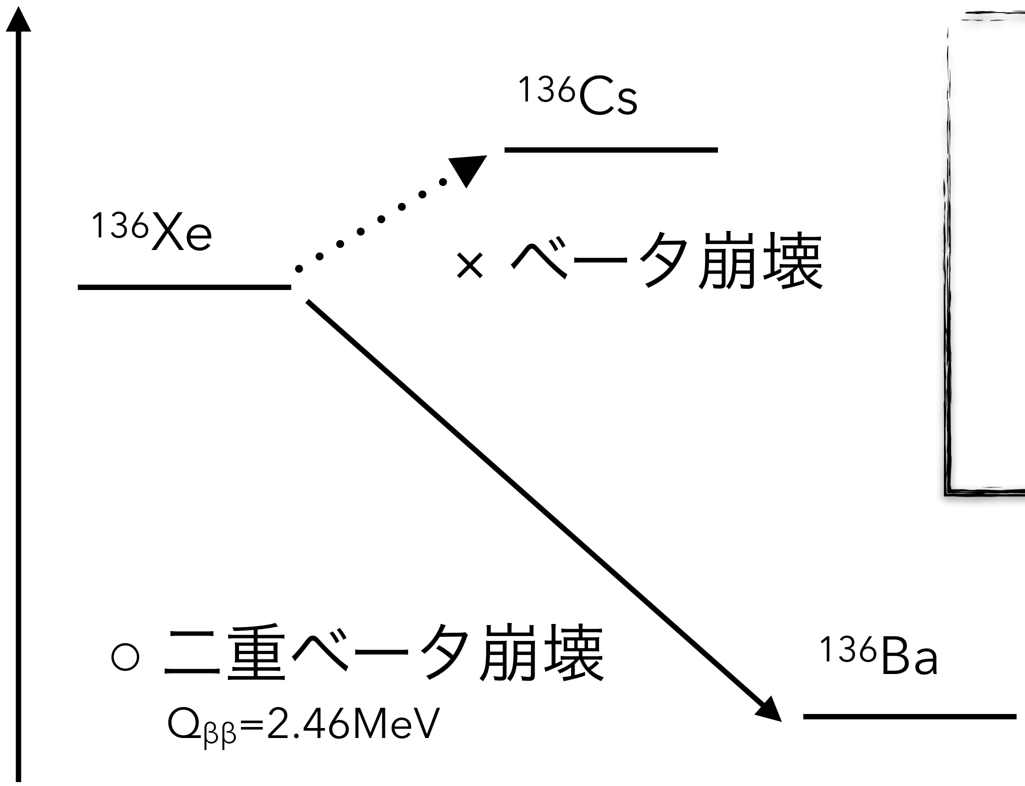
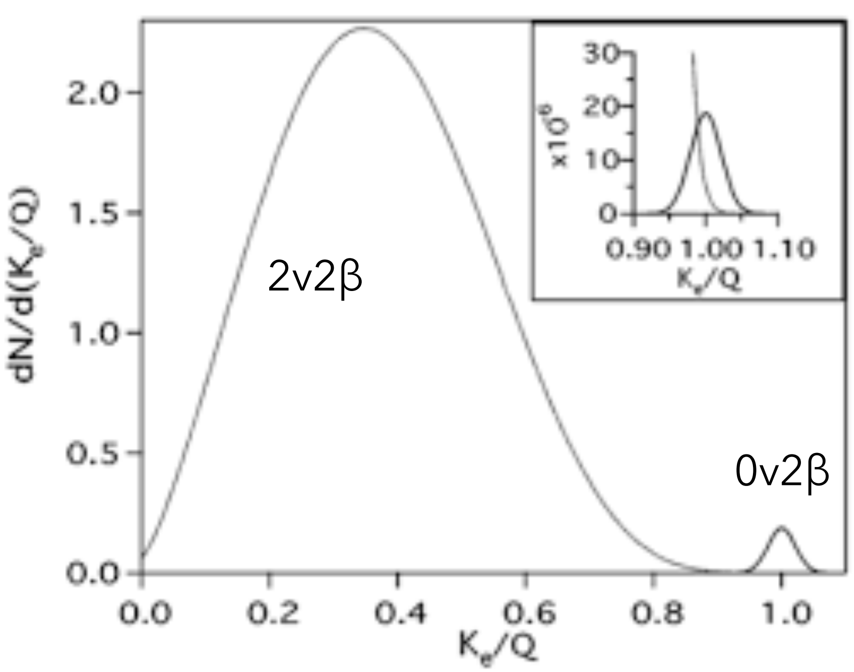
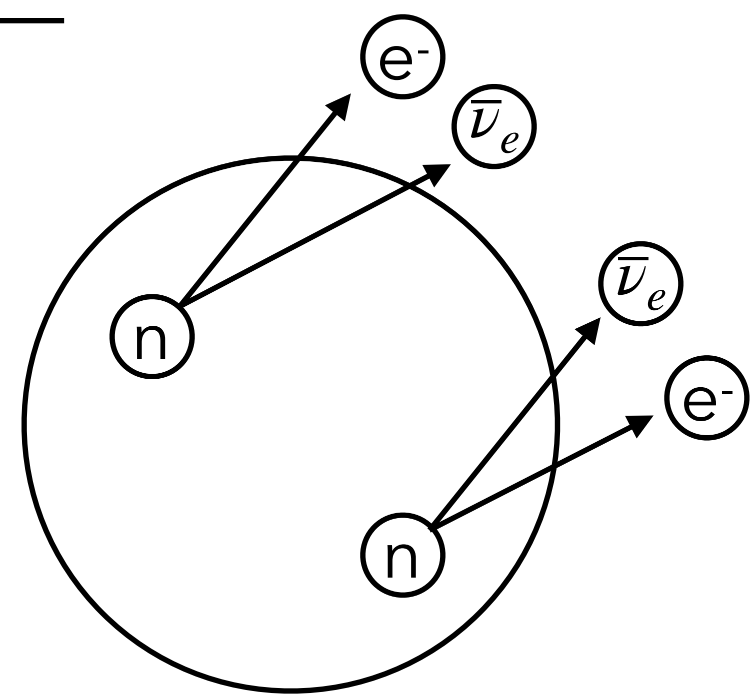
二重ベータ崩壊とは



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

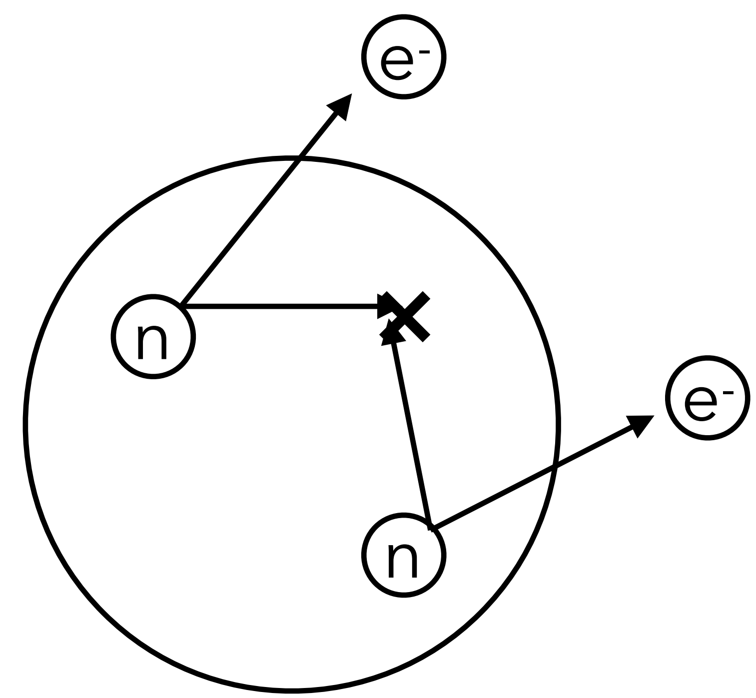


2v2β モード



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

0v2β モード



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

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, MAJOARANA
^{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

世界の0ν2β探索と将来

✔ 背景事象が感度制限している場合

KamLAND-Zen, SNO+, …

✔ 背景事象が無視できて, 統計が感度制限している場合

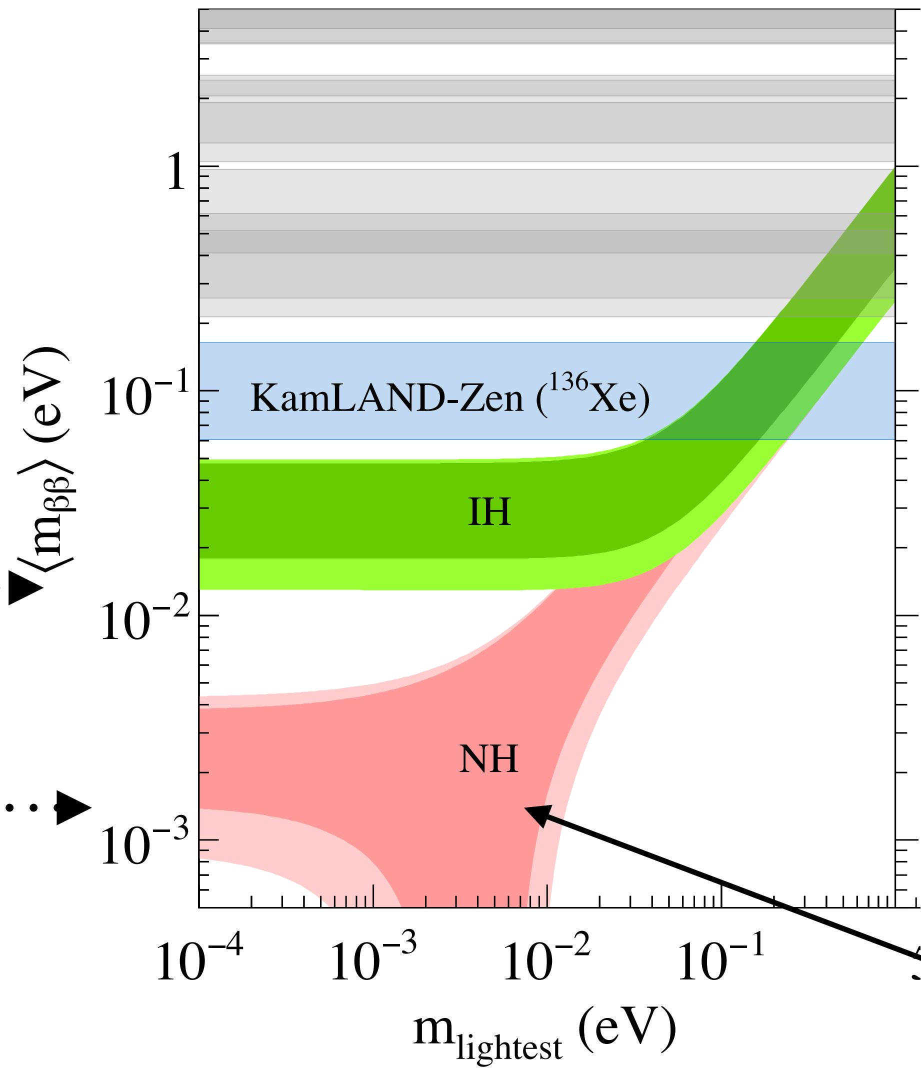
GERDA, MAJORANA, CUORE, …

~500kg-yr ………▶

1 ton × 10yr ………▶

100 ton × 10yr ………▶

◀……… 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"

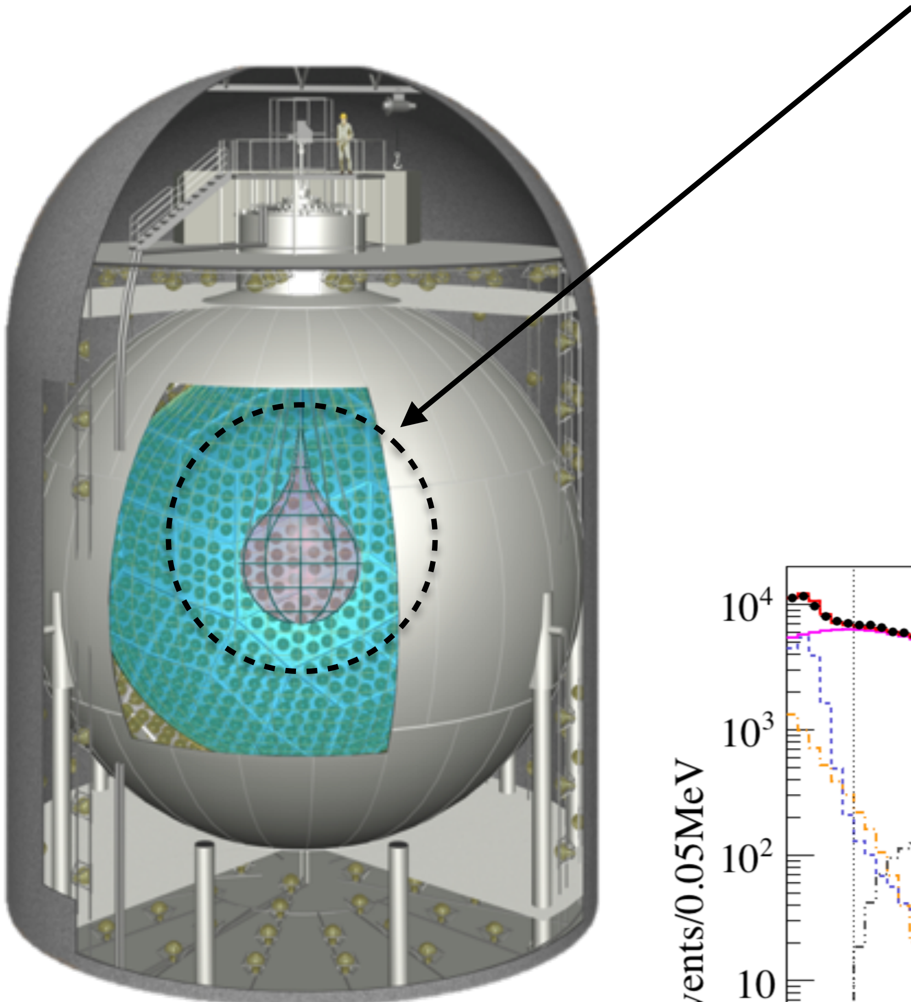
KamLAND-Zen 400

(**KamLAND-Ze**ro **n**eutrino double-beta decay search)

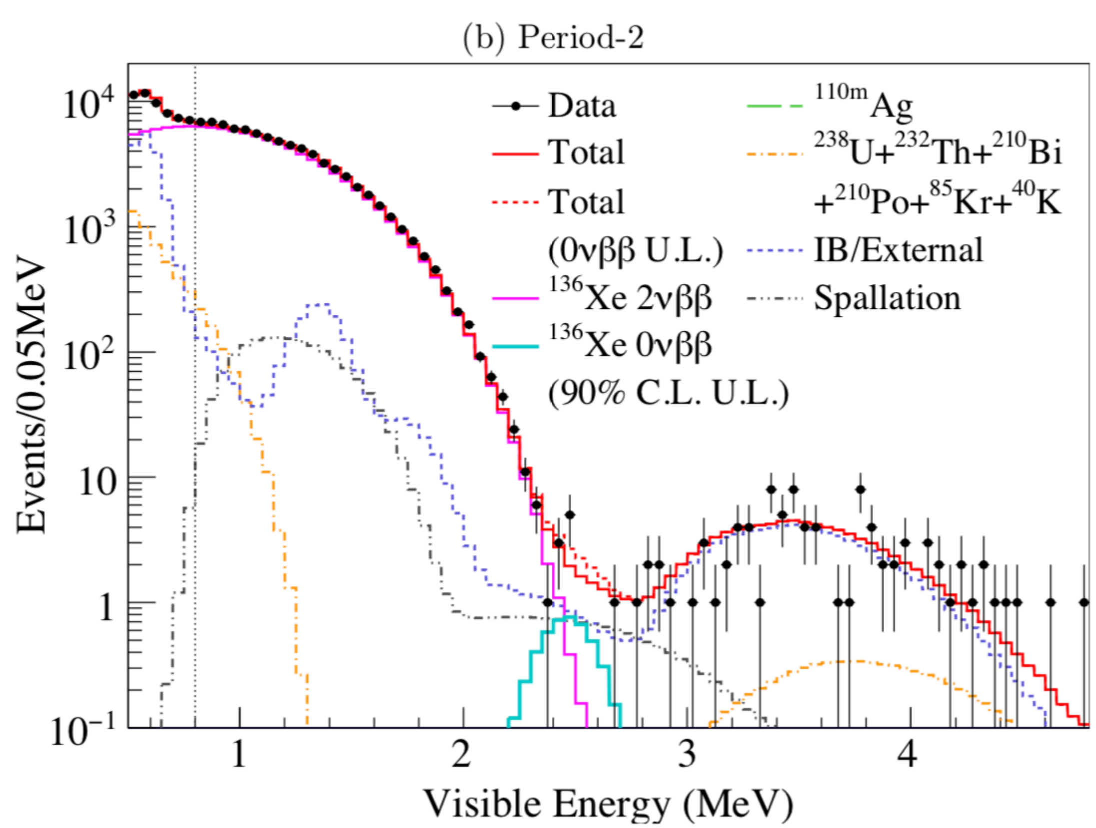
@ Kamioka, Japan

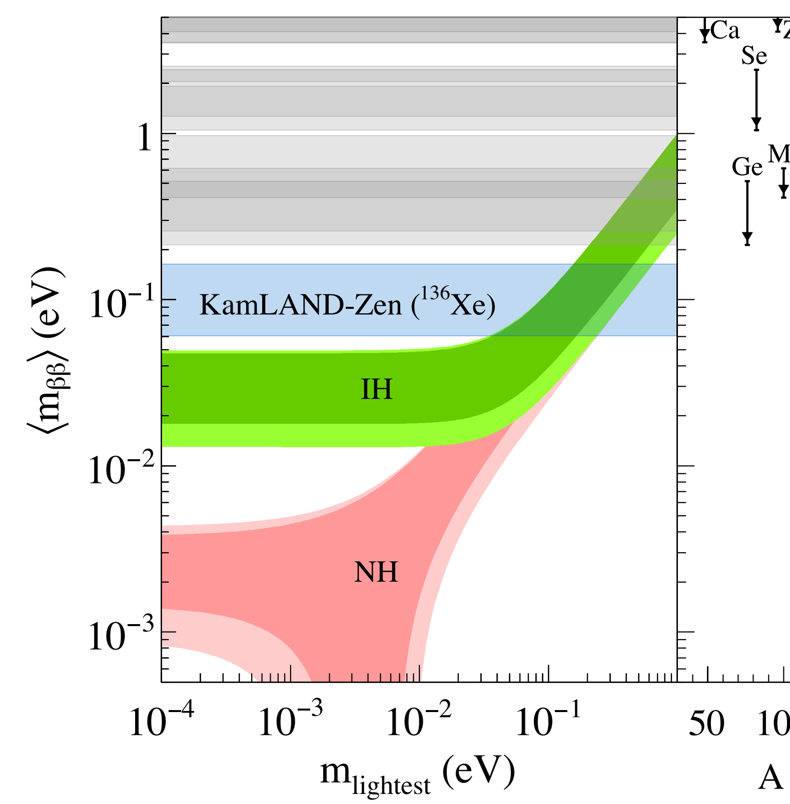
- https://arxiv.org/abs/1605.02889

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



- σ/E = 6.6%/√E
- BG; 2v2b, ^{10}C, ^{214}Bi, ^{110m}Ag
- T>1.07×10^{26} yr (90% C.L.) ⇔ 61-165meV

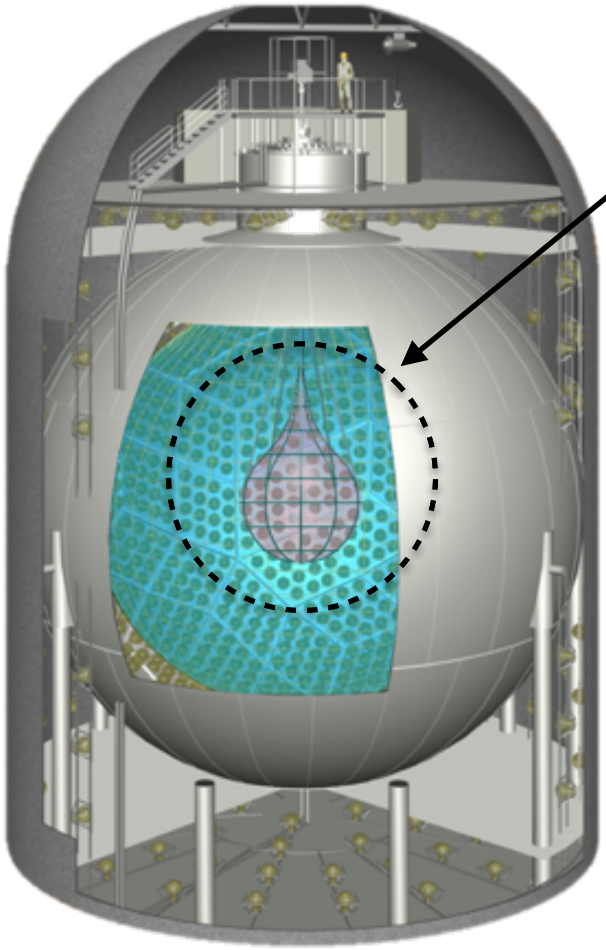




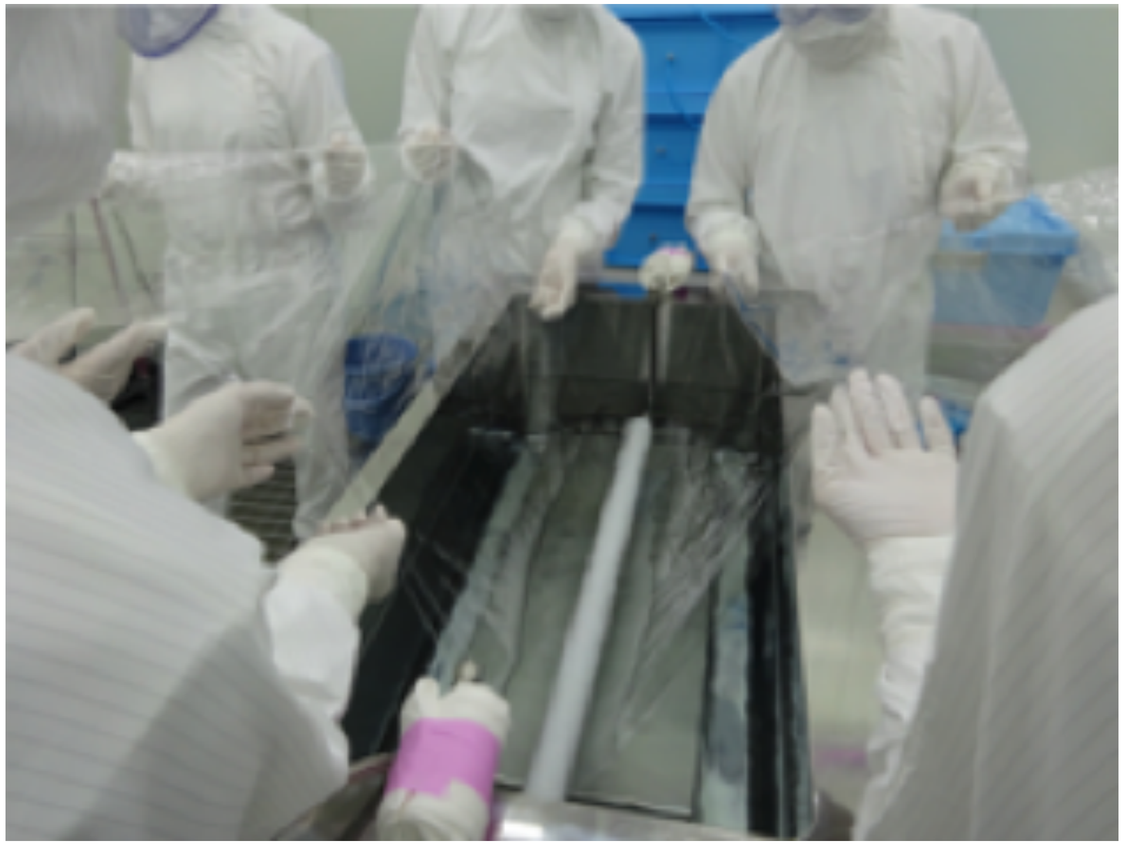
KamLAND-Zen 800

(**KamLAND-Ze**ro **n**eutrino double-beta decay search)　@ Kamioka, Japan

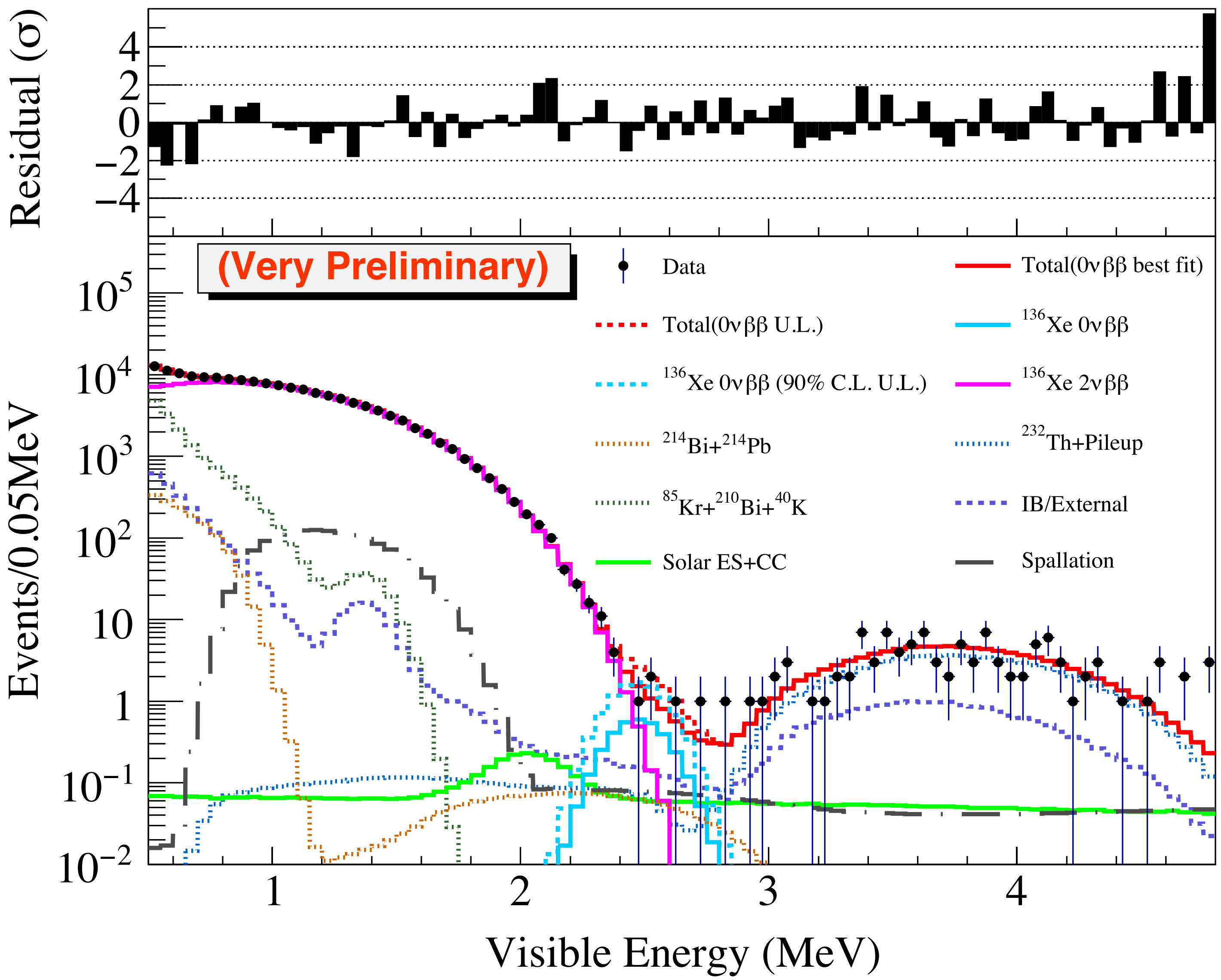
- Use ^{136}Xe loaded liquid-scintillator ; **~780kg**
- **R~1.9m** inner-balloon is a target volume



- 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



Fitting results



Summary of observed & best-fit events in ROI

Observed events	8
Best-fit total events	10.7
$0\nu\beta\beta$	2.8
$2\nu\beta\beta$	5.1
^{214}Bi in LS	0.4
^{212}Bi-^{212}Po pile-up	0.4
Film BG (^{214}Bi)	0.9
Spallation (^{10}C)	0.2
Spallation (^{137}Xe)	0.1
Spallation (short-lived)	0.2
Solar ^{8}B ν	0.4

Best fit : 2.1 events/day/kton-XeLS

90% Upper limit : < 6.0 events/day/kton-XeLS

$T^{0\nu}_{1/2} > 4 \times 10^{25}$ year (90% C.L.)

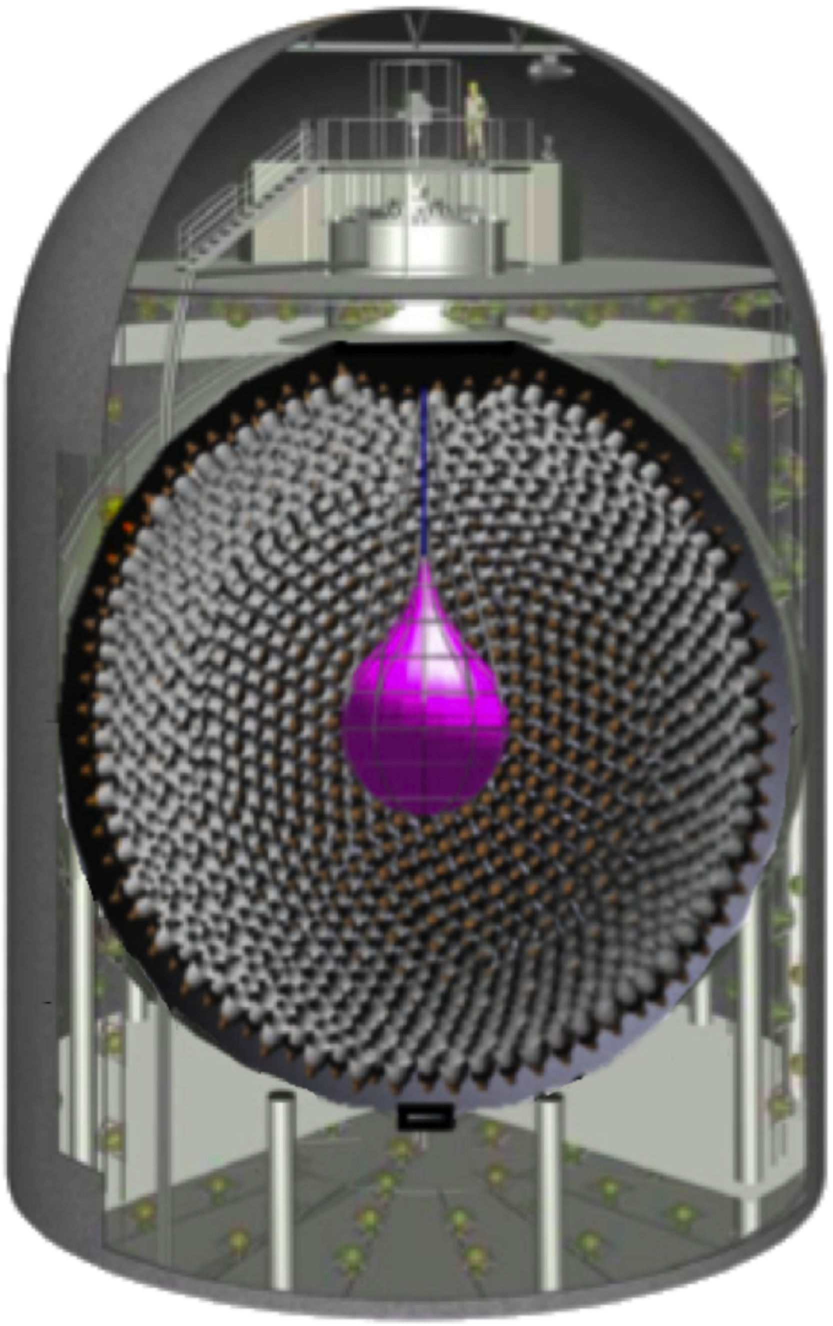
KamLAND2-Zen

(**KamLAND2-Ze**ro **n**eutrino 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; 3.2kg×96 cyrstals
- ^{48}Ca; Q=4.27MeV
- Liquid scintillator; active-veto

Using a pulse shape difference btw CaF2 ⇔ LS

Critical Problem

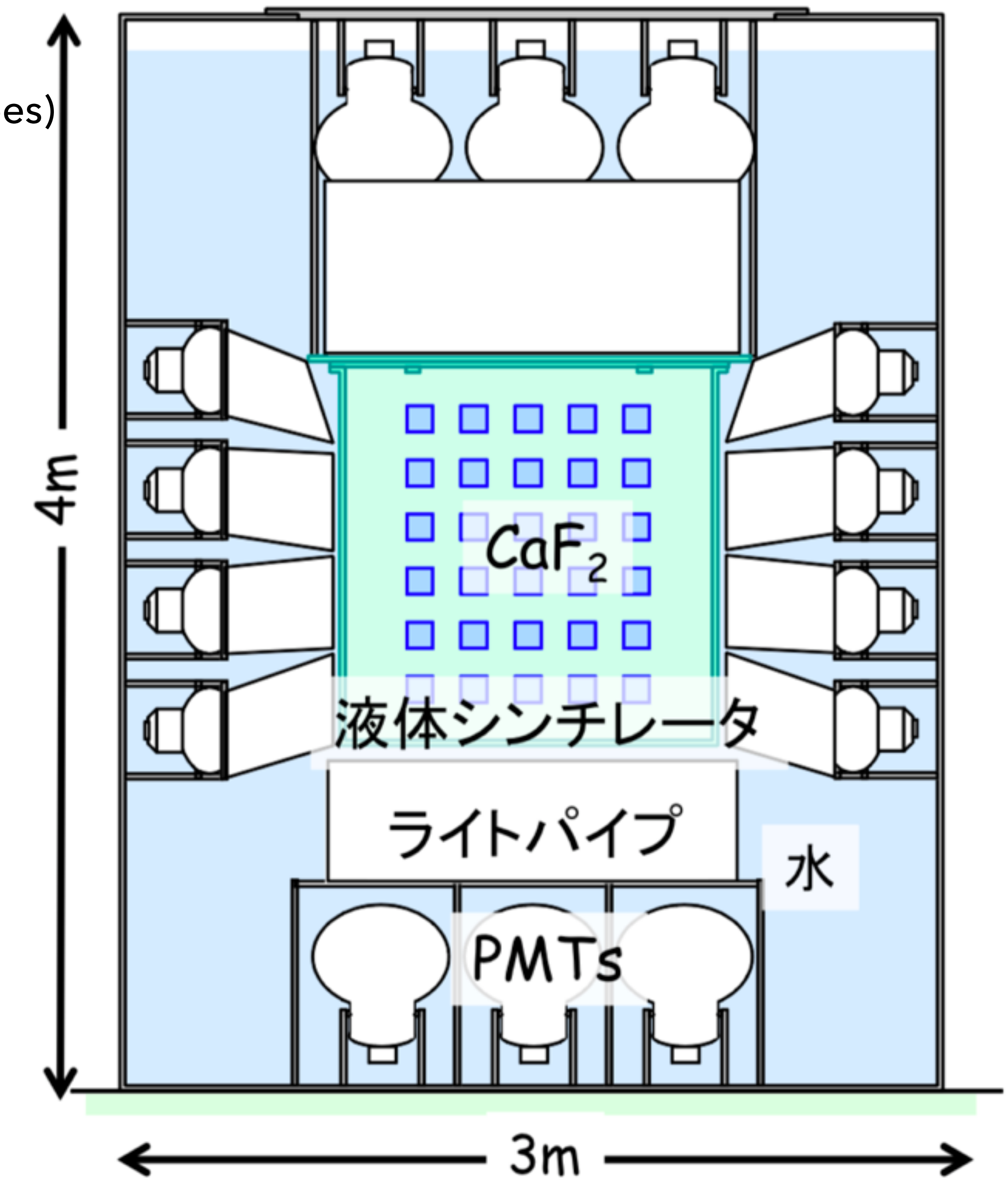
- Too small natural abundance
- Difficult of enrichment

In the future

- Improve the enrichment
- Use “Scintillating Bolometer” ?

Preliminarily

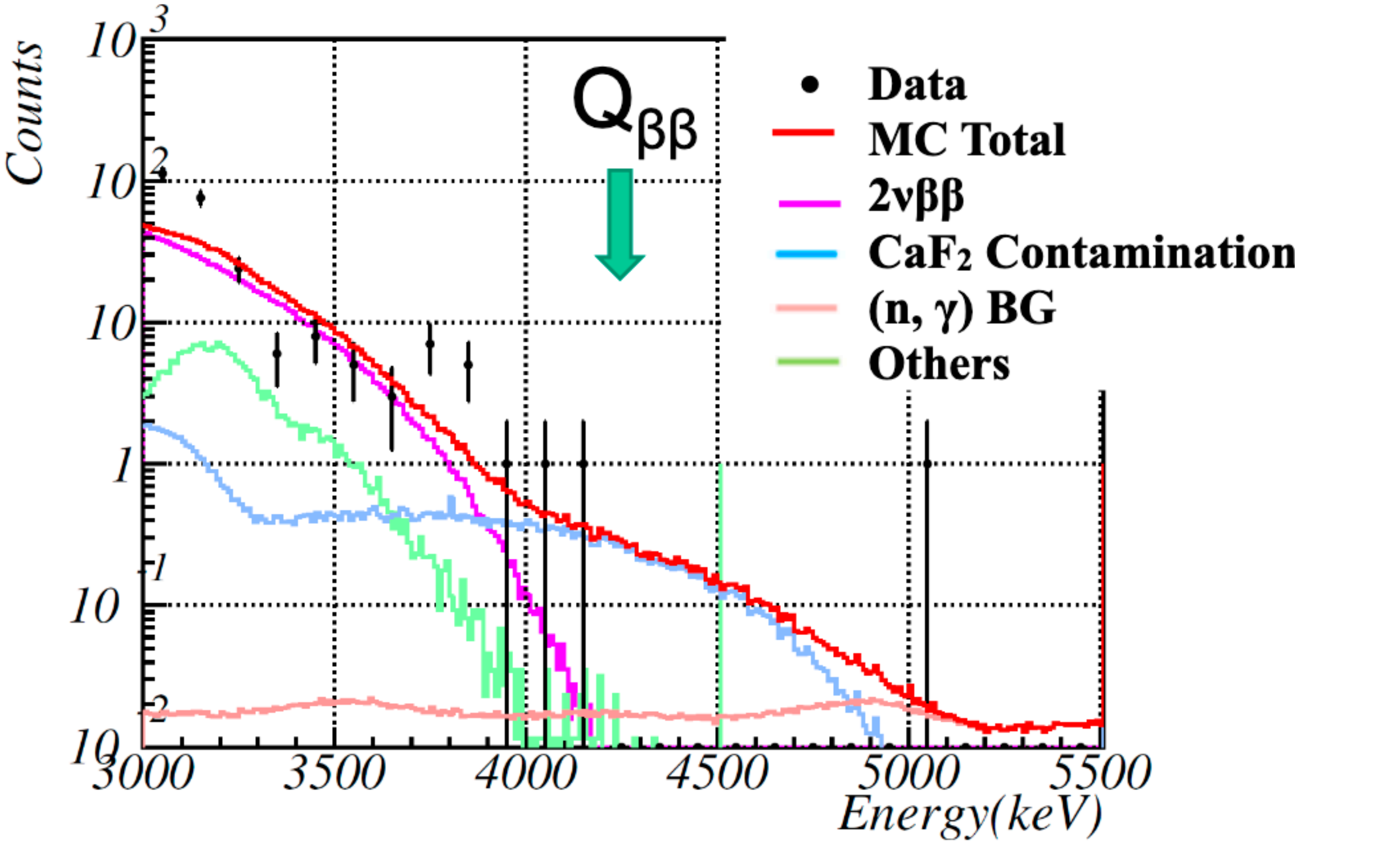
$$T_{1/2}^{0\nu} > 0.33 \times 10^{23} \text{ yr (90\%C.L.)}$$



Results

	27 Crystals
Live time (days)	131
$0\nu\beta\beta$ eff.	0.39±0.06
Event in ROI	0
Expected BG	~1.2
$T^{1/2}_{0\nu\beta\beta}$ ^{48}Ca(yr)	$> 6.2 \times 10^{22}$
Sensitivity (Yr)	3.6×10^{22}

Exp.Data and BG MC in 27 CaF_2



ELEGANT IV (previous study)

Exposure : 4947 kg・d (2yr<)
0νββ eff. : 0.53
$T^{1/2}_{0\nu\beta\beta}$: 5.8×10^{22} yr (^{48}Ca)

- CANDLES is now giving the best lifetime limit !
- Add purity 14 crystals and increase statistics

Taken from TAUP2019

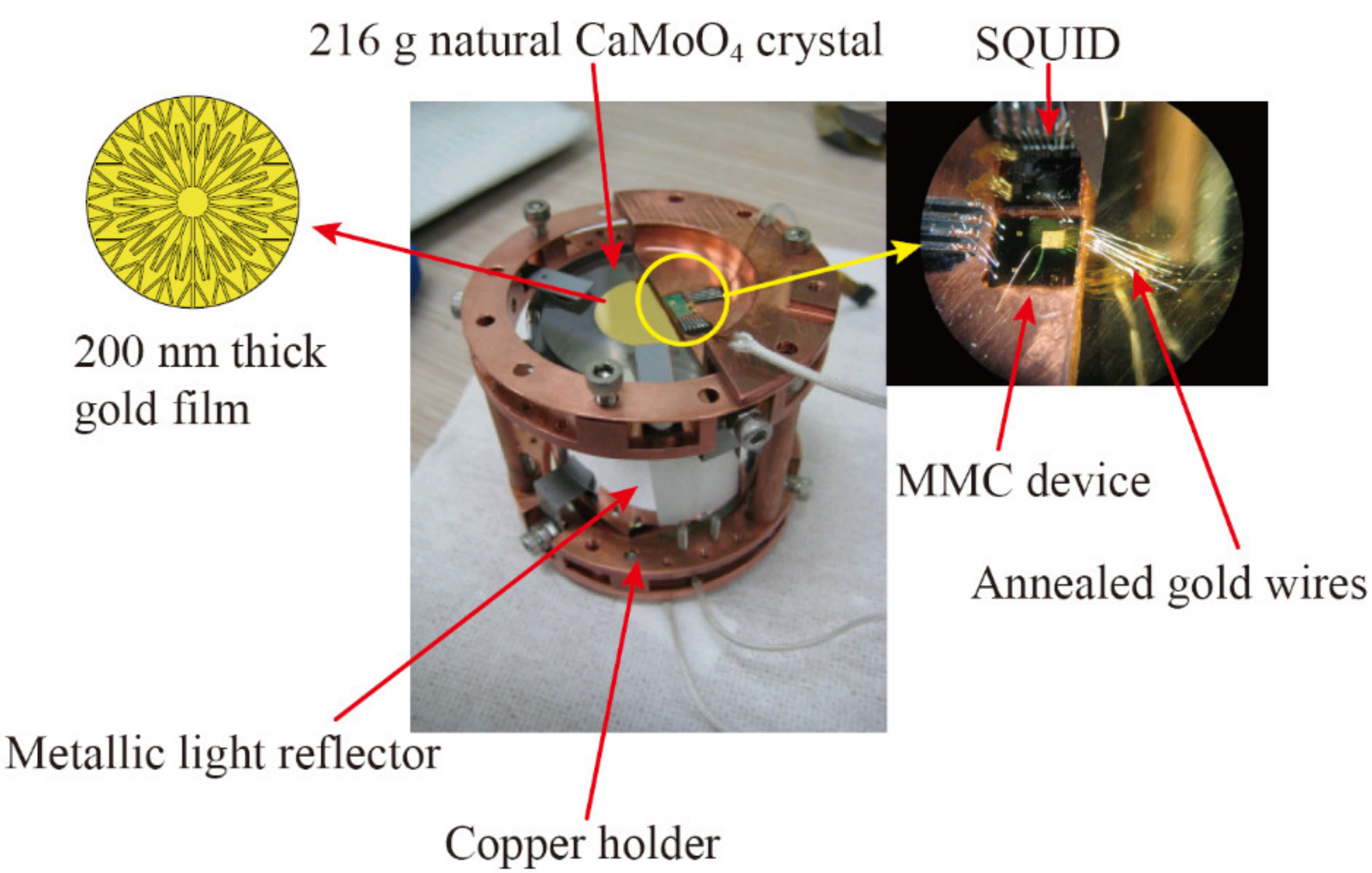
AMoRE @YangYang, Korea

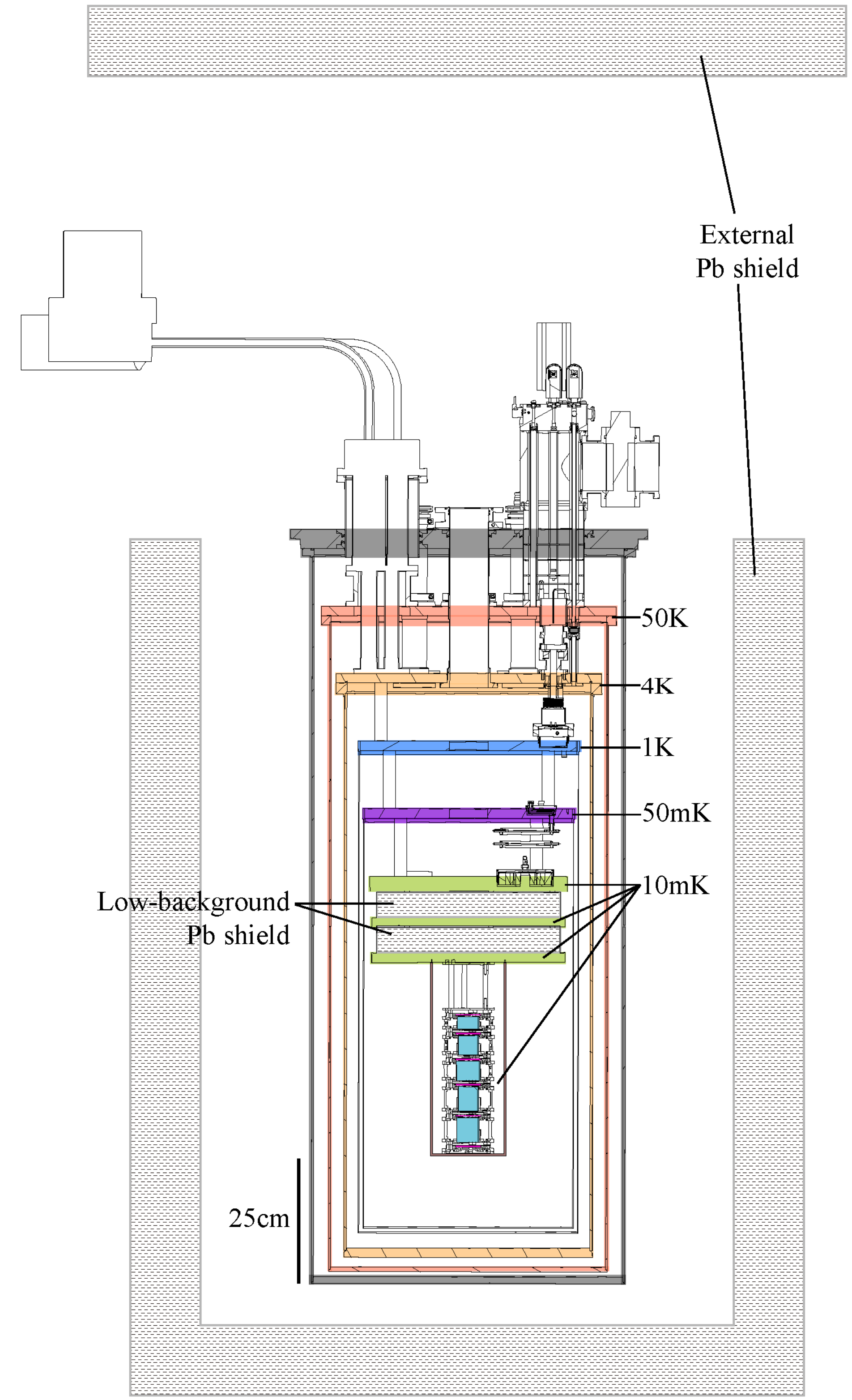
(**A**dvanced **Mo** **R**are process **E**xperiment)

•https://arxiv.org/abs/1512.05957

https://arxiv.org/abs/1903.09483

- Target; ^{100}Mo (Q=3034keV); 1.5-5kg
- Detector; $^{48depl}Ca^{100}MoO_4$ scinti-bolometer
- MMC photon sensor; ΔE=5keV @ 3MeV
- T> 9.5e+22 yr, m<1.2–2.1eV (90%C.L.)

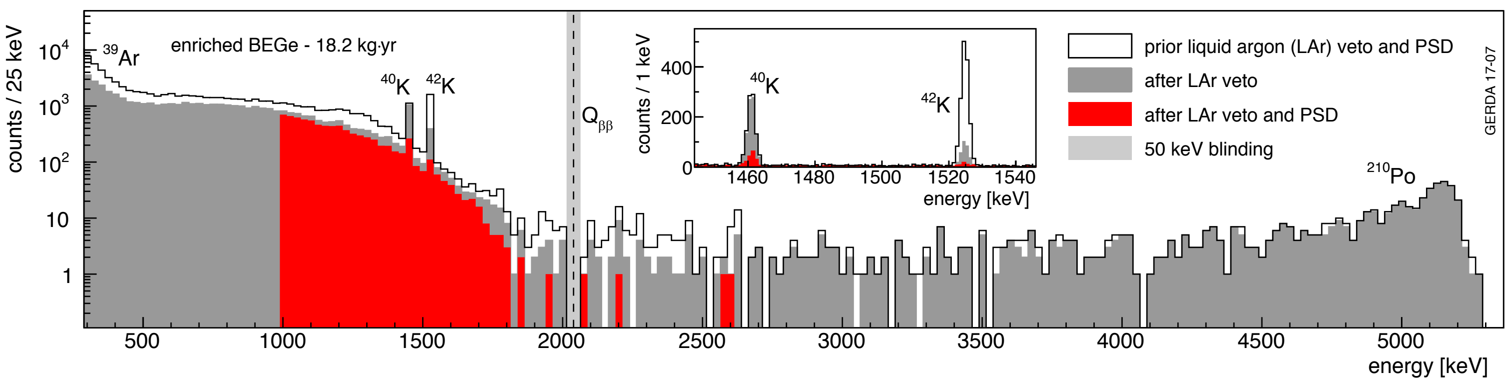




GERDA @ LNGS, Italy

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

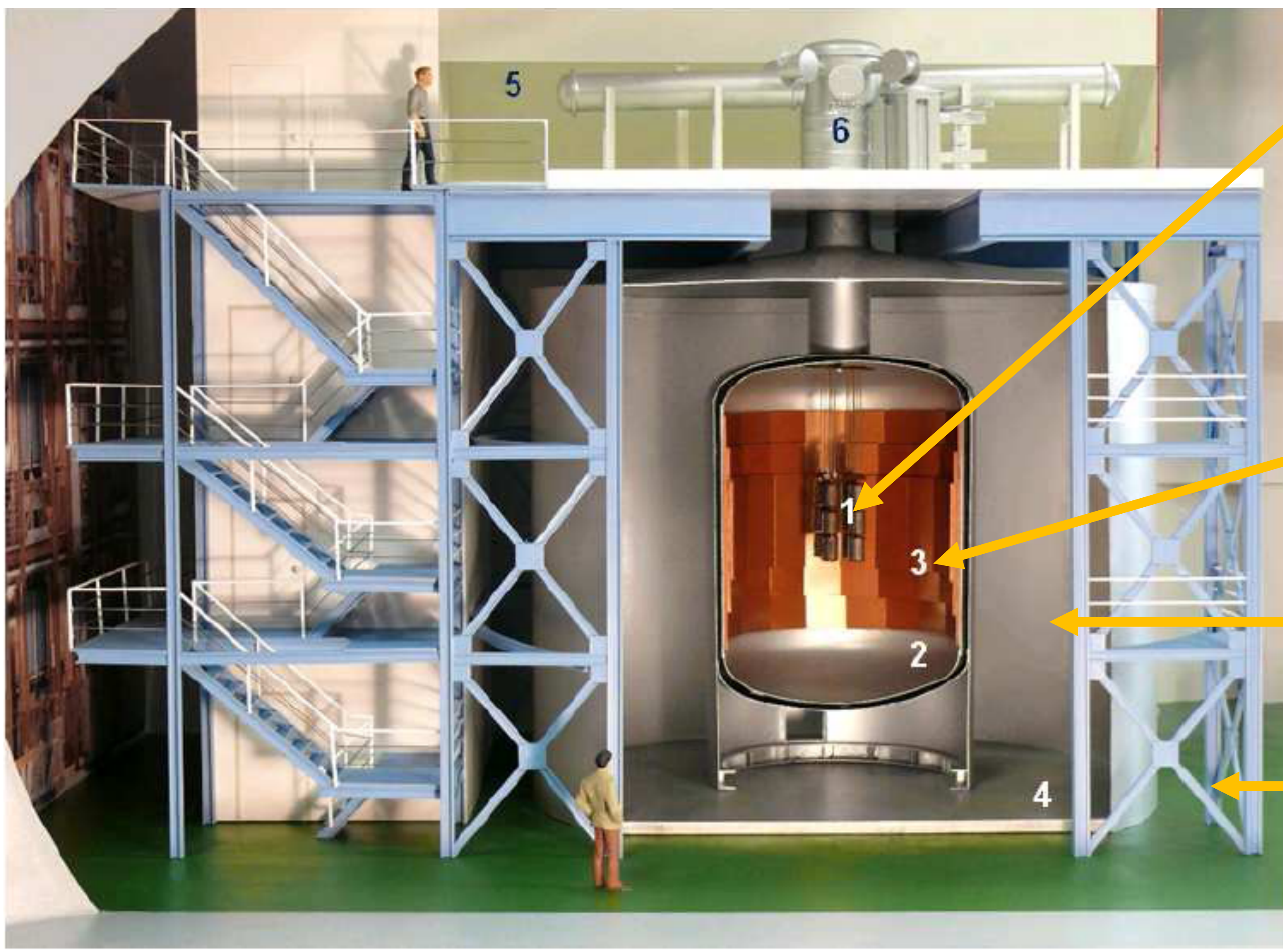
- https://arxiv.org/abs/1212.4067
- https://arxiv.org/abs/1703.00570
- https://arxiv.org/abs/1803.11100



Phase-II started from 2015

Background-free detector

(High energy resolution)



87% enriched ^{76}Ge

Total 31kg

Q=2039keV

ΔE ~ 3-4 keV @ Q-value (FWHM)

Cryostat

64m³ LAr

for cooling & shielding

590m³ Water

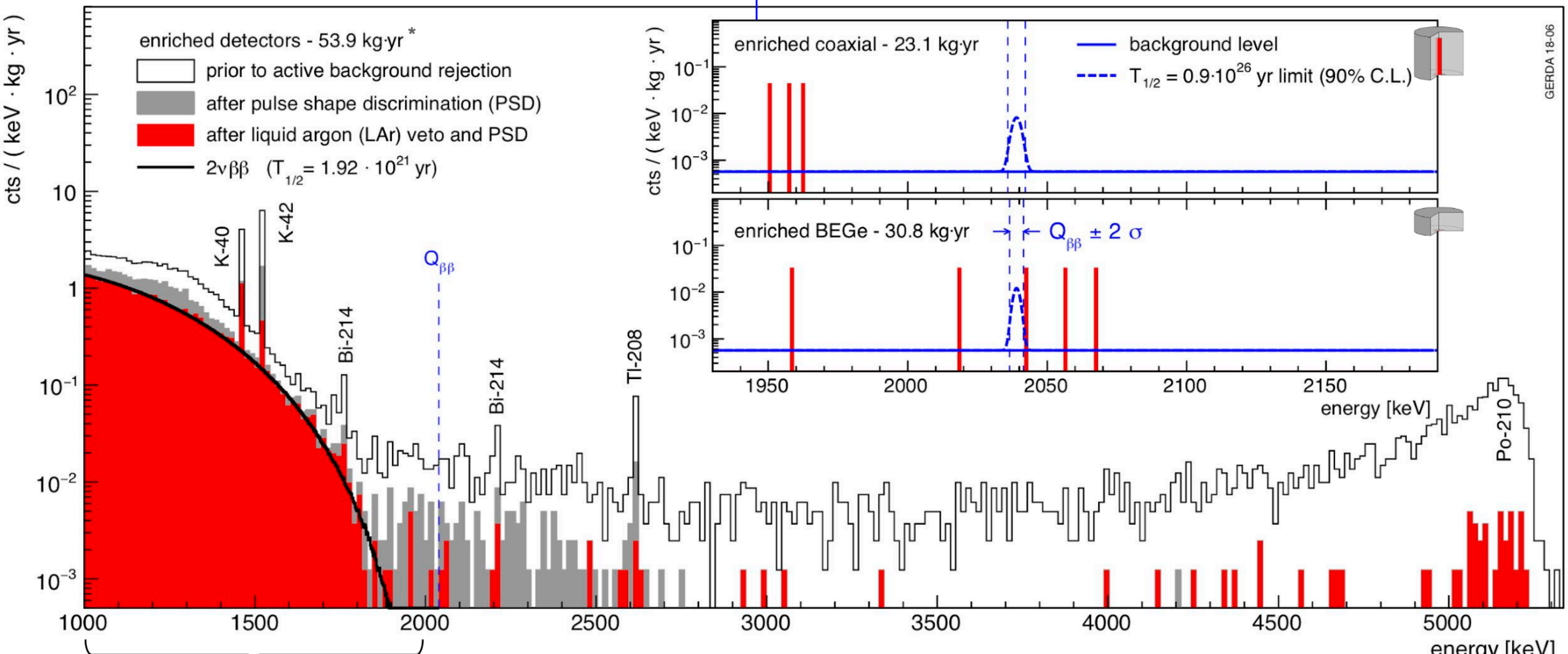
for muon veto

0νββ decay analysis

combined (+ Phase I) unbinned maximum likelihood fit [Nature 544, 47 (2017)]

Frequentist analysis:

- best fit $N^{0\nu} = 0$
- $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (median sensitivity $\mathbf{T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}}$ **yr**) @ 90% C.L.



agreement with $T^{2\nu}_{1/2}$ from Phase I [Eur. Phys. J. C 75 (2015) 416]

*w/o 5.0 kg·yr of coaxial data with different PSD method

9

m < 0.10 – 0.23 eV

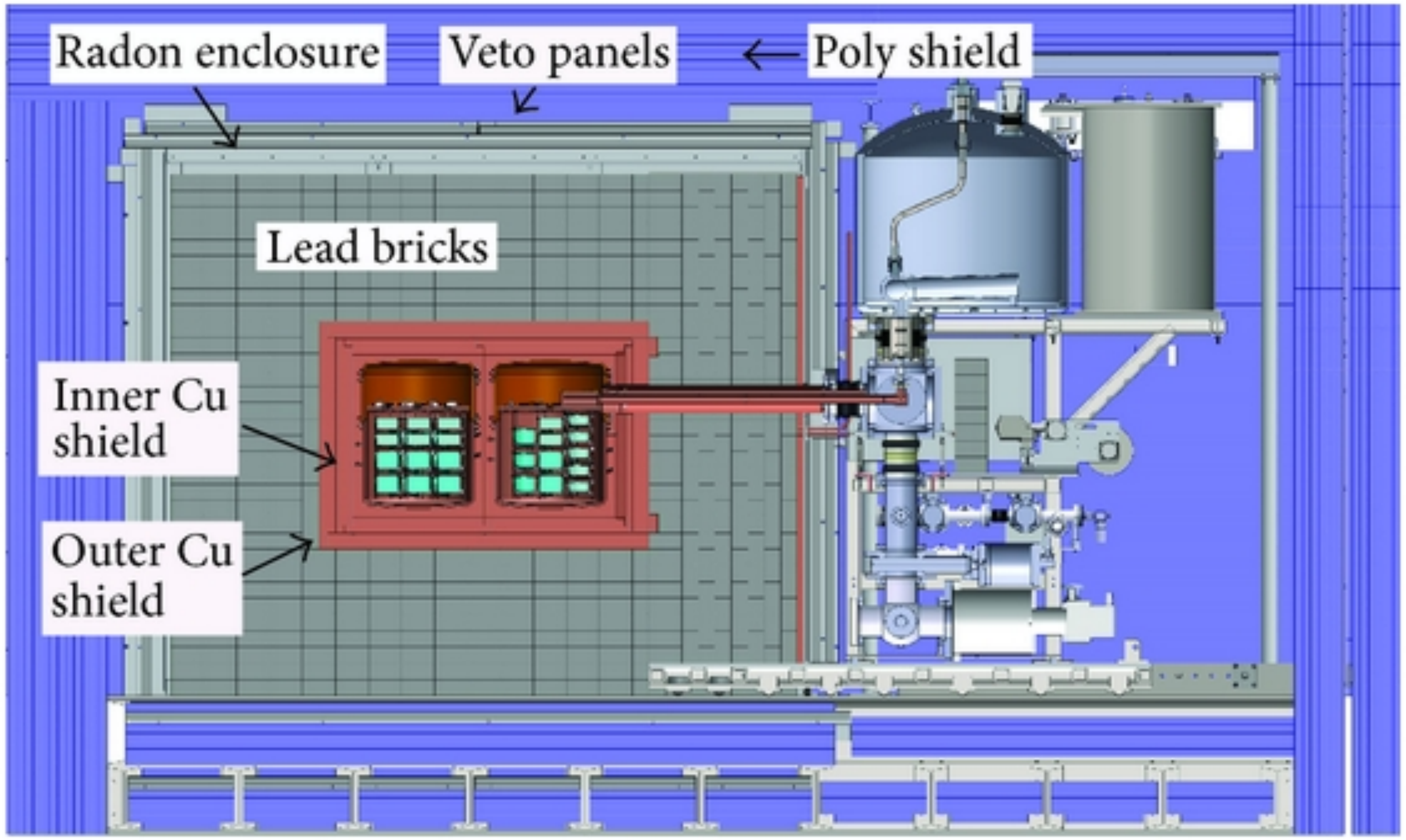
MAJORANA @ SURF

(The MAJORANA DEMONSTRATOR)

- https://arxiv.org/abs/1710.11608
- https://www.hindawi.com/journals/ahep/2014/365432/
- * PRL 120 132502 (2018)
- * PRC 100 025501 (2019)

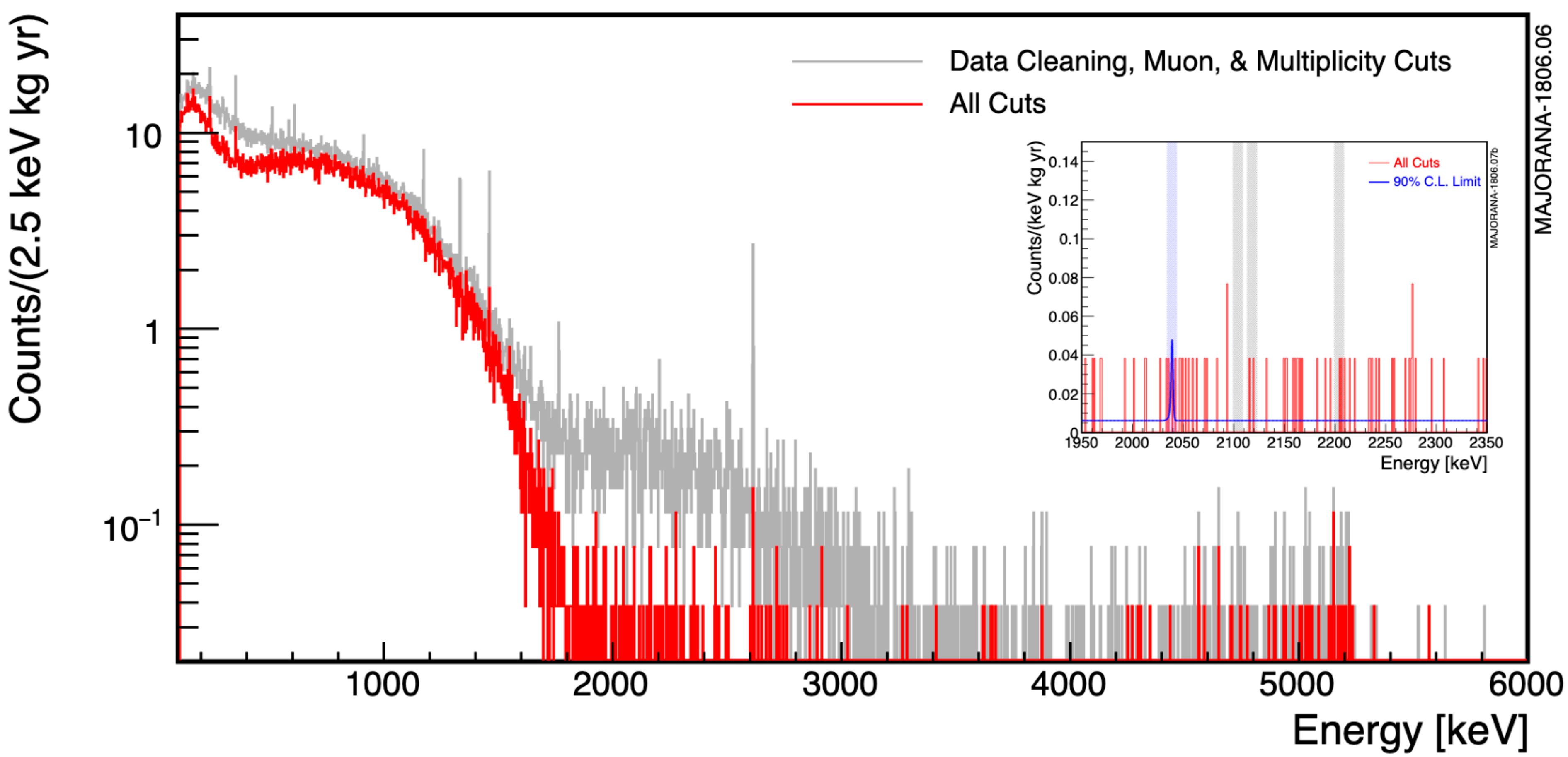
- 30kg of 86% enriched ^{76}Ge
- Δe=0.16% (4keV) @ 2039keV
- **P-type Point-Contact (PPC)** Germanium detectors

Background-free detector



2018 $0\nu\beta\beta$ Result

Operating in a low background regime and benefiting from excellent energy resolution



Initial Release:

9.95 kg-yr open data

[PRL 120 132502 (2018)]

Latest Release:

First unblinding of data

26 kg-yr exposure

[PRC 100 025501 (2019)]

Median $T_{1/2}$ Sensitivity:

4.8×10^{25} yr

Full Exposure Limit:

$T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Background Index at 2039 keV in lowest background config:

11.9 ± 2.0 cts/(FWHM t yr)

LEGEND

(**L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay)

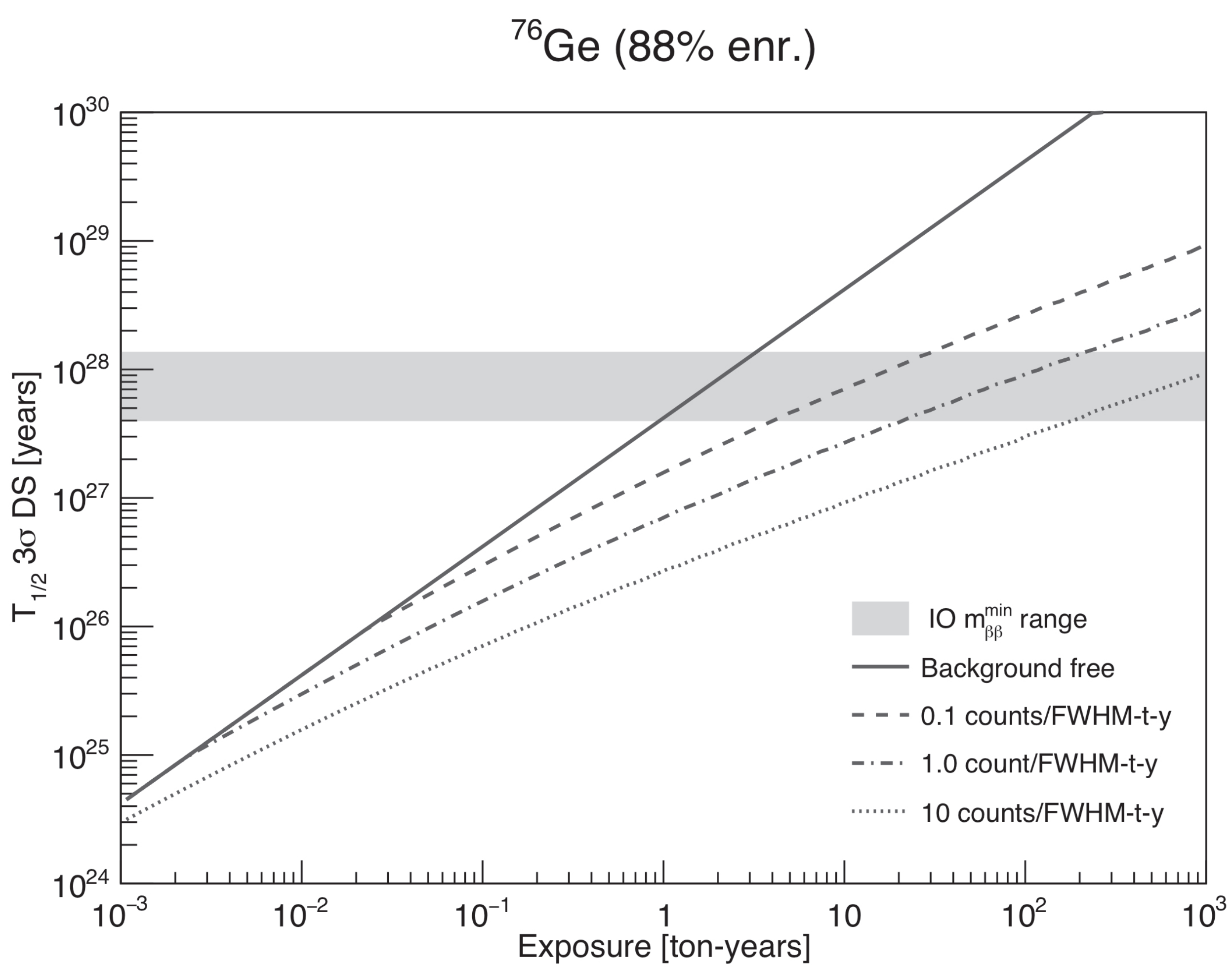
•https://arxiv.org/abs/1709.01980

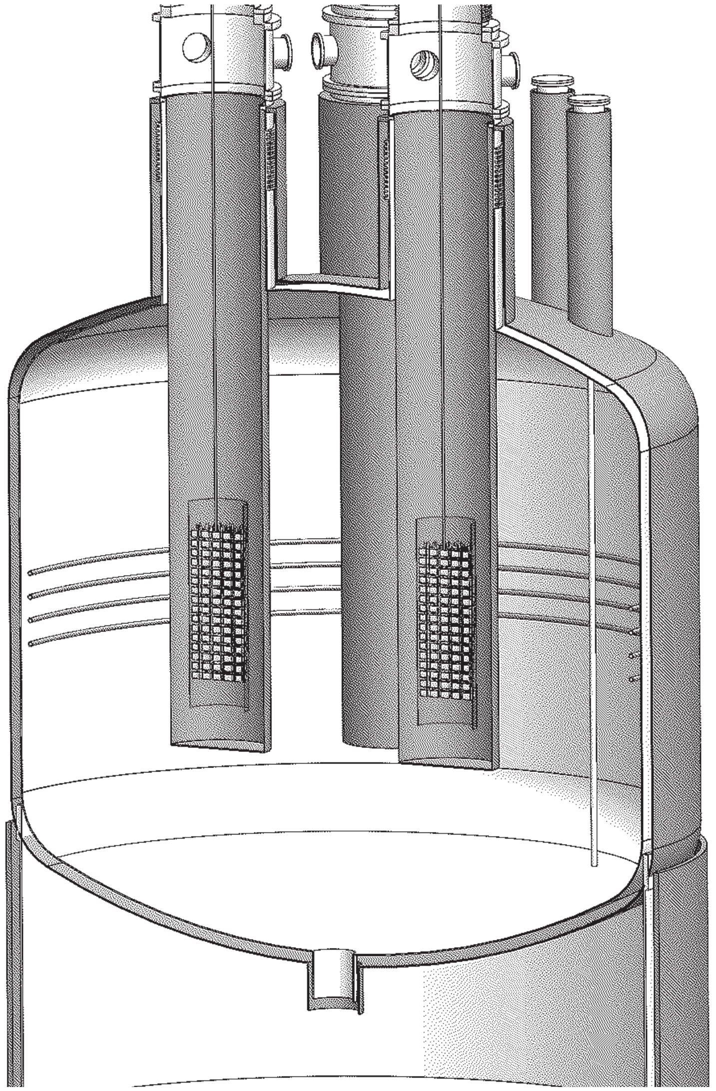
Future project

GERDA + MAJORANA ⇒ LEGEND

Background-free detector

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

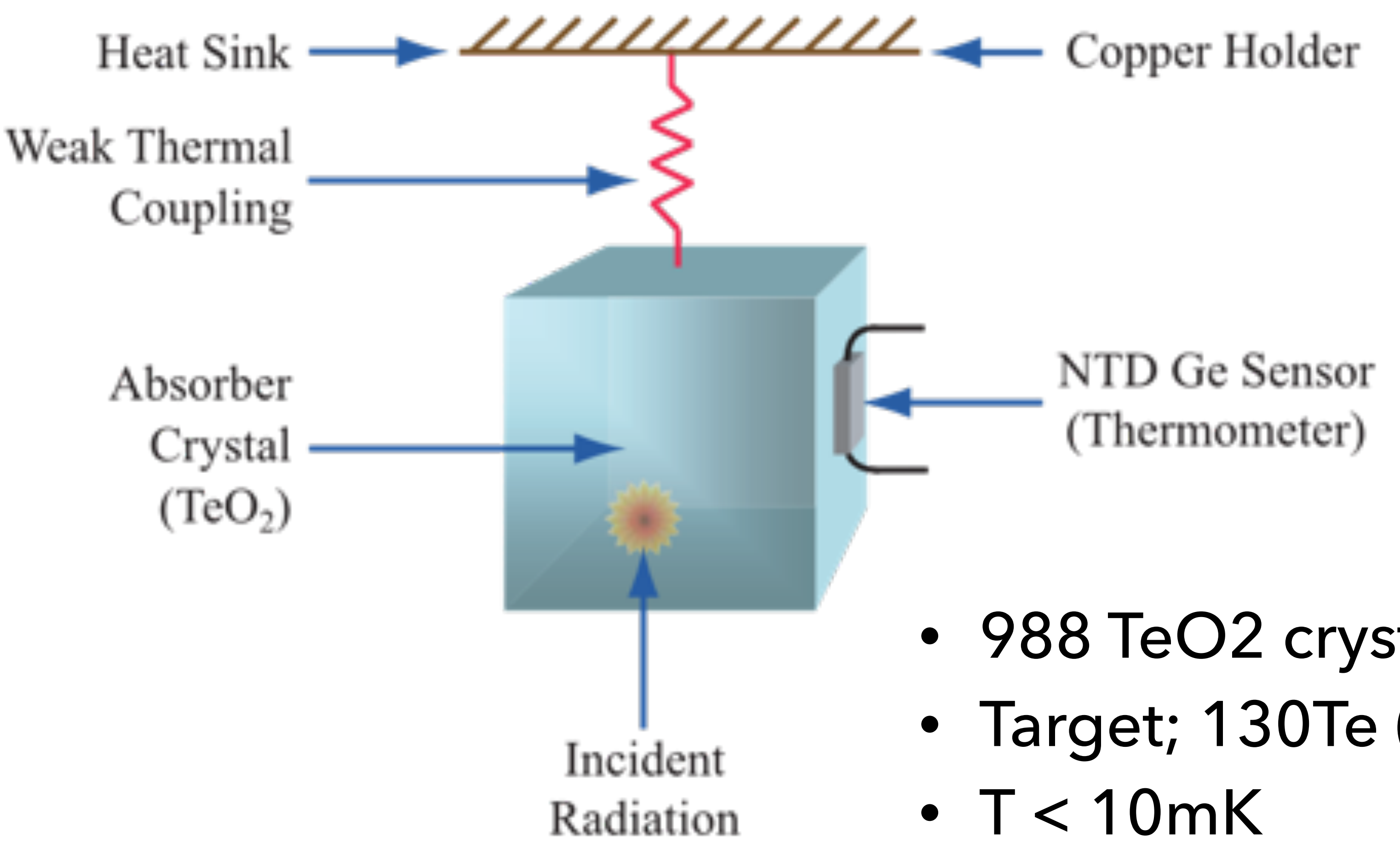


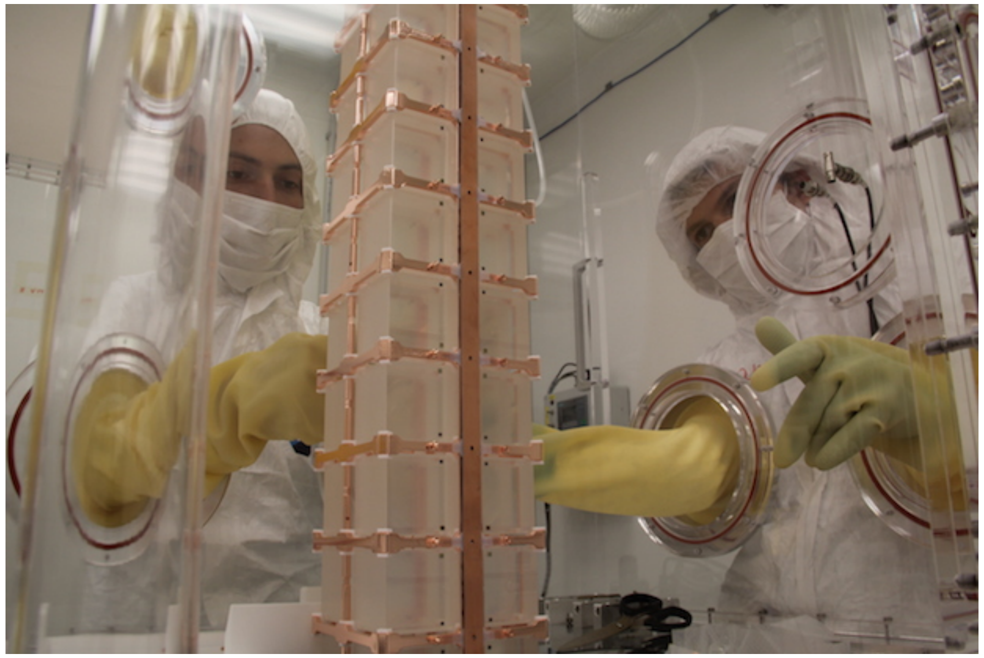


CUORE @ LNGS, Italy

•https://arxiv.org/abs/1710.07988

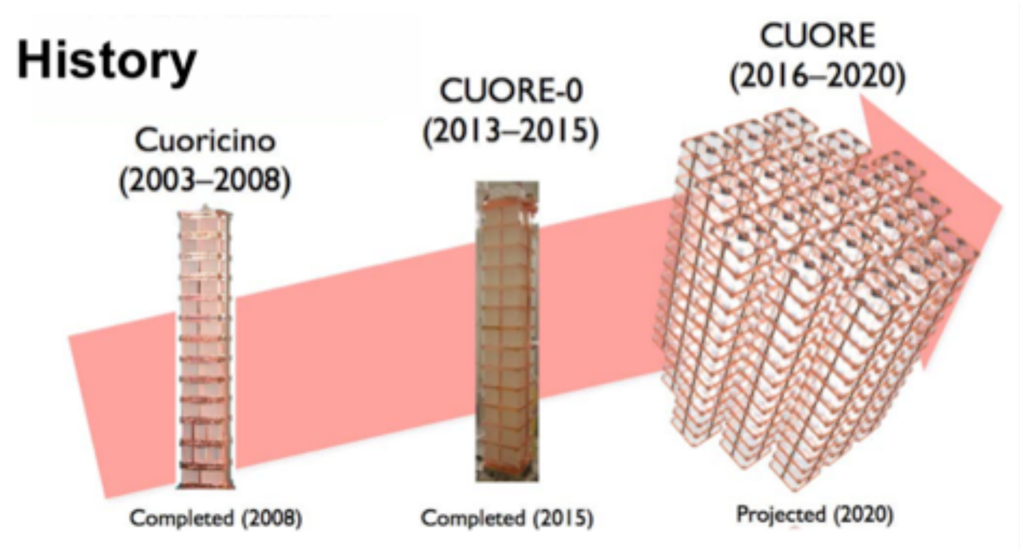
(**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents)

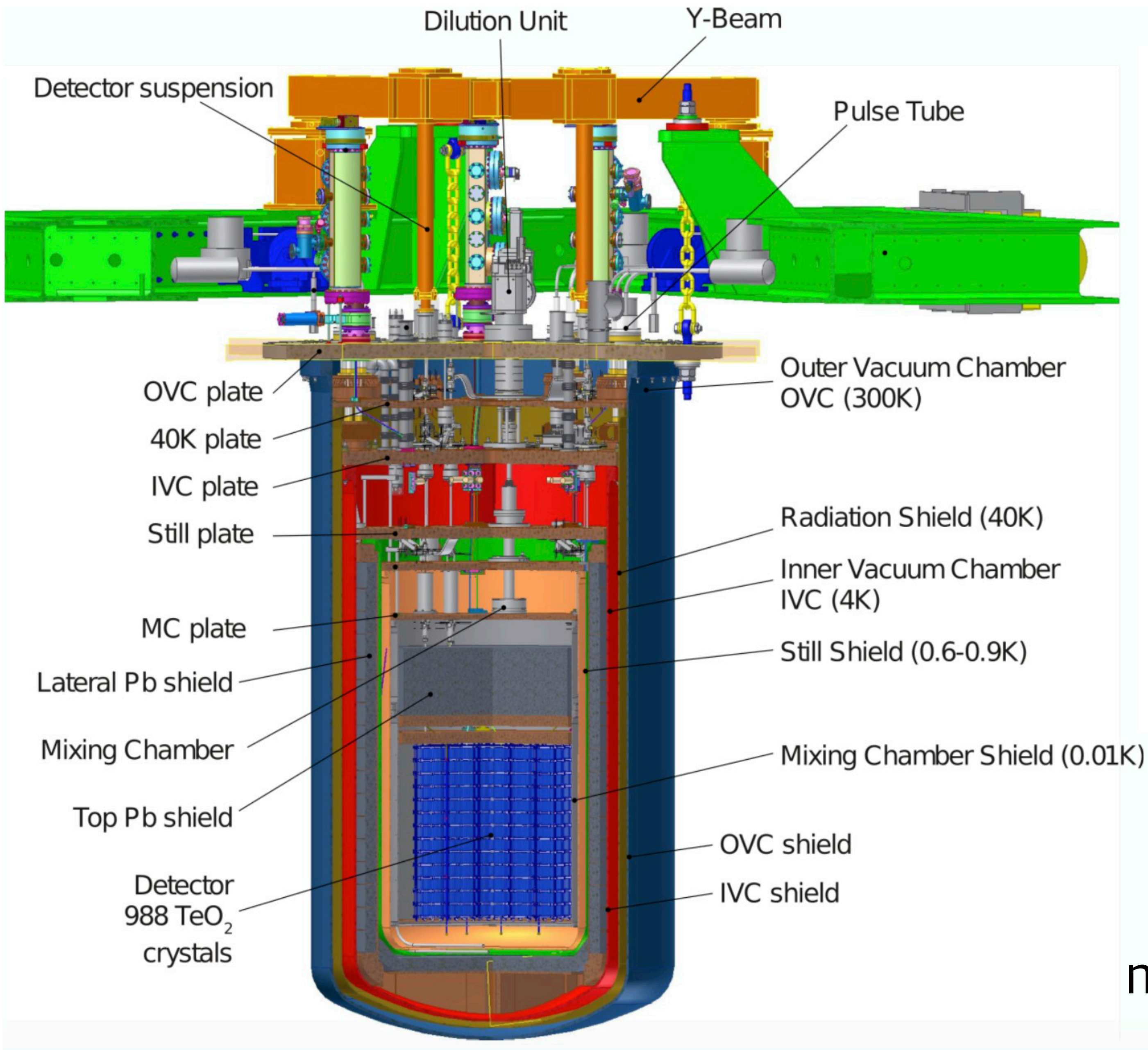


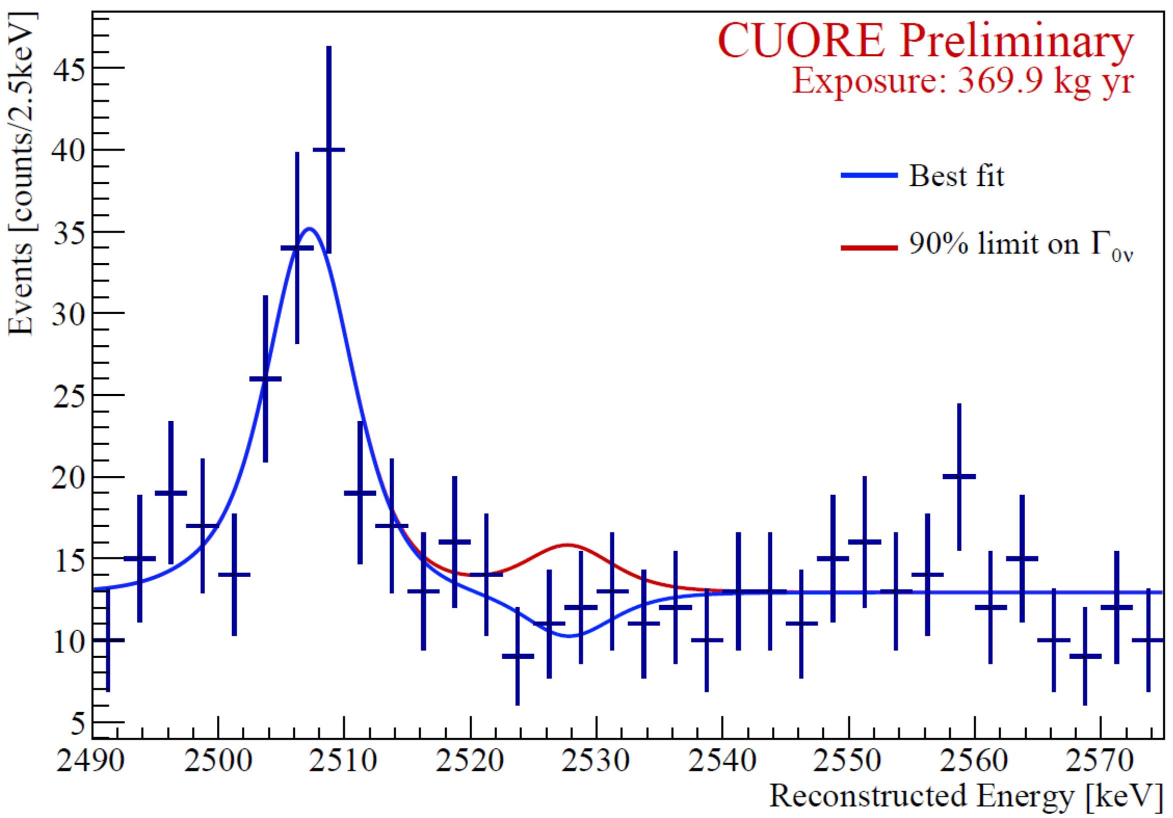


- 988 TeO2 crystals (total 742kg)
- Target; 130Te (Q=2527keV) 34% of nat. (206 kg)
- T < 10mK
- ΔE = (7.7±0.5) keV FWHM –> 5keV(as goal)

High ΔE & Large mass detector







$T^{0\nu}_{1/2} > 2.3\times10^{25}$ yr (90% C.L.)

$m_{bb} < 0.09 - 0.42$ eV (90% C.L.)

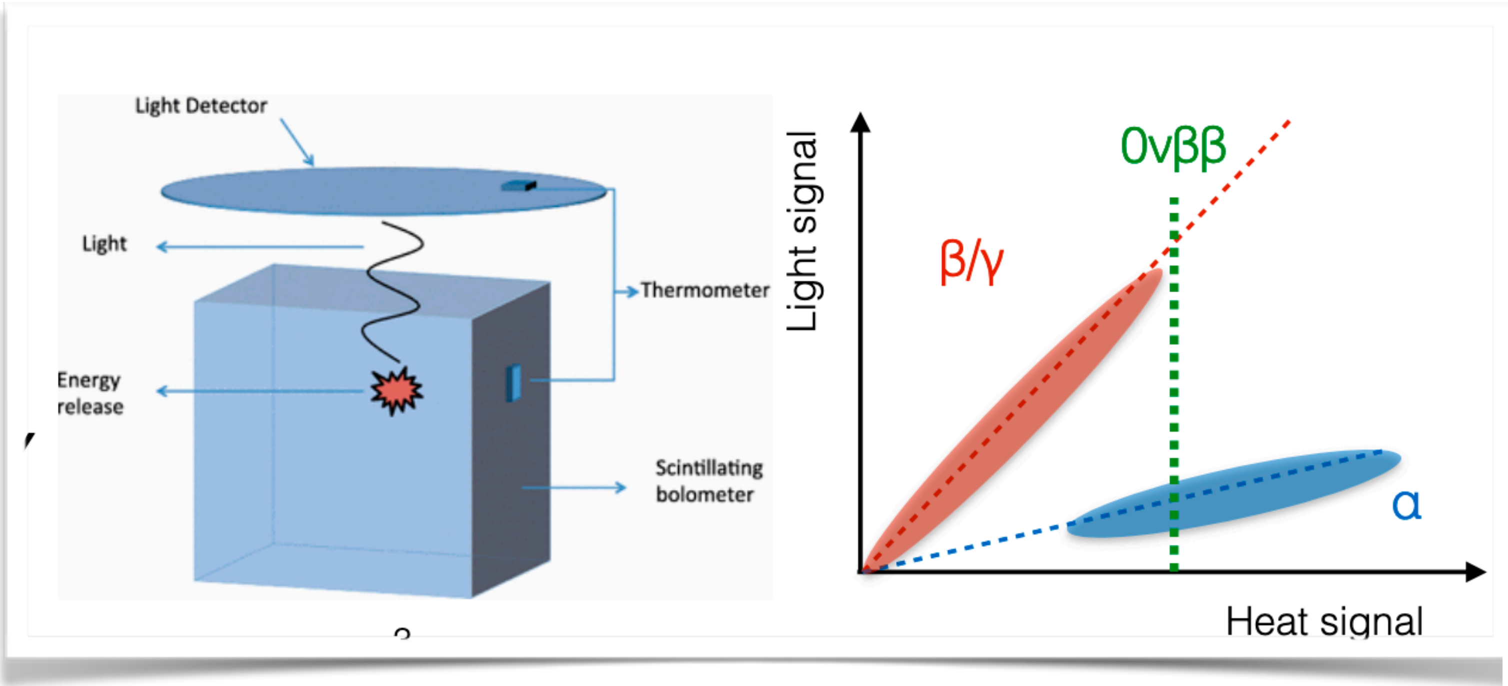
Taken from TAUP2019

CUPID

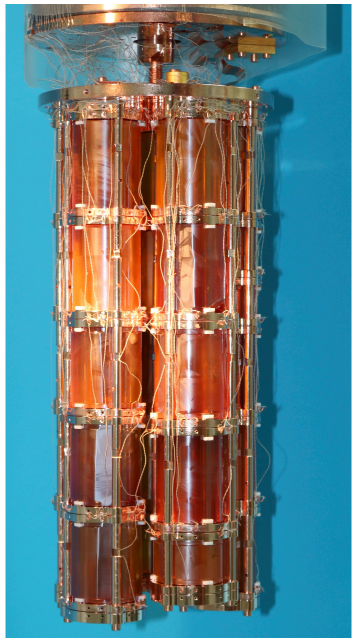
N.Casali et al PRL 123 032501 (2019)

Improvement from CUORE detector

Scintillating-Bolometer ($Zn^{82}Se$)

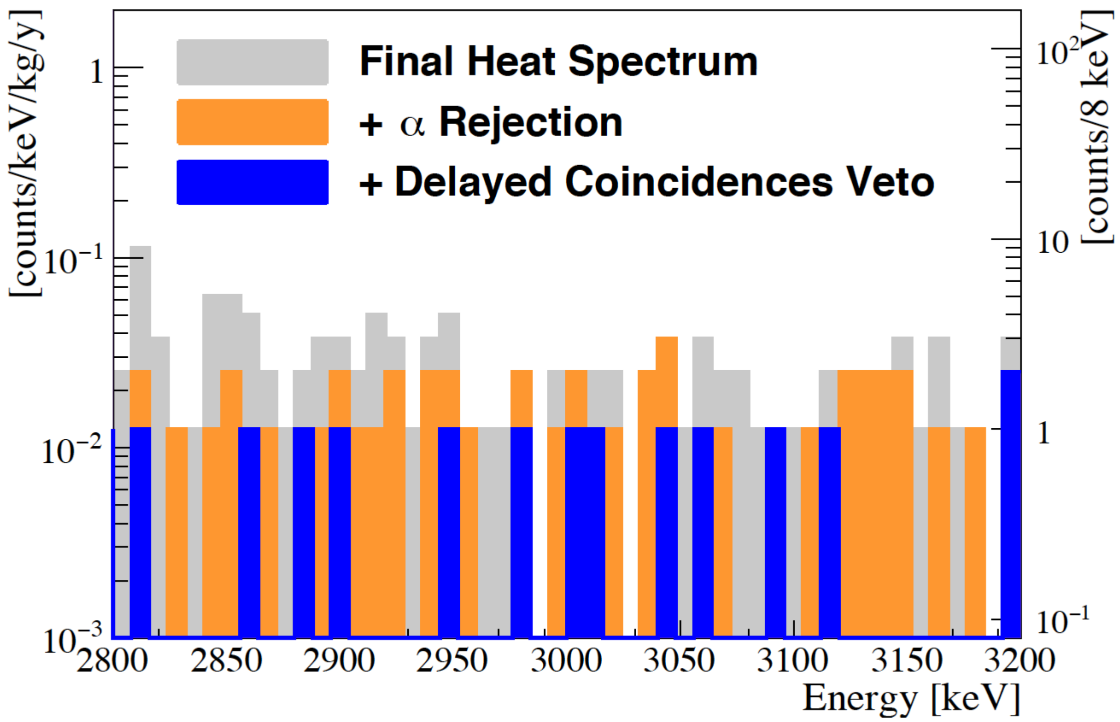


Taken from TAUP2019



- 9.95 kg × yr
- ΔE ~ (20.05±0.34) keV in ROI
- T > 3.5×10^{24} yr

BKG = 3.2×10^{-2} counts/(keV kg yr)
BKG = 1.3×10^{-2} counts/(keV kg yr)
BKG = 3.5×10^{-3} counts/(keV kg yr)

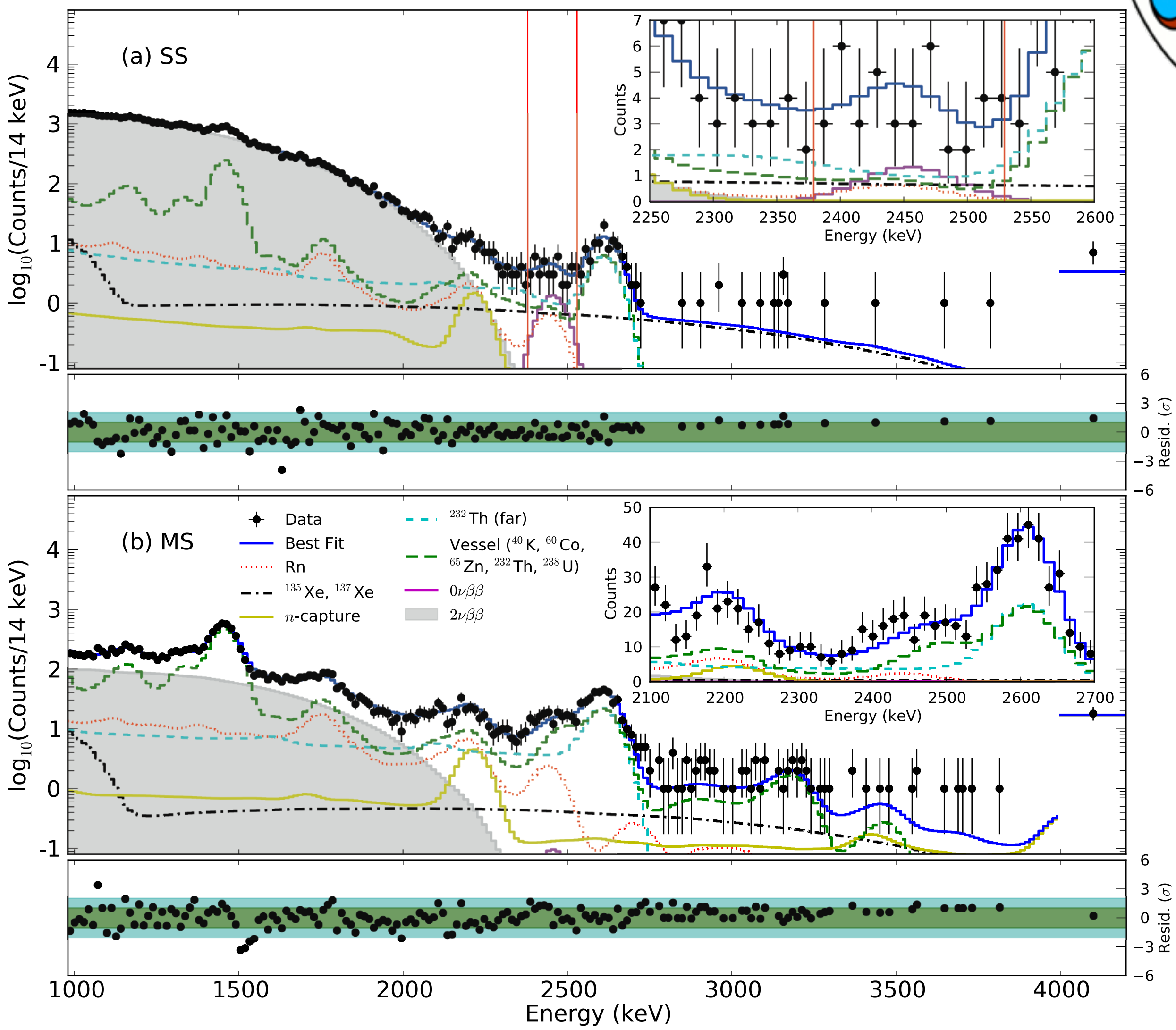


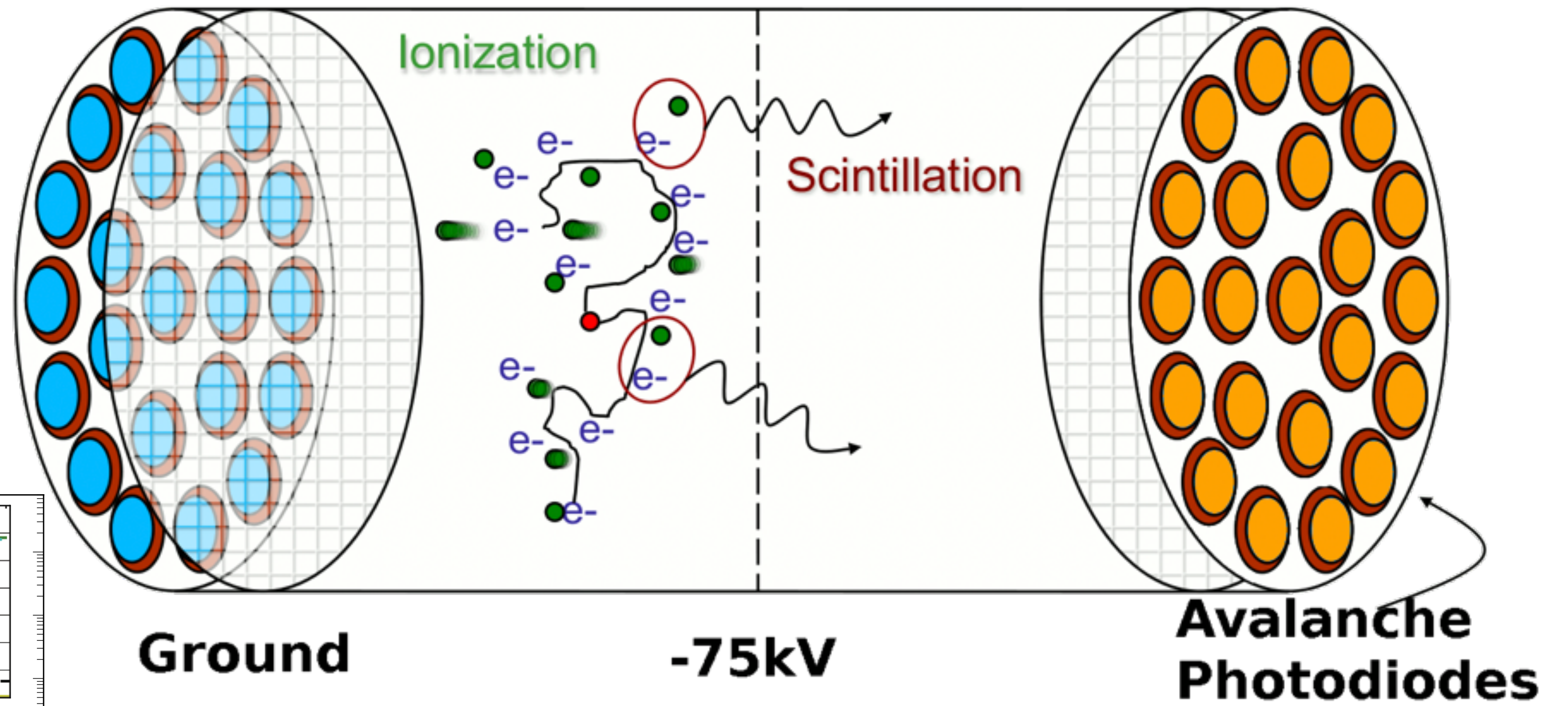
EXO-200 @ WIPP, New Mexco

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

- https://arxiv.org/abs/1402.6956
- https://arxiv.org/abs/1605.06552

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



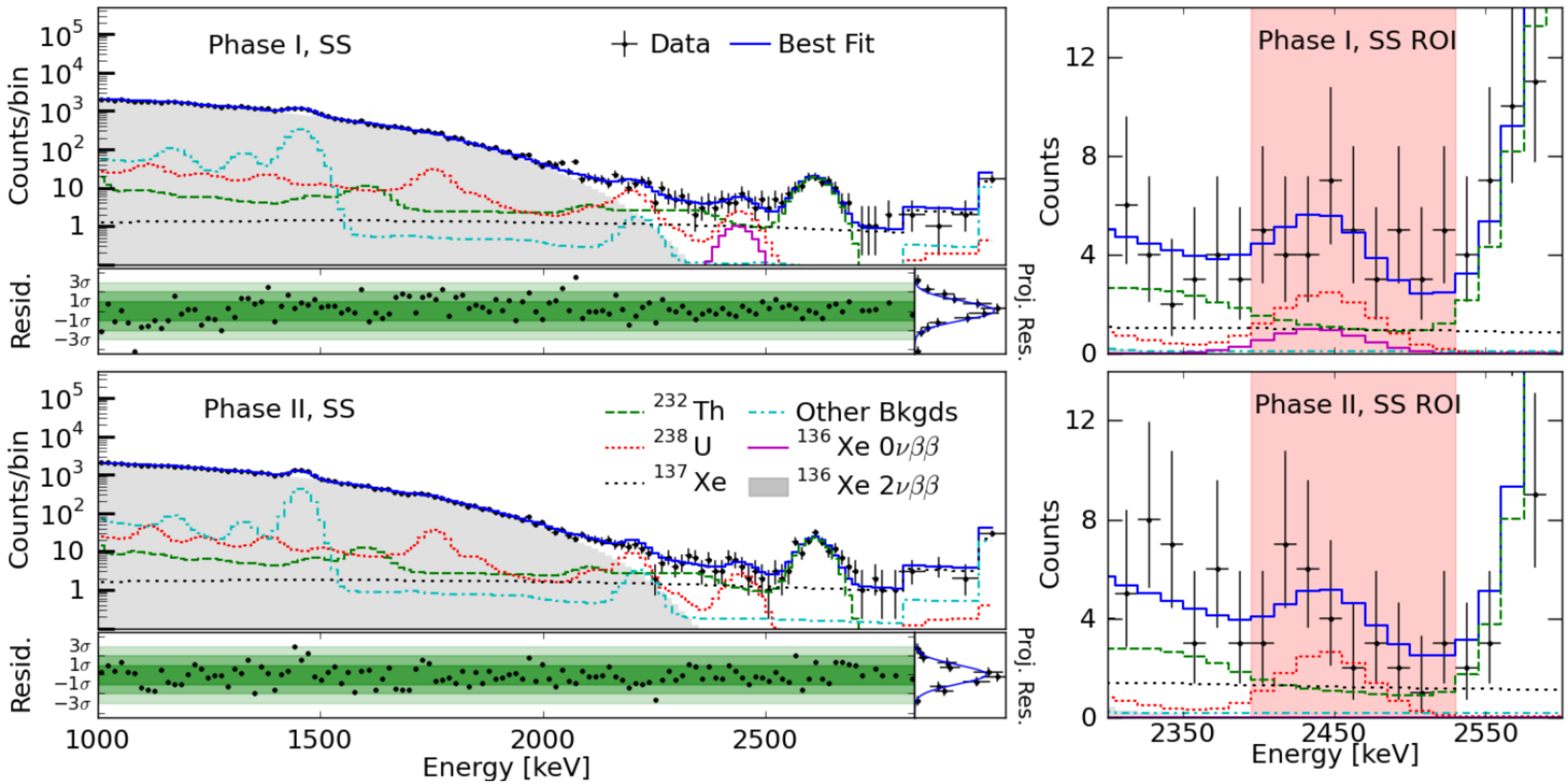


Detection (Signal/Background identification)

- 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)



Exposure: 234.1 kg·yr

Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle$ < (93 – 286) meV [NMEs]

Sensitivity: 5.0×10^{25} yr

2018: Phys.Rev.Lett. 120(2018) 072701
2019: arXiv 1906.02723

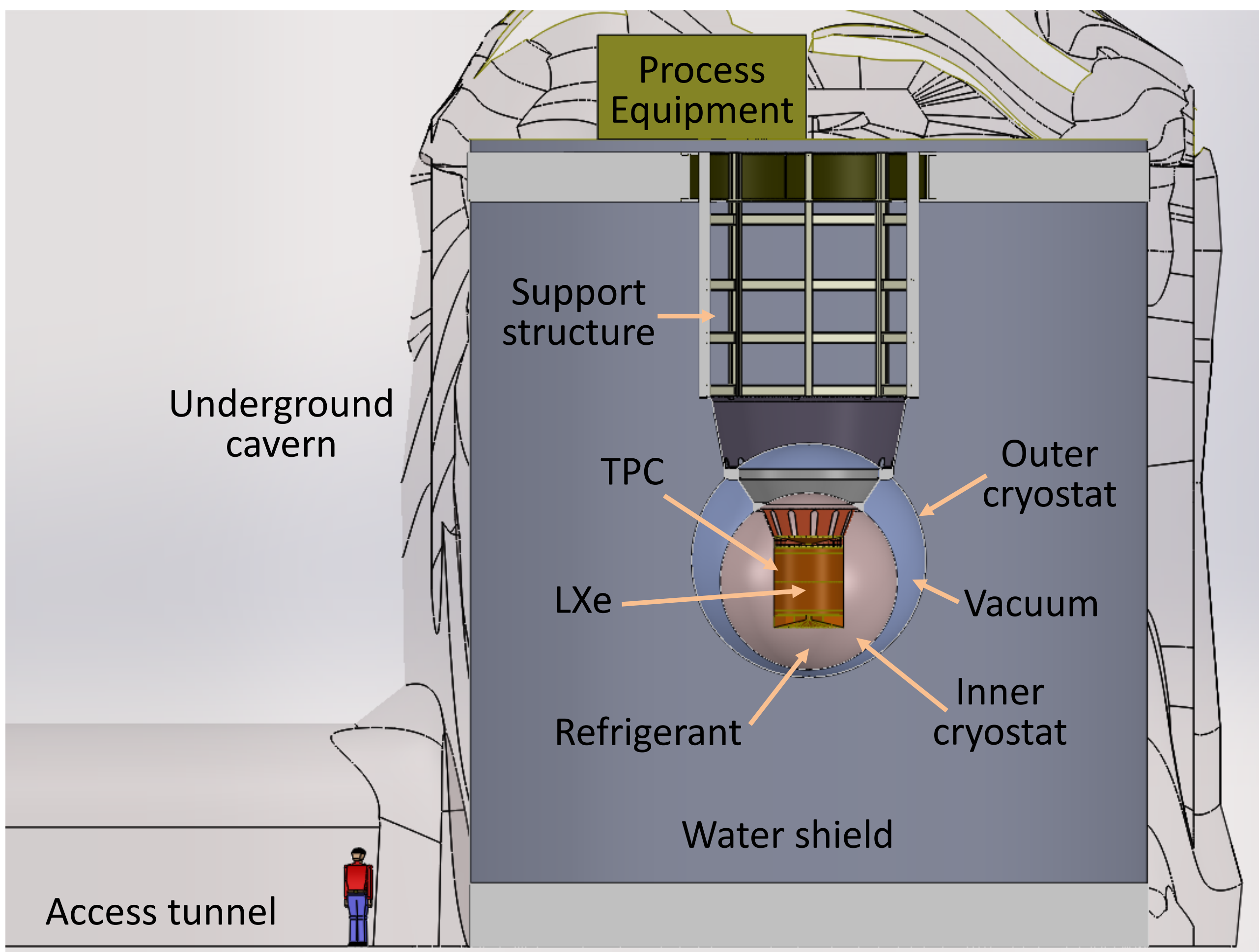
nEXO

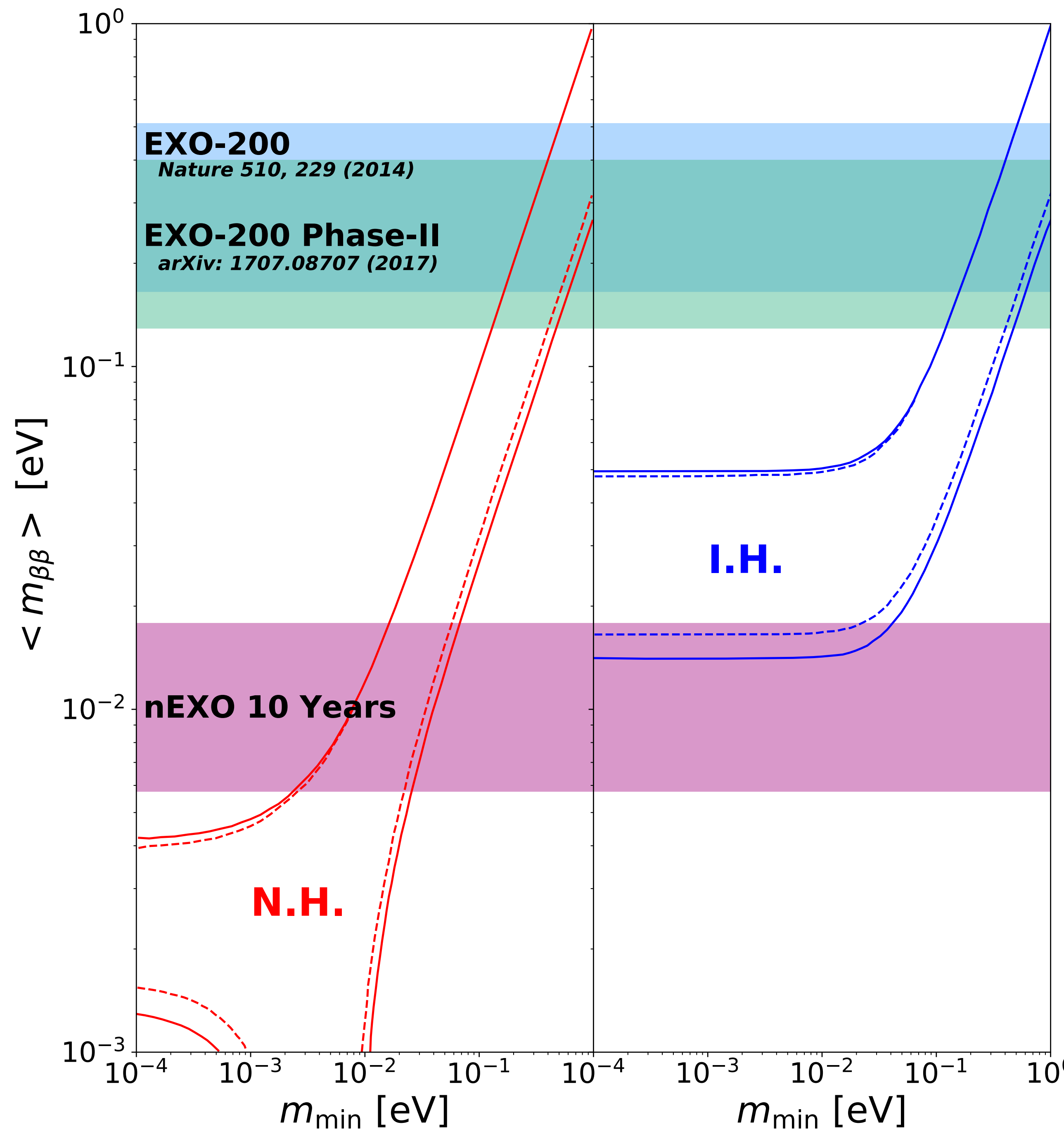
(**n**ext **E**nriched **X**enon **O**bservatory)

•https://arxiv.org/abs/1710.05075

Future project

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





Super-NEMO @ Modane, France

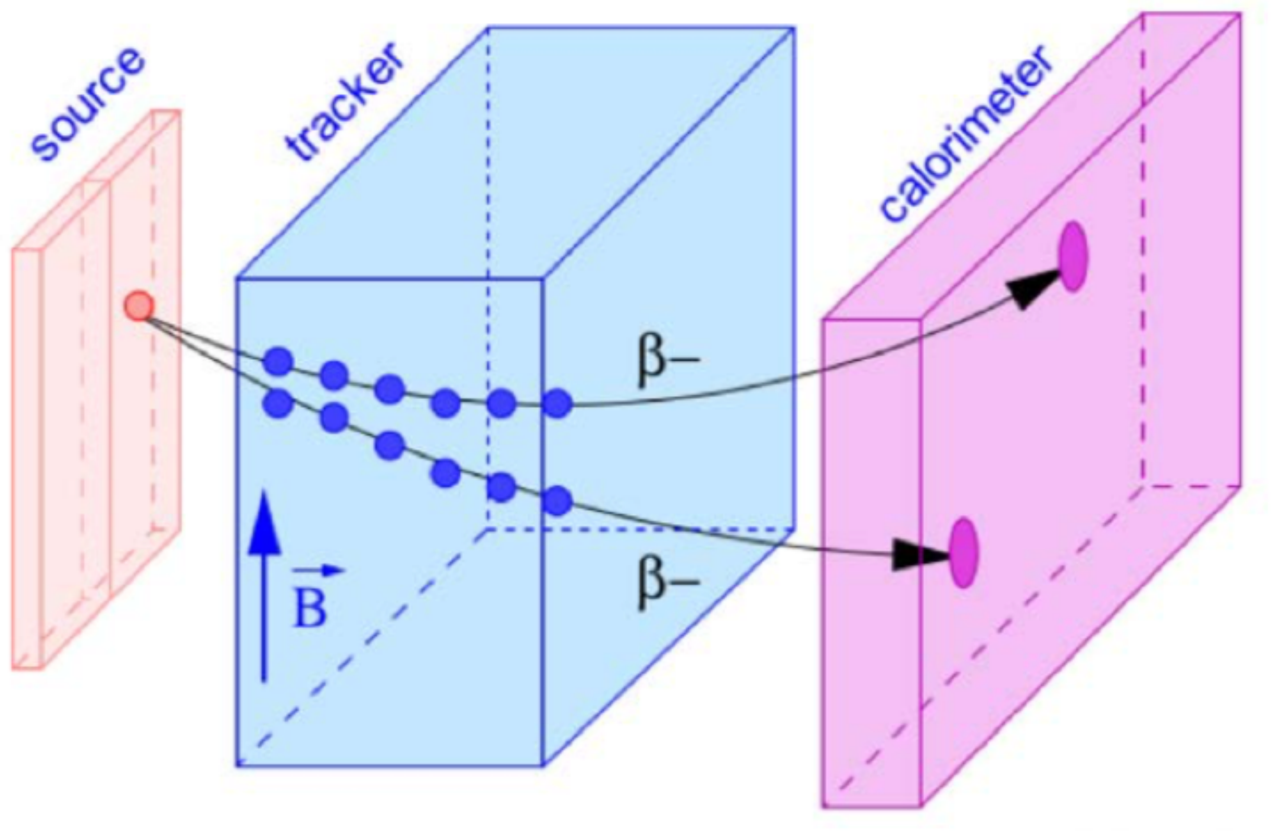
Future project

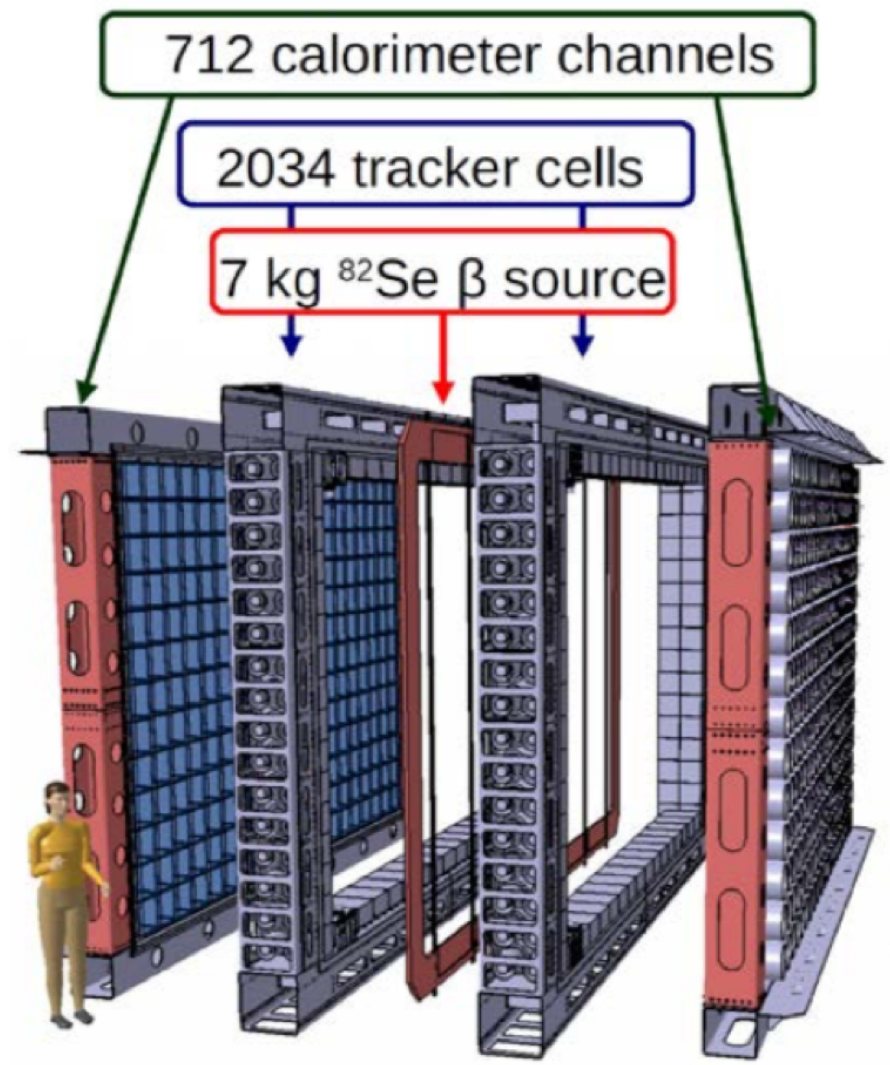
•https://arxiv.org/pdf/1707.06823.pdf

Tracking Detector

- Target; ^{82}Se etc, ~7kg/module (total 100kg)
- ΔE = 8% FWHM @ 1MeV

Currently working as NEMO-3



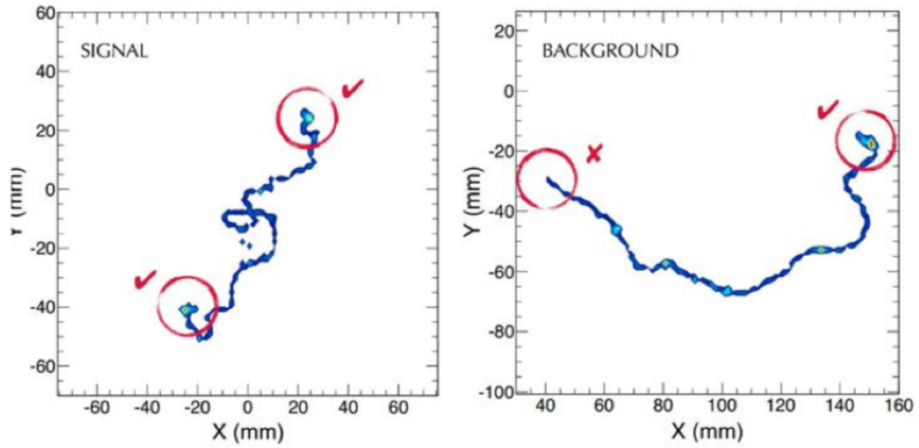


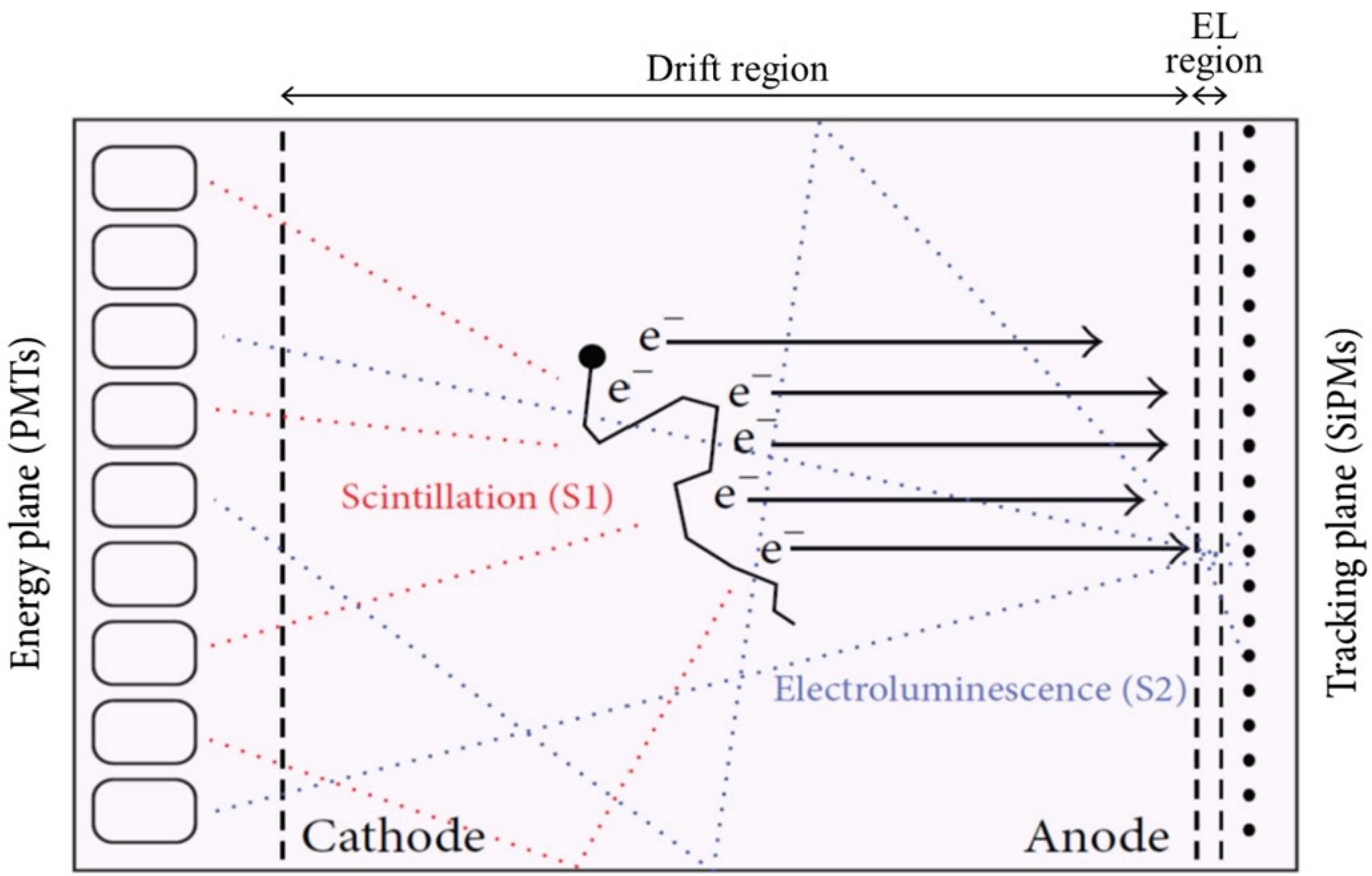
NEXT @ LSC, Spain

(**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

- 10-15bar Gas Xenon TPC; ^{136}Xe ~ 100kg
- ΔE ~ 3% @ 2.5MeV by Electro-Luminesence
- Using event topology



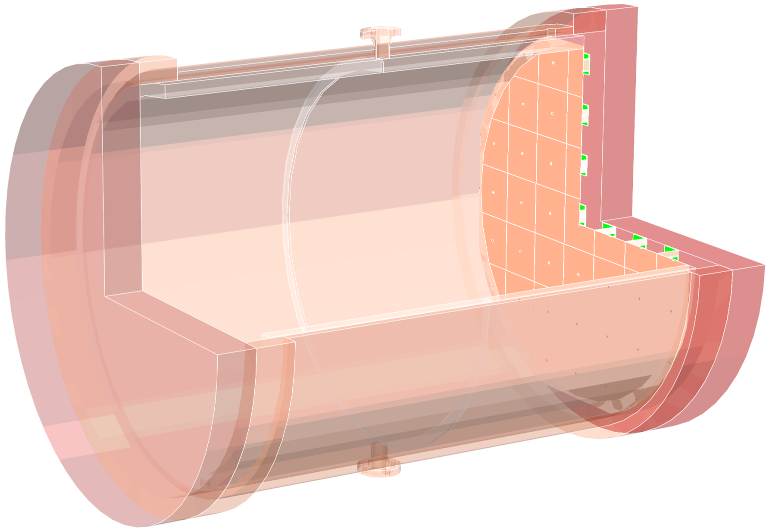


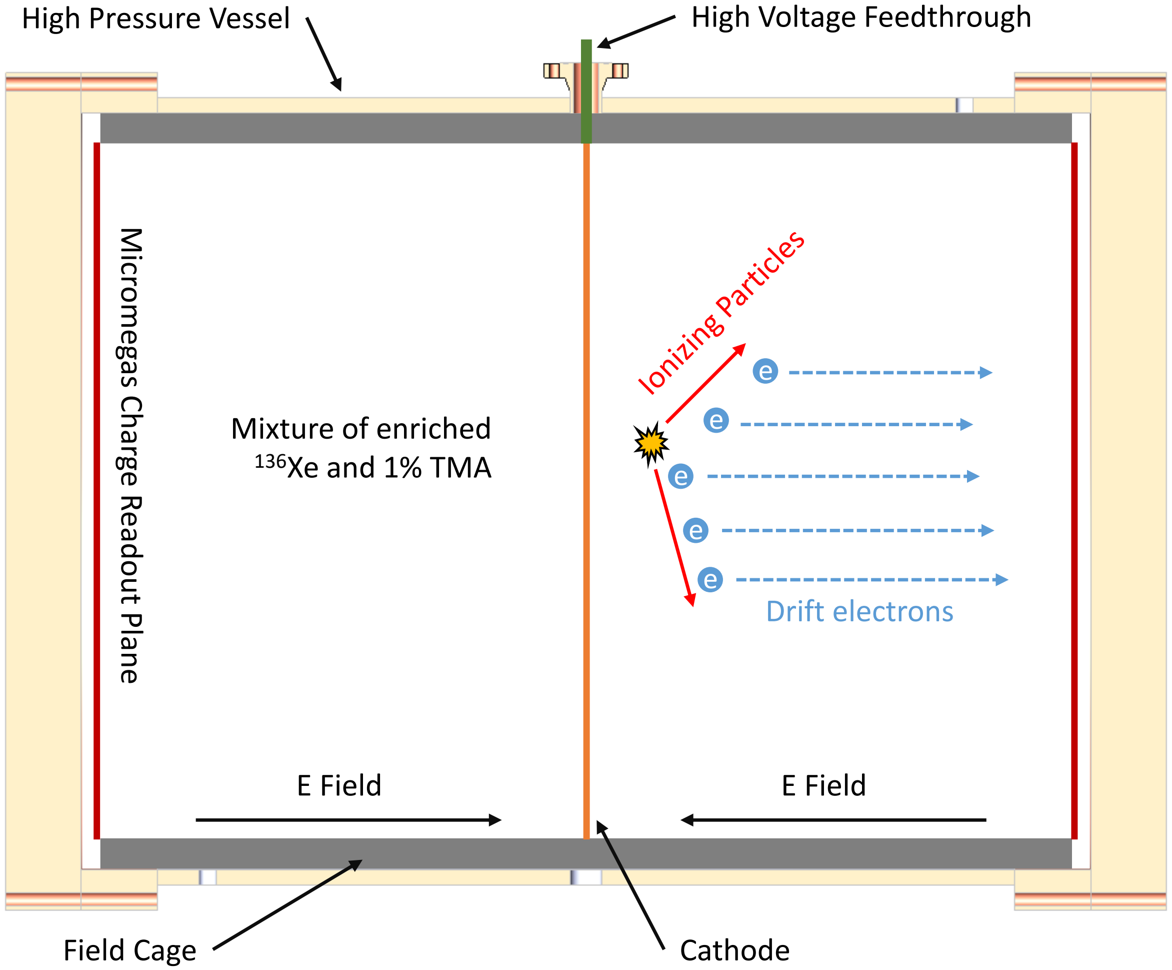
PANDAX-III @ Jin-Ping, China

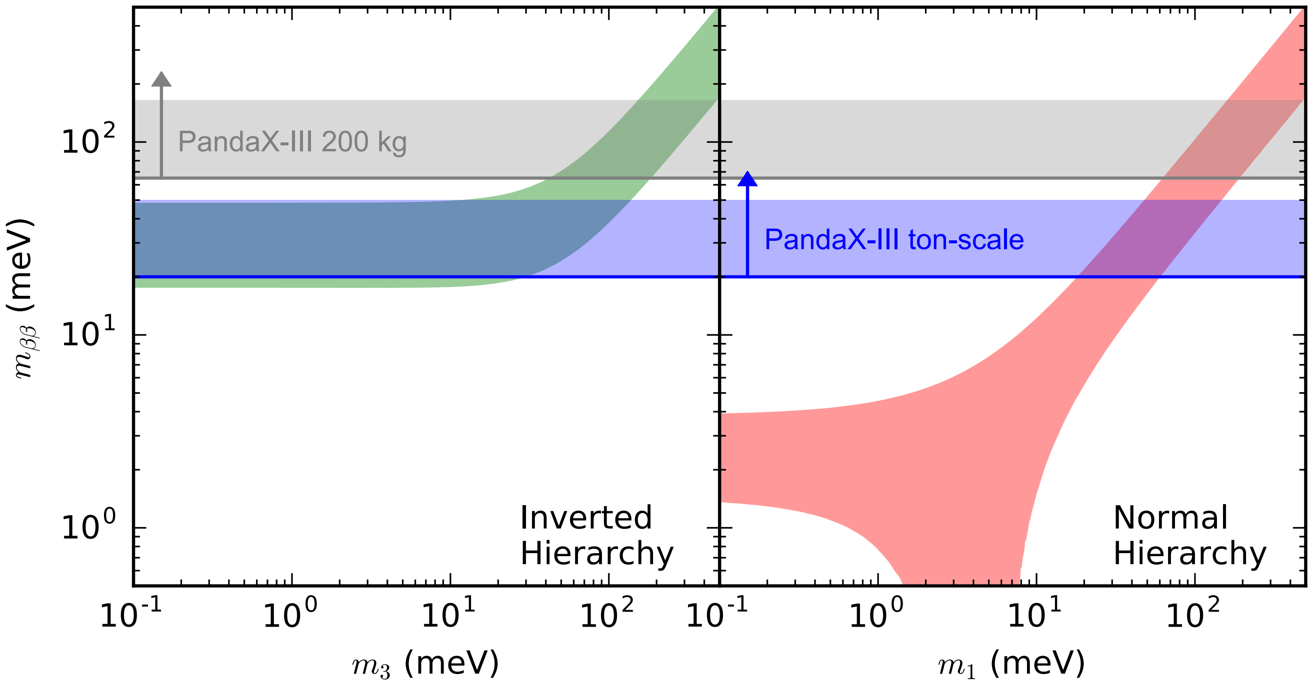
(**P**article **And** **A**strophysical **X**enon Experiment)

•https://arxiv.org/abs/1710.08908

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



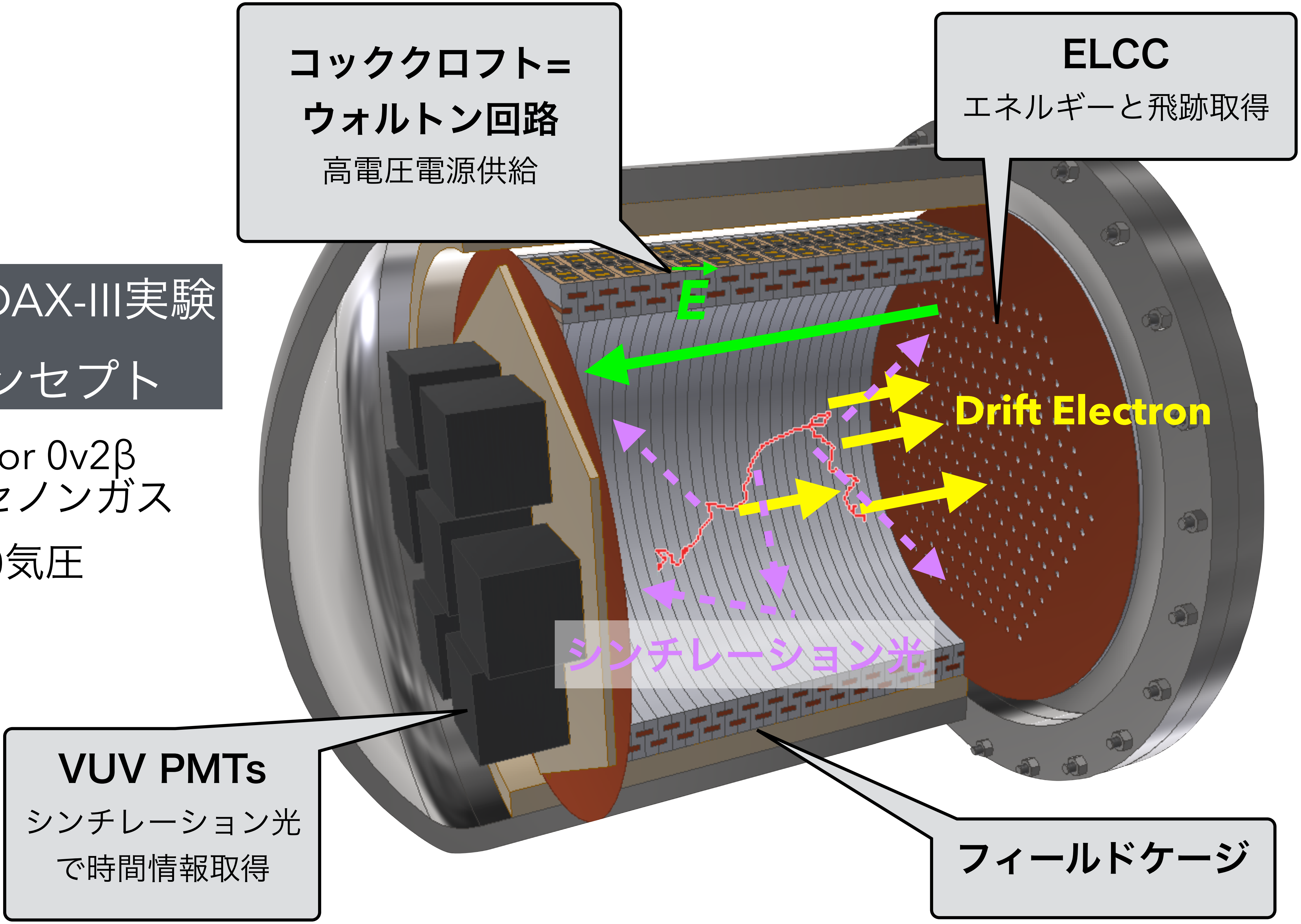




AXEL (**A** **X**enon **E**lectro**L**uminescence detector)

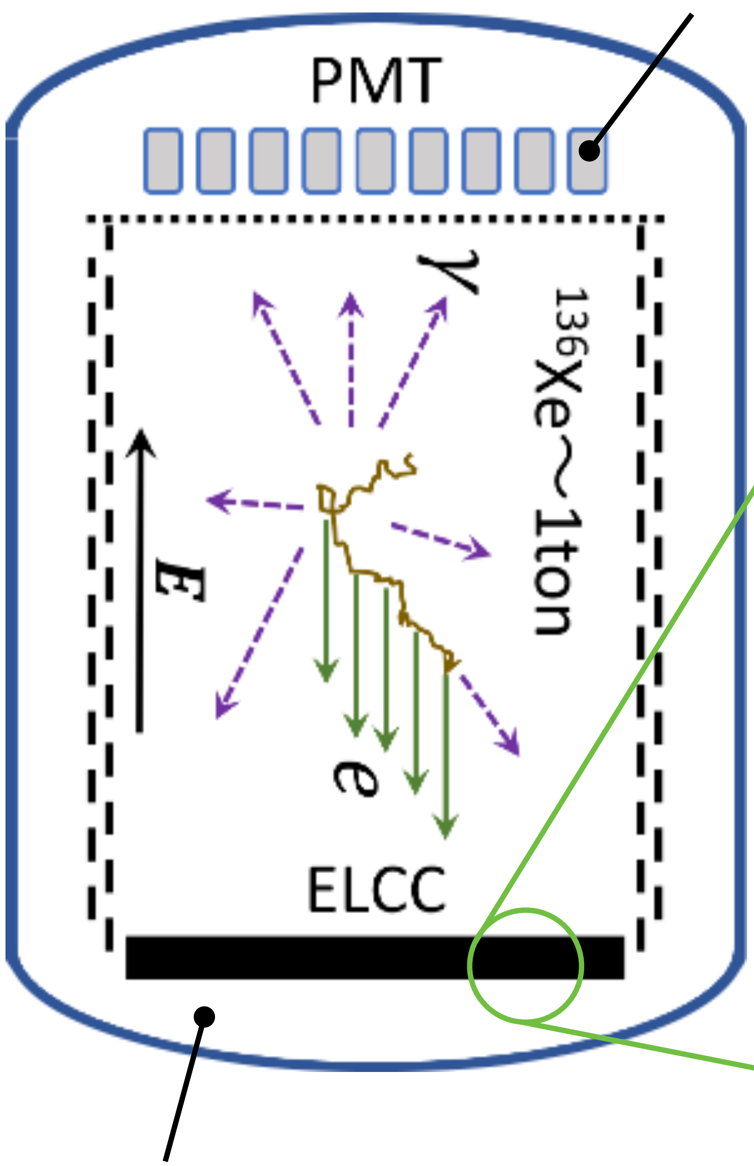
NEXT, PANDAX-III実験
と似たコンセプト

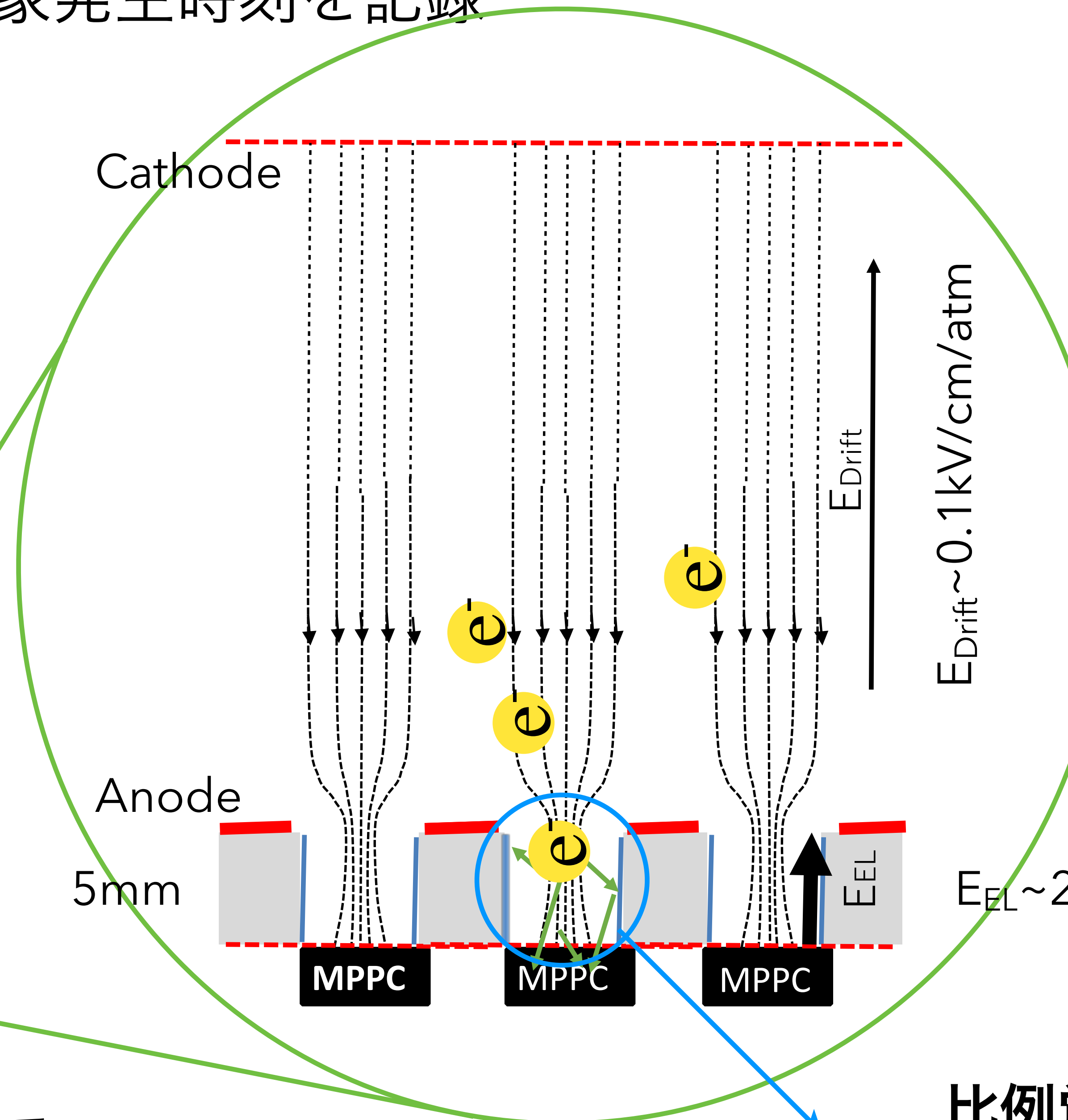
- ^{136}Xe for 0ν2β
- 1ton キセノンガス
- ~10気圧

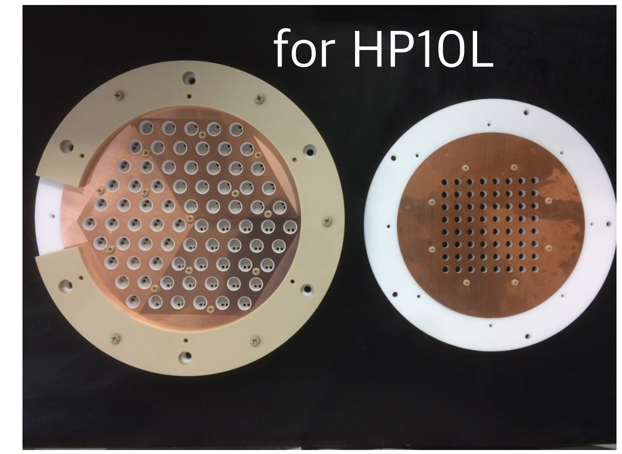


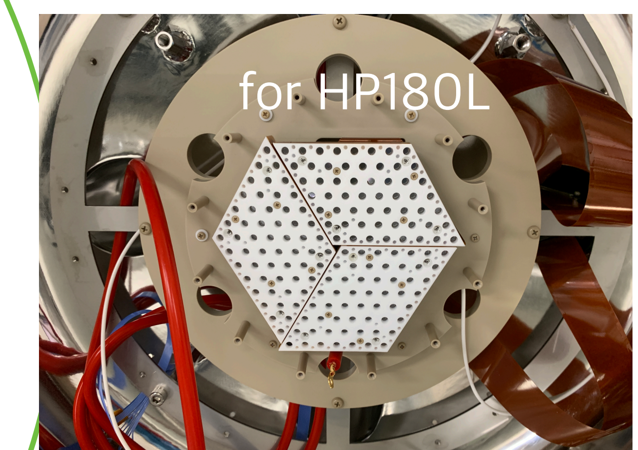
AXEL検出器 & ELCC

PMT; Xe-シンチを捉えて事象発生時刻を記録







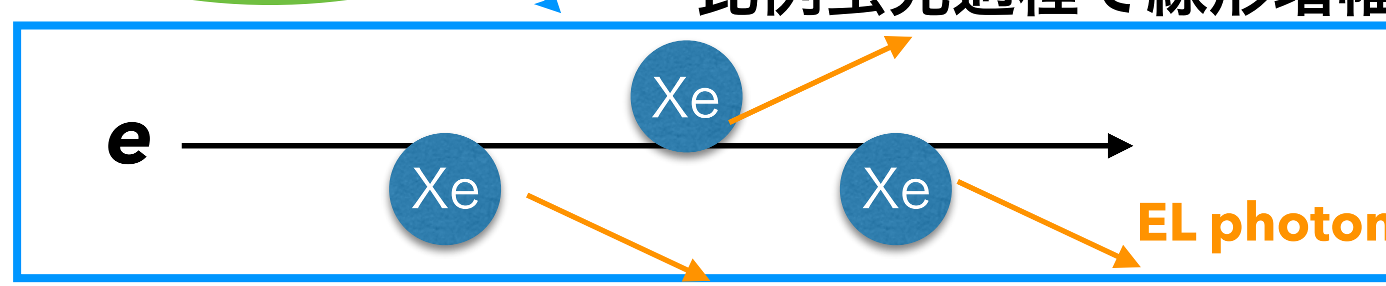


ELCC; 電離電子を捉えて

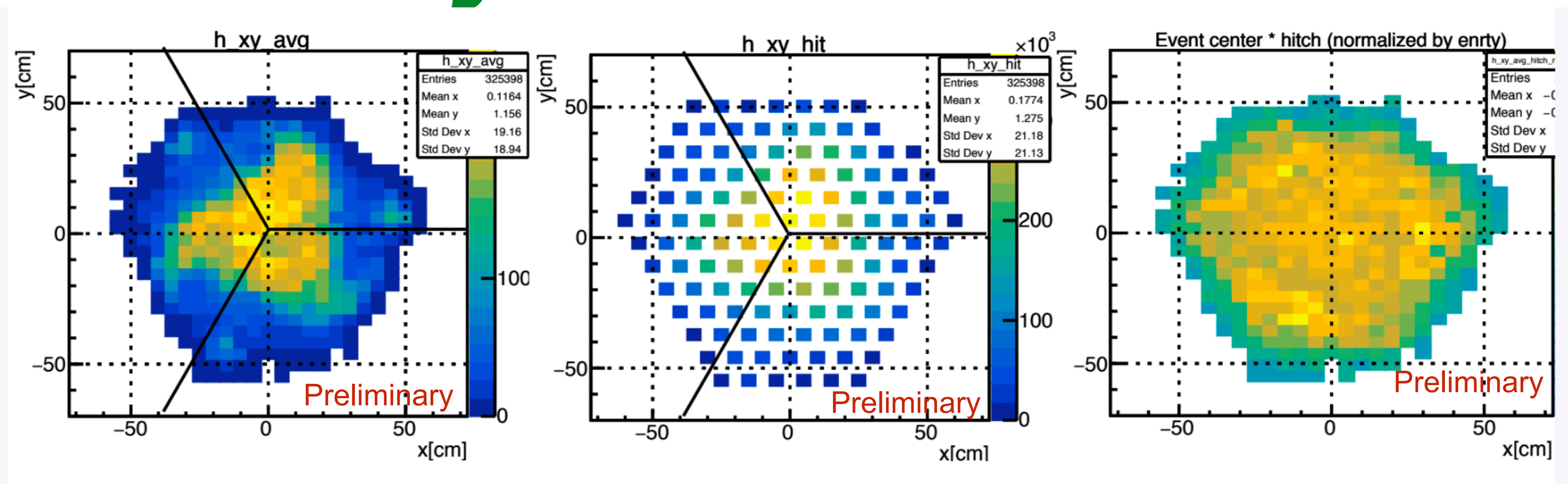
エネルギー & 飛跡取得

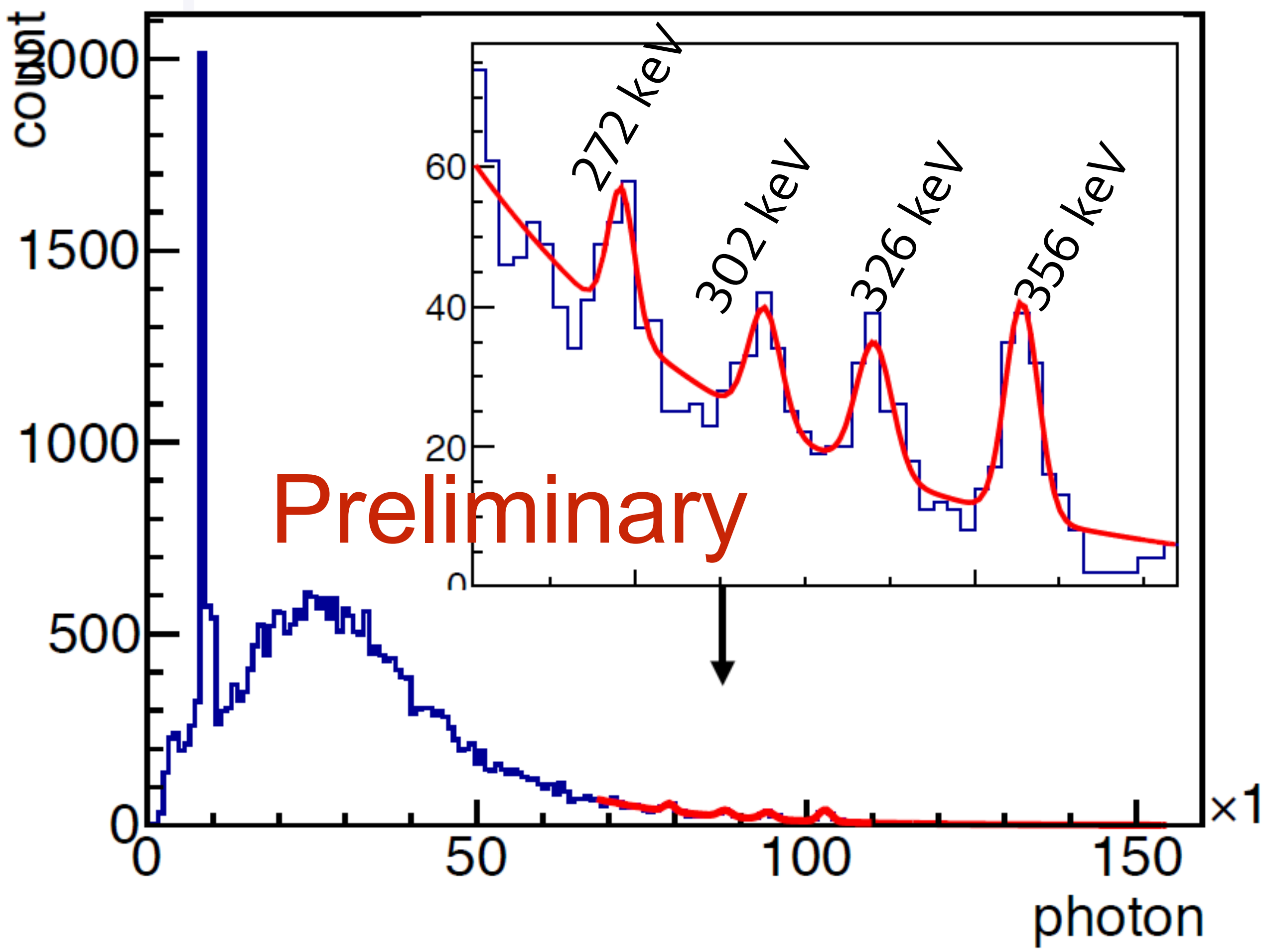
(ElectroLuminescence Collection Cell)

比例蛍光過程で線形増幅



Preliminary Results from HP180L





- ΔE ~ 0.8% (FWHM) @ 2.46MeV
- Goal —> 0.5% (FWHM) @ 2.46MeV

まとめ

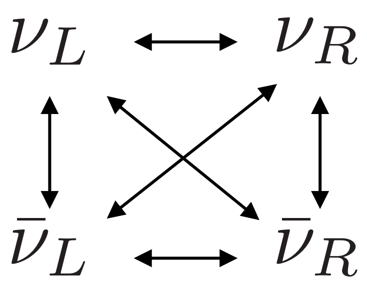
- 将来の二重ベータ崩壊探索(正常階層領域)には,
    - 大きい質量, 背景事象ゼロが重要
    - ⇒ 高エネルギー分解能, Scalability, 飛跡
    - みんな色々な検出器で頑張っている
    - とりあえず逆階層構造の探索
- AXEL検出器
    - 高圧キセノンガスTPC
    - 独自の飛跡読み出しシステム; ELCC
    - 現在180Lサイズの試作機製作中; Q値の分解能評価

Backup

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 (ν=ν^C ; Majorana condition)
- ν_L = anti-ν_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≠反粒子は分かっている



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

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

シーソー機構

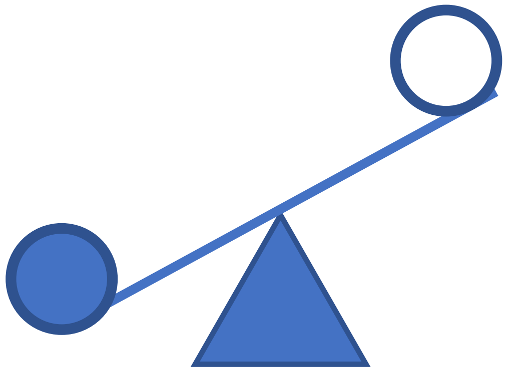
いわゆる "type-I see-saw"

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($m_R >> m_D$, m_L~0)とすると

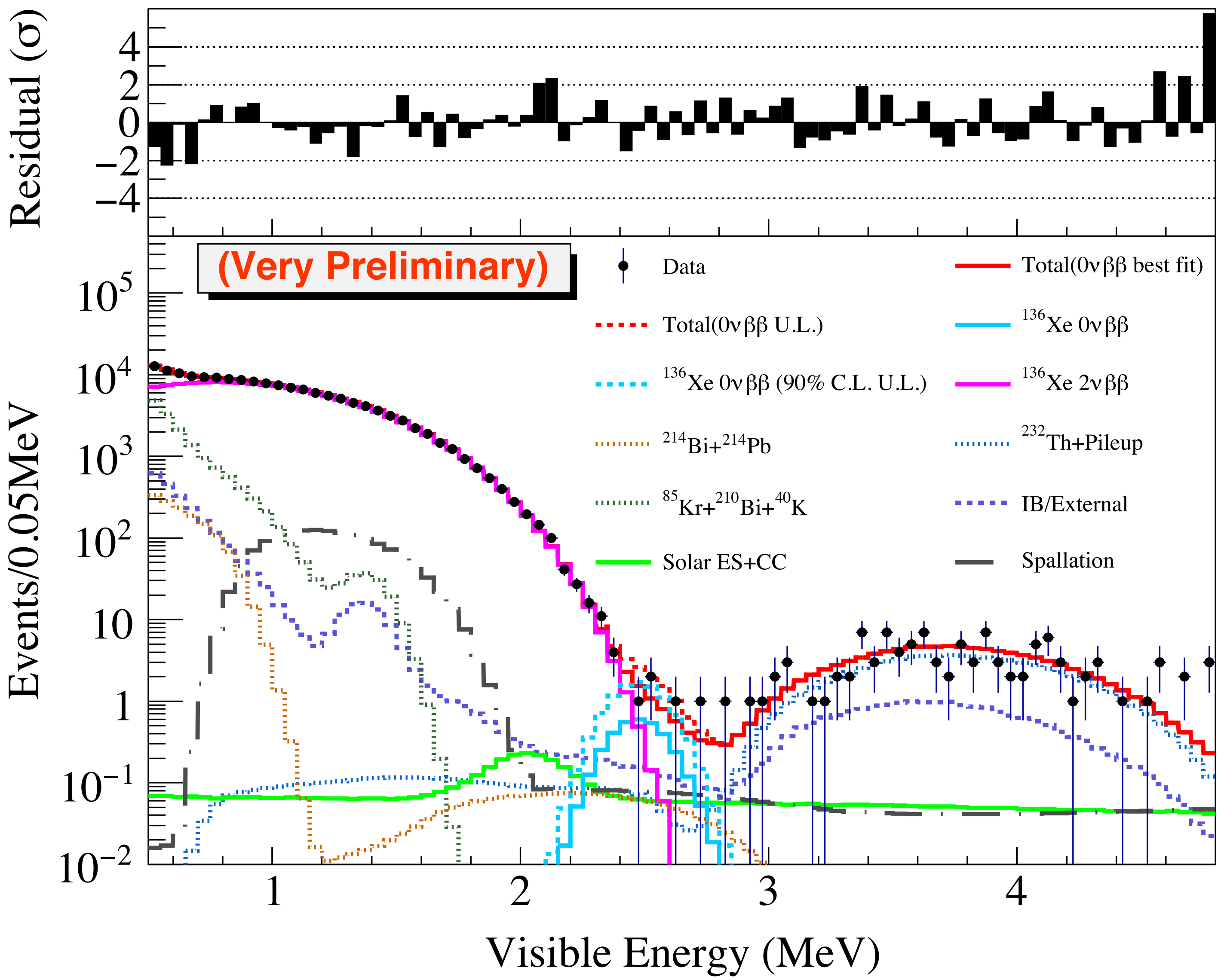
$$\mathcal{L}_{D+M} = \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

$$\longrightarrow \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} \frac{m_D^2}{m_R} & 0 \\ 0 & m_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$



右巻き質量を重くすることで左巻きが極端に軽くなる

Fitting results



Best fit : 2.1 events/day/kton-XeLS

90% Upper limit : < 6.0 events/day/kton-XeLS

$T^{0\nu}_{1/2}$ > 4 × 10^{25} year (90% C.L.)

<u>Summary of observed & best-fit events in ROI</u>

Observed events	8
Best-fit total events	10.7
0νββ	2.8
2νββ	5.1
^{214}Bi in LS	0.4
^{212}Bi-^{212}Po pile-up	0.4
Film BG (^{214}Bi)	0.9
Spallation (^{10}C)	0.2
Spallation (^{137}Xe)	0.1
Spallation (short-lived)	0.2
Solar ^{8}B ν	0.4