

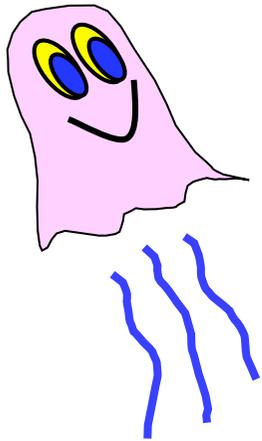
Neutrino Physics



Neutrinoless

Double Beta Decay

$0\nu\beta\beta$



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Tohoku University

PANIC, Sep.1, 2017, Beijing, China

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Introduction

$0\nu\beta\beta$  and experimental challenges

KamLAND-Zen

Summary

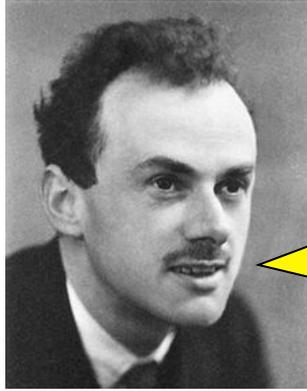
# Neutrinos : Finite Masses, but still mysterious !

$\nu_e$	$\nu_\mu$	$\nu_\tau$
$e$	$\mu$	$\tau$

$m_\nu \ll m_{q,\ell}$   
Absolute val. of  $m_\nu$ s  
 $\nu \neq \bar{\nu}$  ? or  $\nu = \bar{\nu}$  ?

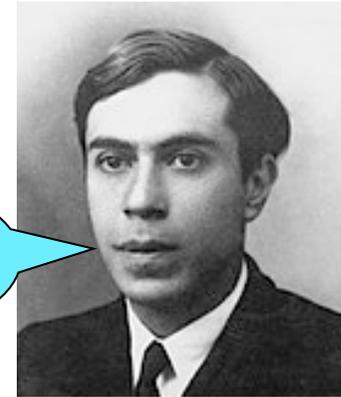
$\theta_{12}, \theta_{23}, \theta_{13}$   
 $\Delta m_{21}^2, \Delta m_{32}^2,$   
 $\delta_{CP}, \Delta m_{31}^2 \gtrless 0 ?$

Origin of the mass.  
Fundamental problem !



Dirac

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



Majorana

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

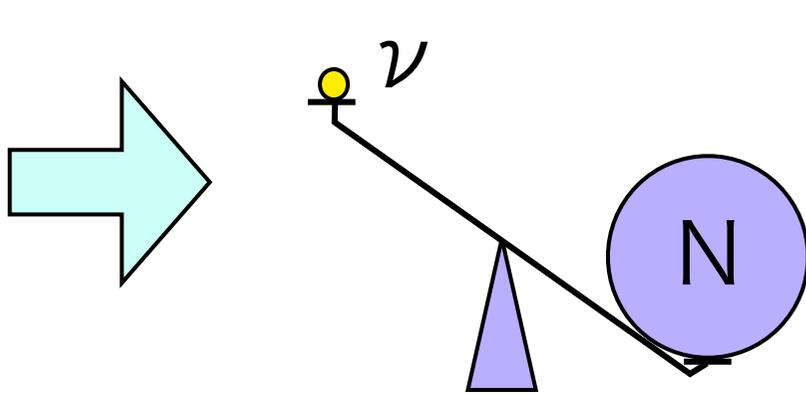
Dirac Mass term

$$-L_m = M_D (\bar{\psi}_R \psi_L + \text{h.c.}) +$$

$$(M_L/2) [(\bar{\psi}^c)_R \psi_L + \text{h.c.}] + (M_R/2) [(\bar{\psi}^c)_L \psi_R + \text{h.c.}].$$

Majorana Mass term

two mass eigenstates

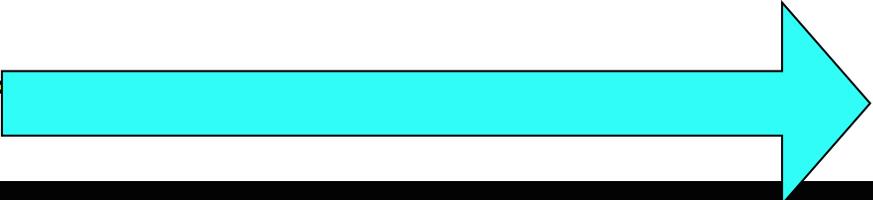


See-saw mechanism

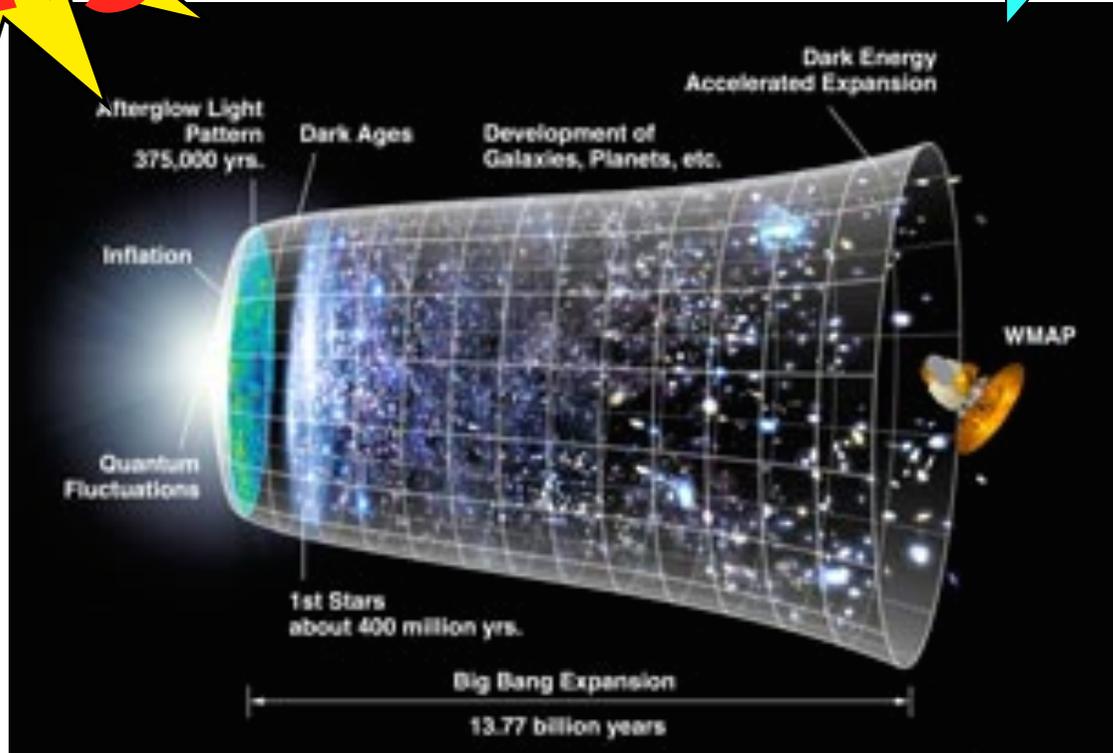
$$\left\{ \begin{array}{l} \Rightarrow m_\nu = \frac{M_{q,\ell}^2}{M_N} \ll M_{q,\ell} \\ \Rightarrow N: \text{ Important roles} \end{array} \right.$$

in the early Universe !

**Big bang**



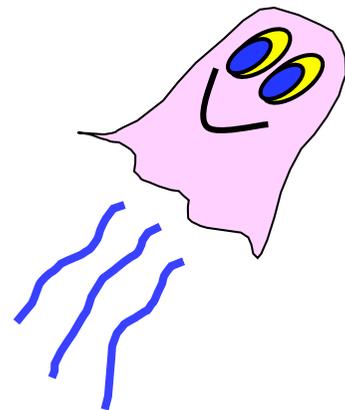
Matter dominance world



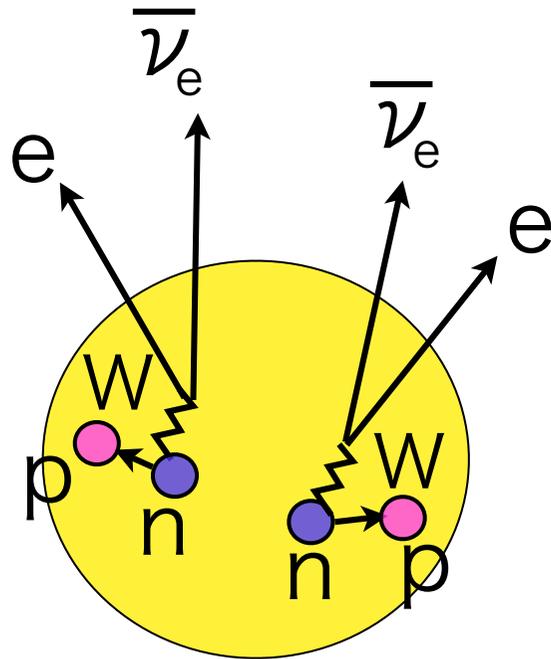
Sakharov's conditions  
Super-heavy Majorana  $\nu$   
 $\Delta L \neq 0 \Rightarrow \Delta (B-L) = 0 \Rightarrow \Delta B \neq 0$   
(Leptogenesis)

**Majorana nature of  $\nu$  is very important and should be checked!**

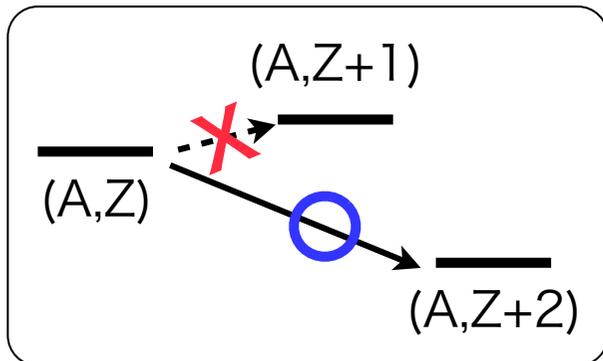
Nuclear  $\beta\beta$  decay  
provides the most feasible and  
sensitive way to study the  
Majorana nature of neutrinos !



$2\nu\beta\beta$



$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



SM process, but very rare!

$$T_{1/2}^{0\nu} \sim 10^{19} - 10^{21} \text{ yr}$$

There are ~35 natural isotopes which can double-beta decay.

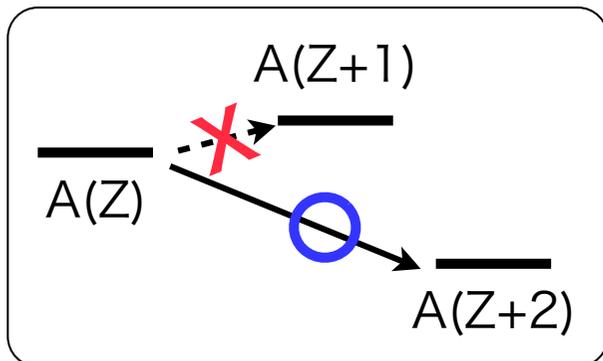
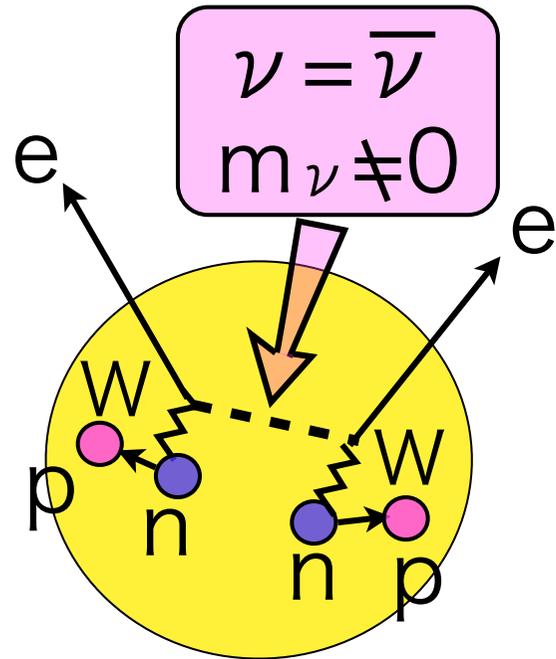
$^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{110}\text{Pd}$ ,  $^{116}\text{Cd}$ ,  
 $^{124}\text{Sn}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$ , etc. are observed

**PERIODIC TABLE OF THE ELEMENTS**

1 IA Hydrogen 1.00794	2 IIA Helium 4.002602											13 IIIA Boron 10.811	14 IVA Carbon 12.0107	15 VA Nitrogen 14.0067	16 VIA Oxygen 15.9994	17 VIIA Fluorine 18.9984032	18 VIIIA Neon 20.1797
3 Li 6.941	4 Be 9.012182											5 B 10.811	6 C 12.0107	7 N 14.0067	8 O 15.9994	9 F 18.9984032	10 Ne 20.1797
11 Na 22.98976928	12 Mg 24.3050	3 IIIB Scandium 44.955912	4 IVB Titanium 47.867	5 VB Vanadium 50.9415	6 VIB Chromium 51.9961	7 VIIB Manganese 54.938045	8 VIII Iron 55.845	9 VIII Cobalt 58.933195	10 VIII Nickel 58.6934	11 IB Copper 63.546	12 IIB Zinc 65.38	13 Al 26.9815386	14 Si 28.0855	15 P 30.973762	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.955912	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938045	26 Fe 55.845	27 Co 58.933195	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.798
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.96	43 Tc 97.90722	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.90447	54 Xe 131.293
55 Cs 132.9054519	56 Ba 137.327	57-71 Lanthanides	72 Hf 178.49	73 Ta 180.94788	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.084	79 Au 196.966569	80 Hg 200.59	81 Tl 204.3833	82 Pb 208.98040	83 Bi 208.98040	84 Po (209)	85 At (209)	86 Rn (222)
87 Fr (223.01974)	88 Ra (226.02541)	89-103 Actinides	104 Rf (261.108)	105 Db (262.109)	106 Sg (263.109)	107 Bh (264.109)	108 Hs (265.109)	109 Mt (266.109)	110 Ds (267.109)	111 Rg (268.109)	112 Cn (269.109)	113 Nh (270.109)	114 Fl (271.109)	115 Mc (272.109)	116 Lv (273.109)	117 Ts (274.109)	118 Og (277)
Lanthanide series		57 La 138.90547	58 Ce 140.116	59 Pr 140.90765	60 Nd 144.242	61 Pm (144.91275)	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92535	66 Dy 162.500	67 Ho 164.93032	68 Er 167.259	69 Tm 168.93421	70 Yb 173.054	71 Lu 174.9668	
Actinide series		89 Ac (227.02775)	90 Th 232.03806	91 Pa 231.03888	92 U 238.02891	93 Np (237.04817)	94 Pu (244.06420)	95 Am (243.06138)	96 Cm (247.07035)	97 Bk (247.07031)	98 Cf (251.07959)	99 Es (252.0830)	100 Fm (257.09510)	101 Md (258.09843)	102 No (259.1010)	103 Lr (262.110)	

   $Q_{\beta\beta} > 2\text{MeV}$

# $0\nu\beta\beta$



Beyond the SM process  
Total lepton number violation.

Not found  $T_{1/2}^{0\nu} > 10^{26} \text{yr}$

Light Majorana  $\nu$  exch. is considered as the dominant process.

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

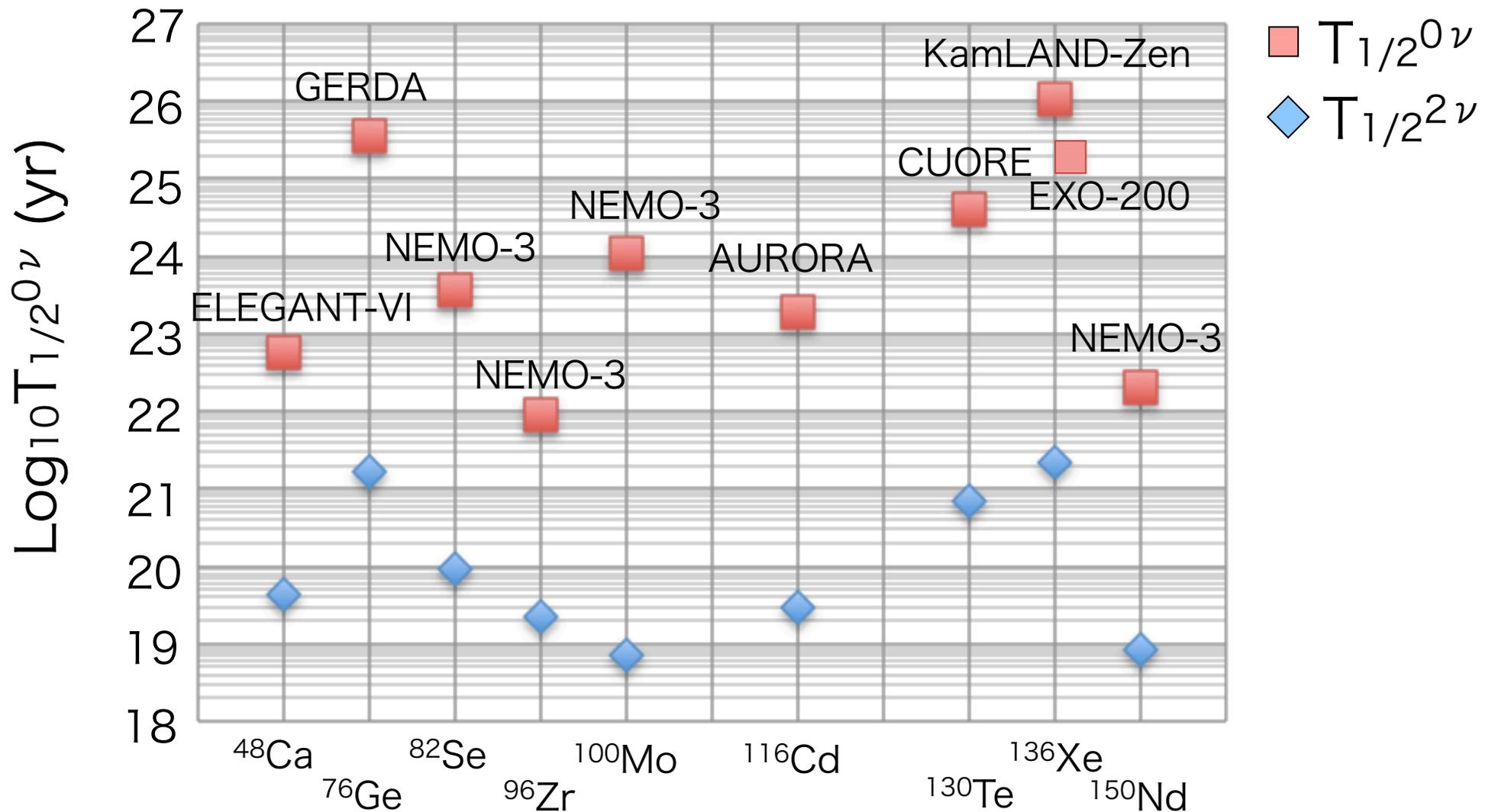
↑ Phase space factor
↑ Nuclear matrix element
↑ Effective Majorana neutrino mass

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

$$= \left| (m_1 c_{12}^2 + m_2 s_{12}^2 e^{i\alpha_{21}}) c_{13}^2 + m_3 s_{13}^2 e^{i(\alpha_{31} - 2\delta)} \right|$$

All information of the neutrinos are contained;  
Oscillation parameters, Absolute  $\nu$  masses,  
Majorana CP-phases.

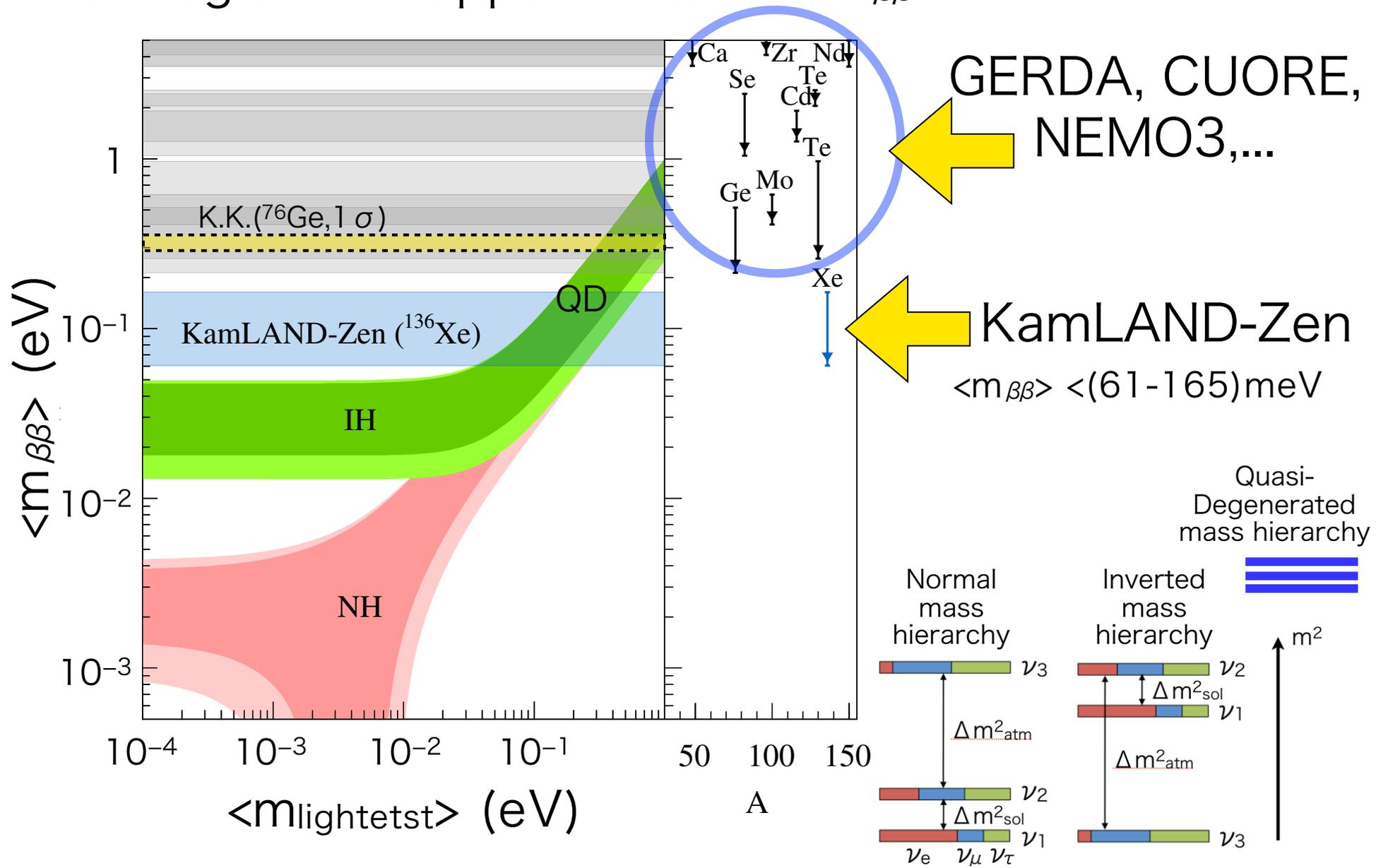
# $T_{1/2}^{0\nu}$ lower limits (90%C.L.) and $T_{1/2}^{2\nu}$



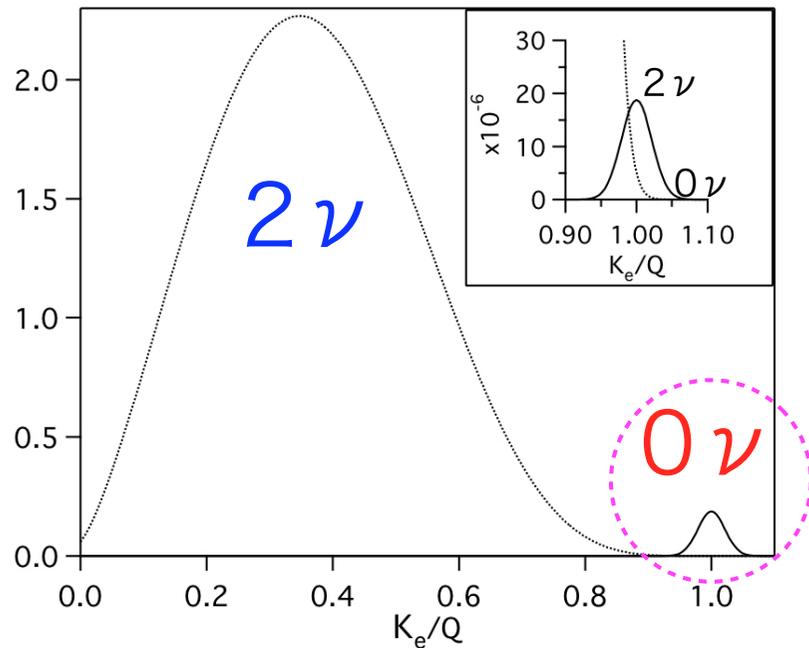
There are many ongoing and planned experiments !

Most sensitive experiments have provided  $T_{1/2}^{0\nu} > 10^{25}\sim 10^{26}$  yr.

# Allowed region and upper limits on $\langle m_{\beta\beta} \rangle$



$\langle m_{\beta\beta} \rangle$  limit is close to the bottom of the QD region.  
 Positive claim on  $^{76}\text{Ge}$  was refuted (KL-Zen and GERDA).



Summed energy of electrons normalized by  $Q_{\beta\beta}$

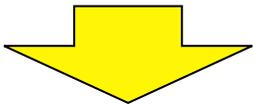
## FOM for the sensitivity

$$T_{1/2}^{0\nu} \propto \epsilon a \sqrt{\frac{MT}{b \Delta E}}$$

Isotope mass (points to  $M$ )  
 Data taking period (points to  $T$ )  
 detection efficiency (points to  $\epsilon$ )  
 Isotopic abundance/enrichment factor (points to  $a$ )  
 Background index ( $\text{keV}^{-1}\text{kg}^{-1}\text{yr}^{-1}$ ) (points to  $b$ )  
 Region of interest  $\sim$  Energy resolution (points to  $\Delta E$ )

Large amount of isotope  
 Remove BG (Ext./Int.)  
 Good energy resolution  
 Isotope selection by large  $a$ ,  
 $Q_{\beta\beta}$  and long  $T_{1/2}^{2\nu}$

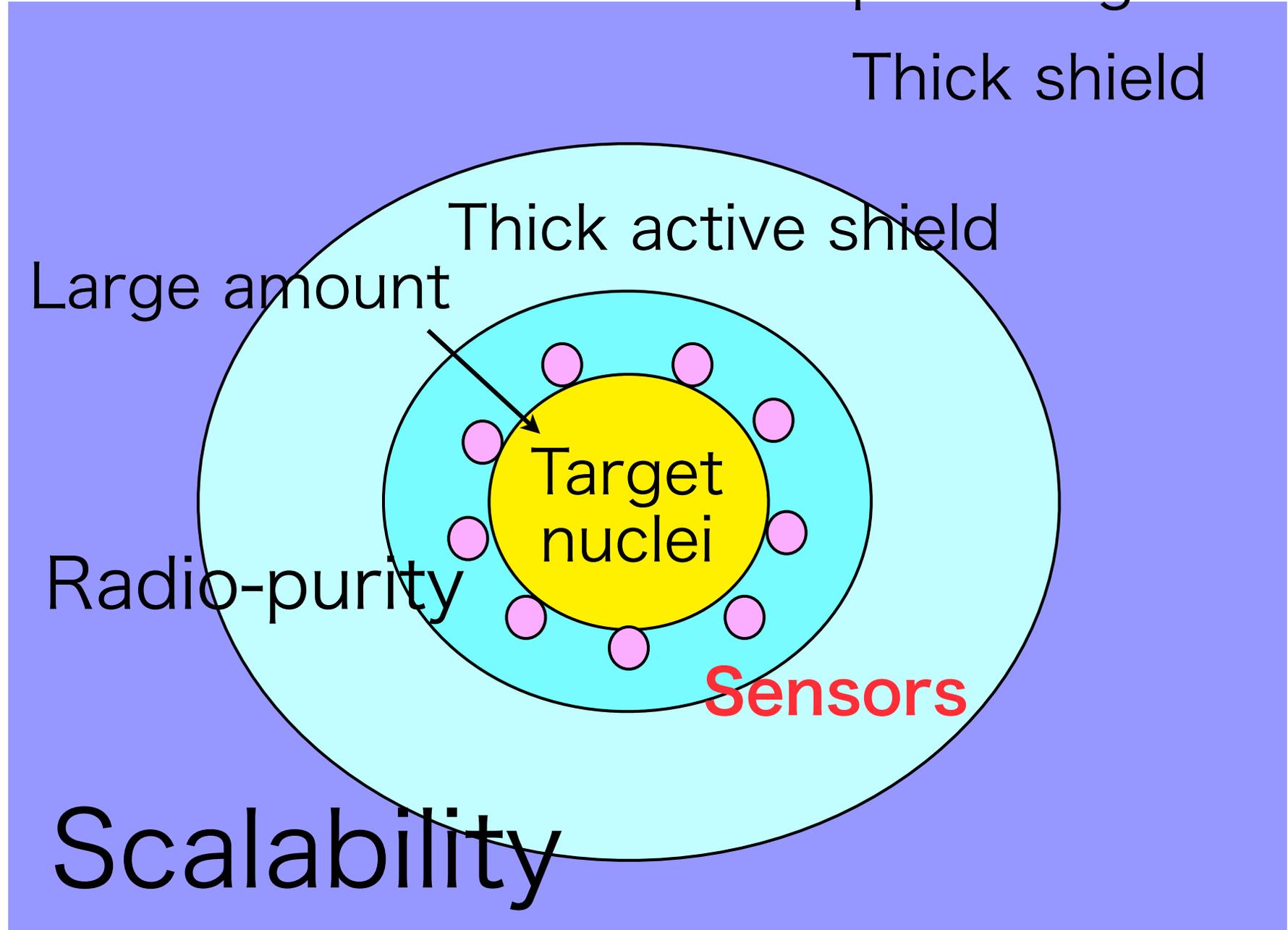
Current  $10^{25} \sim 10^{26}$  yr  
 Planned  $\sim 10^{27}$  yr  
 $O(100)\text{kg} \Rightarrow O(1)$  ton

  
 $\langle m_{\beta\beta} \rangle \sim 0.02\text{eV (IH)}$

# Concept of the experiment

Deep Underground

Thick shield



Large amount

Thick active shield

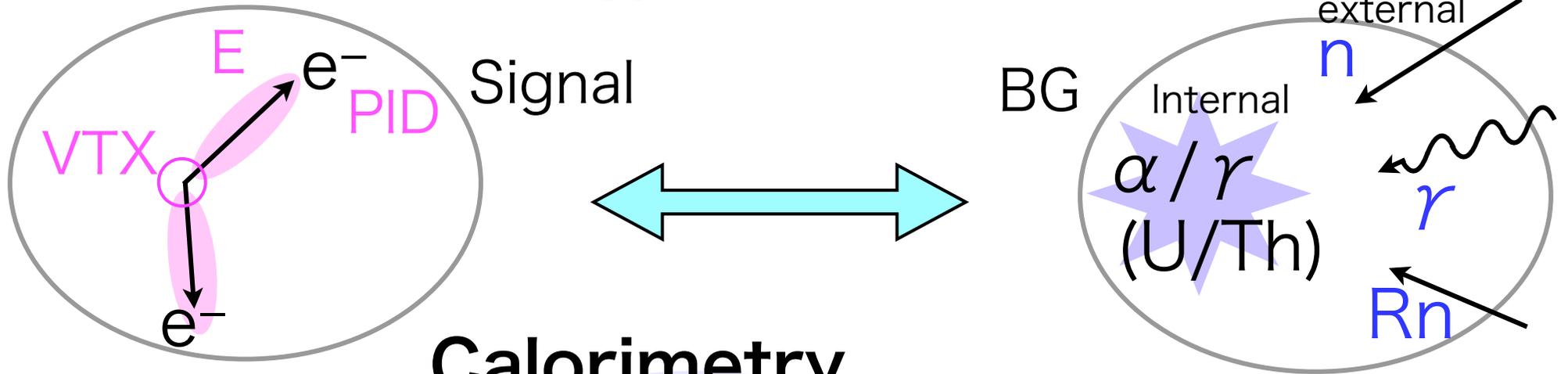
Radio-purity

Target nuclei

Sensors

Scalability

# Detection Strategy



## Calorimetry

Ionization

Phonons  
(Bolometer)

Scintillation

Crystal

(A,Z)+LS

TPC (Gas, Liq.)

Tracking

Event  
topology

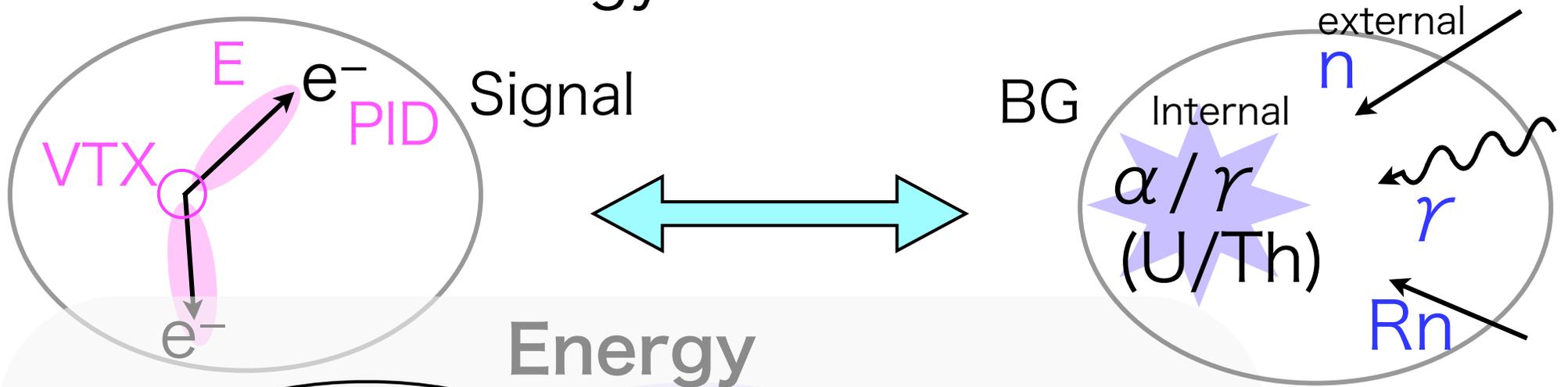
## PID

Time  
Position  
Pulse shape

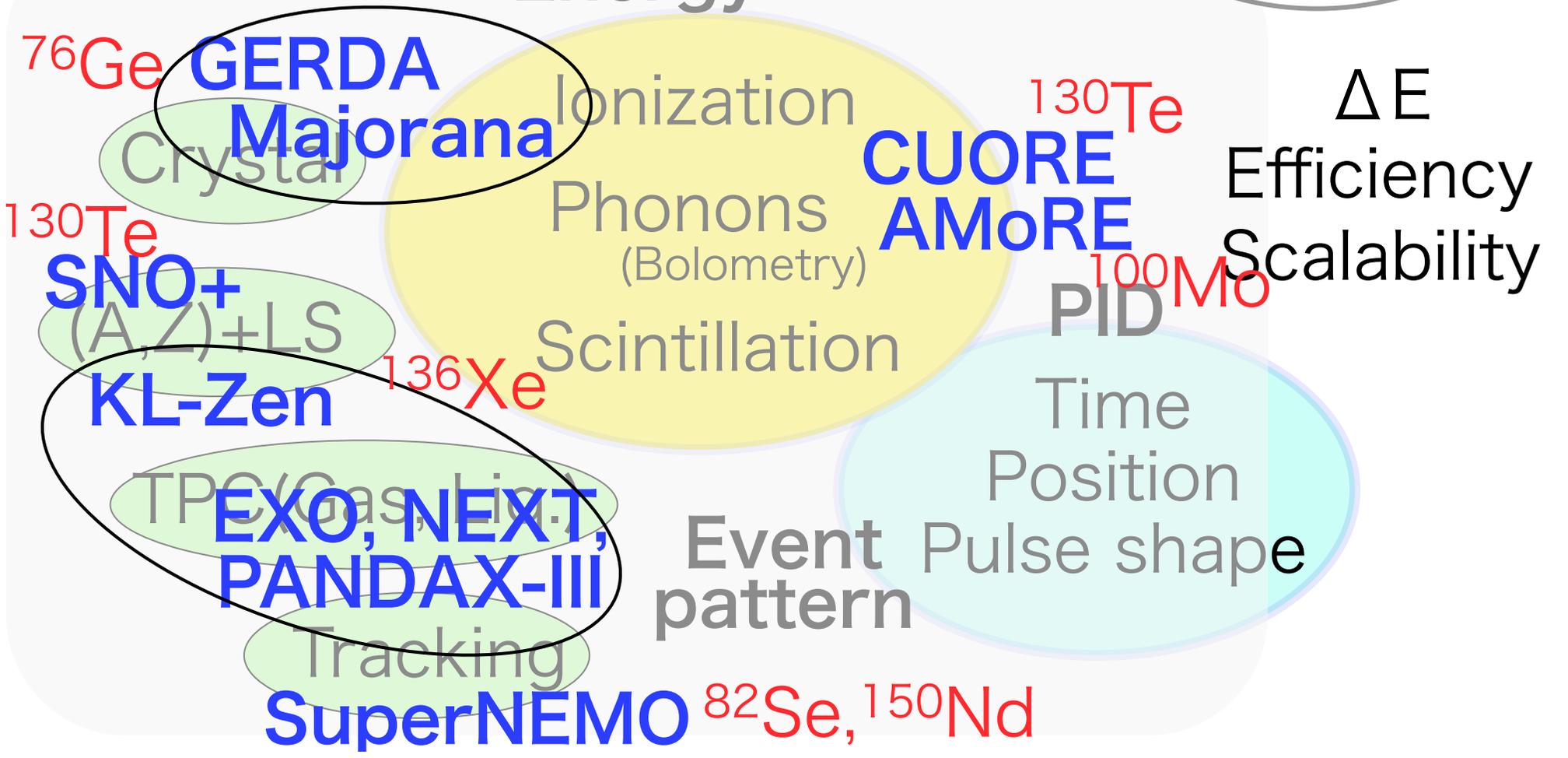
$\Delta E$

Efficiency  
Scalability

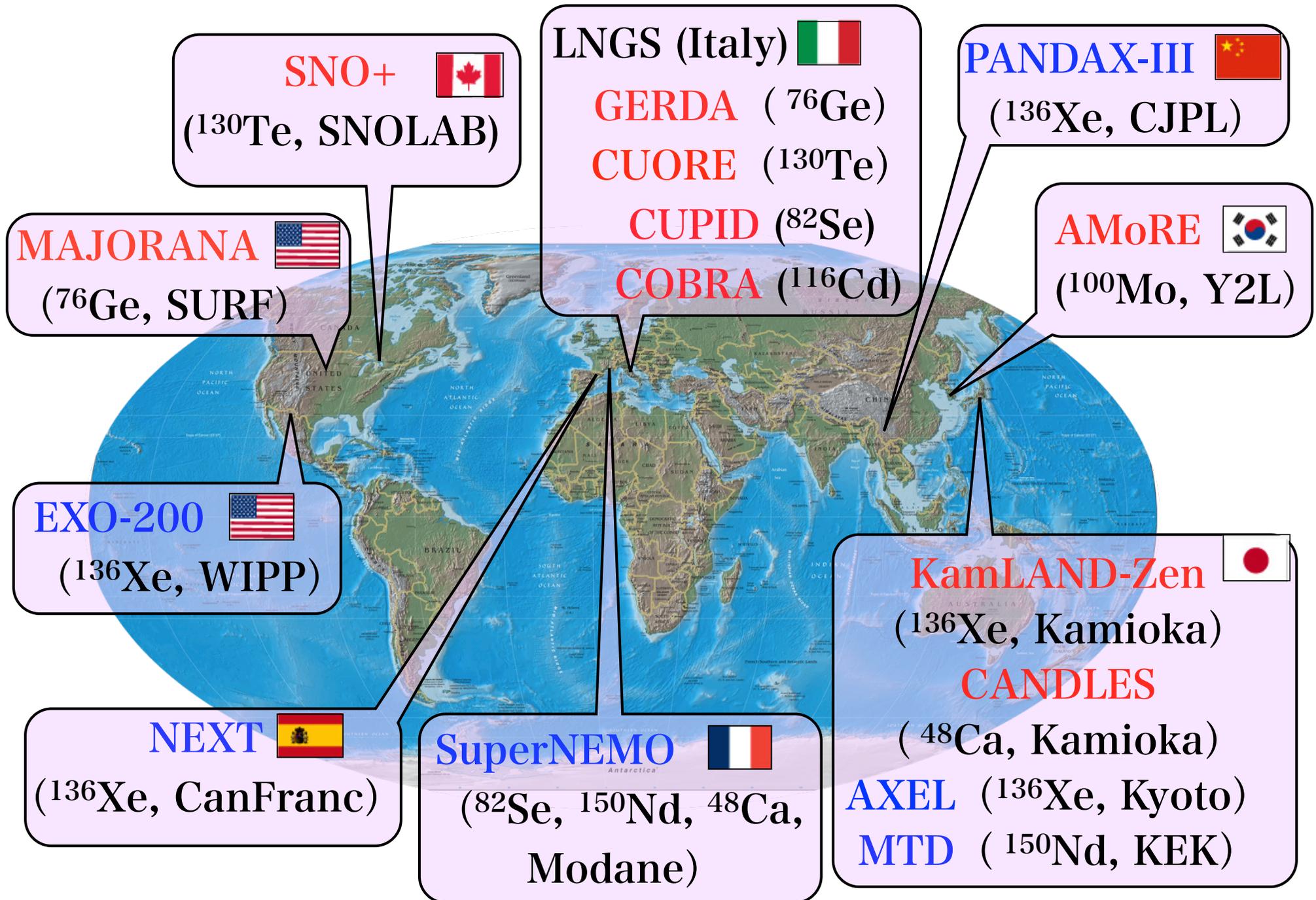
# Detection Strategy



Energy



# $0\nu\beta\beta$ activities in the world (Calorimetric, tracking/TPC)

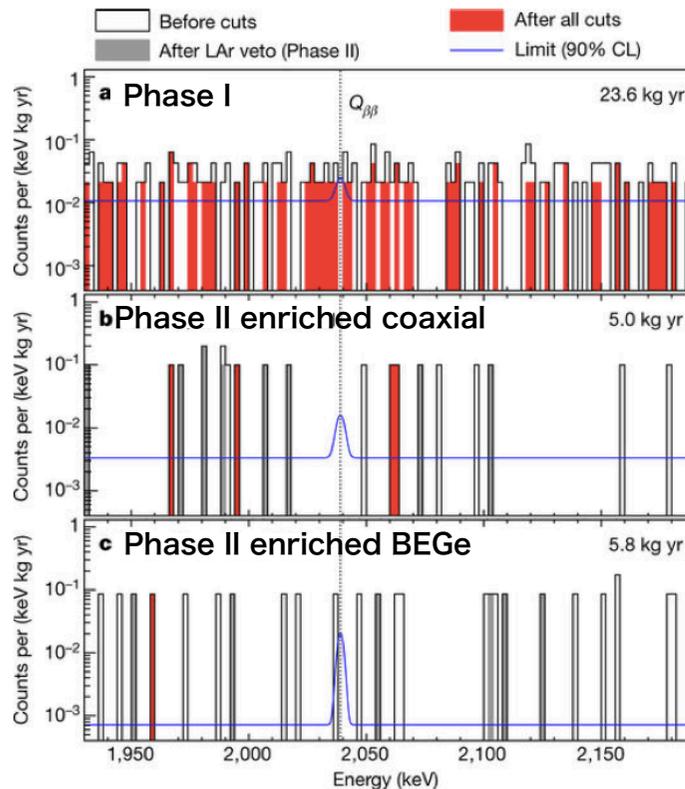
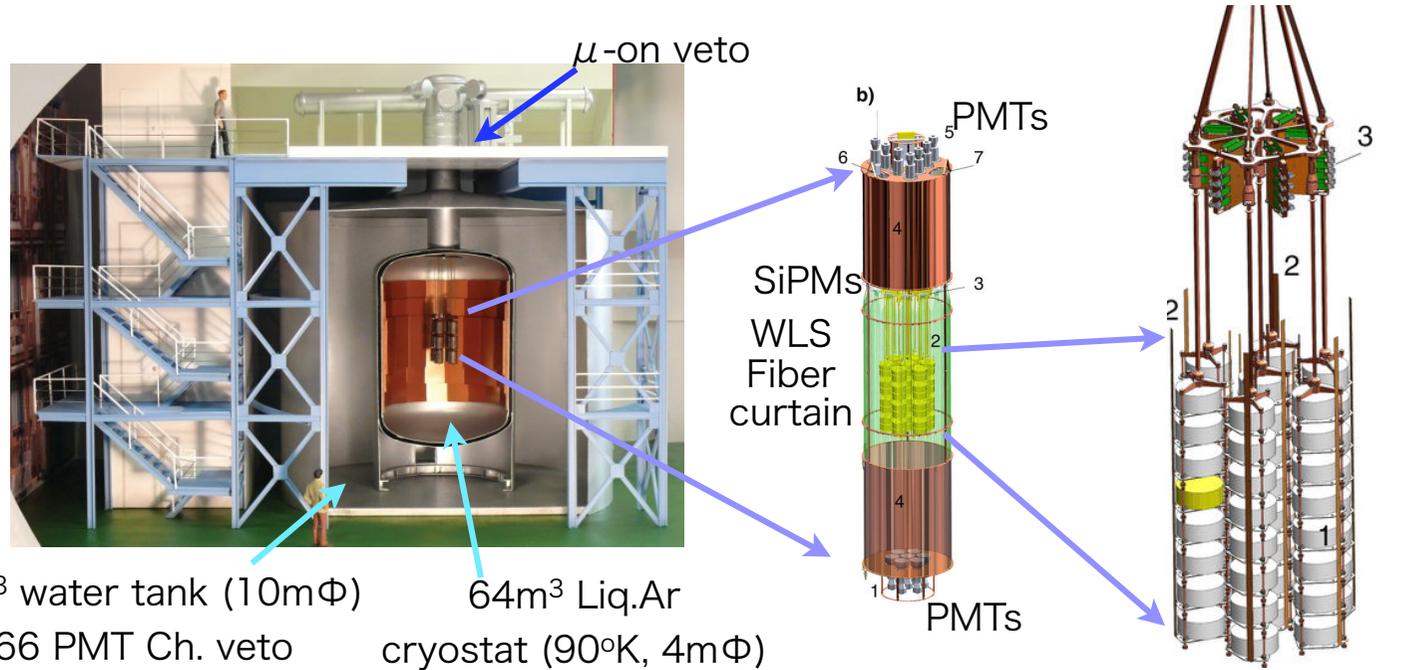


# GERDA\*

GERmanium Detector Array

LNGS 3600m.w.e.
$^{76}\text{Ge}$ Q: 2,039 keV
enrich. HPGe Phase I+II 34.4kg yr
$BI=0.7^{+1.1}_{-0.5}$ $\times 10^{-3}$ $\text{kg}^{-1}\text{keV}^{-1}\text{yr}^{-1}$

Achieved !  
 $\Delta E_{\text{FWHM}} = 2.8\text{keV}$   
@Q(BEGe)



LAr Veto, PSD Analysis  
(<sup>42</sup>K) (SS vs MS, A/E)

$T^{0\nu}_{1/2} > 5.3 \times 10^{25}$  yr (90% C.L.)

$\langle m_{\beta\beta} \rangle < (150-330)\text{meV}$

Sensitivity  $T^{0\nu}_{1/2} = 4 \times 10^{25}$  yr

No signal in ROI, BG free search !

Prospects

200kg Ge (Current Cryostat)

$\downarrow$   $T^{0\nu}_{1/2} > 10^{27}$  yr (5yrs)

1000kg Ge (LEGEND)

$T^{0\nu}_{1/2} > 10^{28}$  yr

$\langle m_{\beta\beta} \rangle < (10-20)\text{meV}$

# CUORE\*

Cryogenic Underground Observatory for Rare Events

LNGS 3600m.w.e.
$^{130}\text{Te}$ Q: 2,528 keV
Nat. $\text{TeO}_2$ 34.1% ( $^{130}\text{Te}$ )

CUORE-0  
1 tower  
(4 crystals  
 $\times 13$  piles)

CUORE  
19 towers  
988  $\text{TeO}_2$   
(750kg)



CUORICINO

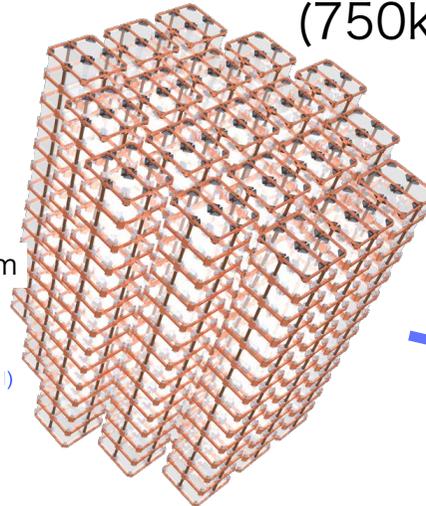
(2003-2008)

19.75kg yr  
( $^{130}\text{Te}$ )

$T^{0\nu}_{1/2}$   
 $> 2.8 \times 10^{24}$  yr

9.8kg yr  
( $^{130}\text{Te}$ )

CUORE-0  
Combined  
 $> 4 \times 10^{24}$  yr

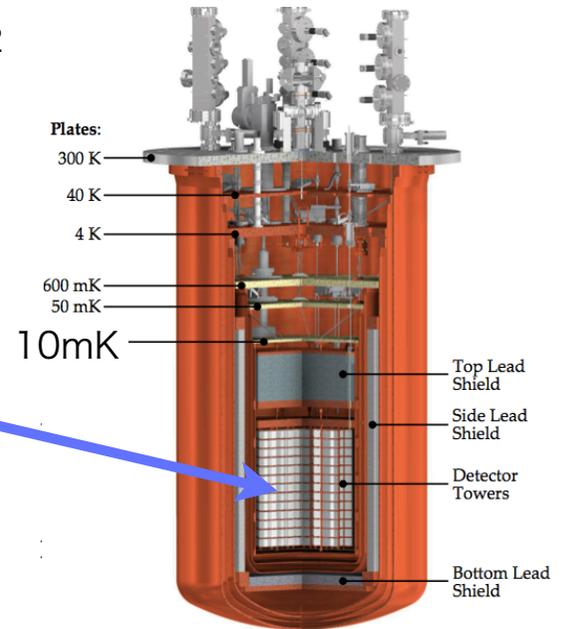


65cm

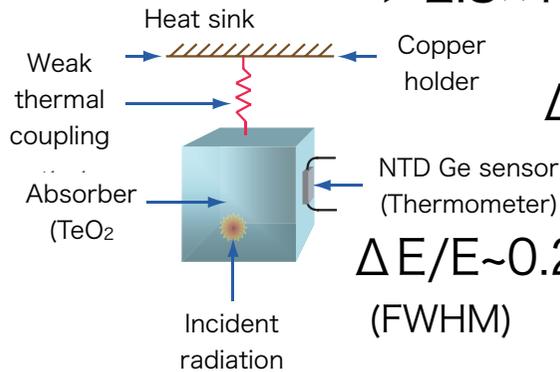
206kg ( $^{130}\text{Te}$ )  
 $0.01 \text{ kg}^{-1} \text{ keV}^{-1} \text{ yr}^{-1}$   
 $> 9 \times 10^{25}$  yr  
(5 yr)

38.1kg yr (10.6kg  $^{130}\text{Te}$ )  
CUORE Combined

$> 6.6 \times 10^{24}$  yr  
 $\langle m_{\beta\beta} \rangle < (210-590) \text{ meV}$



Jan.2017~: Cool down  
April-June: Science run  
 $\Delta E = 7.9 \pm 0.6 \text{ keV}$   
(FWHM) @ 2615 keV



$$\Delta T \propto E_{\text{dep}} / C$$

$$C \propto T^3$$

$\Delta E/E \sim 0.2\%$  @  $Q_{\beta\beta}$   
(FWHM)

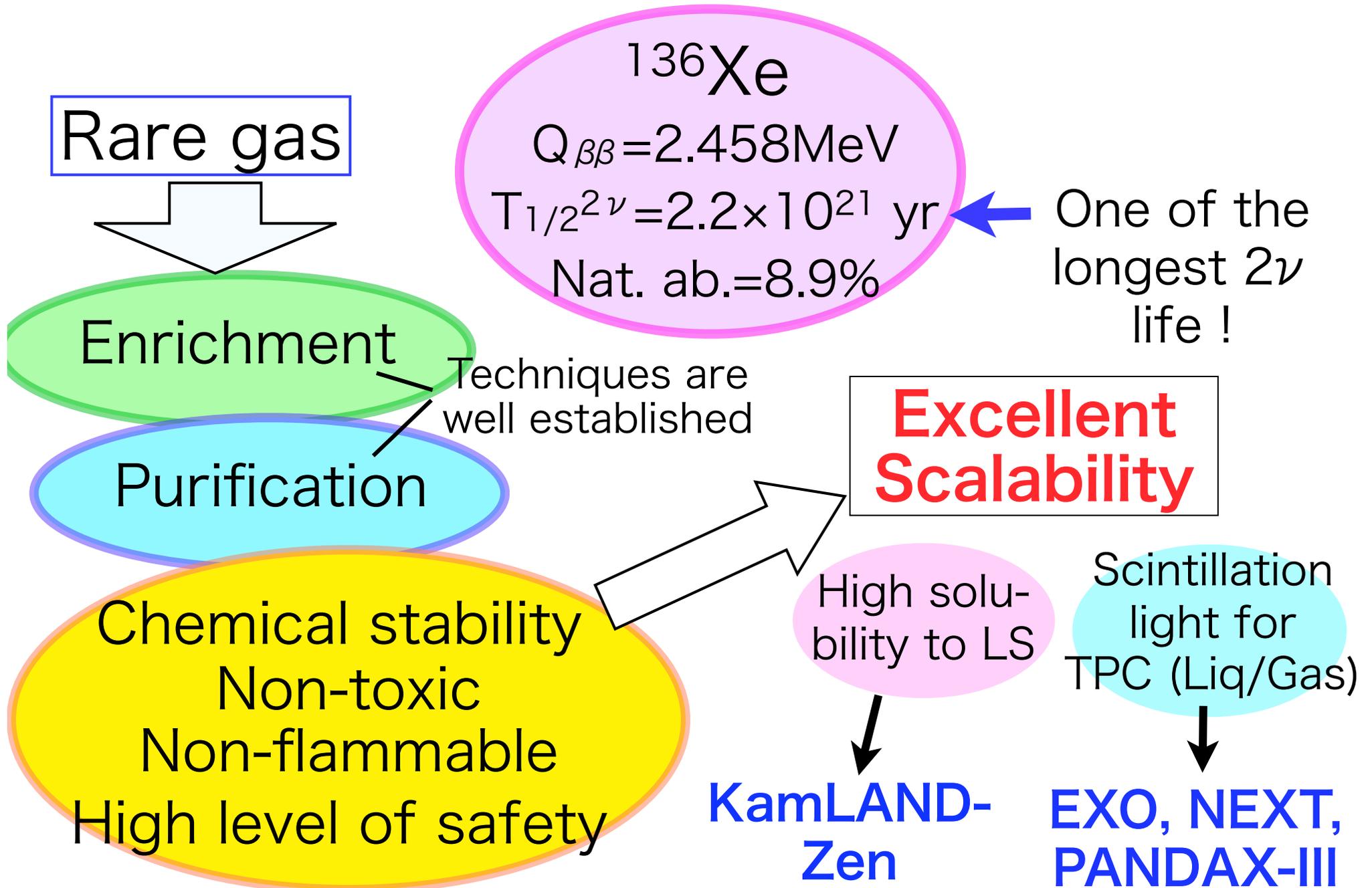
## Challenging items

Long-term stable operation of a ton-sized bolometric detector !

Validation of the background model in ROI ( $\alpha, \beta/\gamma$ ) will be established.

**CUPID**  
CUORE Upgrade  
with Particle ID

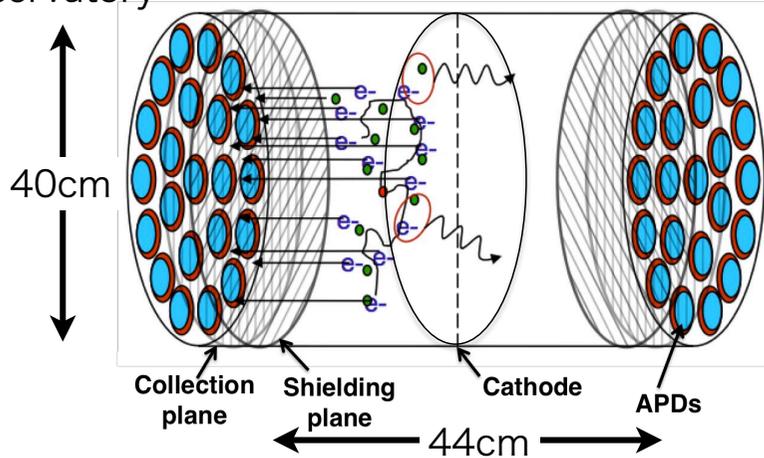
$^{136}\text{Xe}$  has nice characteristics for  $0\nu\beta\beta$  search !



# EXO-200

Enriched Xenon Observatory

WIPP (NM,USA) 1585 m.w.e.
$^{136}\text{Xe}$ Q: 2,458 keV
Liq.Xe TPC enrich:80.6%
$(1.5 \pm 0.2) \times 10^{-3}$ $\text{kg}^{-1}\text{keV}^{-1}\text{yr}^{-1}$

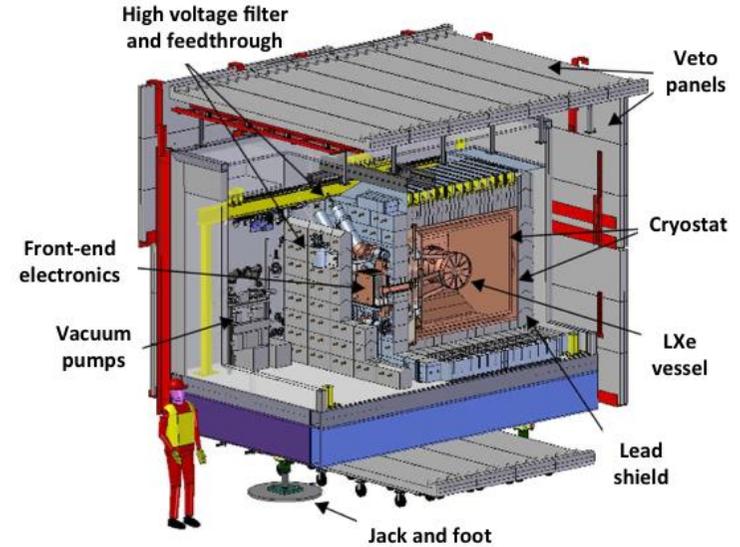


Scintillation+ionization

$$\sigma / E = 1.23\%$$

SS vs. MS

Detector schematic:



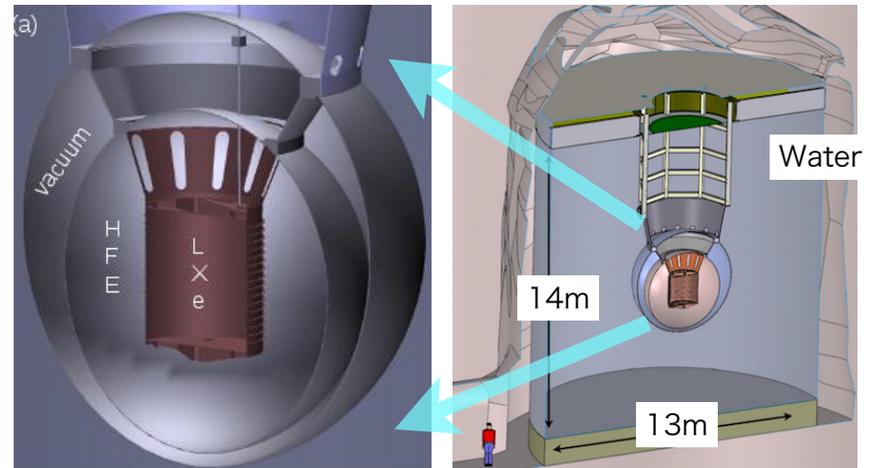
nEXO 5ton enriched Liq.Xe TPC  
planned installation at SNOLAB  
Sensitivity:  $T_{1/2}^{0\nu} \sim 10^{28}\text{yr}$  (with Ba-tag)

Phase I (Sep.2011-Feb.2014) 122 kg yr  
Phase II (Jan.-May, 2016) 55.6kg yr  
Hardware upgrade

$$T_{1/2}^{0\nu} > 1.8 \times 10^{25} \text{ yr}$$

$$\langle m_{\beta\beta} \rangle < (147-398) \text{ meV}$$

(90%C.L.)

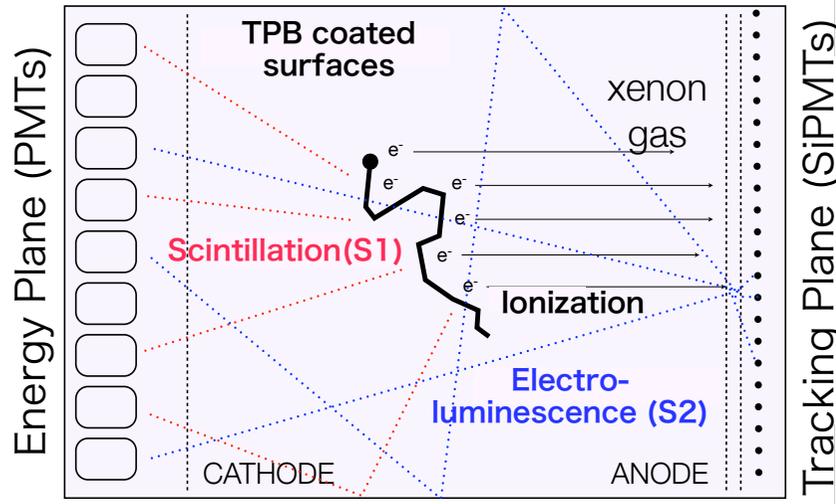


# NEXT\*

Neutrino Experiment with a Xenon TPC

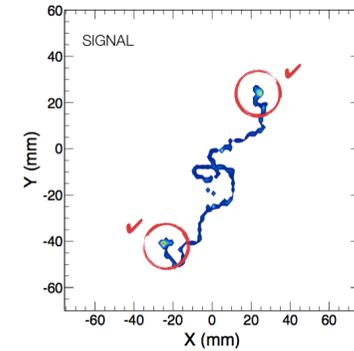
CanFranc 850 m.w.e.
136Xe Q: 2,458 keV
10-20bar TPC

## Detector concept

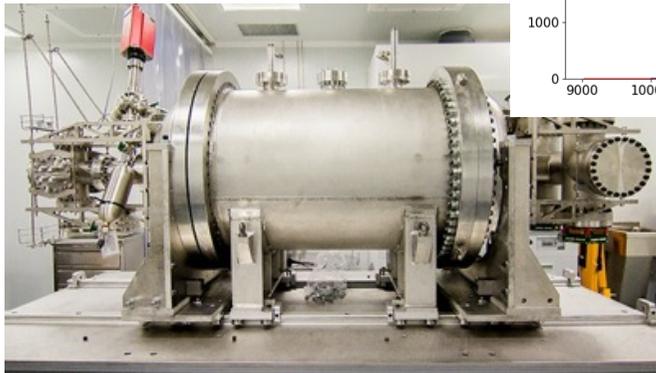


Electro-luminescence (EL) amplification  
 $\Delta E/E \sim 0.5\%$   
 (FWHM)@ $Q_{\beta\beta}$

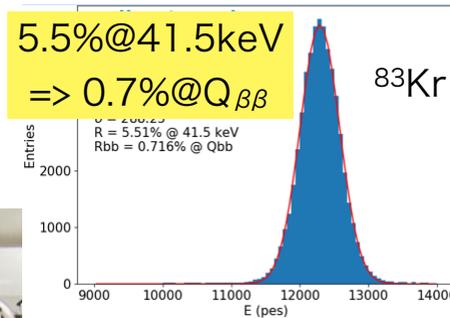
Topological signature for BG suppression.



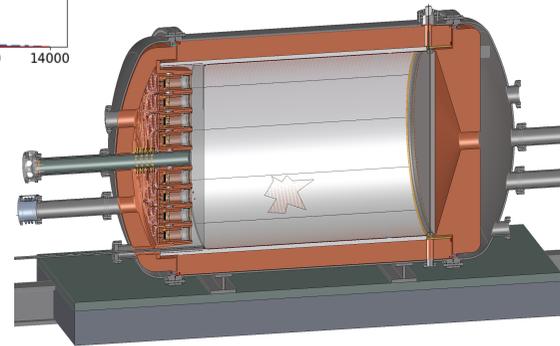
## NEW (2015-2018)



5~10kg Xe,  
 50cm drift, 20cm radius,  
 1792 SiPMs, 12PMTs

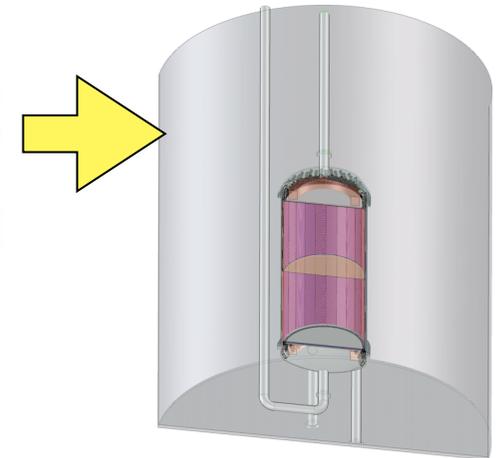


## NEXT-100 (2019~)



100kg enriched Xe,  
 $0\nu\beta\beta$  search  
 for  $T_{1/2} 5 \times 10^{25}$  yr.

## NEXT-ton



# PANDAX-III\*

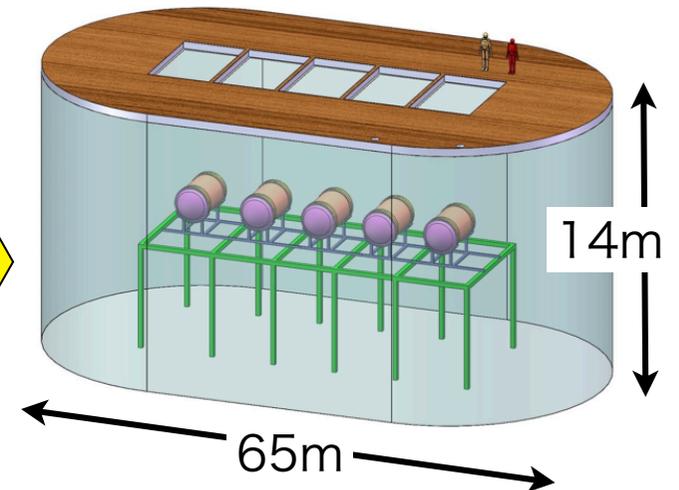
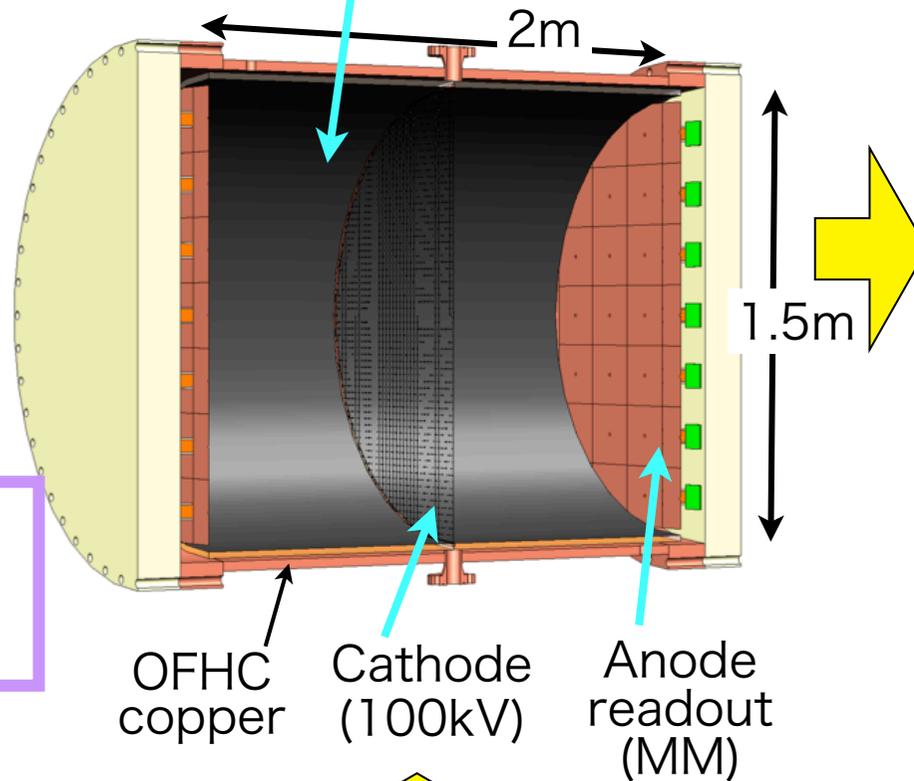
Particle and Astrophysical  
Xenon Detector

High press. (10bar)  
enriched  $^{136}\text{Xe}$  (200kg)  
+TMA(1%),  $3.5\text{m}^3$

200kg $\times$ 5 Xe TPC  
modules in a water pool,  
 $\Delta E/E \sim 1\%$ (FWHM) @ $Q_{\beta\beta}$ .

CJPL 6720 m.w.e.
$^{136}\text{Xe}$ Q: 2,458 keV
90% enrich.
TPC 200k $\times$ 5

World's deepest !  
 $0.2\mu\text{'s}/\text{m}^2/\text{d}$   
Horizontal shaft !



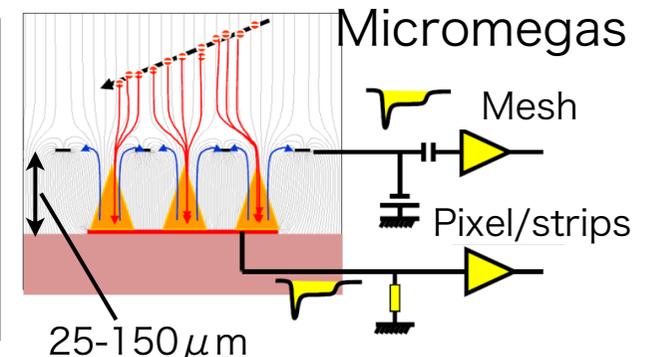
Water pool construction  
finished in Jun.2016.

$T_{1/2}^{0\nu} \sim 10^{27}\text{yr}$

Prototype (16kg Xe, 10 bar)



R&Ds for Readout; improve  
 $\Delta E/E \sim 3\%$ (FWHM) @ $Q_{\beta\beta}$ .  
with Microbulk Micromegas  
 $\Rightarrow 1\%$  (Direct pixel readout  
without gas amplification)



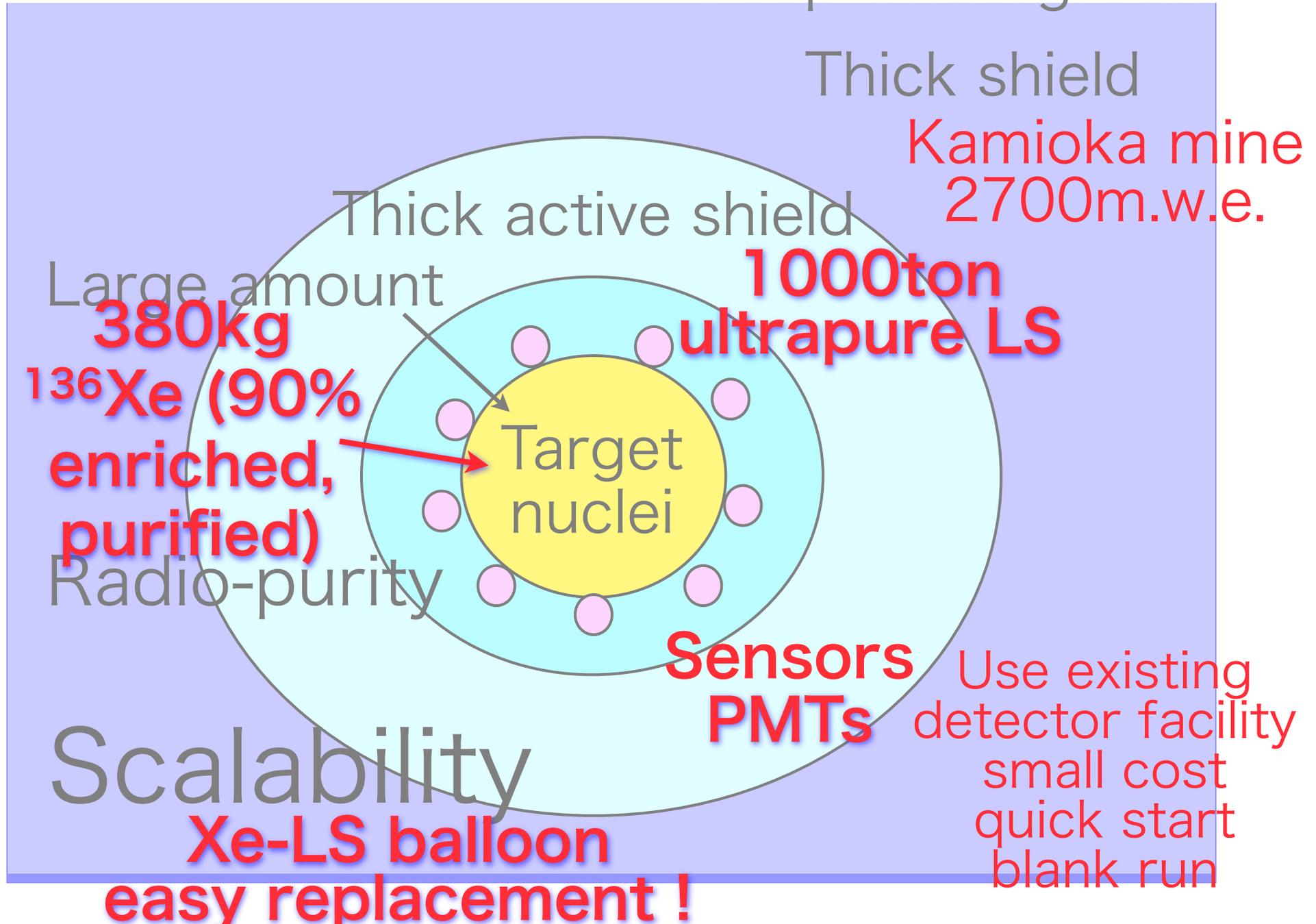
# KamLAND-Zen

Zero-neutrino  
double beta decay



# Concept of the KamLAND-Zen

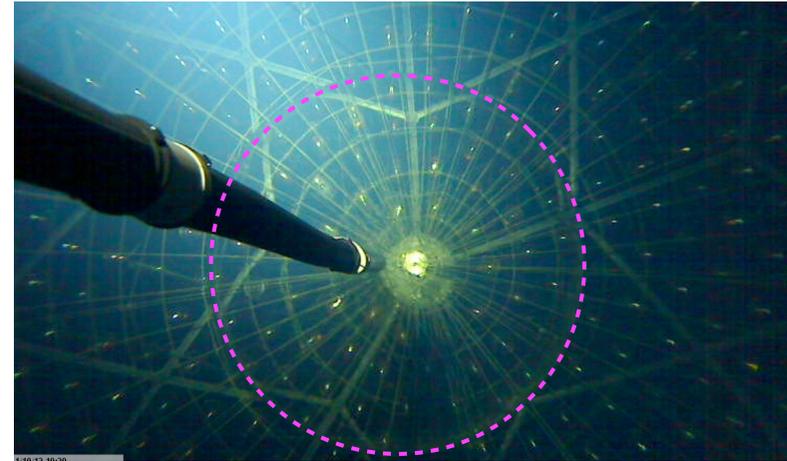
Deep Underground



# KamLAND-Zen 400

Kamioka mine  
2700 m.w.e.

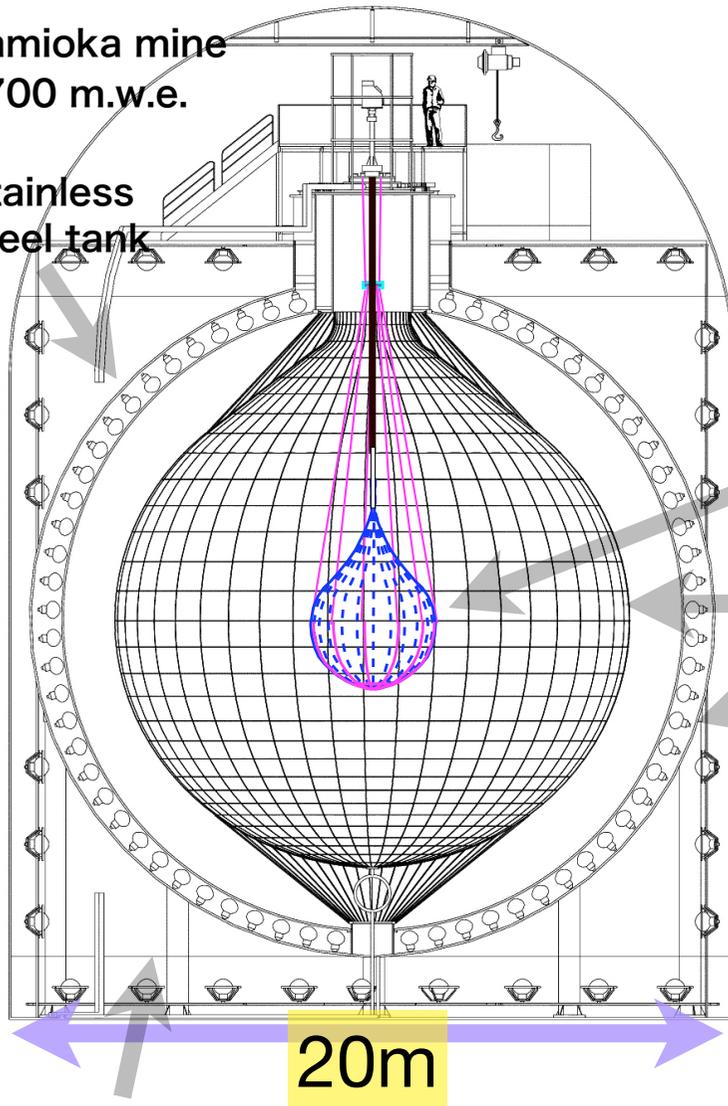
Stainless  
steel tank



**Mini-balloon (MIB, ~3mφ) : Xe (320 ~ 380kg, 91% <sup>136</sup>Xe)+Decane-based LS**

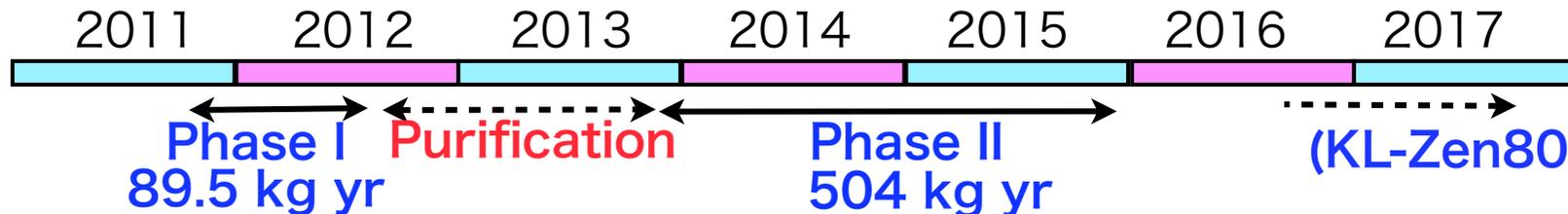
**Main Balloon (13mφ, 1000ton Ultra-pure LS)  
PMTs (1325 17"+ 554 20")**

- Small modification: Cost effective, Quick start.
- Active shield of 1000 ton ultrapure LS.
- Easy handling: Xe Collection, Repurify, Blank run.
- Excellent scalability!
- Physics in parallel: Geo  $\nu$ , SuperNovae, etc.



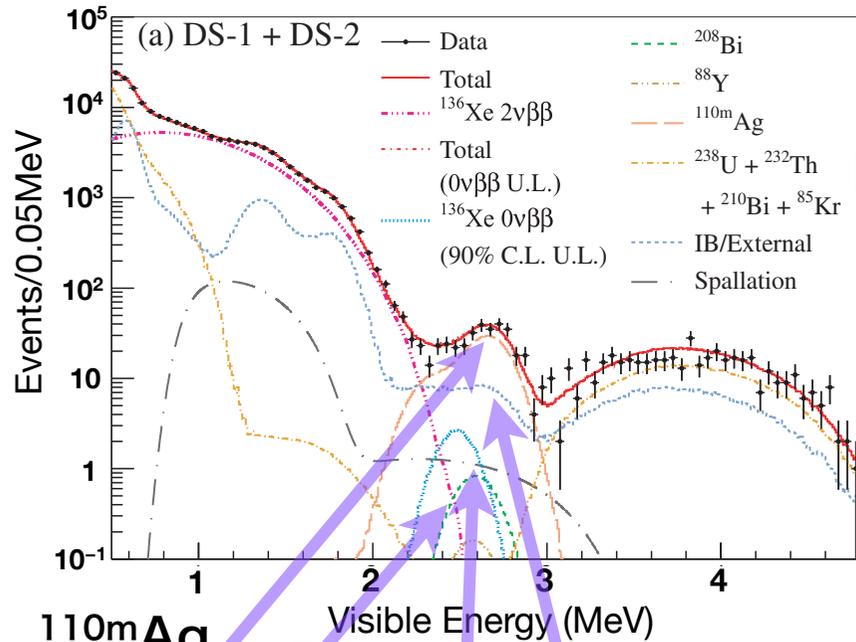
20m

3200ton  
Water Ch.  
225 PMTs

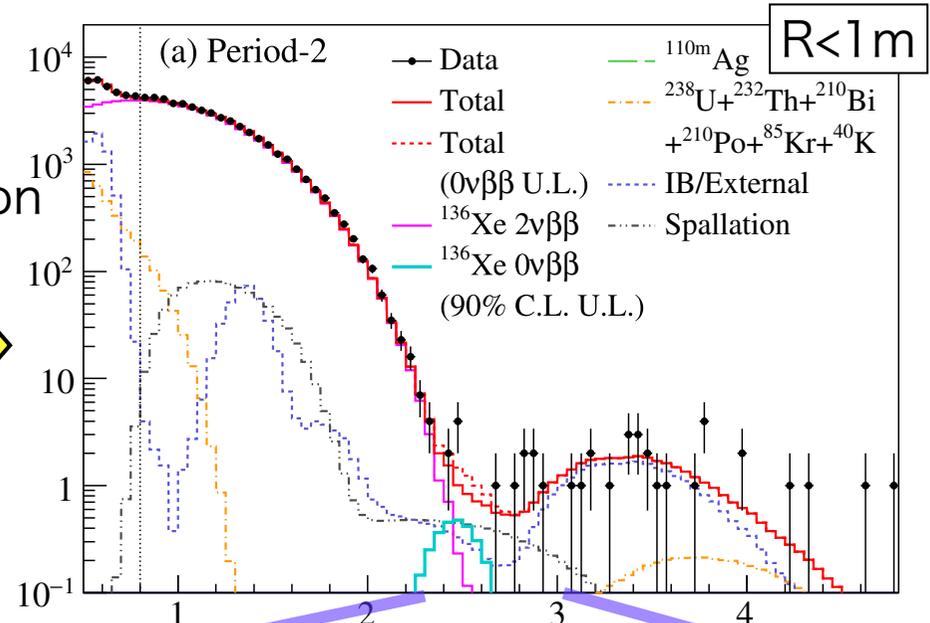


# KL-Zen400 results

Phase I 89.5kg·yr PRL110,062502(2013)

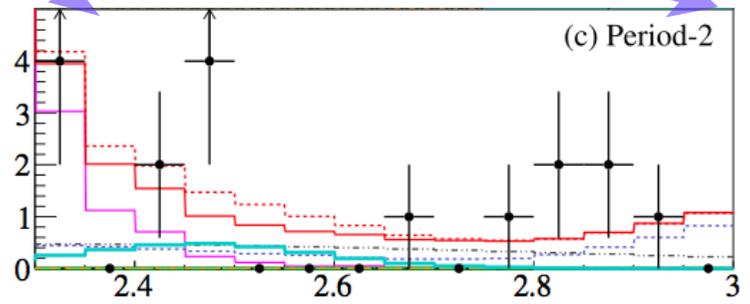


Phase II 504 kg·yr PRL117,082503(2016)



**110mAg**  
**Xe-LS**  
**2ν**  
**10C**  
**μ-spallation**  
**214Bi**  
**Balloon**

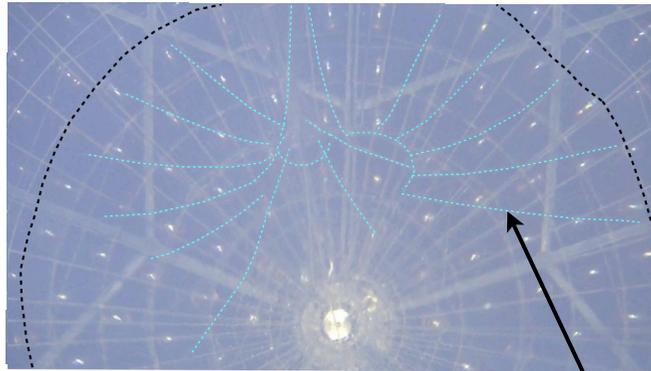
Make better the  $\sigma_E$ .  
 ( $\mu$ -n- $^{10}\text{C}$ ) triple coincidence by n-detection. => further improved  
**Change balloon to much cleaner one!**



**$^{110\text{m}}\text{Ag}$  has gone !**  
 Sensitivity:  $T_{1/2}^{0\nu} = 5.6 \times 10^{25}$  yr  
 Phase I+II Limits (90% C.L.):  
 $T_{1/2}^{0\nu} = 1.07 \times 10^{26}$  yr  
 $\langle m_{\beta\beta} \rangle < (61-165) \text{ meV}$

# KamLAND-Zen 800

Aug.2016



Welding line

Xe : 380kg =>750kg

Much cleaner balloon !

2015-2016: the new balloon was made.

Deployed into KamLAND in Aug.2016.

3 times less Bi→Po (U/Th) on the balloon !

Leaks were found and we collected the balloon

Class-1 super-clean room in Tohoku U.



Film washing device



film cutting



New welding machine

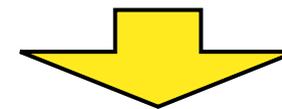


Gore welding underway.

Welding methods are improved by careful studies !

Start balloon making in May. Efficient film washing and a new welding machine. Established cleanliness control.

Balloon deployment in this autumn !



$\langle m_{\beta\beta} \rangle < 0.04-0.08 \text{ eV}$

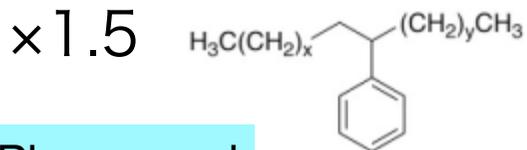
# KamLAND2-Zen

More photons ( $\times 5.5$ )  
and  $^{214}\text{Bi}$  rejection

$> 1\text{ ton Xe}$ ,  $2\nu\beta\beta$  rejection by  
improving  $\Delta E/E$  to 2% @  $Q_{\beta\beta}$ !

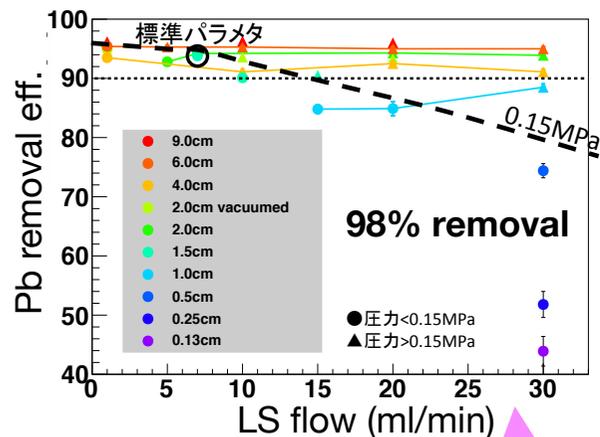
$\Rightarrow$  Full coverage of IH region,  
 $\langle m_{\beta\beta} \rangle \sim 0.02\text{eV}$ .

## LAB based LS

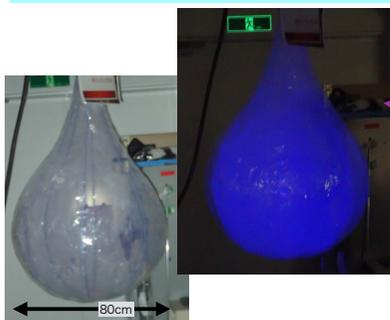


### $^{210}\text{Pb}$ removal

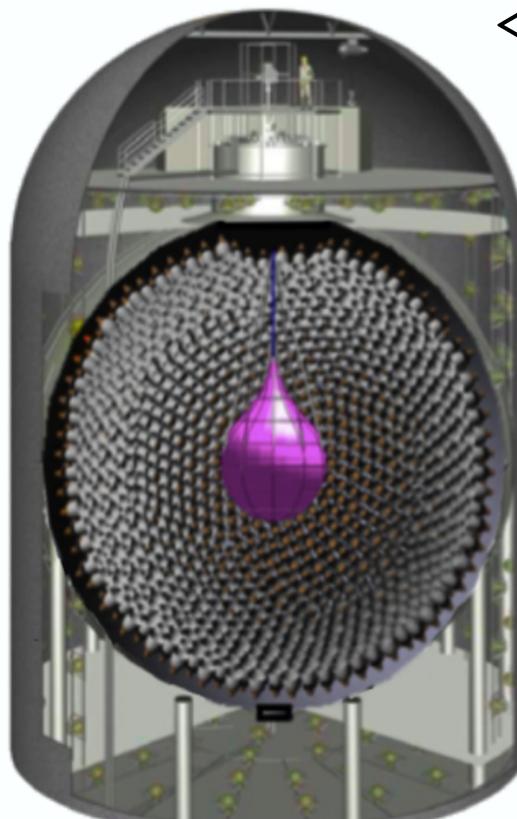
Metal scavenger (R-Cat-Sil AP)



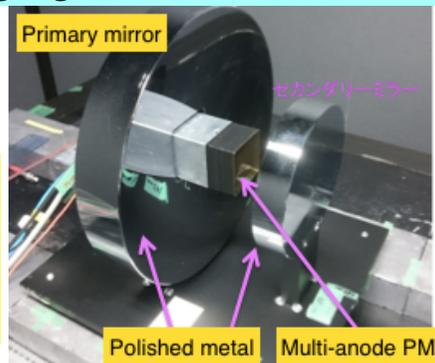
### Scintillating balloon



Improve  $^{214}\text{Bi}$  tagging on the balloon



Imaging device for  $\beta \Leftrightarrow \gamma$



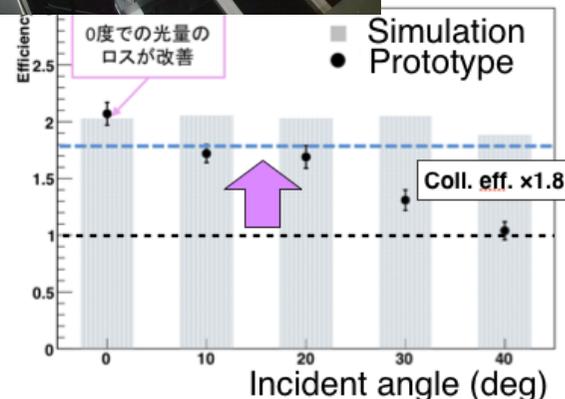
## HQE 20" PMT

$\times 2.1$



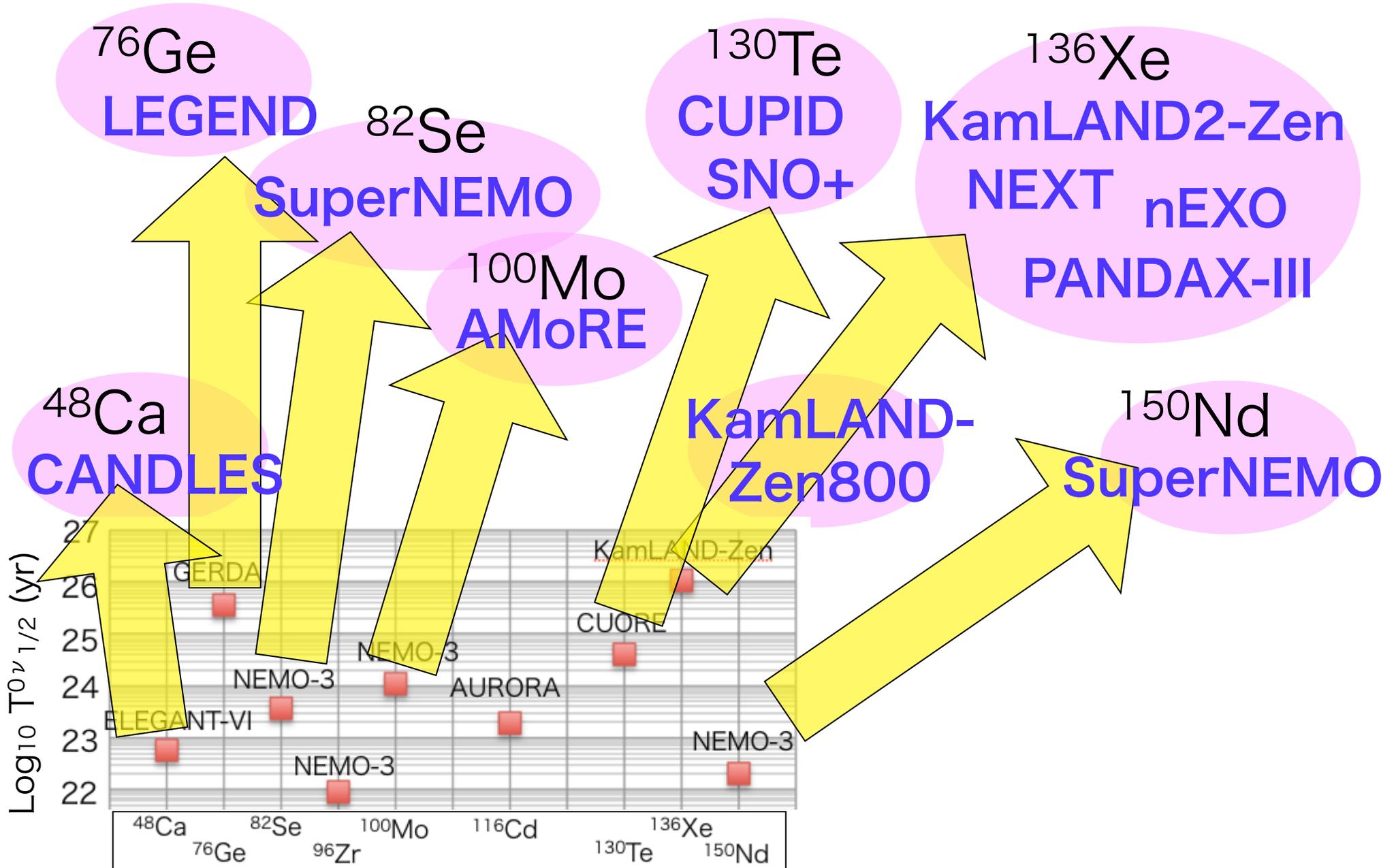
## Light cone

$\times 1.8$



Many projects  
 O(1)ton, Low BG,  $\Delta E$

$T_{1/2} \Rightarrow 10^{27} \sim 10^{28} \text{yr}$   
 $\langle m_{\beta\beta} \rangle \Rightarrow 0.02 \sim 0.05 \text{eV}$

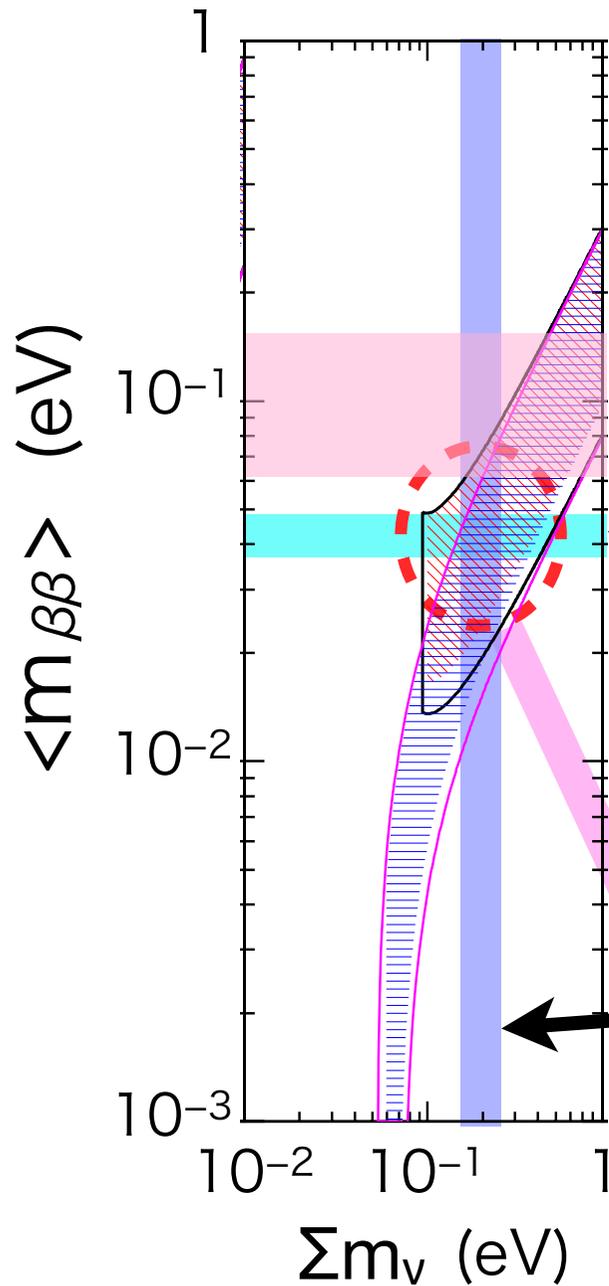


# Prospect

## $0\nu\beta\beta$ searches

KL2-Zen, LEGEND, CUPID,  
PANDAX-III, nEXO, SNO+,  
SuperNemo, NEXT, AMoRE, ...

*IH region*



$\langle m_{\beta\beta} \rangle$  can be in the  
“IH-region”, suggested  
by theoretical models.

Constraint on  $\Sigma m_\nu$  from cosmological  
observation (CMB, BAO, etc) :  
 $< O(100)\text{meV}$

Accelerator/Atmospheric  $\nu$   
experiments (NH ? not fixed)

**“ Big SURPRISE ” may happen !**

# Summary

- Majorana nature of neutrinos is a key to understand the fundamental problems not only in the particle physics but the origin of the Universe.
- $0\nu\beta\beta$  is the beyond-the-SM process and best feasible to test the Majorana nature of neutrinos.
- Challenges are made worldwide using various nuclei of O(100)kg to O(1)ton and cutting edge technologies aiming at the search in IH region.
- KamLAND-Zen with an unique strategy will start a new phase using 750kg enriched  $^{136}\text{Xe}$  this year.

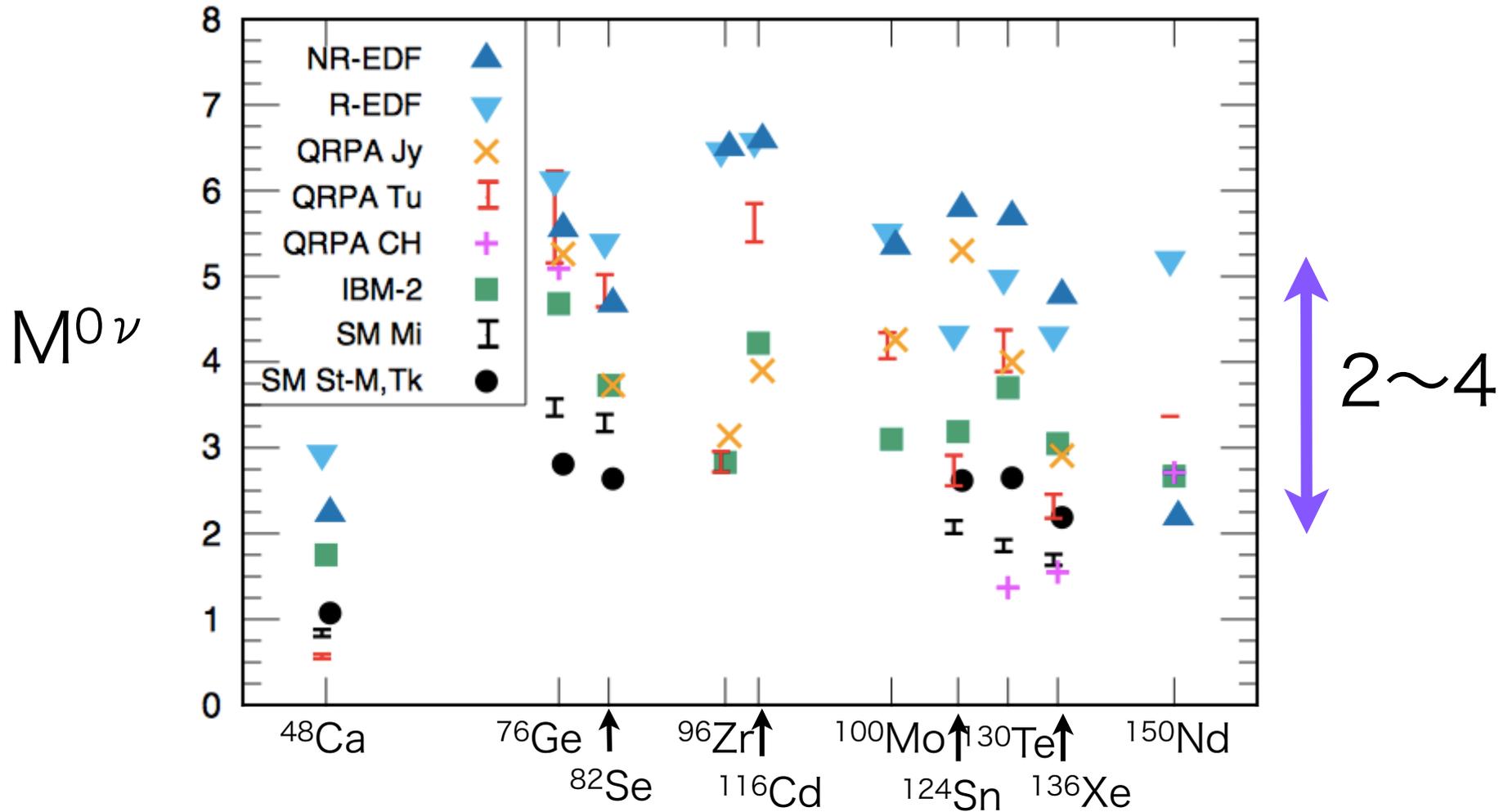
# Thank you !



appendix

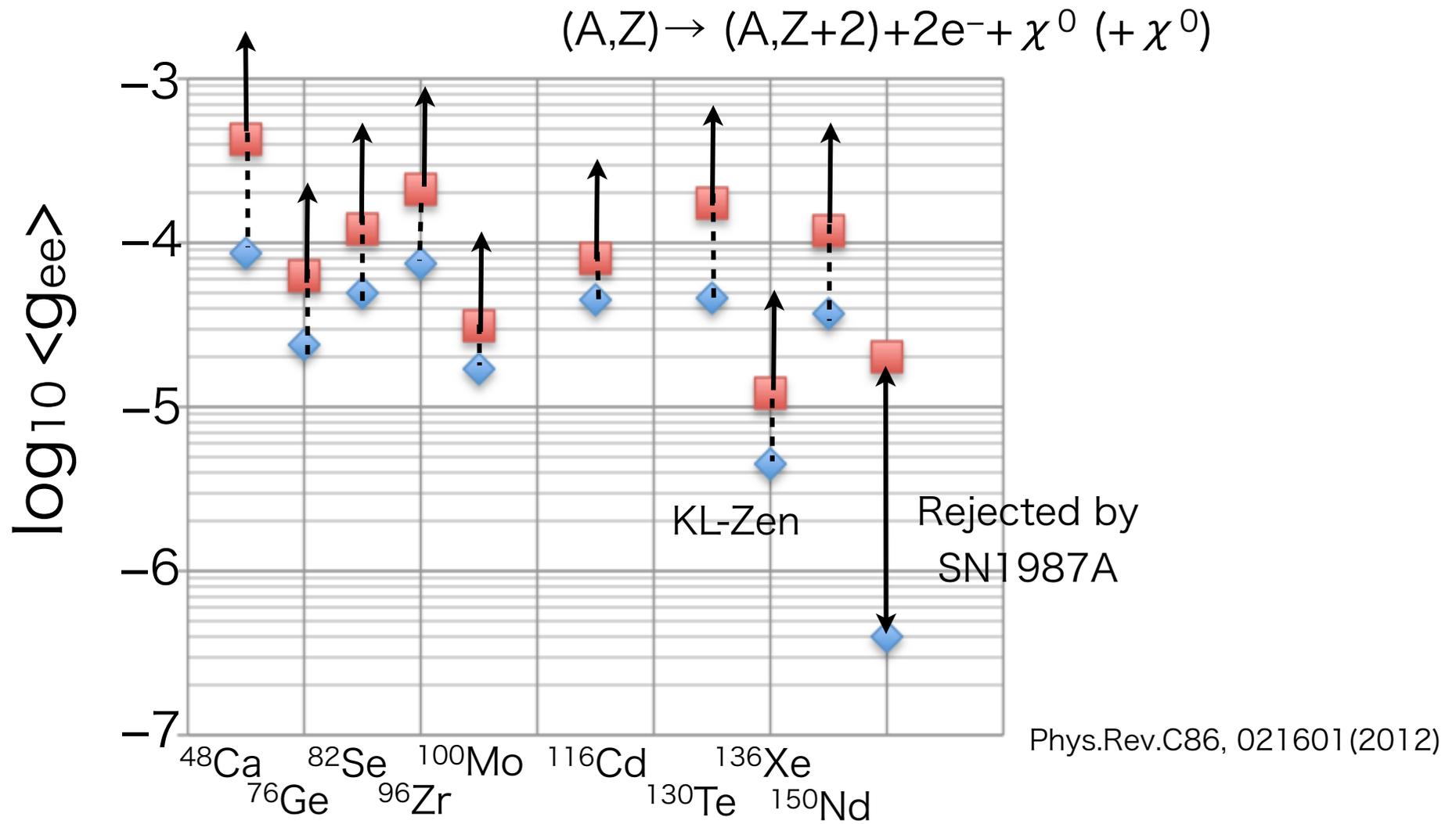
# Large uncertainty in $M^{0\nu}$

J.Engel, arXiv: 1610.06548



Improving the discovery potential is crucial.  
Experiments with different nuclei are necessary.

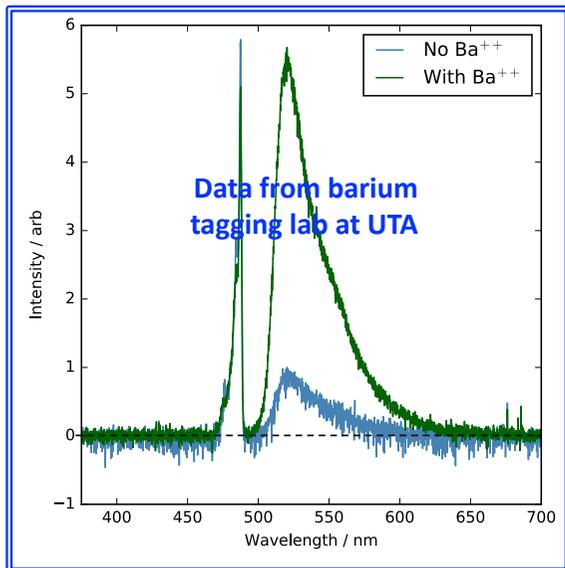
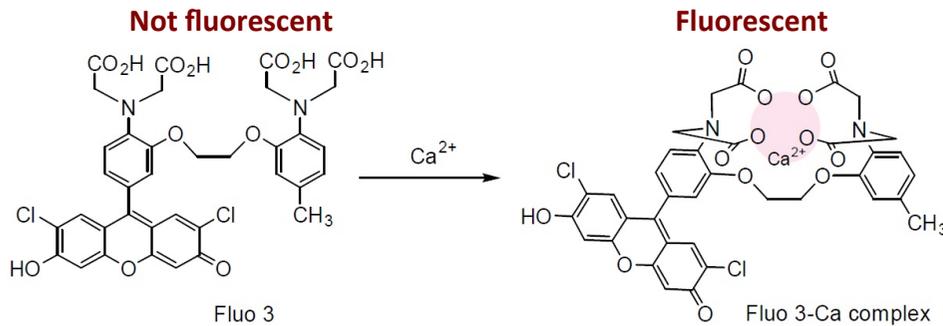
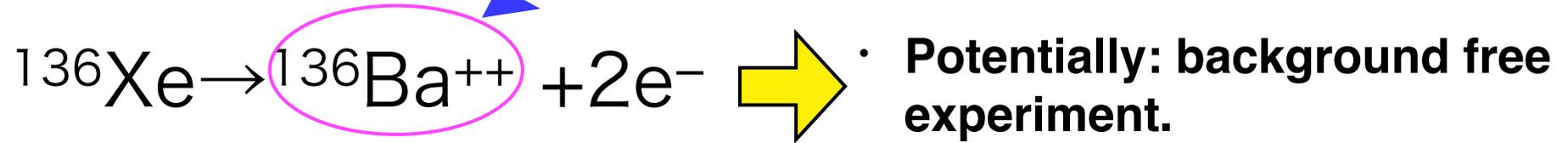
# Limits on effective Majoron-neutrino coupling constants, $\langle g_{ee} \rangle$



KamLAND provides a most stringent limit on the normal Majoron and excludes a small allowed gap.  
 SN1987 extends the limit down to  $10^{-7}$ .

# Ba tagging

J.J.Gomez-Cadenas



- Xe-136 decays produce Ba<sup>++</sup>
- Ba<sup>++</sup> will drift towards cathode (hopefully without recombining)
- Coat cathode with PSMA\* molecule, which will capture BA<sup>++</sup>
- PSMA + BA<sup>++</sup> will fluoresce when illuminated with 342 nm light (broad band, 360-430... can design a system to detect blue light. Interrogation rate at ~100 kHz.
- This idea is a new form of Ba-tagging in gas which does not involve extracting the Ba<sup>++</sup> ion to vacuum.

\* Prostate-specific membrane antigen