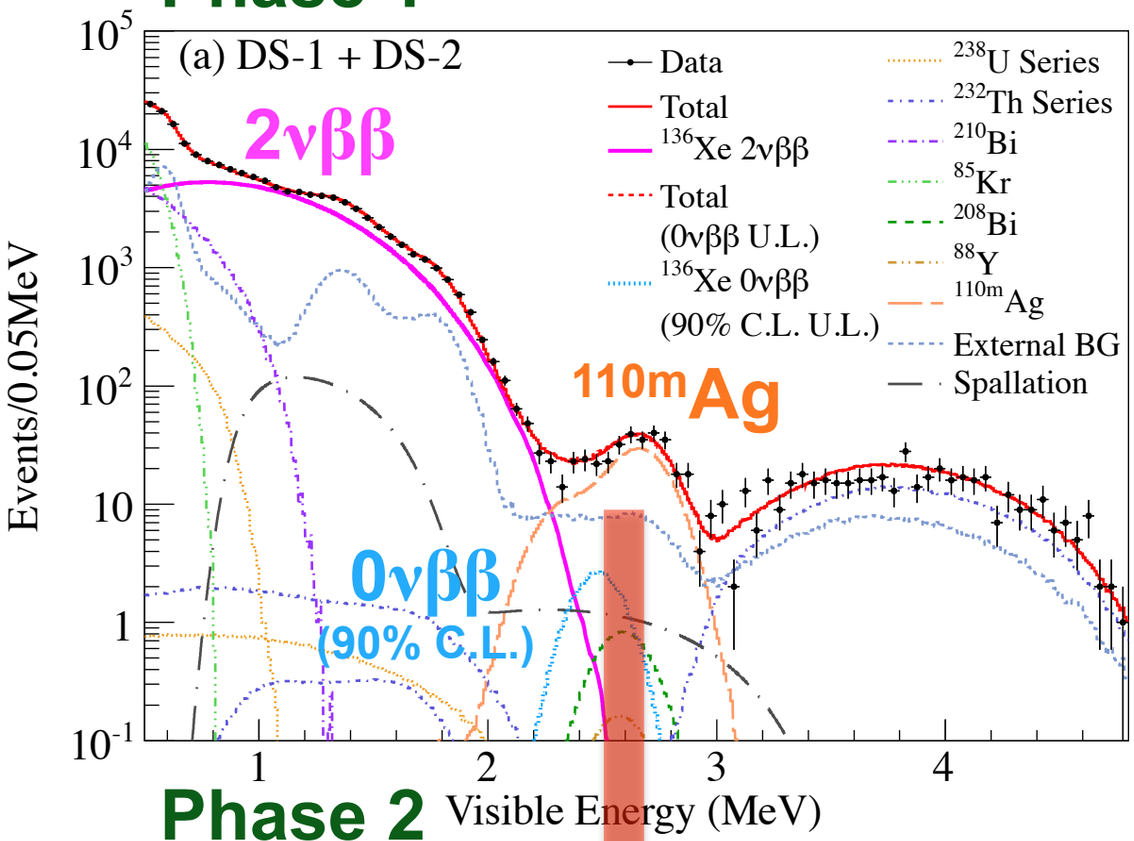
Purification Strategy



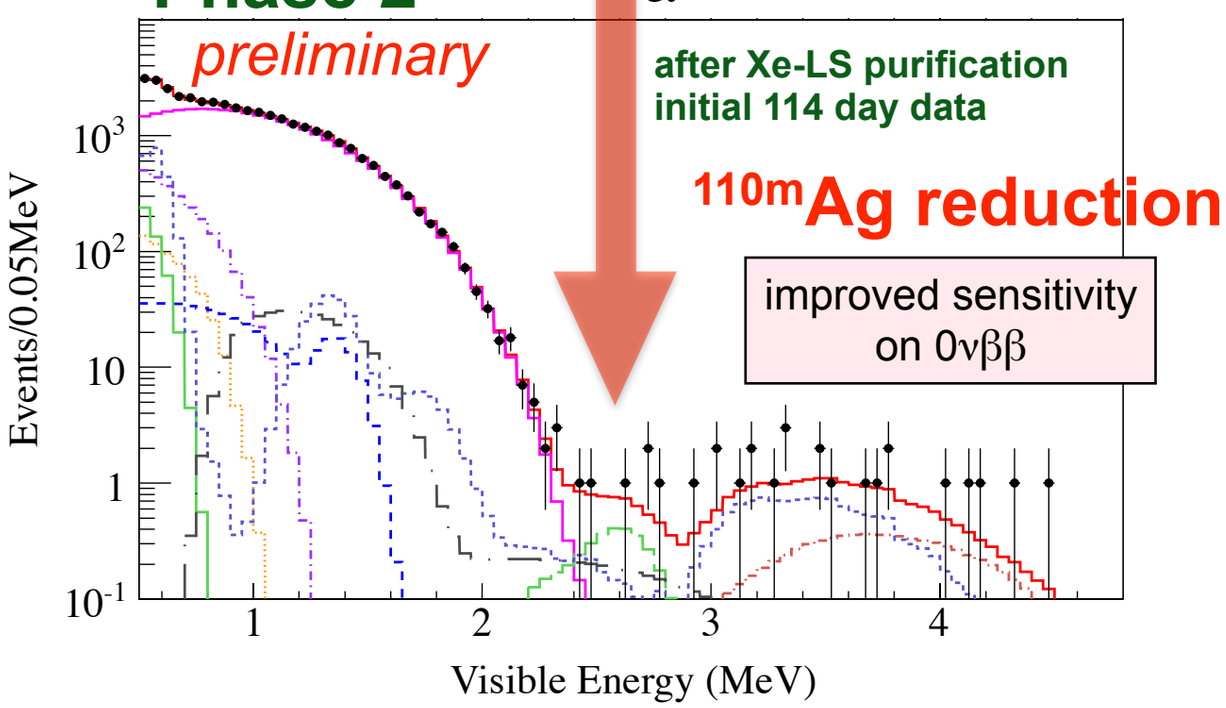
Xenon and LS purification to reduce radioactive impurities

KamLAND-Zen Phase 2 start

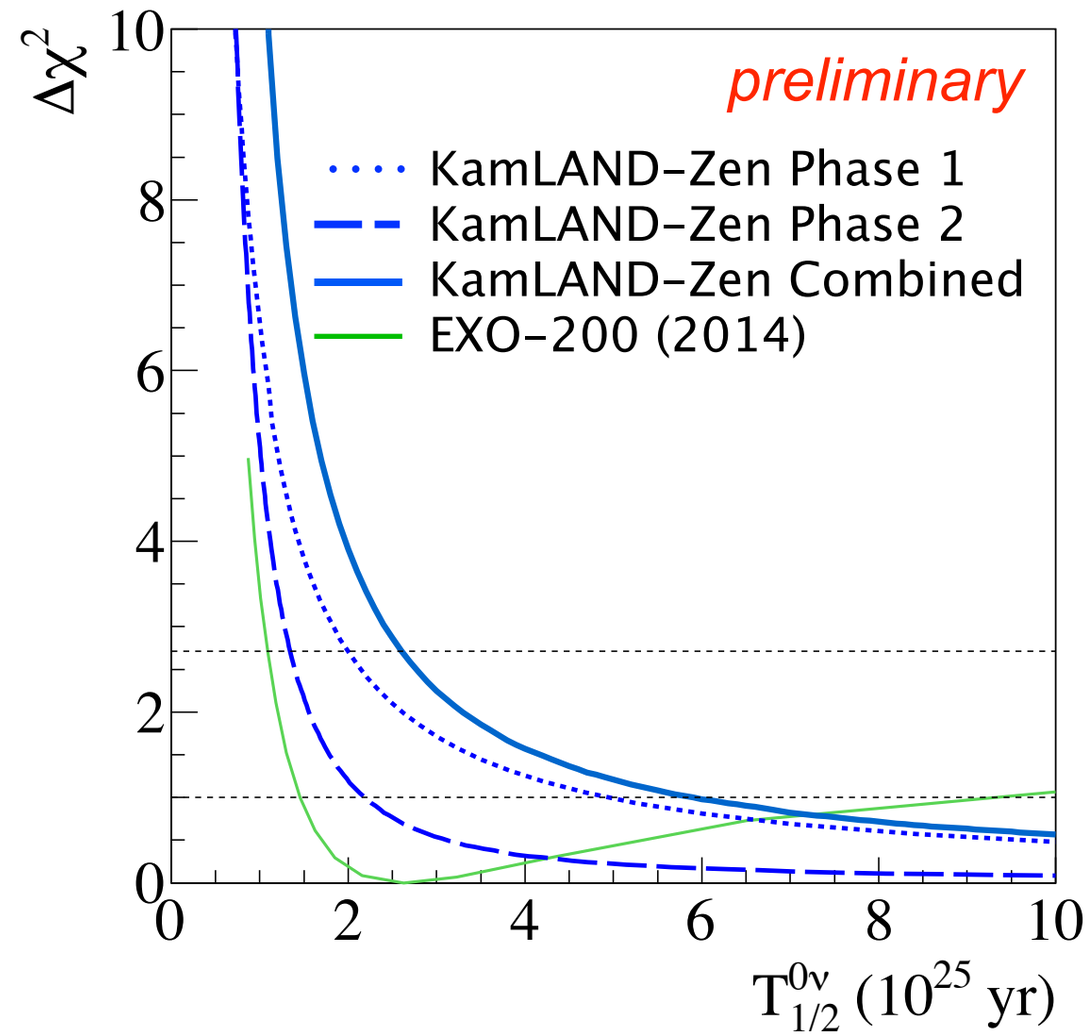
Phase 1



Phase 2



combined result (Phase 1 + 2)



<u>KamLAND-Zen limit at 90% C.L.</u>

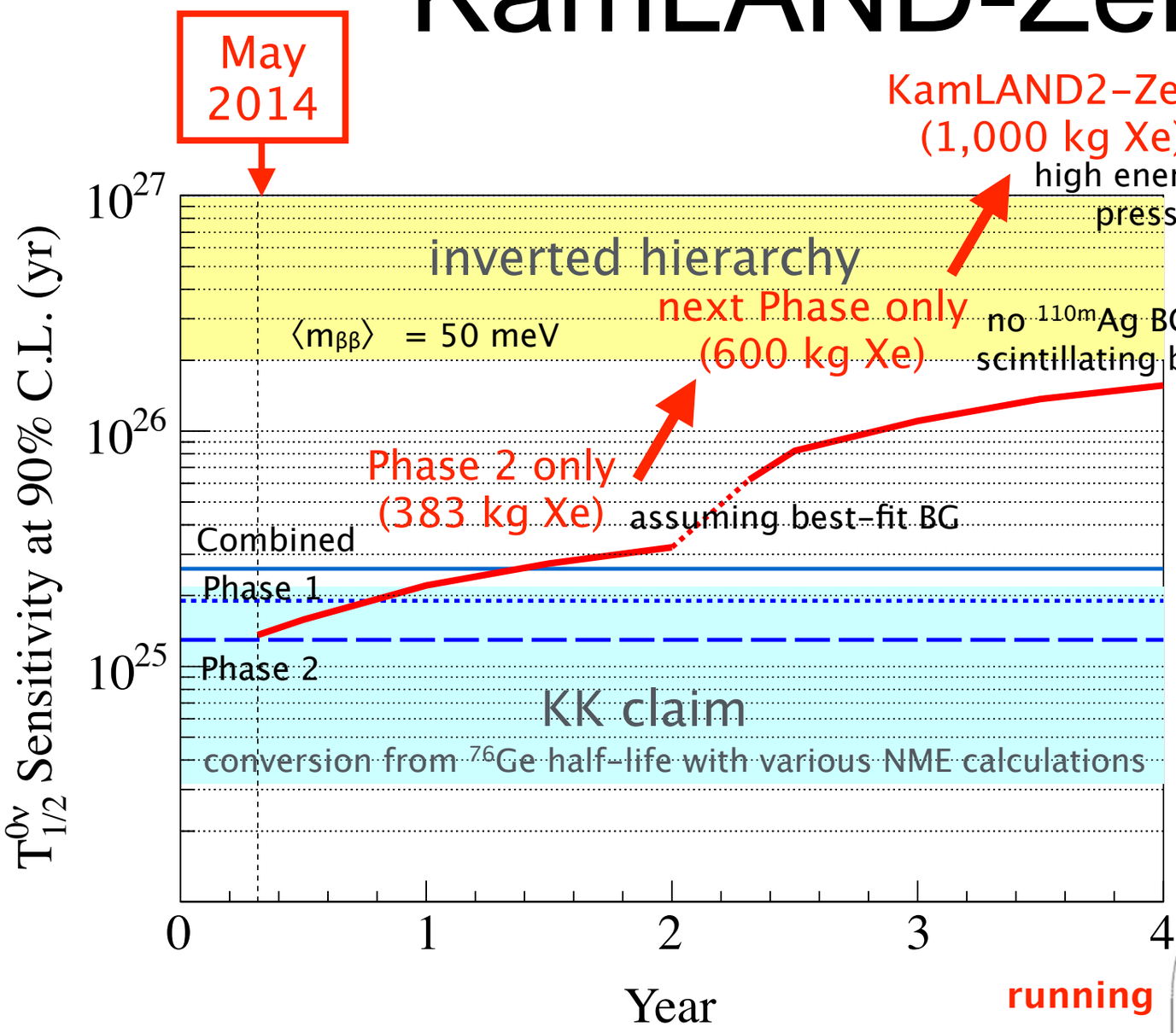
Phase 1 (213 days) + Phase 2 (115 days)

$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 140 - 280$ meV

KamLAND-Zen Prospect



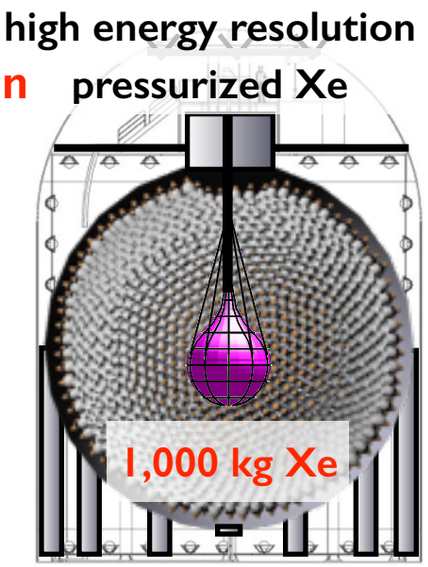
Future sensitivity
KamLAND-Zen Phase 1
KamLAND-Zen Phase 2
KamLAND-Zen Combined

KamLAND2-Zen

test of inverted neutrino mass hierarchy

target ⟨mββ⟩ ~ 20 meV

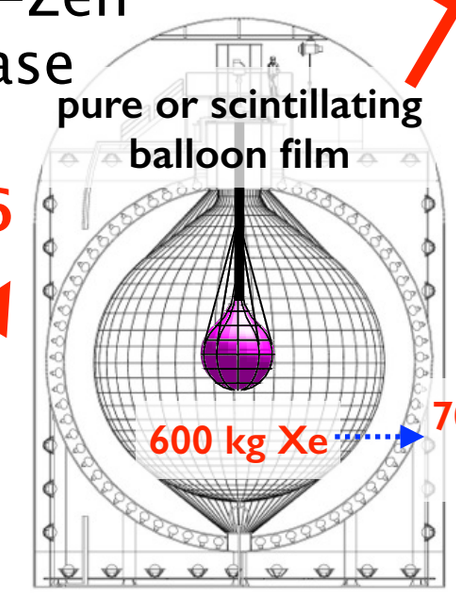
plan



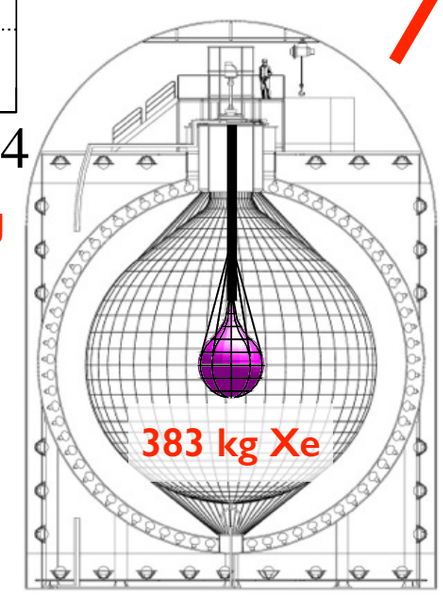
KamLAND-Zen next phase

funded

Start in 2016



running



KamLAND-Zen Phase 2

Detector improvements are planned in the near future

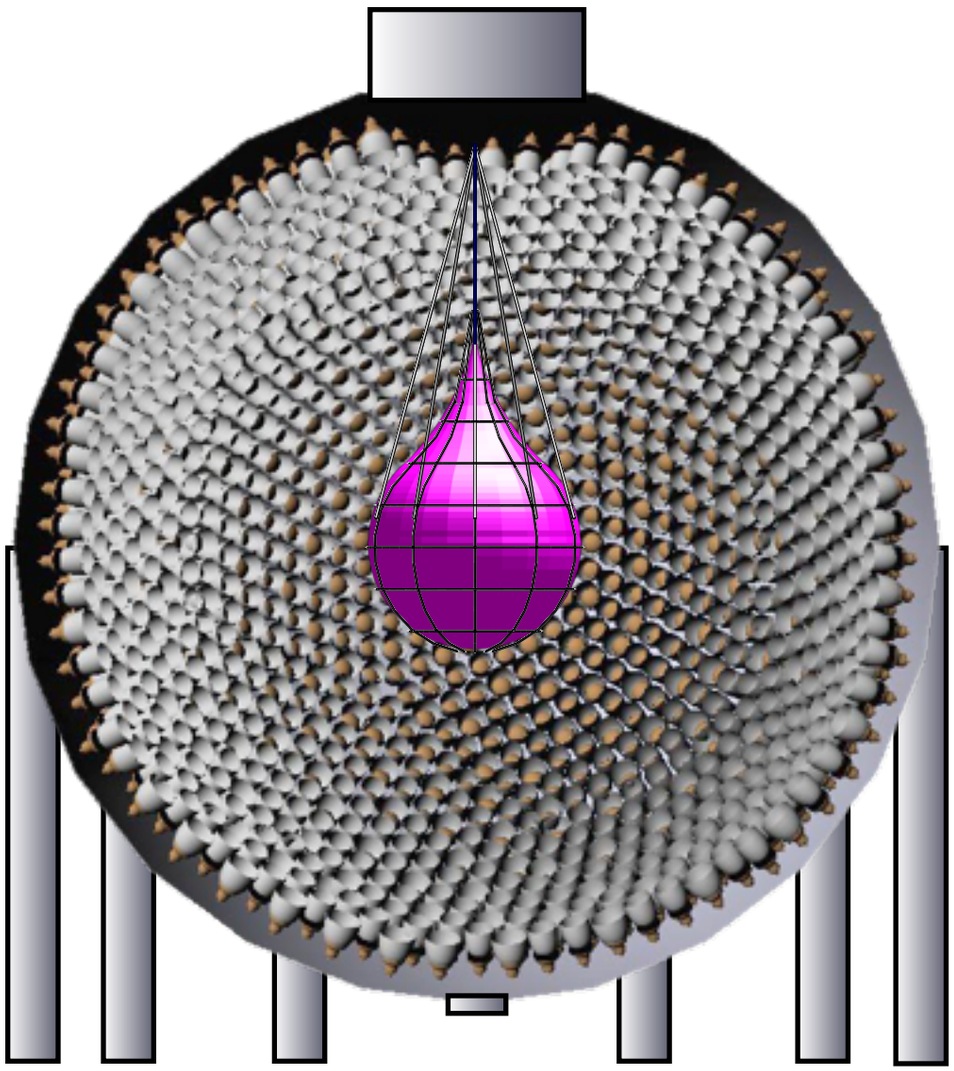
KamLAND2-Zen

General-purpose

larger crane
strengthen floor
enlarge opening

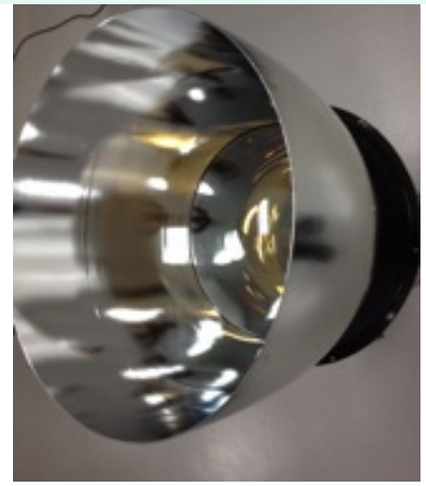
accommodate various devices
CaF_2, $CdWO_4$, NaI, …

1000 kg enriched Xe

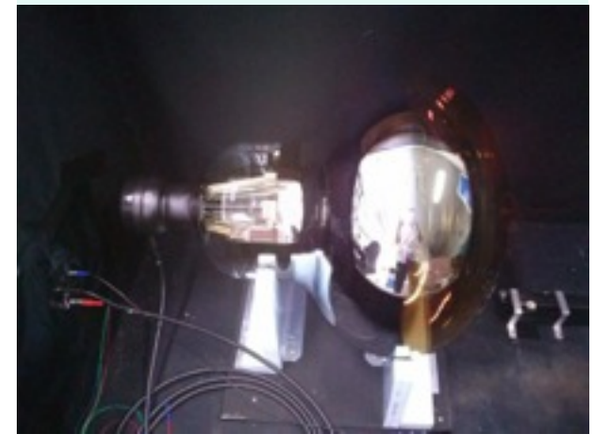


High performance

Winstone Cone



High Q.E. PMT



17”Φ→20”Φ, ε=22% → 30%

Photo-coverage > **x2**

Light Collection Eff. > **x1.8**

x1.9

New Liquid Scintillator

x1.4

KamLAND liquid scintillator	8,000 photon/MeV
typical liquid scintillator	12,000 photon/MeV

σ(2.6MeV)= 4% → < 2.5%

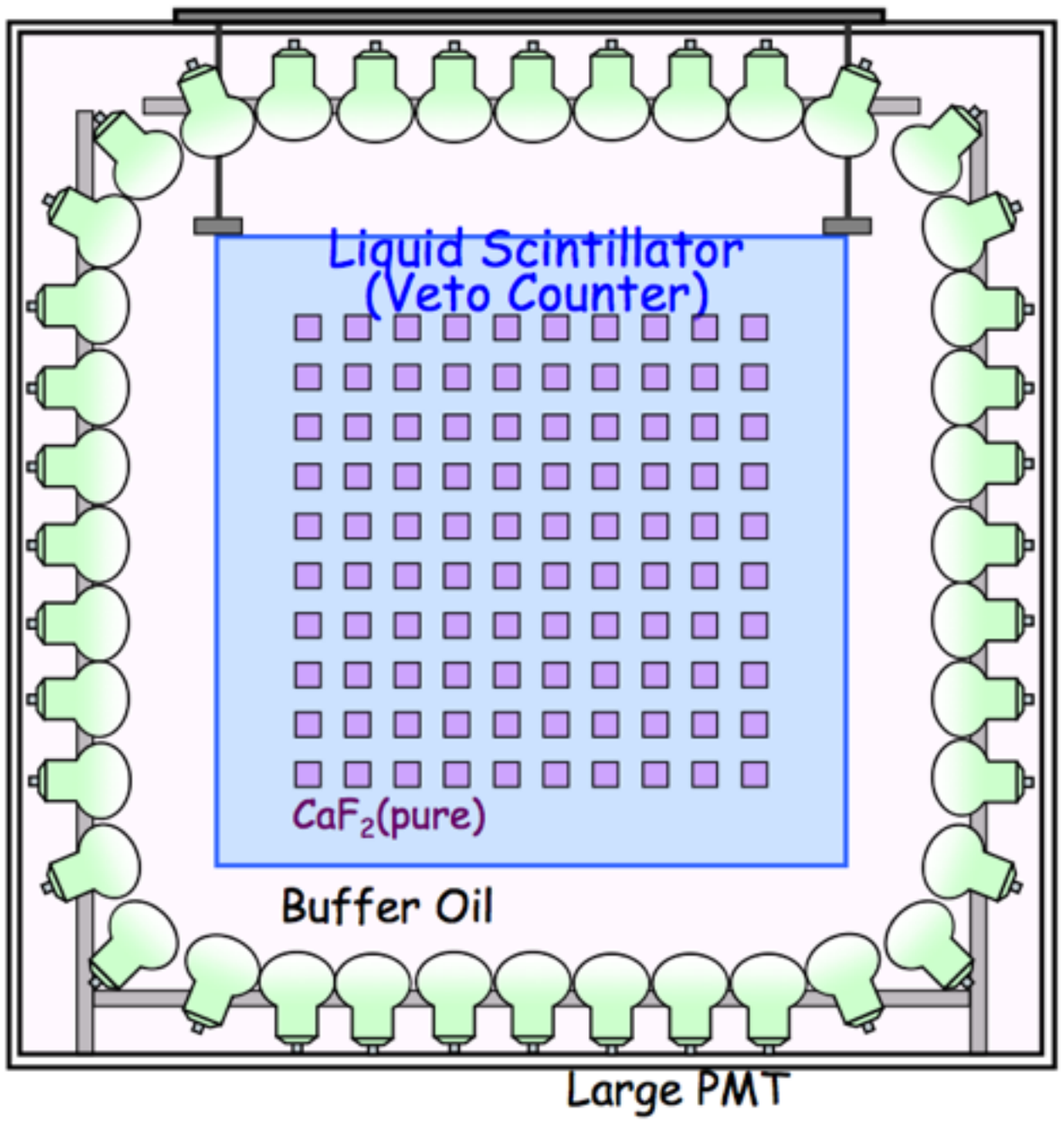
naive calc. < 2%

target $\langle m_{\beta\beta} \rangle$ ~ 20 meV / 5 year

CANDLES

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters
by Low Energy Spectrometer



Why ^{48}Ca?

- highest Q-value (^{48}Ca ββ-decay : 4.27 MeV)
- little background from natural radioactivities
- natural abundance of ^{48}Ca : 0.187% (small)

→ need isotope enrichment

- CaF_2 (pure) scintillator

transparent, ultra-pure crystal

200 kg, 300 kg, 2 ton, … enrichment of ^{48}Ca

- Liquid scintillator

wavelength shifter, CaF_2 emission ~ 280 nm

4π active shield (surrounded by passive shield)

- Large PMT

high energy resolution

pulse shape of scintillation light from CaF_2 & LS

CANDLES Prospect

- ELEGANT VI
- CANDLES I, II

background free measurement with 4π active shield

↓

larger amount of ^{48}Ca in CANDLES

- CANDLES III

now

performance of 96 CaF_2 in LS active shield will be tested at underground

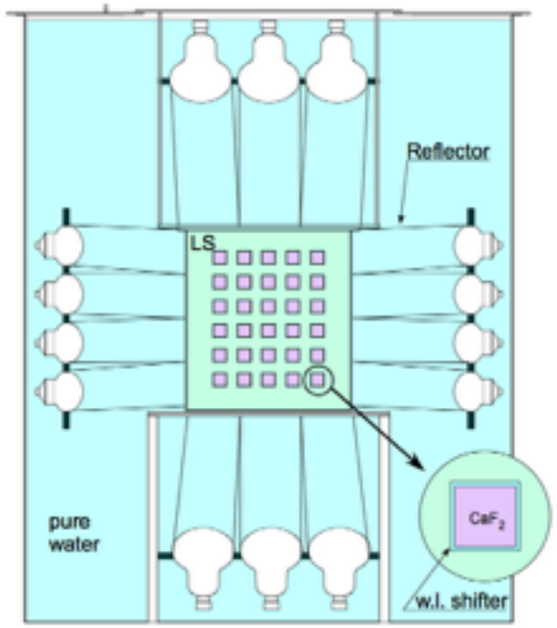
future option

enrichment of ^{48}Ca with Crown Ether chromatography is in R&D stage

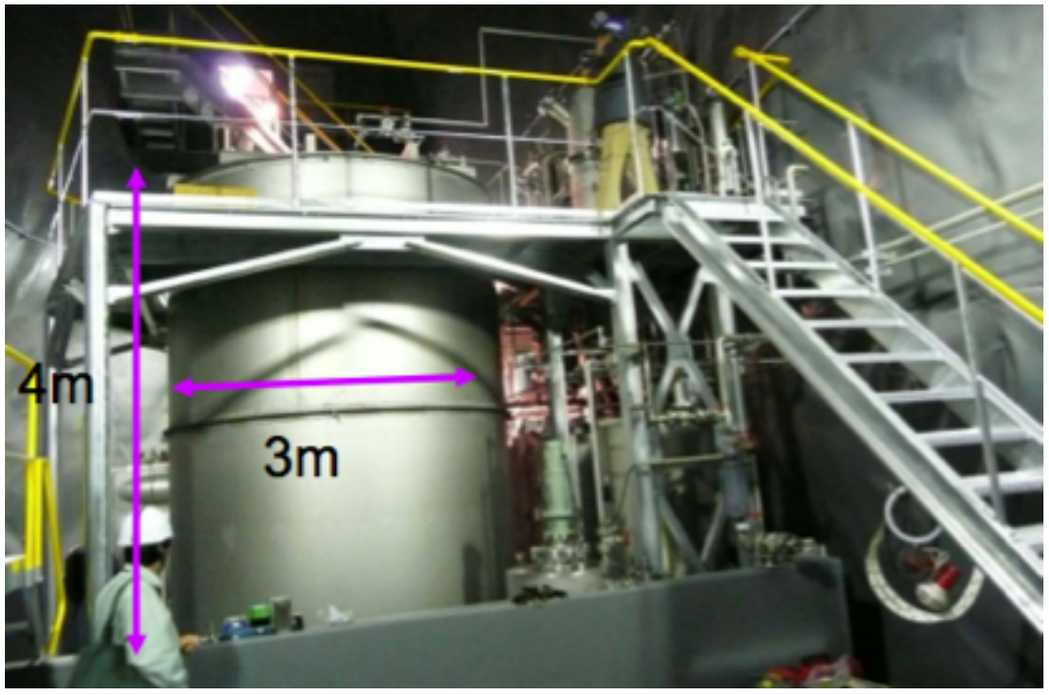
- Next CANDLES

increase CaF_2 in large LS detector

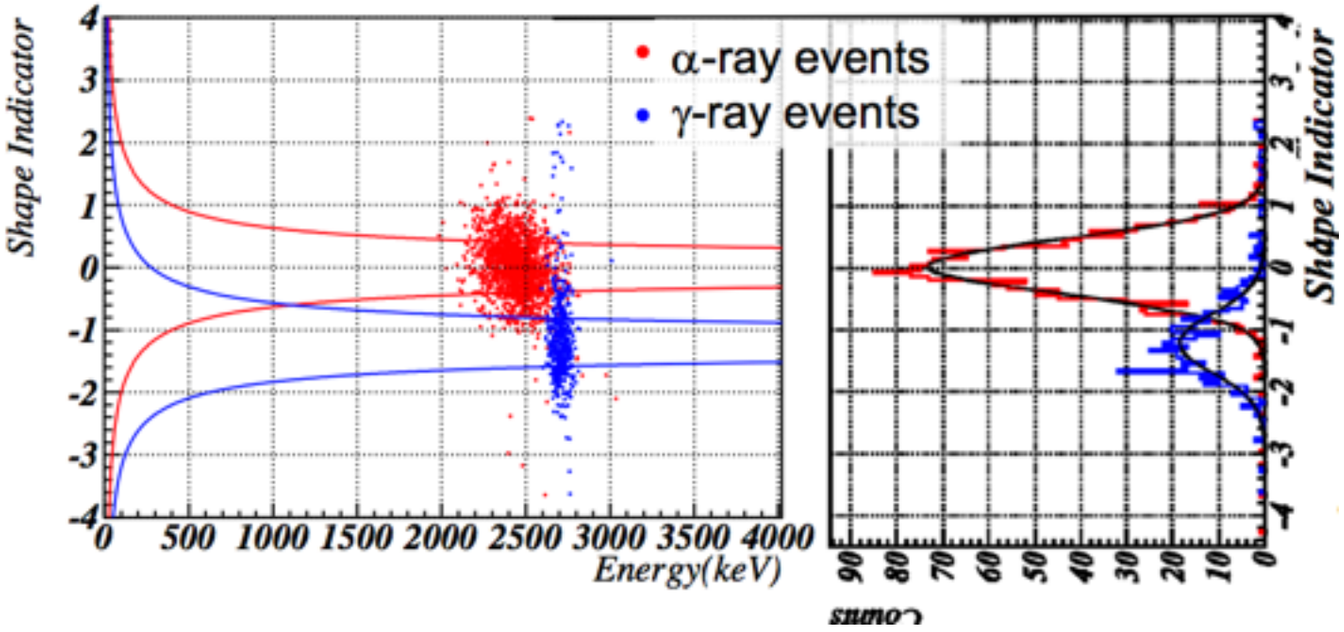
CANDLES III
96 CaF_2 scintillators



CANDLES III @ Kamioka



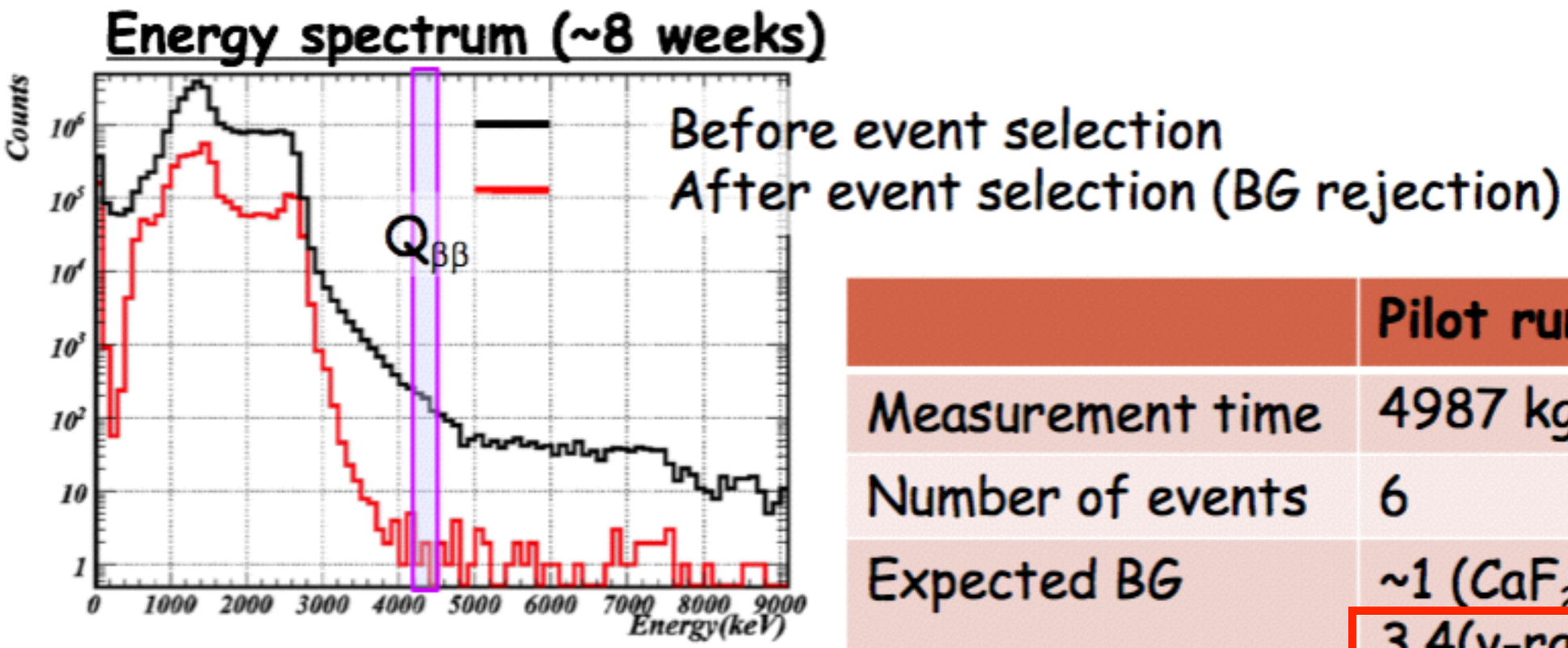
Pulse shape discrimination between α and γ



S. Umehara DBD11

Energy Spectrum in CANDLES III

~8 week measurement with high purity 26 CaF_2



S. Yoshida - DBD14

	Pilot run data
Measurement time	4987 kg · days
Number of events	6
Expected BG	~1 (CaF_2 crystal) 3.4(γ-rays)
Sensitivity	0.8×10^{22} year

(n, γ) reaction at surrounding materials

Internal BG : almost OK

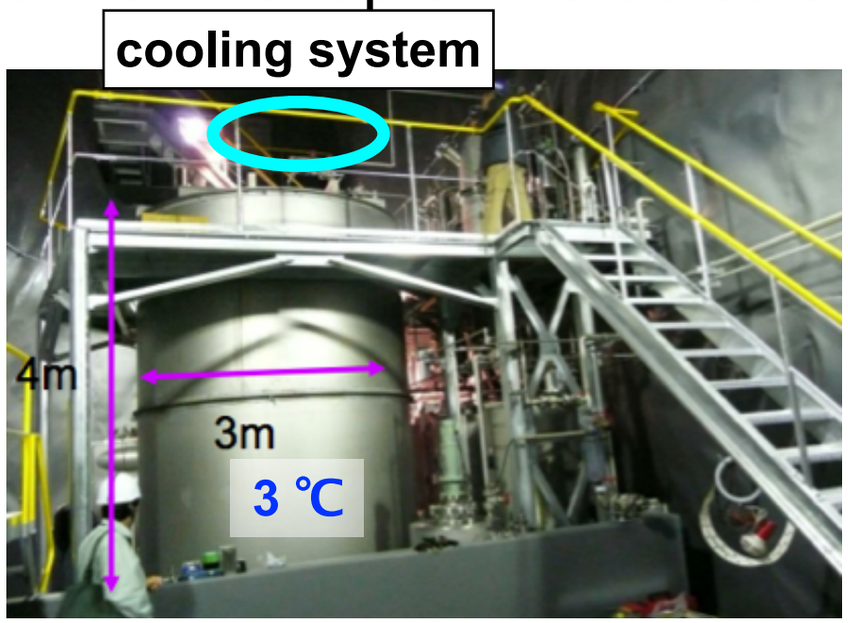
External BG : need to be reduced

newly install shield system for external γ-rays (neutron origin)

→ expected $\langle m_{\beta\beta}\rangle$ sensitivity ~ 0.5 eV

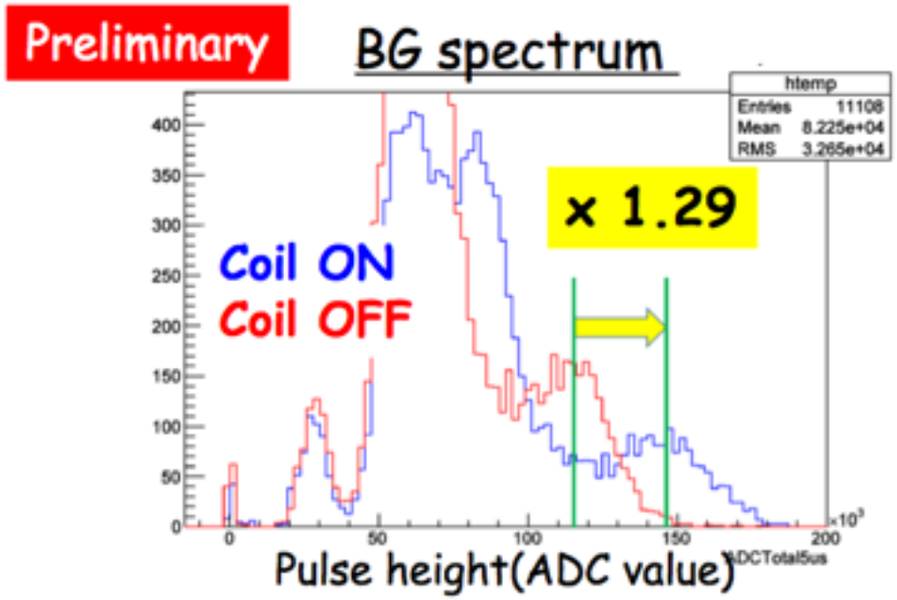
Further Development

1. Installation of the cooling system at the top of the detector



light output increase at low temperature

2. Installation of the "Geomagnetic cancellation coil" for PMTs

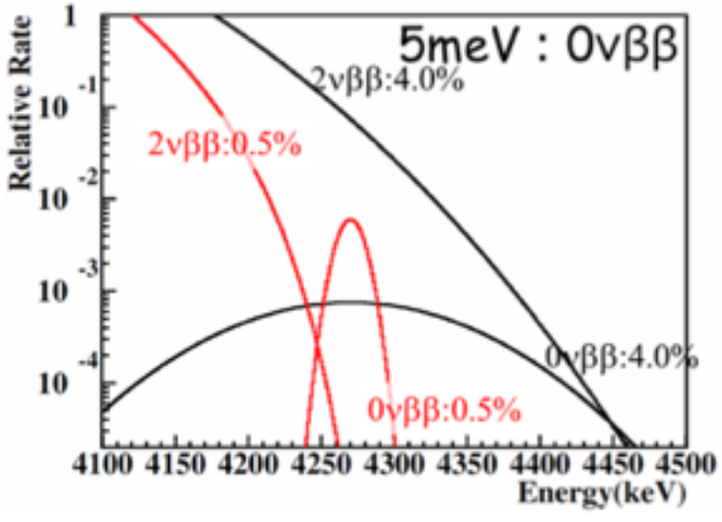


improved p.e. collection efficiency

expected energy resolution ~ 4% (FWHM) @ Q-value

Sensitivity of CANDLES

	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		scintillating bolometer



S. Yoshida - DBD14

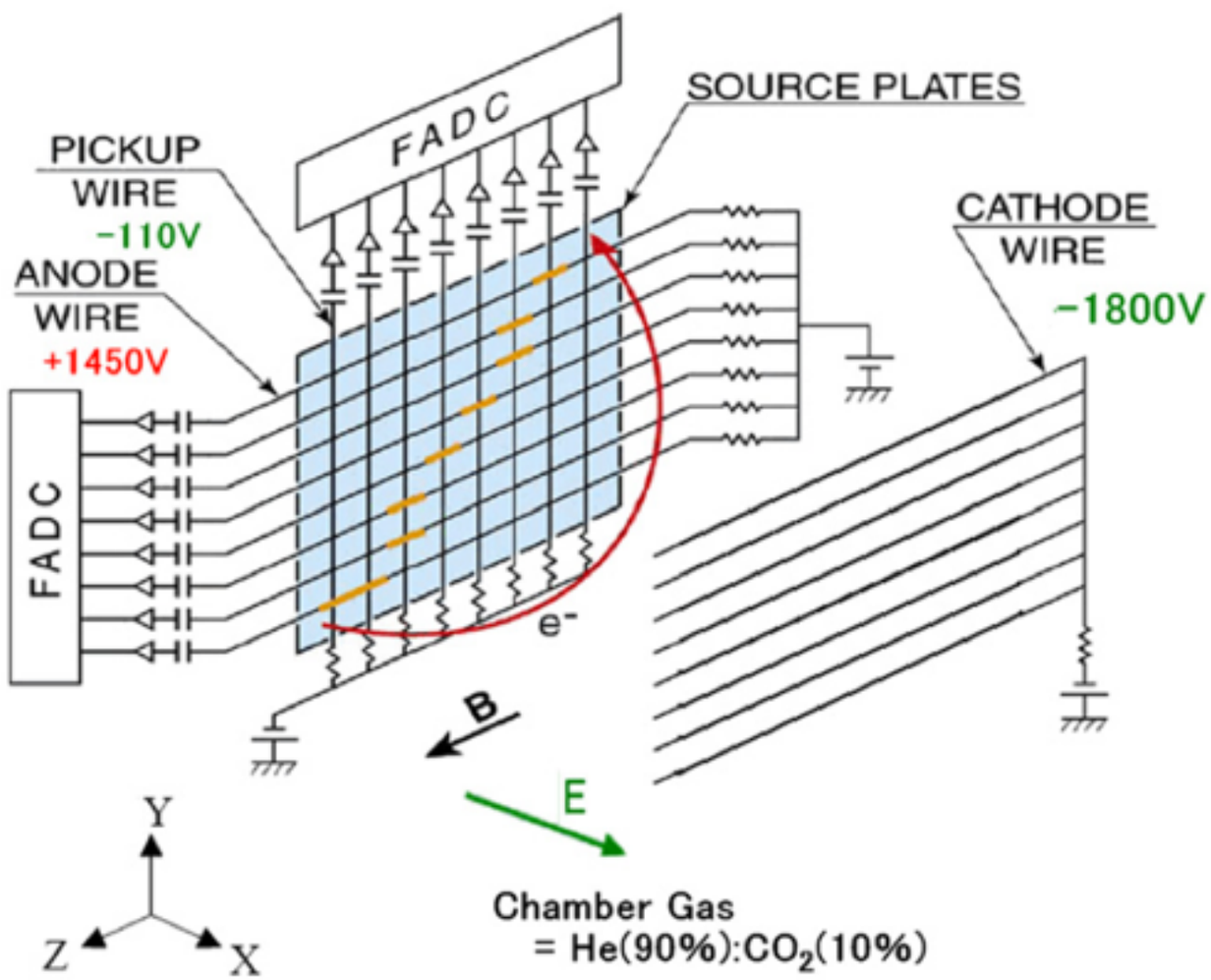
DCBA

DCBA

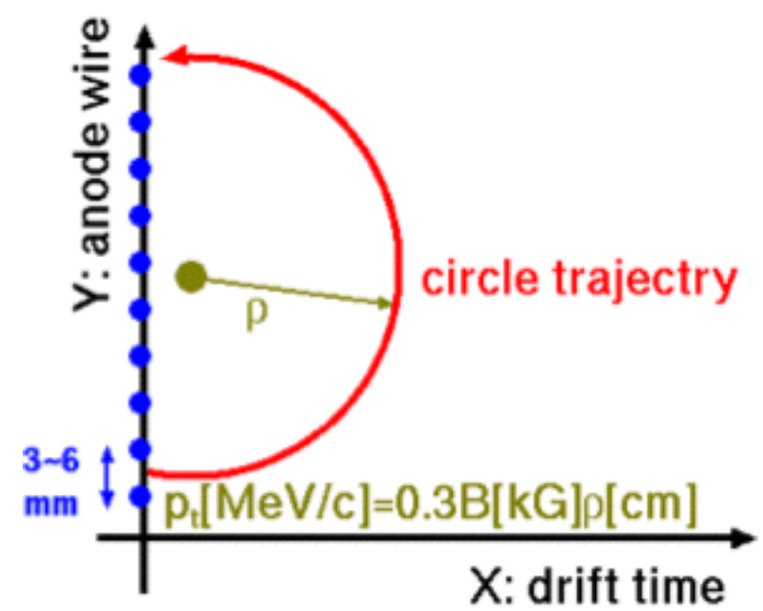
Drift Chamber Beta-ray Analyzer

Track / Position reconstruction

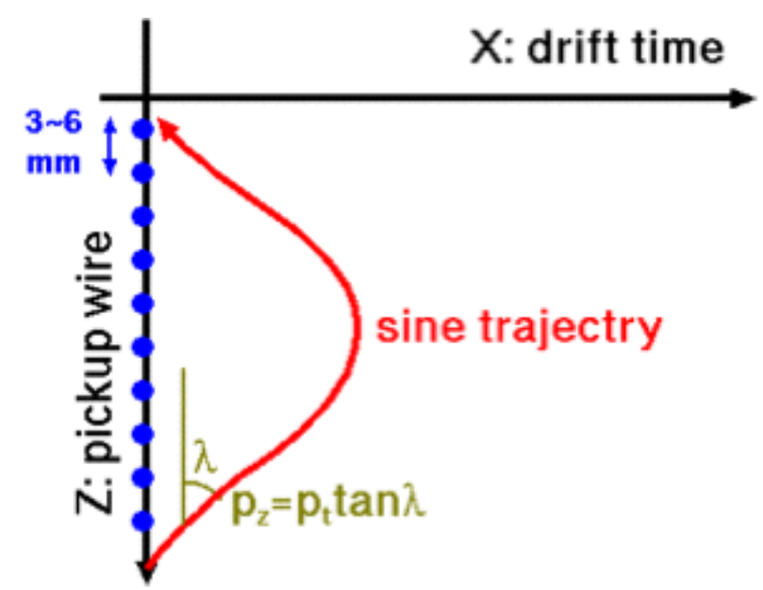
X : drift time
Y : hit position of anode wire
Z : hit position of pickup wire



Momentum reconstruction



p_t

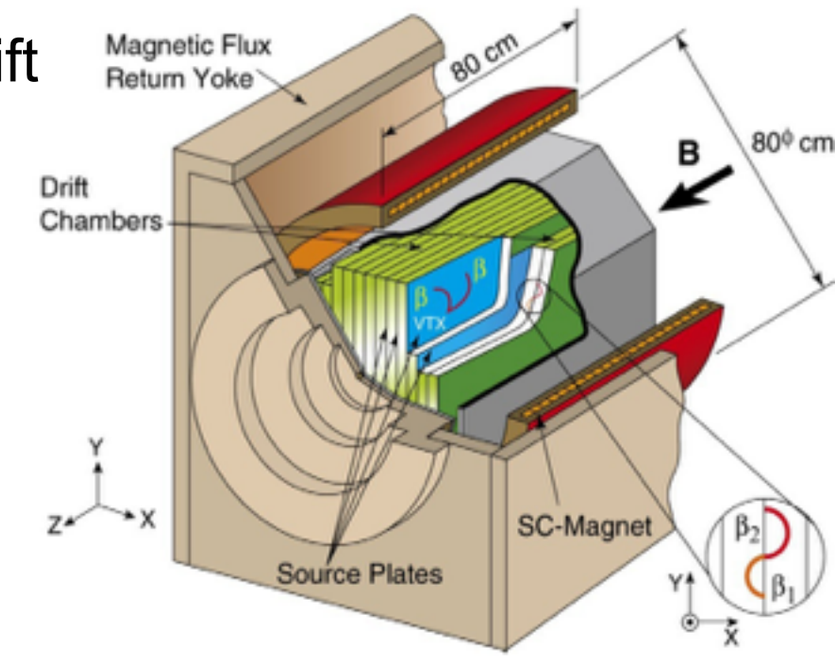


p_z

DCBA Prospect

2005	DCBA	
2007	DCBA-T2	demonstrate the principal of drift chamber tracking technique
2011	DCBA-T2.5	
2014	DCBA-T3	prototype for MTD
now		precise measurement of $2\nu\beta\beta$
2017	MTD	search for $0\nu\beta\beta$

DCBA-T3



ββ isotope ^{150}Nd (natural, enriched)

DCBA-T3: 0.18 mol ^{150}Nd $Q_{\beta\beta}$ = 3370 keV

MTD-full: **several 10 kg ^{150}Nd (60% enriched)**

Resolution FWHM

DCBA-T3: ~3.4% @ ROI DCBA-T2: ~6.2%

(foreseen: 2.4 kG magnetic field)

Background

$2\nu\beta\beta$: reduction with better energy resolution

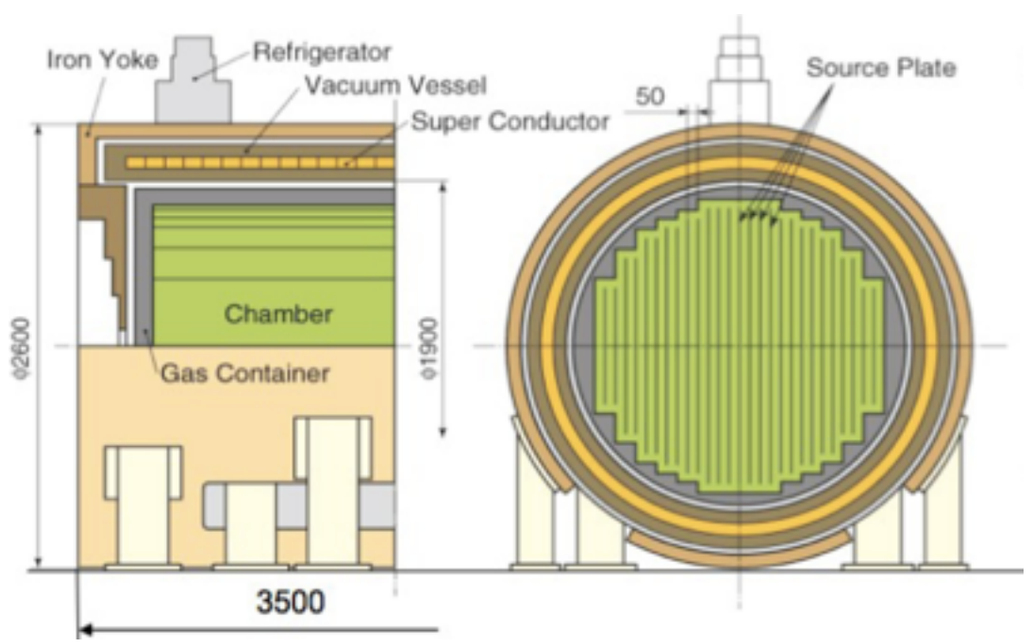
^{214}Bi: tagged by ^{214}Po alpha

Projected sensitivity @ 90% C.L.

DCBA-T3: $\langle m_{\beta\beta}\rangle$ < ~4 eV

MTD-full: **$\langle m_{\beta\beta}\rangle$ < ~30 meV**

MTD (Magnetic Tracking Detector)

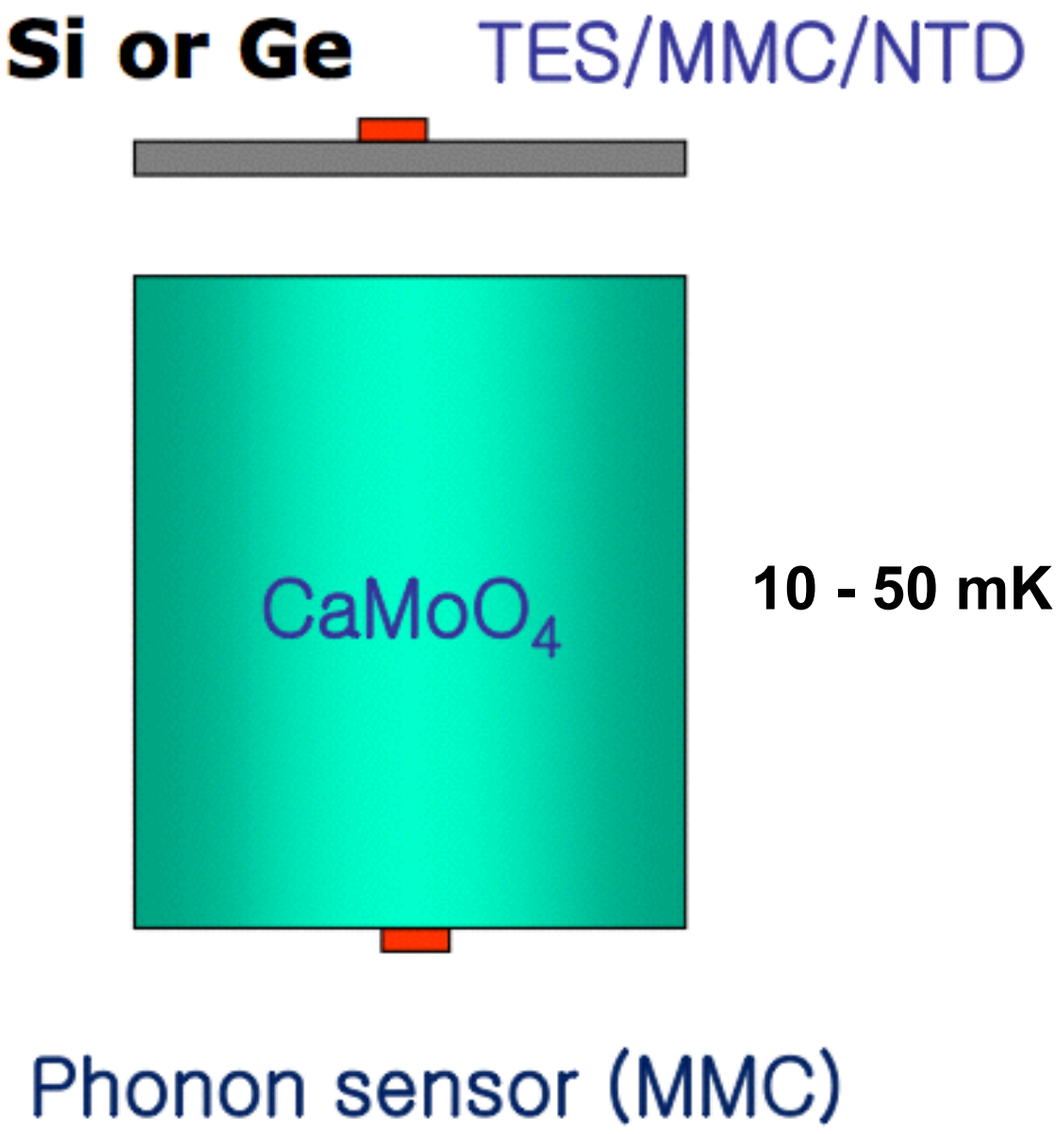


H. Iwase DBD11

AMoRE

AMoRE

Advanced Mo-based Rare process Experiment



V. N. Kornoukhov - TAUP 2011

Why $CaMoO_4$?

- highest light yield among Mo-crystals
- high Q-value (^{100}Mo ββ-decay : 3.03 MeV)
- less background from natural radioactivities
- enrichment of ^{100}Mo > 90% not so difficult
- ^{48}Ca needs to be depleted

- $CaMoO_4$ scintillator

transparent, ultra-pure crystal

1 kg, 10 kg, 200 kg, … $^{40}Ca^{100}MoO_4$

- Phonon + Light sensor (MMC)

scintillating bolometer (Debye temp. = 438 K)

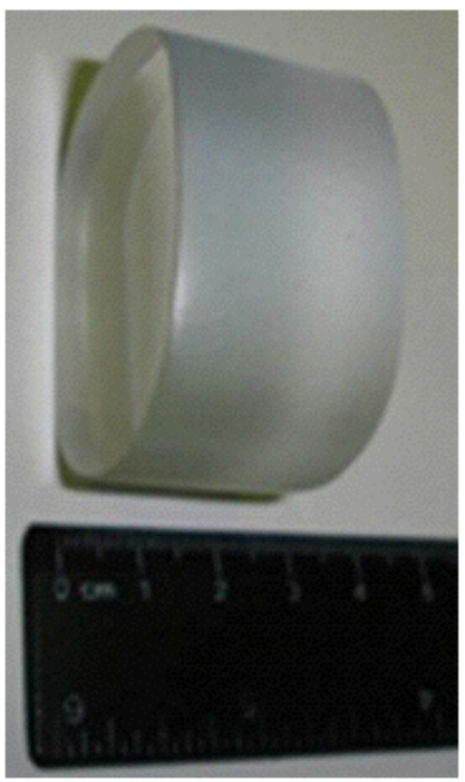
metallic magnetic calorimeter, fast signals

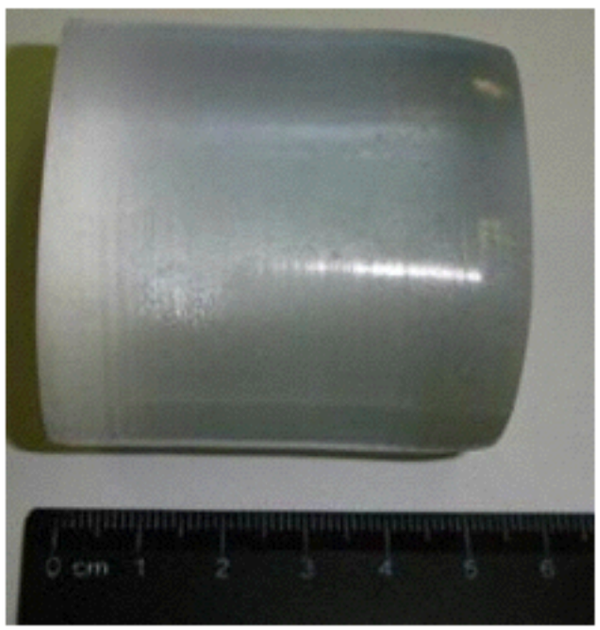
light yield at low temp. ~ 30,000 photon / MeV

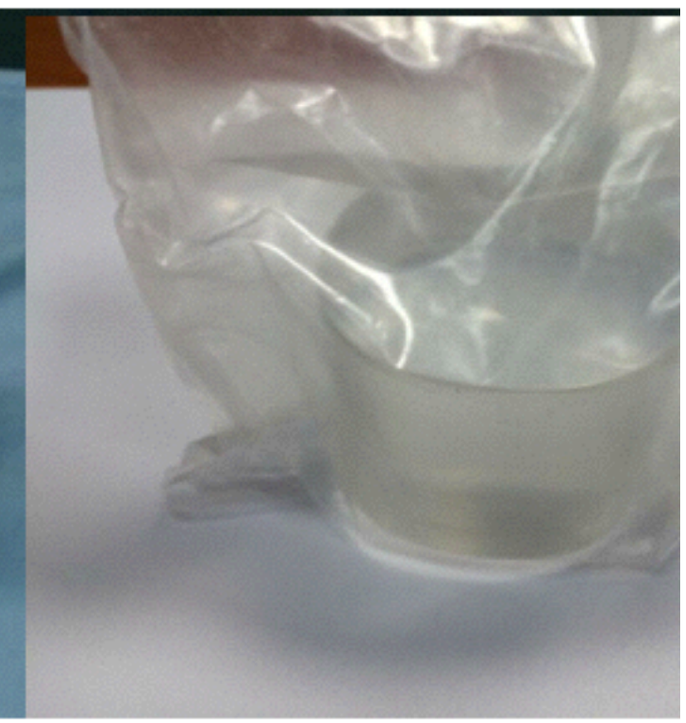
alpha / gamma separation

$^{40}Ca^{100}MoO_4$ Crystal

- **SB28**
  weight 196 g
- **SB29**
  weight 390 g
- **S35**
  weight ~300 g
- **SS68**
  weight ~300 g



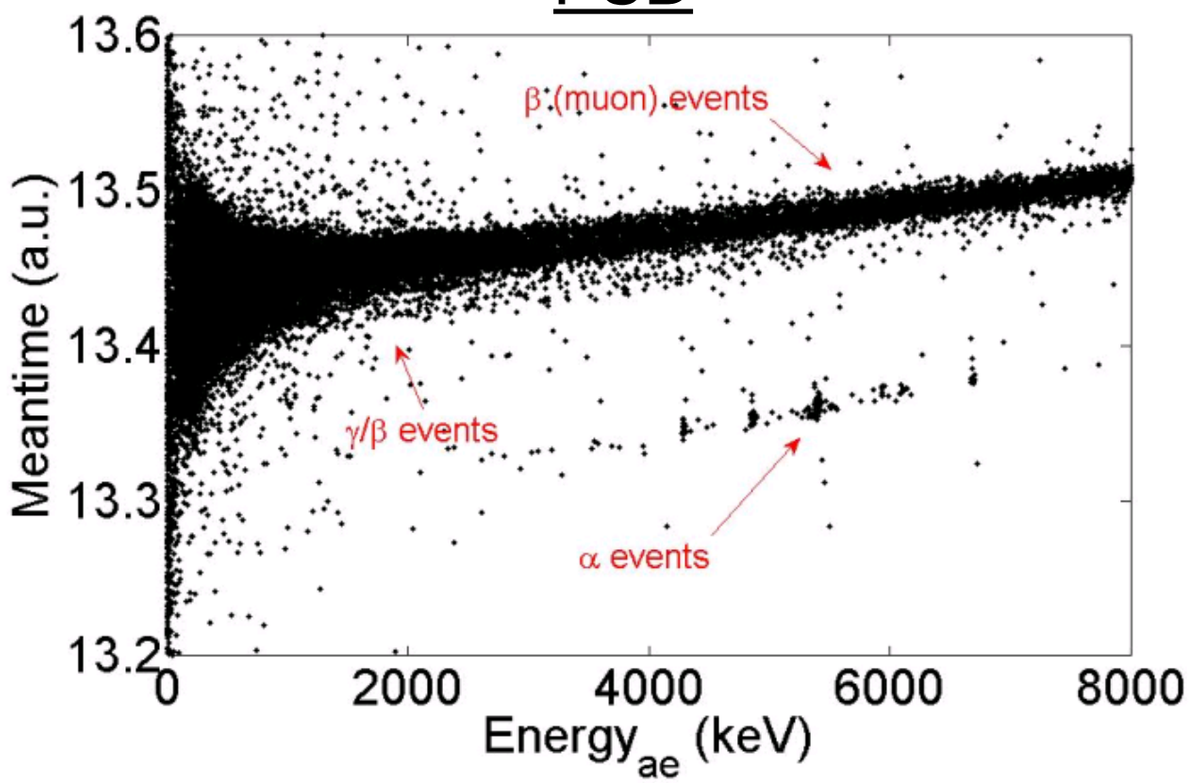




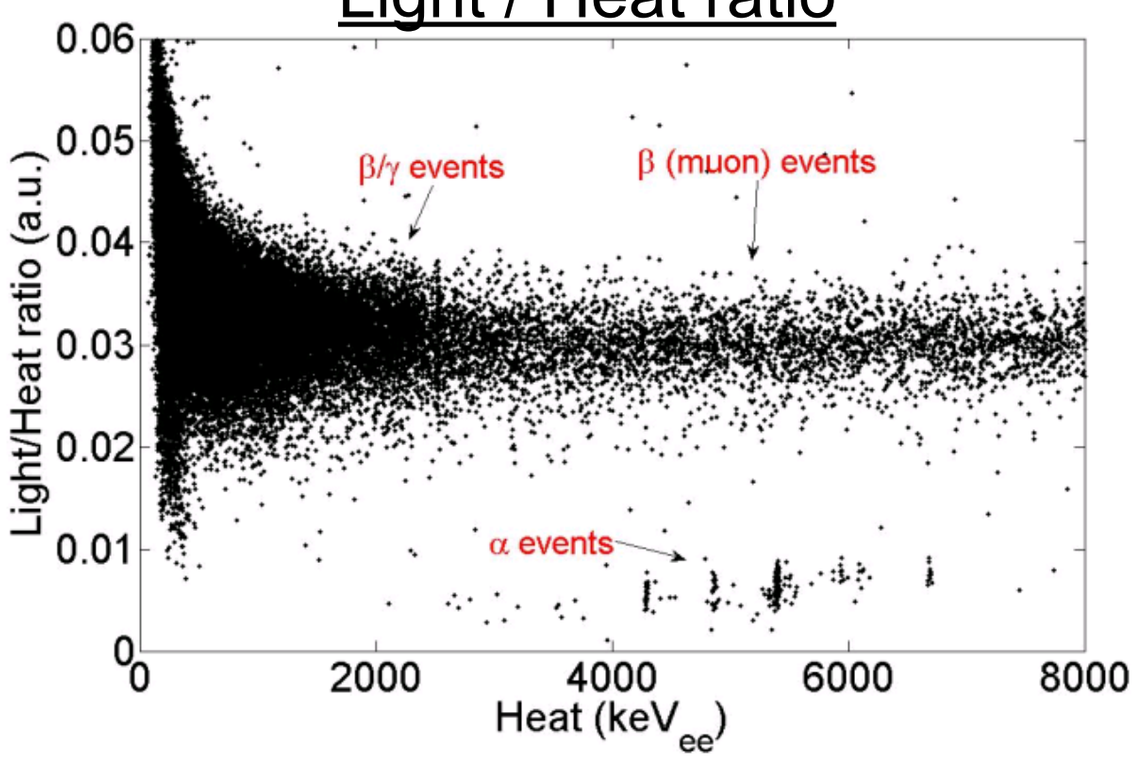
New S68
Under test
(Nb doped)

Detector Performance

PSD

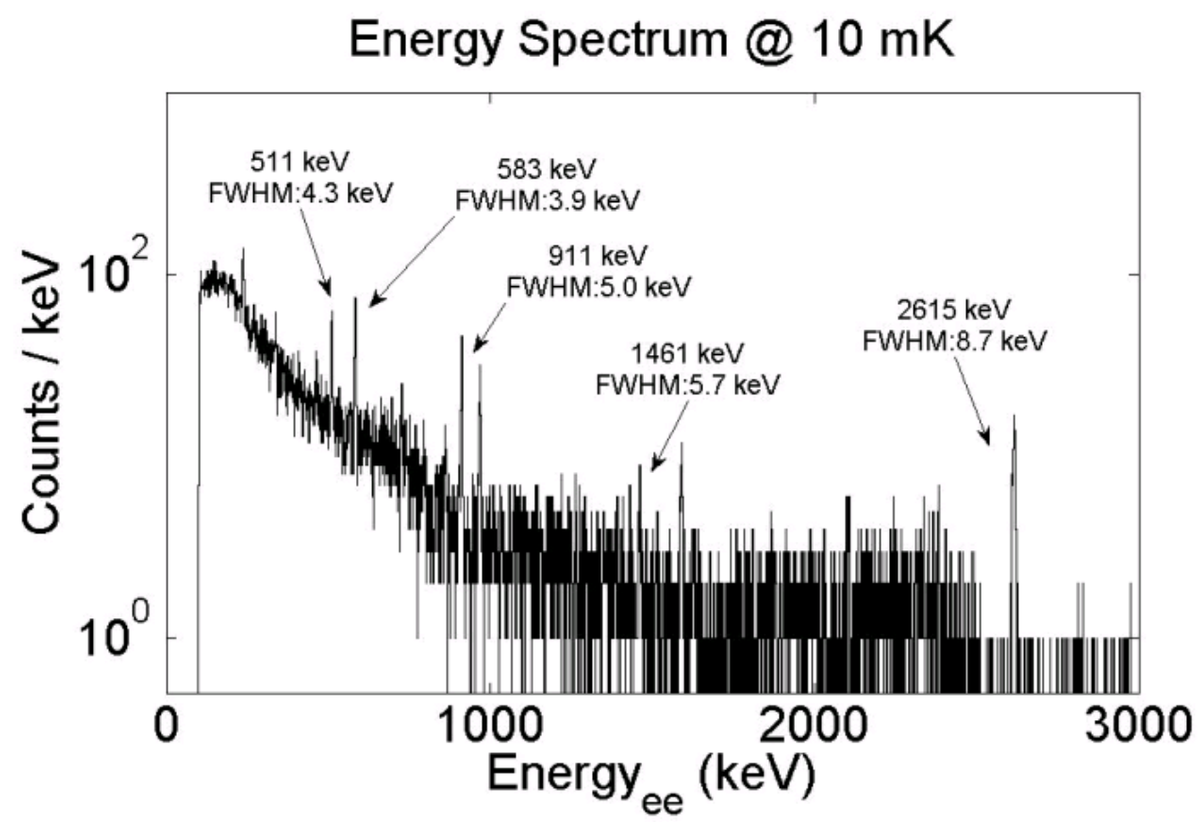


Light / Heat ratio



measurement @ over-ground

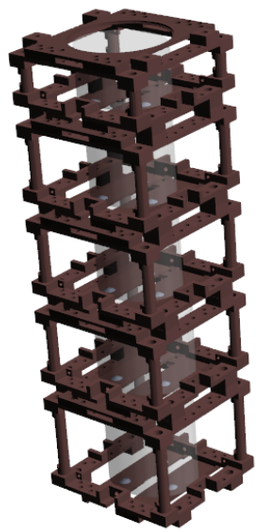
- α / e separation in **PSD and Light / Heat ratio**
- **high energy resolution** with cryogenic technique



energy resolution :
FWHM = 8.7 keV @ 2615 keV

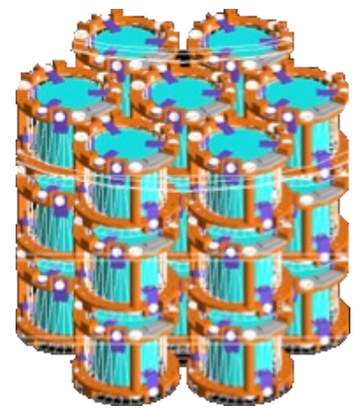
AMoRE Prospect

Pilot



5 CMOs ~ 1 kg

Phase I

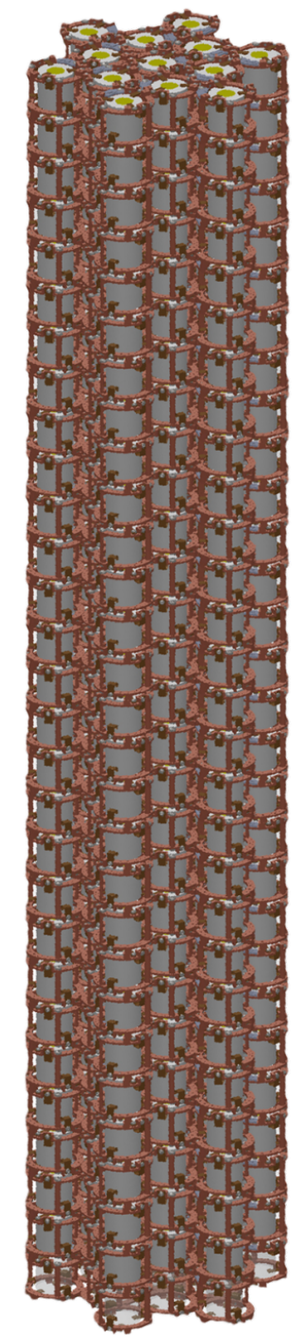


CMO ~ 300 g

5 layers - 7 columns

10 kg

Phase II



200 kg

	Pilot	Phase I	Phase II
Mass	1 kg	10 kg	200 kg
Sensitivity(m_{ee}) (meV)	300-900	60-180	10-30
Location	Y2L	Y2L	New Lab
Schedule	2015	2016	2019

Summary

- Neutrino mass measurements in Asia are reviewed

	Double Beta Decay		Neutrino Oscillation
Japan	**KamLAND-Zen**	**^{136}Xe**	Super-K / T2K **MH test**
	CANDLES	**^{48}Ca**	KamLAND
	DCBA	**^{150}Nd, ^{82}Se, ^{100}Mo**	Hyper-K (future)
	AXEL (future)	**^{136}Xe**	
	ZICOS (future)	**^{96}Zr**	
Korea	**AMoRE**	**^{100}Mo**	RENO
			RENO-50 (future)
China			Daya Bay
			JUNO (future)
India			INO (future)

- Several double-beta decay experiments will reach the **sensitivity to test the inverted hierarchy** in the near future