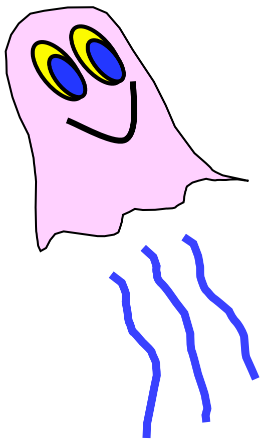
Neutrino Physics

Neutrinoless Double Beta Decay

$0\nu\beta\beta$



Junpei Shirai

Research Center for Neutrino Science,

Tohoku University

PANIC, Sep.1, 2017, Beijing, China

Contents

Neutrinos : Finite Masses, but still mysterious !

ν_e	ν_μ	ν_τ
e	μ	τ

$m_\nu \ll m_{q,\ell}$

Absolute val. of m_νs

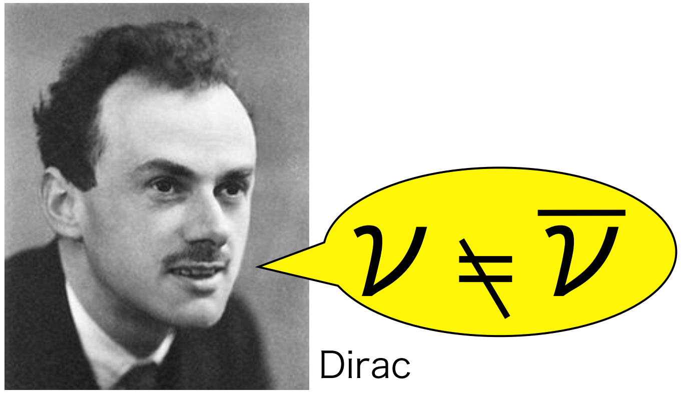
$\nu \neq \bar{\nu}$? or $\nu = \bar{\nu}$?

θ_{12} , θ_{23} , θ_{13}

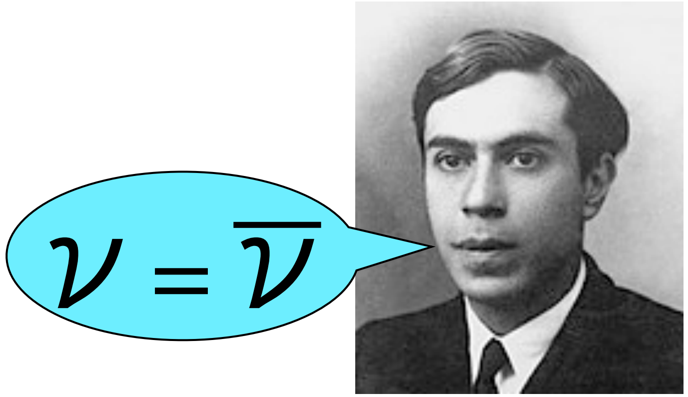
Δm^2_{21}, Δm^2_{32} ,

δ_{CP}, $\Delta m^2_{31} \gtrless 0$?

Origin of the mass.
Fundamental
problem !



Dirac



Majorana

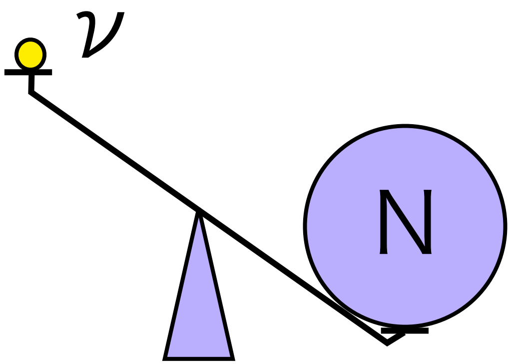
Dirac Mass term

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

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

Majorana Mass term

two mass eigenstates

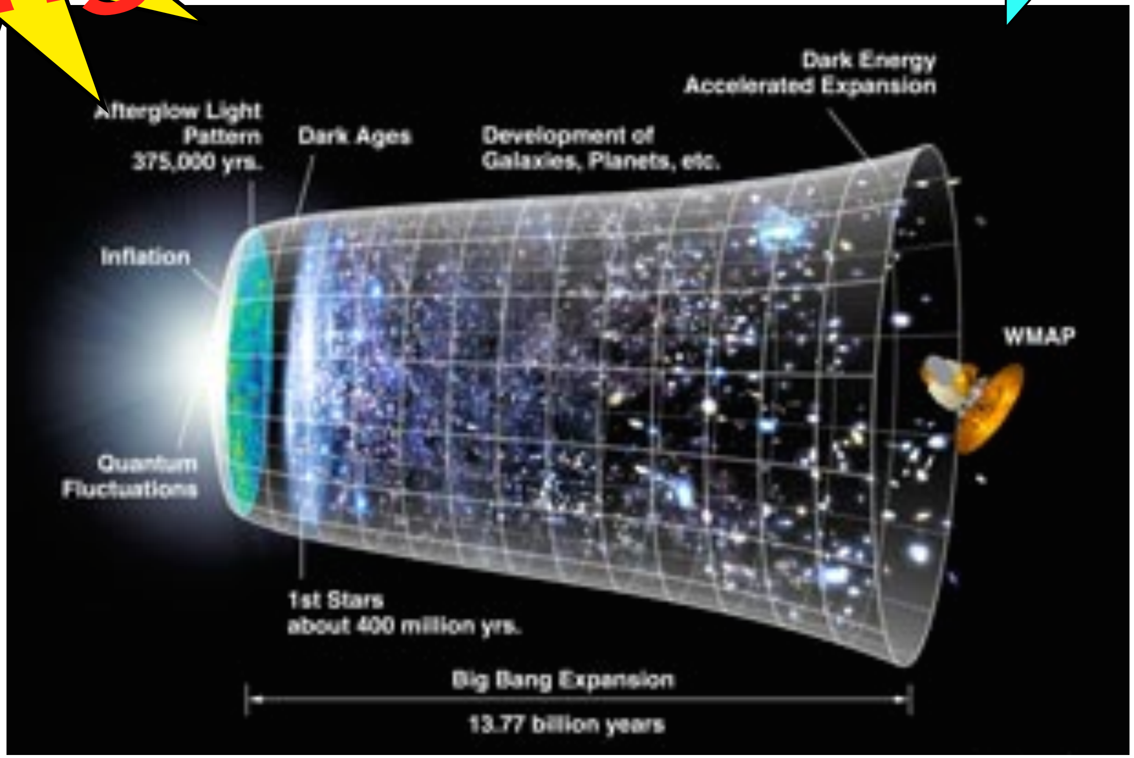


See-saw mechanism

$$m_\nu = \frac{M_{q,\ell}^2}{M_N} \ll M_{q,\ell}$$

N: Important roles in the early Universe !

Big bang → Matter dominance world



Sakharov's conditions

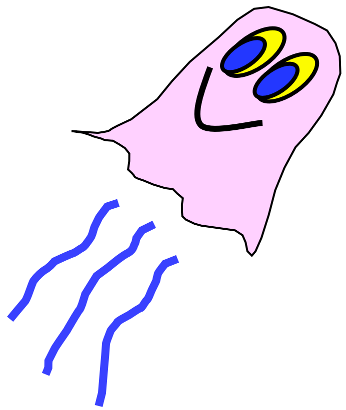
Super-heavy Majorana ν

$\Delta L \neq 0 \Rightarrow \Delta(B-L)=0 \Rightarrow \Delta B \neq 0$

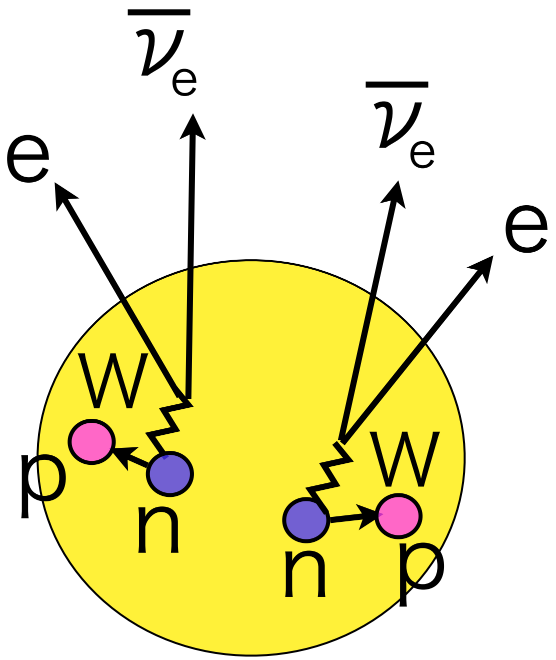
(Leptogenesis)

Majorana nature of ν is very important and should be checked !

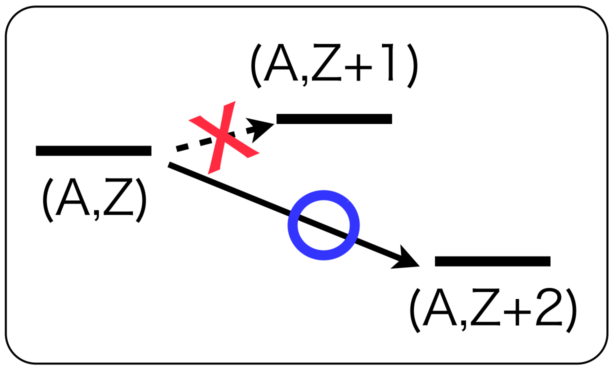
Nuclear $\beta\beta$ decay provides the most feasible and sensitive way to study the Majorana nature of neutrinos !



$2\nu\beta\beta$



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

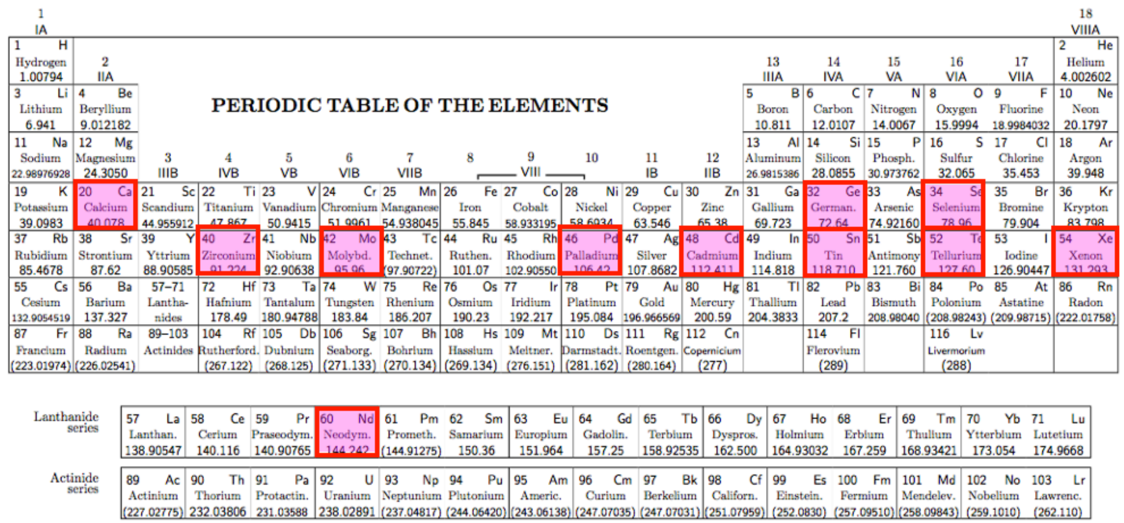


SM process, but very rare!

$T^{0\nu}_{1/2} \sim 10^{19}\text{–}10^{21}\,\text{yr}$

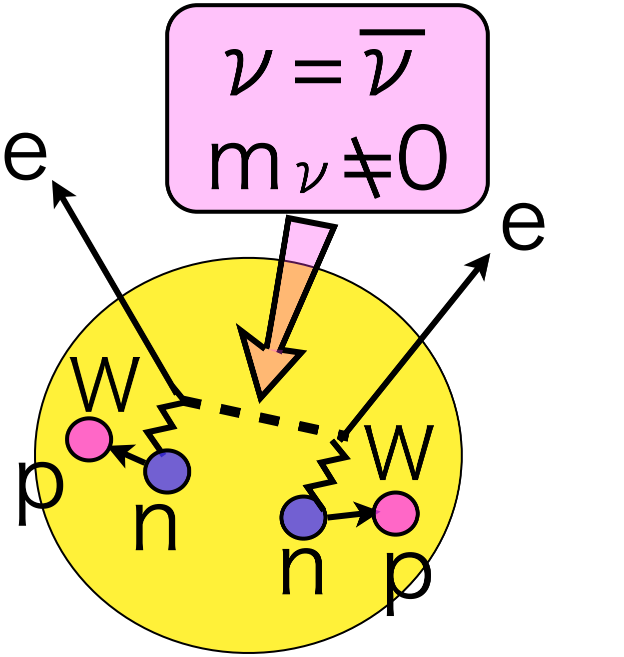
There are ~35 natural isotopes which can double-beta decay.

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

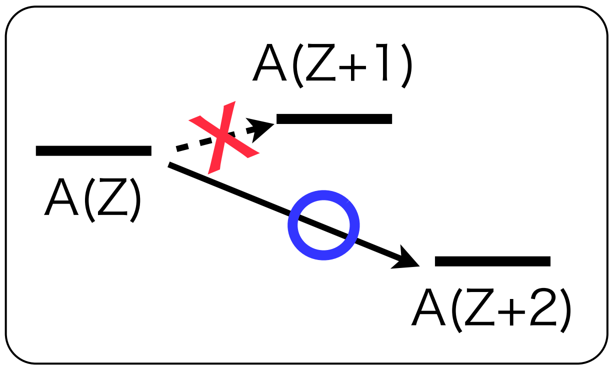


$Q_{\beta\beta}$>2MeV

$0\nu\beta\beta$



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



Beyond the SM process

Total lepton number violation.

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

Light Majorana ν exch. is considered as the dominant process.

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

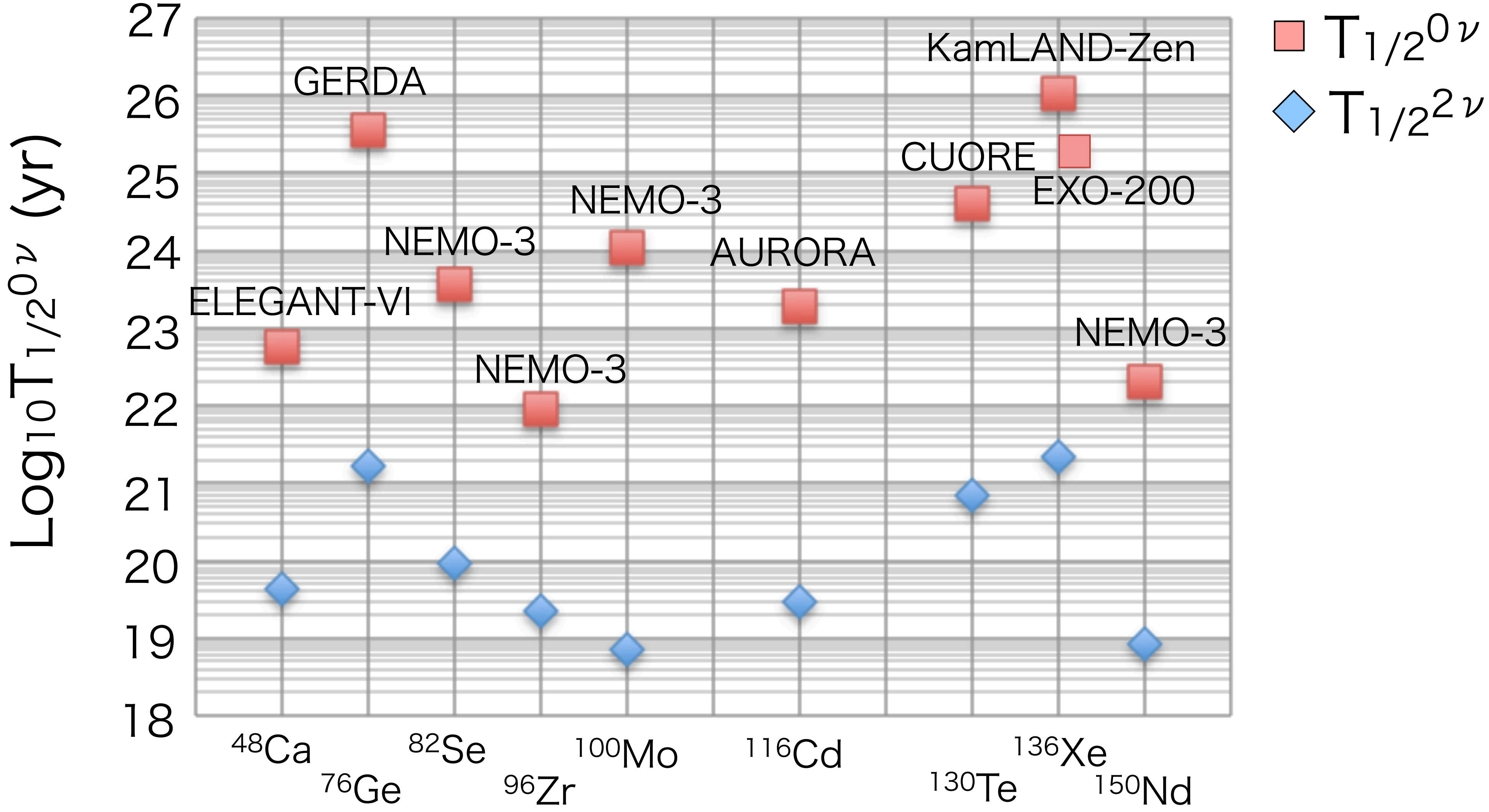
↑ Phase space factor ↑ Nuclear matrix element ↑ Effective Majorana neutrino mass

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

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

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

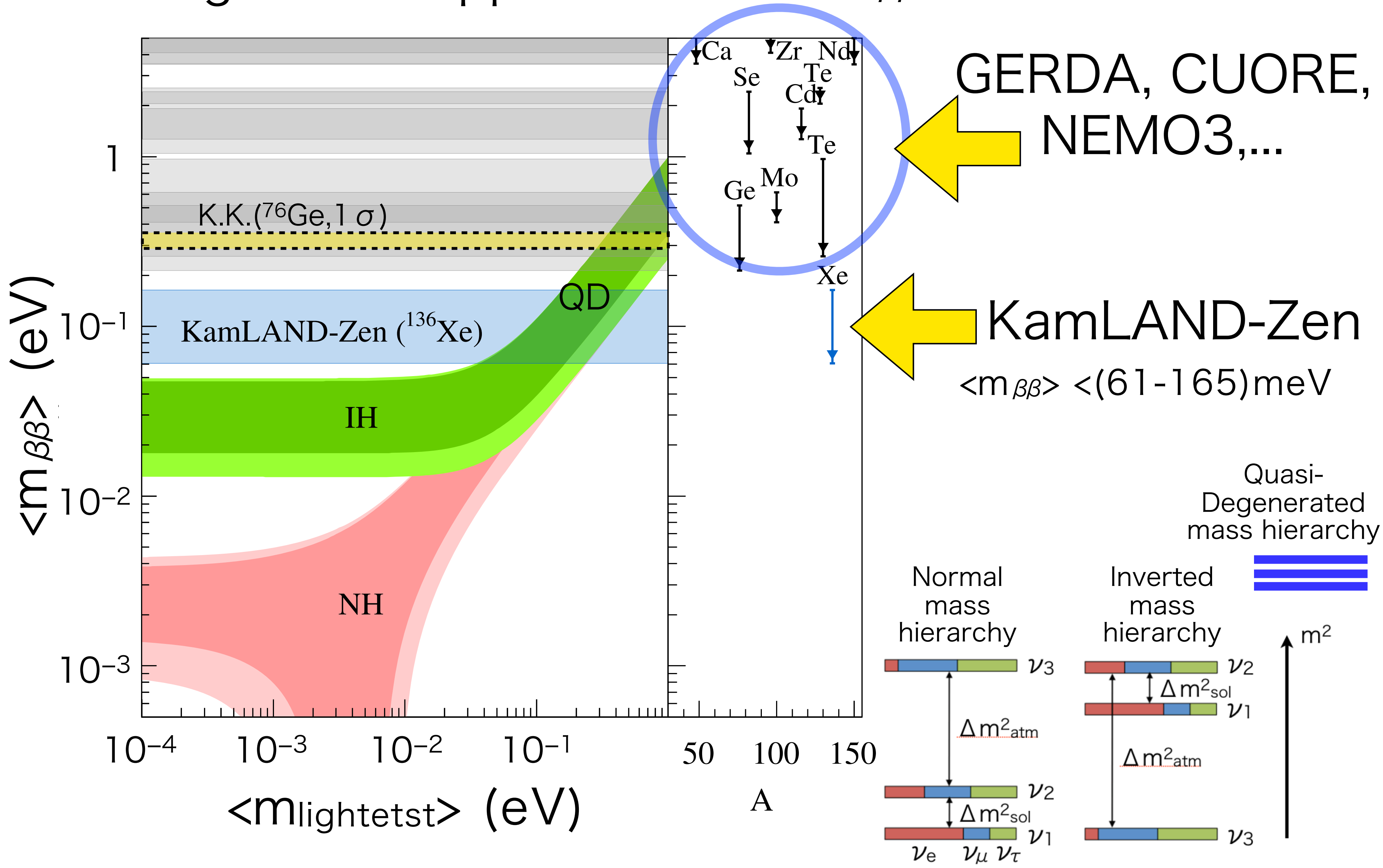
$T_{1/2}^{0\nu}$ lower limits (90%C.L.) and $T_{1/2}^{2\nu}$



There are many ongoing and planned experiments !

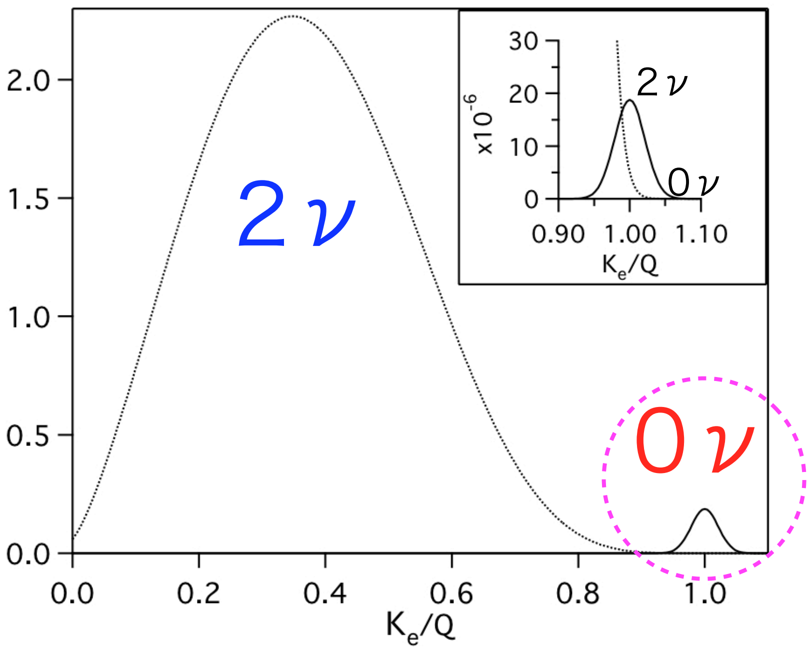
Most sensitive experiments have provided $T_{1/2}^{0\nu}$ > 10^25~10^26 yr.

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}Ge was refuted (KL-Zen and GERDA).



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

FOM for the sensitivity

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

- ε: detection efficiency
- a: Isotopic abundance/ enrichment factor
- M: Isotope mass
- T: Data taking period
- b: Background index ($keV^{-1}kg^{-1}yr^{-1}$)
- ΔE: Region of interest ~Energy resolution

Large amount of isotope

Remove BG (Ext./Int.)

Good energy resolution

Isotope selection by large a, $Q_{\beta\beta}$ and long $T_{1/2}^{2\nu}$

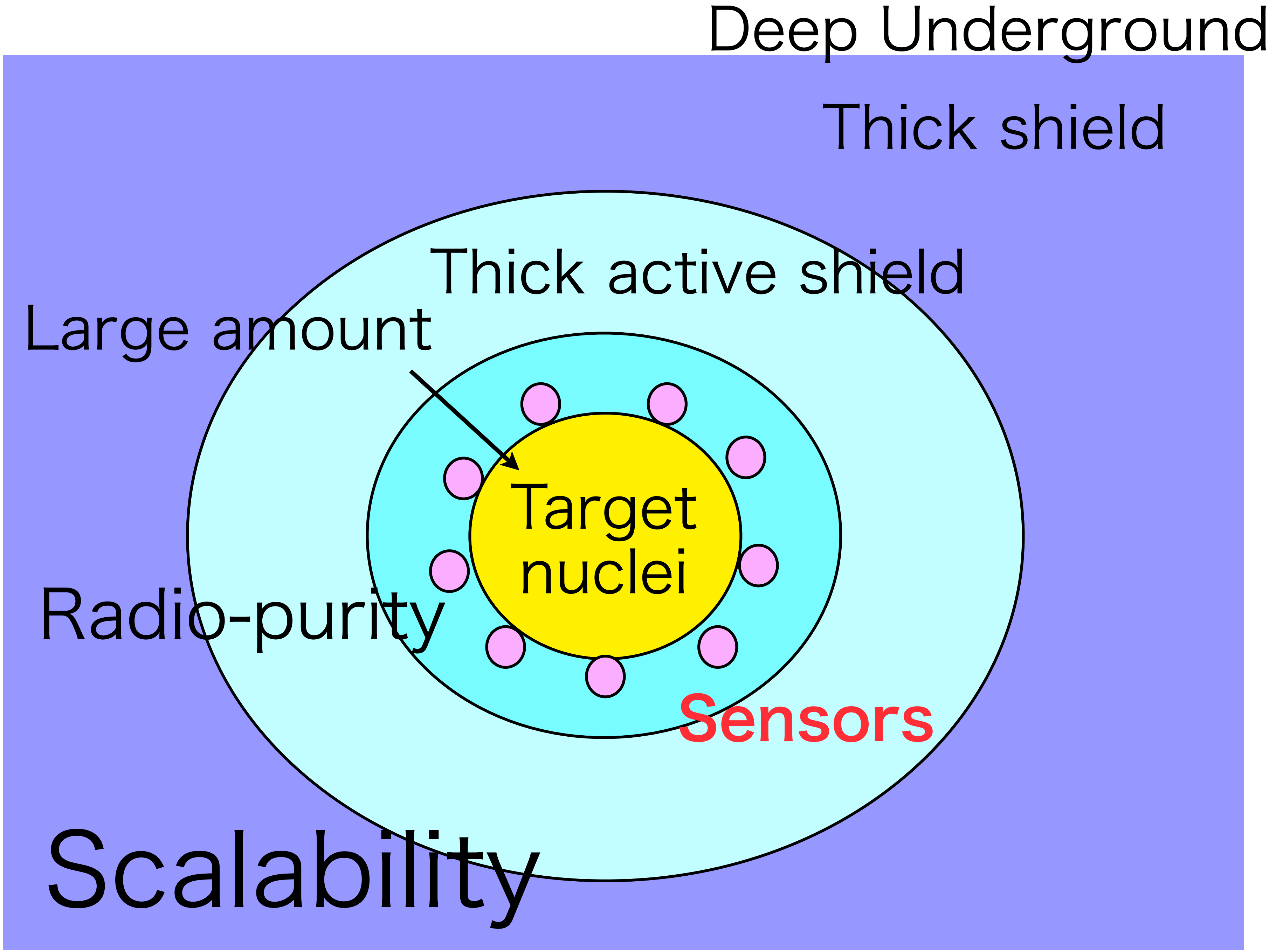
Current 10^{25}~10^{26} yr

Planned ~10^{27} yr

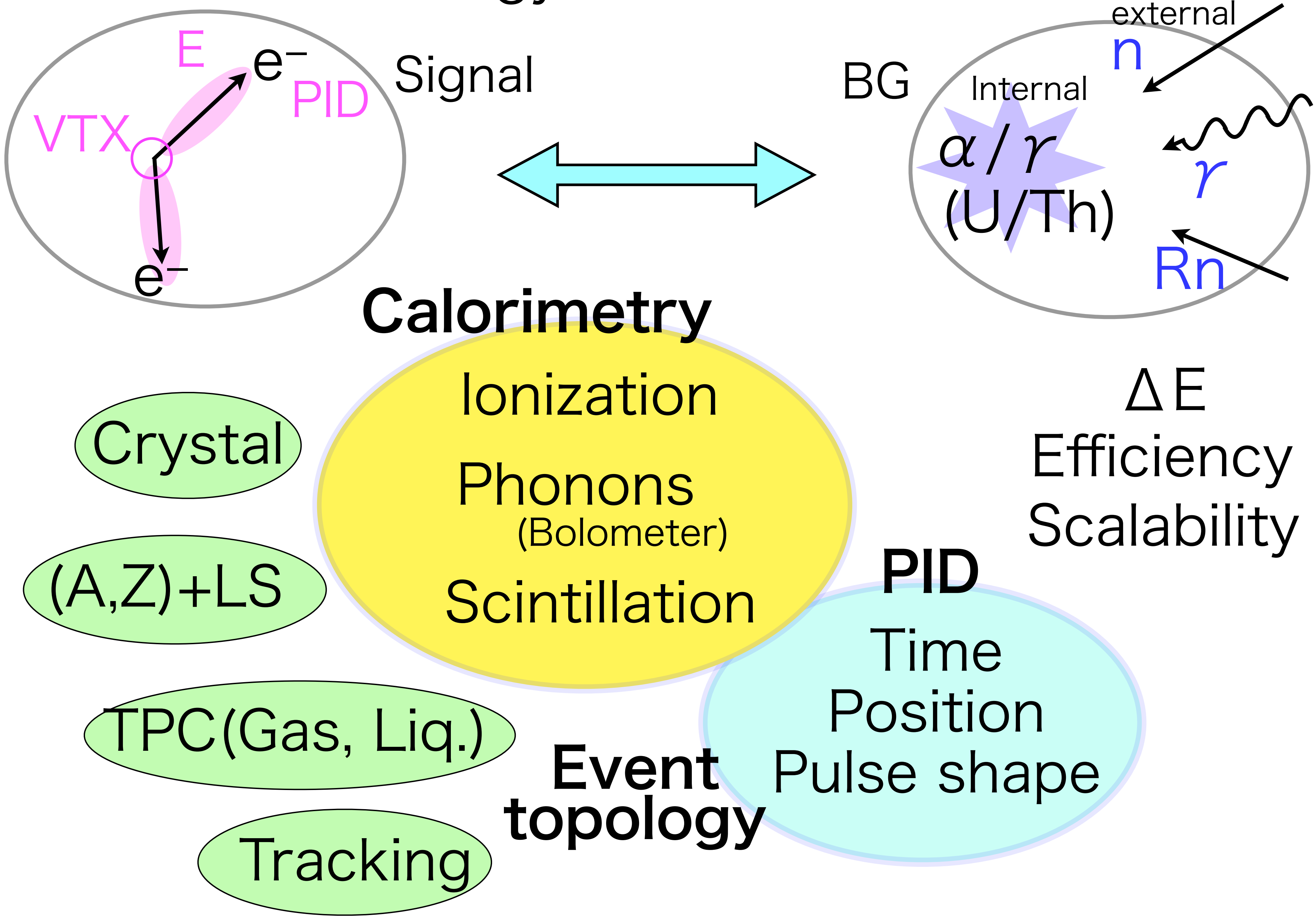
O(100)kg => O(1) ton

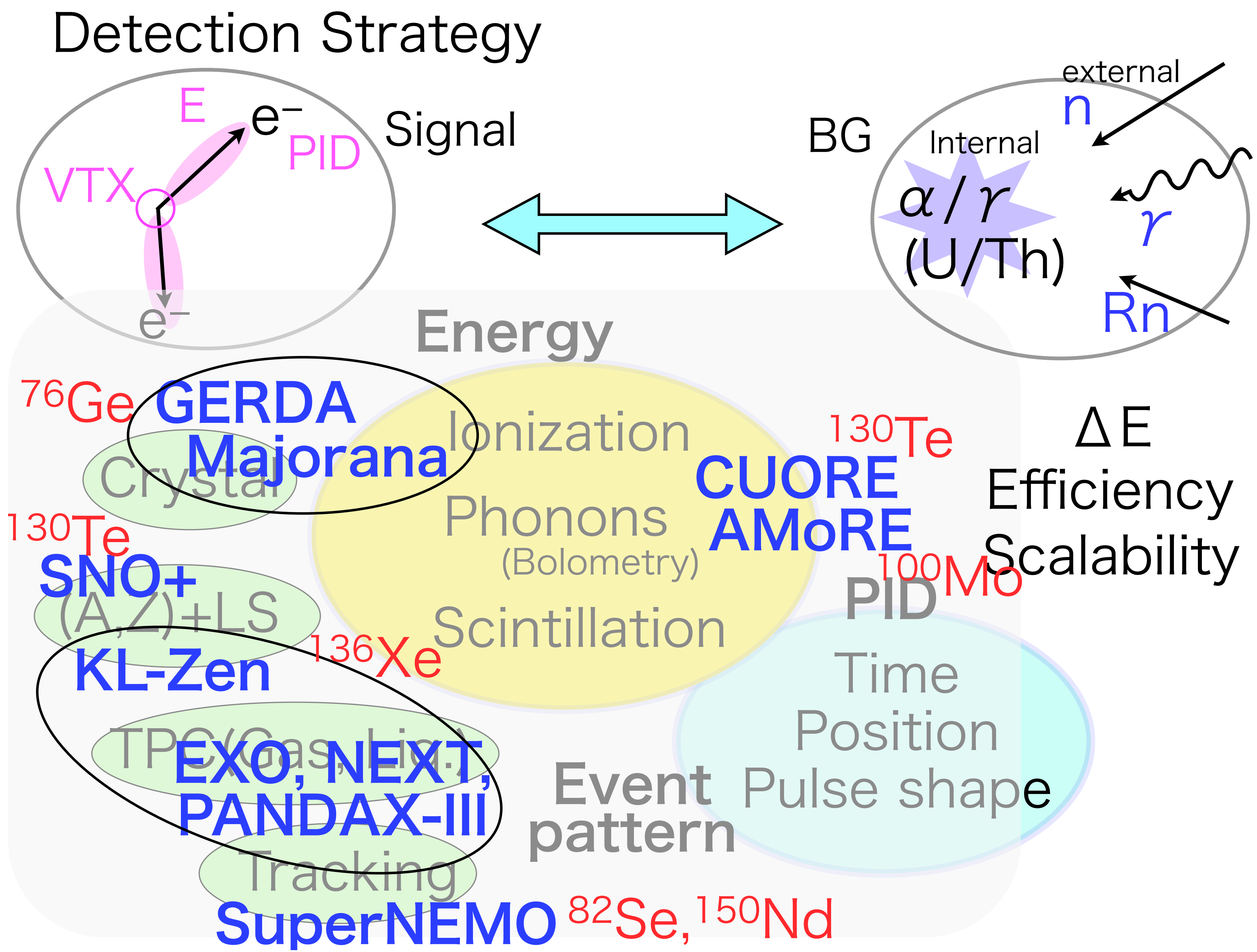
$\langle m_{\beta\beta} \rangle \sim 0.02$eV (IH)

Concept of the experiment



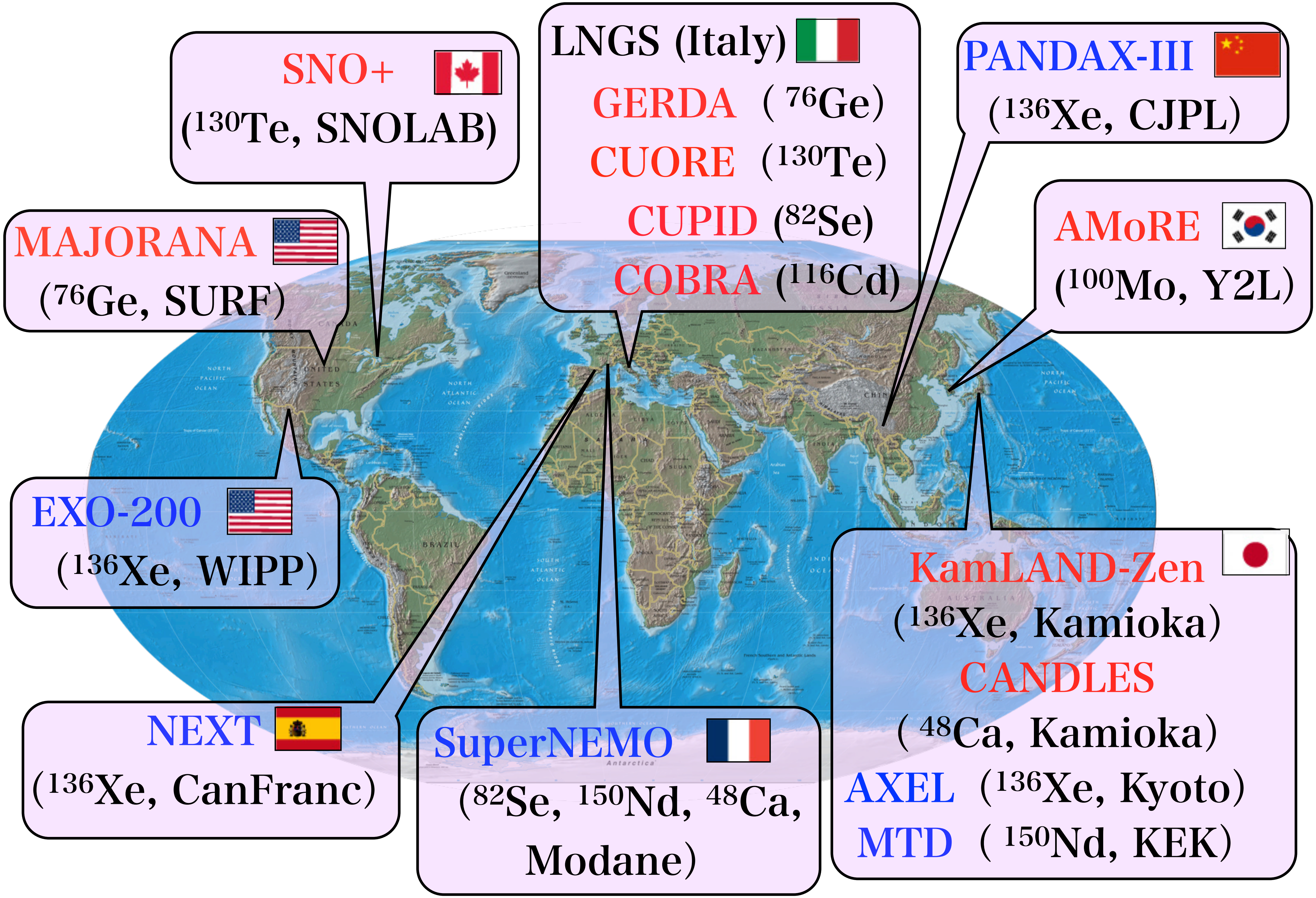
Detection Strategy





Detection Strategy
E
e−
PID
VTX
e−
Signal
BG
external
n
Internal
α / γ
(U/Th)
γ
Rn
Energy
76Ge
GERDA
Majorana
Crystal
Ionization
Phonons
(Bolometry)
Scintillation
130Te
CUORE
AMoRE
100Mo
ΔE
Efficiency
Scalability
130Te
SNO+
(A,Z)+LS
KL-Zen
136Xe
PID
Time
Position
Pulse shape
TPC(Gas, Liq.)
EXO, NEXT,
PANDAX-III
Event
pattern
Tracking
SuperNEMO
82Se, 150Nd

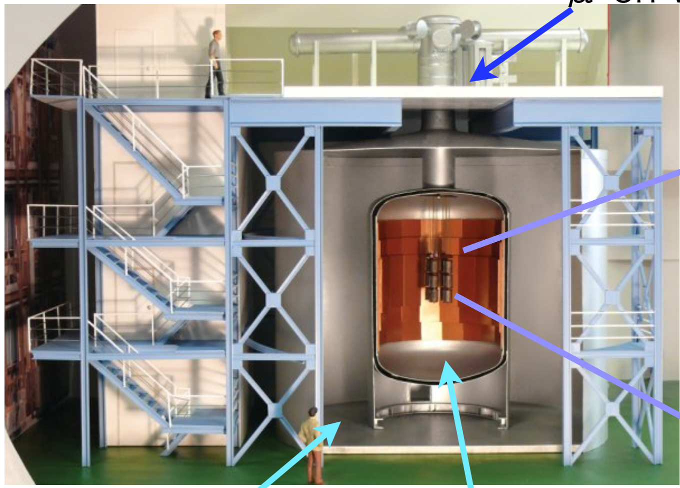
$0\nu\beta\beta$ activities in the world (Calorimetric, tracking/TPC)

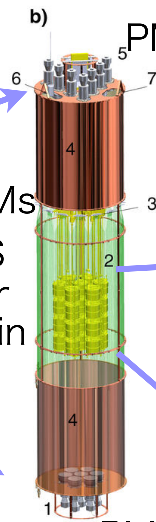


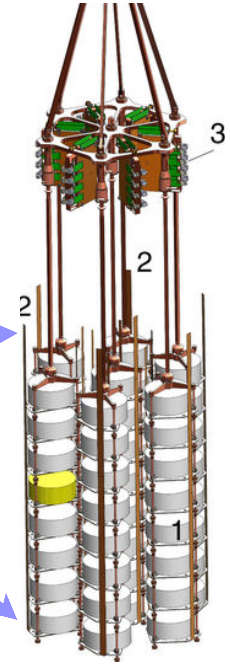
GERDA*

GERmanium Detector Array

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





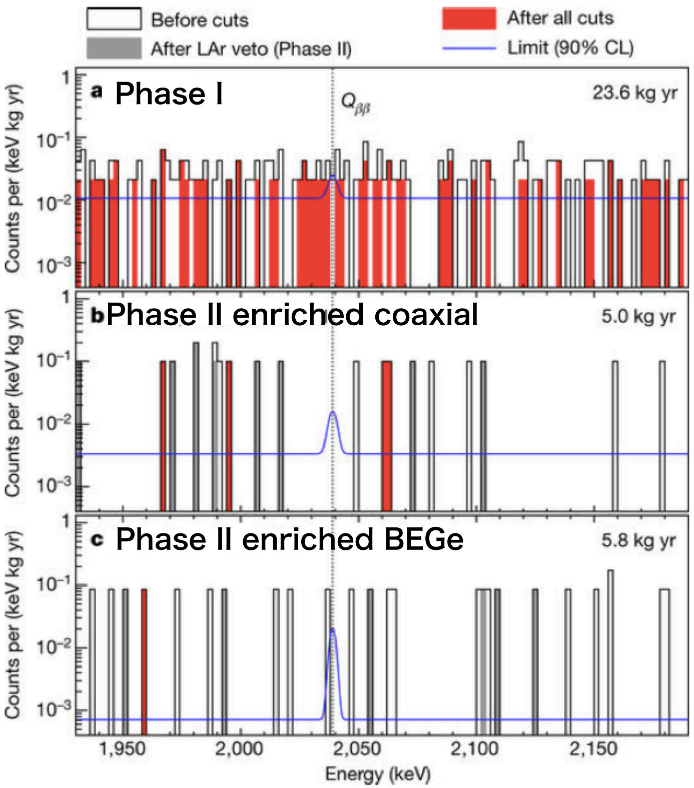


Achieved !

ΔE_{FWHM}=

2.8keV

@Q(BEGe)



LAr Veto, PSD Analysis

(^{42}K) (SS vs MS, A/E)

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

<m$_{\beta\beta}$> <(150-330)meV

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

No signal in ROI, BG free search !

Prospects

200kg Ge (Current Cryostat)

↓ $T^{0\nu}_{1/2}$ >10^27 yr (5yrs)

1000kg Ge (LEGEND)

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

<m$_{\beta\beta}$> <(10-20)meV

CUORE*

Cryogenic Underground Observatory for Rare Events

LNGS 3600m.w.e.
130Te Q: 2,528 keV
Nat.TeO_2 34.1%(^{130}Te)

CUORICINO

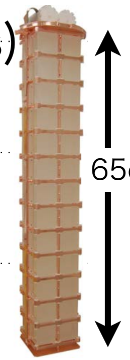
(2003-2008)

19.75kg yr (^{130}Te)

$T^{0\nu}_{1/2}$ > 2.8×10^{24}yr → CUORE-0 Combined > 4×10^{24}yr

CUORE-0

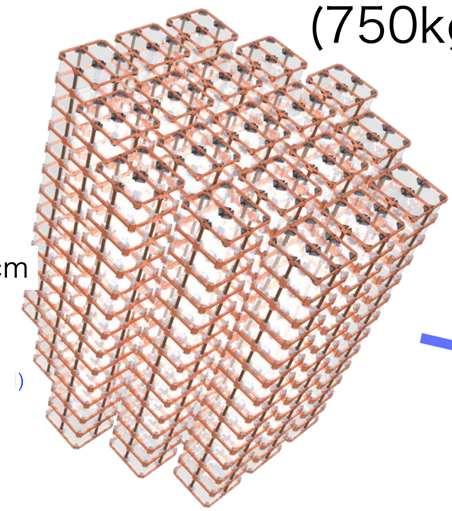
1 tower (4 crystals ×13piles)



9.8kg yr (^{130}Te)

CUORE

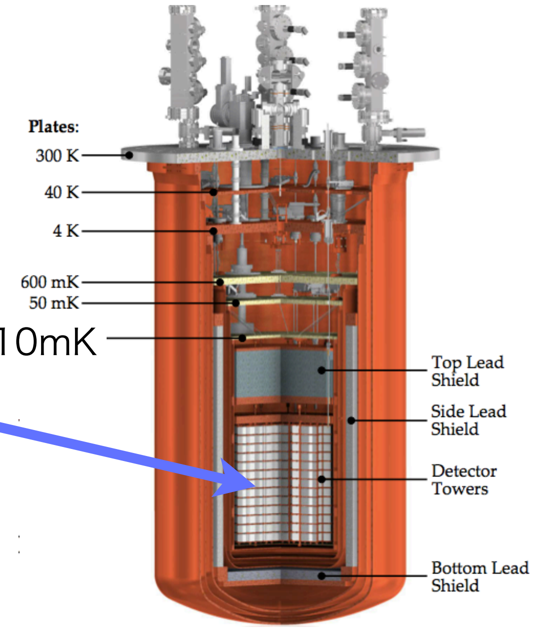
19 towers
988 TeO_2
(750kg)



206kg(^{130}Te)

0.01 $kg^{-1}keV^{-1}yr^{-1}$

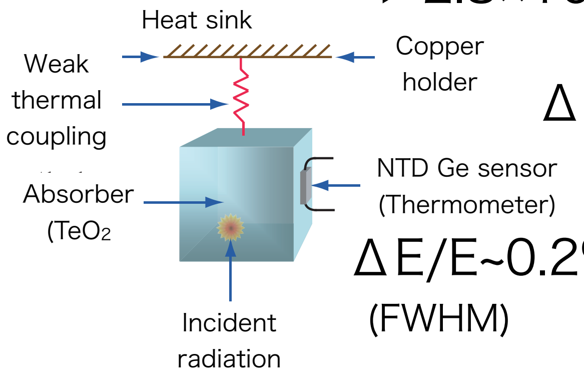
> 9×10^{25}yr (5 yr)



Jan.2017~: Cool down

April-June: Science run

$\Delta E=7.9\pm0.6$keV (FWHM)@2615keV



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

$C \propto T^3$

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

38.1kg yr (10.6kg ^{130}Te)

CUORE Combined

> 6.6×10^{24}yr

$\langle m_{\beta\beta}\rangle$ < (210-590)meV

CUPID

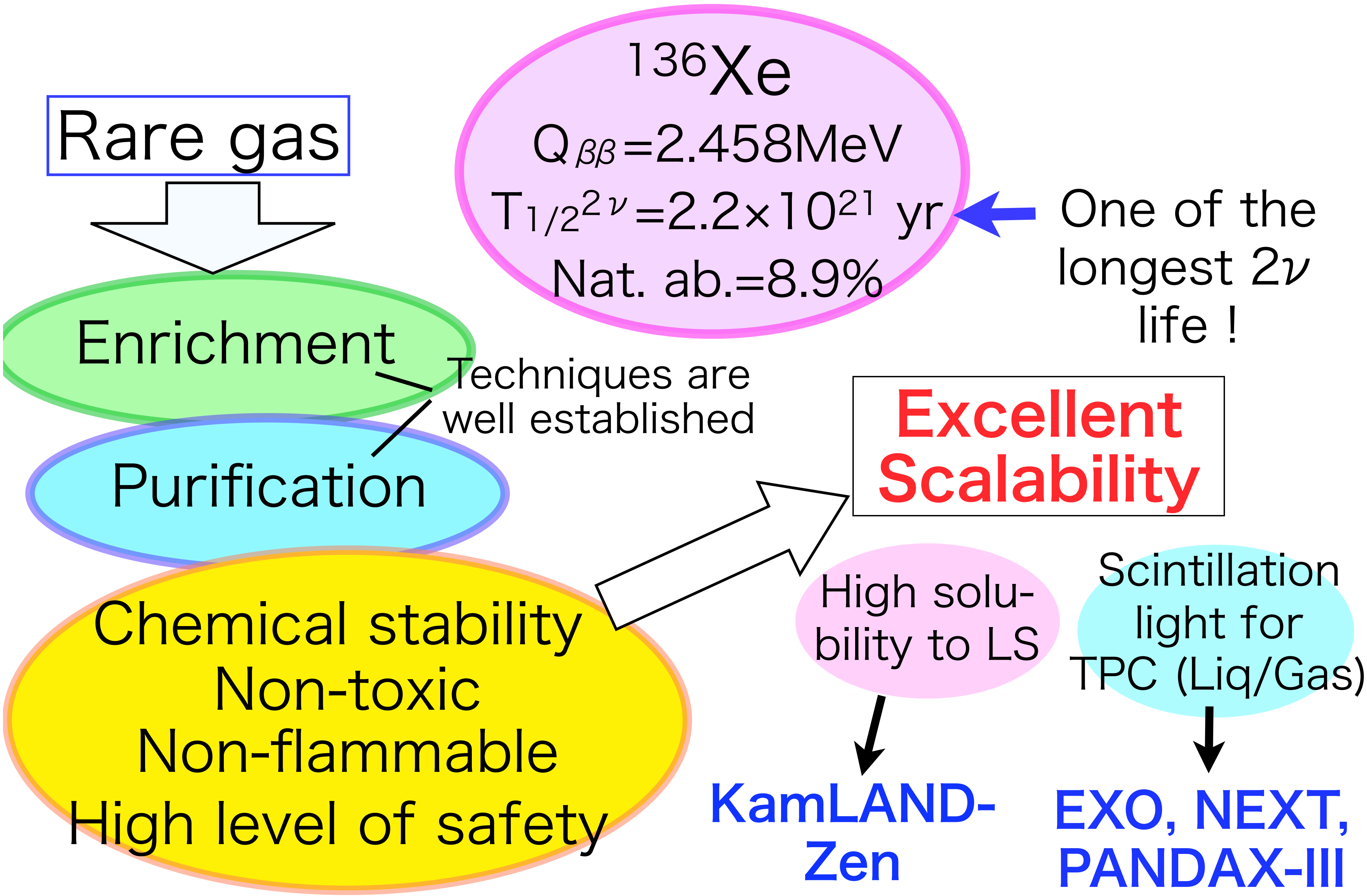
CUORE Upgrade with Particle ID

Challenging items

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

Validation of the background model in ROI (α, β/γ) will be established.

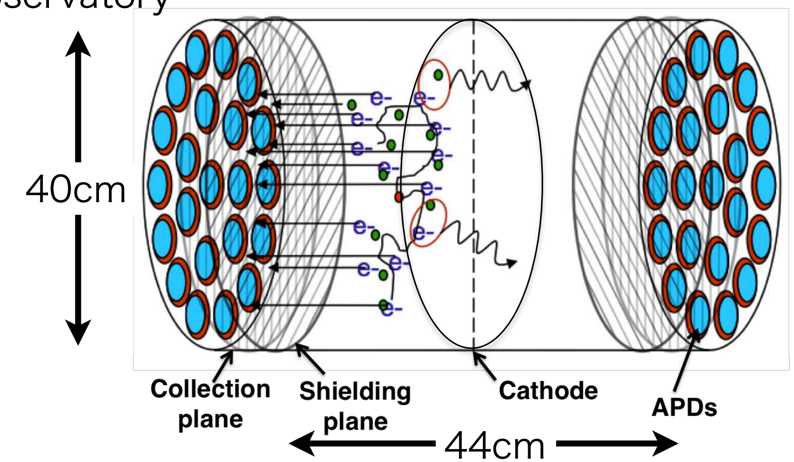
^{136}Xe has nice characteristics for $0\nu\beta\beta$ search !

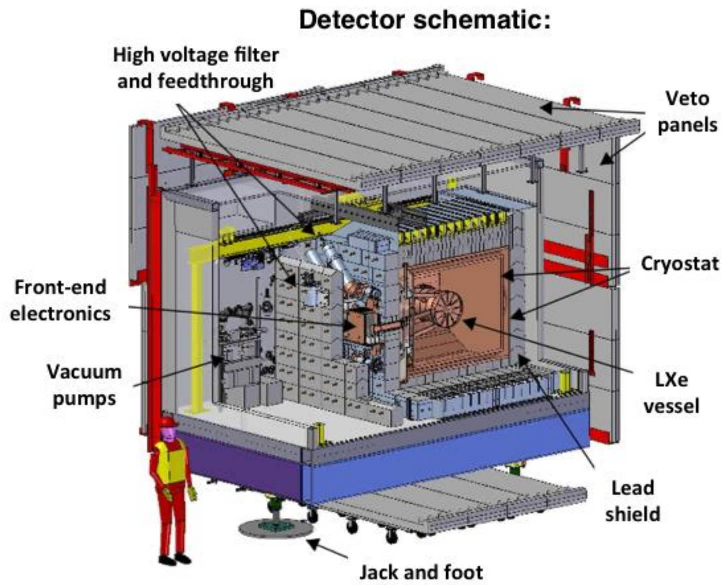


EXO-200

Enriched Xenon Observatory

WIPP (NM,USA) 1585 m.w.e.
136Xe Q: 2,458 keV
Liq.Xe TPC enrich:80.6%
$(1.5\pm0.2)\times10^{-3}$ $kg^{-1}keV^{-1}yr^{-1}$





Scintillation+Ionization

$\sigma/E=1.23\%$

SS vs. MS

Phase I (Sep.2011-Feb.2014) 122 kg yr

Phase II (Jan.-May, 2016) 55.6kg yr

Hardware upgrade

$T_{1/2}^{0\nu} > 1.8\times10^{25}$ yr

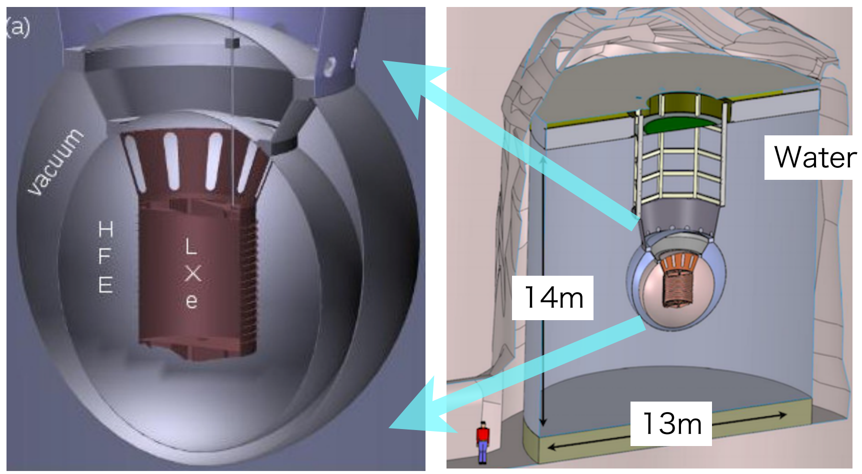
$<m_{\beta\beta}> < (147\text{-}398)$ meV

(90%C.L.)

nEXO 5ton enriched Liq.Xe TPC

planned installation at SNOLAB

Sensitivity: $T_{1/2}^{0\nu}\sim10^{28}$yr (with Ba-tag)

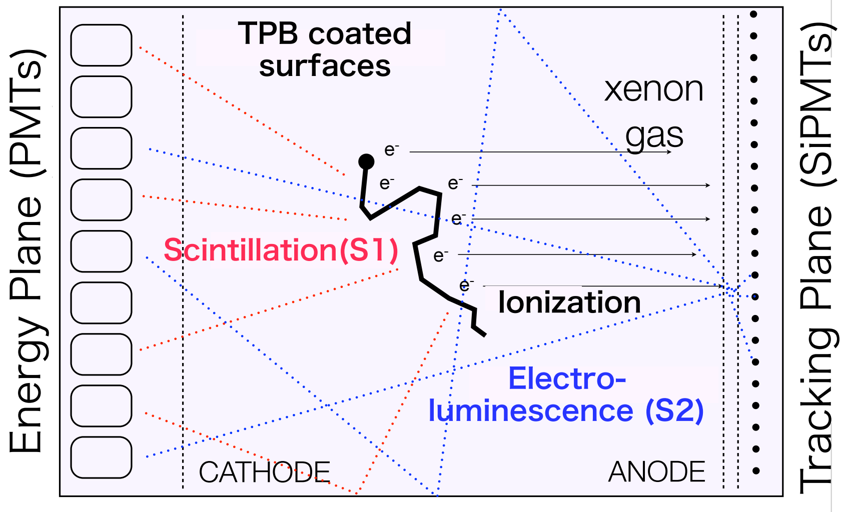


NEXT*

Neutrino Experiment with a Xenon TPC

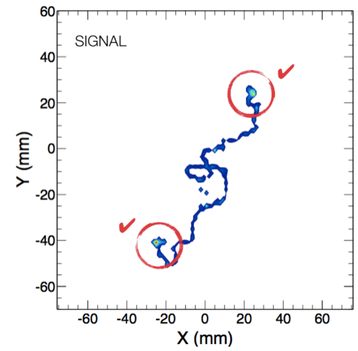
CanFranc 850 m.w.e.
136Xe Q: 2,458 keV
10-20bar TPC

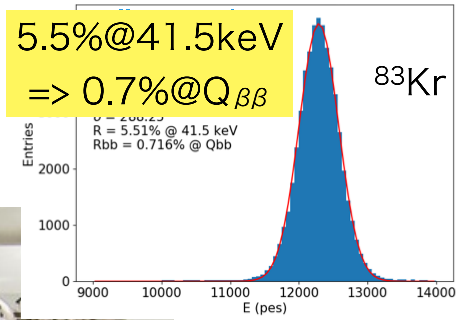
Detector concept



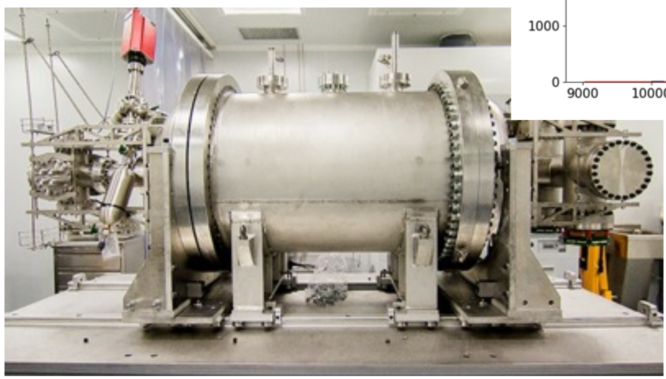
Electro-luminescence (EL) amplification
$\Delta E/E$~0.5% (FWHM)@$Q_{\beta\beta}$

Topological signature for BG suppression.



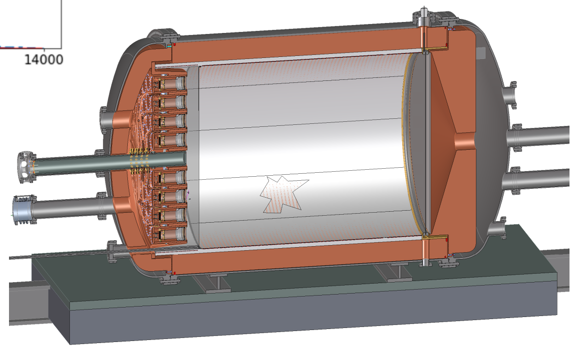


NEW (2015-2018)



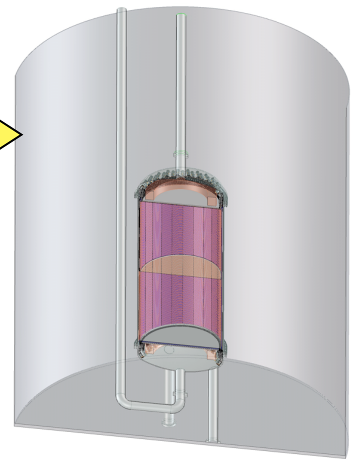
5~10kg Xe,
50cm drift, 20cm radius,
1792 SiPMs, 12PMTs

NEXT-100 (2019~)



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

NEXT-ton



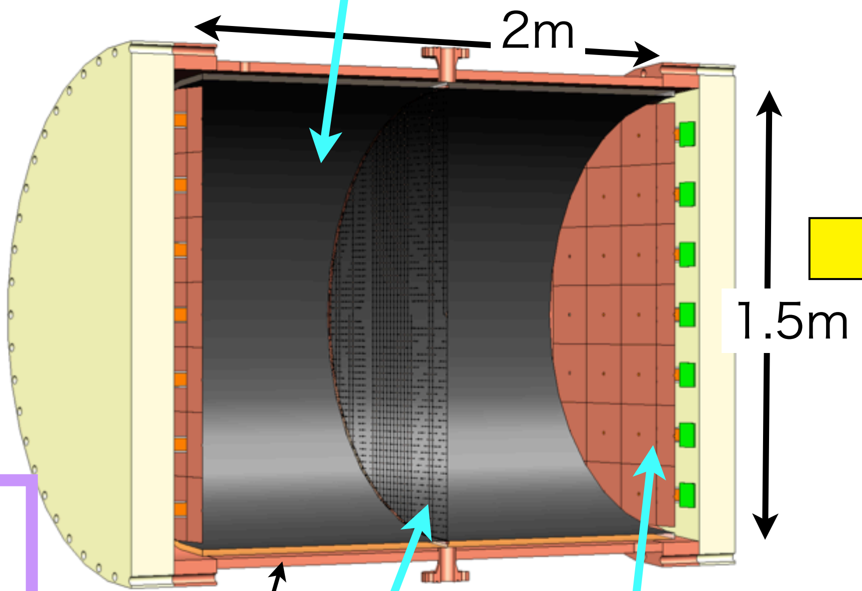
PANDAX-III*

Particle and Astrophysical Xenon Detector

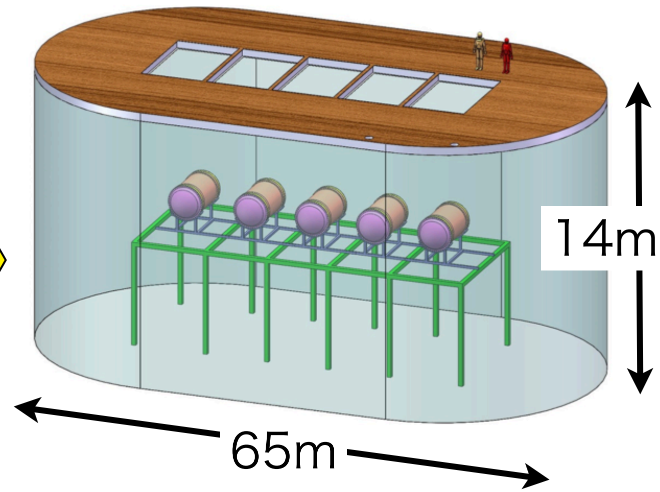
CJPL 6720 m.w.e.
136Xe Q: 2,458 keV
90% enrich.
TPC 200kg×5

World's deepest ! 0.2μ's/m^2/d Horizontal shaft !

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



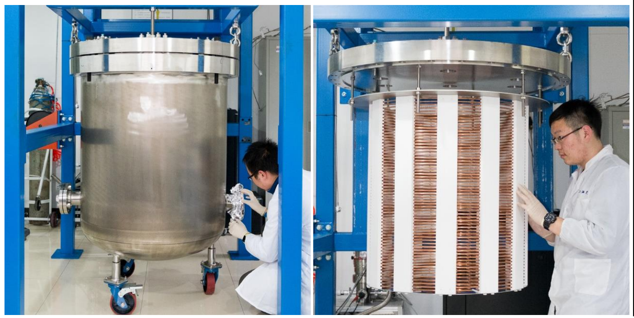
200kg×5 Xe TPC modules in a water pool, $\Delta E/E$~1%(FWHM) @$Q_{\beta\beta}$.



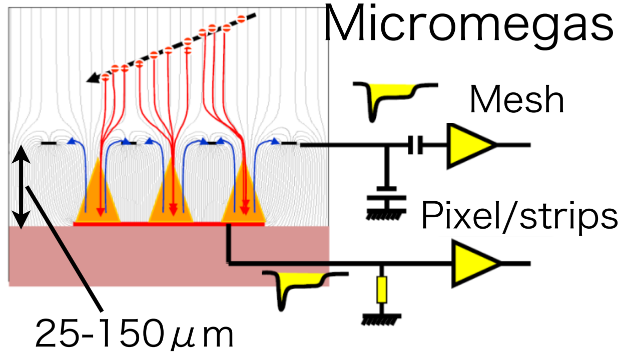
Water pool construction finished in Jun.2016.

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

Prototype (16kg Xe, 10 bar)



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

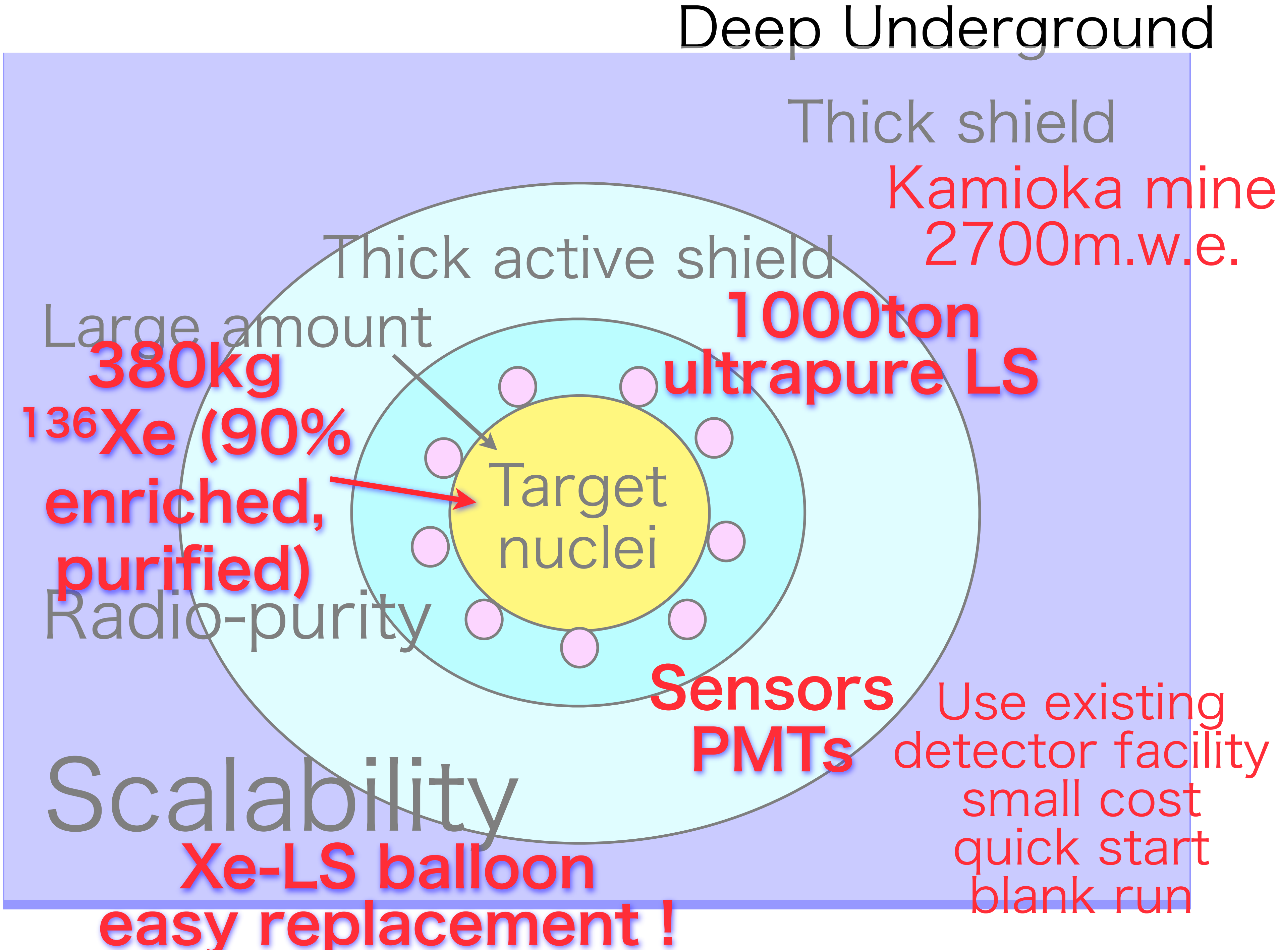


KamLAND-Zen

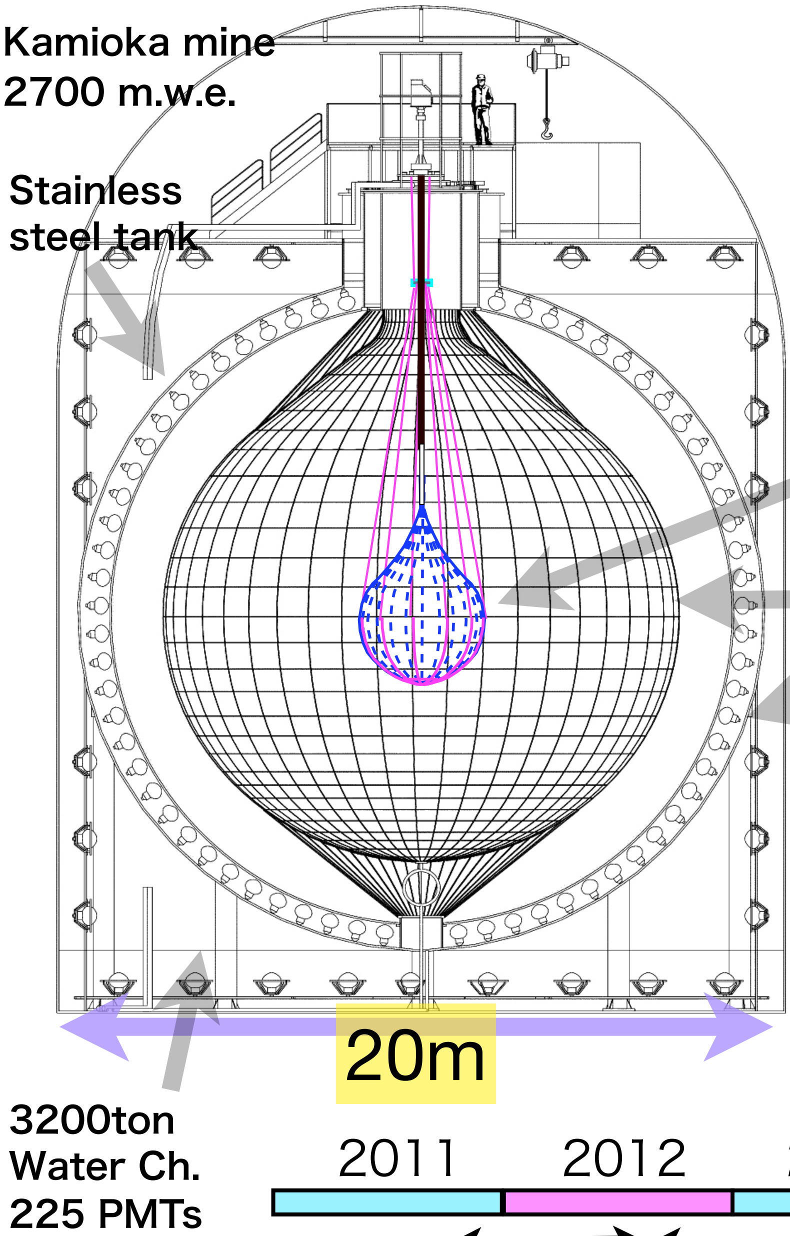
Zero-neutrino

double beta decay

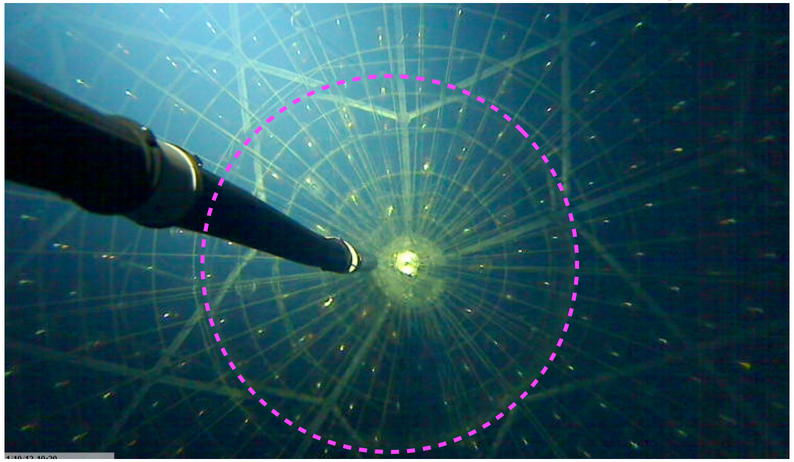
Concept of the KamLAND-Zen



KamLAND-Zen 400



Aug.2011

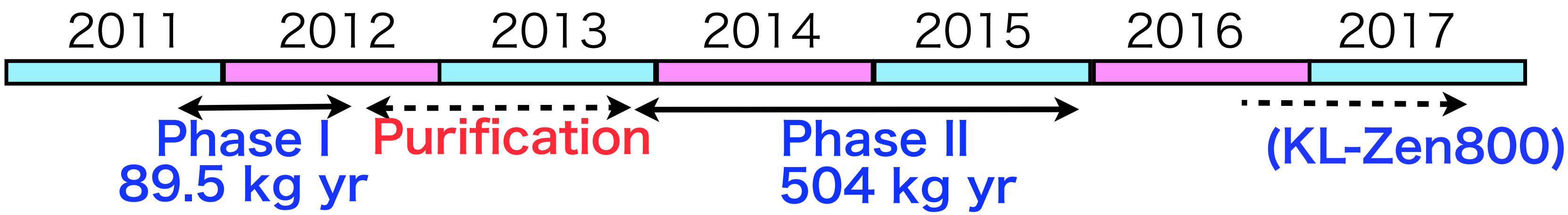


Mini-balloon (MIB, ~3mϕ) : Xe (320 ~ 380kg, 91% ^{136}Xe)+Decane-based LS

Main Balloon (13m ϕ,1000ton Ultra-pure LS)

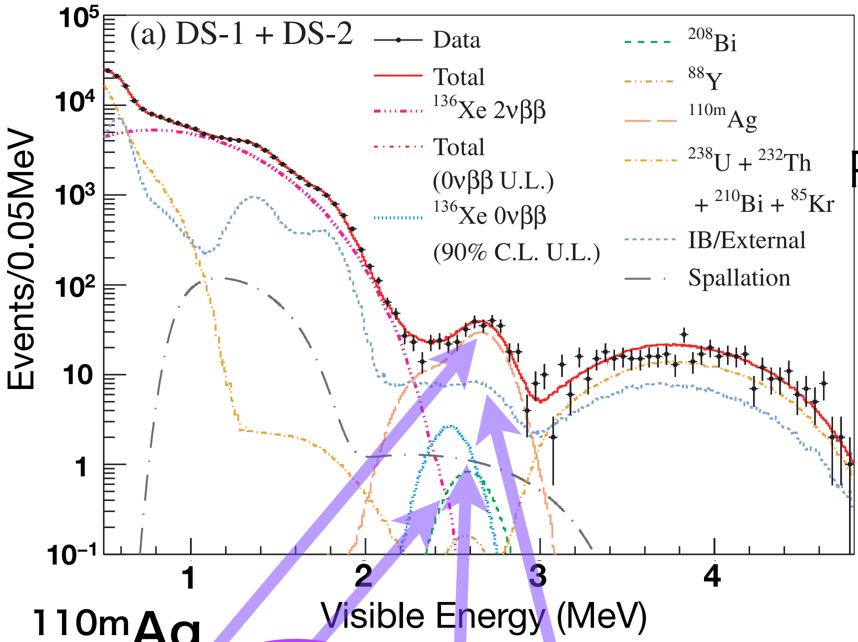
PMTs (1325 17”+ 554 20”)

- 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 ν , SuperNovae, etc.



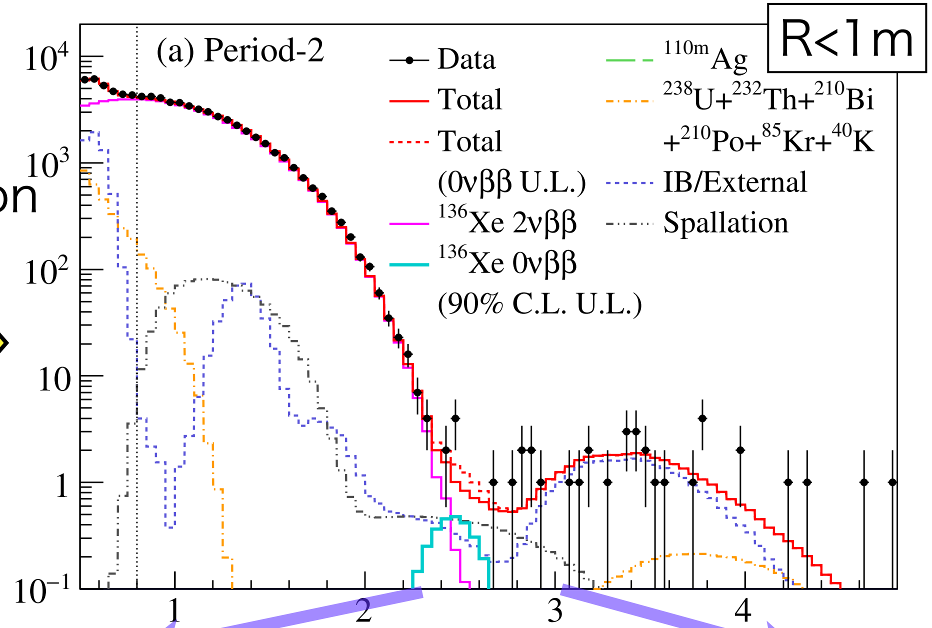
KL-Zen400 results

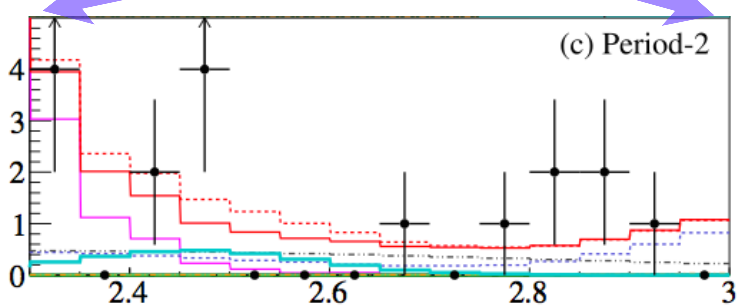
Phase I 89.5kg·yr PRL110,062502(2013)



Xe-LS Purification

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





^{110m}Ag Xe-LS

2ν

^{10}C μ-spallation

^{214}Bi Balloon

Make better the σ_E.

(μ-n-^{10}C) triple coincidence by n-detection.=> further improved

Change balloon to much cleaner one!

^{110m}Ag has gone !

Sensitivity: $T_{1/2}^{0\nu}$=5.6×10^25 yr

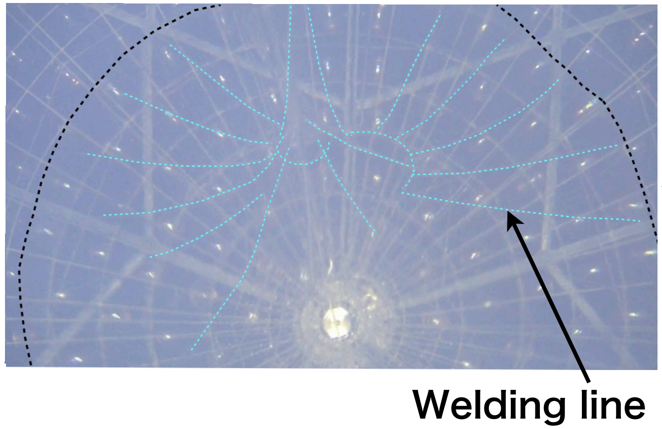
PhaseI+II Limits (90%C.L.):

$T_{1/2}^{0\nu}$=1.07×10^26 yr

<$m_{\beta\beta}$> <(61-165)meV

KamLAND-Zen 800

Aug.2016



Xe : 380kg =>750kg

Much cleaner balloon !

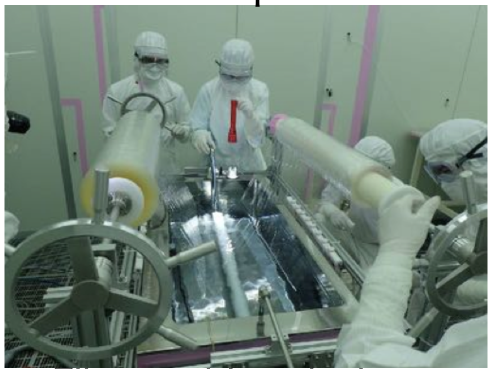
2015-2016: the new balloon was made.

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 eV

KamLAND2-Zen

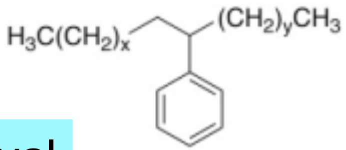
More photons (×5.5) and ^{214}Bi rejection

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

=> Full coverage of IH region, $\langle m_{\beta\beta}\rangle$~0.02eV.

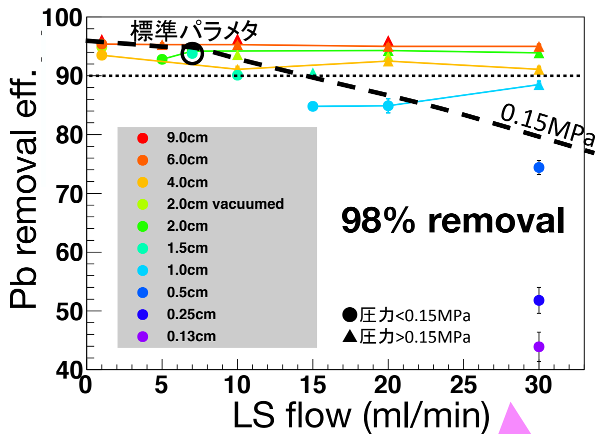
LAB based LS

×1.5



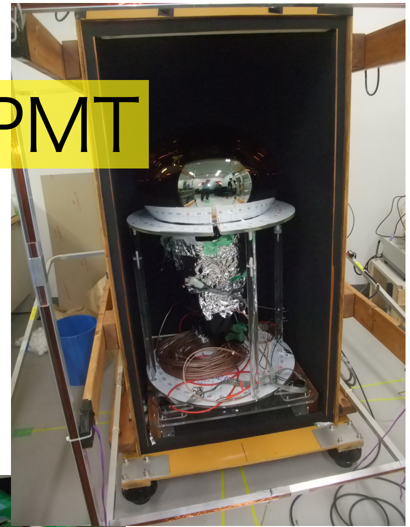
^{210}Pb removal

Metal scavenger (R-Cat-Sil AP)



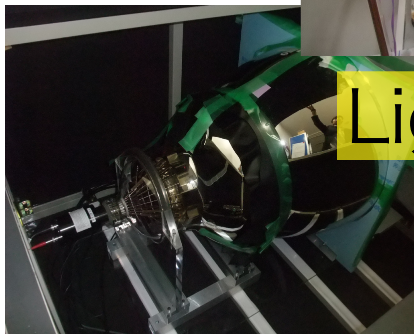
HQE 20”PMT

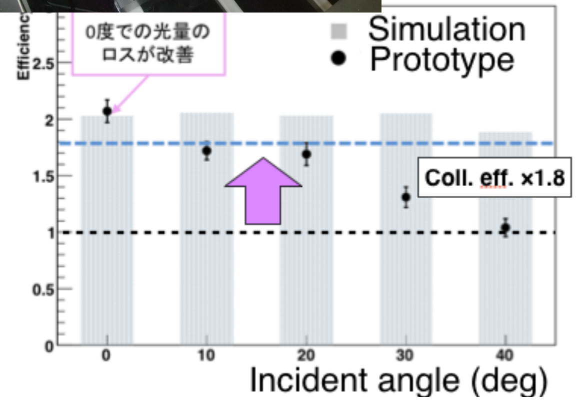
×2.1



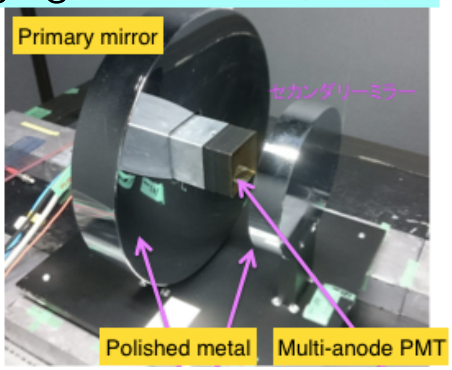
Light cone

×1.8





Imaging device for $\beta \Leftrightarrow \gamma$



Scintillating balloon

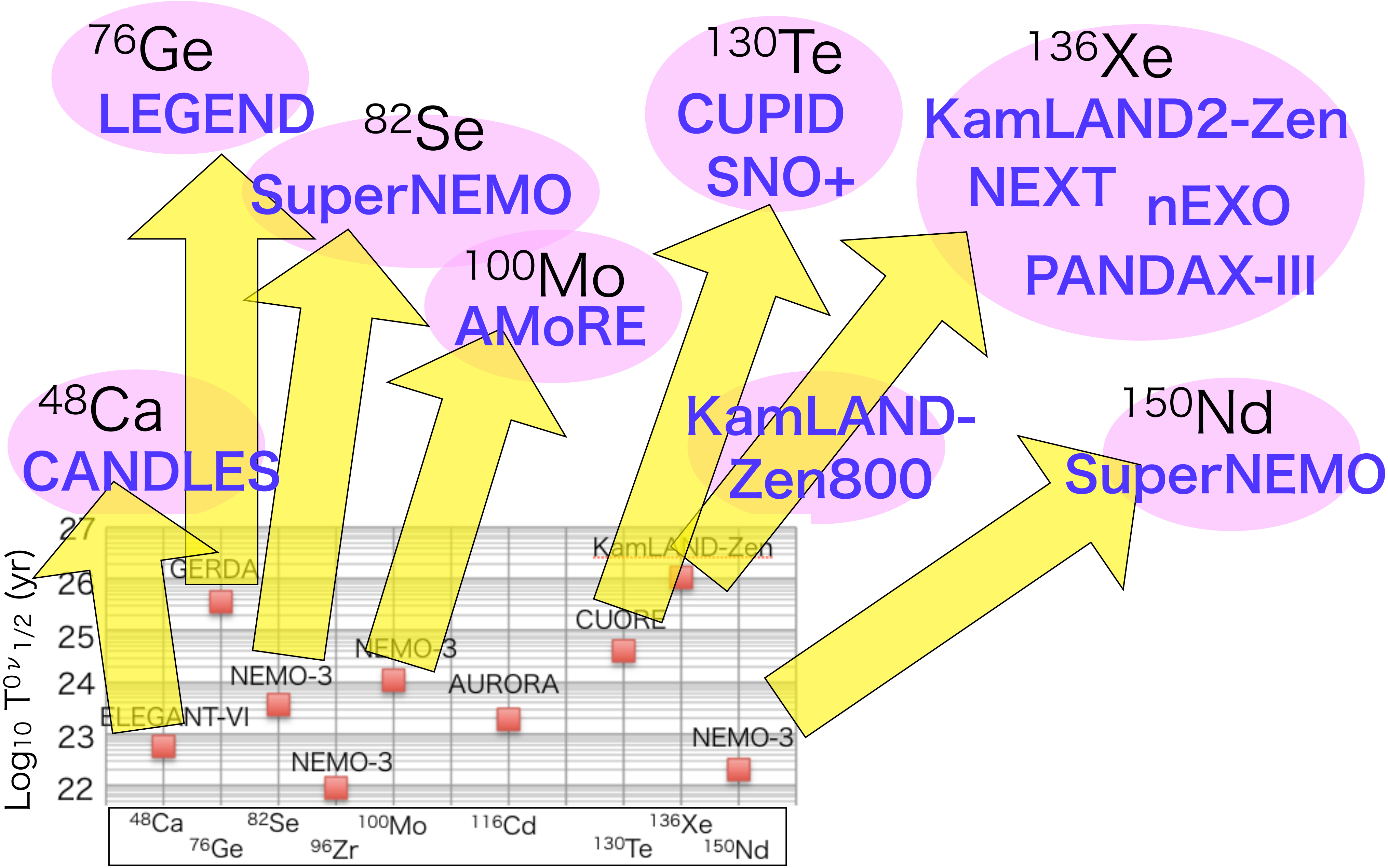
Improve 214Bi tagging on the balloon

Many projects

O(1)ton, Low BG, ΔE

$T_{1/2}$=>10^{27}~10^{28}yr

<$m_{\beta\beta}$>=> 0.02~0.05eV

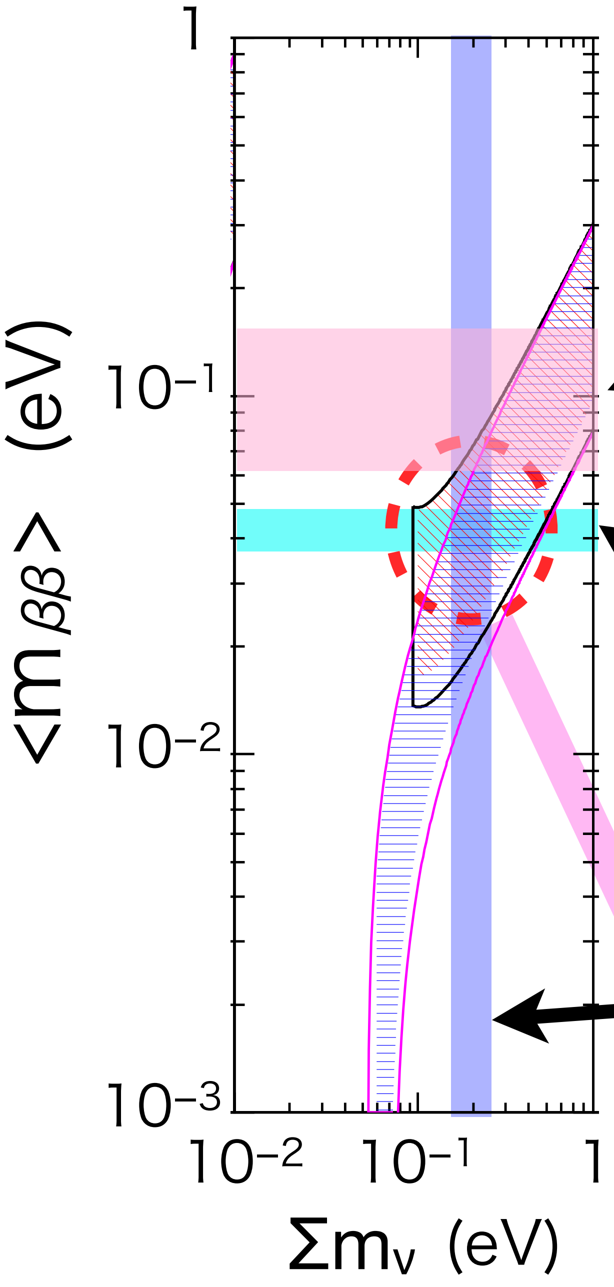


Prospect

0νββ 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 Σm_ν from cosmological observation (CMB, BAO, etc) : < O(100)meV

Accelerator/Atmospheric ν experiments (NH ? not fixed)

" Big SURPRISE " may happen !

Summary

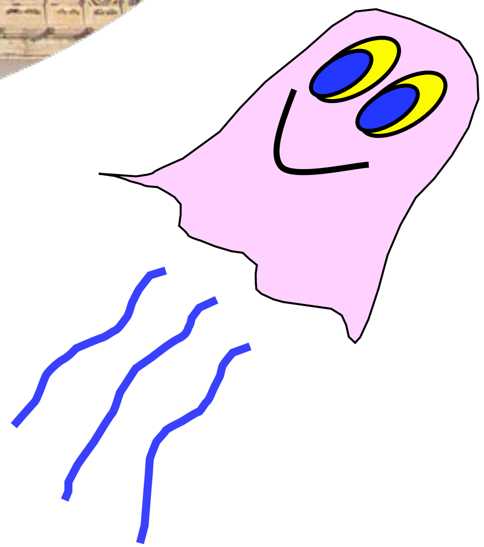
- Majorana nature of neutrinos is a key to understand the fundamental problems not only in the particle physics but the origin of the Universe.

- $0\nu\beta\beta$ 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}Xe this year.

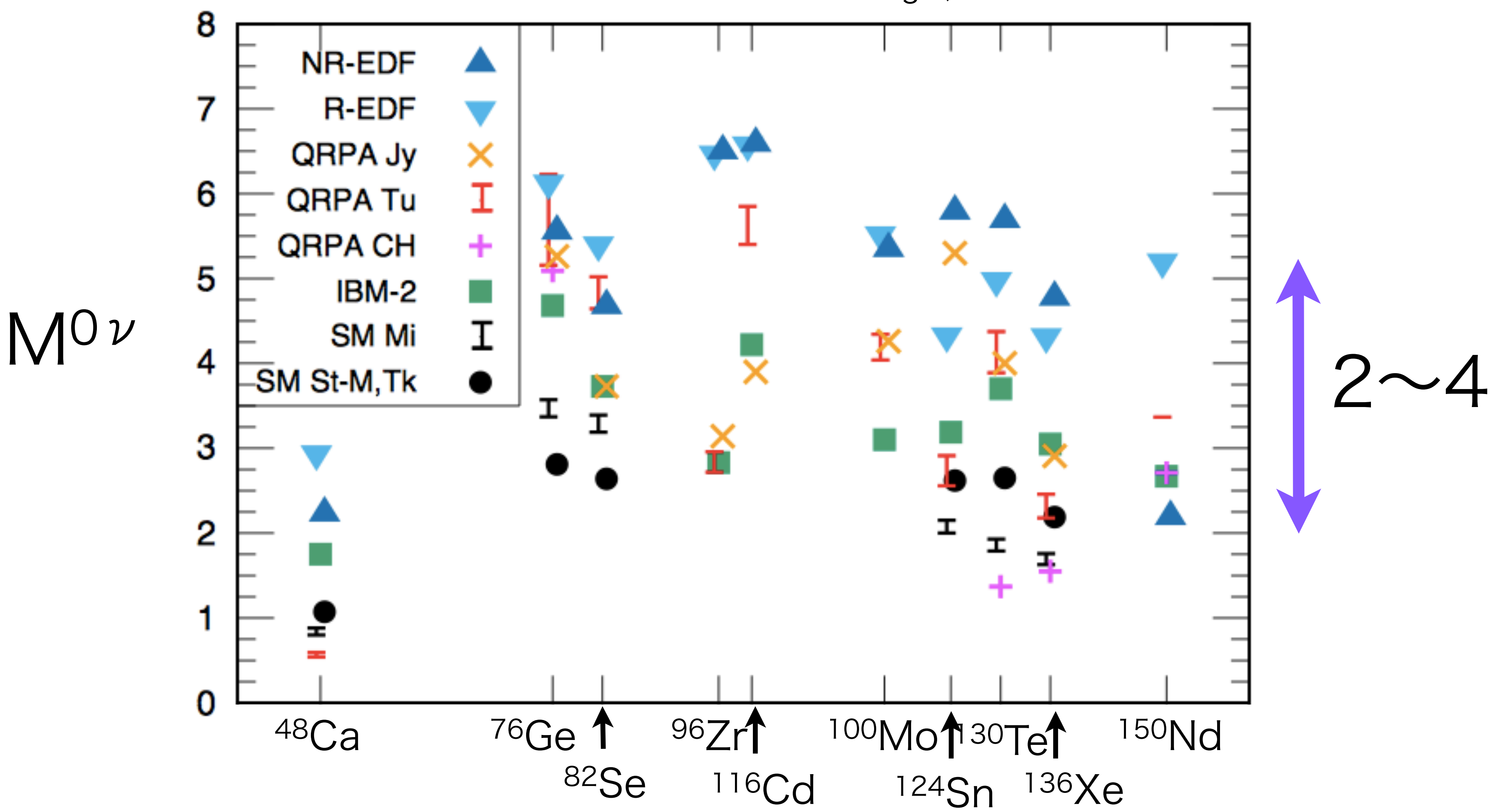
Thank you !



appendix

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

J.Engel, arXiv: 1610.06548

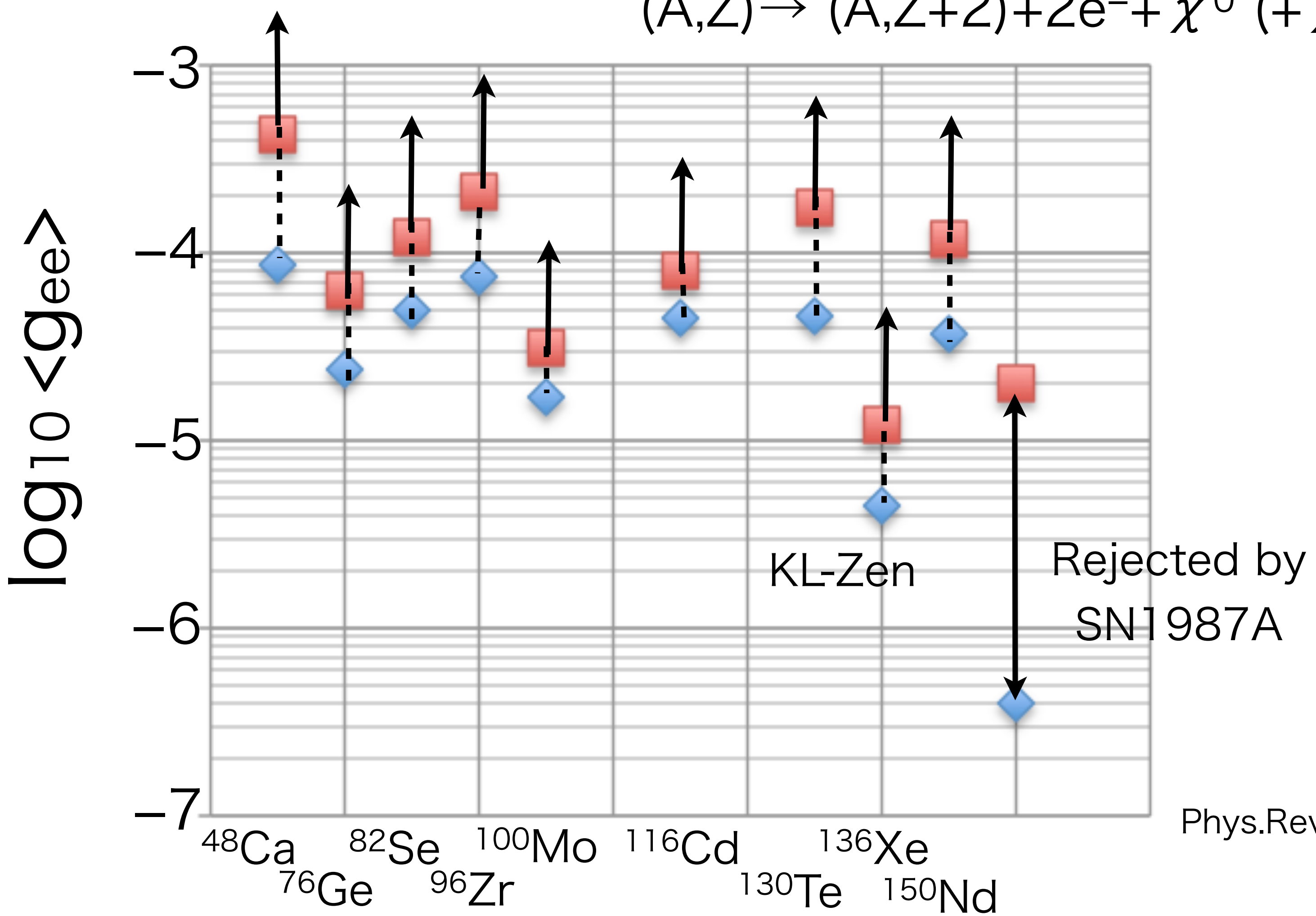


Improving the discovery potential is crucial.

Experiments with different nuclei are necessary.

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

$(A,Z) \rightarrow (A,Z+2)+2e^{-}+\chi^{0}\ (+\chi^{0})$



Phys.Rev.C86, 021601(2012)

KamLAND provides a most stringent limit on the normal Majoron and excludes a small allowed gap.

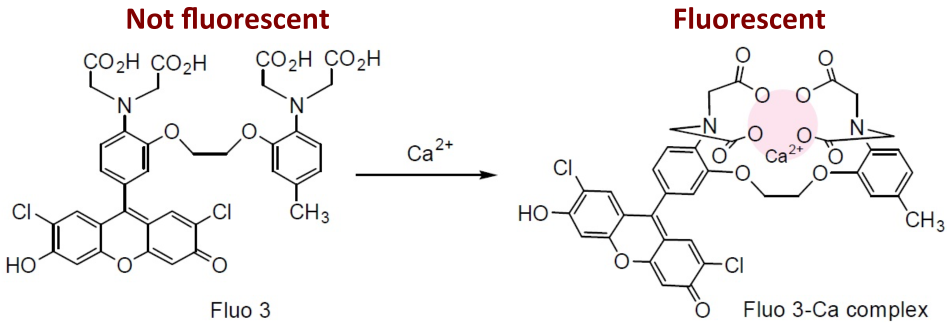
SN1987 extends the limit down to 10^-7.

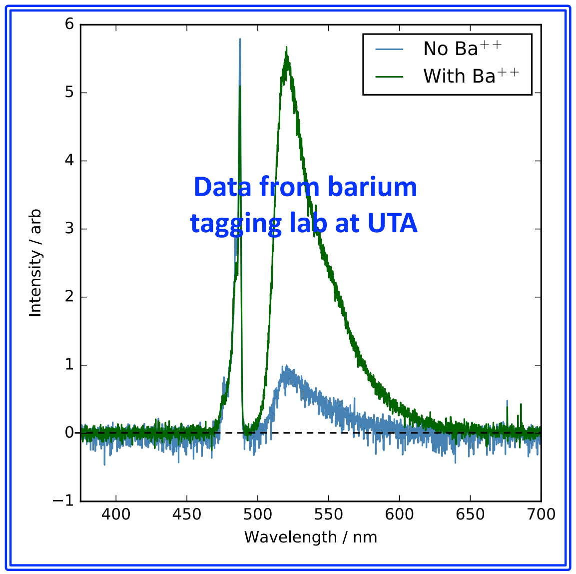
Ba tagging

J.J.Gomez-Cadenas

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

- **Potentially: background free experiment.**





- Xe-136 decays produce Ba++
- Ba++ will drift towards cathode (hopefully without recombining)
- Coat cathode with PSMA*molecule, which will capture BA++
- PSMA + BA++ 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++ ion to vacuum.

* Prostate-specific membrane antigen