$\beta\beta0\nu$ Decay Searches: Current Status and Prospects

10 April 2019

Prospects of Neutrino Physics, Kavli IPMU

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Yet Unknown in neutrinos

- ○ one or three CP phases
- ○ mass (absolute value and hierarchy)
- ● Majorana？ Dirac？
- ○ # of generations

measurable with oscillation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

oscillation	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
neutrinoless double beta	$\langle m_{\beta\beta} \rangle = \lvert \Sigma\, m_i \lvert U_{ei} \rvert^2 \varepsilon_i \rvert$
cosmology	$M = \Sigma\, m_i$
single beta	$\langle m_\beta \rangle^2 = \Sigma\, m_i^2 \lvert U_{ei} \rvert^2$

indispensable

double beta

realistic test of Majorana nature

sensitive to absolute mass

opens Majorana CP measurement

Dirac vs. Majorana

Discovery of neutrino mass requires right-handed composition.

e		
	LH electron (e^-_L)	RH electron (e^-_R)
	LH positron (e^+_L)	RH positron (e^+_R)

Matter particle (Fermion) has at least 4 components.

It is naturally derived from quantum mechanics and special relativity (Dirac equation).

ν		
	LH ν_L	RH ν_R (N_R) not discovered
	LH $\bar{\nu}_L$ ($\bar{N}_L$) not discovered	RH $\bar{\nu}_R$

Dirac neutrino

ν_L $\underbrace{\nu_R \ \bar{\nu}_L}_{\text{unobservable}}$ $\bar{\nu}_R$

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

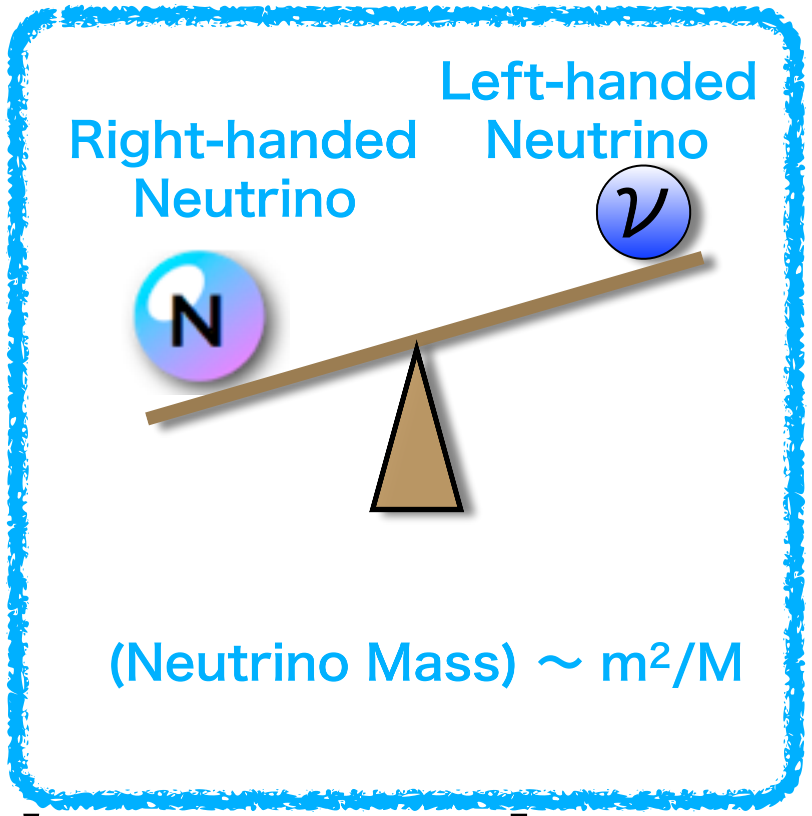
Majorana neutrino (1937)

ν_L $\bar{\nu}_R$ $\underbrace{\bar{N}_L \ N_R}_{\text{just heavy}}$

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

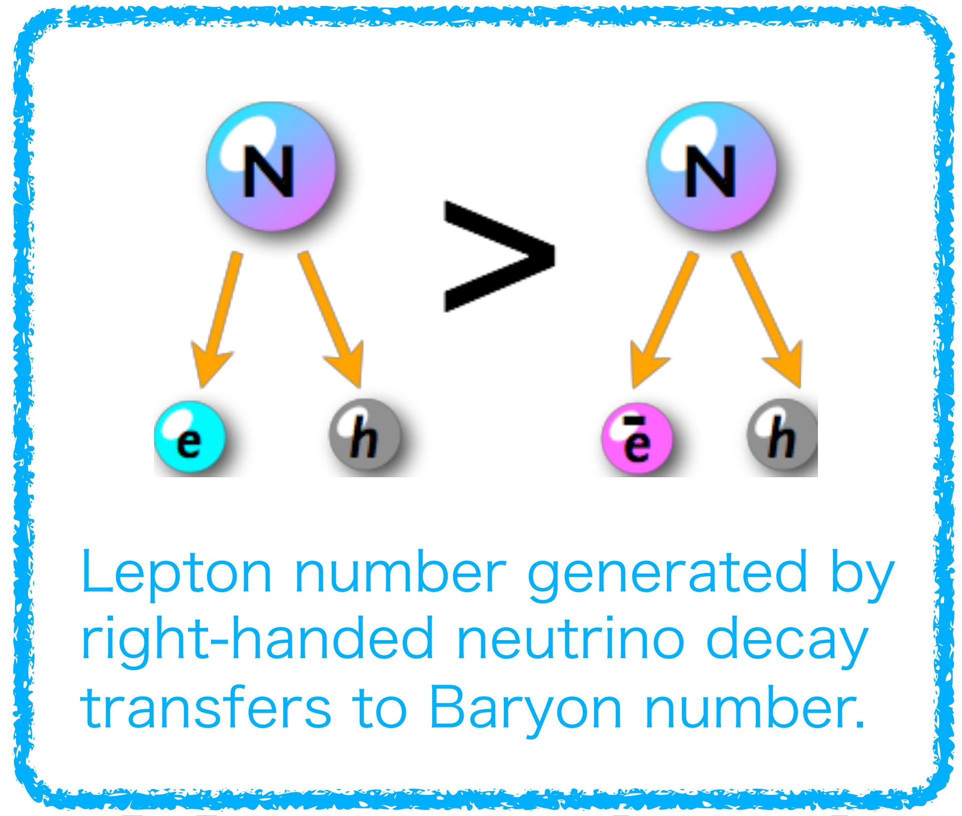
Majorana neutrino violates Lepton #.

Seesaw Mechanism and Light neutrino mass



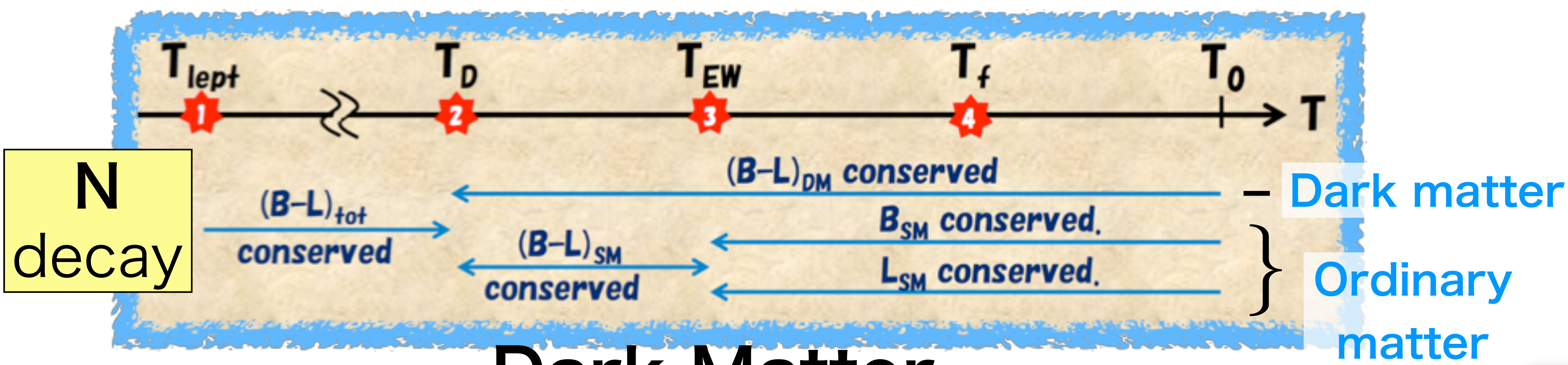
Light neutrino mass

Matter dominance through Leptogenesis



Matter dominance

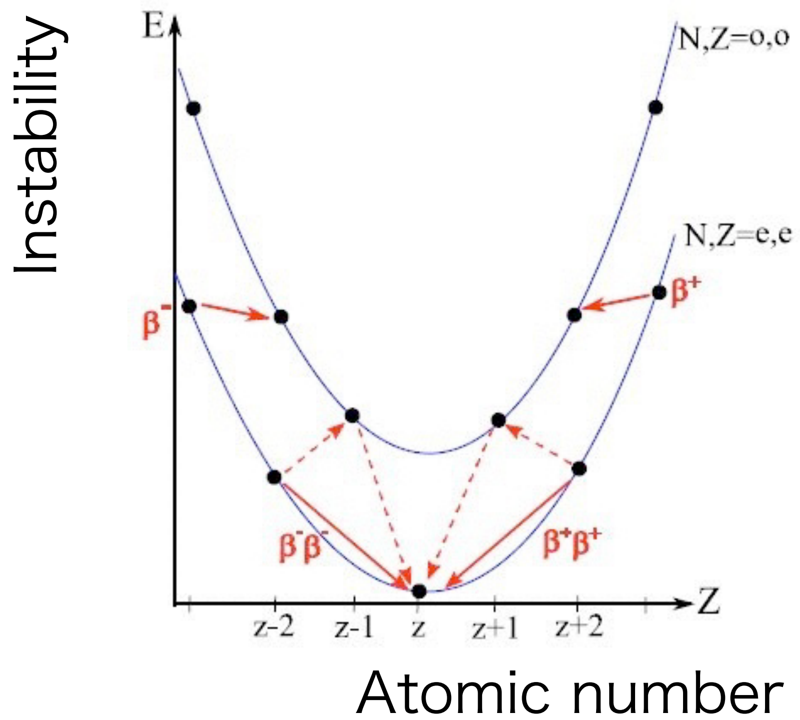
Asymmetric Dark Matter (Dark Matter through Leptogenesis)



Dark Matter

Search for 0ν2β is so far the only way to confirm Majorana nature

Several tens of nuclei undergo “Double Beta Decay”.



^{48}Ca
^{76}Ge
^{100}Mo
^{130}Te
^{136}Xe
^{150}Nd
…

theoretical history

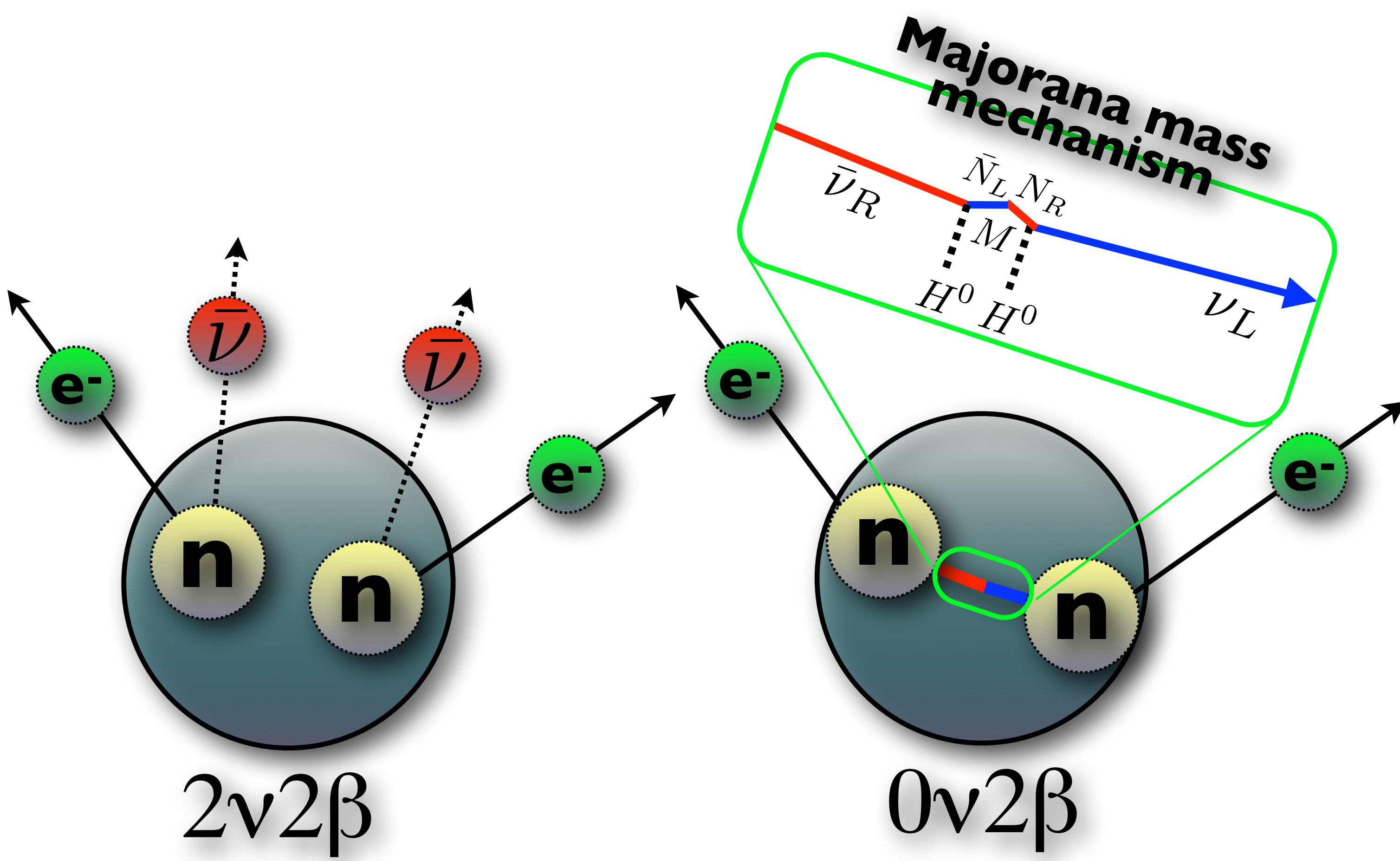
1930 light neutral particle (W.Pauli)
1933 β decay theory (E.Fermi)
1935 $2\nu2\beta$ (M.Goeppert-Mayer)
1937 Majorana neutrino (E.Majorana)
1939 $0\nu2\beta$ (W.Furry)

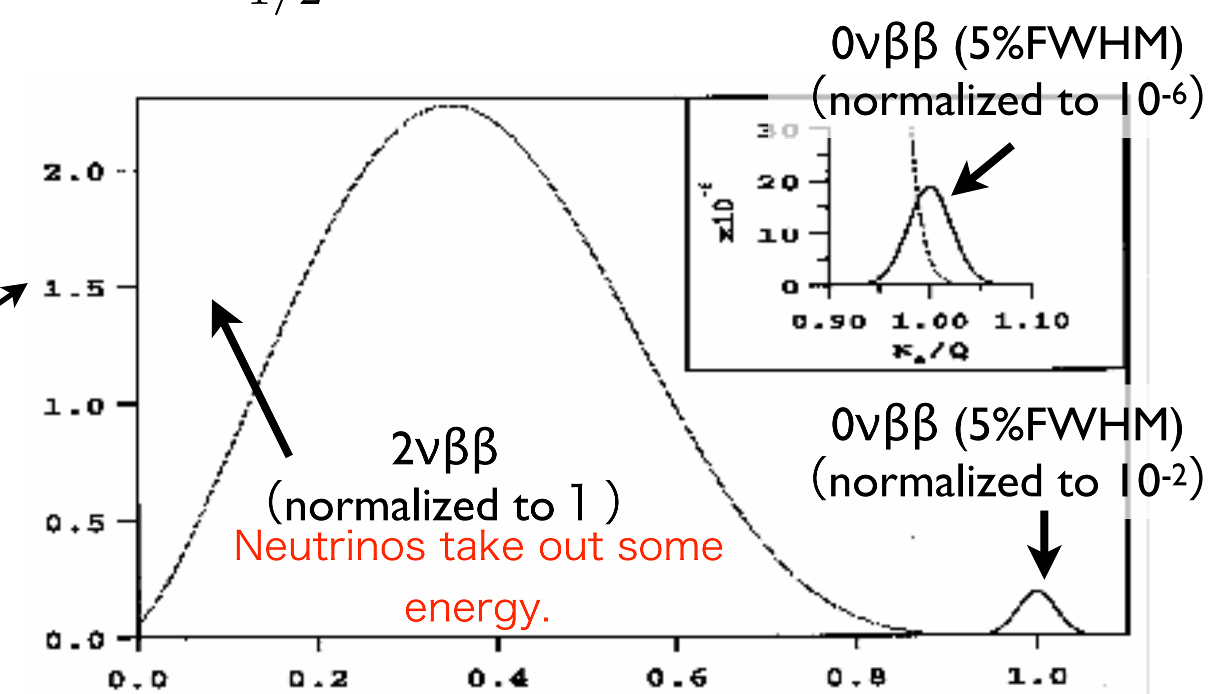
W.Furry

Majorana CP
only accessible by $0\nu2\beta$

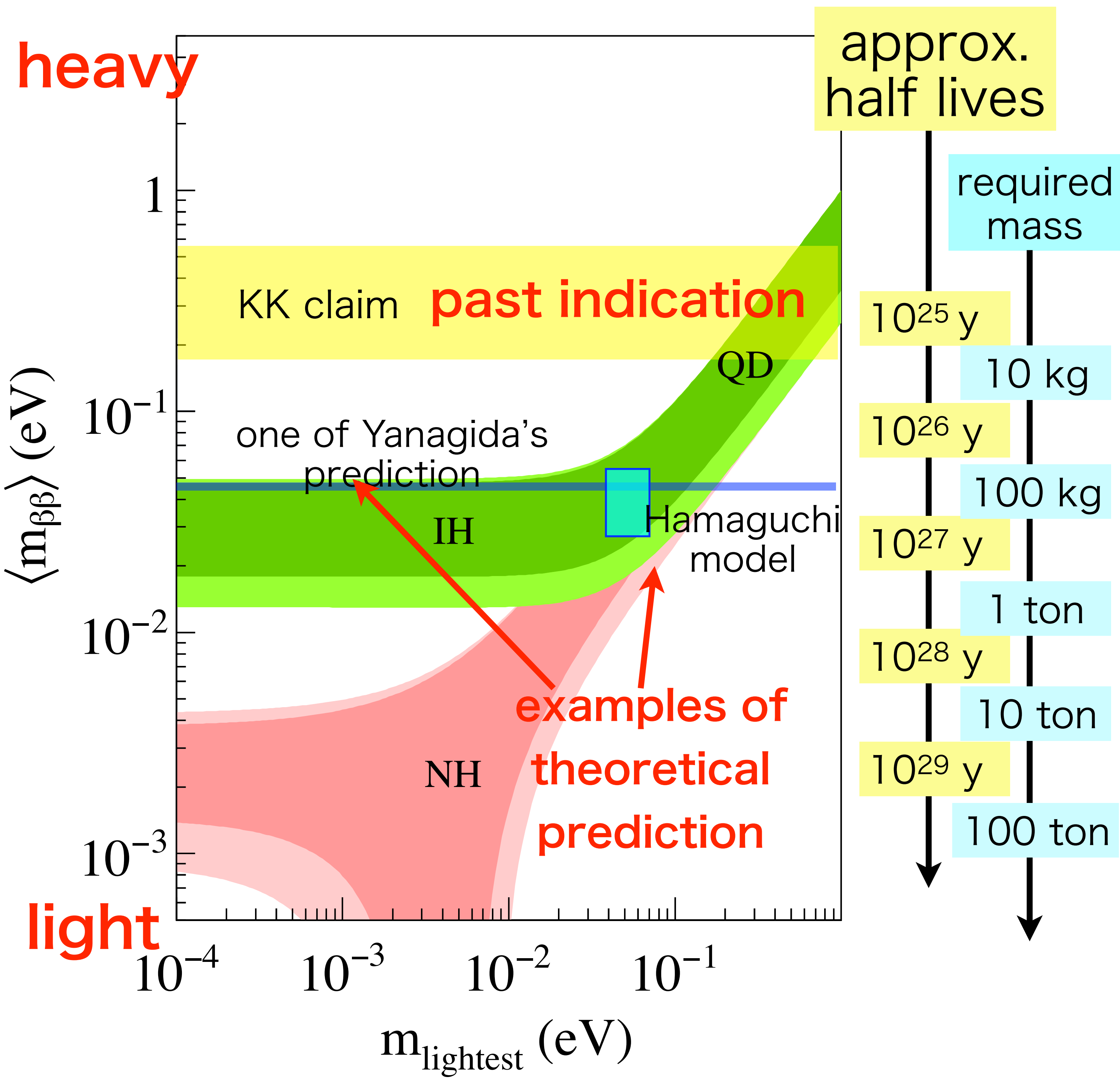
$$\langle m_{\beta\beta}\rangle = \left|\Sigma\, m_i\, |U_{ei}|^2\, \varepsilon_i\right|$$

$$\frac{1}{T_{1/2}} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$





Milestones of $0\nu2\beta$ search



✔ KK claim is refuted

KamLAND-Zen, EXO-200, GERDA

What's next?

✔ covering QD hierarchy

KamLAND-Zen has almost achieved.

- Yanagida's prediction

  47±1 meV PRD86,013002(2012)

- Hamaguchi model

  24-55 meV (1 σ) arXiv:1705.00419

- covering IH

  ~20 meV next generation

- covering NH

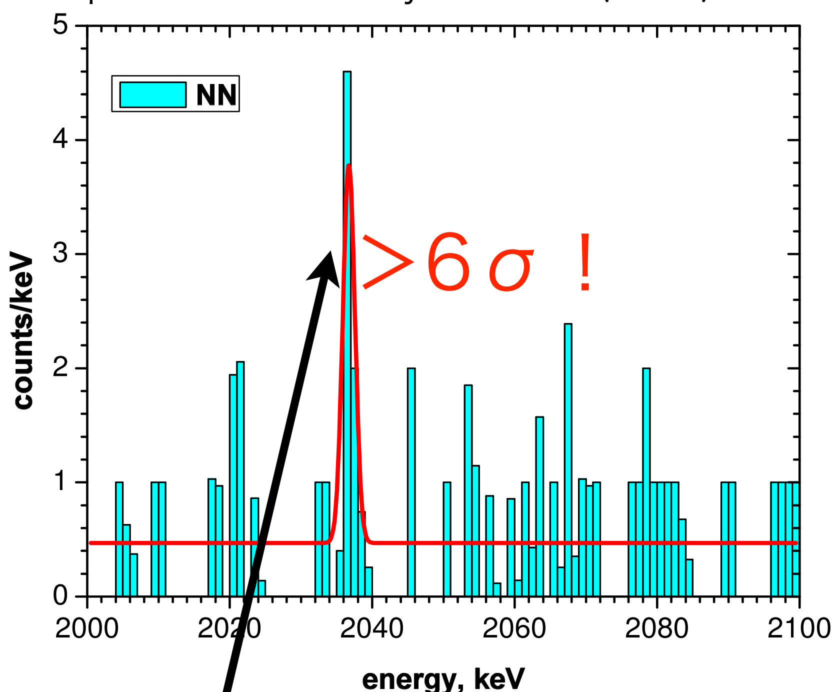
  <1 meV very difficult

past big argument in $0\nu2\beta$ search

KK claim

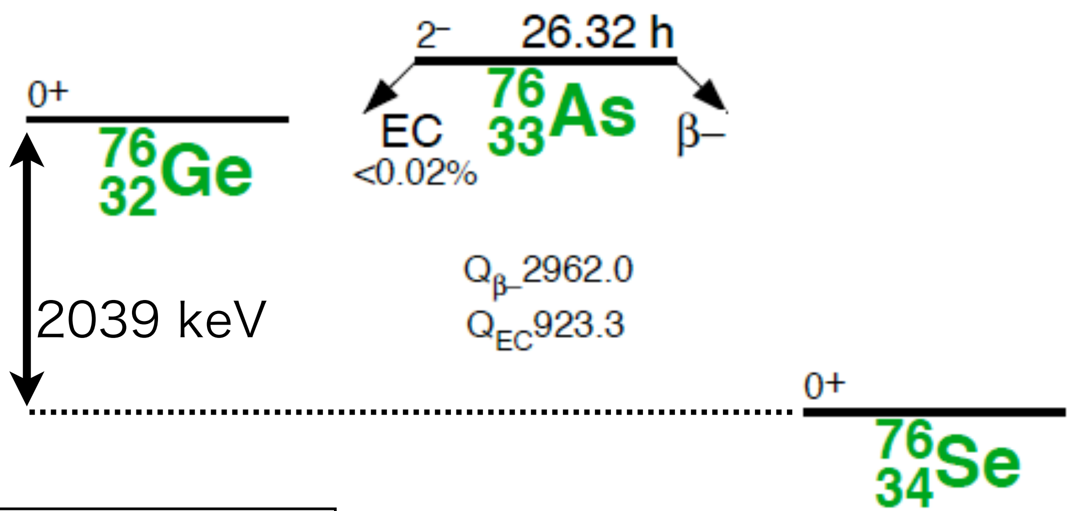
Part of Heidelberg Moscow experiment

Klapdor et al. Mod.Phys.Lett.A21(2006)1547



Evidence of $0\nu2\beta$?

11 kg ^{76}Ge



exposure 71 kg·year

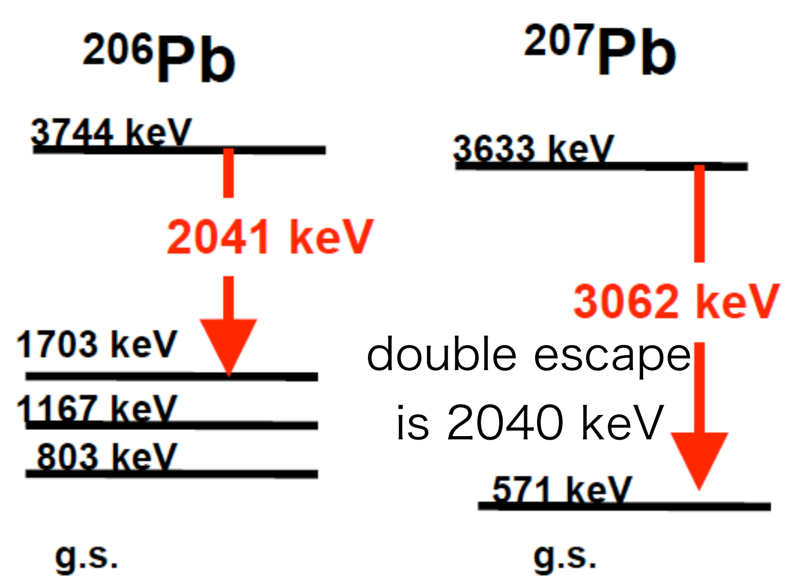
$T_{1/2}=2.23^{+0.44}_{-0.31}\times10^{25}$ years

m_ν =320±30 meV

NME uncertainty not included

Statistical significance is high but there are many **BGs** candidates, and not very convincing

BG candidates



Lesson: "High resolution only" may suffer from unknown lines.

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

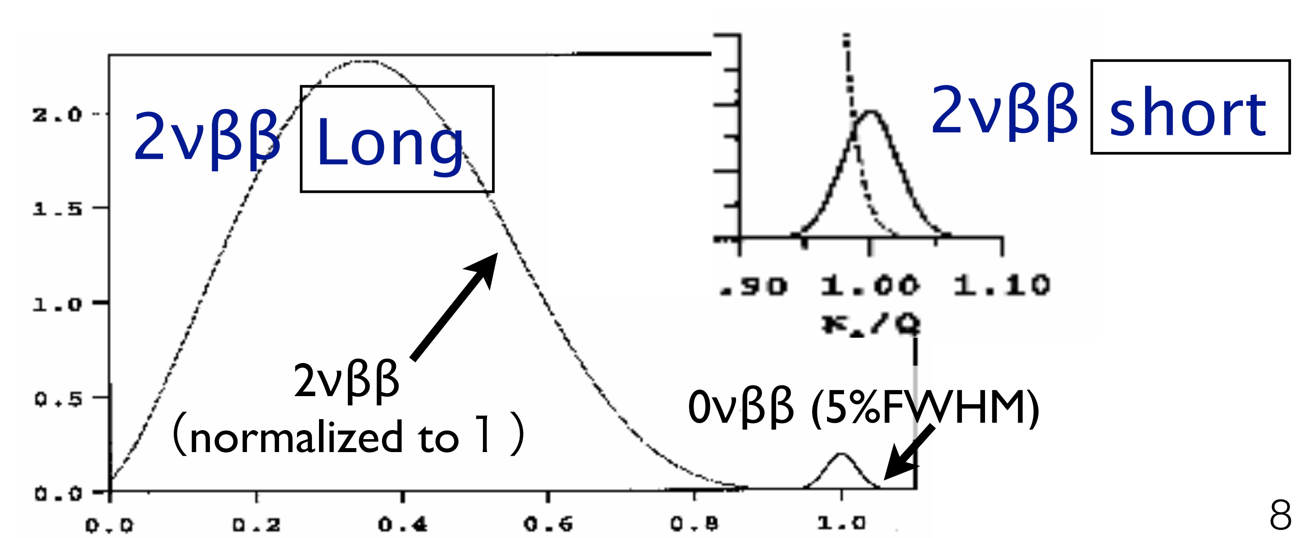
- No perfect isotope for double beta decay

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 **highest**, 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



Approaches and experiments

source = detector

serious BG
benefit

		NOW	MID-TERM	LONG-TERM		
Scalability — Fluid embedded source	Liquid Xe-based TPC	EXO-200		nEXO	self-shield 7.5xλ	ext. γ, ^{222}Rn
	Gas	NEXT-10	NEXT-100 PandaX-III	NEXT-2.0 PandaX-III 1t	low density	ext. γ $\nu_\odot$ rejection
	Liquid scintillator as a matrix	KamLAND-Zen 800	leading	KamLAND2-Zen	self-shield 15xλ	$\nu_\odot$
purification ON/OFF	low res.	SNO+ phase I		SNO+ phase II	low concentration	$2\nu \cdot \nu_\odot$
High ΔE and ε — Crystal embedded source	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000	KK-BG not-understood	surface BG
purification ON/OFF	Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID Mo	AMoRE II	CUPID	huge cryostat	surface BG
			reaching IH	covering IH		

Andrea Giuliani @neutrino2018

Strategy

The discovery may be just around the corner.

- Keep the top runner with **high scalability**

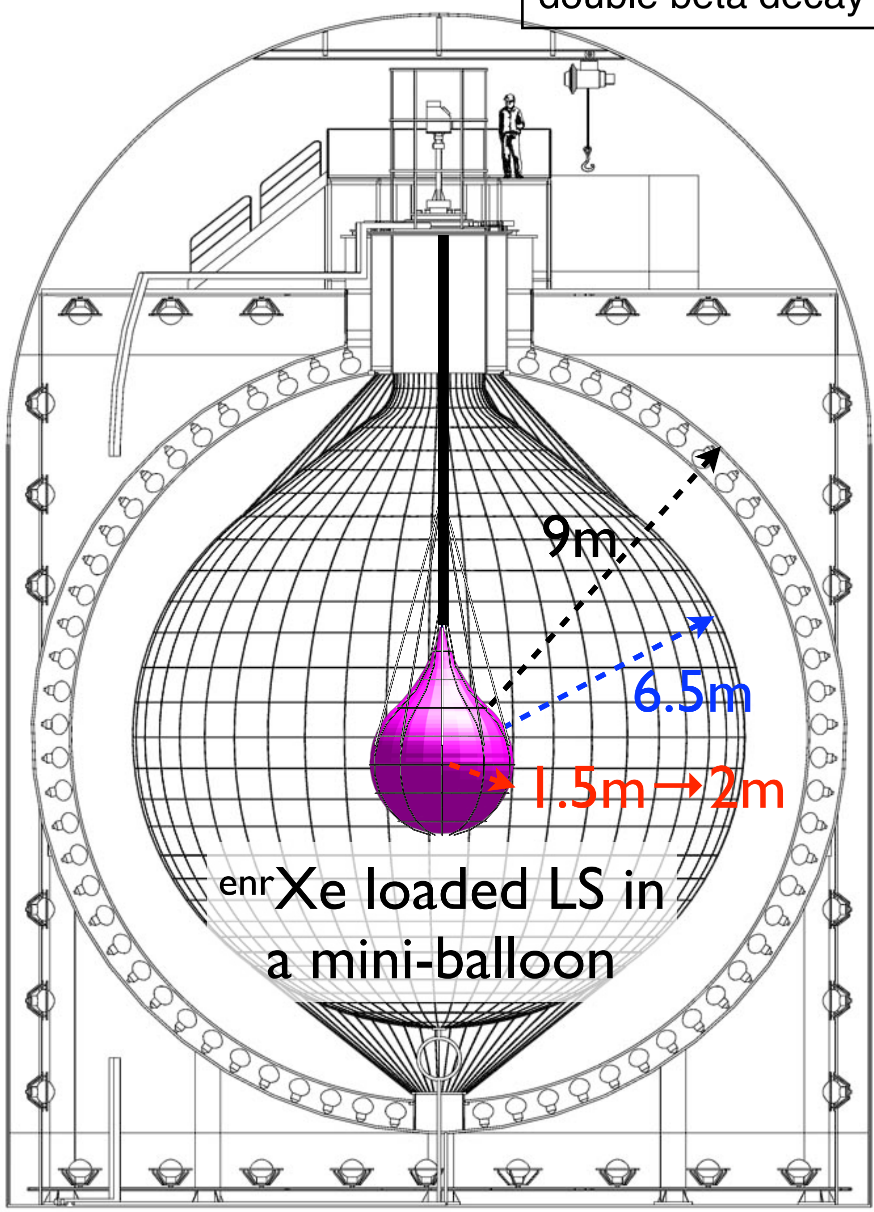
- In case $0\nu2\beta$ is not found,
  - **Full coverage of inverted hierarchy is important**
    - if contradict with cosmology or neutrino oscillation → can say "Neutrino is Dirac"
    - if believing Majorana neutrino → can say "Normal hierarchy" by a process of elimination
  - **Be multi-purpose**

- In case $0\nu2\beta$ is discovered,
  - precision measurement
  - **various nuclei** → reduce error from NME, identify physics background diverse technology
  - **tracking measurement** → identify physics background diverse technology
  - combine with cosmology, β decay → identify physics, possibility of Majorana CP measurement

We chose ^{136}Xe as it can be loaded in LS up to ~3 wt%.

KamLAND-Zen

Zero Neutrino double beta decay search



90% enriched ^{136}Xe
320kg for phase-I
380kg for phase-II
745kg for Zen 800 (started in January)

largest amount so far

^{136}Xe

Noble gas
Centrifugal enrichment possible
$Q_{\beta\beta}$=2459 keV
(below ^{208}Tl 3198-5001 keV)

Advantages of using KamLAND

⓪ low cost and quick start (running detector)
① BG can be identified (full active thick shielding)
② In-situ purification possible (liquid media)
③ On/Off measurements possible (xenon is removable)
④ multi-purpose (geo-neutrino)
⑤ easily scalable (mini-balloon)

KamLAND(-Zen) collaboration

Japan
Tohoku University, RCNS
University of Tokyo, Kavli IPMU
Osaka University
Tokushima University
Kyoto University
US
University of California Berkeley
University of Tennessee
Triangle University Nuclear Laboratory
University of Washington
Massachusetts Institute of Technology
Virginia Polytechnic Institute and State University
University of Hawaii
Boston University
Netherland
Nikhef, University of Amsterdam

※ Second affiliation is not listed.

Collaboration meeting @Tohoku

~50 physicists

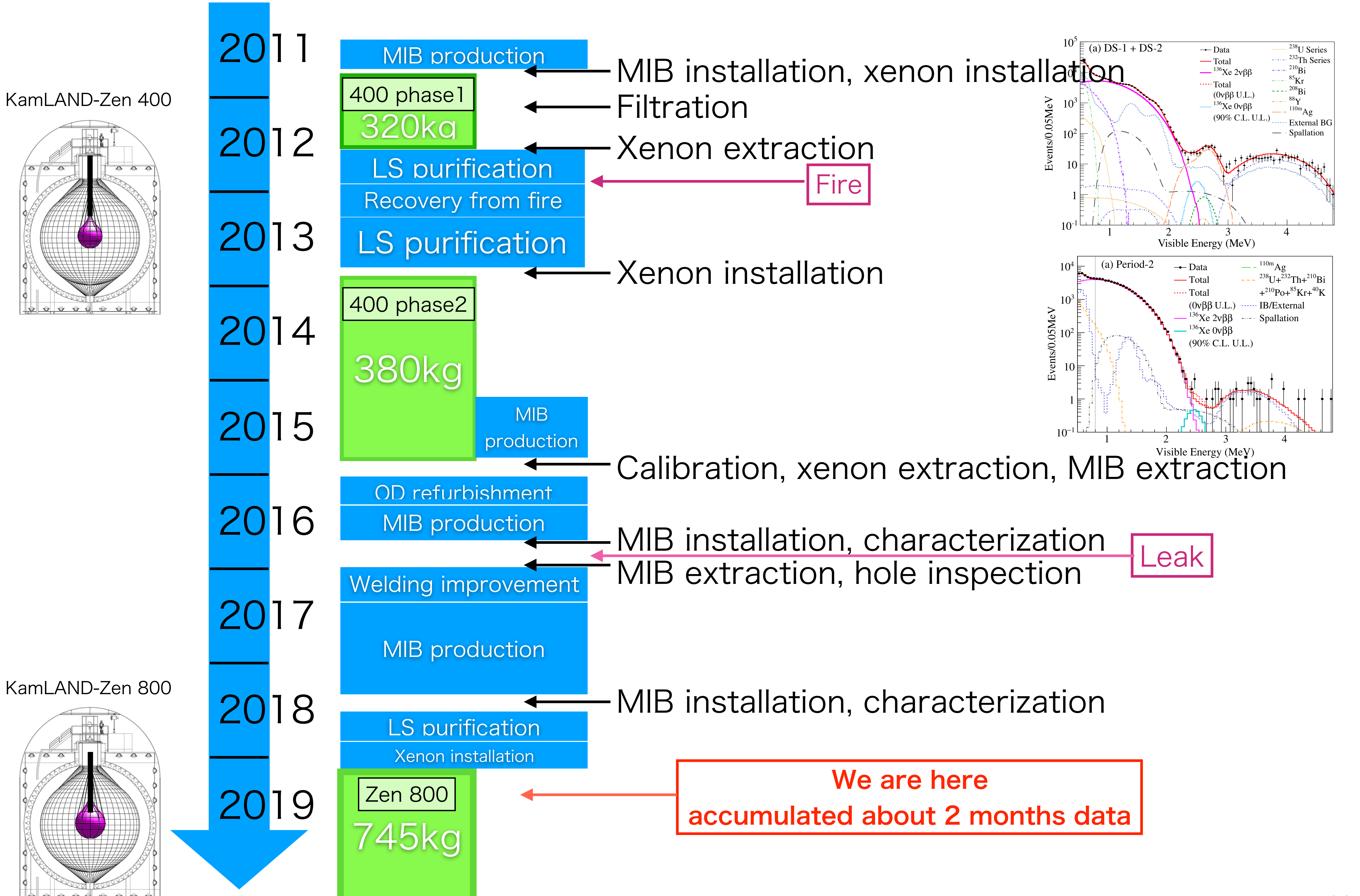
minimum inactive detector material
basically 25μm-t balloon film only

Initial funding in 2009 and picture in September 2011

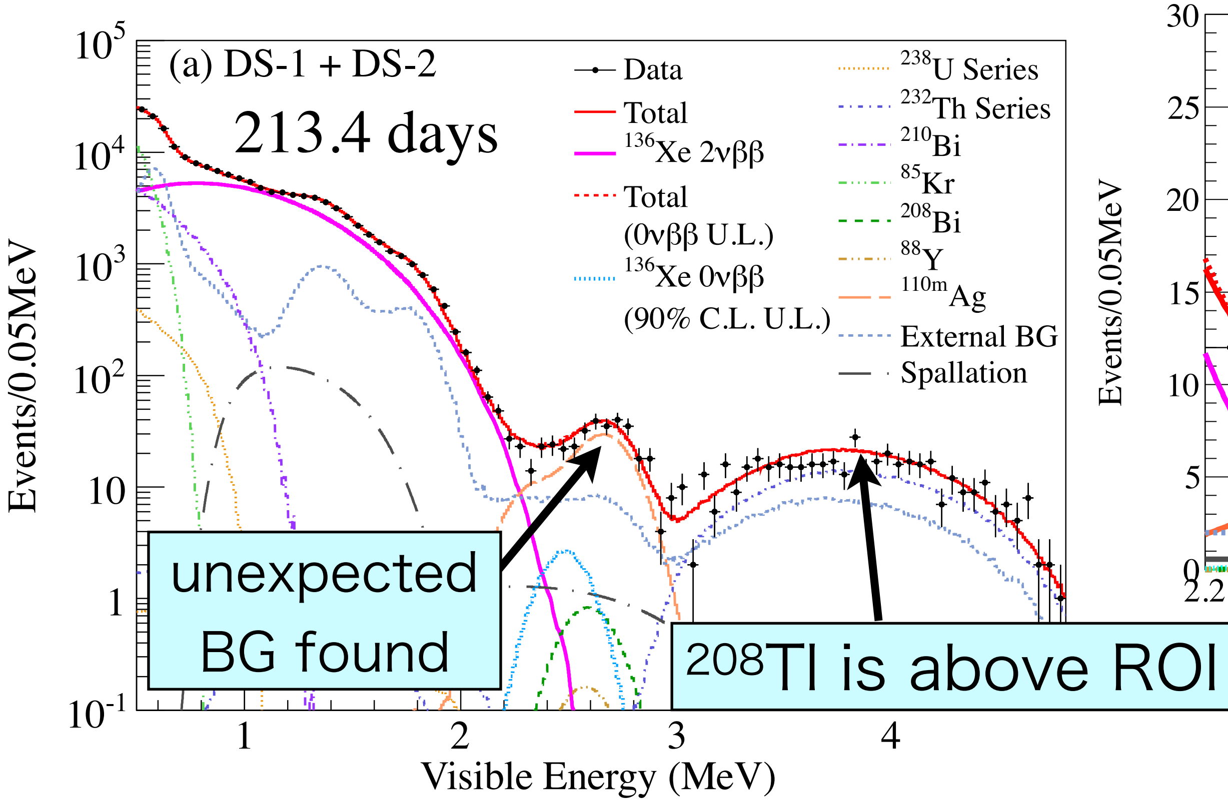
Everything has been done in two years!!

◎ low cost and quick start

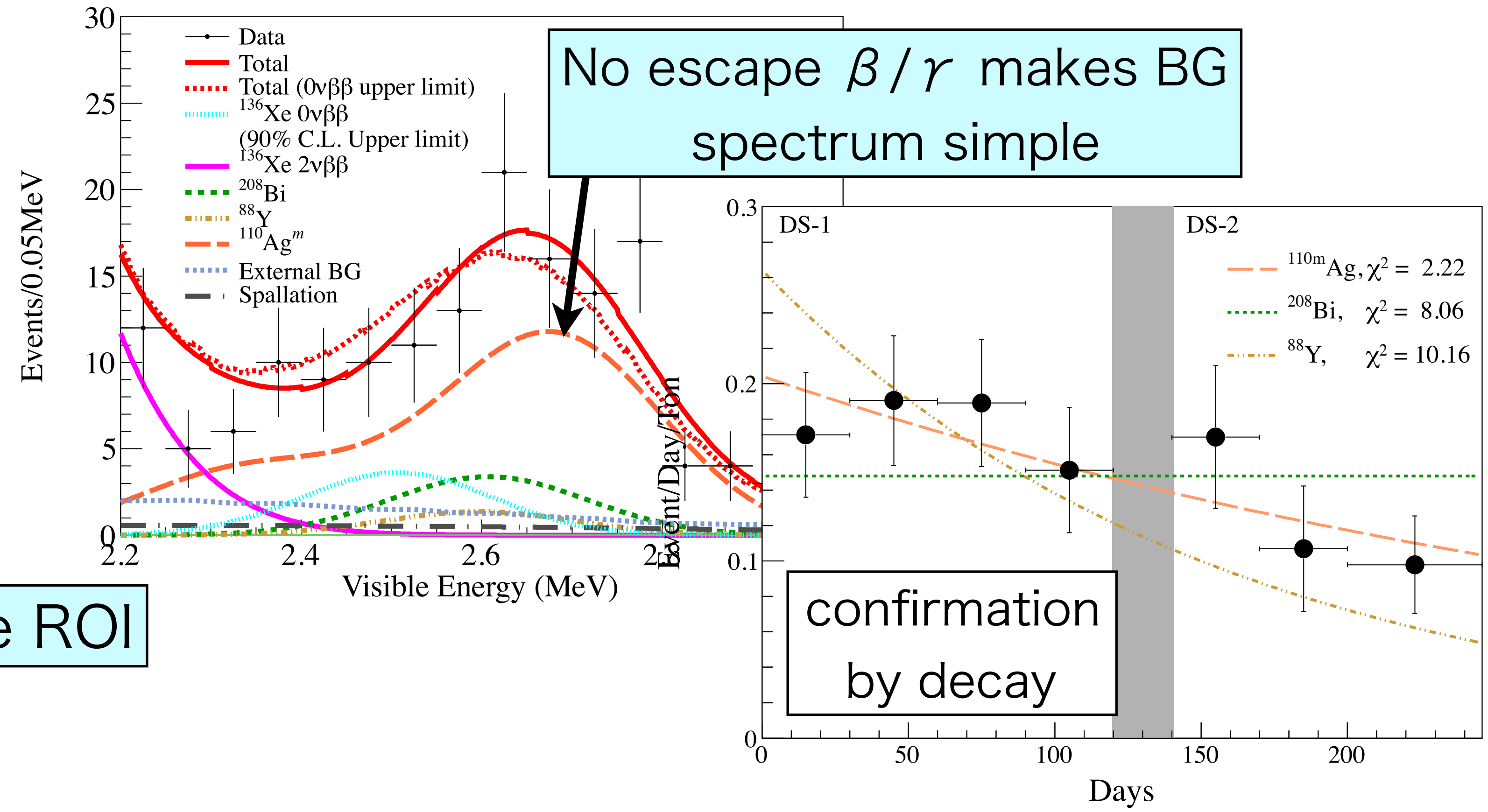
Timeline of KamLAND-Zen

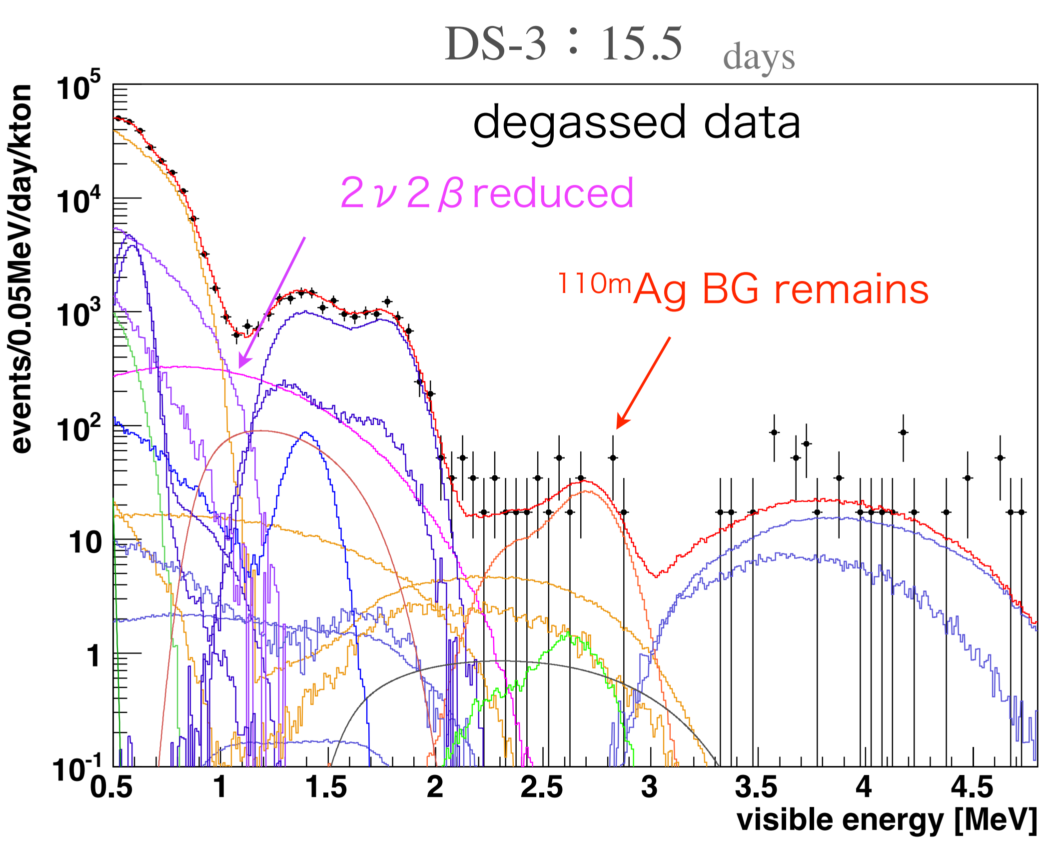


Thanks to full active apparatus,



Dominant ①BG identified as ^{110m}Ag

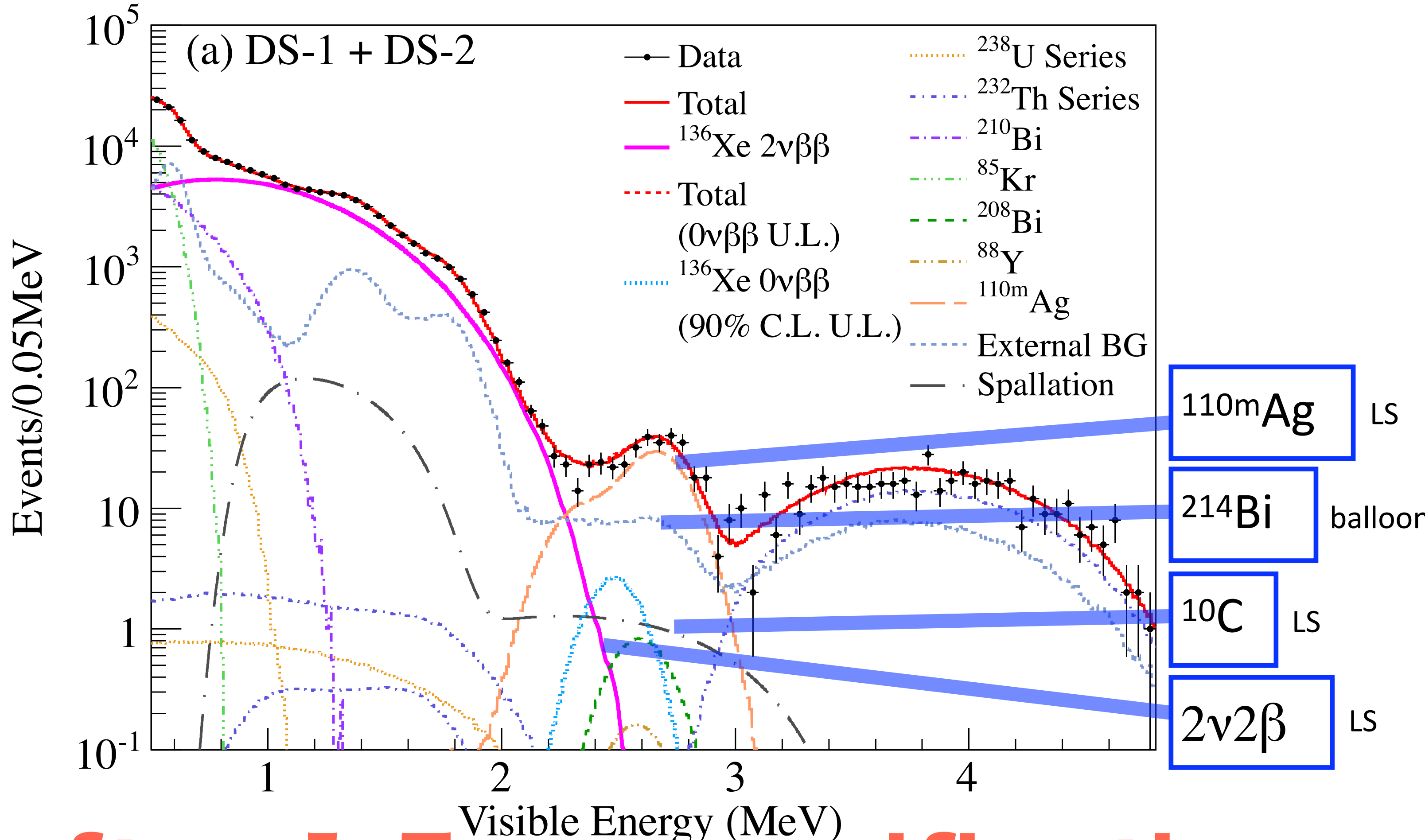




Xenon can be degassed from Xe-LS.
And ^{136}Xe ③on/off measurement has been demonstrated.
(useful for signal confirmation)

Phase-1 320kg

before purification



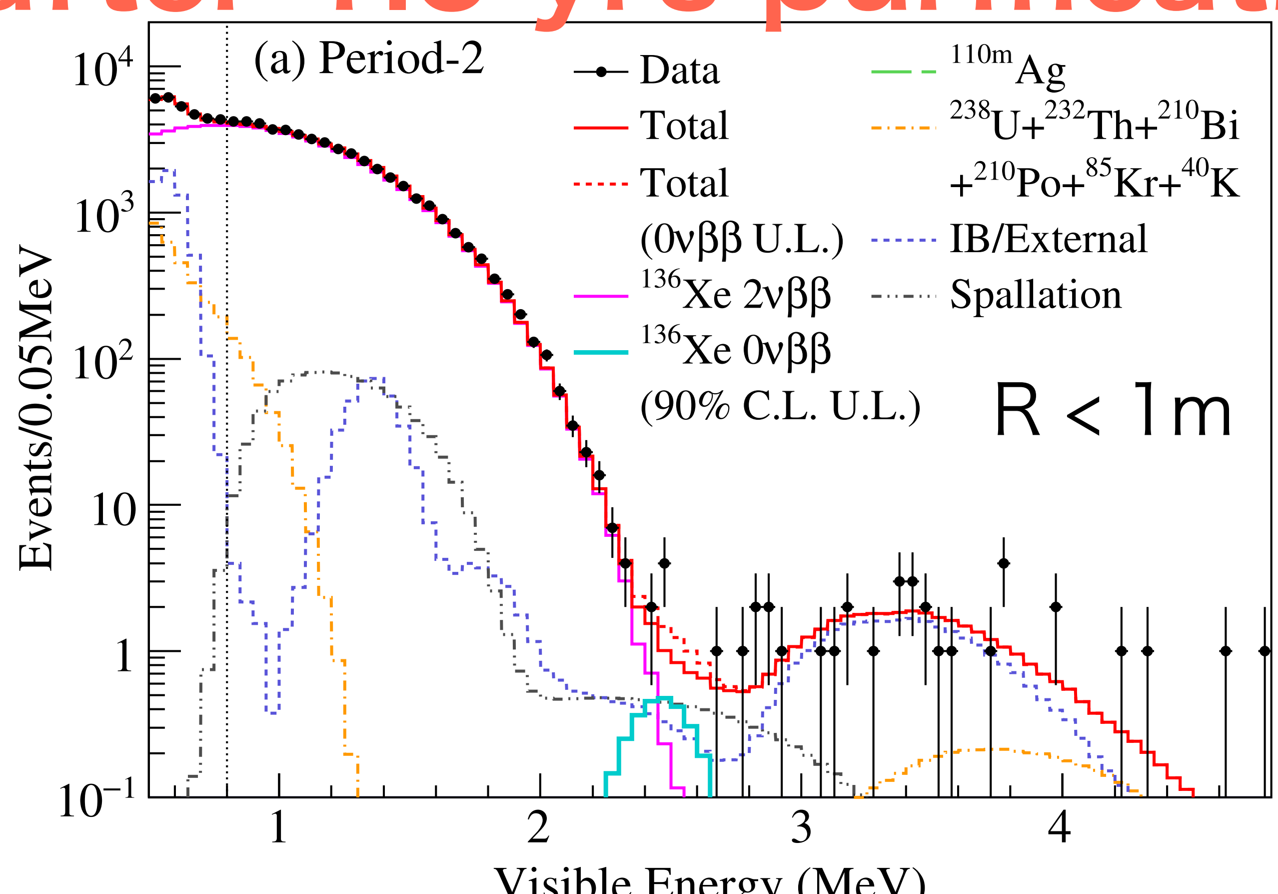
>1.9x10^{25}y

after 1.5 yrs purification

Phase-2 380kg

after purification

^{110m}Ag reduction 1/20



2013/12/11 - 2014/10/27

534.5 days (504 kg-yr)

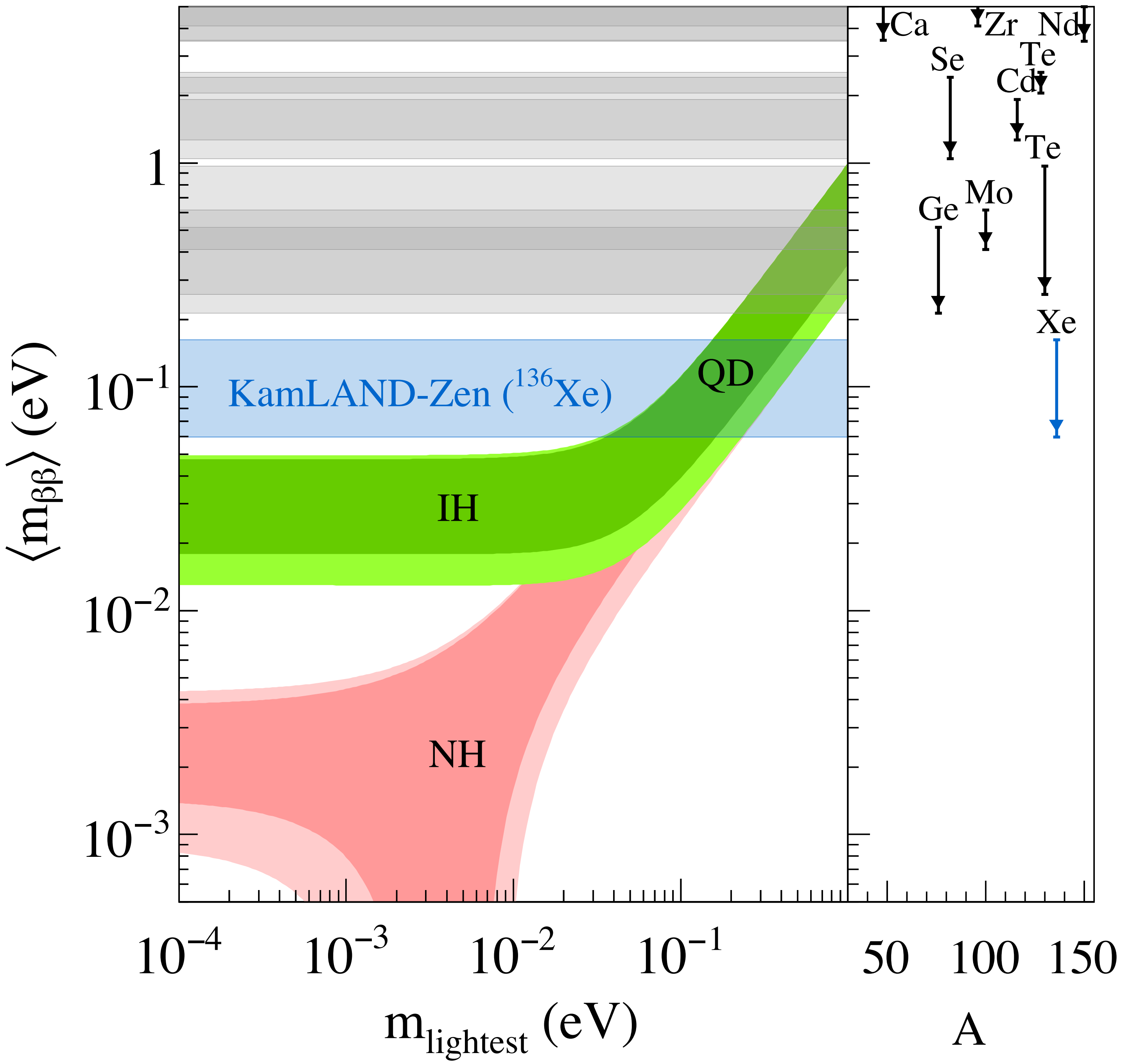
(cf. $T_{1/2}$(^{110m}Ag)=250 days)

②in-situ purification possible!!

KamLAND-Zen 400 Phase 1+2 combined

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

(sensitivity 5.6×10^{25} yr)



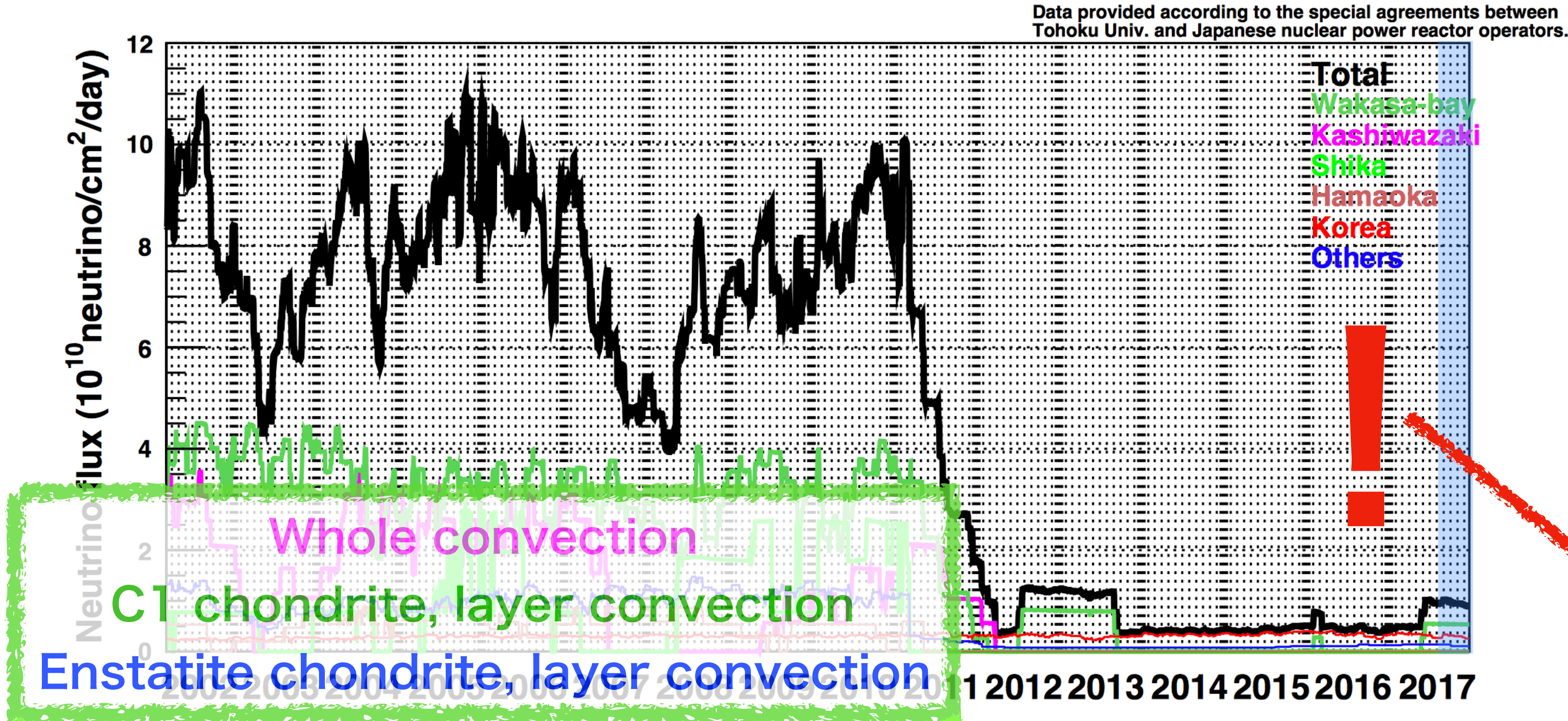
It also provides upper limit of $m_{lightest}$ at 180-480 meV.

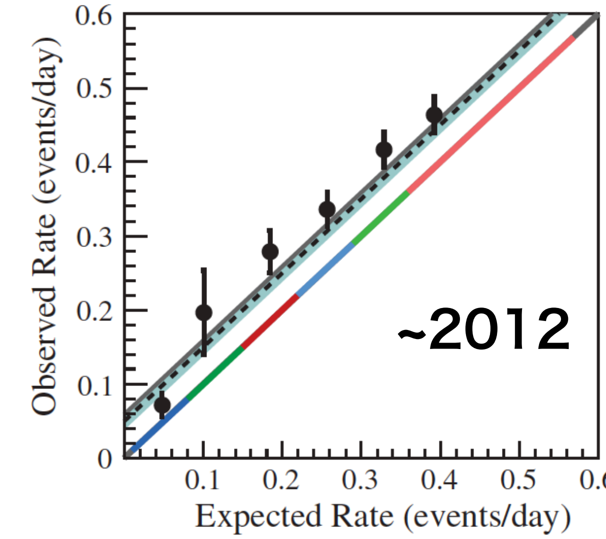
$$\langle m_{\beta\beta}\rangle < (61 - 165)\ \mathrm{meV}$$

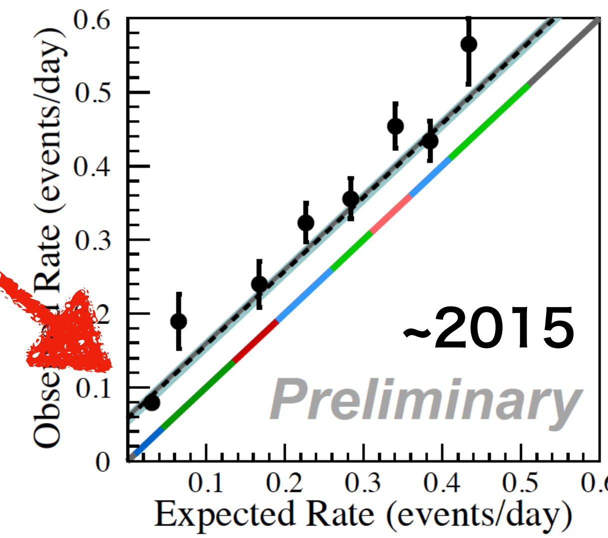
PRL117, 082503 (2016)

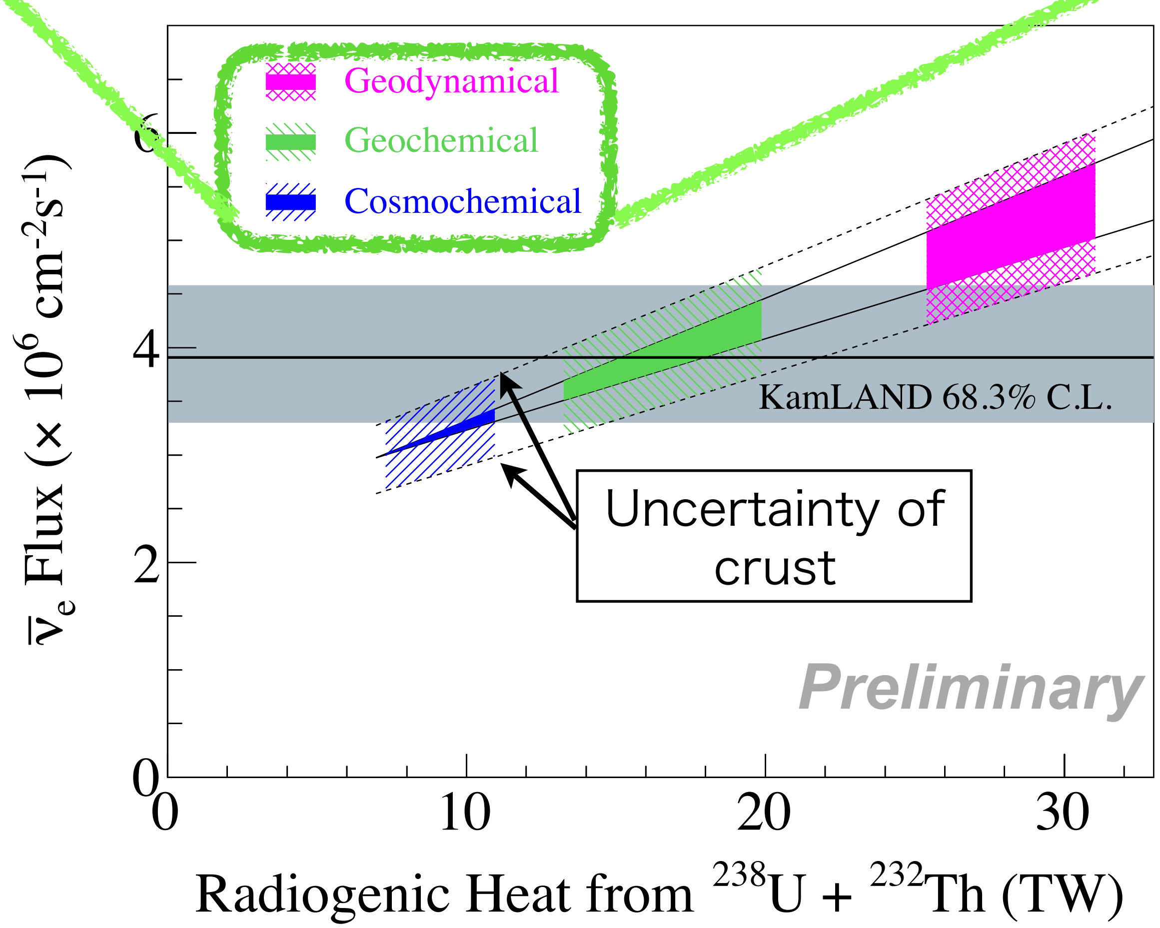
Big leap toward IH region !

④ multi-purpose









Geo-neutrino observation may conclude primordial meteorite of the earth, and dynamics of the mantle !!

And more …

○Pre-supernova alarm with silicon-burning neutrinos

○Simultaneous measurement of supernova temperature and luminosity with neutrino coherent scattering on hydrogen

○Very long baseline (Korean) reactor oscillation (if Japanese ones are suspended)

○Verification of CPT in comparison with neutrino and anti-neutrino oscillation (when Japanese reactors come up)

○MSW upturn of solar ^{8}B neutrinos above 2 MeV

○CNO cycle neutrinos (maybe with new electronics)

○Physics with J-PARC neutrino beam

○Search for charged dark matter with small mass difference to LSP

○Sterile neutrino search with cyclotron (IsoDAR)

○Verification of DAMA/LIBRA with NaI deployment

Yes, KamLAND-Zen has diverse physics targets

“Advantages of using KamLAND”

have been almost demonstrated;

⓪ low cost and quick start (running detector) ✅ ran in 2 years

① BG can be identified (full active thick shielding) ✅ ^{110m}Ag identified

② In-situ purification possible (liquid media) ✅ ^{110m}Ag removed

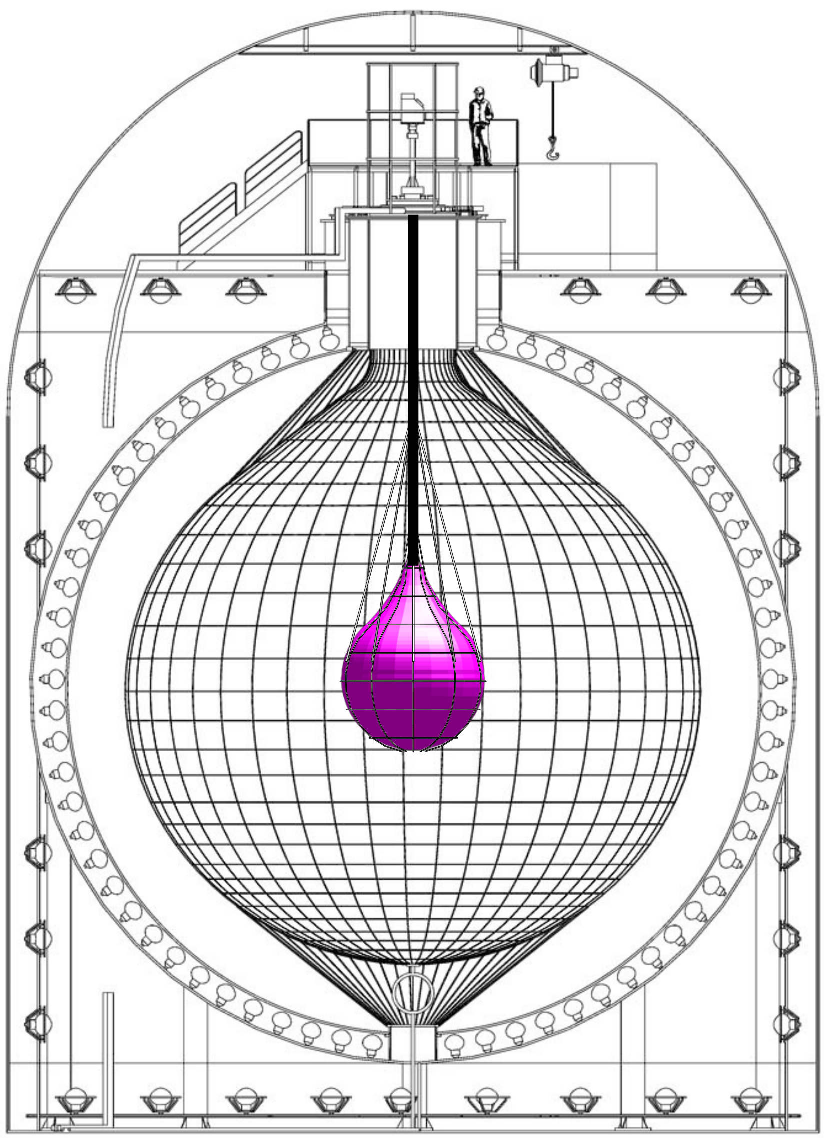
③ On/Off measurements possible (xenon is removable) ✅ BG confirmed by degassing

④ multi-purpose (ex. geo-neutrino) ✅ leading geo-ν

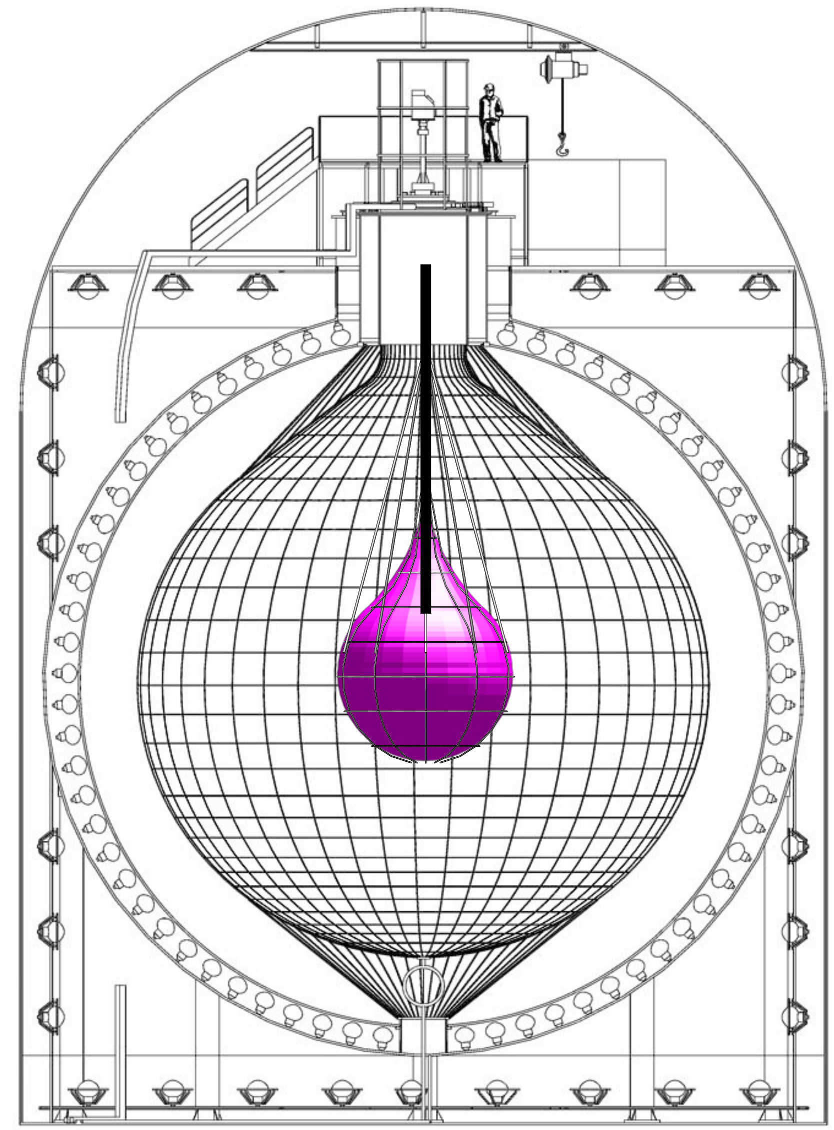
⑤ easily scalable (mini-balloon)

⑤ easily scalable

KamLAND-Zen 400



KamLAND-Zen 800



double size mini-balloon fabrication

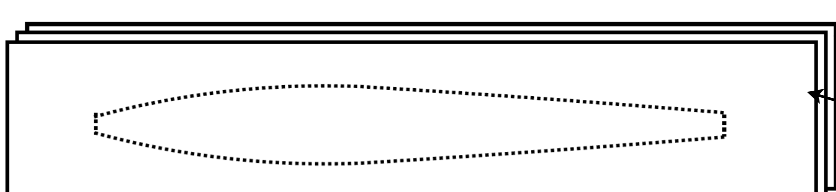
cleaning, cleaning and
cleaning as usual

Example of improvements

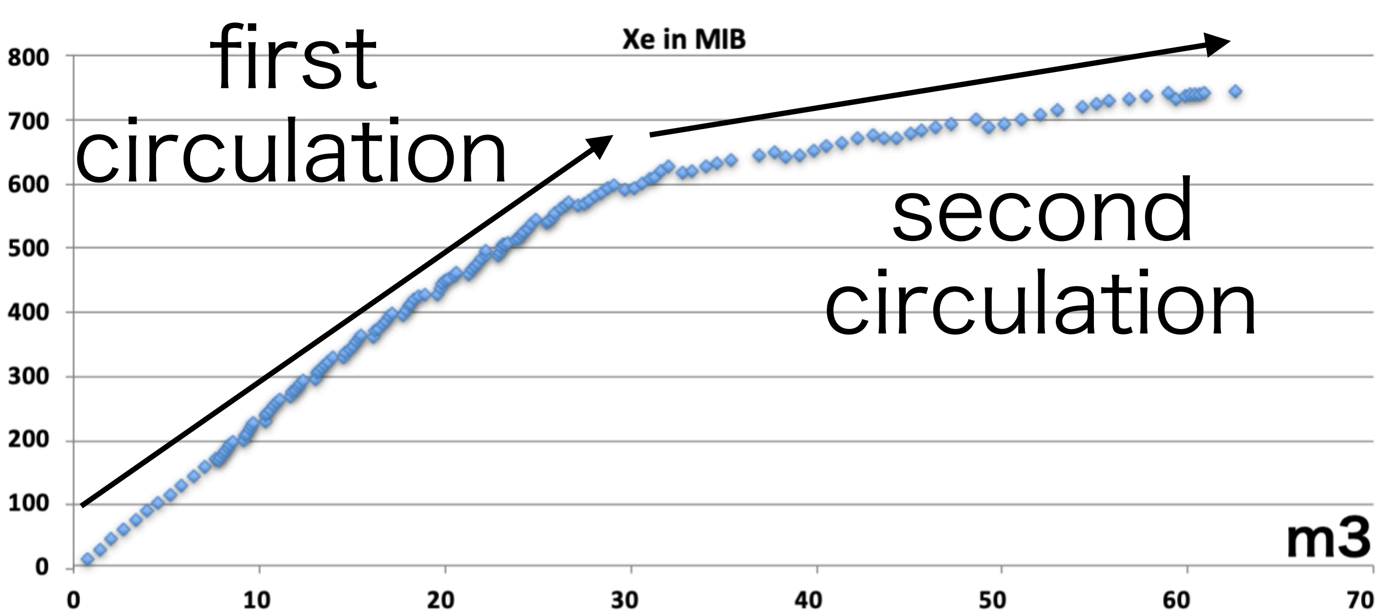
before

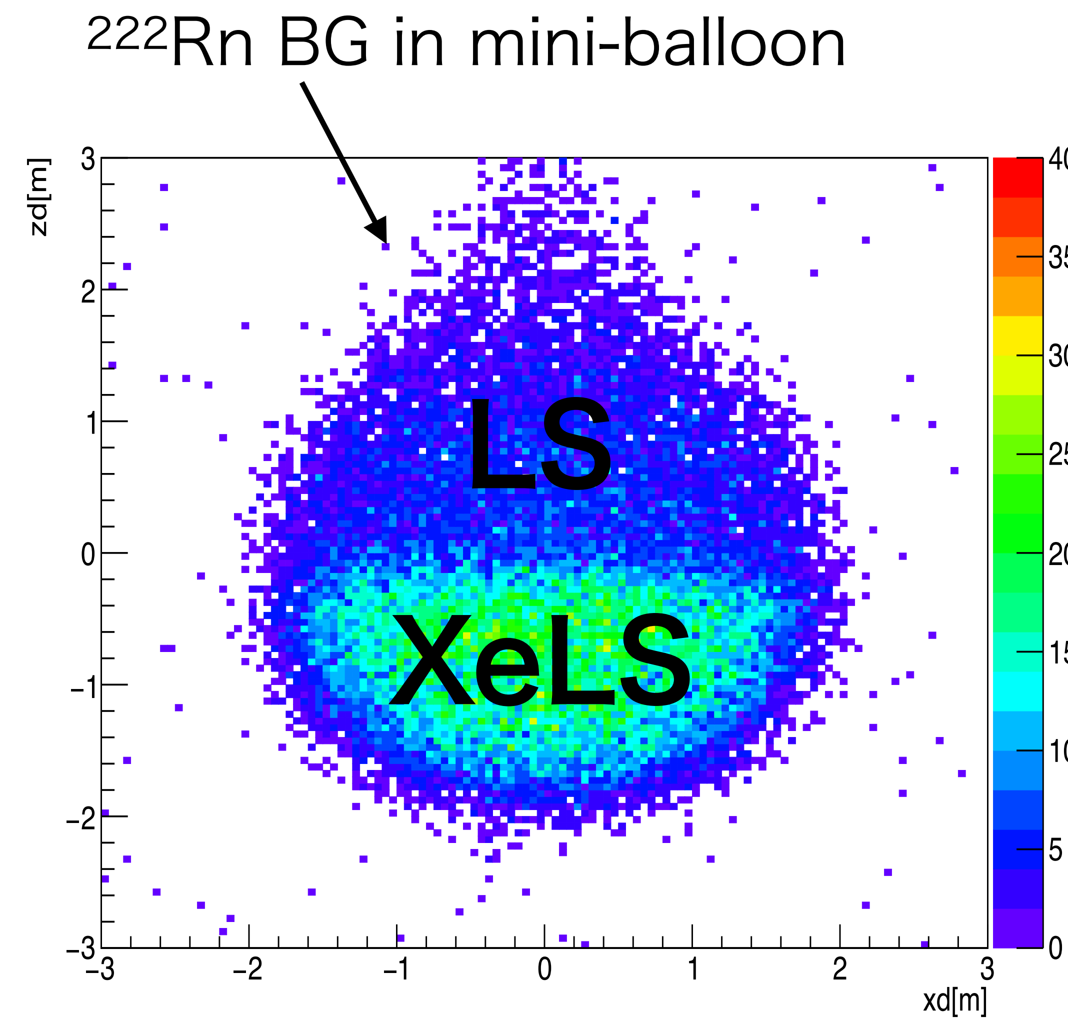
after

keep staying away
goggle
welding machine
cover sheet
glove on glove
laundry twice a day
clean underwear
changing room in a clean room
dust visualization
more neutralizer
・・・



Add 91% enriched ^{136}Xe by recirculation (bottom supply, top extraction)



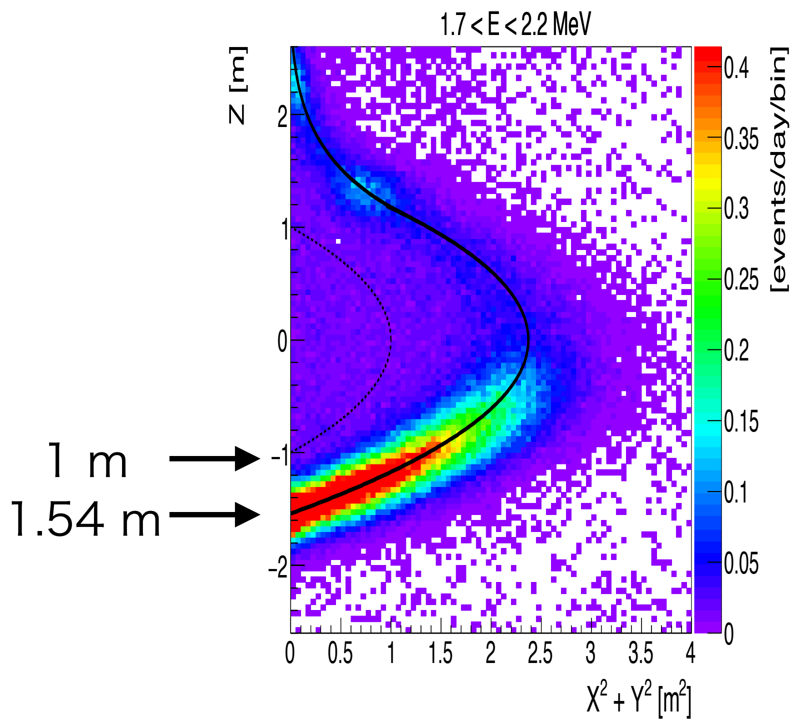


World largest amount of double beta decay nuclei, ~745kg, has been installed.

Physics run has started on January 22, 2019.

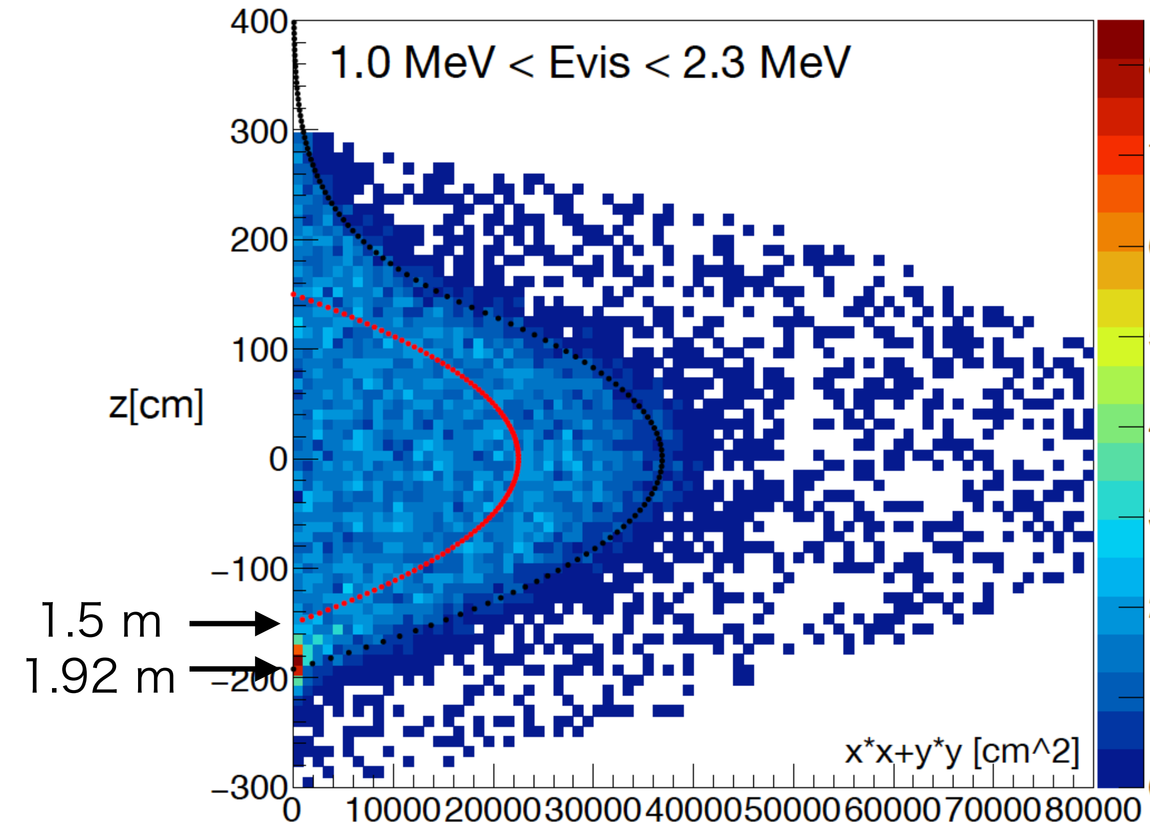
2ν region Z vs ρ^2

Zen 400 phase 2



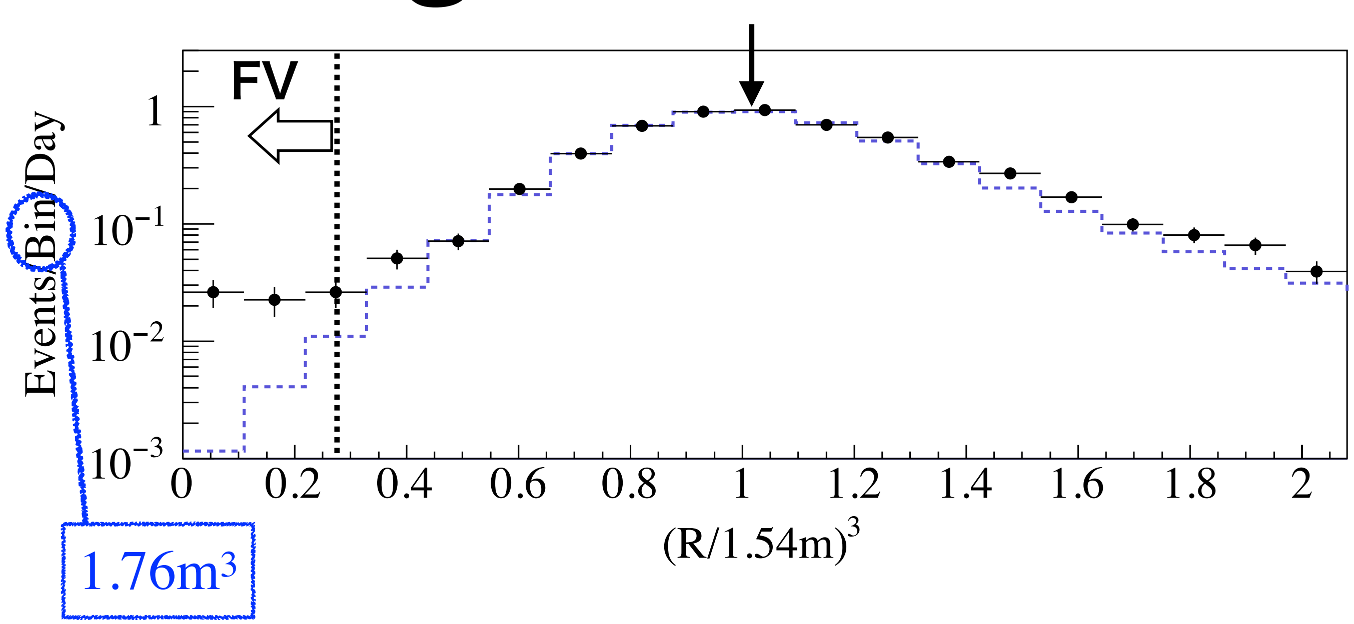
contaminated with ^{134}Cs,
dust sank

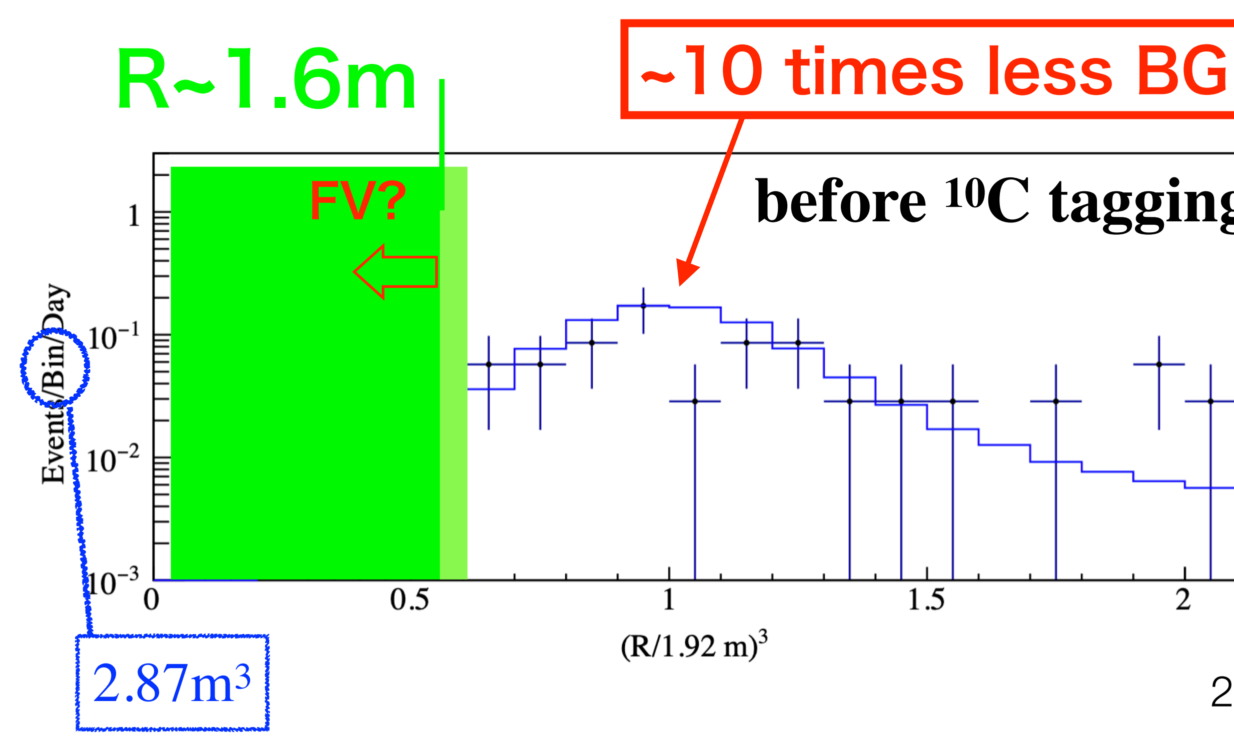
Zen 800



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

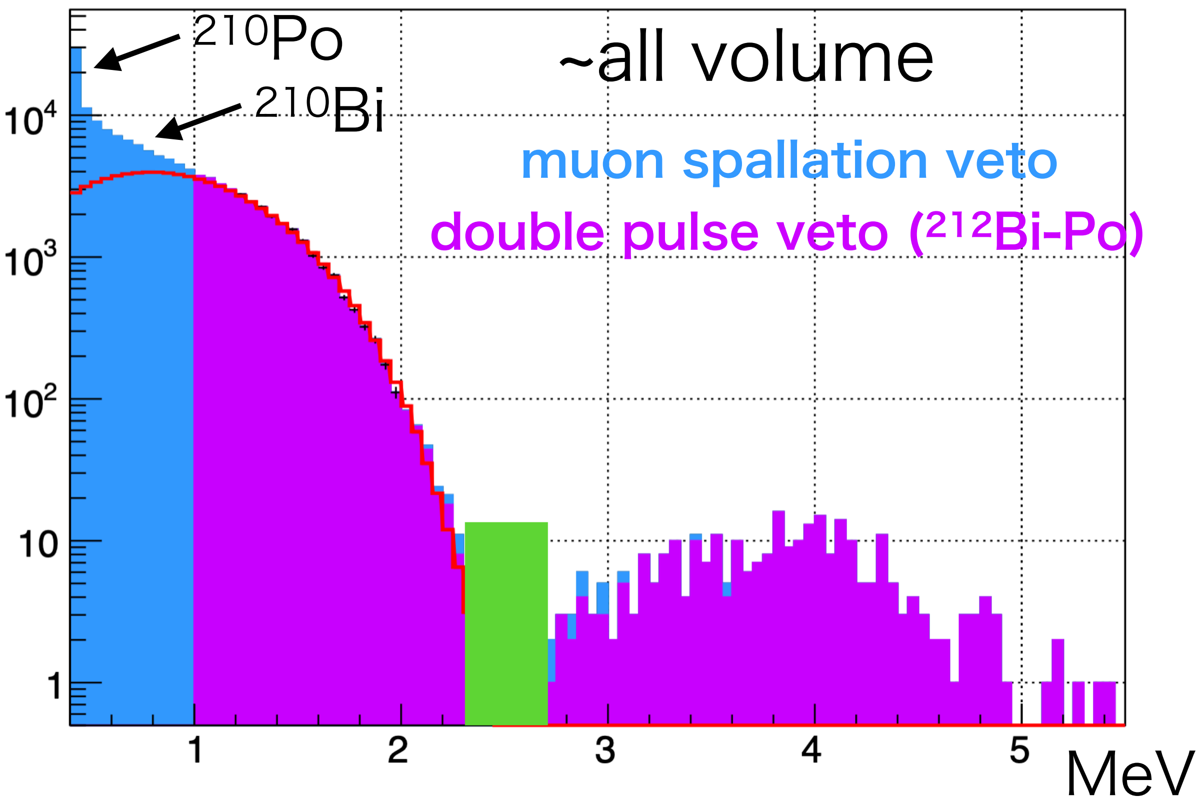
0ν region (2.3-2.7 MeV) r^3

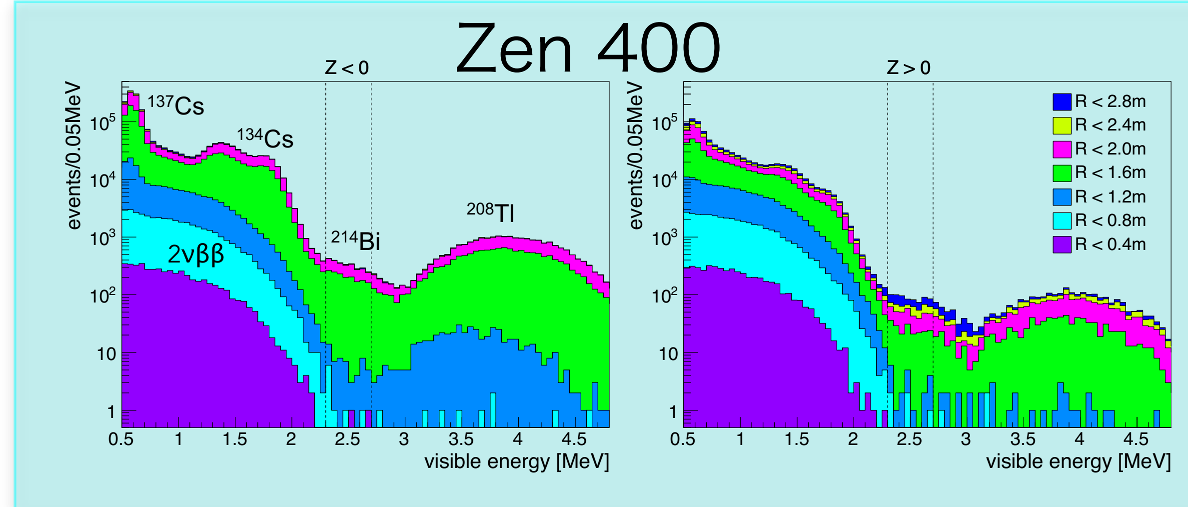




after ^{214}Bi-Po cut

r < 220 cm (r$_{balloon}$ =1.92m)



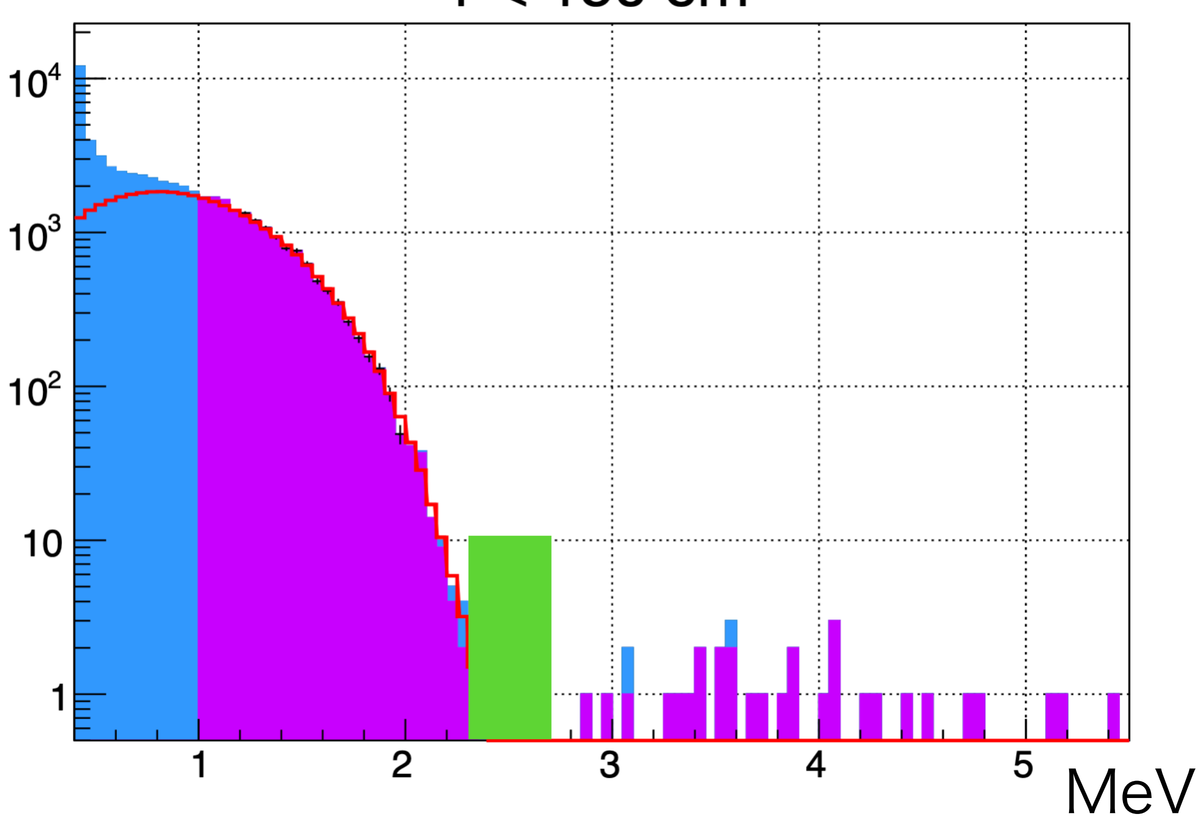


No strange BG is seen in $2\nu 2\beta$ region even in all volume.

^{208}Tl and probably ^{214}Bi are seen in higher energies.

^{214}Bi rejection efficiency on the mini-balloon is ~50%.

r < 150 cm



Radius cut reduces ^{208}Tl and ^{214}Bi (potential BG) very well.

FV can be 3~4 times larger and equivalent with all volume of Zen 400.

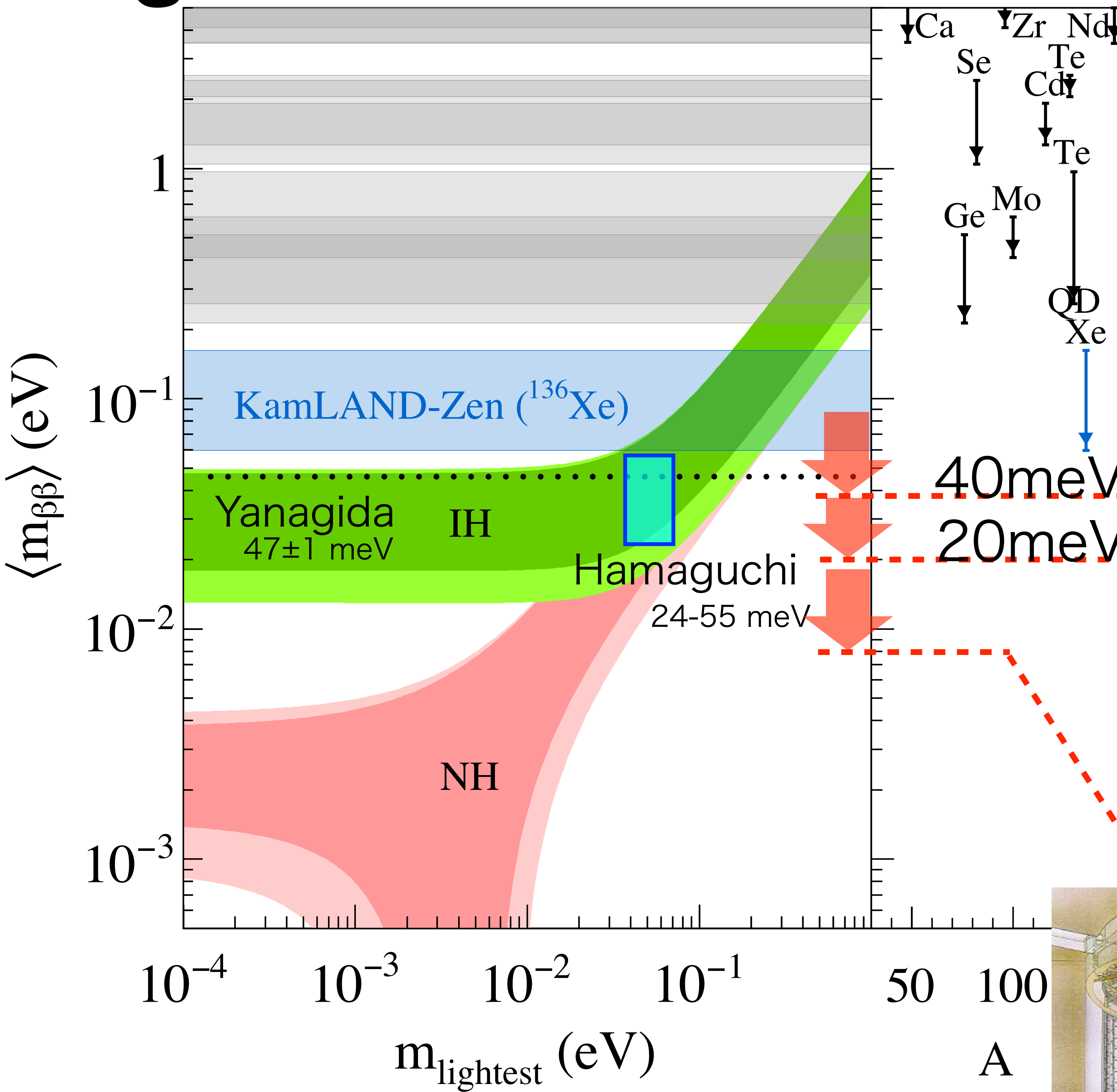
Finally,

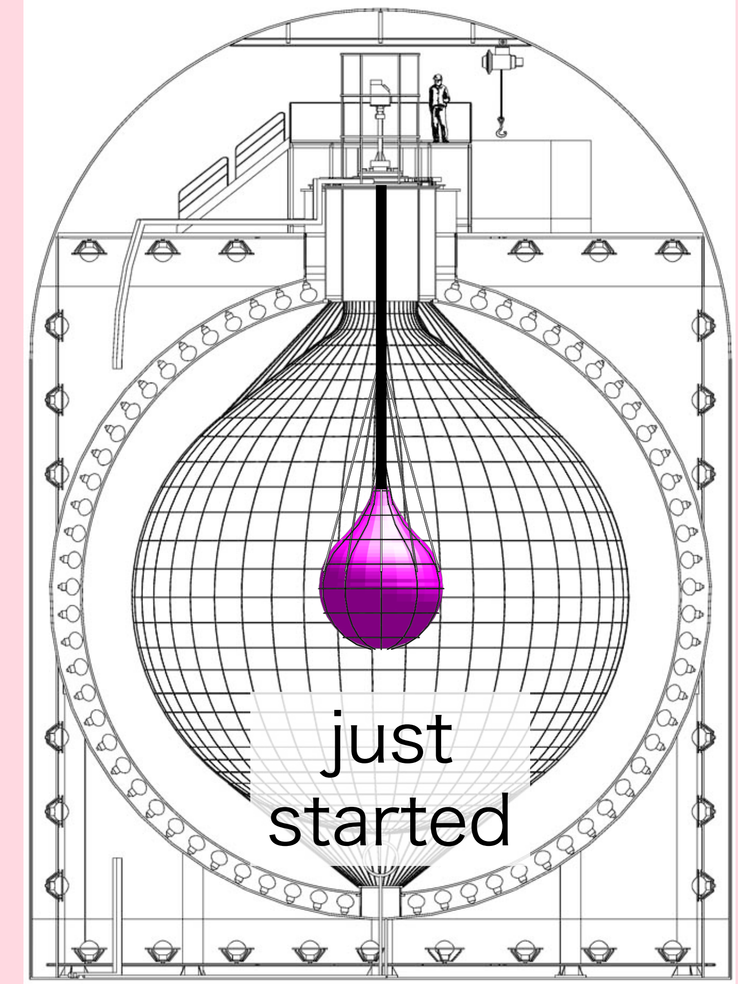
"Advantages of using KamLAND"

have been all demonstrated;

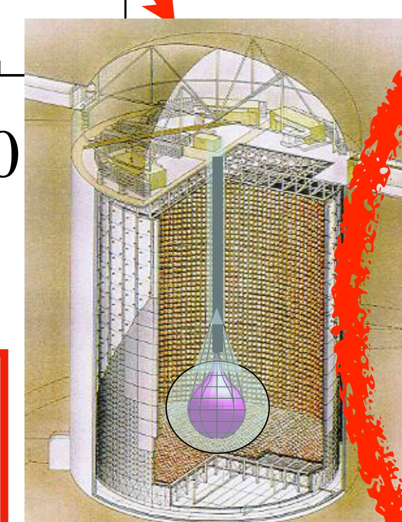
⓪ low cost and quick start (running detector)	✅	ran in 2 years
① BG can be identified (full active thick shielding)	✅	^{110m}Ag identified
② In-situ purification possible (liquid media)	✅	^{110m}Ag removed
③ On/Off measurements possible (xenon is removable)	✅	BG confirmed by degassing
④ multi-purpose (ex. geo-neutrino)	✅	leading geo-ν
⑤ easily? scalable (mini-balloon)	✅	mass doubled

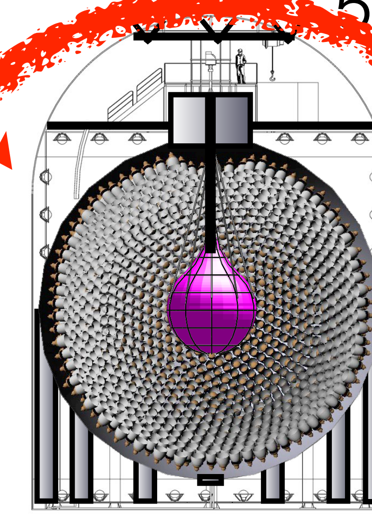
Target sensitivities





low BG film, 750 kg xenon
KamLAND-Zen 800
$5x10^{26}$y (5y)





~30M$

better resolution
scintillating film
KamLAND2-Zen
$2x10^{27}$y (5y)

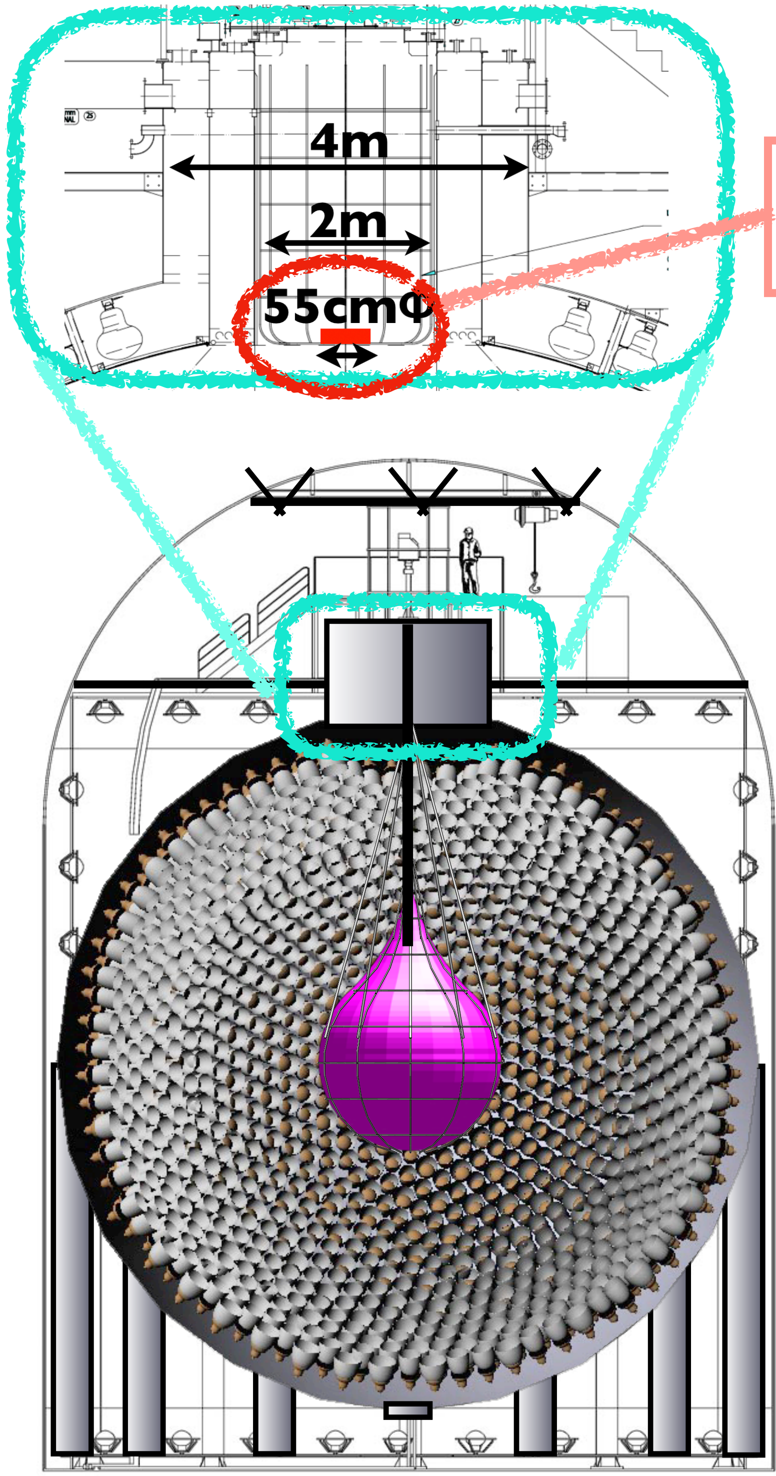
The discovery may be just around the corner.

KamLAND-Zen is closest !!!

And more future plans!

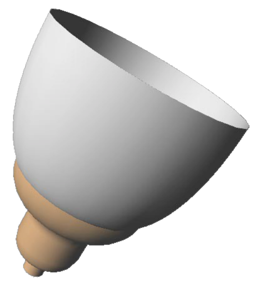
Higher energy resolution for reducing 2ν BG

⇒ KamLAND2-Zen



Expansion of entrance

1000+ kg xenon



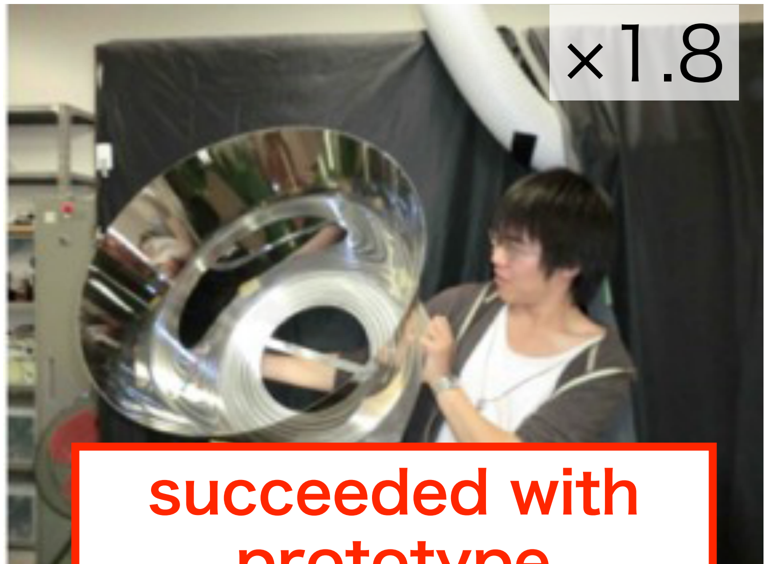
Winston cone	light collection ×1.8
high q.e. PMT 17"ϕ→20"ϕ ε=22→30+%	light collection ×1.9
New LAB LS (better transparency)	light collection ×1.4

expected σ(2.6MeV)= 4% → ~2%

target sensitivity 20 meV

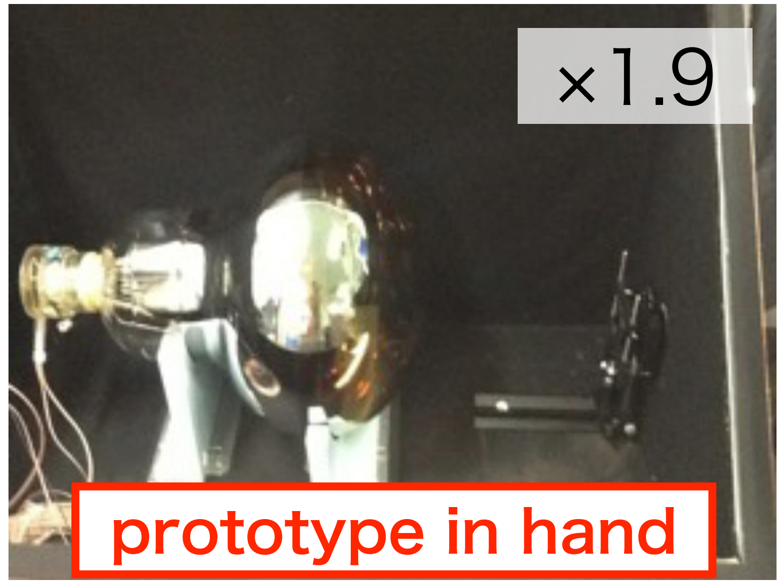
R&D for KamLAND2-Zen and future

○ winston cone



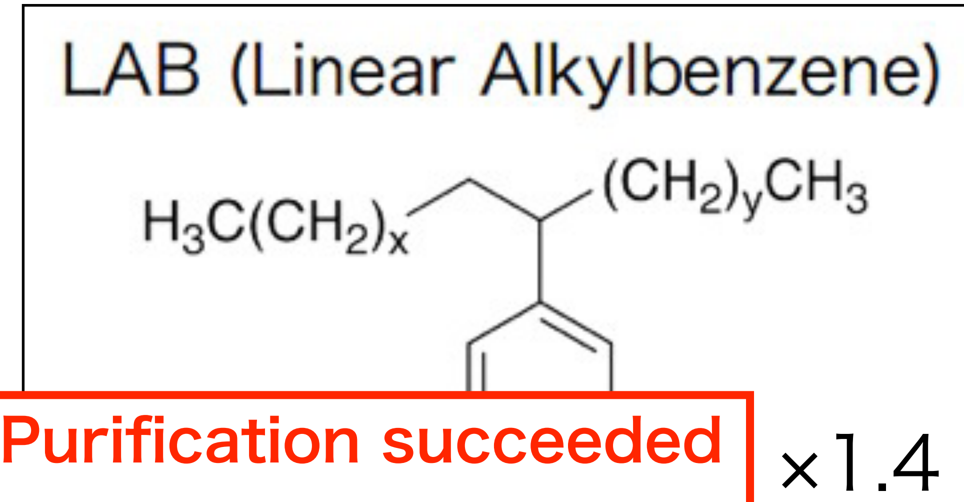
succeeded with prototype

○ HQE-PMT



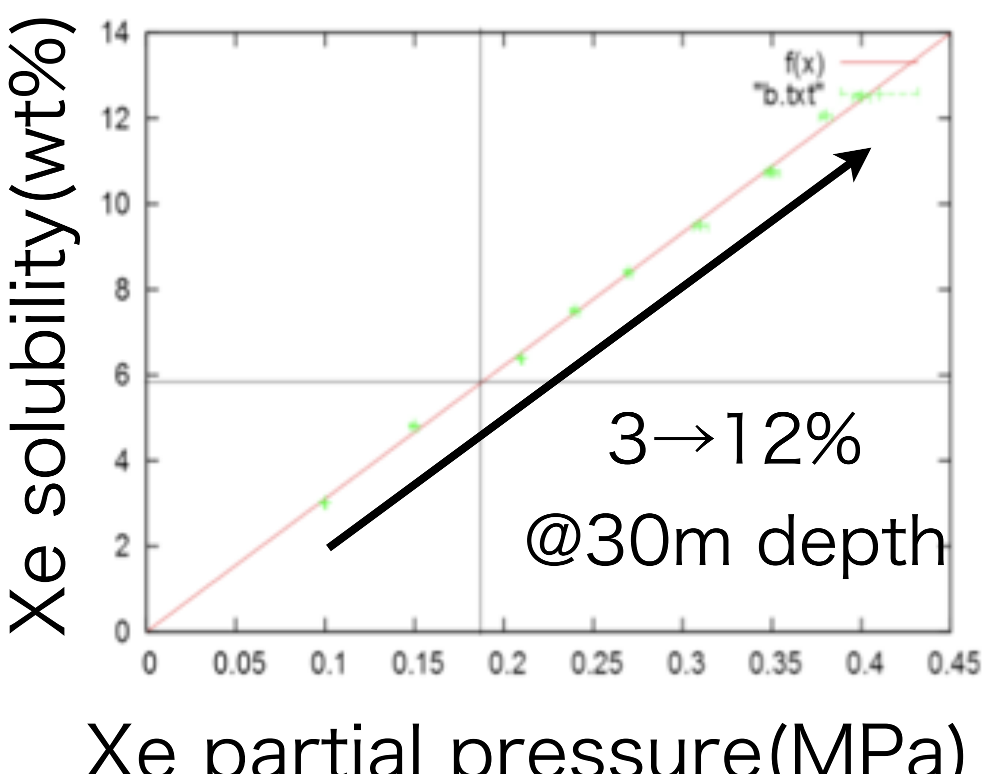
prototype in hand

○ New LAB-LS



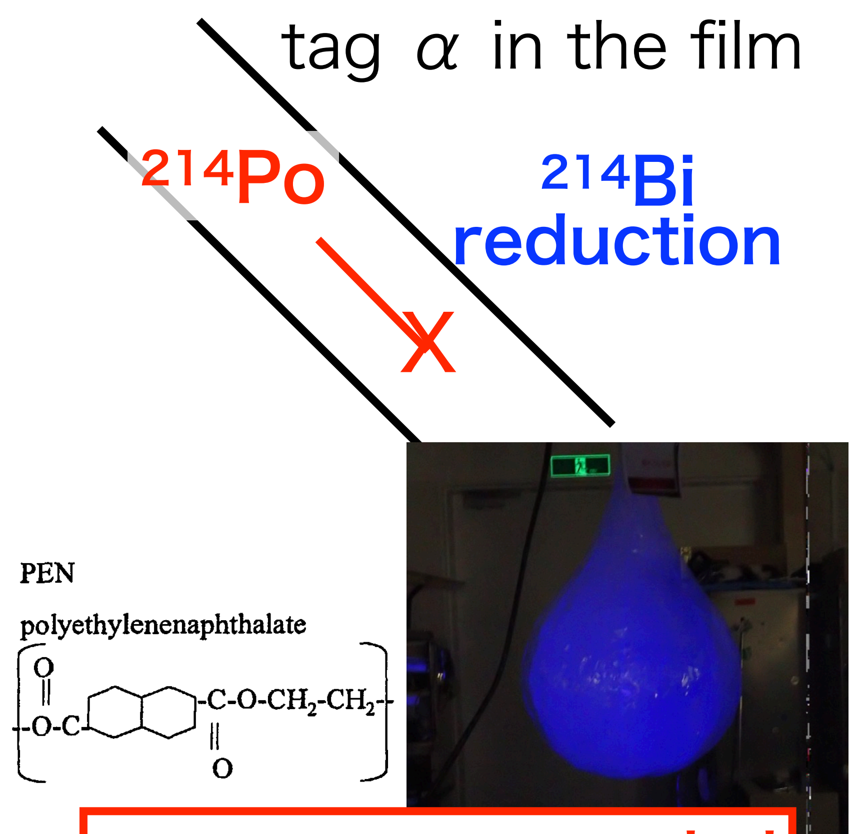
Purification succeeded with charcoal

○ denser xenon



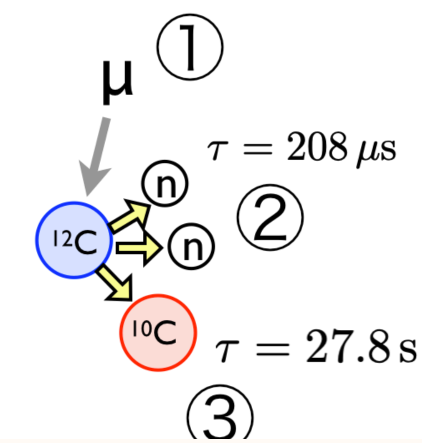
principle confirmed

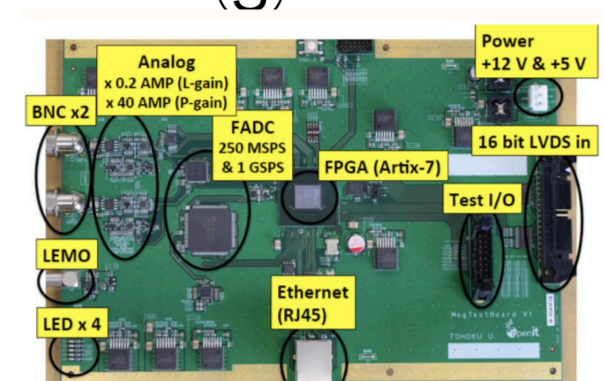
○ scintillator film



prototype succeeded

○ ^{10}C tag





2ch prototype

Conceptual design of KamLAND2-Zen

Rough extrapolation of BG estimation & sensitivity

	KamLAND-Zen 400	KamLAND-Zen 800	KamLAND2-Zen 2.38-2.58 MeV	KamLAND2-Zen High P
$2\nu2\beta$ [/100kgXe/y]	7.4	7.4	→ <0.15 (σE)	<0.15
^{10}C [/100kgXe/y]	1.3	→ 0.18 (analysis)	→ 0.09 (σE)	→ 0.05 (1.8 atm)
$^{8}B\nu$ [/100kgXe/y]	0.33	0.33	→ 0.16 (σE)	→ 0.09 (1.8 atm)
FV (loading) [kgXe]	100 (380)	300+ (745)	→ 1000 (1000) (PEN)	1000 (1000)
(Expected) reach	61-165 meV 1.07×10^{26}yr	40 meV 5×10^{26}yr	20 meV 2×10^{27}yr	<20meV $>2\times10^{27}$yr

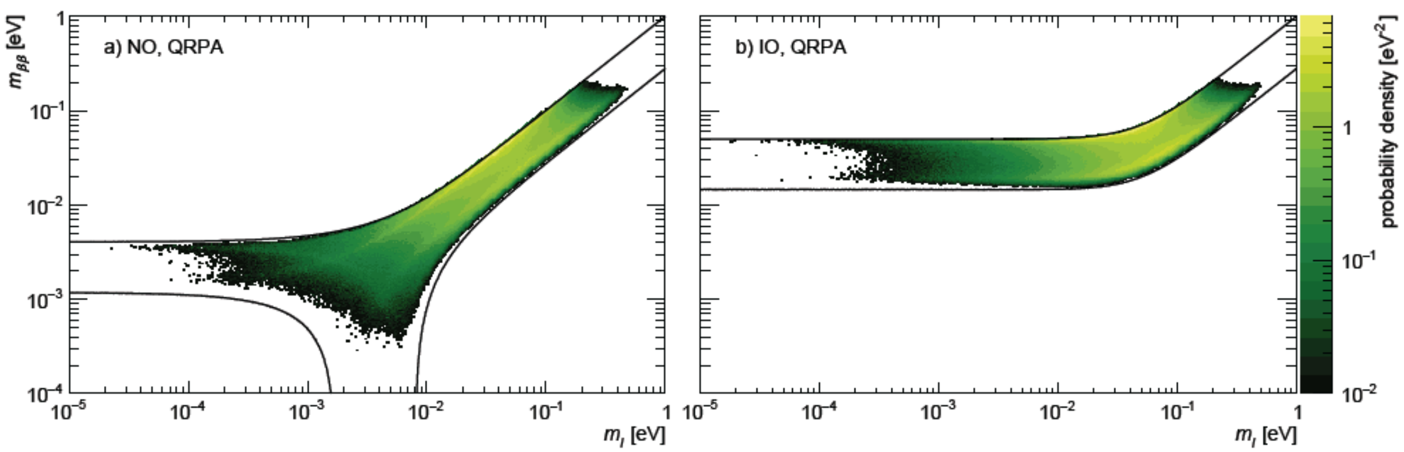
↑ baseline

further options

- high pressure xenon for better S/N
- β/γ discrimination with imaging
- $\beta/2\beta$ discrimination with Cherenkov

PRD96,053001(2017)

Posterior distribution



Prior choice

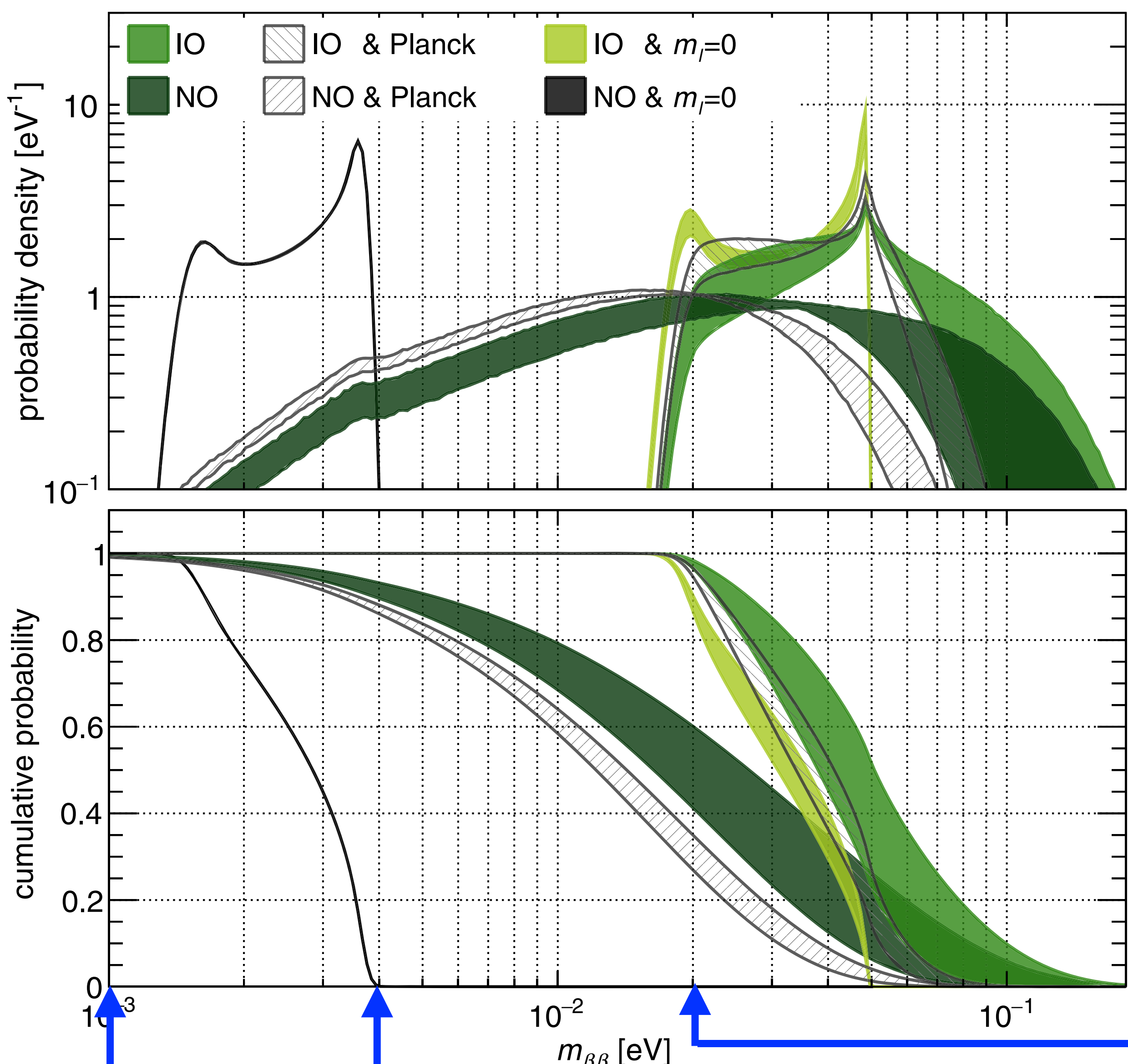
NO IO

$$\{\Sigma, \Delta m^2_{21}, \Delta m^2_{31} \,\mathrm{or}\, \Delta m^2_{23}, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31}-\delta)\}$$

logarithmic flat

Likelihood test

$$\mathcal{L} = \mathcal{L}(\mathcal{D}_{\rm osc}|\Delta m^2_{21}) \cdot \mathcal{L}(\mathcal{D}_{\rm osc}|\Delta m^2_{31}/\Delta m^2_{23}) \cdot \mathcal{L}(\mathcal{D}_{\rm osc}|s^2_{12}) \cdot \mathcal{L}(\mathcal{D}_{\rm osc}|s^2_{13}) \cdot \mathcal{L}(\mathcal{D}_{\rm Troitsk}|m_\beta) \cdot \mathcal{L}(\mathcal{D}_{0\nu\beta\beta}|m_{\beta\beta})$$



20meV covers 95% of IH and 50% NH

1meV

No coverage above 4meV, if NH & m_{min}=0.

Toward High resolution & BG discrimination

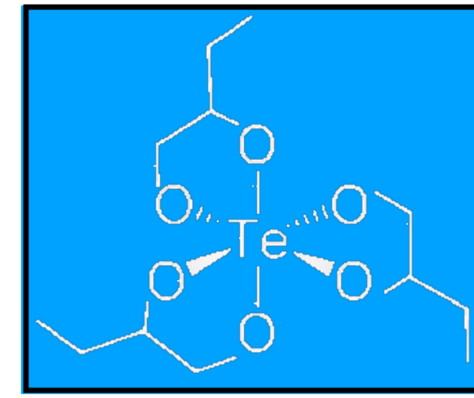
poor resolution ↕ good resolution

projects listed in
"report to NSAC, NLDBD2015"

LS	KamLAND-Zen → KLZ 800 → KL2Z
	→ SNO+ phase I → SNO+ phase II
Track-Calo	NEMO-3 → SuperNEMO
Xe TPC	→ NEXT-100 → NEXT-1.5k
	→ PandaX-III 200 → PandaX-III 1k
liq.Xe TPC	EXO-200 → nEXO
Bolometer	CUORE → CUPID
Germanium	GERDA → LEGNED 200 → LEGEND 1k
	Majorana ↗ (LEGNED 200)

SNO+

uniformly dissolved
Tellurium-ButaneDiol



natural abundance of ^{130}Te: **34%**

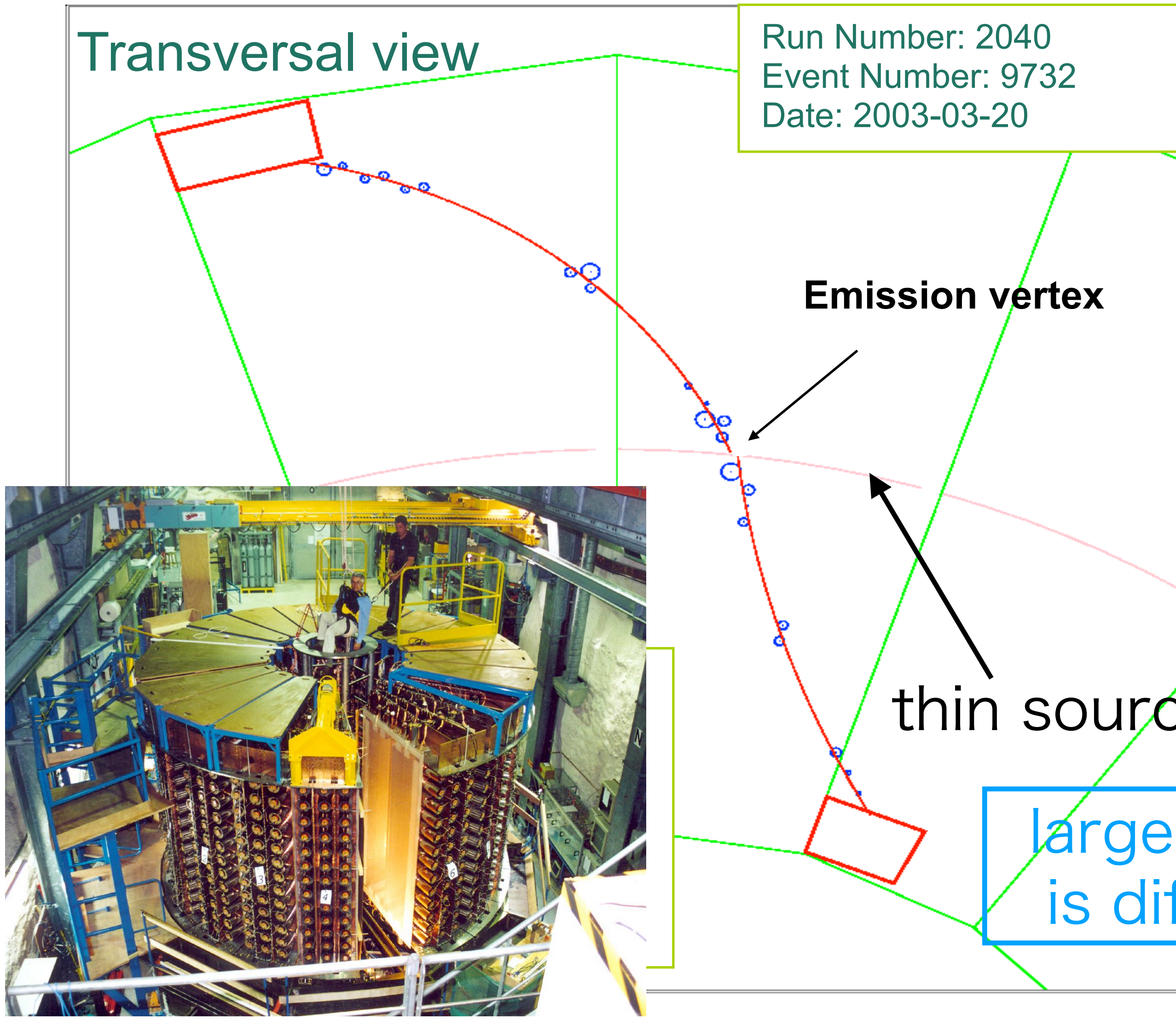
phase I, 0.5 wt% loading
(1.3t, 260kg fiducial)
sensitivity: 2×10^{26} yr, 38~92 meV (5y)

phase II, 2wt% loading + HQE PMTs
target sensitivity: 10^{27} yr, 17~41 meV

Enrichment is not necessary.

Negligible spallation BGs. (deep site)

NEMO-3 → SuperNEMO

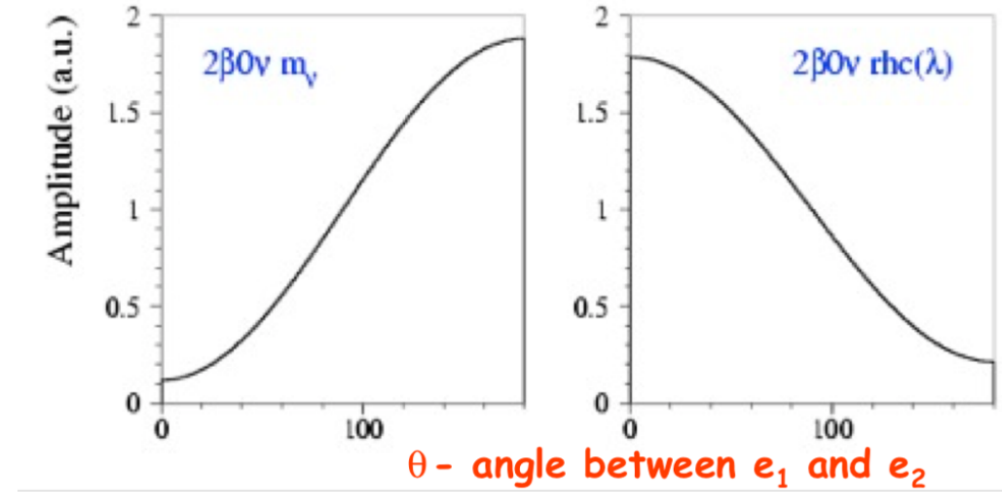


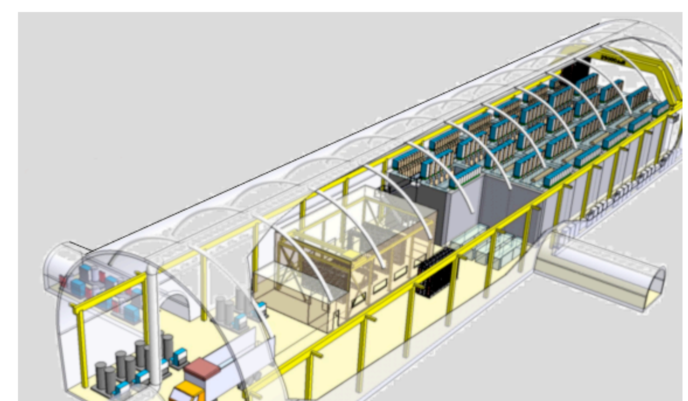
Many different nuclei have been measured.

^{100}Mo, ^{82}Se, ^{150}Nd, ^{130}Te, ^{96}Zr, ^{48}Ca, ^{116}Cd

$T_{1/2} > 1 \times 10^{24}$ y (7kg)
m > 0.47~0.96 eV

Angular distribution is important to understand physics behind.



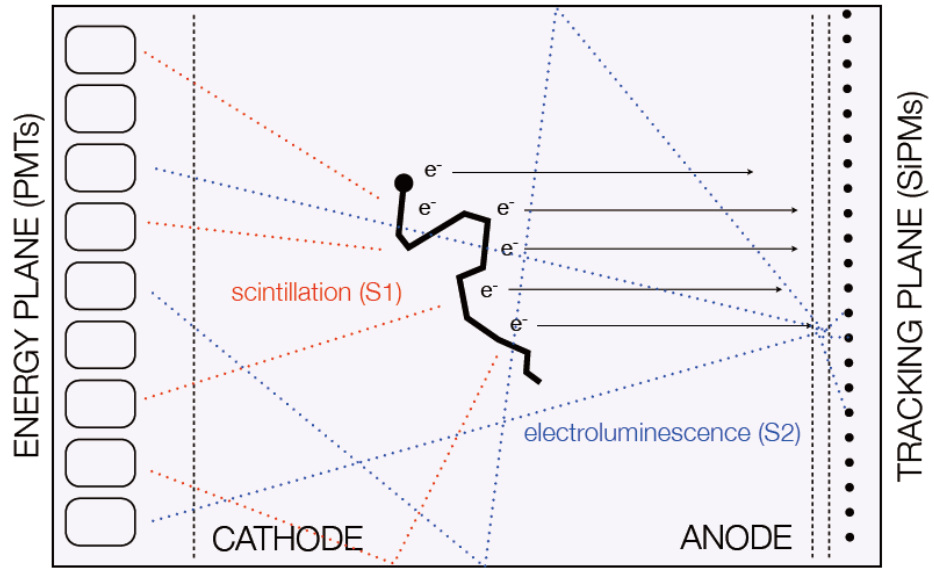


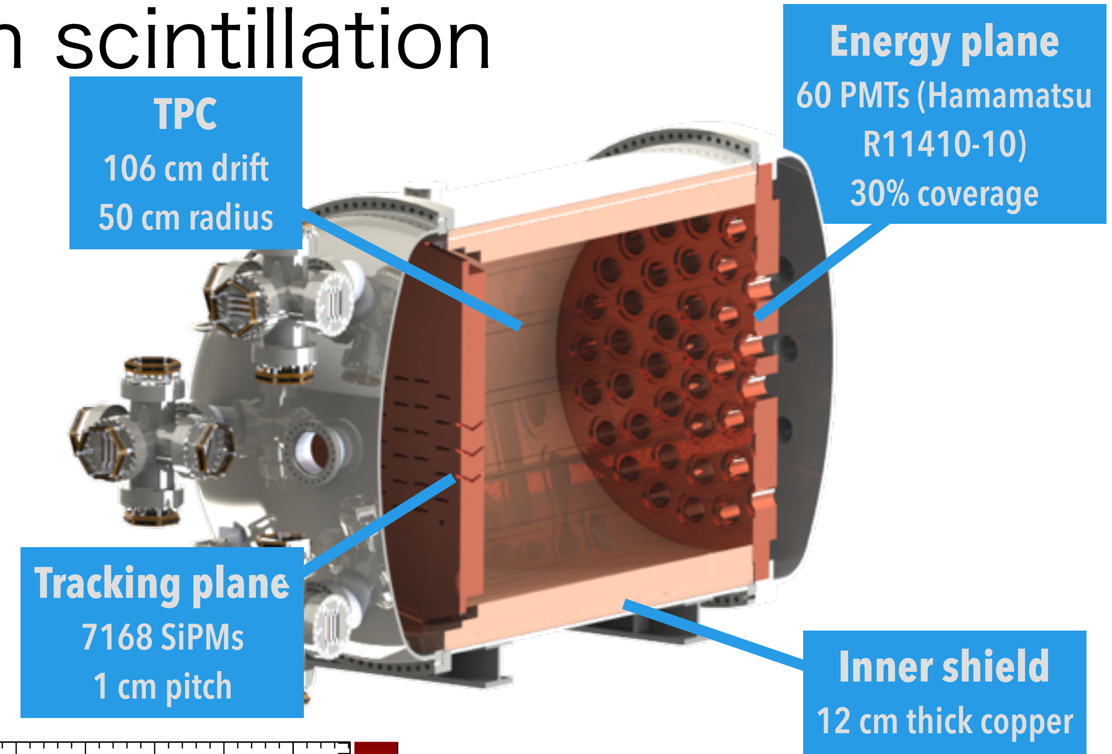
Expected sensitivity of SuperNEMO
50~100 meV (5 y, 100 kg ^{82}Se)

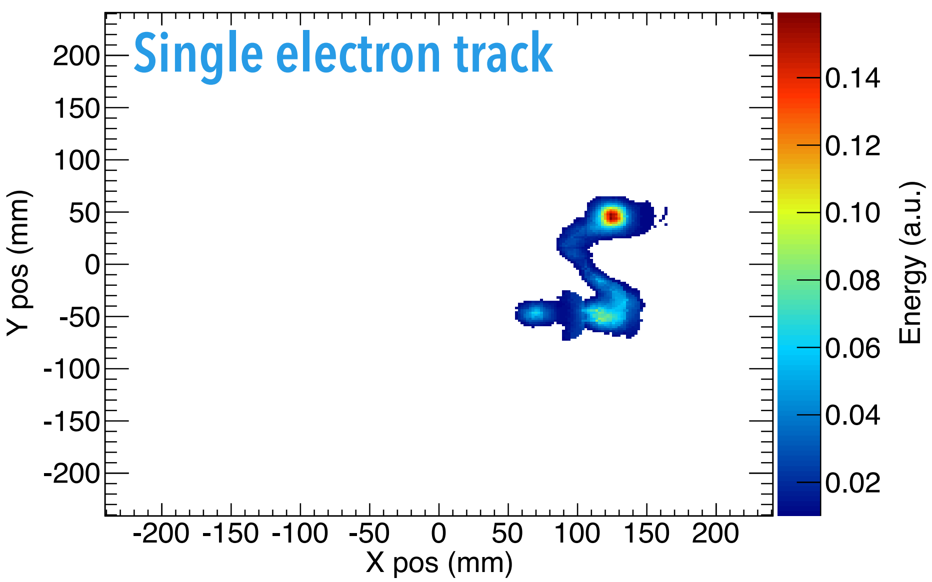
Once $0\nu 2\beta$ is found, this type of experiment becomes very important.

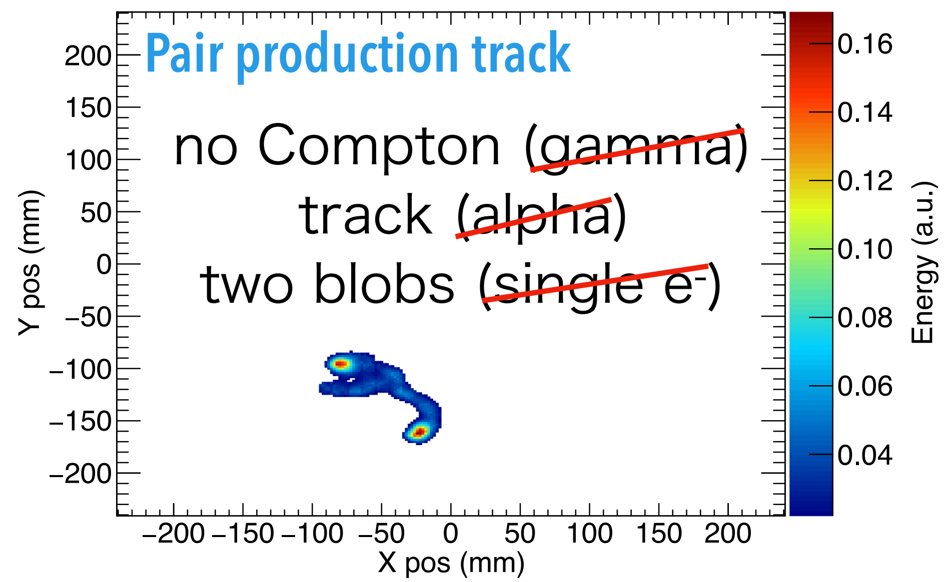
NEXT-100 → NEXT-1.5k

High pressure xenon gas TPC with scintillation









Single electron/ gamma / alpha can be discriminated.

External gamma need to be suppressed.
Large mass requires huge detector.
Angular distribution will be difficult.

NEXT-100 will starts by the end of 2018 with sensitivity of 5×10^{25} yrs in 3yrs, 90-180 meV.

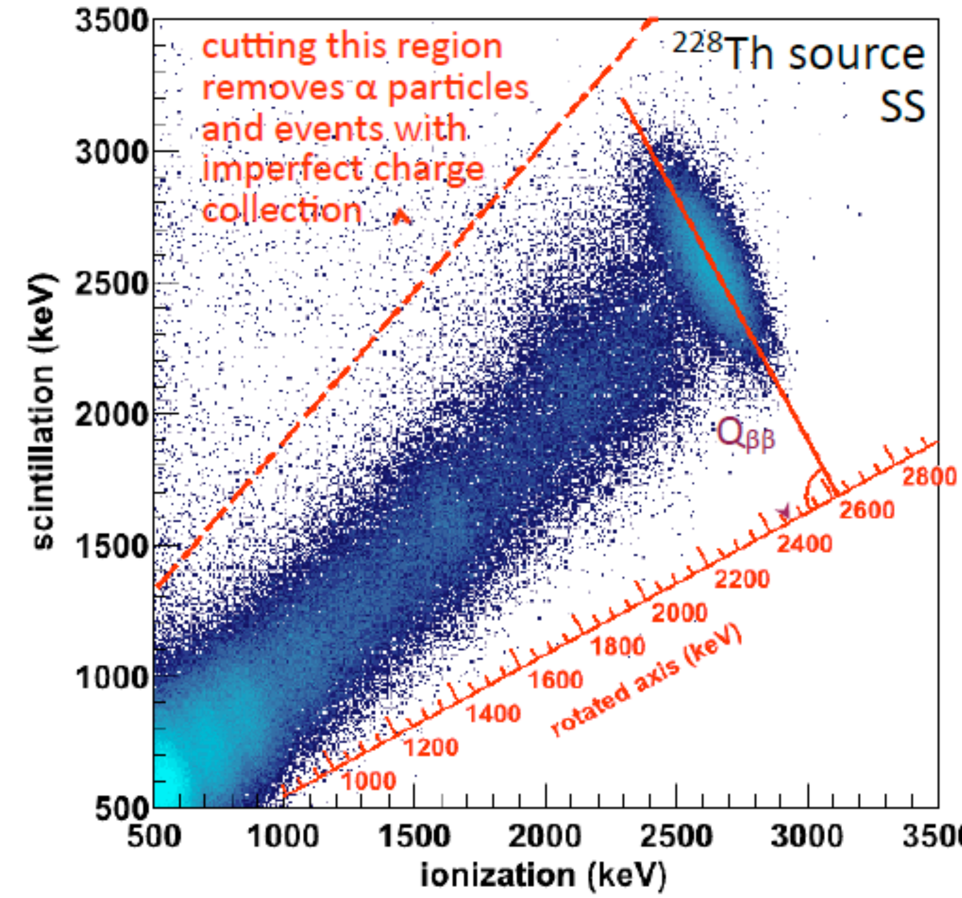
EXO-200 → nEXO

liquid xenon TPC with scintillation

Xenon amount 200 kg (80% enrichment)

→ 5t in nEXO

No track information, but multi-site vs single-site separation very efficient to reduce Compton BG.

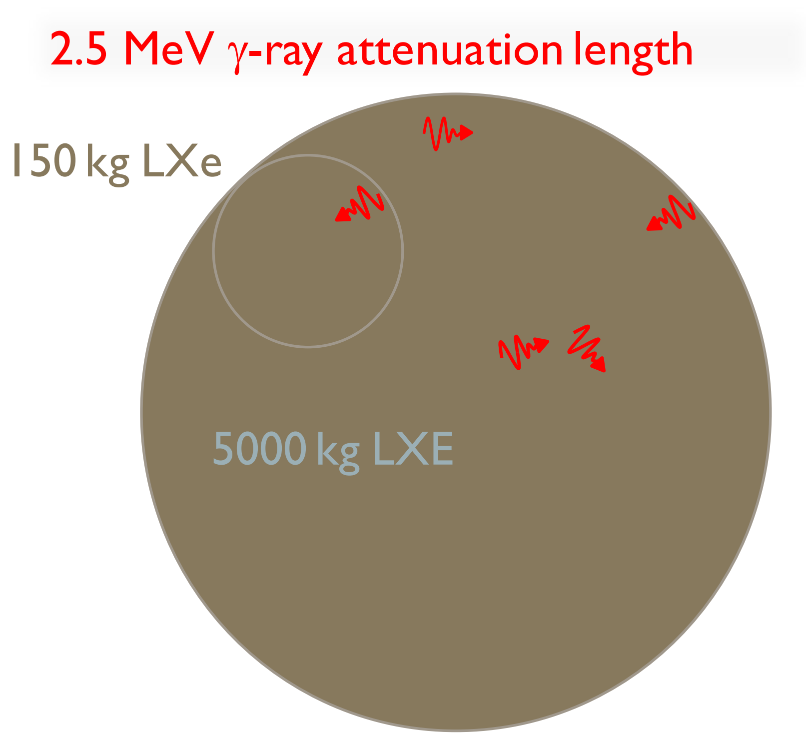


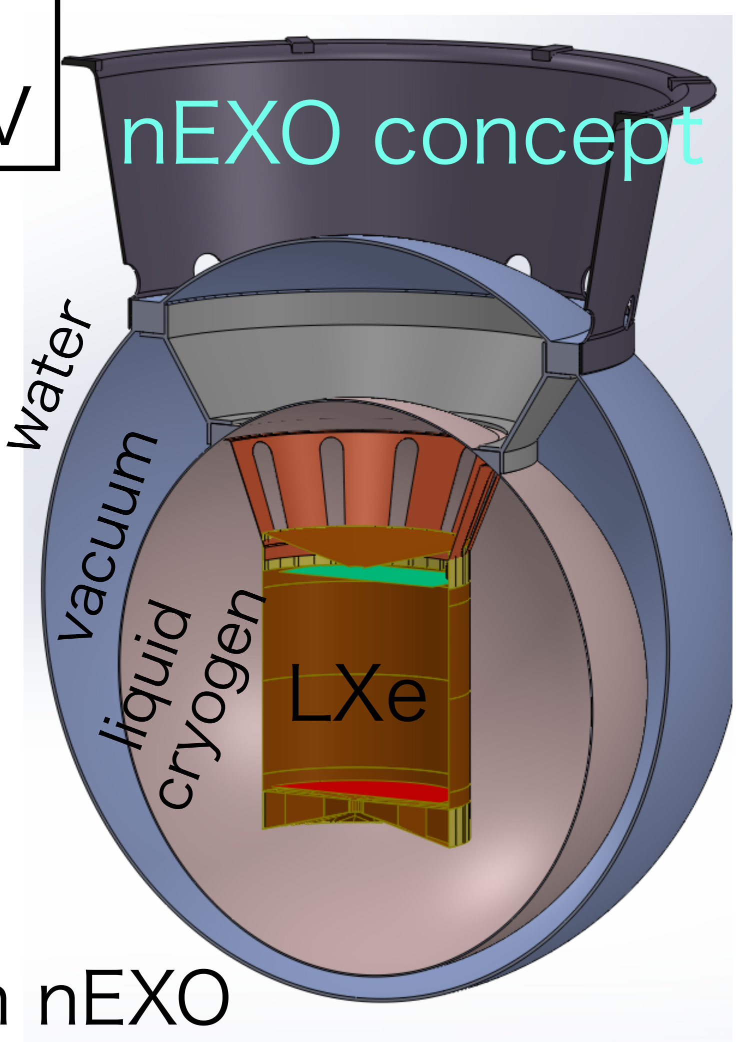
Correlation of ionization & scintillation provides good enough energy resolution.

~1.2%/√E (200 phase II)

arXiv:1707.08707

current EXO-200 result
$T_{1/2}>1.8\times10^{25}$ y
m < 147~398 meV

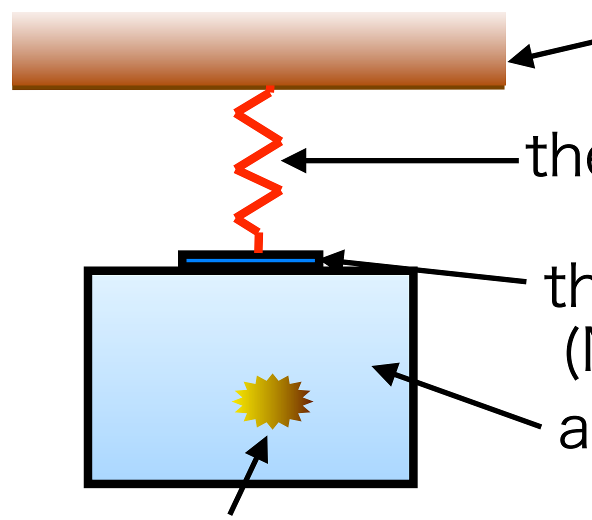




powerful self-shielding in nEXO

nEXO target
9.2×10^{27}y (10y)
6~18 meV

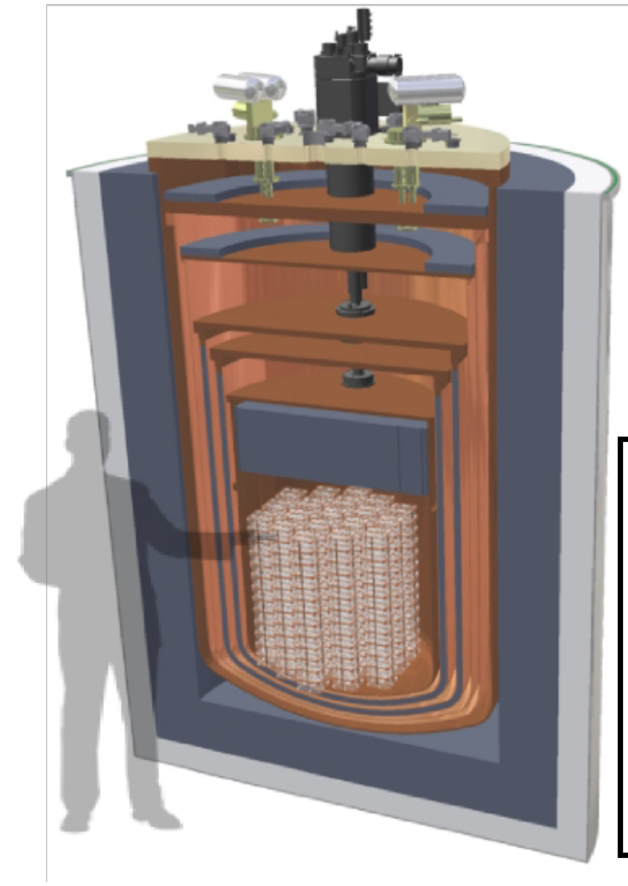
CUORE → CUPID (CUORE Upgrade with Particle Identification)



heat sink (Cu)
$C \propto T^3$, **~10mK**
thermal coupling (PTFE)
thermistor (NTD-Ge)
absorber (TeO_2)
energy deposit

ΔT=~0.1mK/MeV

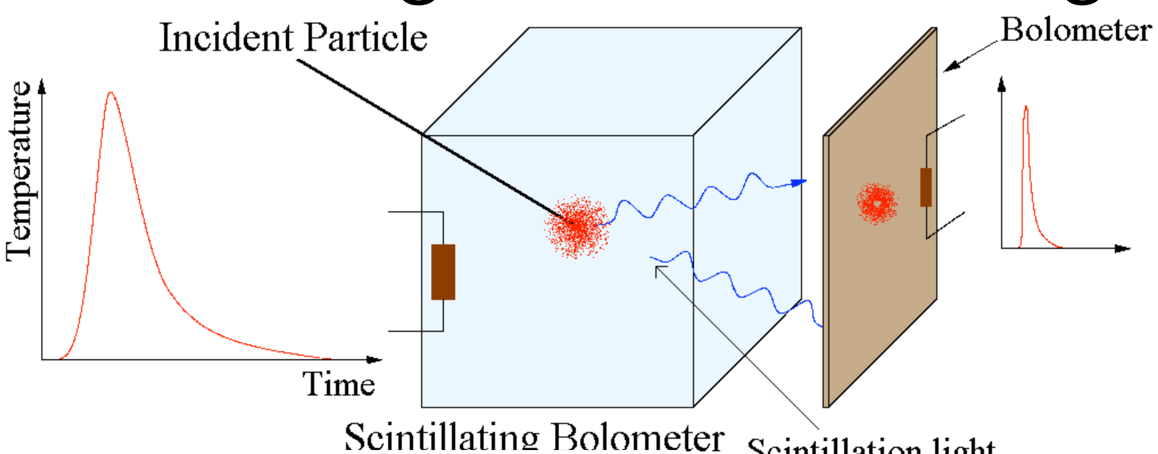
effective resolution
7.7keV FWHM@2527keV

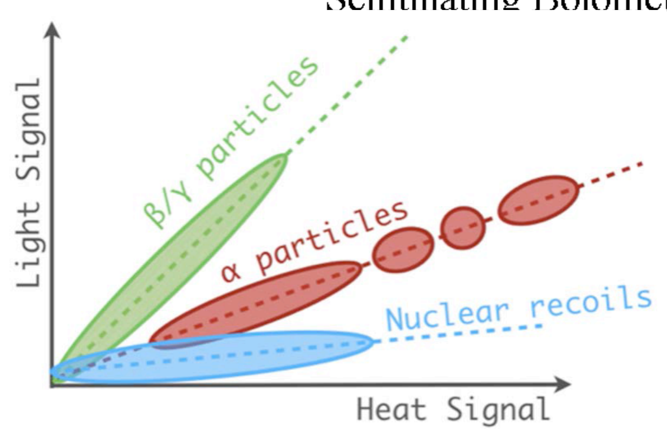


988 detectors
741 kg of TeO_2
204 kg of ^{130}Te

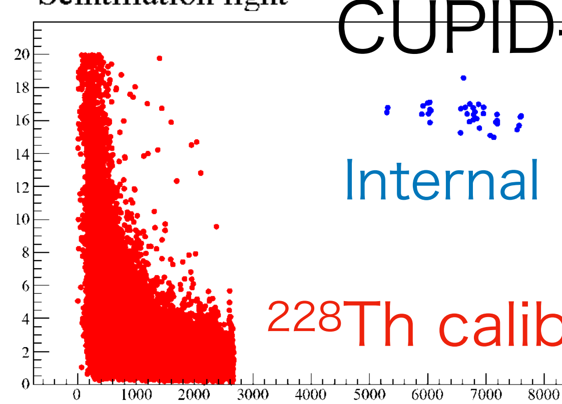
current CUORE result
PRL 120, 132051 (2018)
$T_{1/2} > 1.5 \times 10^{25}$ yr (90%)
m_{ee}<110~520 meV

Scintillating bolometer brings PID





CUPID-0

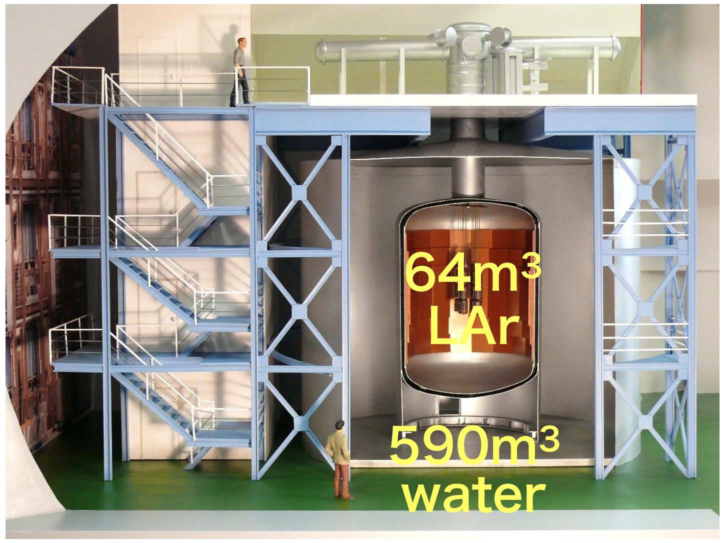


Unfortunately,
TeO_2 doesn't scintillate.
There are other candidates;
$Zn^{82}Se$, $Zn^{100}MoO_4$, $^{116}CdWO_4$

Target sensitivity
$Zn^{82}Se$ case (335kg ^{82}Se)
$T_{1/2} > 4.2 \times 10^{27}$ yrs (10y)
m_{ee} < 6-19 meV

GERDA, Majorana → LEGEND

Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay



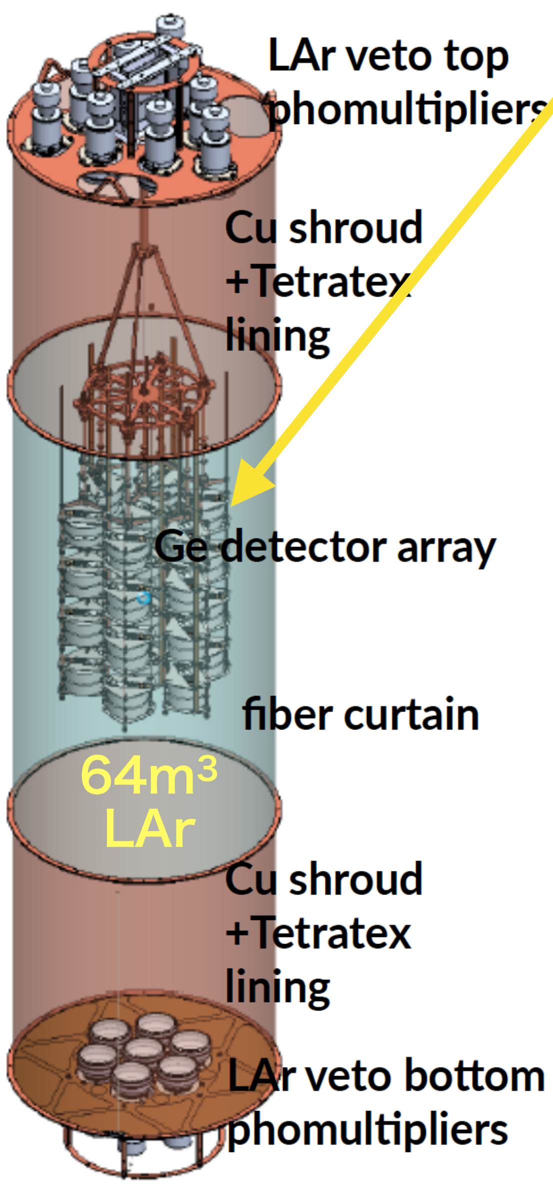
810 scintillator fibers coupled to 90 SiPMs

GERDA Phase II result

PRL 120, 132503 (2018)

$T_{1/2}$> 8.0x10^{25} yrs (90%)

mee < 120~260meV

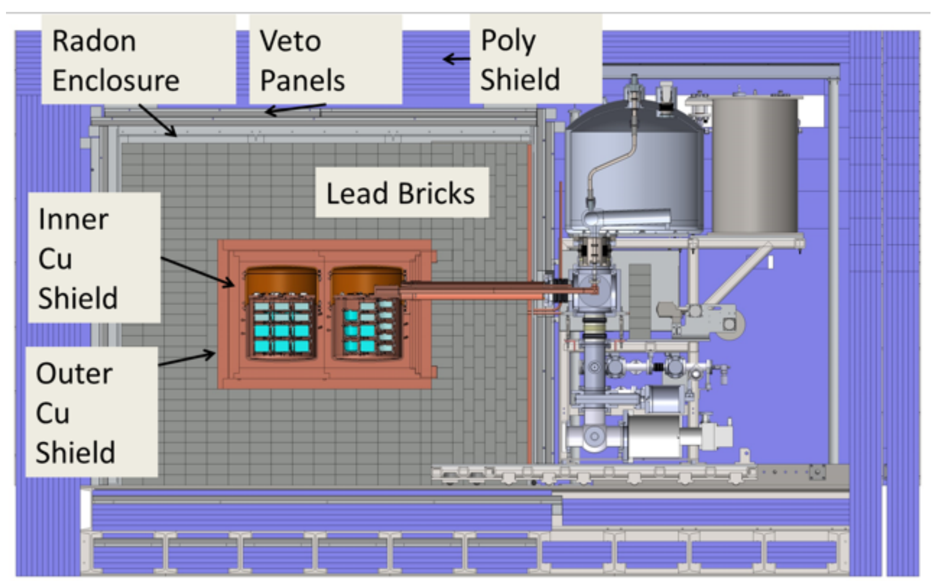


GERDA uses liquid argon active veto.

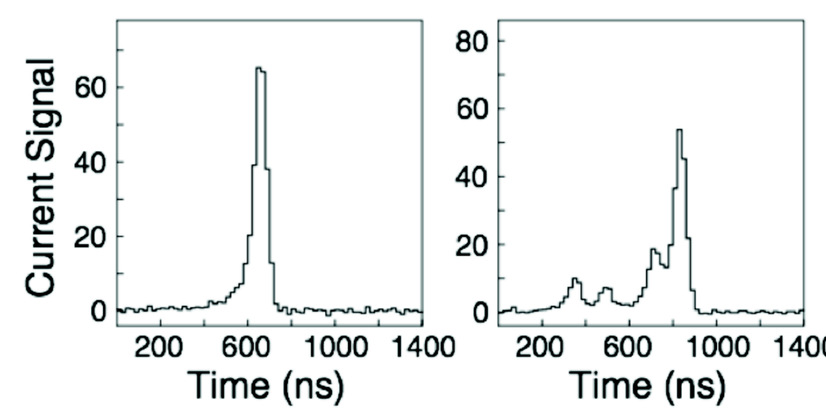
35.8kg enriched + 7.6 kg natural Ge **3keV FWHM@2039keV**

Majorana (demo.) uses better signal processing.

12.9kg enriched + 8.8 kg natural Ge



single-site vs multi-site



LEGEND combines them.

Phase I (200kg) starts by 2021 using GERDA infrastructure.

Phase I target sensitivity, $T_{1/2}$ > 10^{28} yrs, m_{ee} < 10~20meV

Score sheet with a personal naive consideration

technology	nuclei	active shielding	minimum insensitive region	in-situ purification, on/off meas.	solar CC	solar ES	exposure × phase space	
semiconductor	^{76}Ge	immersed in liquid Argon	○	×	○	○	×	
liquid TPC	^{136}Xe	self shielding	△	○	○ with MSE	△ with enrich.	△	
gas TPC	^{136}Xe	outer detector	× pressure vessel	○	○ with MSE	○ with 2 brobs	××	
bolometer	^{130}Te	outer detector	× cryo vessel	×	○	○	×	
	^{100}Mo	outer detector	× cryo vessel	×	○	○	×	
	^{48}Ca	outer detector	× cryo vessel	×	-	○	×	
Tracking	except for Xe		△	△ switch foil	○	○	××	rich physics

Summary

・$0\nu 2\beta$ searches are connected with big mysteries of the Universe.

・The current world best limit is from KamLAND-Zen 400.

$$\langle m_{\beta\beta} \rangle < (61 - 165)\,\mathrm{meV}$$ PRL117, 082503

・"Advantages of using KamLAND" has been all validated.

・KamLAND-Zen 800 (40meV) successfully launched and R&D for KamLAND2-Zen (below 20 meV) is going well.

・Full coverage of IH seems to be secured with various approaches.

・Reaching NH (below 5meV) is still very challenging. Required hundreds tons of DBD nuclei may be achieved by ^{136}Xe (centrifugal) or ^{130}Te (natural). Homogeneous self-shielding detector without inactive region and with high energy resolution will be preferred.

nEXO is such structure (but small).

DARWIN (dark matter search) plans 40t LXe TPC (still small).

DUNE (LBNE) plans 70kt LAr TPC.

Maybe, super-nEXO, ^{enr}DARWIN, DUNE-Xe reach NH? Let's dream!