

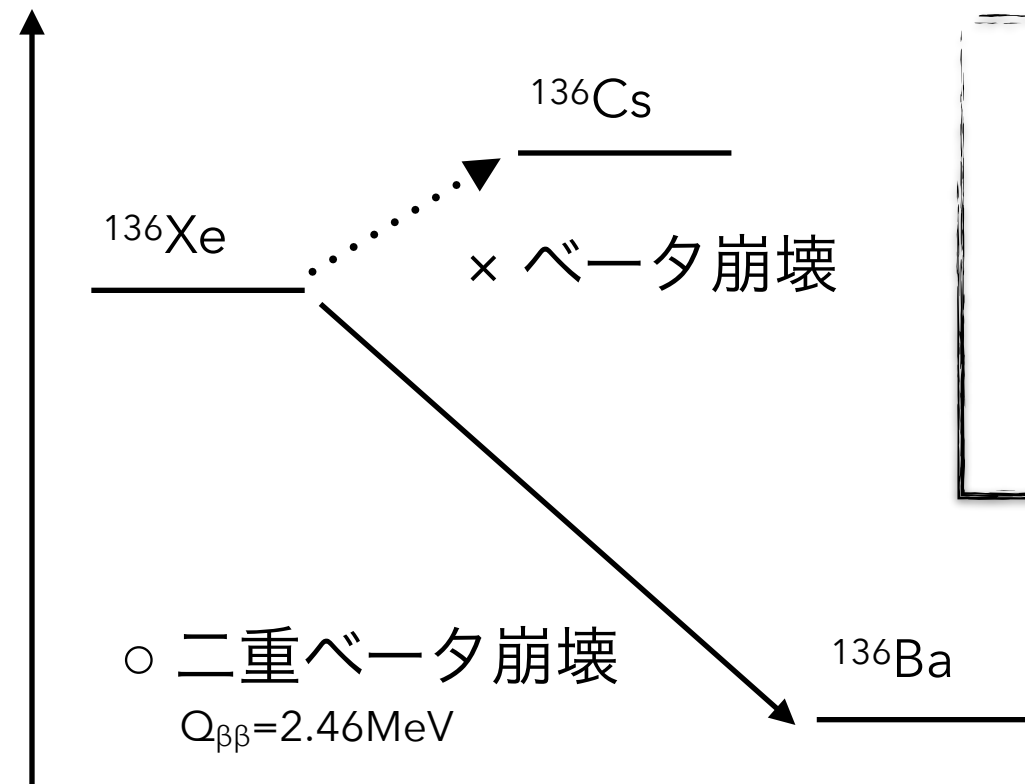


小原脩平
for the AXEL Collaboration

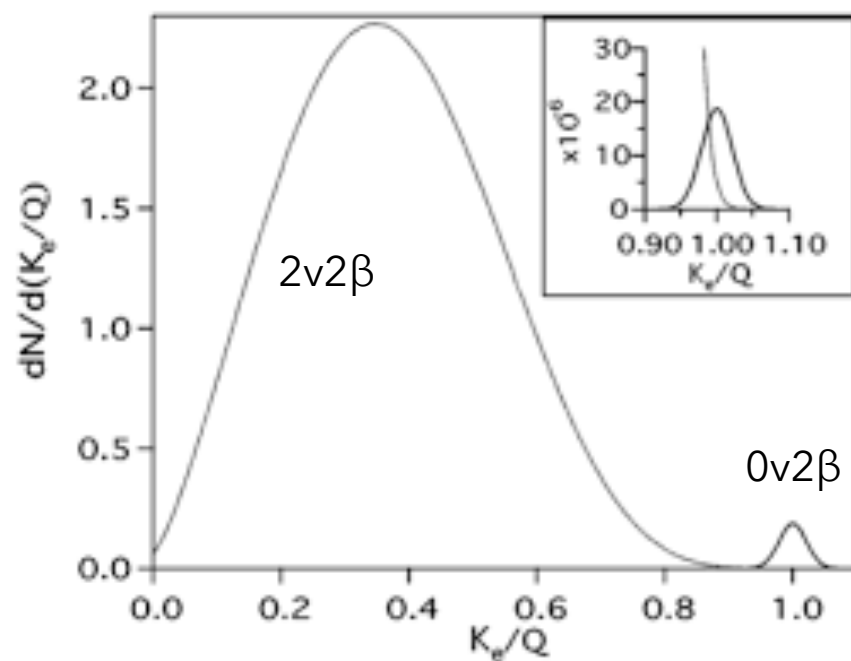
自己紹介的なやつ

- 学生時代; 東北大学でKamLAND/KamLAND-Zen実験
 - クリーンルーム内でバルーン作成
 - 液シンやフィルム状シンチレータ
 - 24時間監視システムのGUIやスクリプト整備など
 - D2の冬にバルーンが破れてD論ネタが亡くなったので,
1年間でSRNについてまとめて無理やり卒業@Last Mar.
- 現在; 京都大学にてAXEL実験 as JSPS-PD

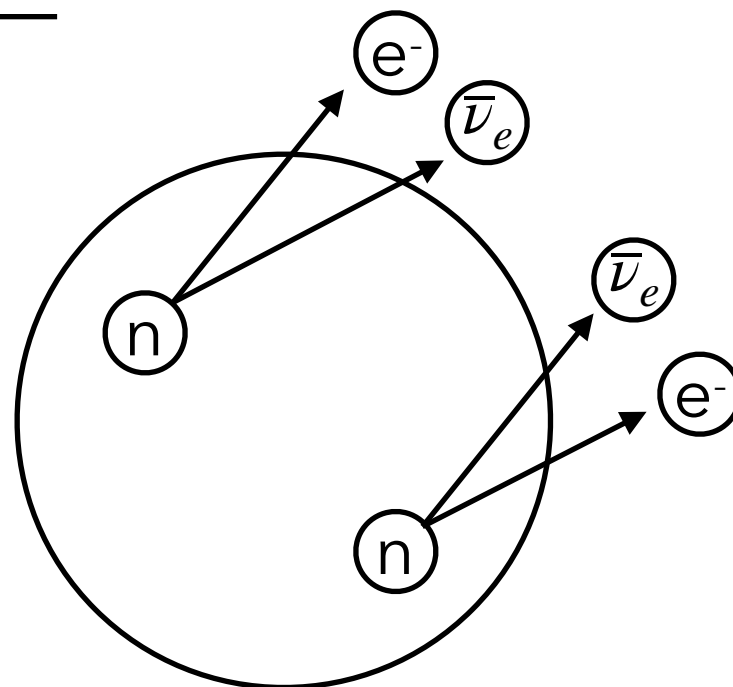
二重ベータ崩壊とは



- なかなか起こらない事象 ($T > 10^{26} \text{ yr}$)
- 2つの電子だけを放出(単色スペクトル)
- マヨラナ性($\nu = \bar{\nu}$)の証拠
- ニュートリノ質量への制限

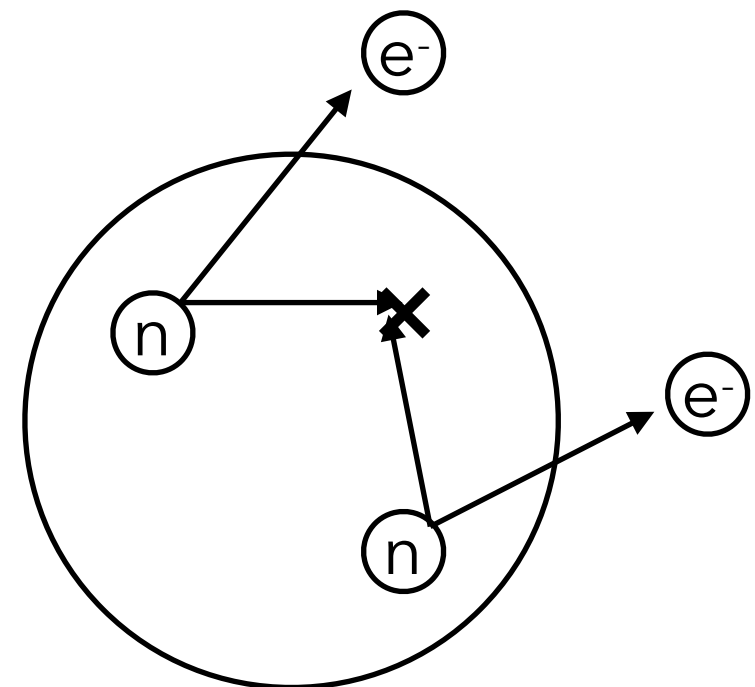


2ν2β モード



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

0ν2β モード



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

世界の $0\nu2\beta$ 探索と将来

✓ 背景事象が

感度制限している場合

KamLAND-Zen, SNO+, ...

~500kg-yr

1 ton × 10yr

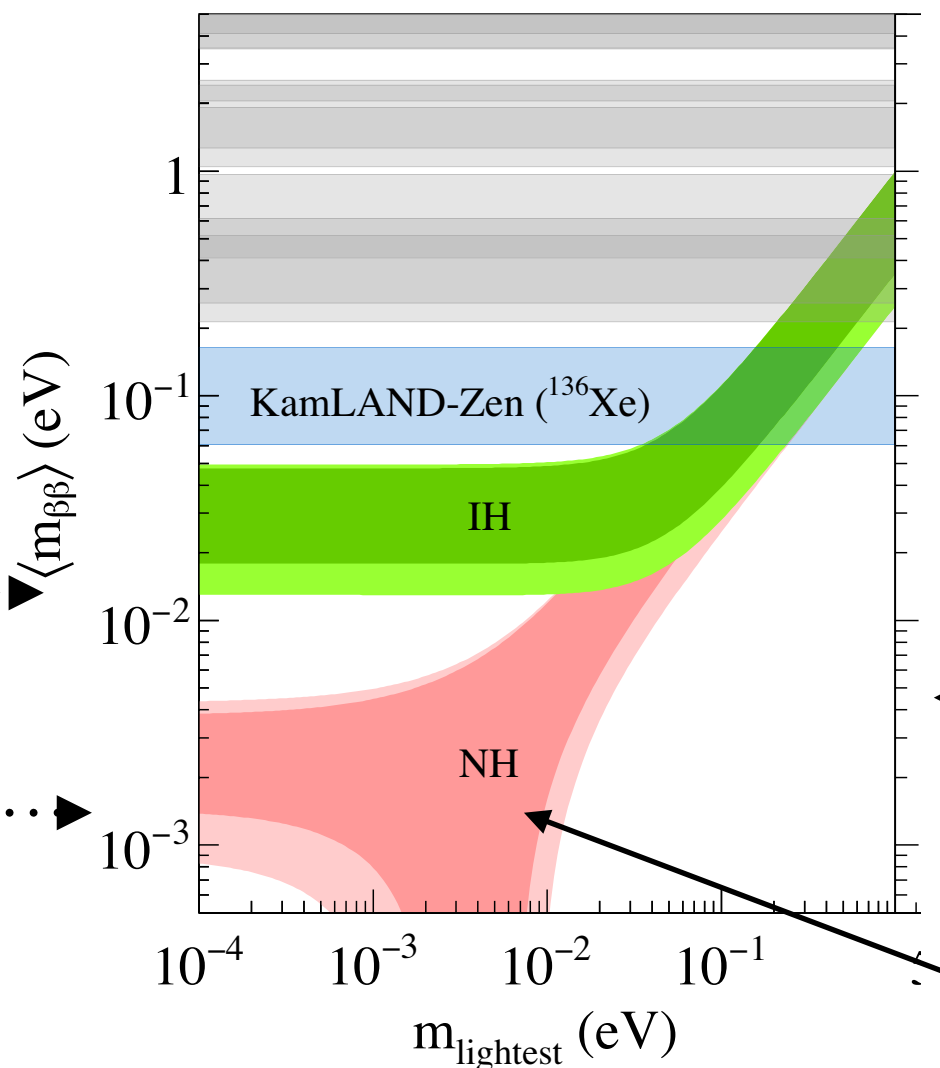
100 ton × 10yr

✓ 背景事象が無視できて、

統計が感度制限している場合

GERDA, MAJORANA, CUORE, ...

arXiv:hep-ph/0202264



1 ton × 10yr

最近のニュートリノ振動実験
は正常階層構造をfavor

これから必要なのは

“背景事象のない, 数tonの検出器”

AXEL

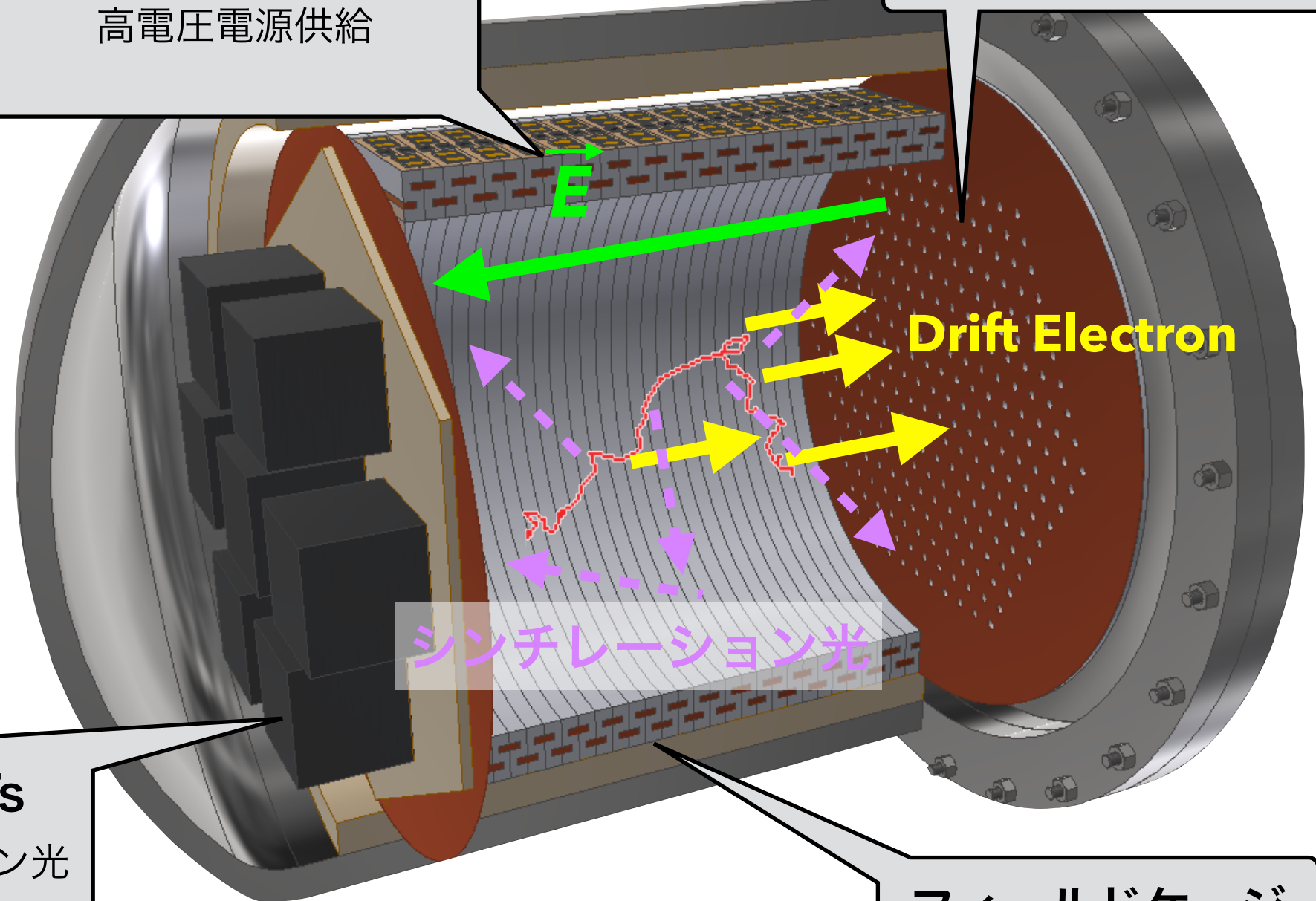
(**A** **X**enon **E**lectro**L**uminescence detector)

NEXT, PANDAX-III実験
と似たコンセプト

- ^{136}Xe for $0\nu 2\beta$
- 1ton キセノンガス
- ~10気圧

コッククロフト=
ウォルトン回路
高電圧電源供給

ELCC
エネルギーと飛跡取得



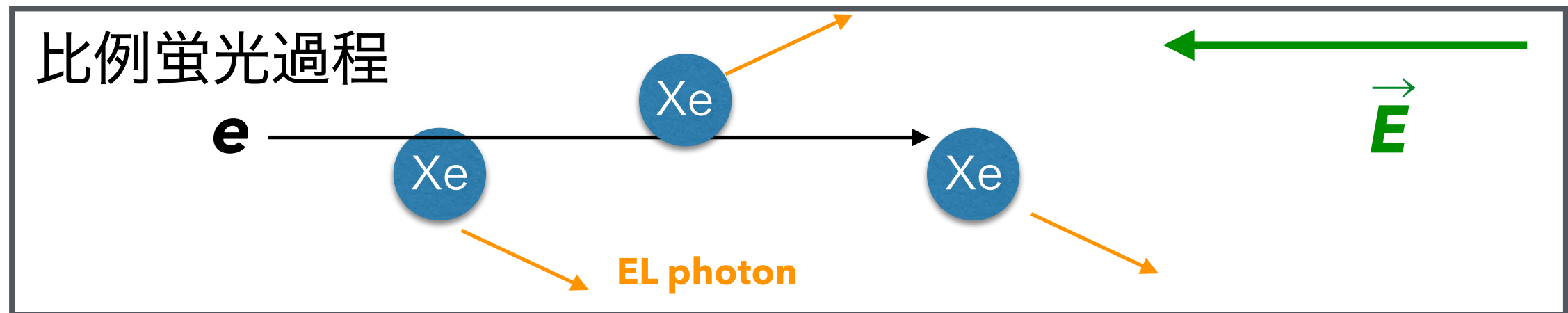
VUV PMTs

シンチレーション光
で時間情報取得

フィールドケージ

ELCC

(**E**lectroluminescence **L**ight **C**ollection **C**ell)

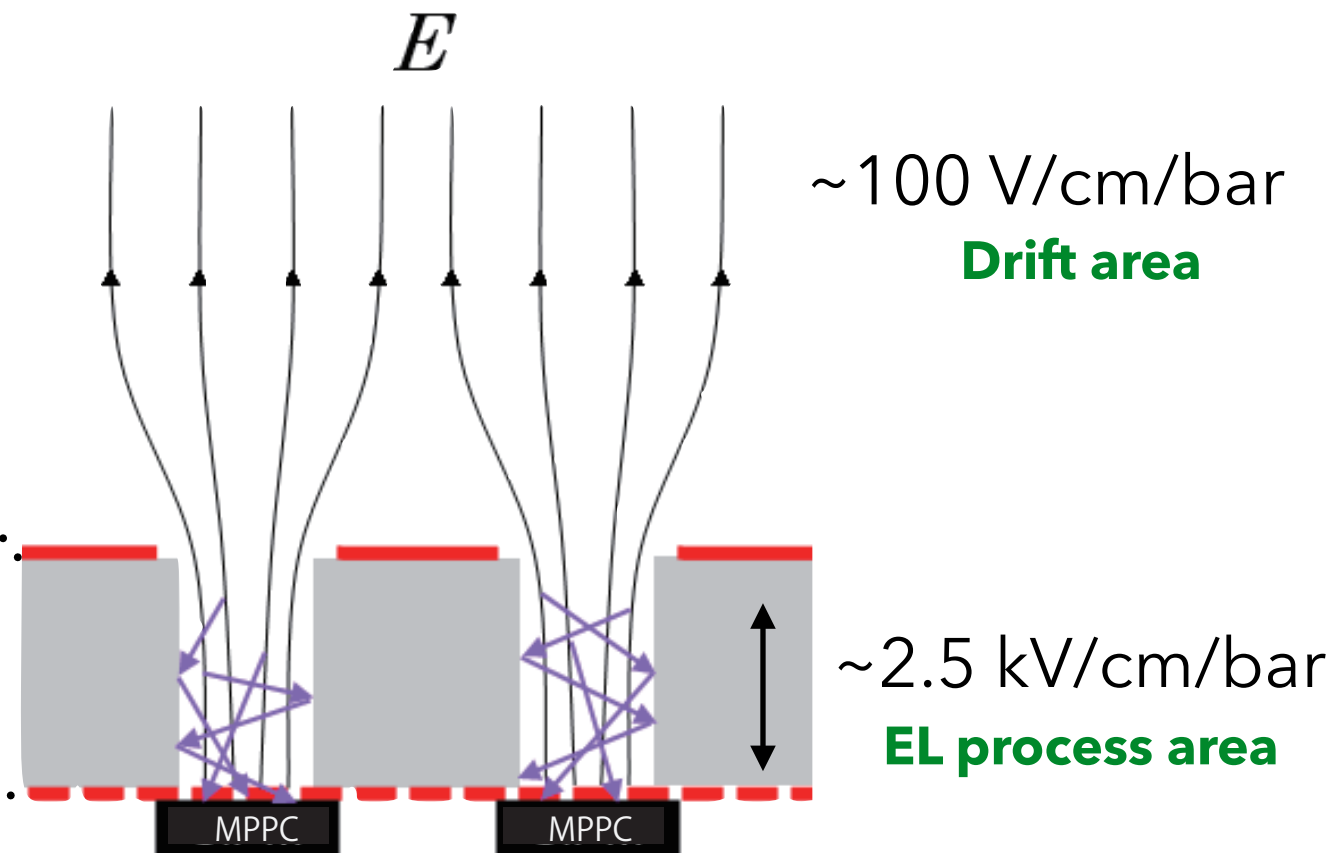
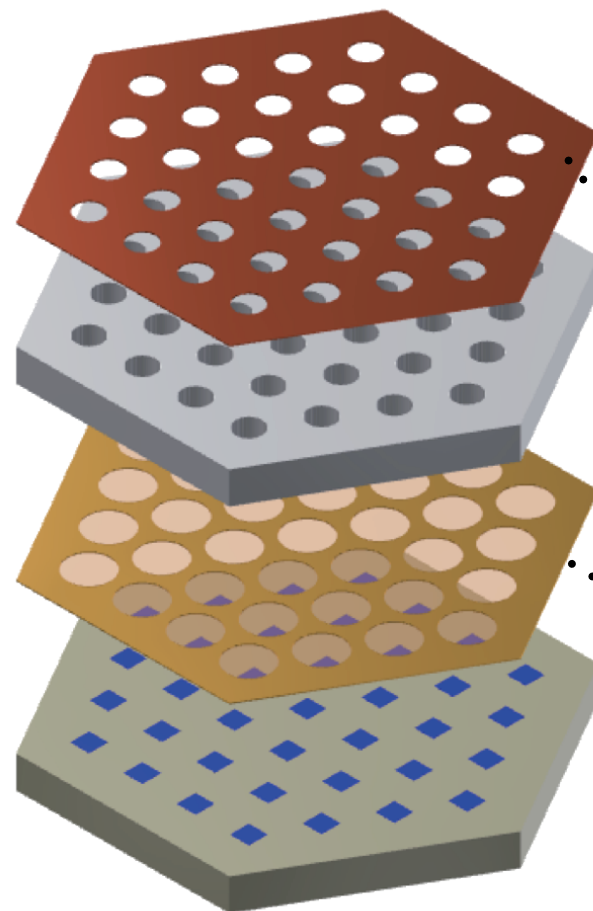


Anode Cu plate

PTFE insulator

Mesh electrode

MPPC array



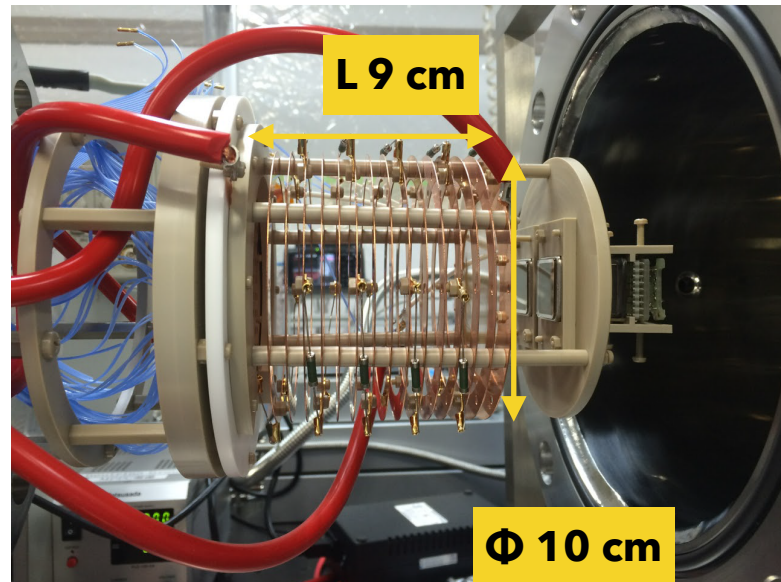
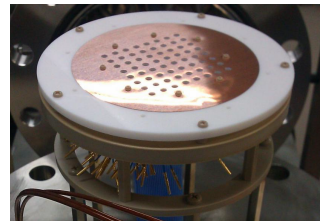
AXEL試作機と将来像

2015

⋮

10L - size (10g xenon)

- ΔE の確認
- ELCCの原理検証



2018

⋮

3000L - size
(100 kg xenon)

- 地下測定開始

202?

⋮

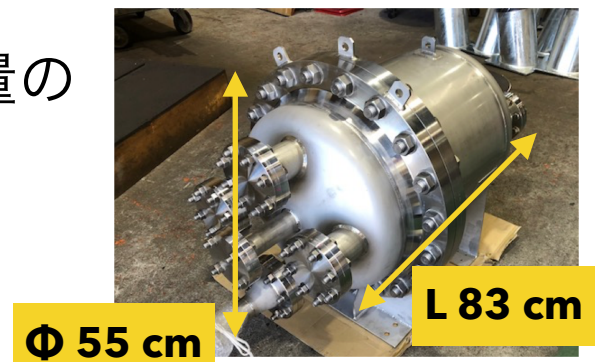
20??

⋮

Large - size

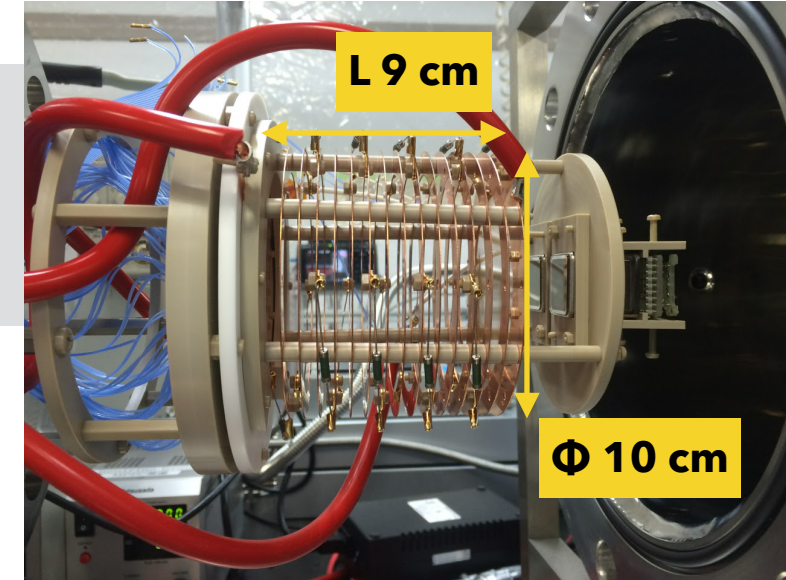
180L - size (8.6kg xenon)

- Q値での ΔE 確認
- 背景事象, 放射性物質混入量の評価
- Now constructing ...

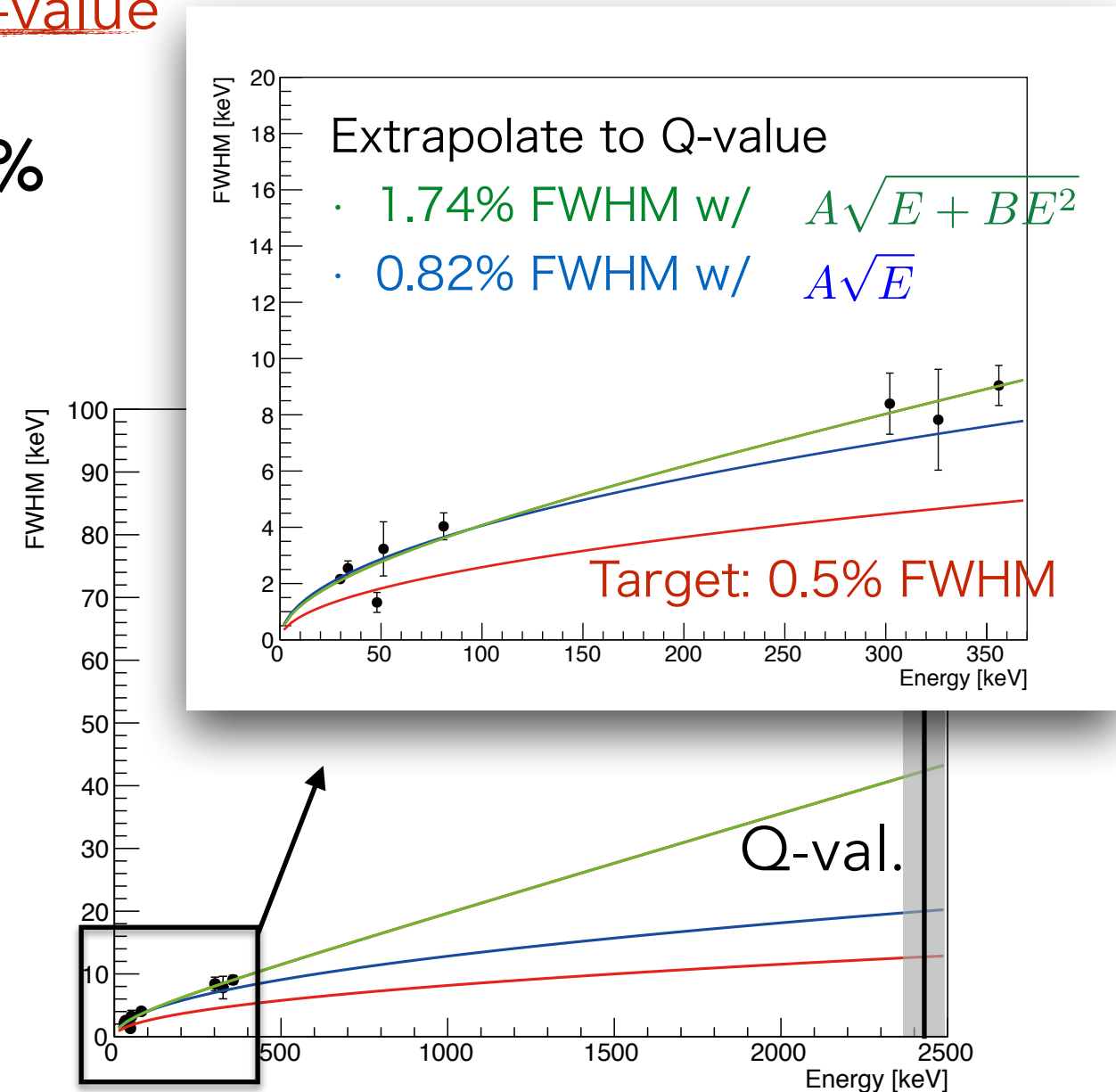
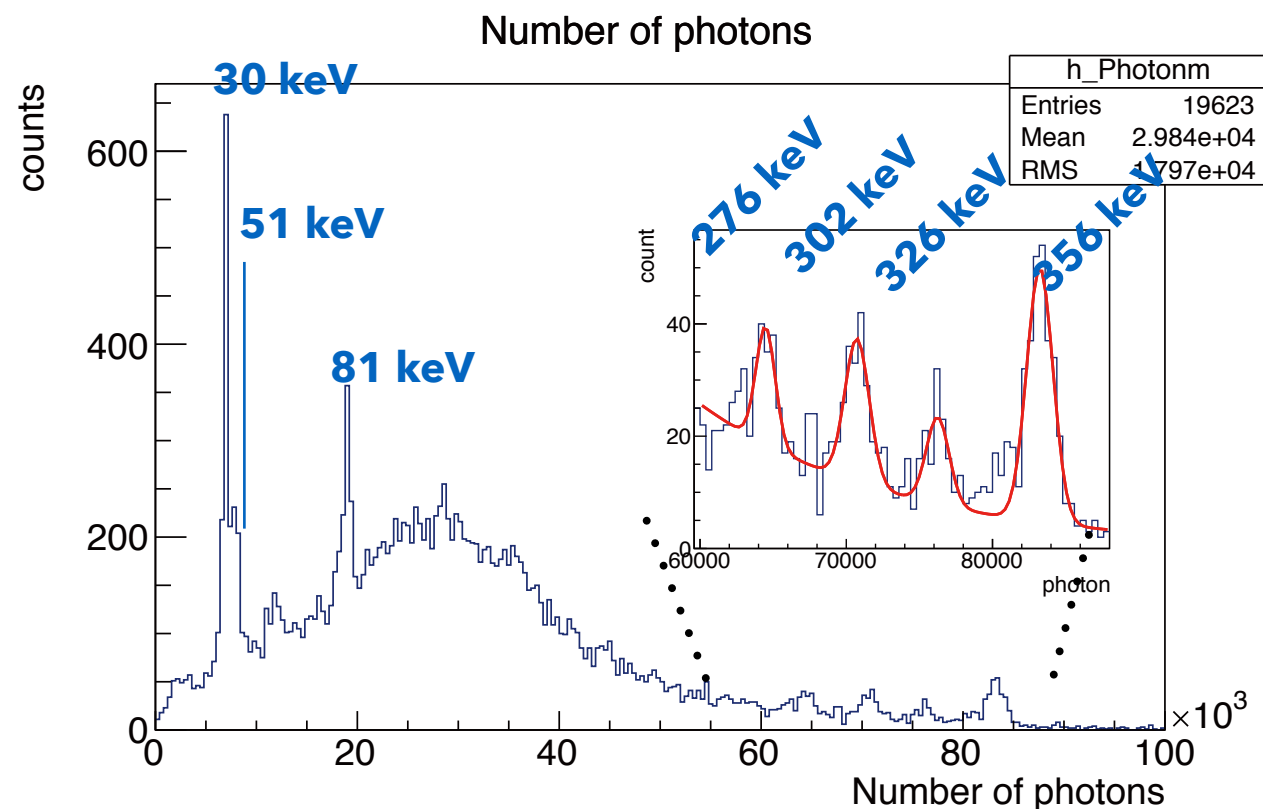


10L-prototype; ΔE

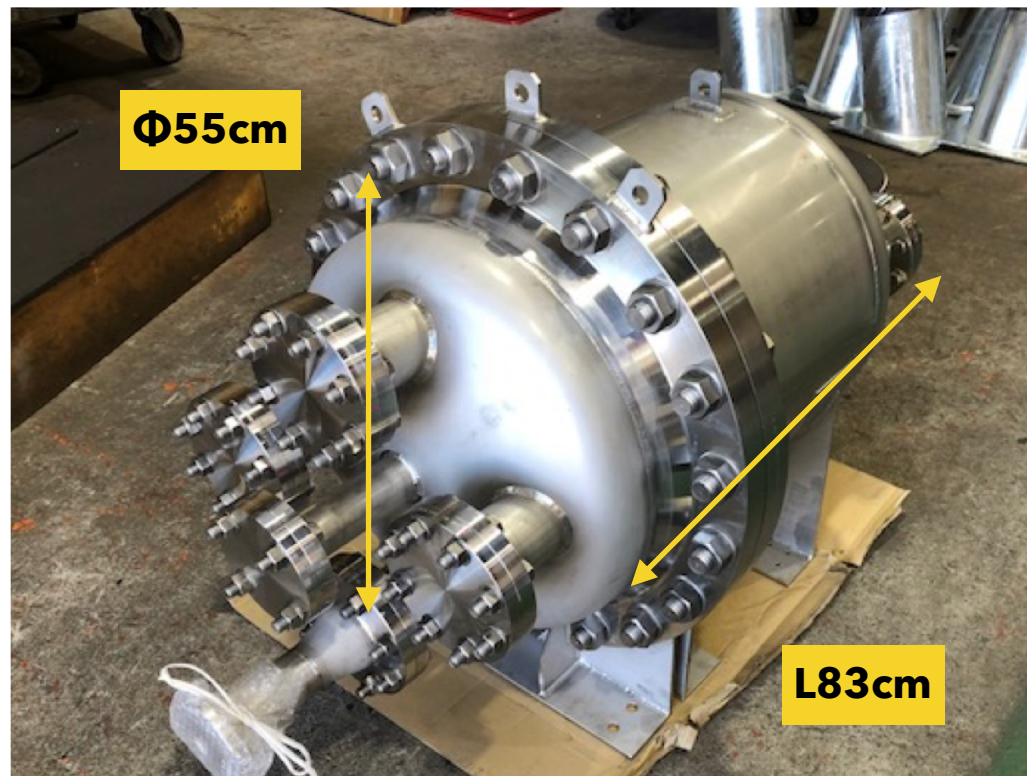
- ^{57}Co , ^{133}Ba などの線源でエネルギー分解能を評価
- Q値2.46 MeVはこのサイズでは収まりきらない
- 外挿して推定; 0.8~1.8% FWHM @ Q-value



でも想定より悪い分解能; cf ~0.5%

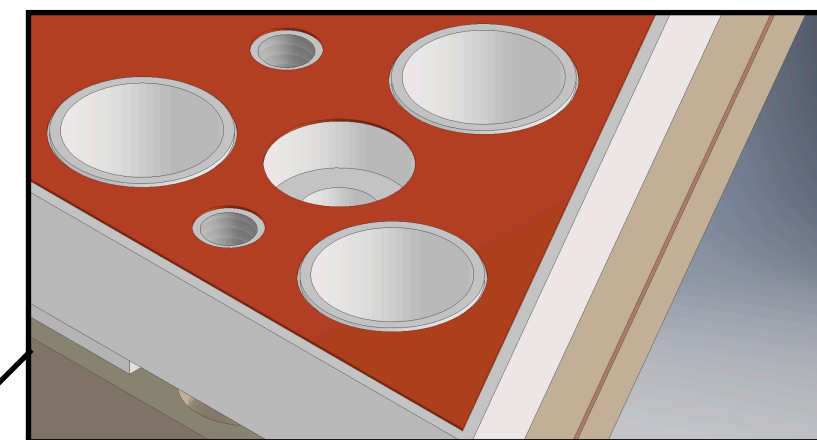
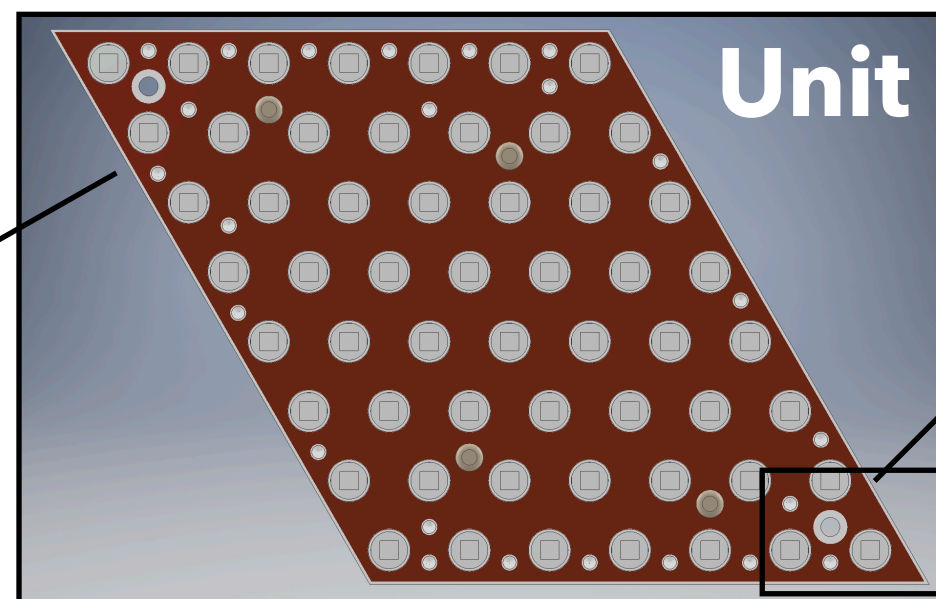
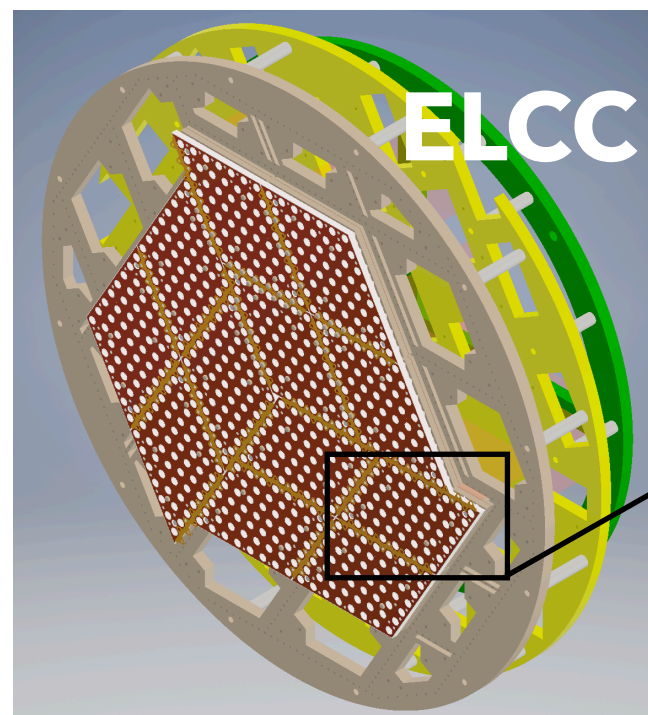


180L prototype detector



現在の試作機(~10L)の10倍の大きさ

- Q値でのエネルギー分解能評価
- Scalabilityの証明
- 地下測定前の原理検証
- 鋭意建設中... !!



背景事象 for $0\nu 2\beta$

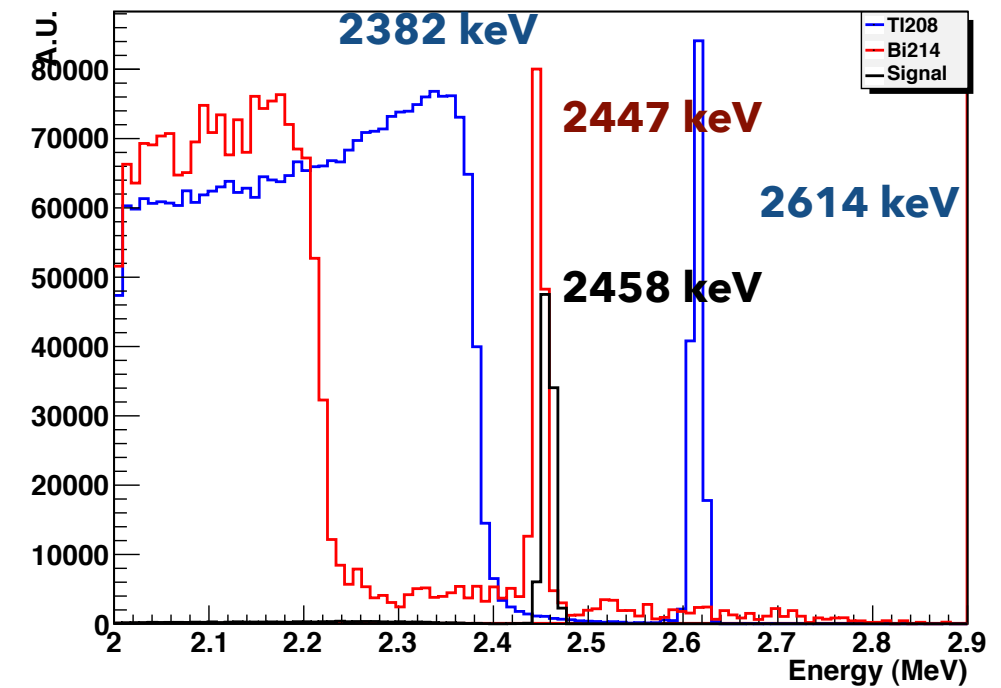
主に圧力容器から出てくる

仮に $\Delta E \sim 0.5\%$ FWHMの分解能を達成しても,

^{214}Bi γ -ray 2447keV

が 2458keVの $0\nu 2\beta$ の背景事象になる

arXiv:1106.3630v1 [physics.ins-det] from NEXT paper



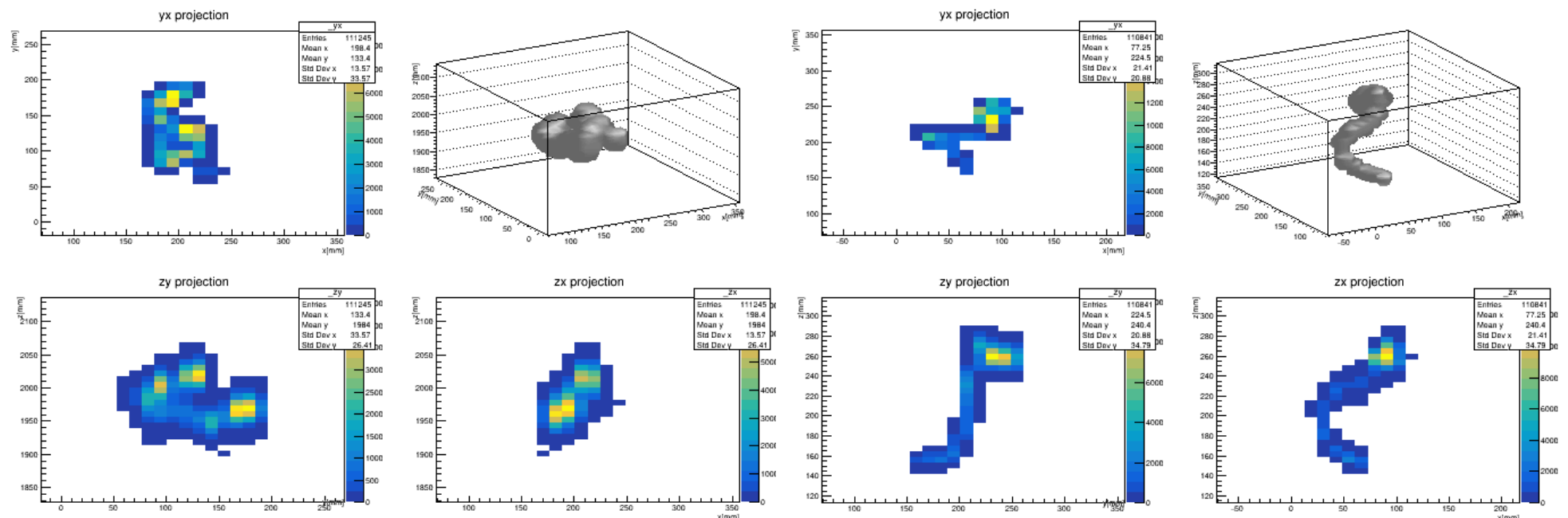
飛跡で分離できるかも !?

$0\nu 2\beta$ (double- β)

^{214}Bi (gamma-ray)

機械学習で

75evt/yr $\Rightarrow$ 6evt/yr

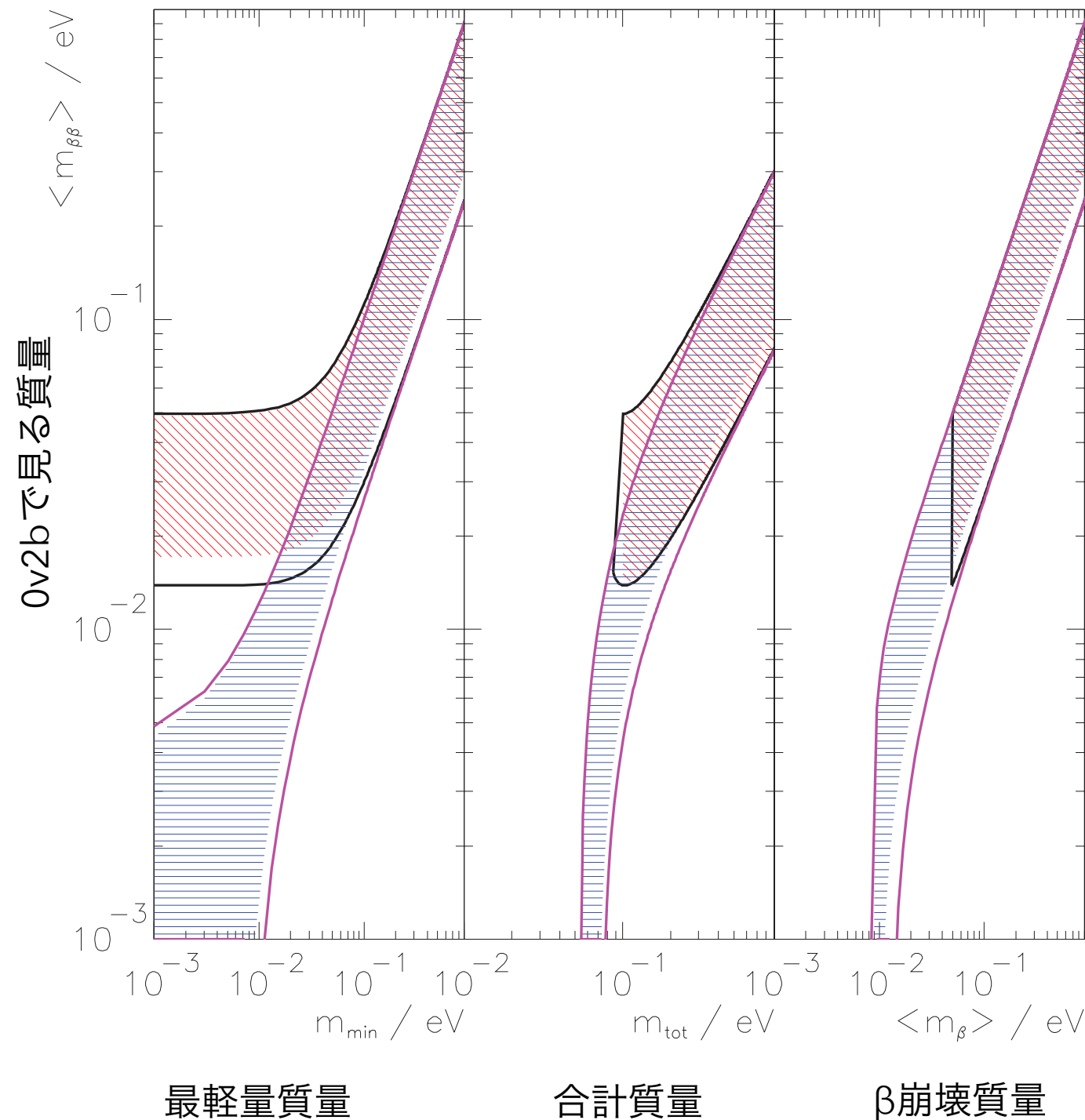


まとめ

- 将来の二重ベータ崩壊探索(正常階層領域)には,
 - 大きい質量, 背景事象ゼロが重要
 - $\Rightarrow$ 高エネルギー分解能, Scalability, 飛跡
- AXEL検出器
 - 高圧キセノンガスTPC
 - 独自の飛跡読み出しシステム; ELCC
 - 現在180Lサイズの試作機製作中; Q値の分解能評価

Backup

0n2b探索とニュートリノ質量階層構造



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

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

- $0\nu 2\beta$ の半減期から階層構造へ制限
- Majorana-CP位相と, ニュートリノ振動パラメータの不定性から幅を持つ
- 実験的にも各行列要素($M^{0\nu}$)の不定性から幅を持った制限になる
- Planck2018; $\Sigma m_\nu < 0.12 \text{eV}$

<https://arxiv.org/abs/1807.06209>

Majorana

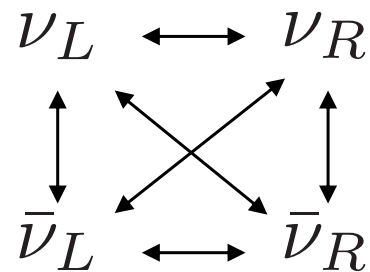


E. Majorana @ Italy
1906/8/5 - 1938?

Majorana粒子の提唱者

1938年船上で行方不明となった

- C変換で対称なら質量項を持てる ($\nu = \nu^C$; Majorana condition)
- $\nu_L = \text{anti-}\nu_R$ ではないことに注意
 - これは当初の原子炉- ν 測定で粒子 $\neq$ 反粒子は分かっている



- ニュートリノの粒子/反粒子区別 $\rightarrow$ 2次粒子の e^+e^-
- 「C変換した粒子」が同一ということ

$$\mathcal{L}_{D+M} = m_D (\bar{\psi}_L \psi_R + \bar{\psi}_L^c \psi_R^c) + \underbrace{m_L \bar{\psi}_L^c \psi_L^c + m_R \bar{\psi}_R^c \psi_R^c}_{\text{Majorana mass term}} + h.c.$$

Majorana mass term

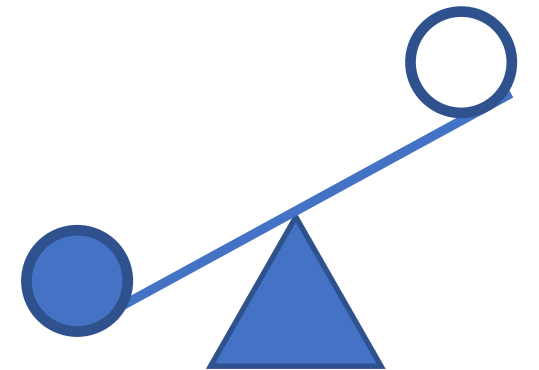
シーソー機構

いわゆる “type-I see-saw”

右巻きマヨラナ質量が左巻き質量やディラック質量よりも

十分重い($m_R \gg m_D, m_L \sim 0$)とすると

$$\mathcal{L}_{D+M} = \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$
$$\longrightarrow \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} \frac{m_D^2}{m_R} & 0 \\ 0 & m_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

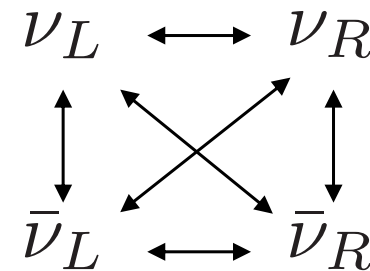


右巻き質量を重くすることで左巻きが極端に軽くなる

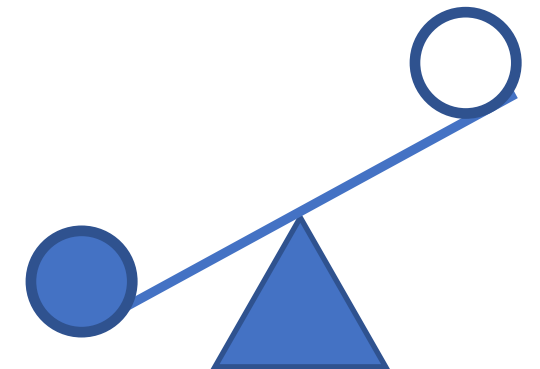
0ν2βが発見できたら

- ニュートリノがマヨラナである直接的証拠

- $\nu = \nu^c$ (Majorana Condition)
- シーソー機構から極小質量を証明

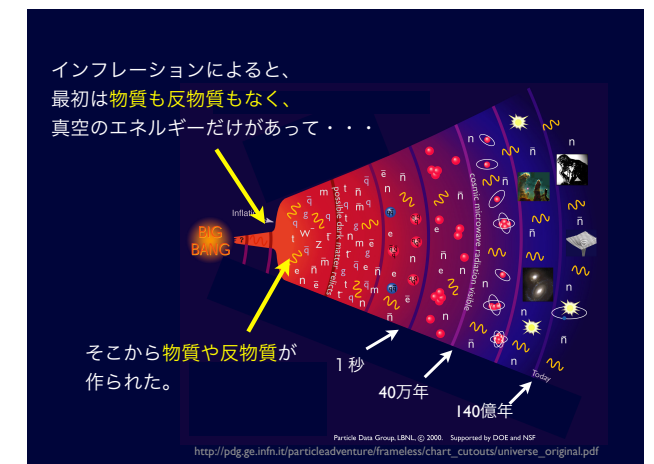


$$m_L \simeq \frac{m_D}{m_R^2}$$

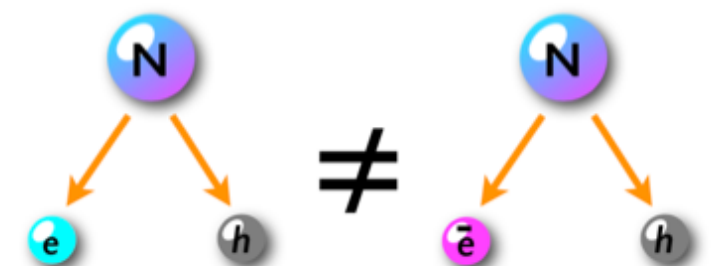


- 宇宙物質優勢のシナリオ; レプトジェネシス

- $T > M_R$; 宇宙の温度がまだ高い
- $T \sim M_R$; 重い右巻きニュートリノが崩壊 $\Delta L \neq 0$
- スファレロン過程 ($B-L=0$); $\Delta L \neq 0 \Rightarrow \Delta B \neq 0$
 - レプトン数の破れがバリオン数の破れに



レプトジェネシス



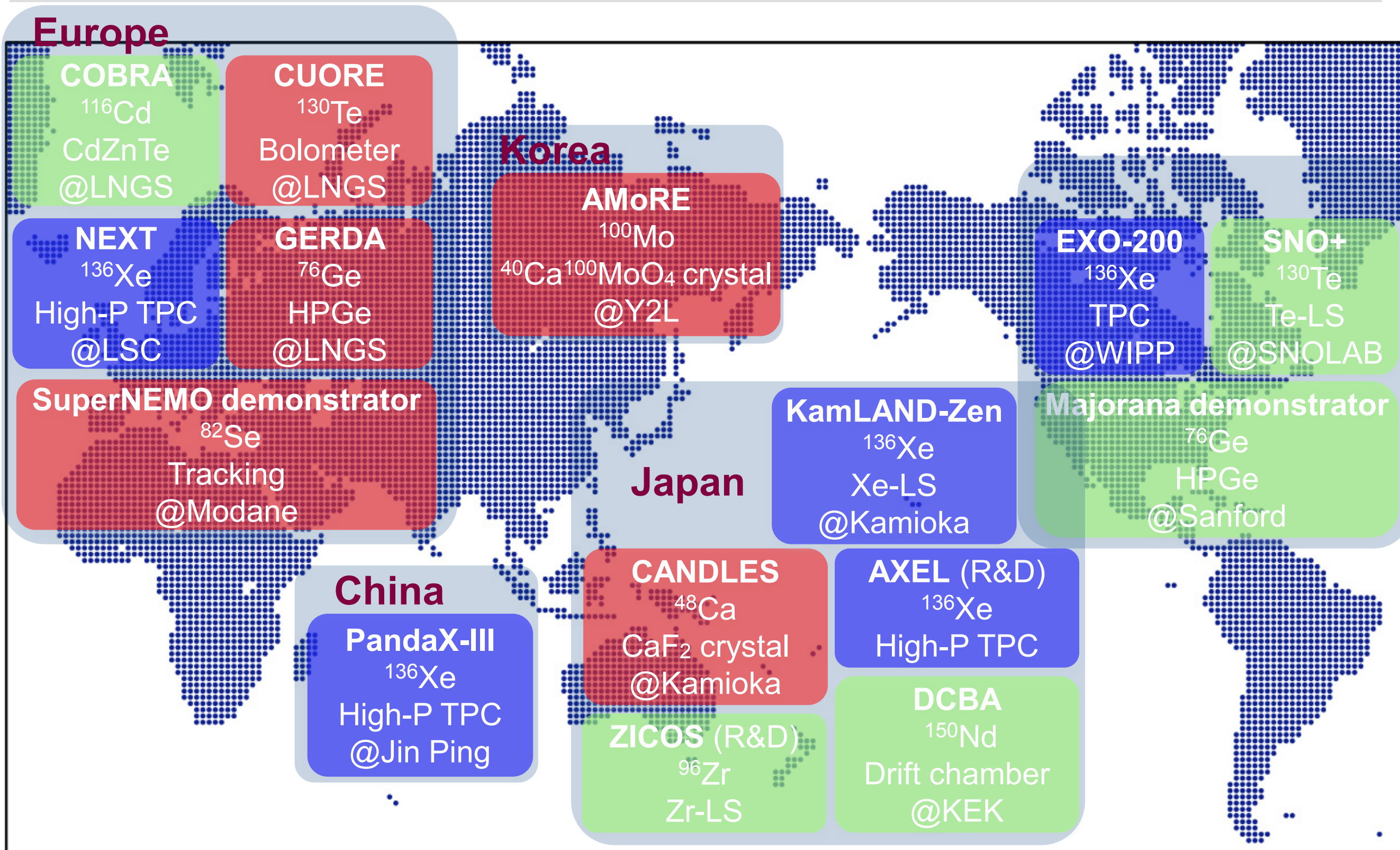
※レプトジェネシスとマヨラナニュートリノに関して詳しく知りたい人には濱口さんの講演資料

(http://www.lowbg.org/ugnd/workshop/sympo_all/201705_Ookayama/slides/21pm/201705_Ookayama_Hamaguchi.pdf)

世界の0ν2β探索

※新学術「地下素核」2017領域研究会, 吉田さんのスライドから

(http://www.lowbg.org/ugnd/workshop/sympo_all/201705_Ookayama/program.html)



二重ベータ崩壊各種

Nucl. Part. Phys. 39 085103 (2012)

核種	Q値[keV]	Nat. [%]	Cost* [M\$/ton]	$T^{2\nu}_{1/2}$ [yr]	メリット	デメリット	実験
^{48}Ca	4271	0.187	> 1000	4.4×10^{19}	最大Q値	低NA, 濃縮難	CANDLES
^{76}Ge	2040	7.7	~80	1.6×10^{21}	長T2v		GERDA, MAJORANA
^{82}Se	2995	9.2	~120	9.6×10^{19}			NEMO-3, Super-NEMO
^{96}Zr	3350	2.8		2.4×10^{19}	Q値大		ZICOS
^{100}Mo	3034	9.6	~80	7.1×10^{18}	Q値大	短T2v	AMoRE, NEMO-3
^{124}Sn	2228	5.64	~300				
^{116}Cd	2802	7.5	~180	2.8×10^{19}			COBRA
^{130}Te	2533	34.5	20	7.0×10^{20}	高NA		CUORE(-0), SNO+
^{136}Xe	2457	8.9	5~10	2.3×10^{21}	長T2v, 容易濃縮		KamLAND-Zen, PANDAX-III, EXO, NEXT, AXEL
^{150}Nd	3367	5.6	> 300	9.1×10^{18}	Q値大	短T2v, 濃縮難	DCBA, NEMO

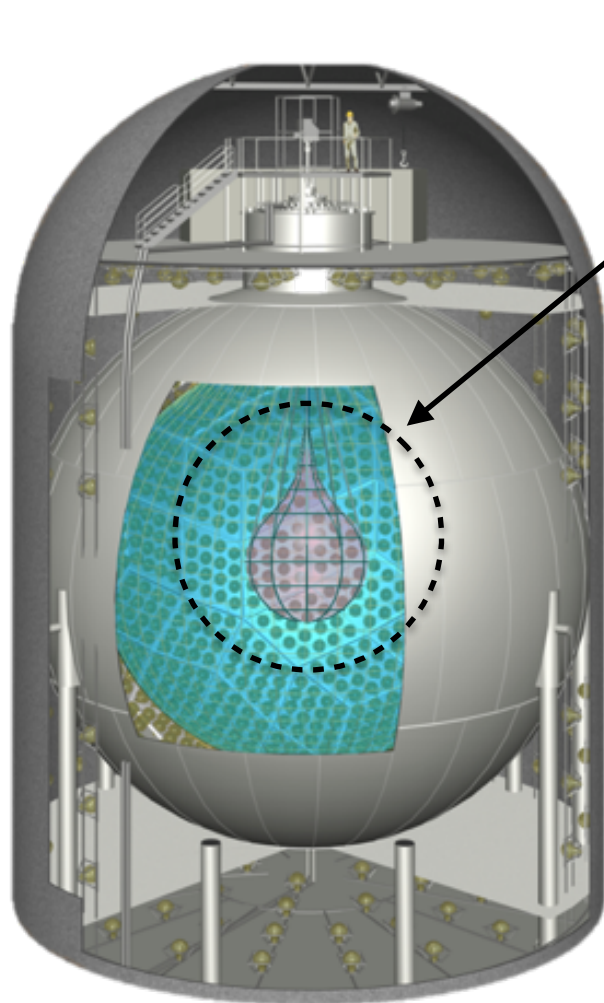
KamLAND-Zen 400

(KamLAND-Zero neutrino double-beta decay search)

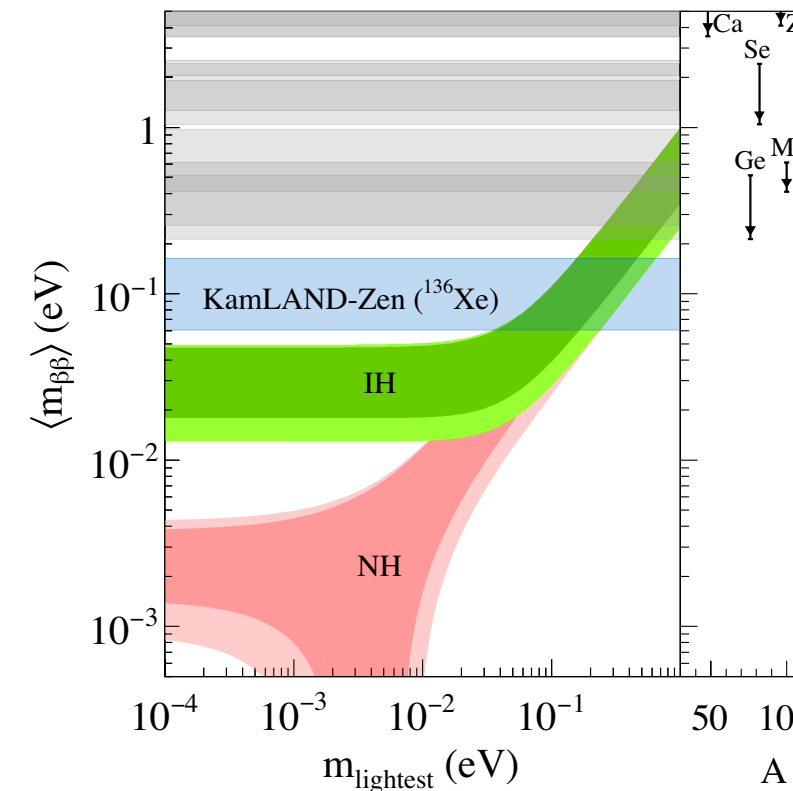
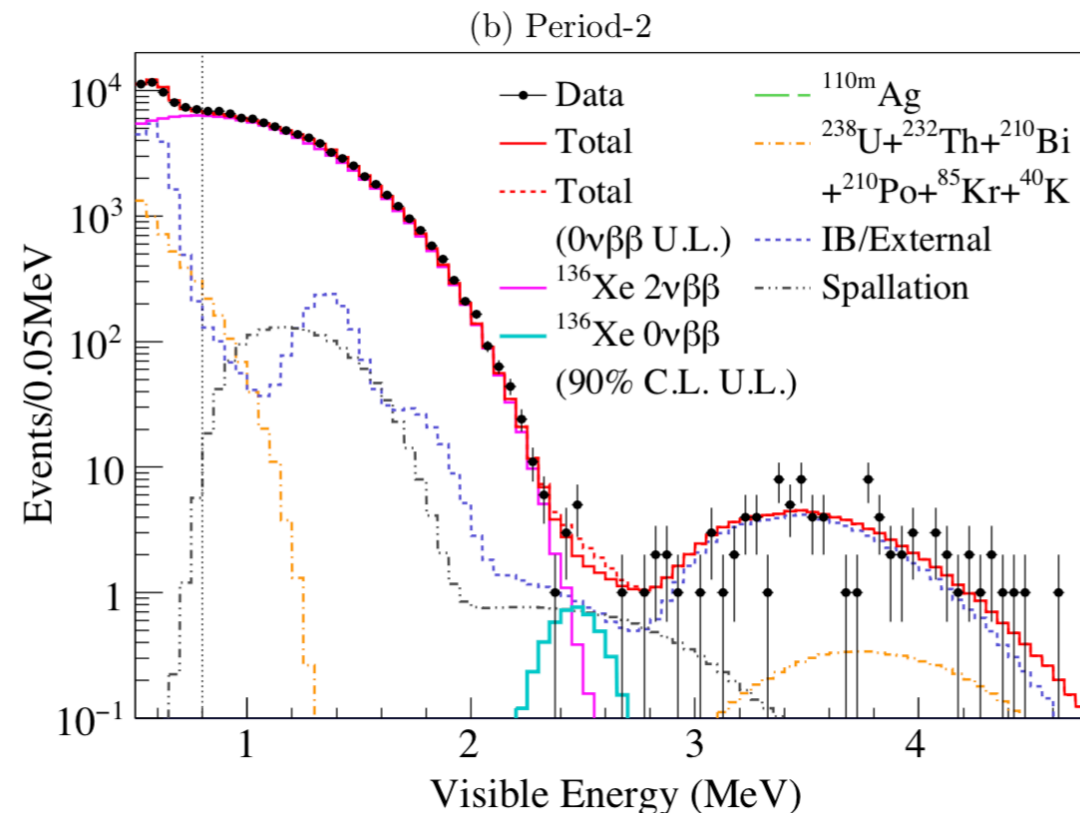
@ Kamioka, Japan

• <https://arxiv.org/abs/1605.02889>

- Use ^{136}Xe loaded liquid-scintillator ; ~380kg
- R~1.5m inner-balloon is a target volume



- $\sigma/E = 6.6\%/\sqrt{E}$
- BG; $2\nu 2b$, ^{10}C , ^{214}Bi , $^{110\text{m}}\text{Ag}$
- $T > 1.07 \times 10^{26} \text{ yr (90\% C.L.)} \Leftrightarrow 61\text{-}165\text{meV}$

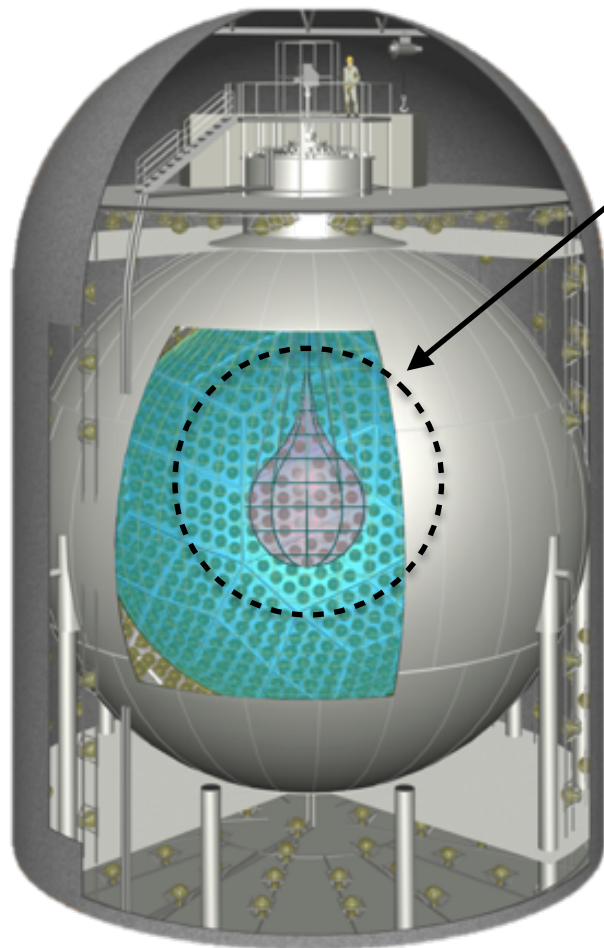


KamLAND-Zen 800

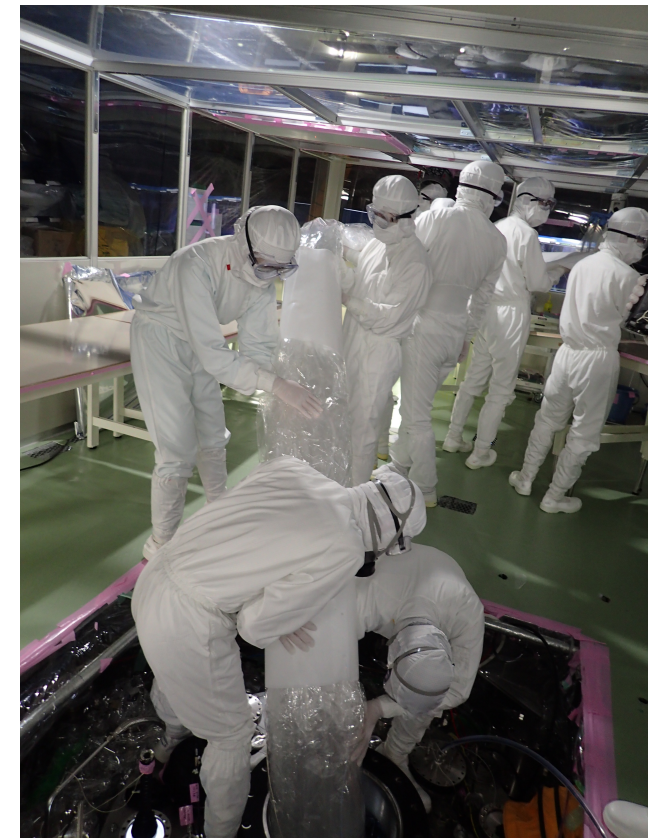
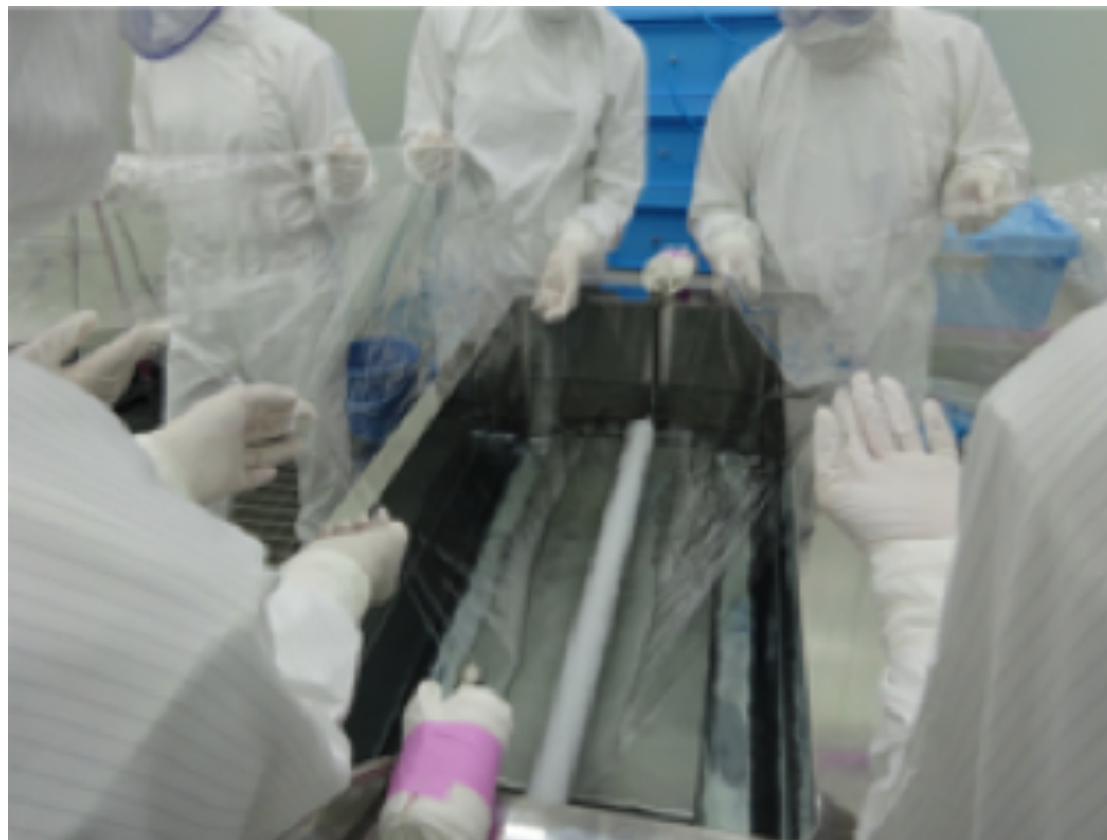
(KamLAND-Zero neutrino double-beta decay search)

@ Kamioka, Japan

- Use ^{136}Xe loaded liquid-scintillator ; ~780kg
- R~1.9m inner-balloon is a target volume



- Re-fabrication of the inner-balloon in order to suppress ^{214}Bi background on the film
- It will start from the end of 2018
- The goal set to be ~ 40meV



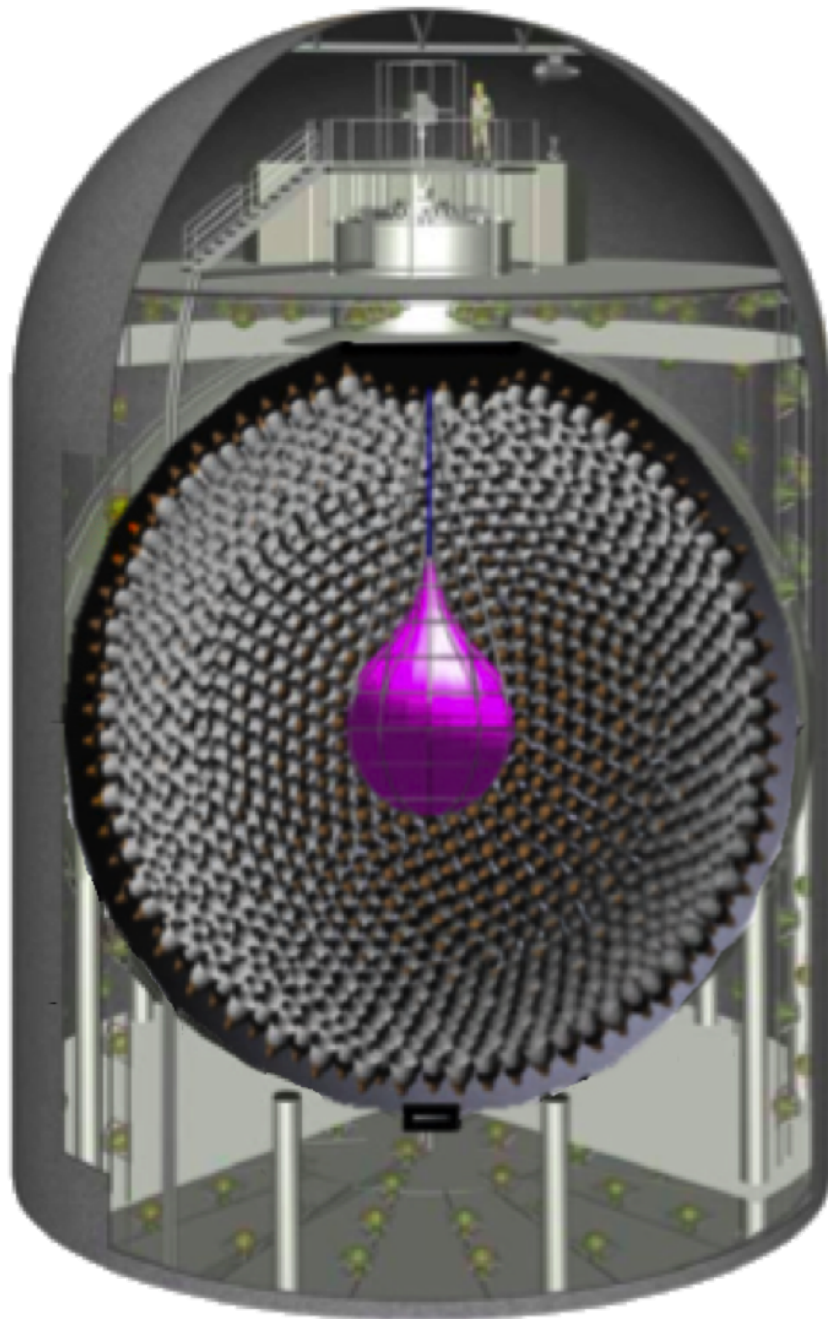
KamLAND2-Zen

(KamLAND2-Zero neutrino double-beta decay search)

@ Kamioka, Japan

Future project

- Use ^{136}Xe loaded liquid-scintillator ; **~1000 kg**
- **R~1.9m** inner-balloon is a target volume



"KamLAND2" is a future detector upgrade plan

- For ΔE improvement;
 - High-Q.E. PMT
 - Winstone cone mirror
 - New LAB-based LS
- The goal set to be ~ 20 meV

CANDLES-III

@ Kamioka, Japan

(**CA**lcium fluoride for studies of **N**eutrino and **D**ark matters by **L**ow **E**nergy **S**pectrometer)

Background-free detector (?)

(High Q-value than other isotopes)

- CaF_2 scintillator; $3.2\text{kg} \times 96$ crystals
- ^{48}Ca ; $Q=4.27\text{MeV}$
- Liquid scintillator; active-veto

Using a pulse shape difference
btw $\text{CaF}_2 \Leftrightarrow \text{LS}$

Critical Problem

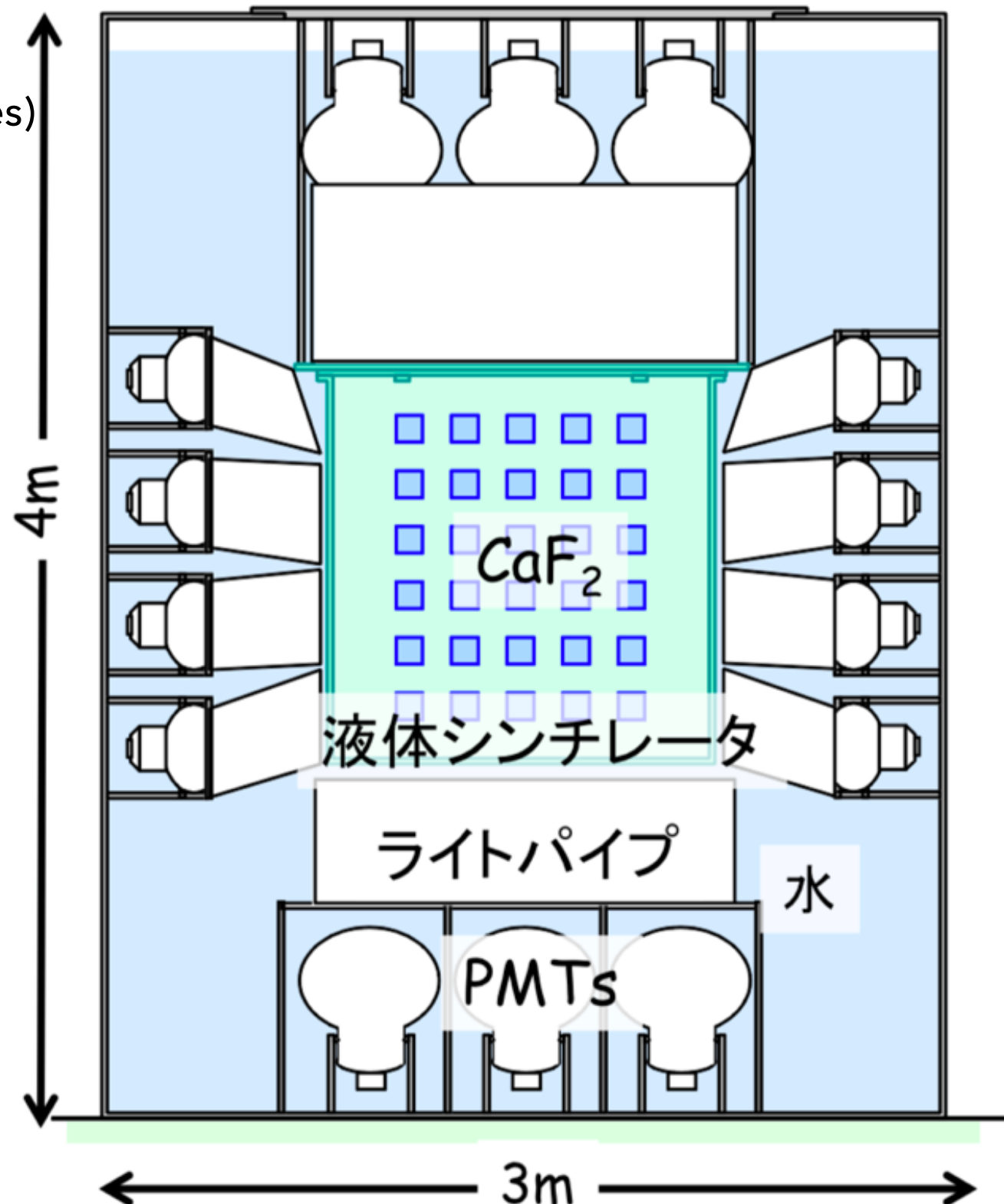
- Too small natural abundance
- Difficult of enrichment

In the future

- Improve the enrichment
- Use "Scintillating Bolometer" ?

Preliminarily

$$T_{1/2}^{0\nu} > 0.33 \times 10^{23} \text{ yr (90\%C.L.)}$$

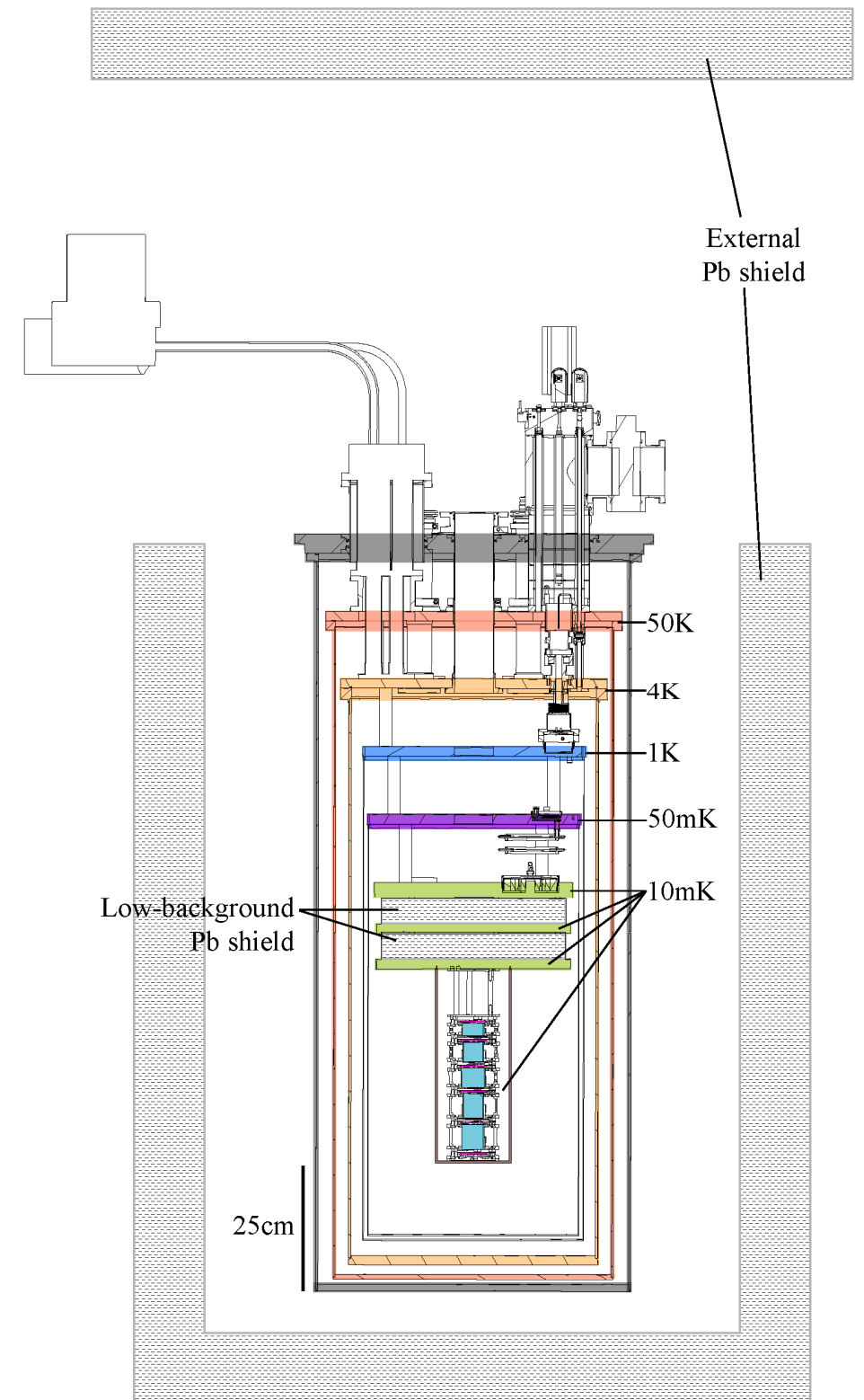
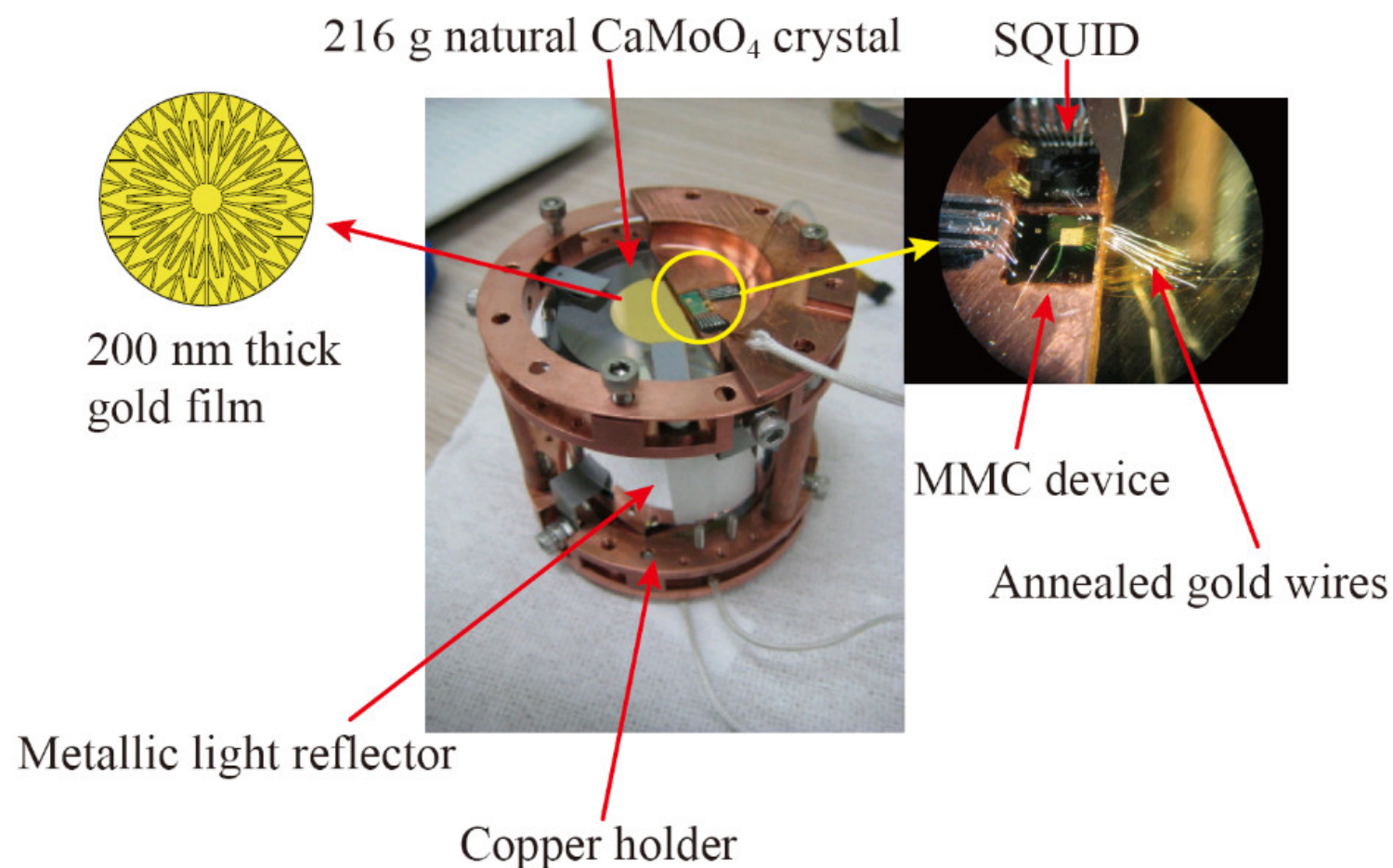


AMoRE @ YangYang, Korea

(Advanced **Mo** Rare process **E**xperiment)

• <https://arxiv.org/abs/1512.05957>

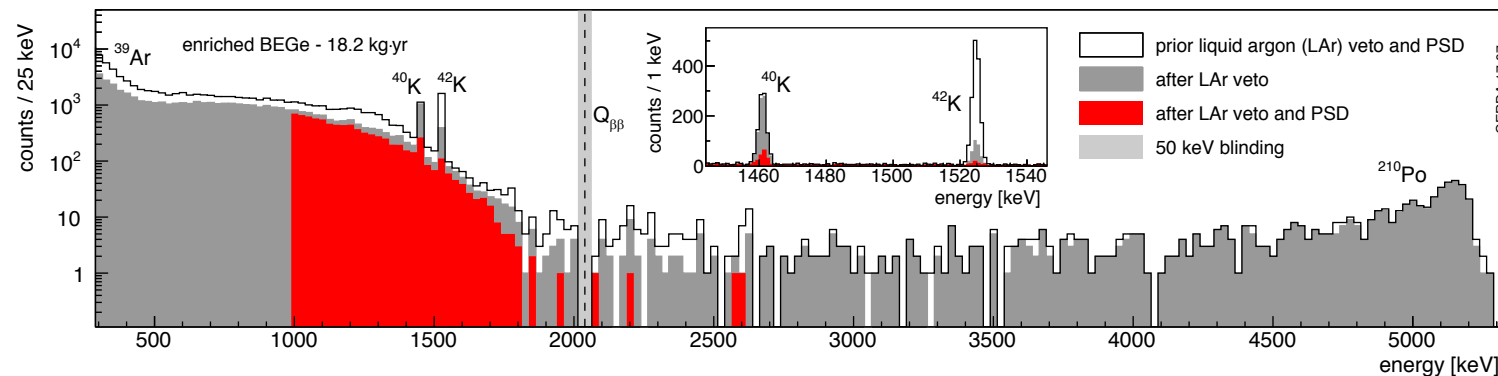
- Target; ^{100}Mo ($Q=3034\text{keV}$); 1.5-5kg
- Detector; $^{40}\text{Ca}^{100}\text{MoO}_4$ scinti-bolometer
- MMC photon sensor; $\Delta E=5\text{keV}$ @ 3MeV



GERDA @ LNGS, Italy

(**GER**manium **D**etector **A**rray)

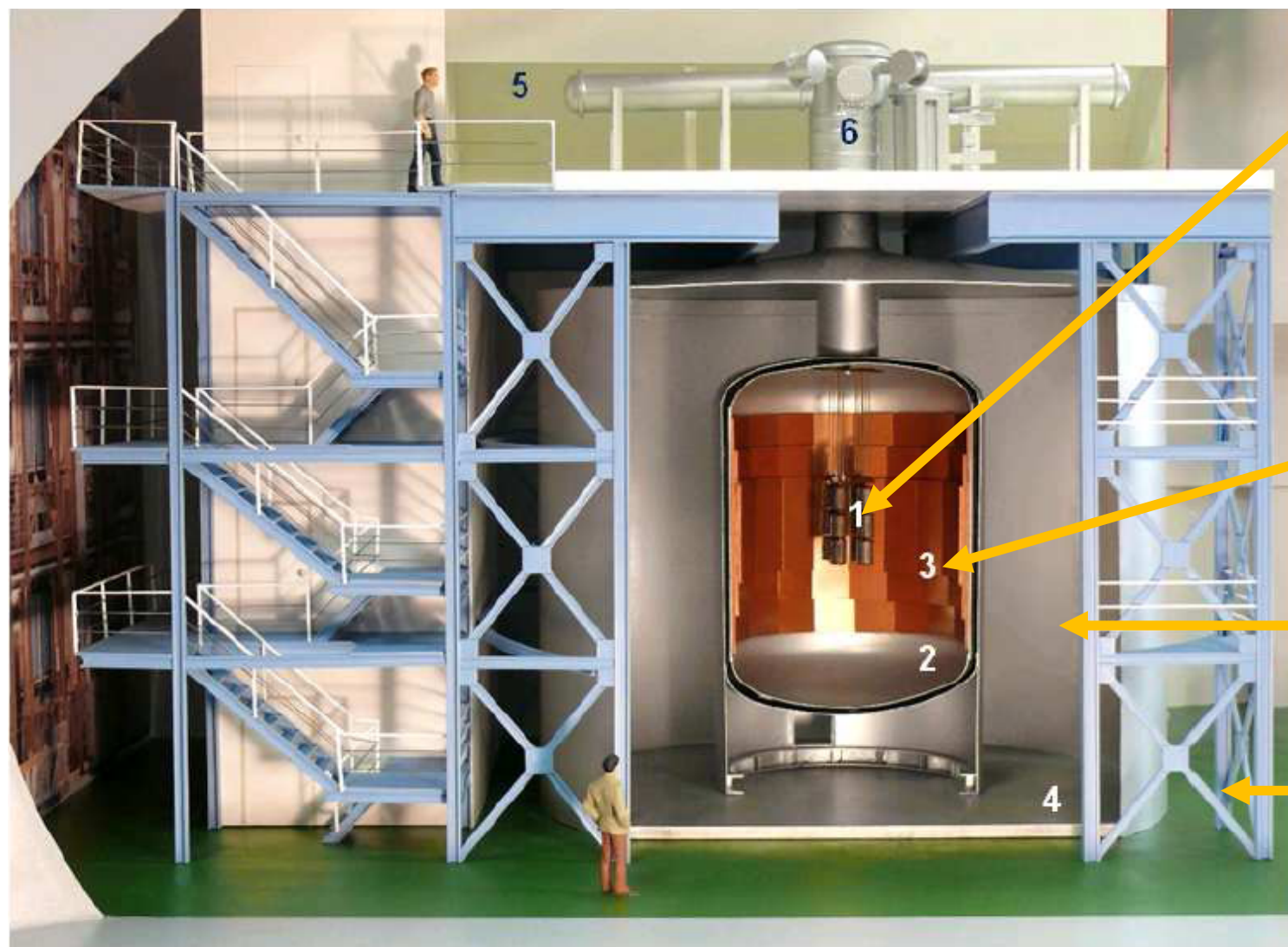
•<https://arxiv.org/abs/1212.4067>
•<https://arxiv.org/abs/1703.00570>
•<https://arxiv.org/abs/1803.11100>



Phase-II started from 2015

Background-free detector

(High energy resolution)



87% enriched ^{76}Ge

Total 31kg

$Q=2039\text{keV}$

$\Delta E \sim 3\text{-}4 \text{ keV @ } Q\text{-value (FWHM)}$

Cryostat

64m³ LAr

for cooling & shielding

590m³ Water

for muon veto

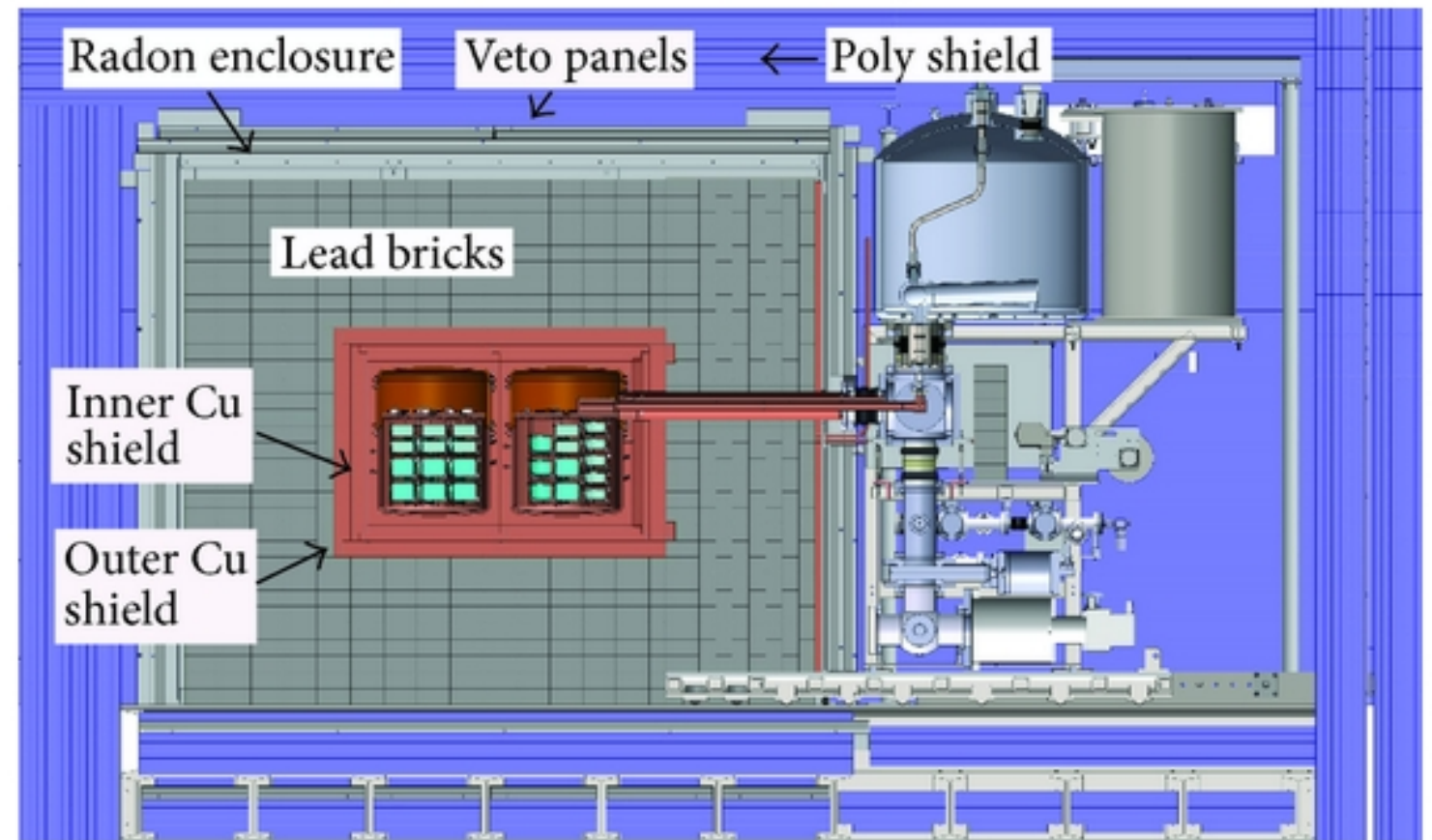
MAJORANA @ SURF

(The MAJORANA DEMONSTRATOR)

• <https://arxiv.org/abs/1710.11608>
• <https://www.hindawi.com/journals/ahep/2014/365432/>

- 30kg of 86% enriched ^{76}Ge
- $\Delta e = 0.16\%$ (4keV) @ 2039keV
- **P-type Point-Contact (PPC)** Germanium detectors

Background-free detector



PPC HPGe
Detector



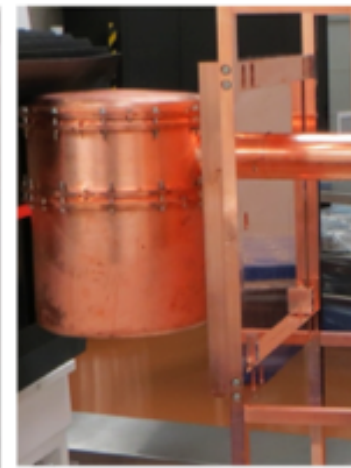
Low-Mass
Mount



String



7-String Array



Cryostat



Shield

LEGEND

(Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay)

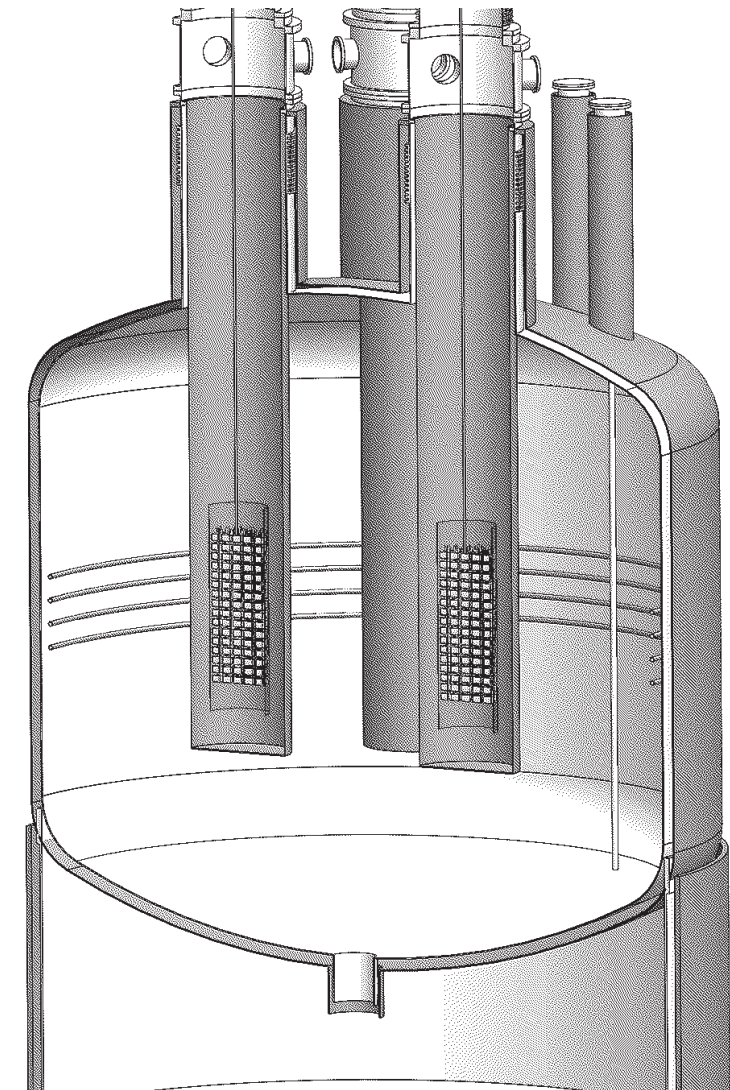
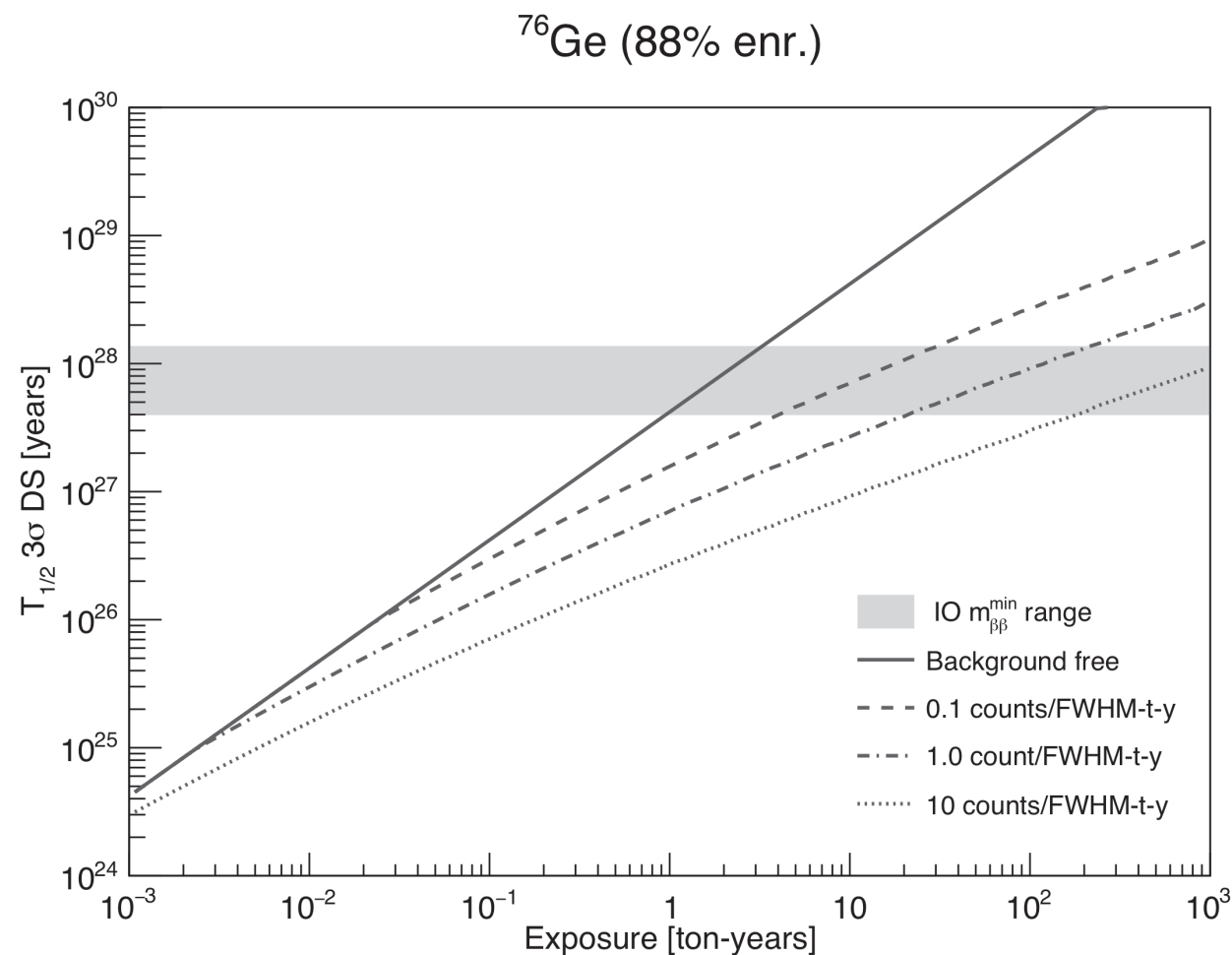
• <https://arxiv.org/abs/1709.01980>

Future project

GERDA + MAJORANA $\Rightarrow$ LEGEND

Background-free detector

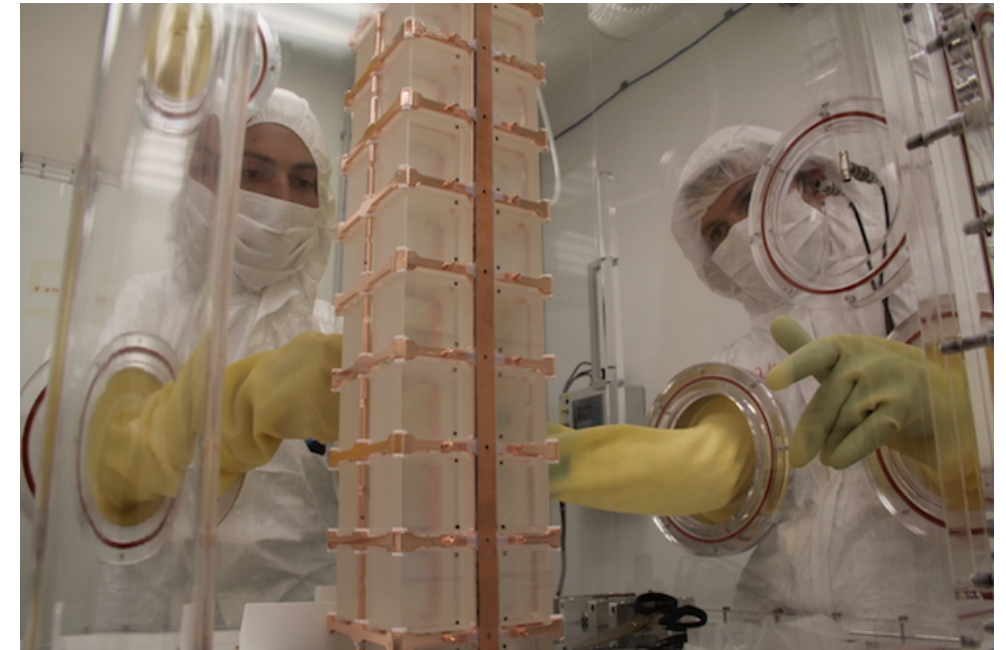
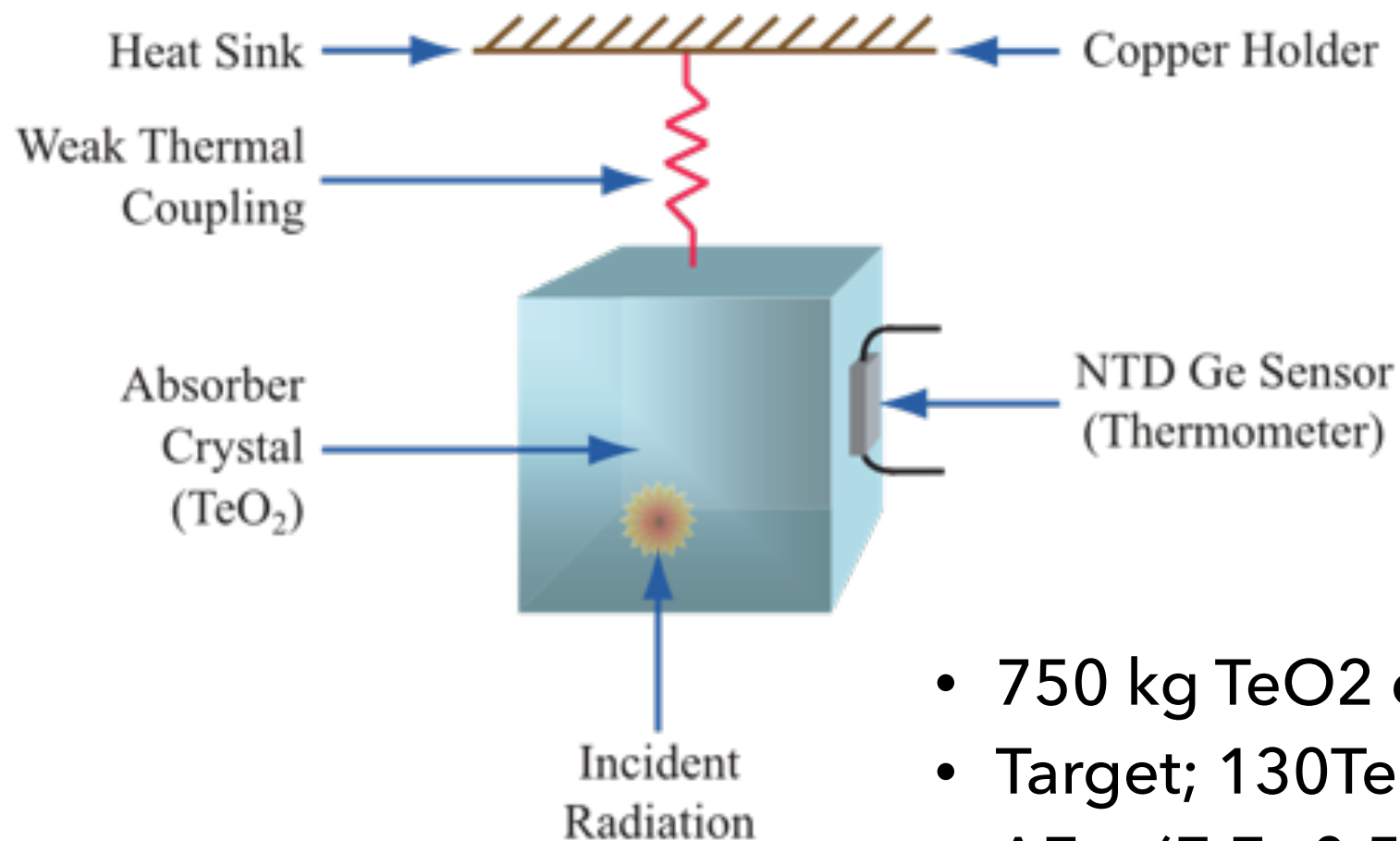
Using high purity ^{76}Ge with ton-scale



CUORE @ LNGS, Italy

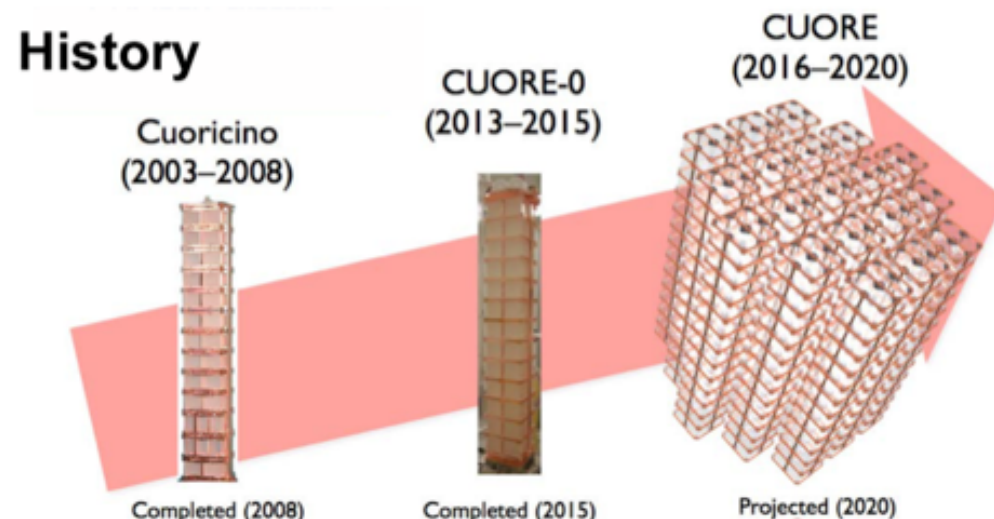
• <https://arxiv.org/abs/1710.07988>

(Cryogenic U nderground O bservatory for R are E vents)



- 750 kg TeO₂ crystals
- Target; ¹³⁰Te ($Q=2527\text{keV}$) 34% of nat.
- $\Delta E = (7.7 \pm 0.5) \text{ keV FWHM}$

High ΔE & Large mass detector



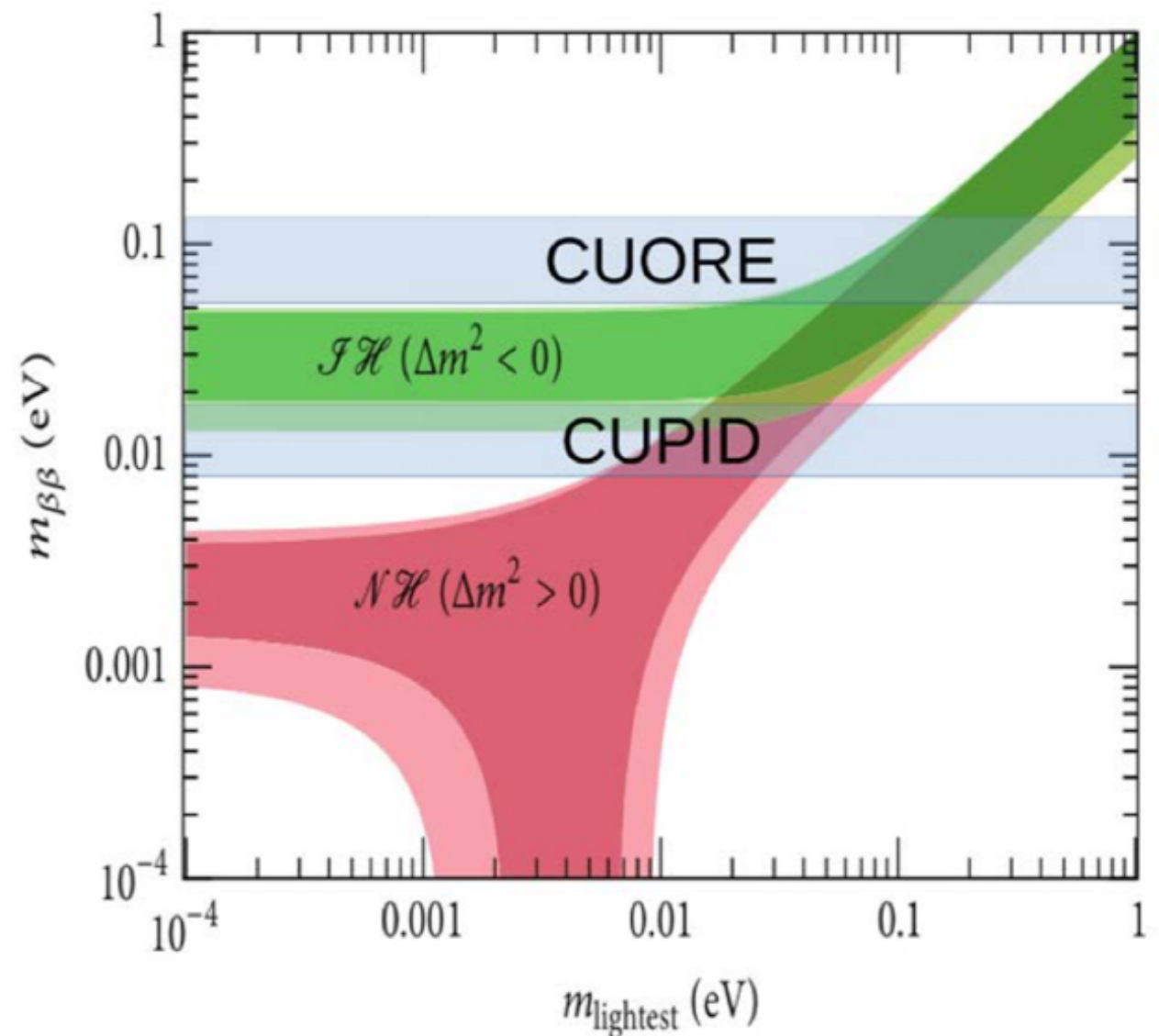
CUPID

Future project

Improvement from CUORE detector

Option1; Scintillating-Bolometer ($\text{Zn}^{82}\text{Se}/\text{Li}_2^{100}\text{MoO}_4$)

Option2; TeO_2 + Light-detector (PI by Cerenkov photon)

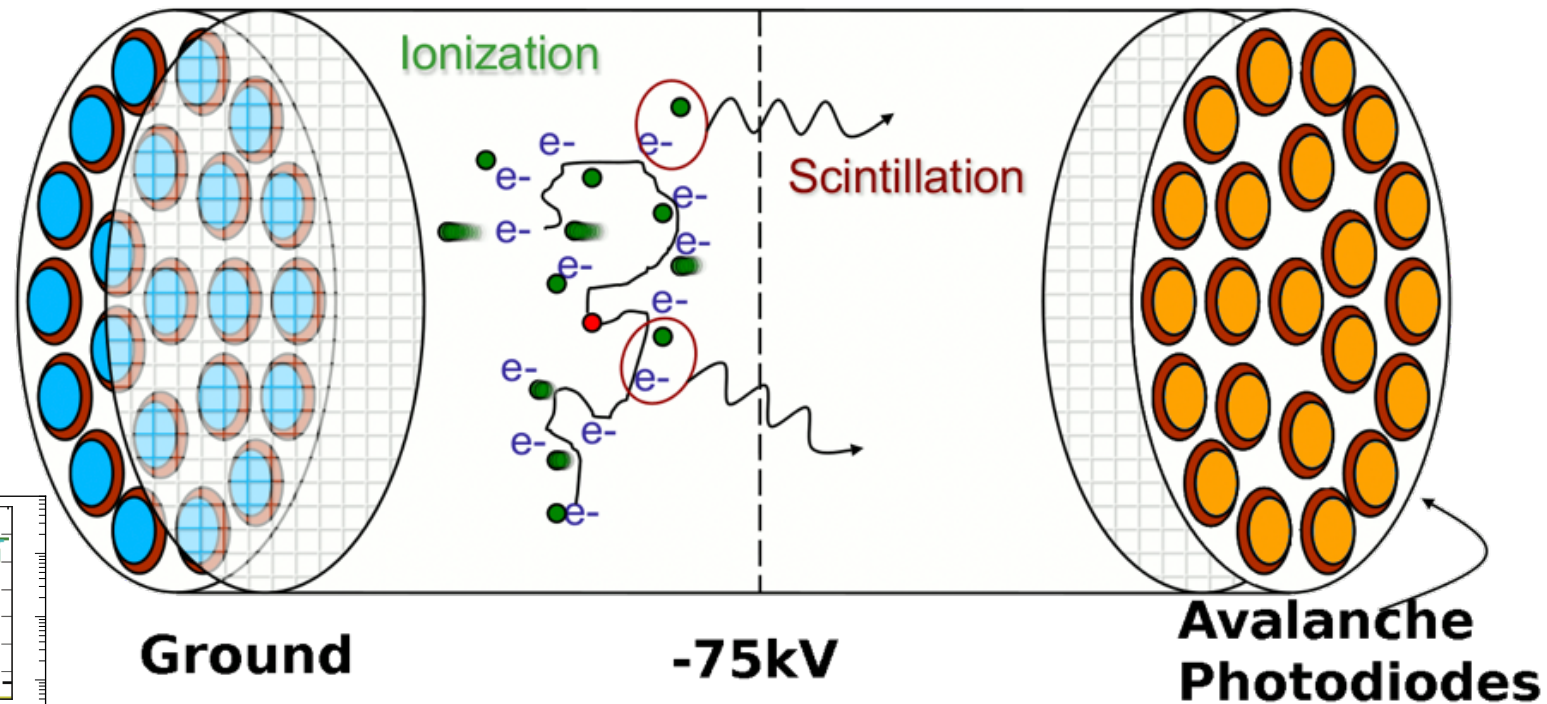


EXO-200 @ WIPP, New Mexico

(Enriched Xenon Observatory)

• <https://arxiv.org/abs/1402.6956>
 • <https://arxiv.org/abs/1605.06552>

- Liquid Xenon TPC; 175kg×86% of ^{136}Xe + LAAPD
- $\sigma/E = 1.53\%$ @ Q-value
- Ba tagging ?

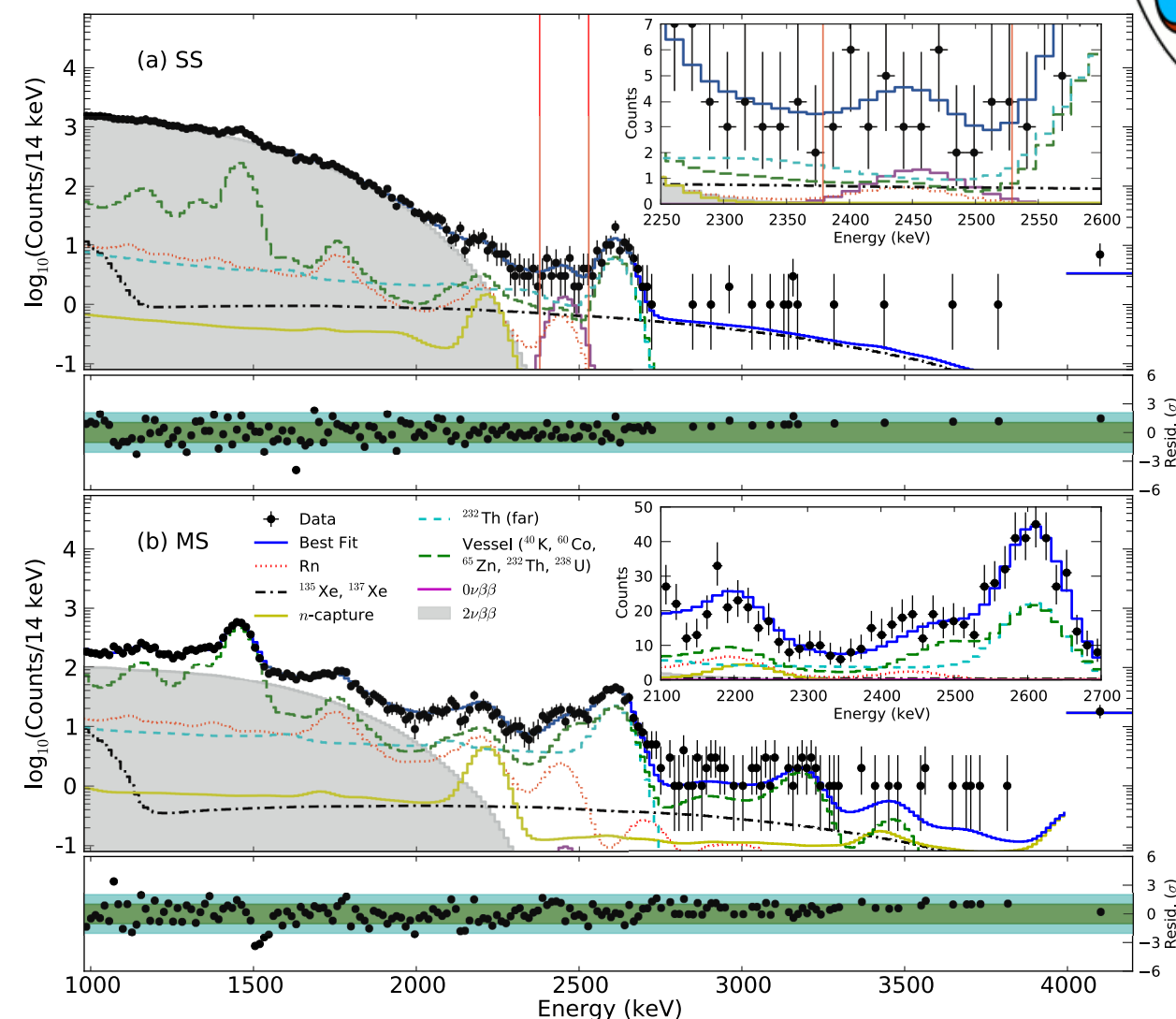


Detection (Signal/Background identification)

- TPC observes "e-" from ionization; → Identification Single/Multi-site
- APD detects "scintillation light"; → Energy, alpha-particle

Exotic double-beta

- Majoran (<https://arxiv.org/abs/1409.6829>)
- TPC violation (<https://arxiv.org/abs/1601.07266>)



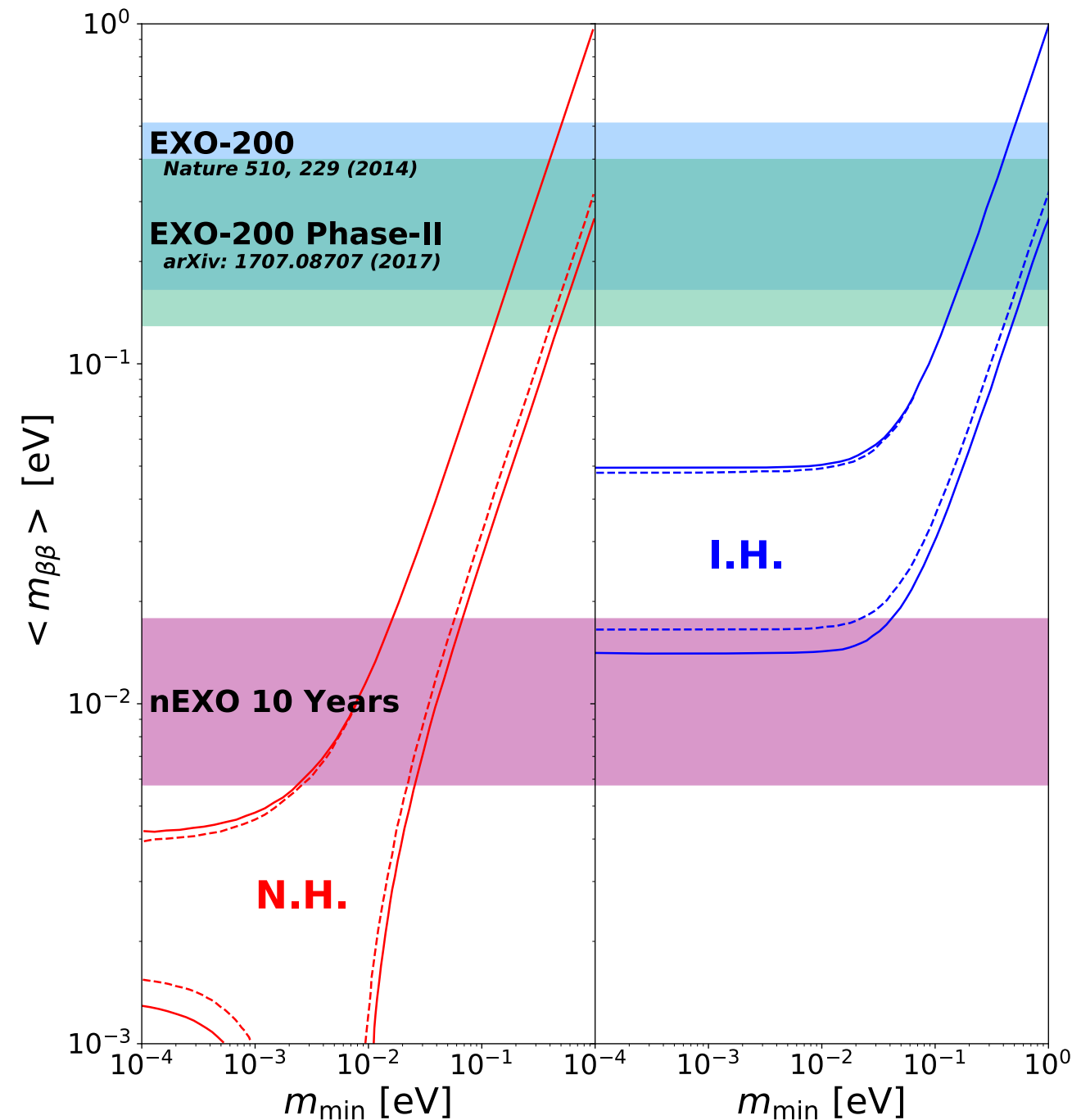
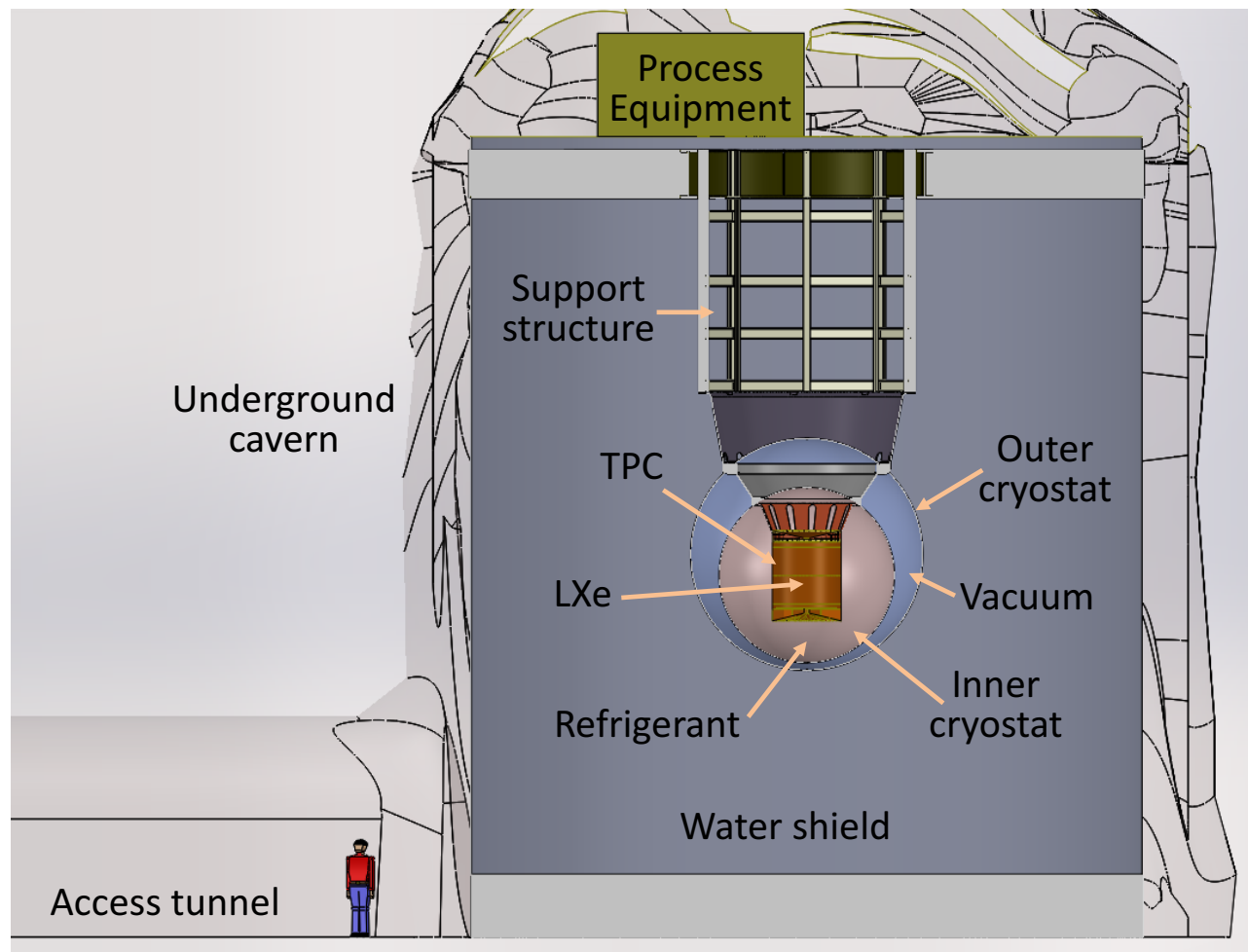
nEXO

(**n**ext **E**nriched **X**enon **O**bservatory)

• <https://arxiv.org/abs/1710.05075>

Future project

- ~5000kg of LXe
(TPC Xenon is ~ 4000kg)
- $\sigma/E < 1.0\%$
- In SNO Lab.



Super-NEMO@ Modane, France

()

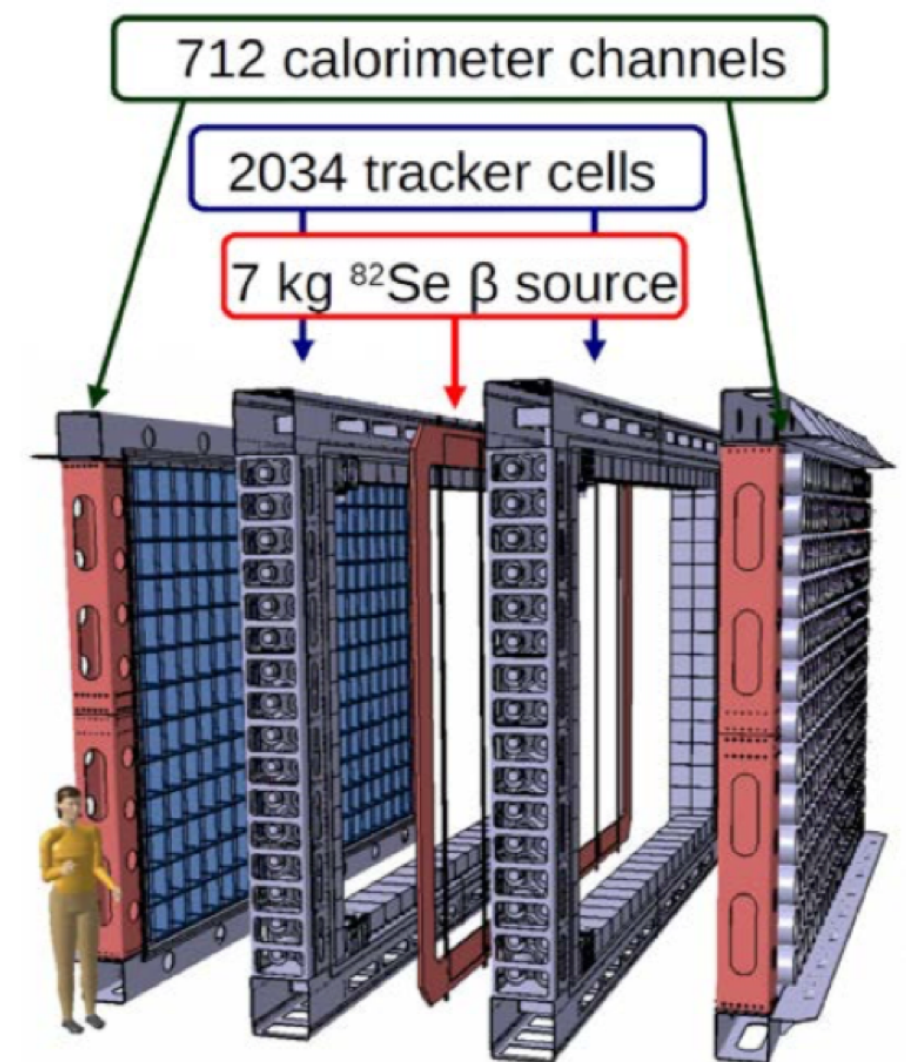
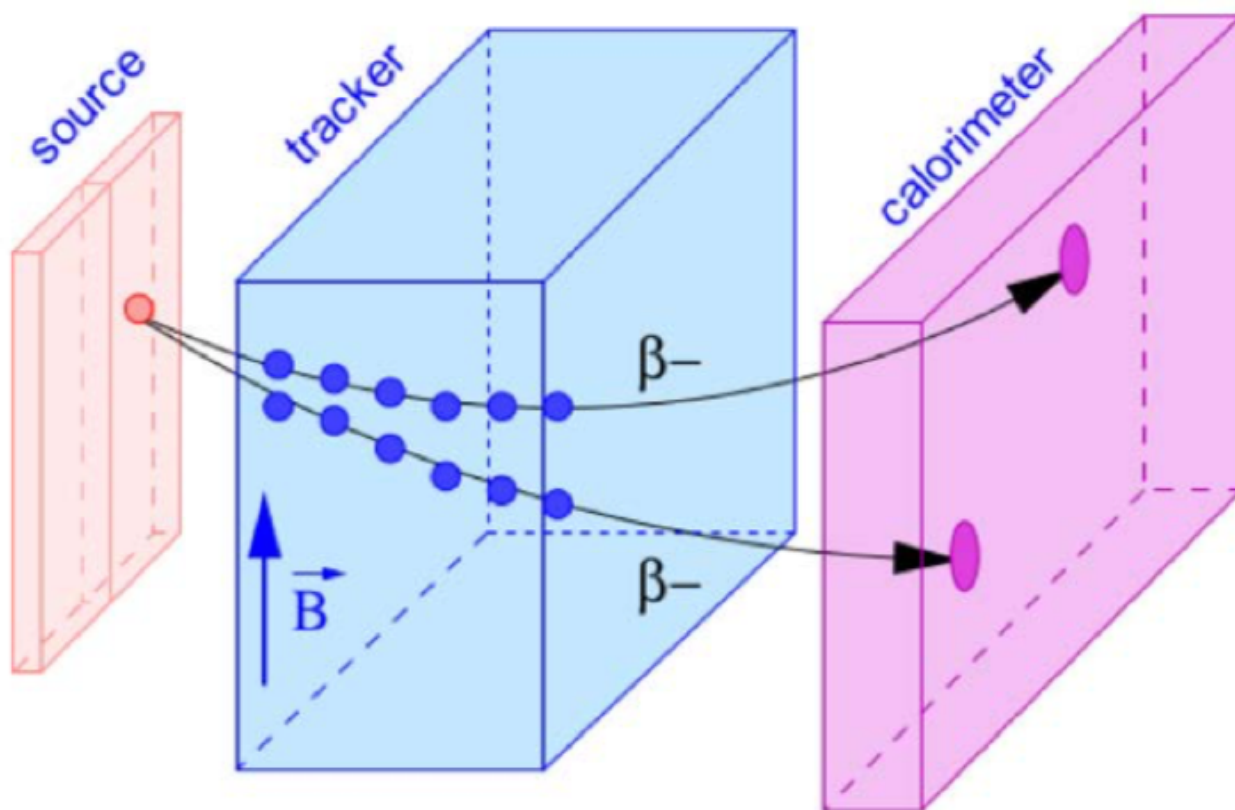
• <https://arxiv.org/pdf/1707.06823.pdf>

Future project

Tracking Detector

- Target; ^{82}Se etc, $\sim 7\text{kg/module}$ (total 100kg)
- $\Delta E = 8\% \text{ FWHM @ } 1\text{MeV}$

Currently working as NEMO-3



NEXT @ LSC, Spain

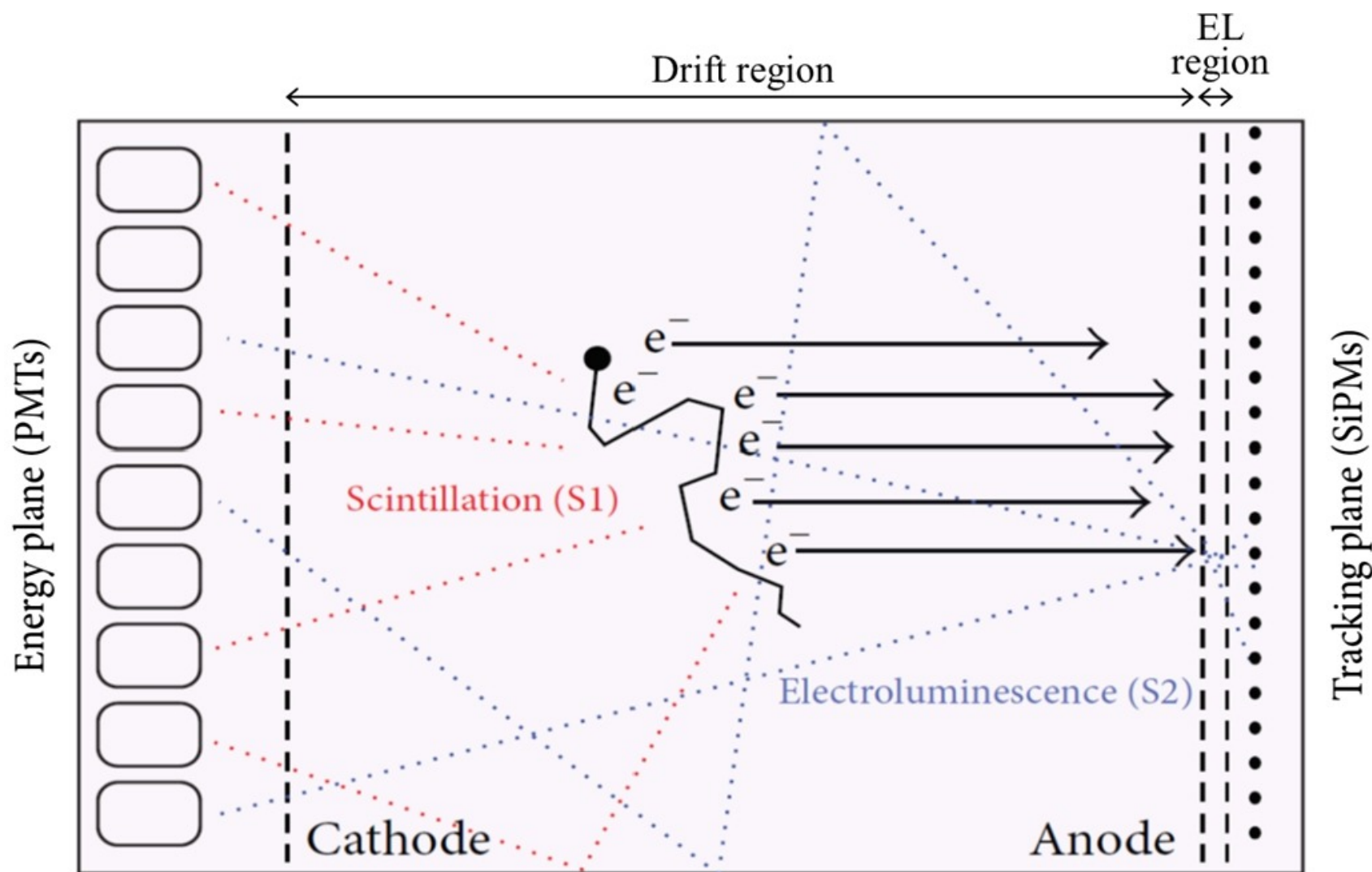
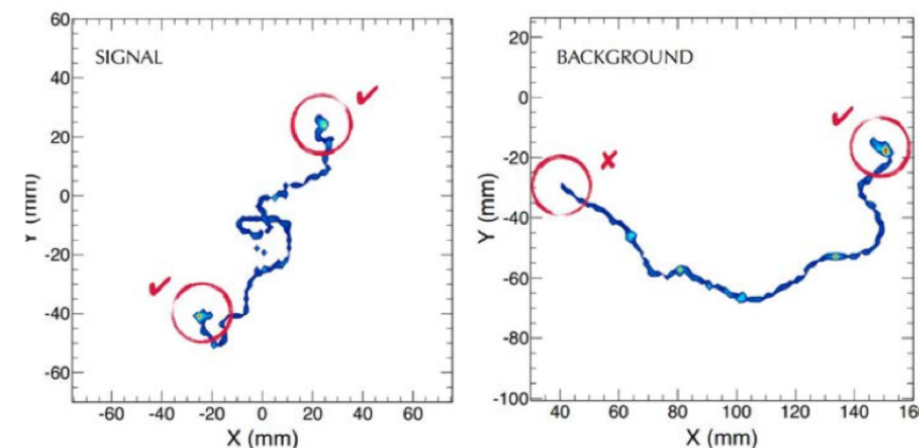
(**N**eutrino **E**xperiment with a **X**enon **T**PC)

• <http://iopscience.iop.org/article/10.1088/1748-0221/7/06/T06001/pdf>

• <https://www.sciencedirect.com/science/article/pii/S0370269317307153?via%3Dihub>

Future project

- 10-15bar Gas Xenon TPC; $^{136}\text{Xe} \sim 100\text{kg}$
- $\Delta E \sim 3\%$ @ 2.5MeV by Electro-Luminescence
- Using event topology



PANDAX-III

@ Jin-Ping, China

(Particle **A**nd **A**strophysical **X**enon Experiment)

• <https://arxiv.org/abs/1710.08908>

Future project

- 10-15bar Gas Xenon TPC; ^{136}Xe ~ 200kg
- Currently data taking with 20kg scale prototype

