Double Beta Decay Experiments – Focusing on AMoRE project

Yeongduk Kim
Institute for Basic Science

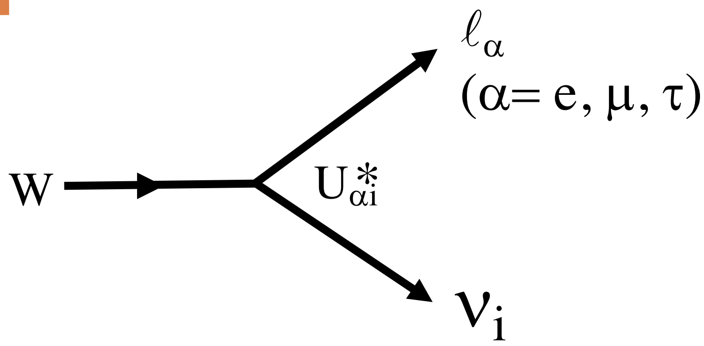
2021. 9. 7.

Corfu, "Workshop on the Standard Model and Beyond"

I will talk about

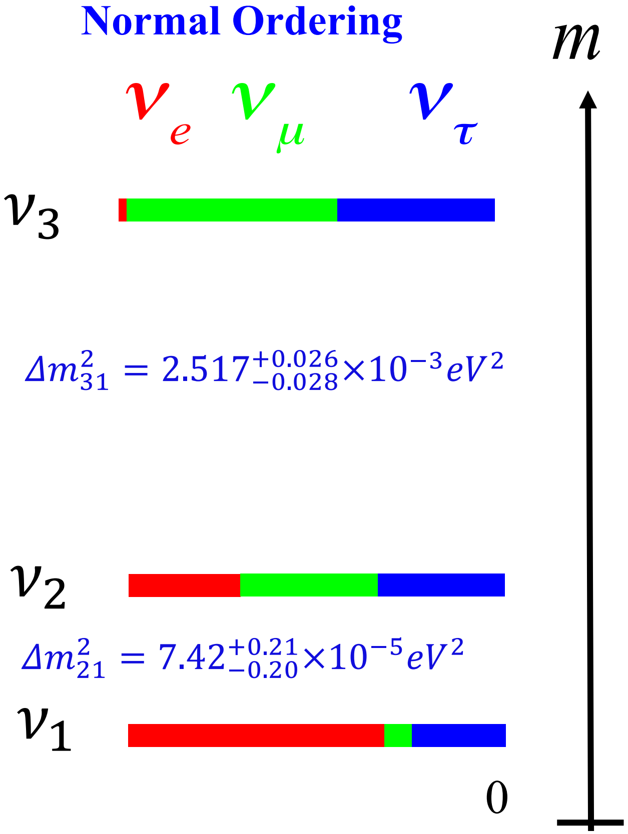
1. Motivation of Neutrinoless DBD
2. Current status & Comparisons
3. Status of AMoRE experiment

Status of Neutrino mixing & oscillation



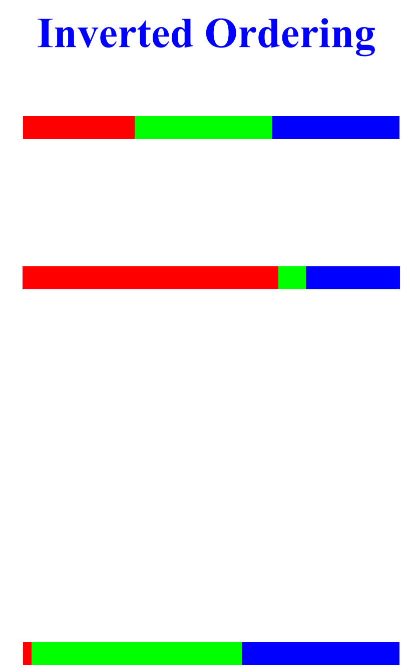
Parameters

- 3 mixing angles.
- 2 mass differences
- 1 Dirac CP phase
- + 2 Majorana phase
  (if Majorana neutrinos)



	NO
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$
δ^{CP}	197^{+27}_{-24}

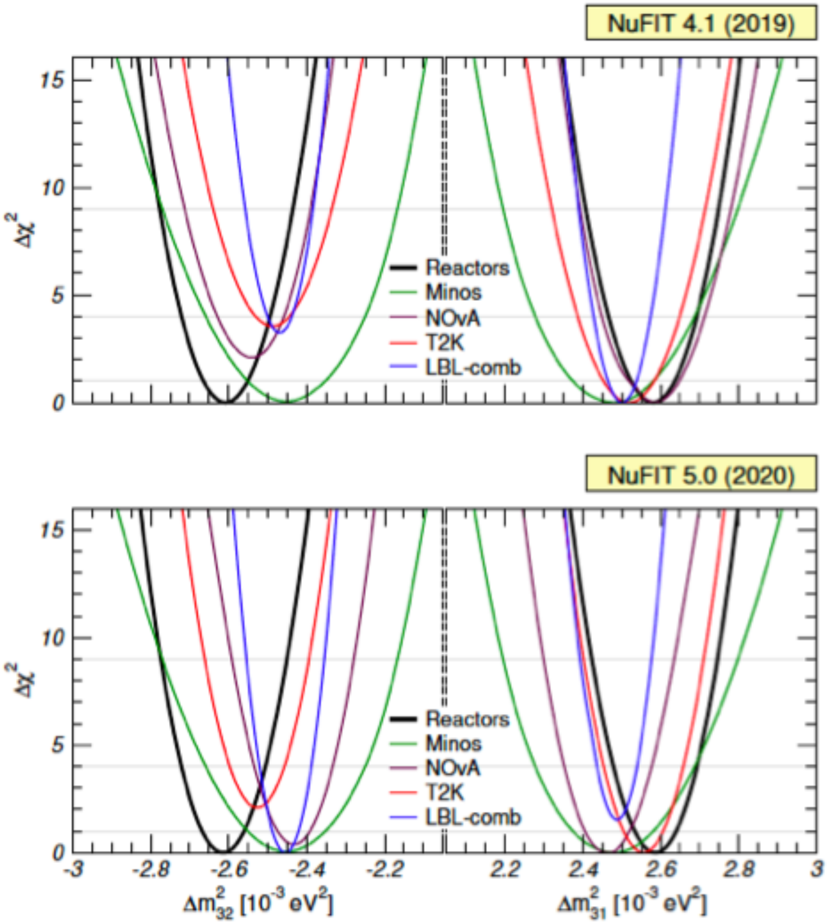
$$P(\nu_\alpha \to \nu_\alpha) = 1\text{-}\sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{E_\nu}\right)$$



Experiments for neutrino mass

- Mass Ordering ?
- Mass limits from single beta decay
- Are neutrinos and antineutrinos the same particles ?
- Mass limits from $0\nu\beta\beta$ experiments.
- Neutrino mass from cosmology observation
- Are there sterile neutrinos ?

Updates for mass ordering in 2020



Esteban et al., JHEP09 2020, 178

- The best fit remains for the normal mass ordering, however, with reduced significance.
- Without SK-atm, inverted ordering is disfavored only with $\Delta\chi^2 = 2.7(1.6\sigma)$ to be compared with $\Delta\chi^2 = 6.2(2.5\sigma)$ in 2019.
- This change is driven by the new LBL results from T2K and NOvA.

- For experimentalists, we need to assume Normal Ordering.

Eligio Lisi @ Neutel 2021

Cosmo data can add from ~0 to ~0.7σ to the ~2.7σ oscillation preference for NO

→ overall ~ 2.7−3.4 σ hint for NO vs IO

Motivation of 0νββ - Most promising BSM Physics !

SM has only left(right)-handed massless (anti)neutrinos.

Dirac Neutrino Masses

$$L_D = -m_D(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R)$$

- Lepton # $is\ conserved$.
- Higgs mechanism needs right-handed neutrinos, ν_R.

$y^\nu: Yukawa\ Coupling \sim 10^{-12}$

Majorana Masses

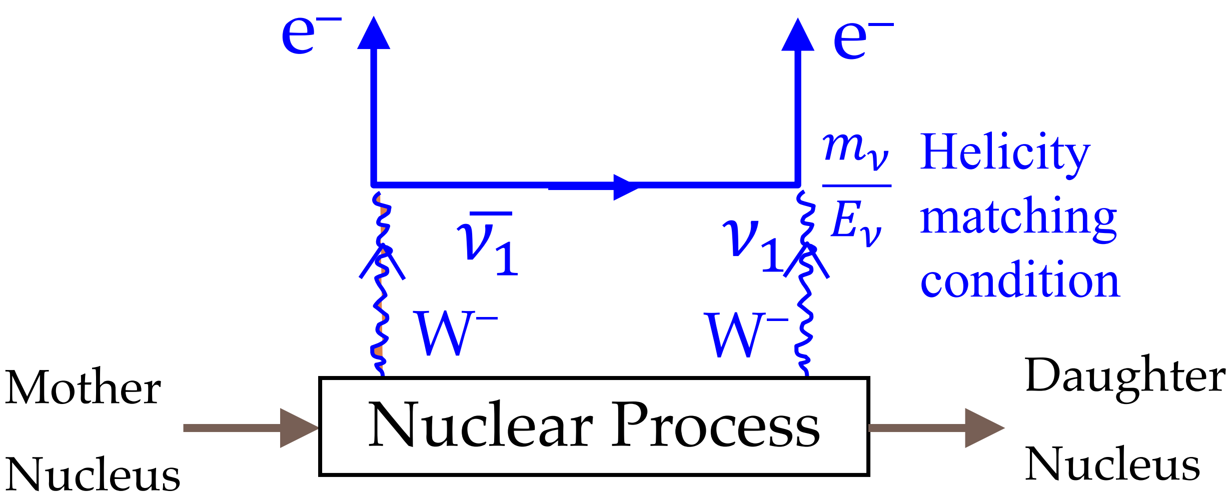
- "right-handed Majorana mass term" can be ; $L_R = -m_R/2\left[\overline{(\nu_R)^c}\nu_R + \overline{\nu_R}(\nu_R)^c\right]$
- $(\nu)^c = \nu \ \rightarrow$ Majorana particle (No L# is needed)
- See-Saw Mechanism gives two Majorana mass eigenstates,

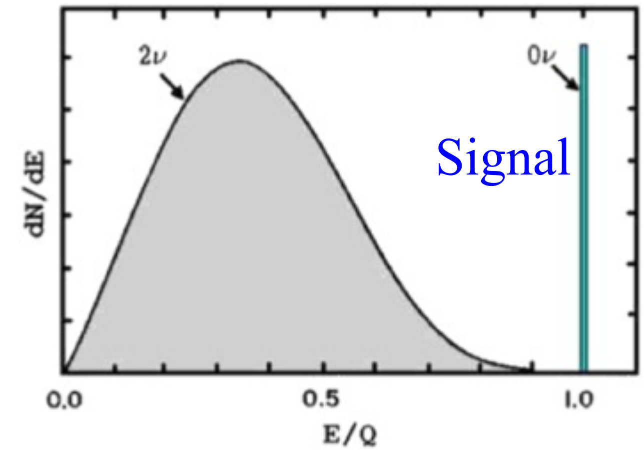
$$m_1 \simeq \frac{m_D^2}{m_R}$$

$$m_2 \simeq m_R$$

How to test if neutrinos are Majorana particles ?

- Seek Neutrinoless Double Beta decay (0νββ)





- 1939, Furry already suggested to search 0νββ to check Majorana's theory. Furry PR56, 1184(1939)

More quantitatively…

- **$T_{1/2}$ of 0νββ decay are inversely proportional to effective 0νββ neutrino mass, $m_{\beta\beta}$, which is a function of neutrino masses, mixing angles, and Majorana phases.**

for light neutrino exchange model.

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Phase factor

Half-life Measured

Nuclear Matrix Element

Neutrino Mass

effective 0νββ neutrino mass is ;

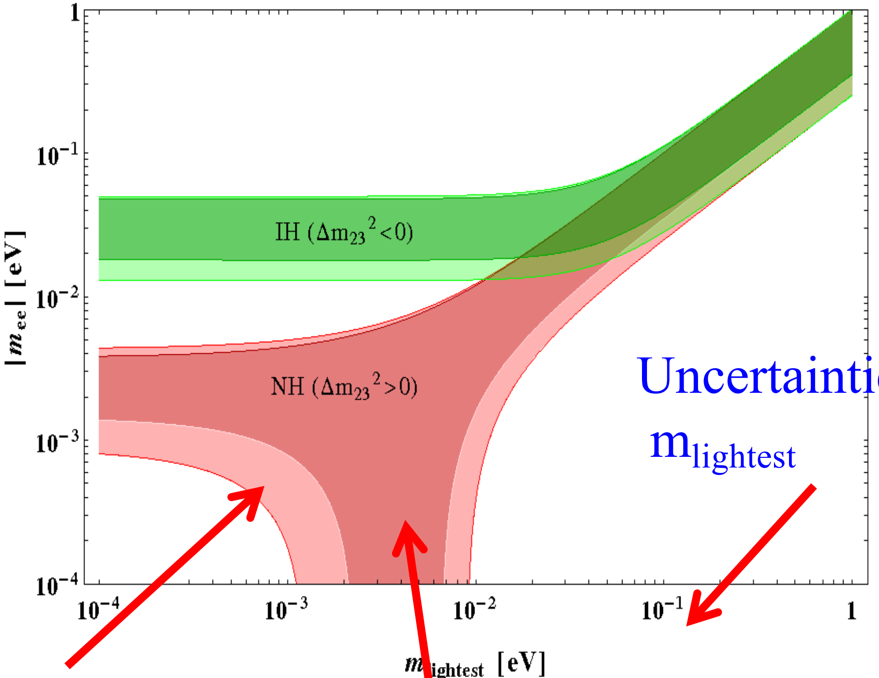
$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| = \left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$

$$T_{1/2}^{0\nu} \rightarrow m_{\beta\beta}$$

Expectation on effective 0νββ mass

for light neutrino exchange model.

$m_{\beta\beta}$

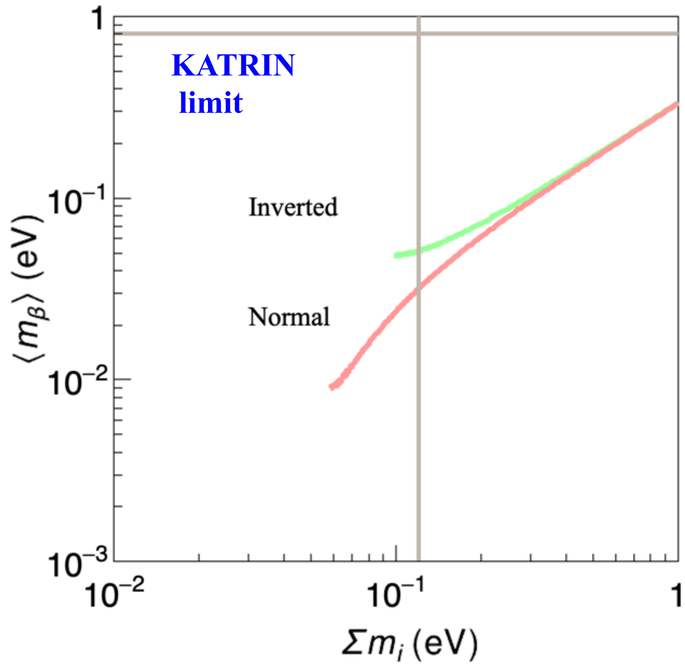


Uncertainties from $m_{lightest}$

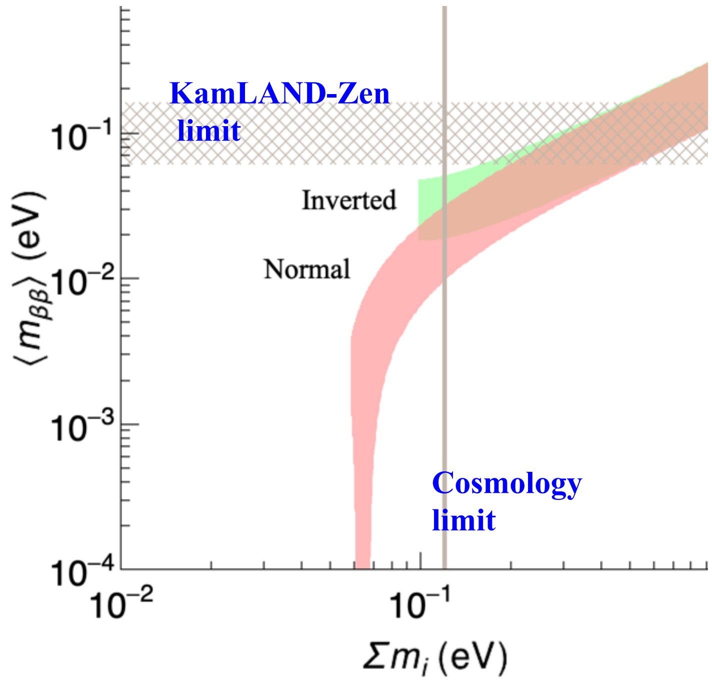
Uncertainties from mixing angles

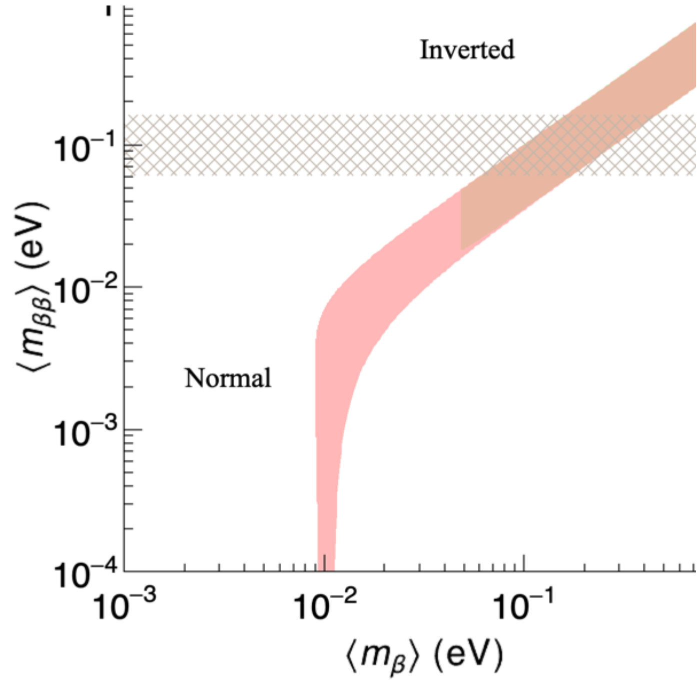
Uncertainties from phases

Current Mass Limits



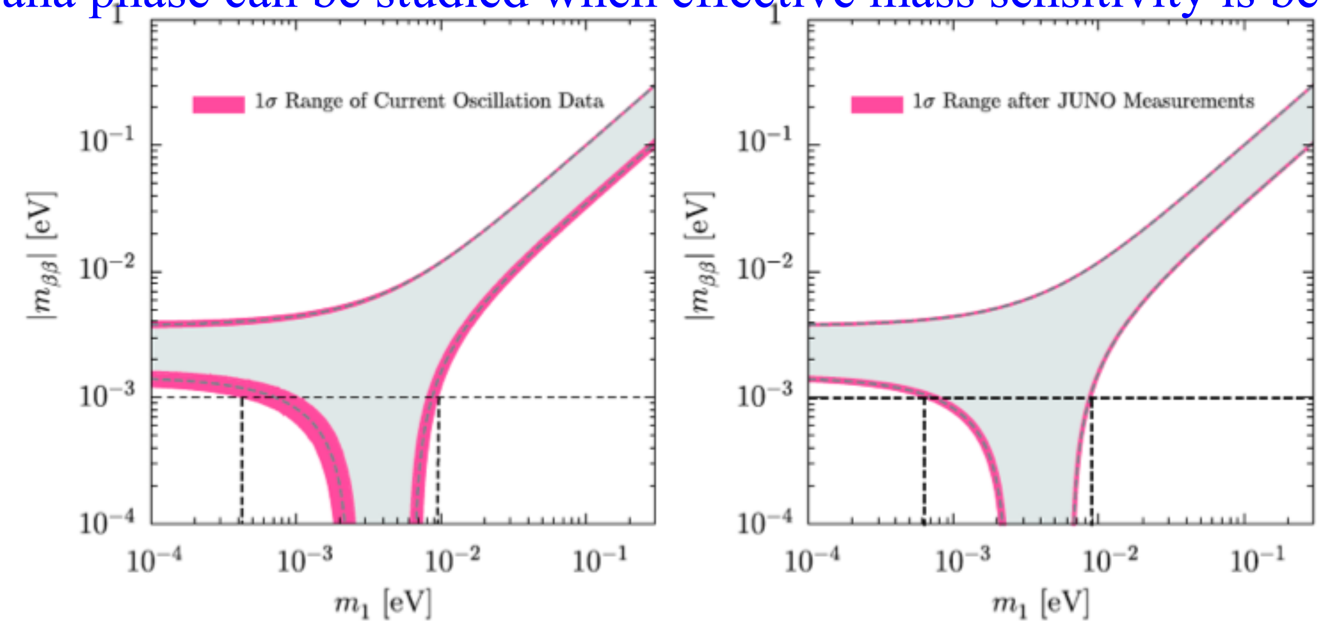
- Neutrino mass is ultra small, and we don't understand its origin. It is related to if neutrinos are Majorana particles.
- Neutrino mass is constrained by beta decays and cosmology.

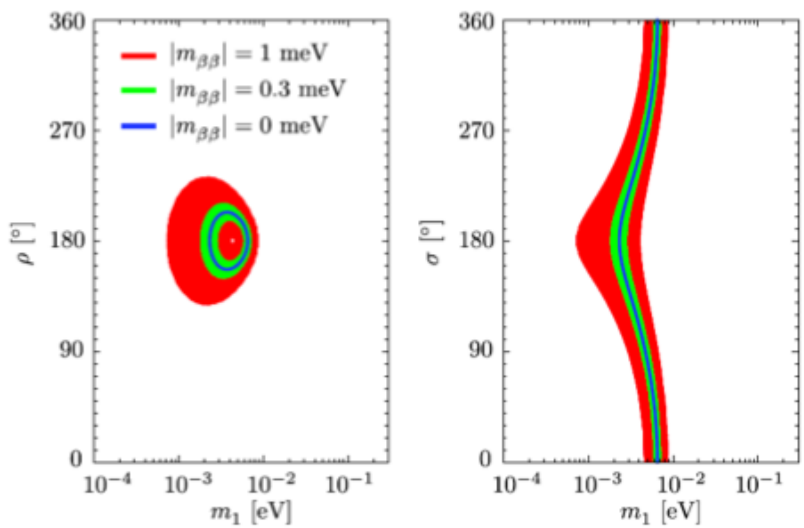




Towards Majorana phases

Majorana phase can be studied when effective mass sensitivity is below ~ 1meV





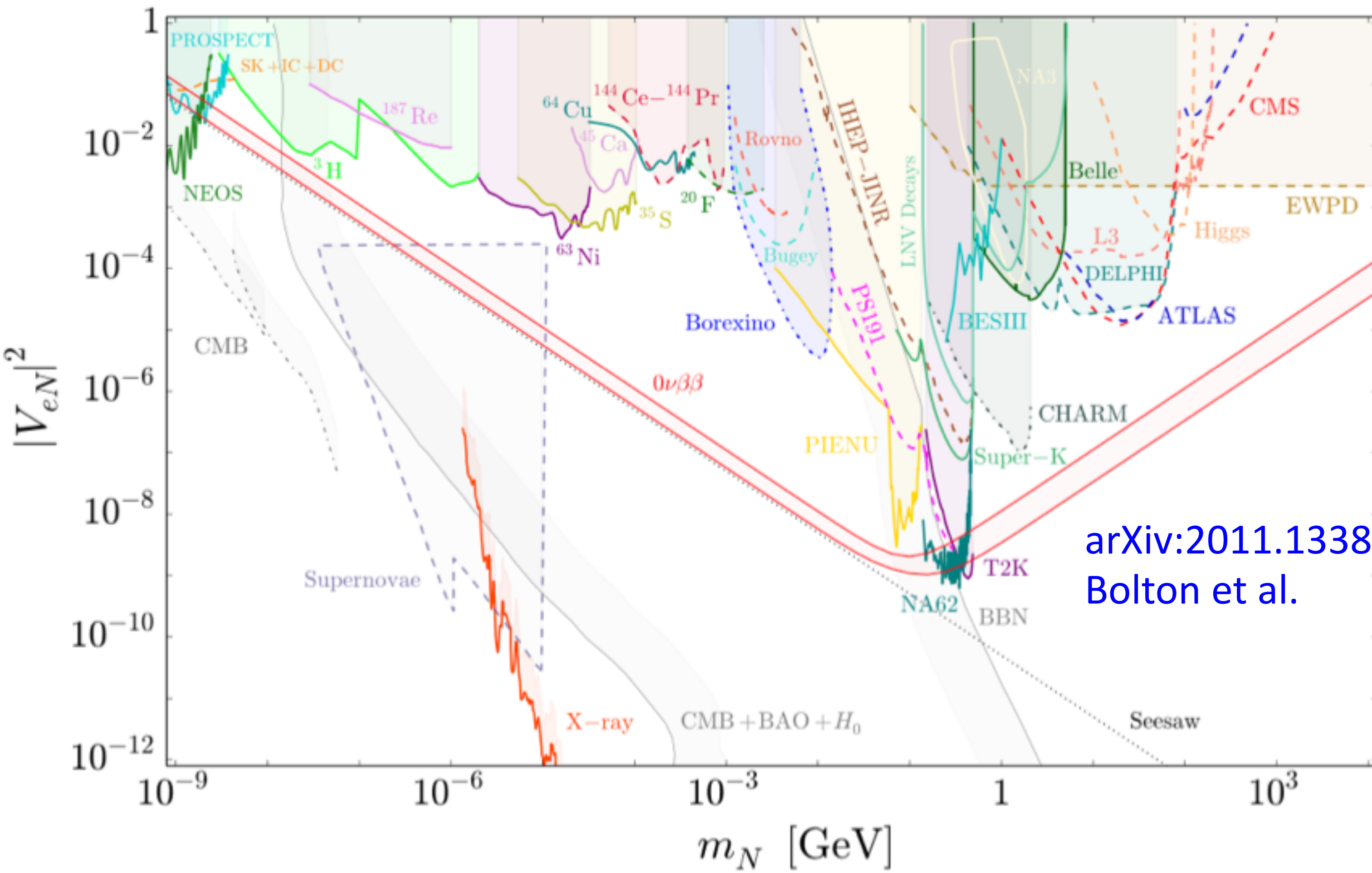
$$m_{\beta\beta} = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|$$
$$= \left| c_{13}^2 c_{12}^2 e^{i\rho} m_1 + c_{13}^2 s_{12}^2 m_2 + s_{13}^2 e^{i\sigma} m_3 \right|$$

But, what about the uncertainty in nuclear matrix elements ?

Cao et al., CPC44, 031001 (2020)

$0\nu\beta\beta$ vs sterile neutrinos

- $0\nu\beta\beta$ limits can be converted to limits for heavy sterile neutrino mixing with electron neutrinos. (only for Majorana neutrino case)
- It is more severe than the direct beta decay limits.

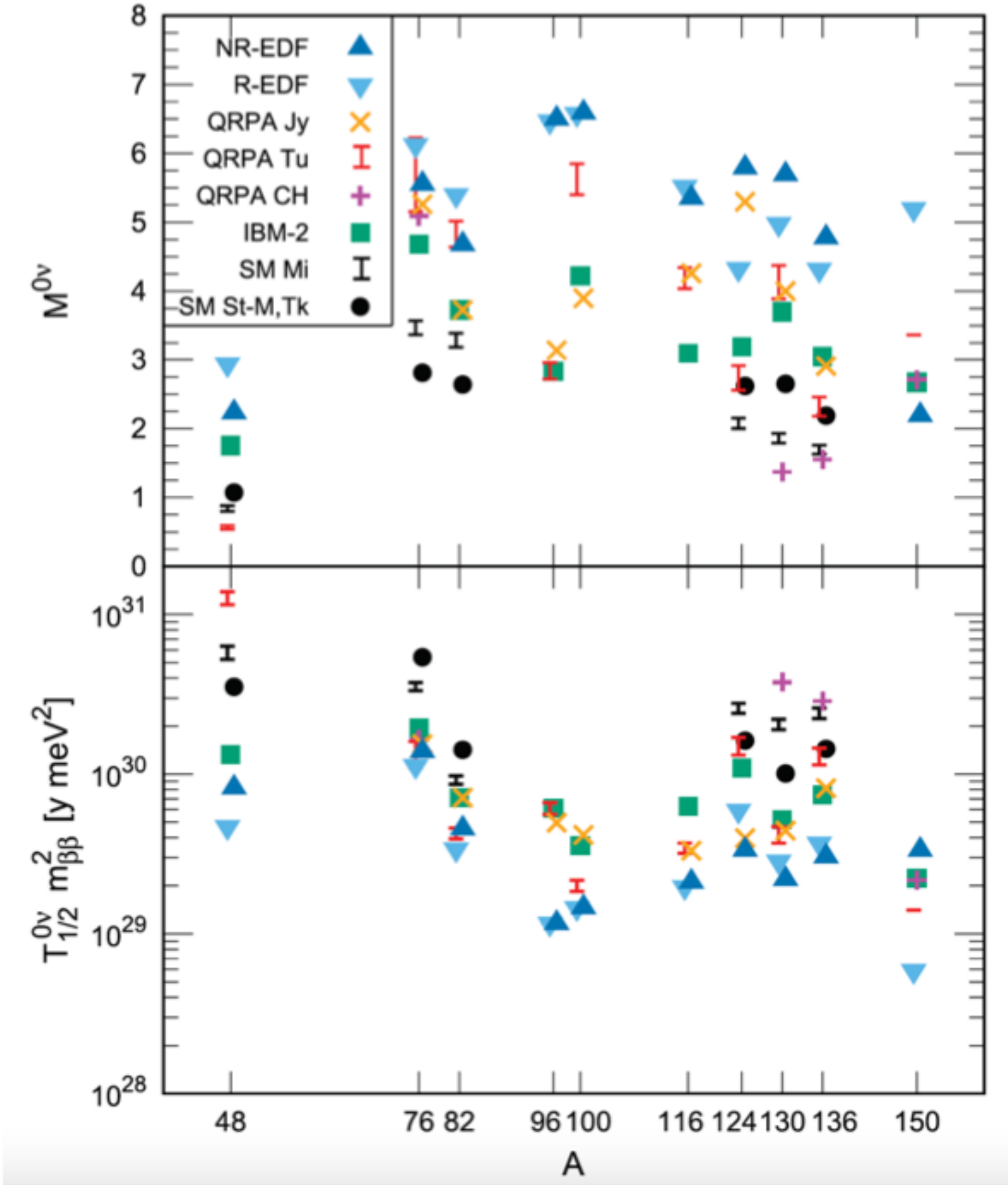


arXiv:2011.13387, Bolton et al.

In summary, $0\nu\beta\beta$ will

- confirm
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.
- support on
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

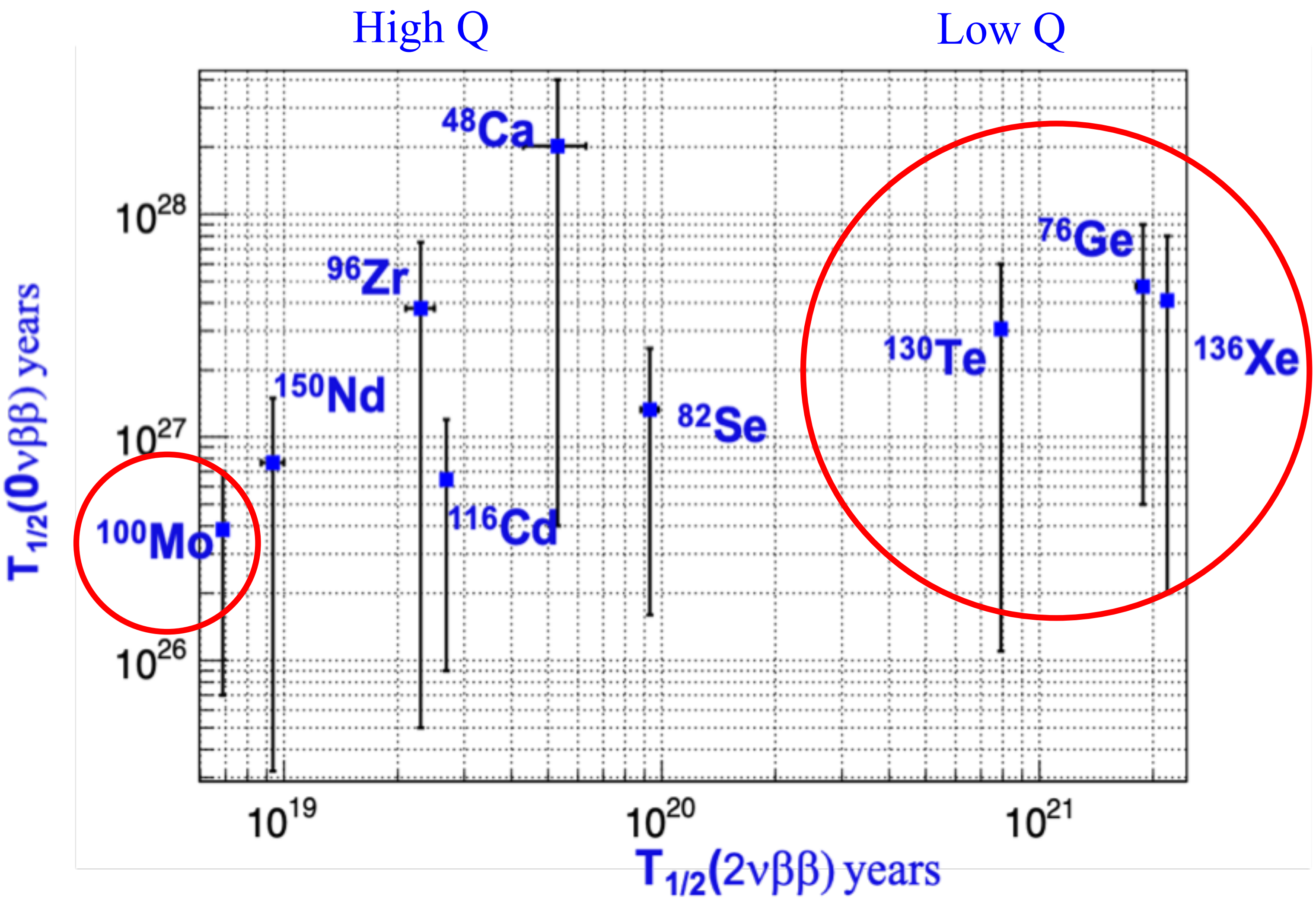
Best isotope for experiment ?



Engel & Menendez
RPP 80(2017)

0νββ vs 2νββ T(1/2)

- **Many isotopes are used for** 0νββ searches.
- **A correlation between** 2νββ **half-life(measured) vs** 0νββ half-life calculated with various models for inverted mass ordering(20-49 meV).



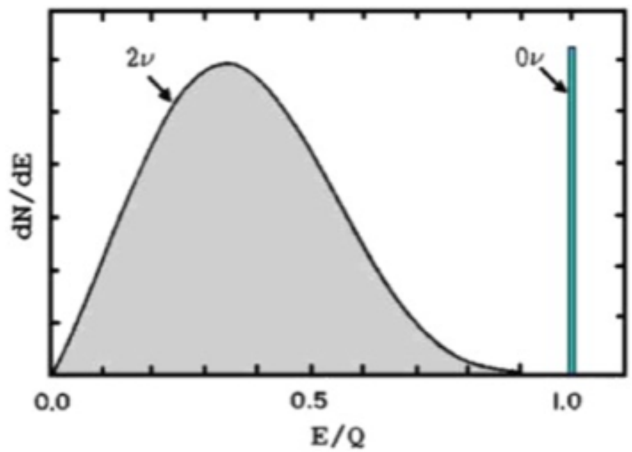
Now, how sensitive are the 0νββ experiments ?

- 0νββ needs a good energy resolution and extremely low backgrounds.
- Sensitivities on the half-life depends on background and exposure

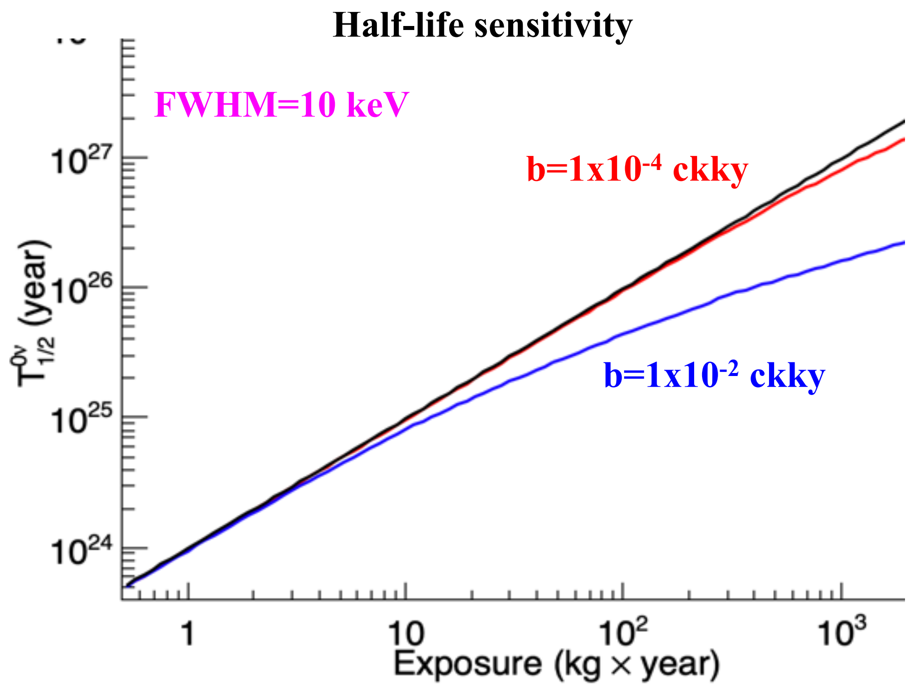
$T^{0\nu}_{1/2} \propto \sqrt{\frac{MT}{b\Delta E}}$ (for finite backgrounds)

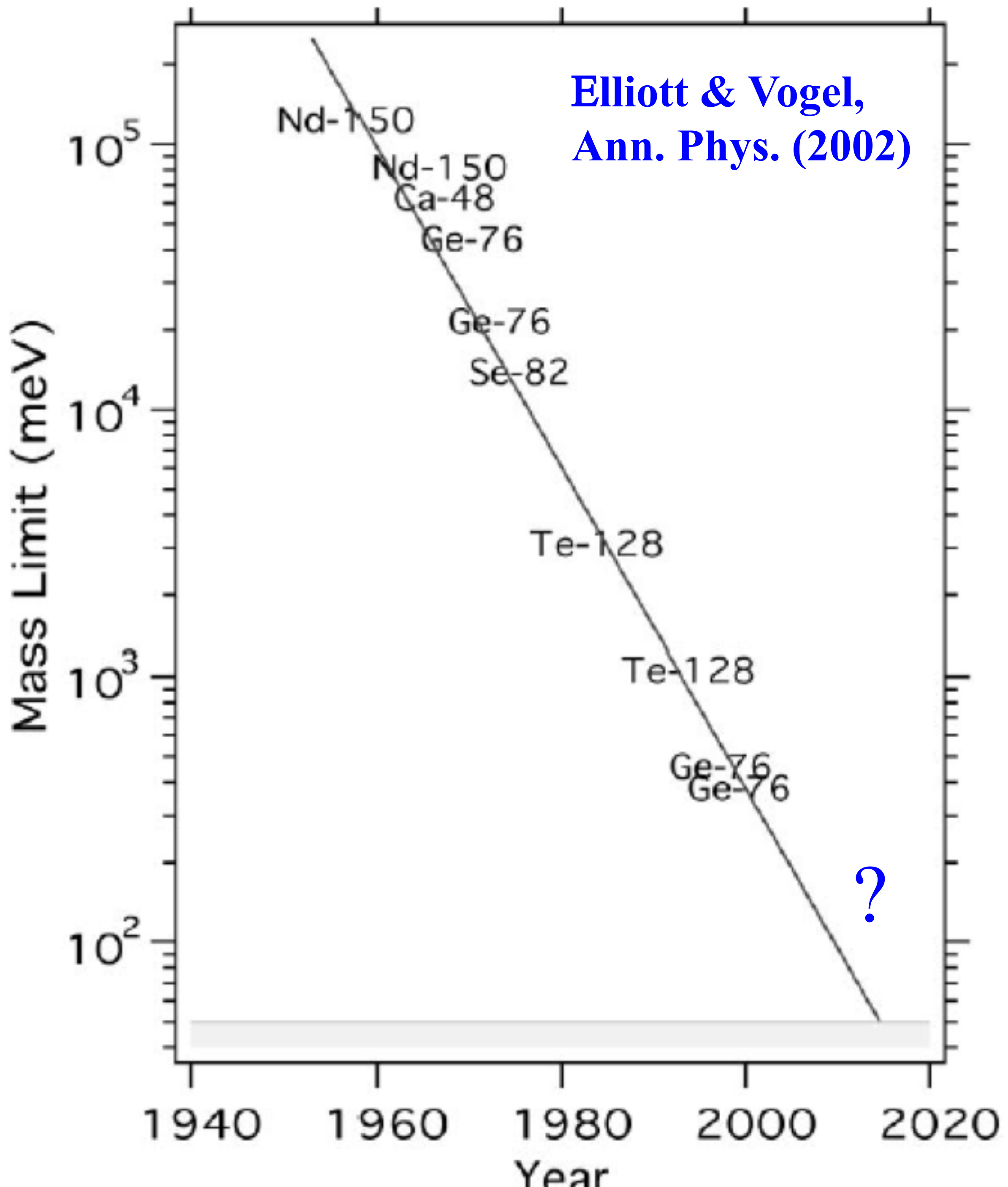
$T^{0\nu}_{1/2} \propto MT$ (for "0" backgronds)

Signal : sharp peak @ Q-value



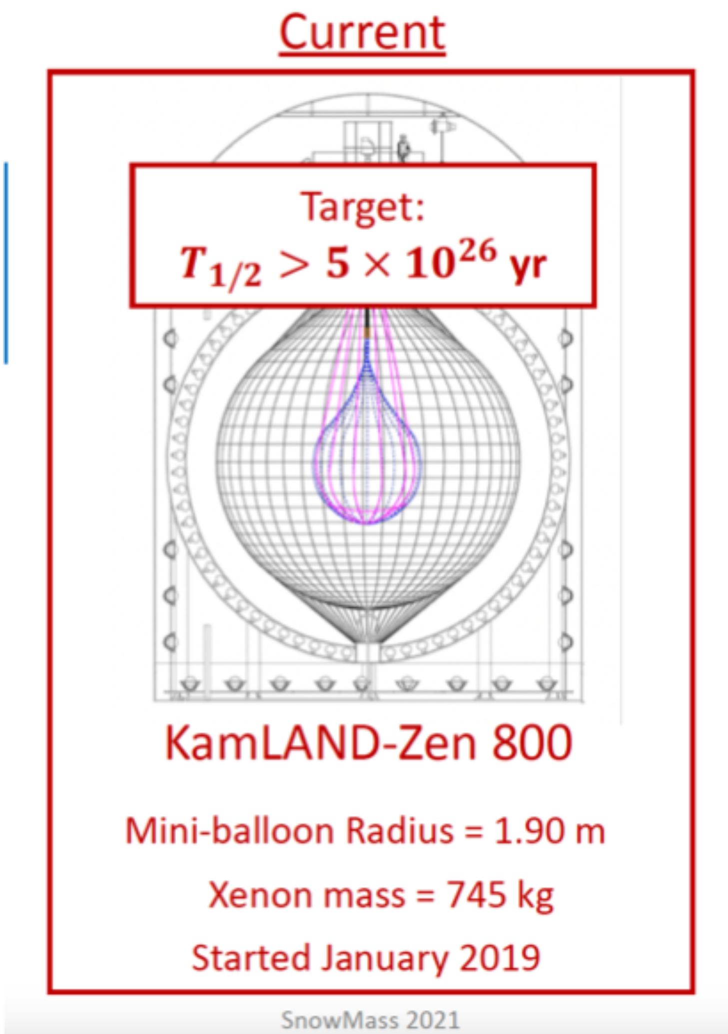
Background Unit :
ckky=counts/(keV kg year)



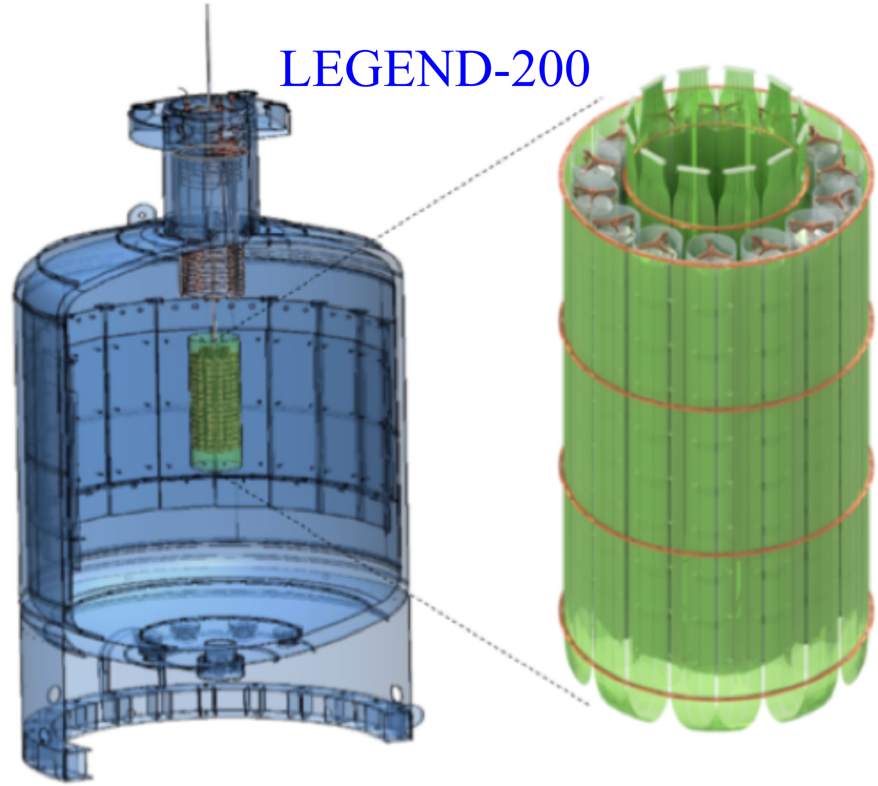


Elliott & Vogel,
Ann. Phys. (2002)
Mass Limit (meV)
10^5
10^4
10^3
10^2
Nd-150
Nd-150
Ca-48
Ge-76
Ge-76
Se-82
Te-128
Te-128
Ge-76
Ge-76
?
1940
1960
1980
2000
2020
Year

Future experiments



LEGEND-200

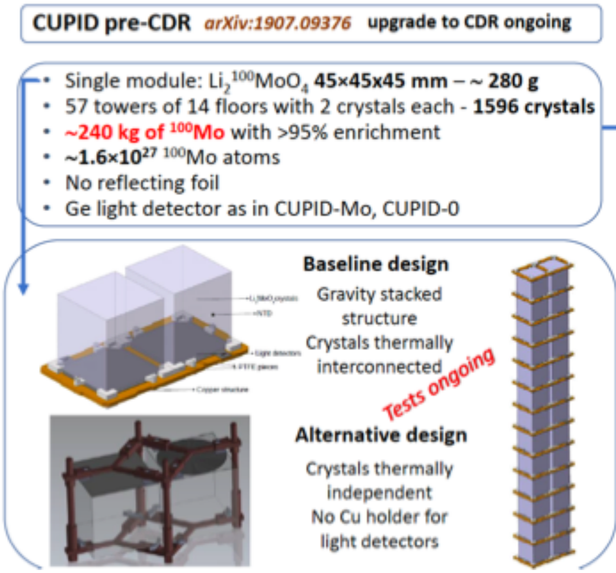


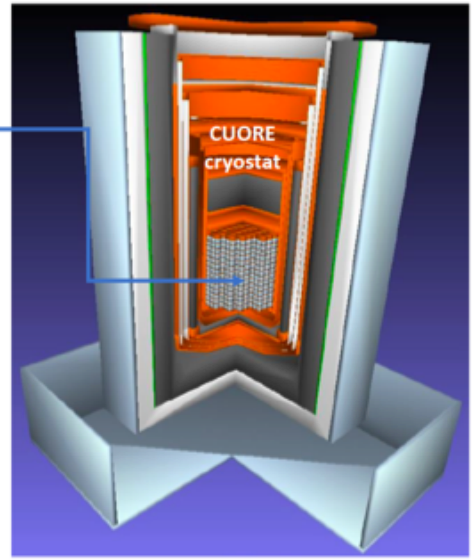
+ LEGEND-1000

KamLAND-Zen

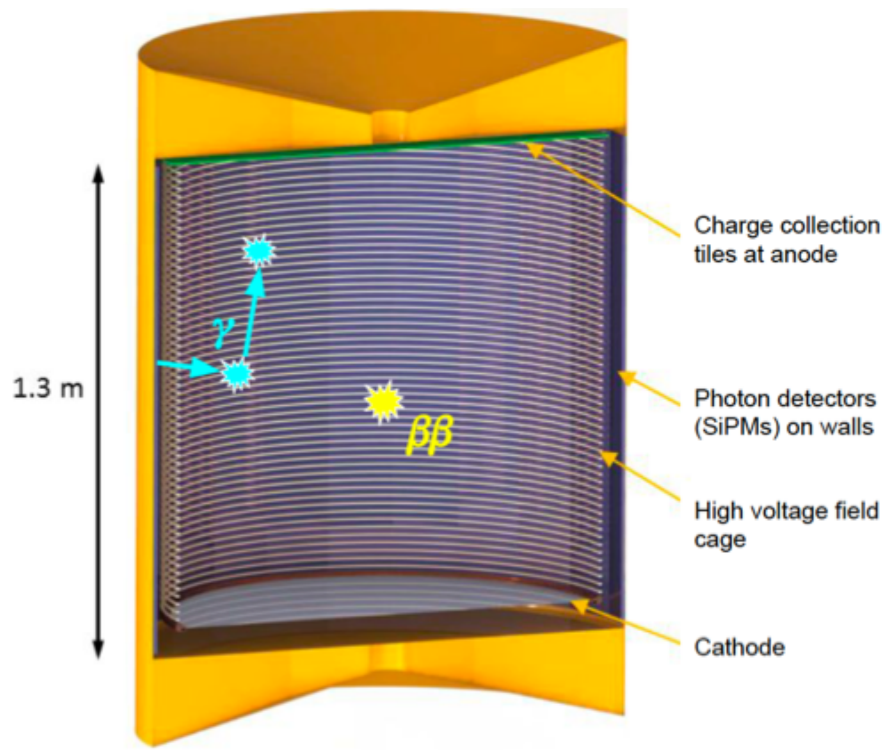
+ KamLAND2-Zen

CUPID

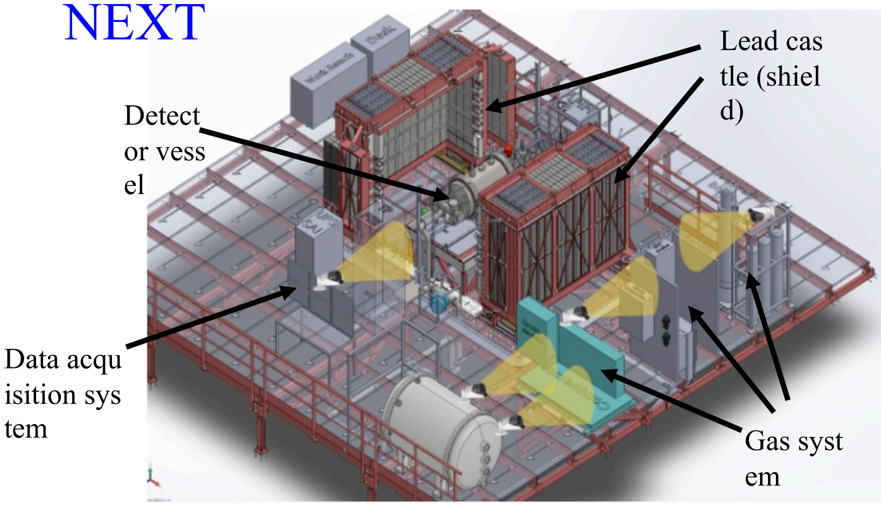




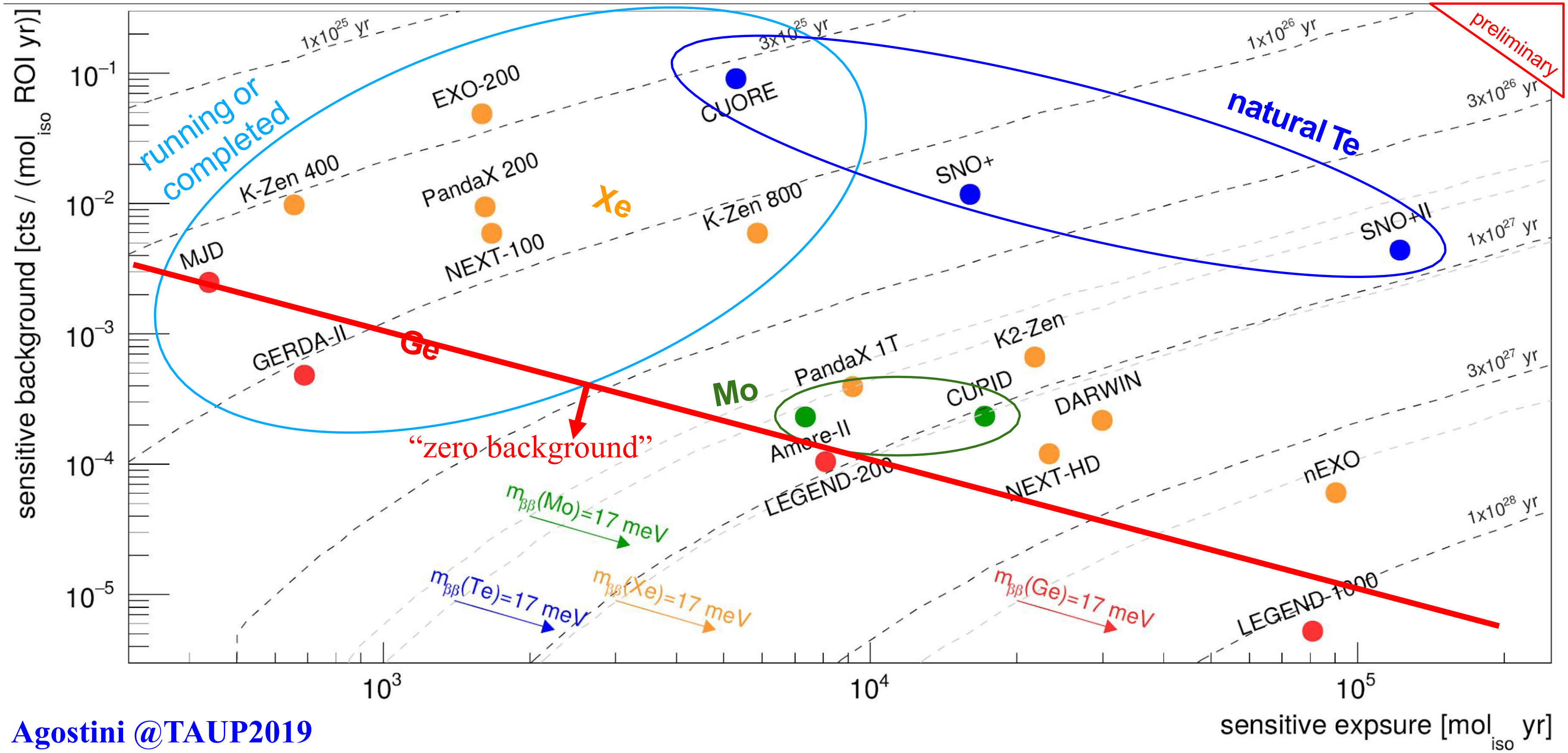
nEXO



NEXT



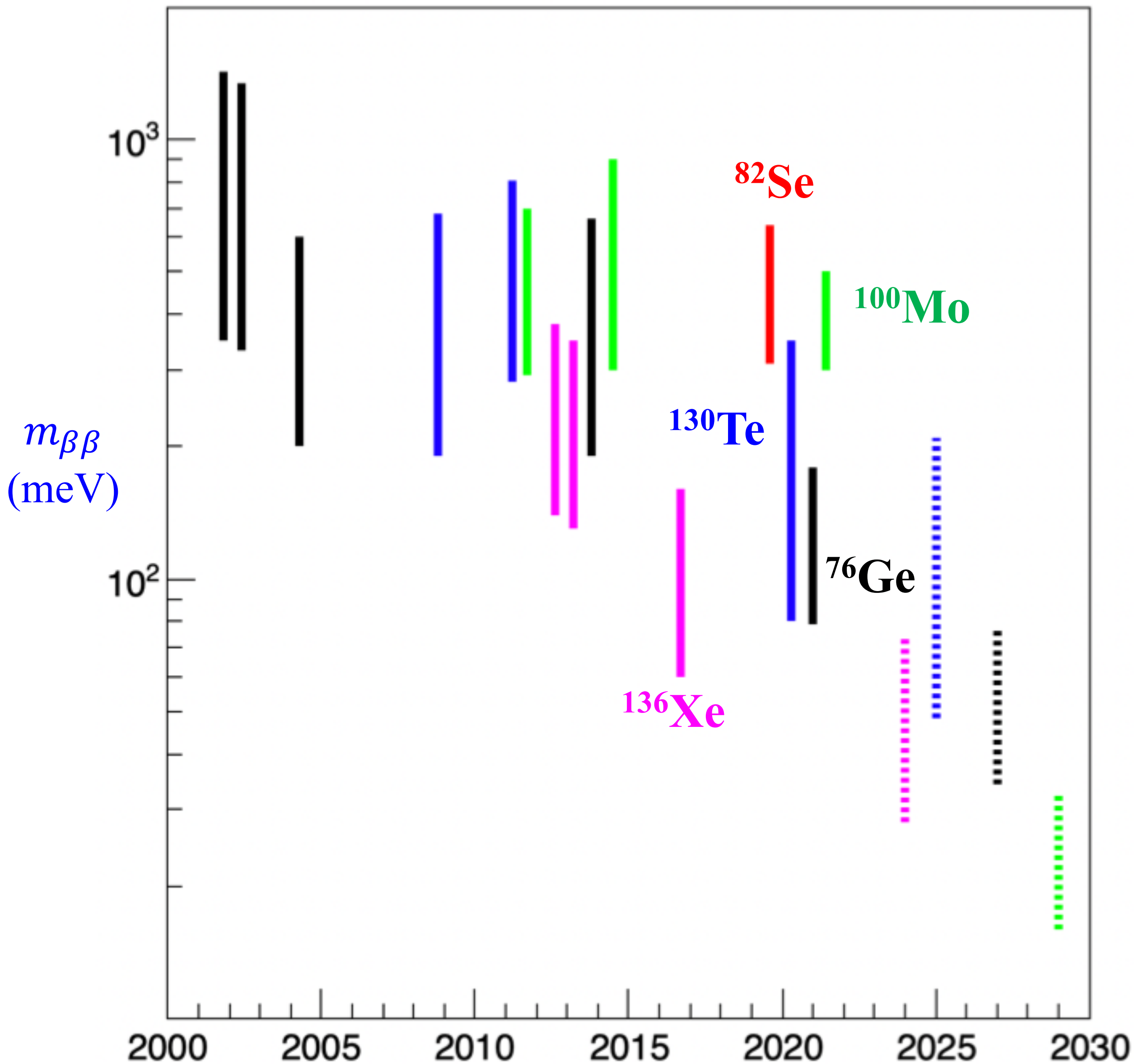
Comparison with other experiments.



Agostini @TAUP2019

- AMoRE-II is comparable to CUPID, LEGEND-200, KamLAND2-ZEN.
- IBS(CUP) has a MOU with INFN(Gran Sasso) to collaborate between AMoR E and CUPID.

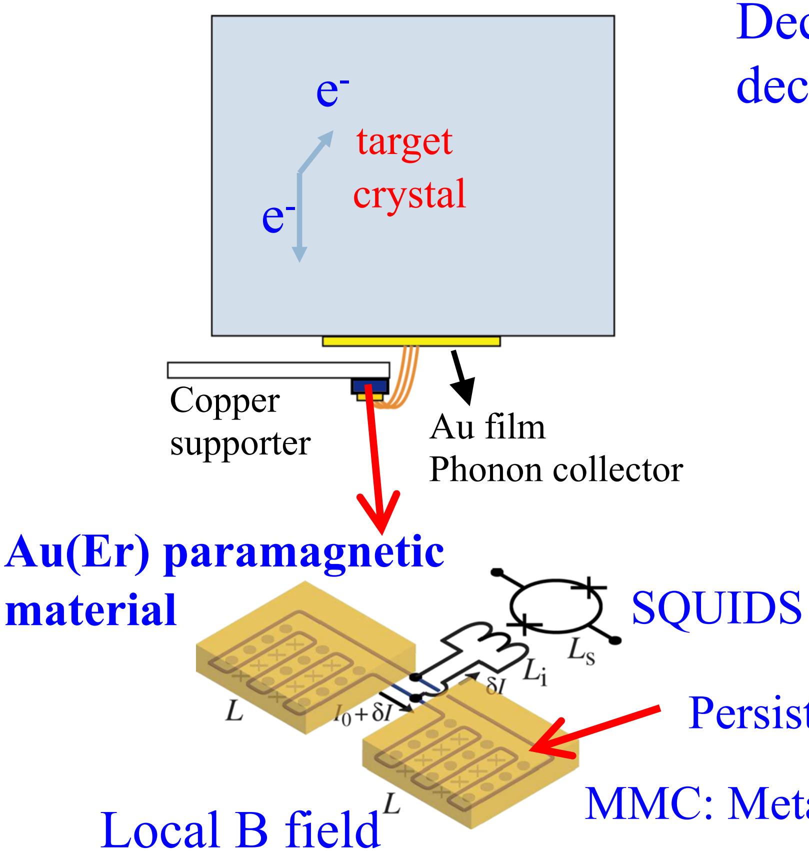
Recent Limits & Persepectives

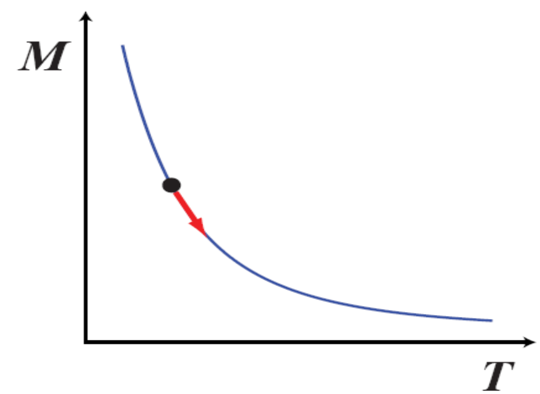


Principle of AMoRE Detector

- Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC
- For Each crystal, phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal). Highly Technical !

Decay→temperature increase→Magnetization decrese→ SQUID pick the change.



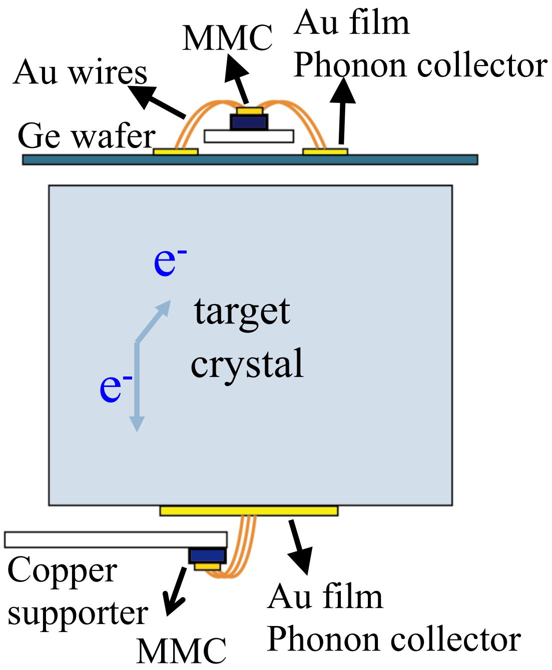


Persistent current in superconductor

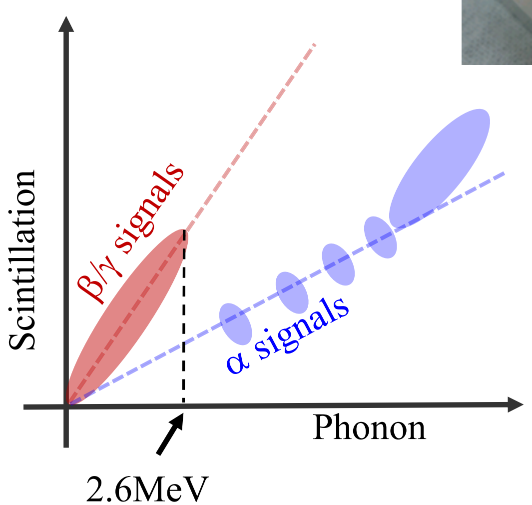
MMC: Metallic Magnetic Calorimeter

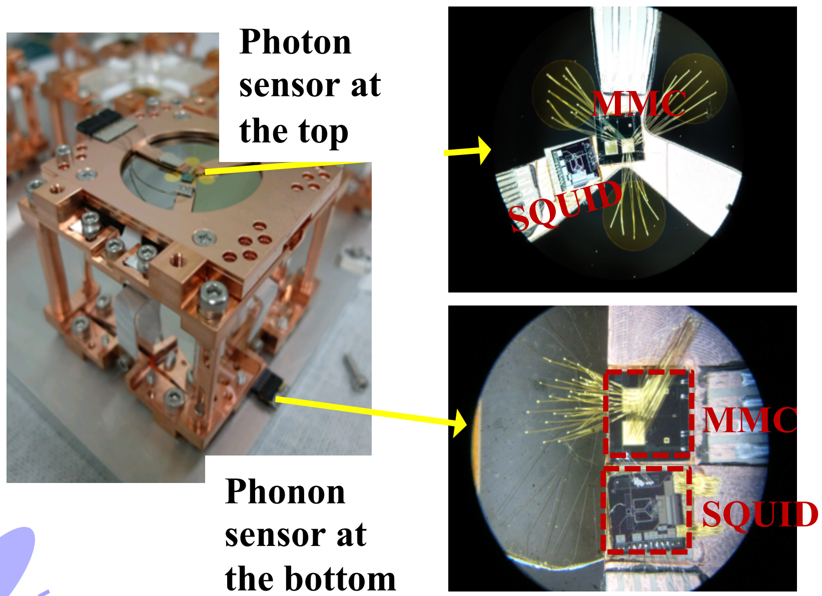
Real AMoRE Detector

- **Additionnally detect lights from scintillating crystal → can remove continuous alpha backgrounds.**

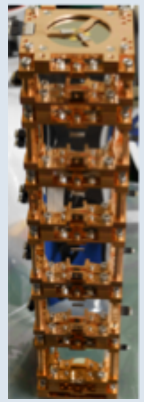
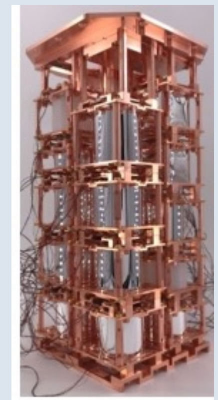
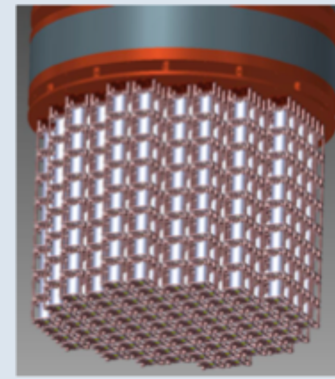


Light detector added



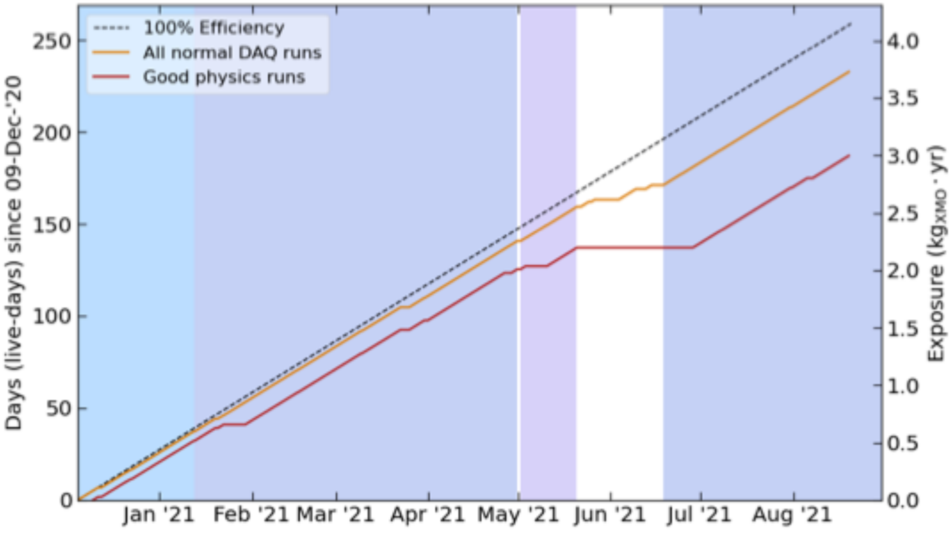


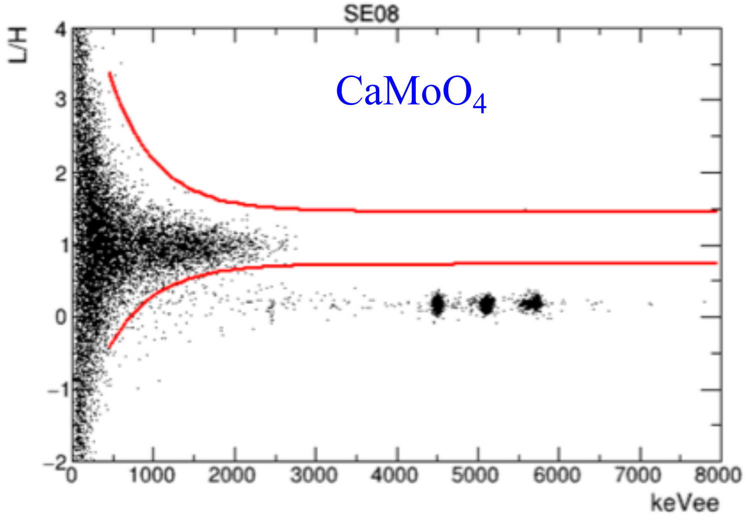
Plan of AMoRE Project

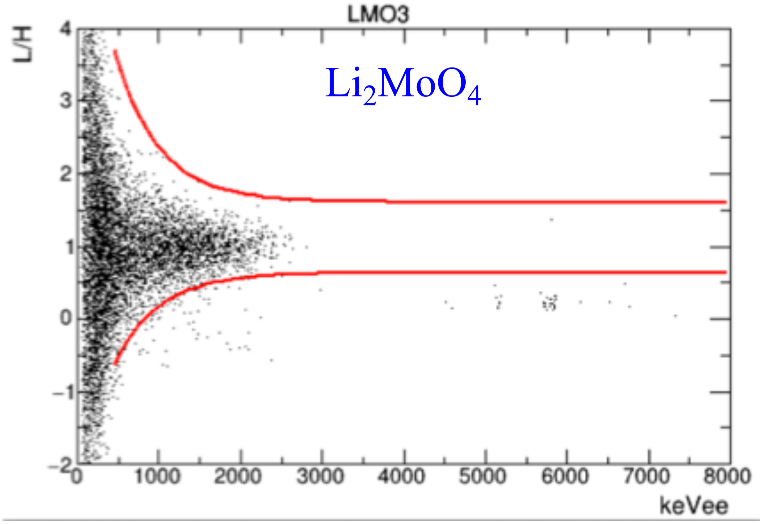
Phases	AMoRE-Pilot	AMoRE-I	AMoRE-II
Detector Setup (Not in scale)			
Crystals	$^{40}Ca^{100}MoO_4$ (CMO)	$(^{40}Ca,Li_2)^{100}MoO_4$	$Li_2{}^{100}MoO_4$ (LMO)
Crystal # & Mass	6, 1.9kg	18, 6.2kg	596, 178kg
Background Goal(**ckky**)	10^{-1}	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$1.0x10^{23}$	$7.0x10^{24}$	$8.0x10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	13-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2022	Yemilab / 2022-2027

AMoRE-I

- AMoRE-I run began Aug. 2020 @ Y2L
- Purpose :
  - Check detector performance (LMO)
  - Understand background better.
- Same cryostat as pilot. 18 crystals.

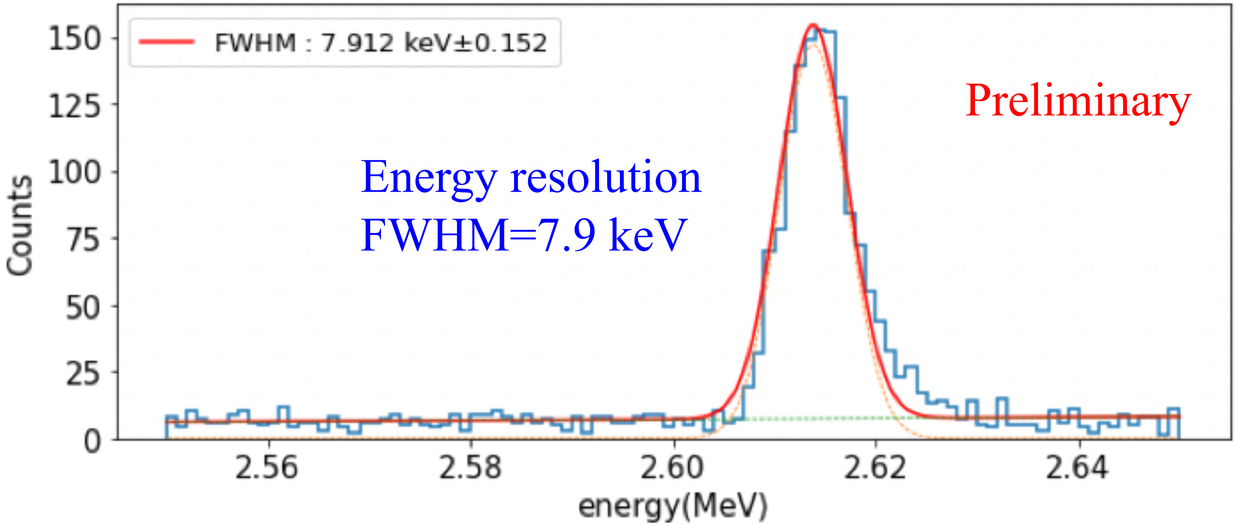






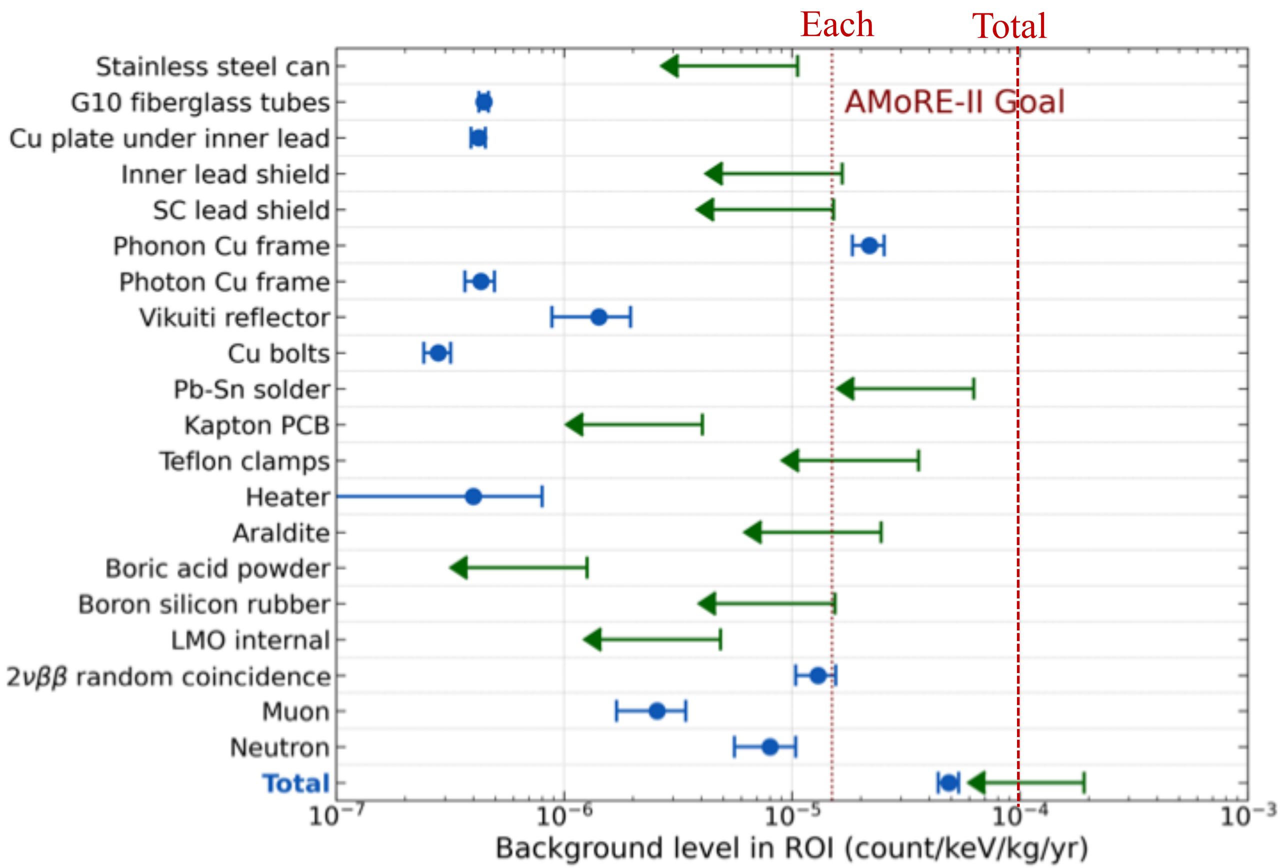
AMoRE-II status

- Tested larger crystal to reduce channel numbers for bigger experiment.
- Preliminary 6cm(D)x6cm(H) crystal result is promising.



Expectation of AMoRE-II Backgrounds

1. All materials inside Pb shielding are measured by ICP-MS and(or) HPGe.
2. All outside sources are estimated by measurements and Geant4 simulation.
3. Muon induced backgrounds are simulated with the expected muon flux.
4. Projected total background level is 4.9(5)x10^{-5} ckky and < 2x10^{-4} ckky for a limiting values.

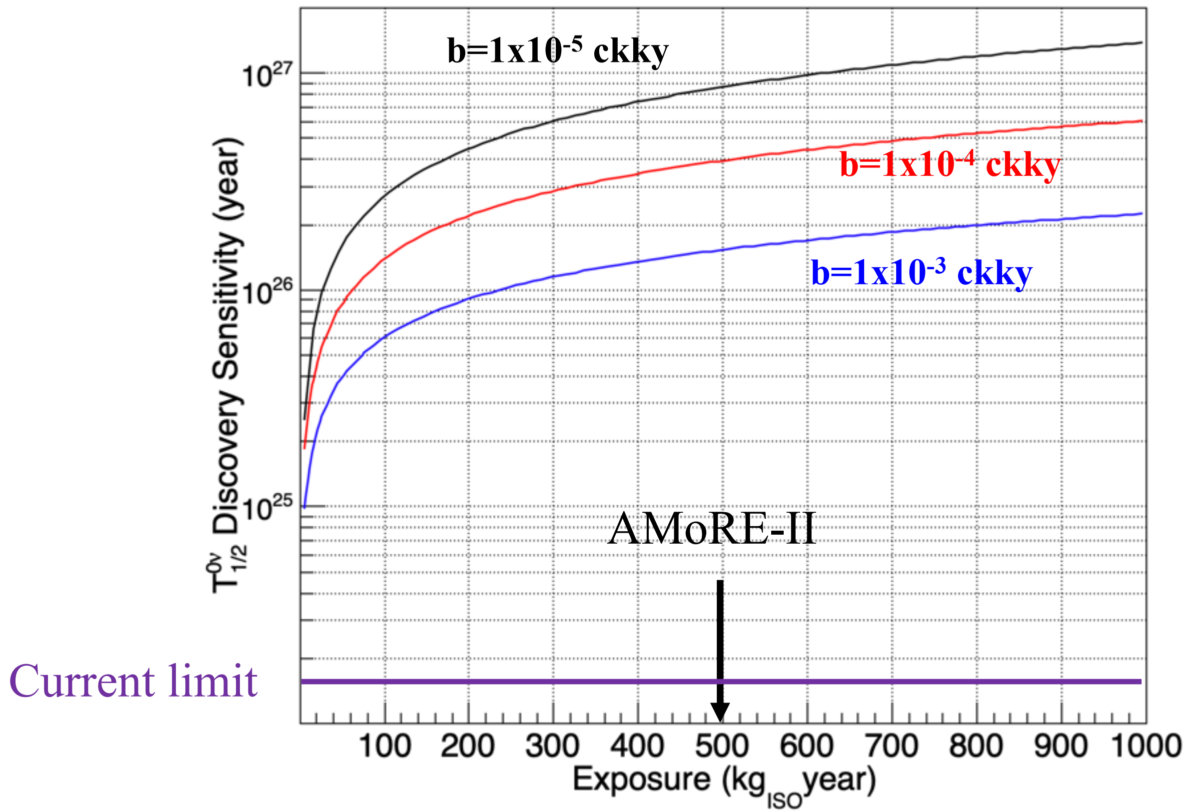


Discovery Sensitivities

Discovery sensitivity :

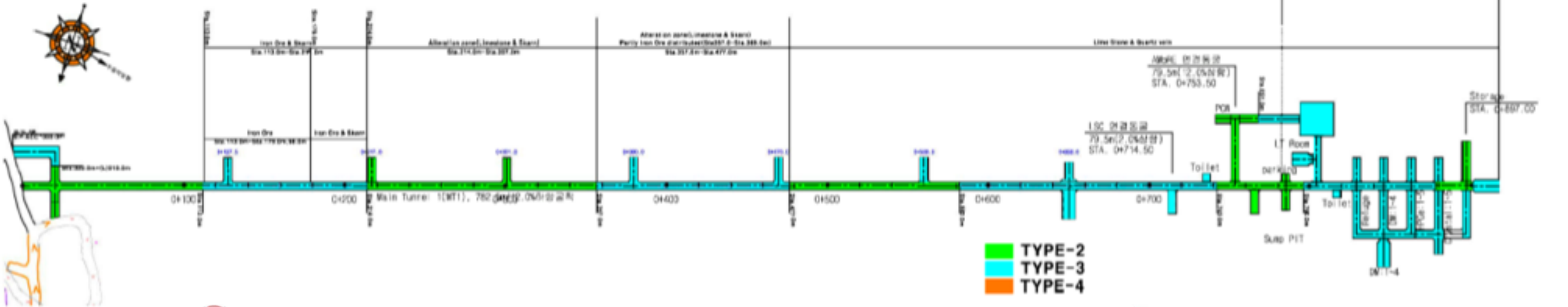
The half-life for which an experiment has a 50% chance to measure a signal above background with a significance of at least 3 sigma (99.7%). 4×10^{26} years

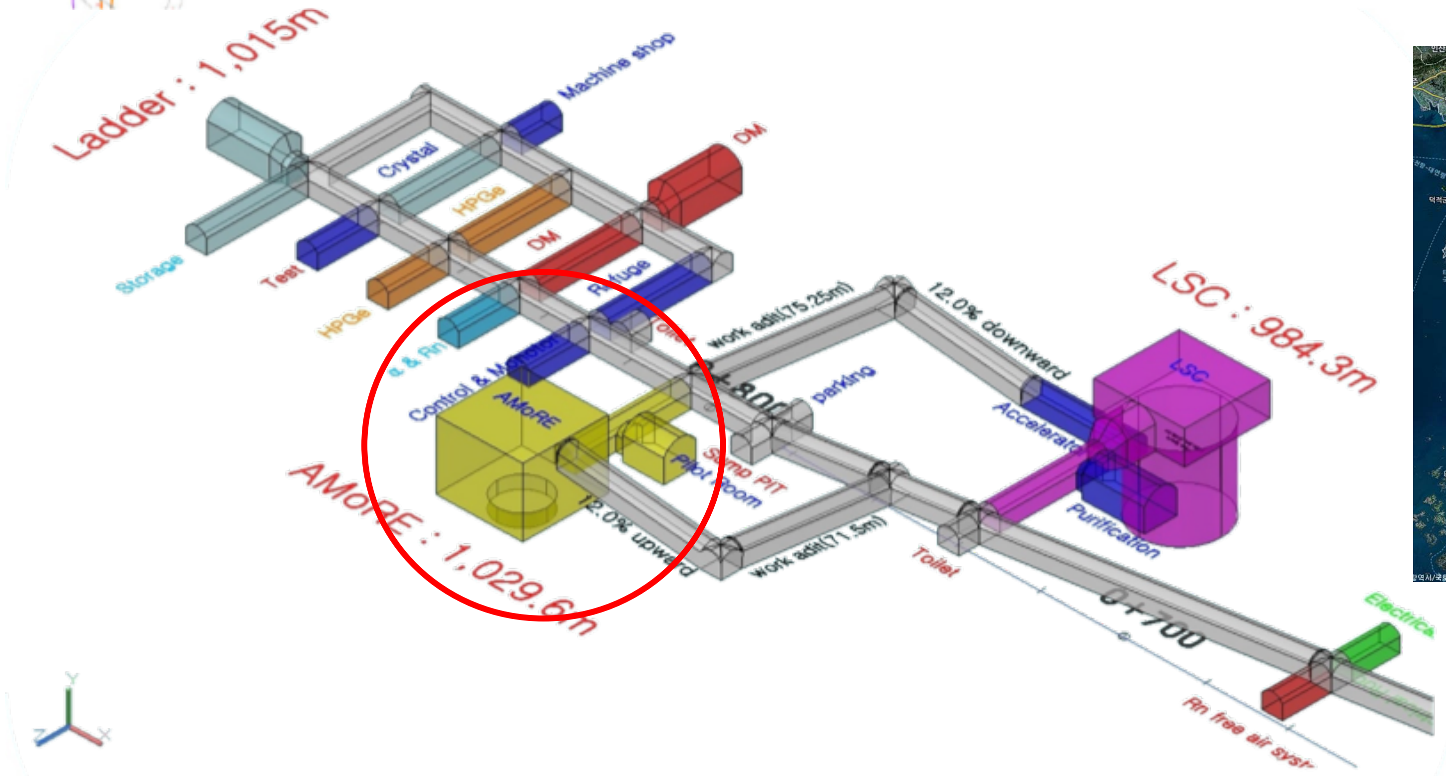
Detection efficiency : 0.7, Background normalized to isotope mass

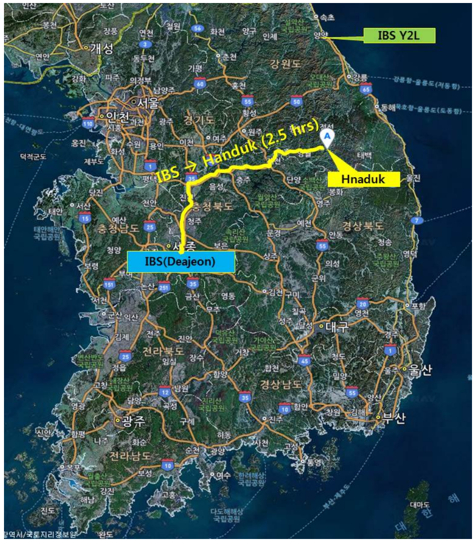


AMoRE-II @ Yemilab

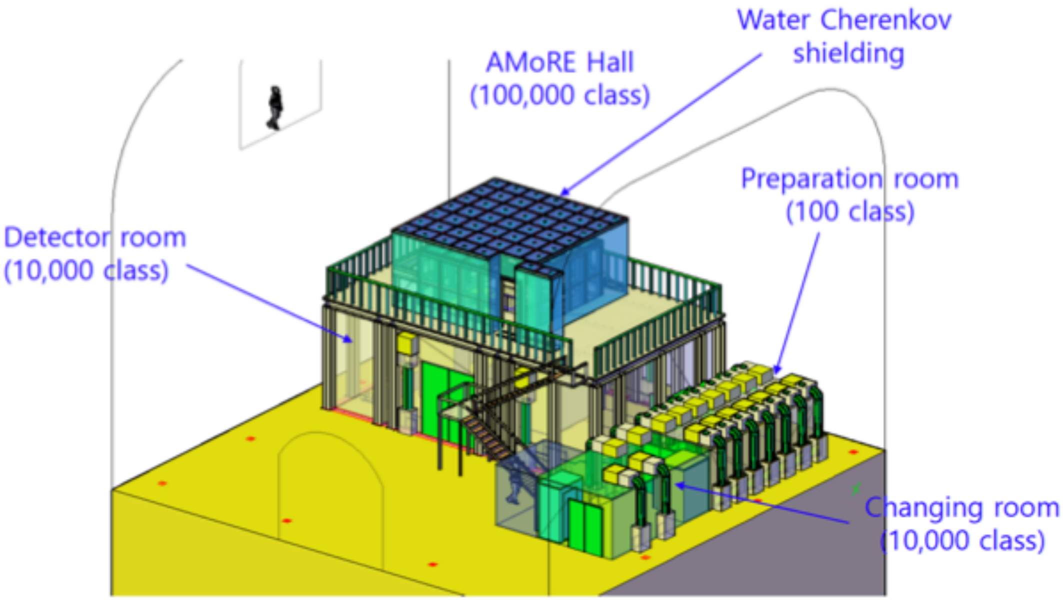
Excavation for AMoRE is finished !

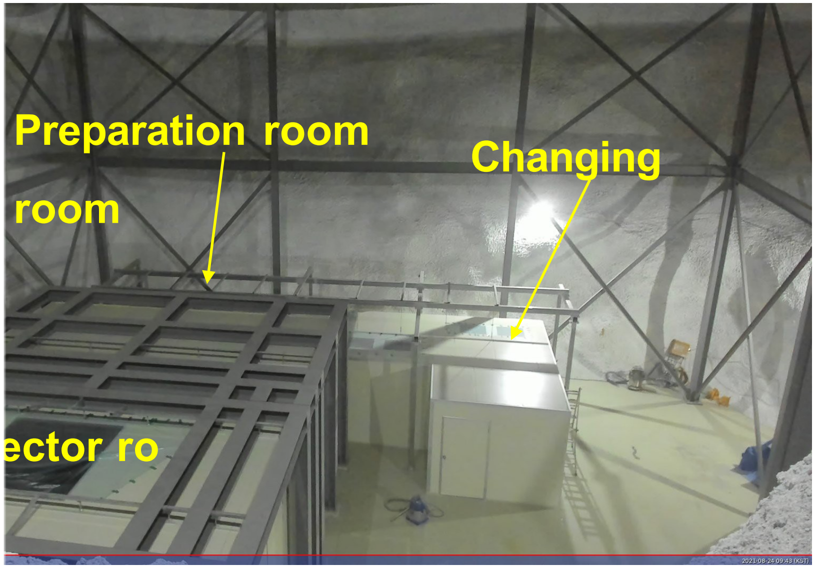




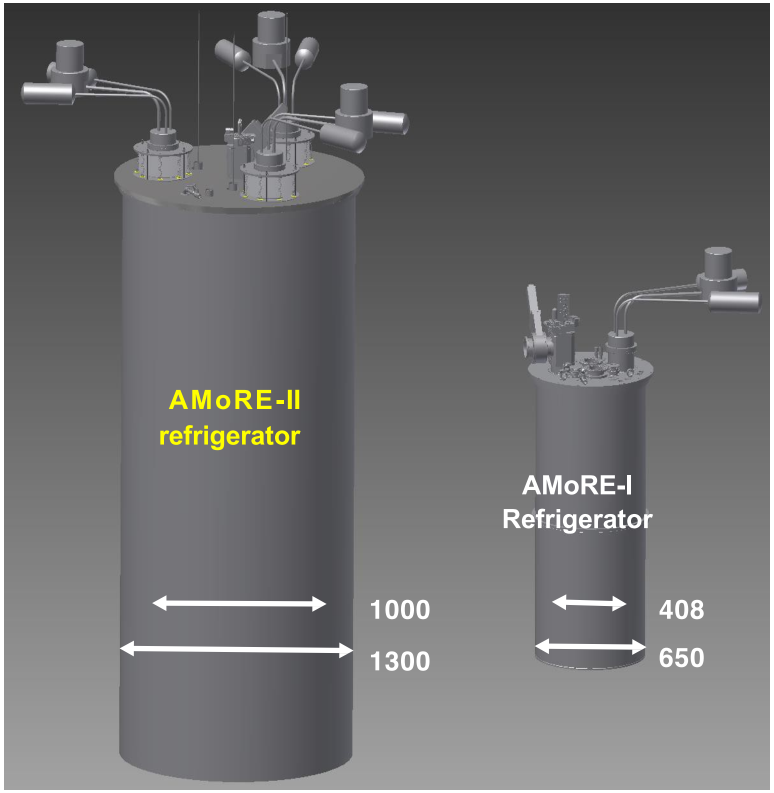


Construction is going on..

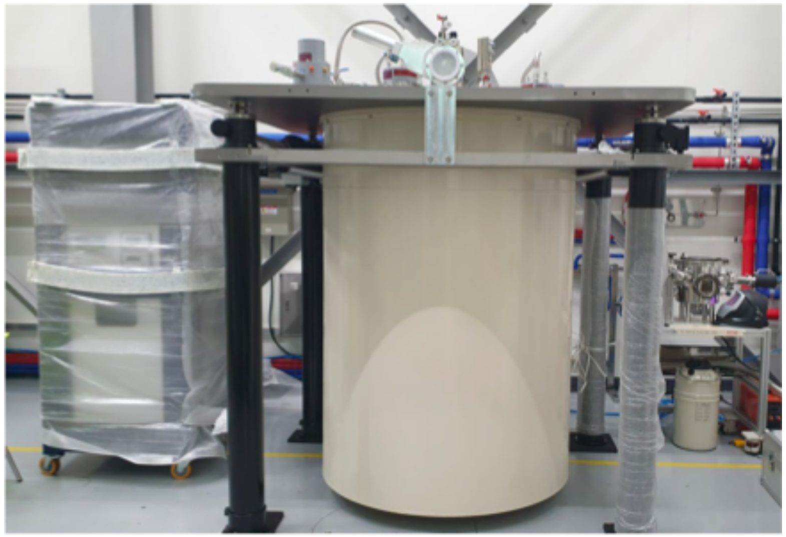




AMoRE-II refrigerator



- Big and powerful dilution Refrigerator
- Three PTR (PT420 RM)
- 2.4 mW @ 120 mK,
- > 5 μW @ 10 mK
- Delivered to IBS in Aug. 2020.



Future

- It should be more clear when we have first data of AMoRE-II with 90 crystals.
- Modular expansion is possible, increasing # of detectors.
- After AMoRE-II, ton scale experiment can be considered. ~ CUPID 1ton.
- Can we try to do research about possibility to enrich Mo-100 ?

- CUPID & AMoRE discuss to collaborate for future combination.

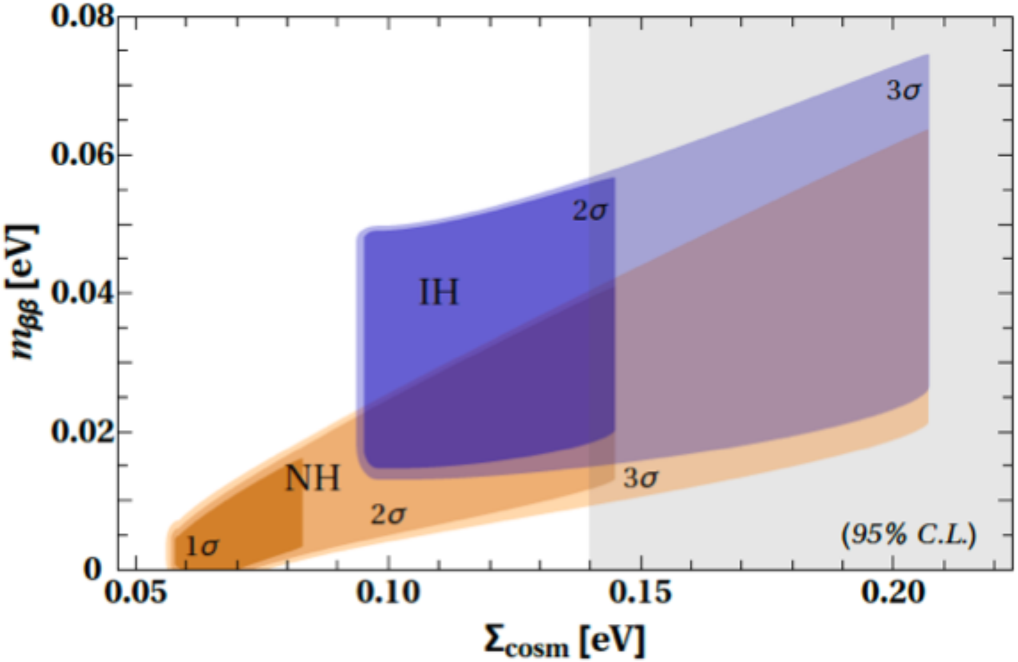
Summary

- $0\nu\beta\beta$ is one of the best probe for BSM physics.
- Experimentally will reach IO region ~ 2030, and will continue to lower the sensitivities.
- AMoRE experiment aims to be sensitive close to 10^{27} year range for ^{100}Mo isotope and will be installed by end of 2022.
- Other experiments, LEGEND, CUPID, nEXO are actively pursued.
- $0\nu\beta\beta$ should be pursued for multiple isotopes.
- $0\nu\beta\beta$ can be discovered at anytime with new sensitivities.

Neutrino 2022
SEOUL
2022. 5. 30 ~ 6. 4 , COEX
Korea

Cosmological constraints

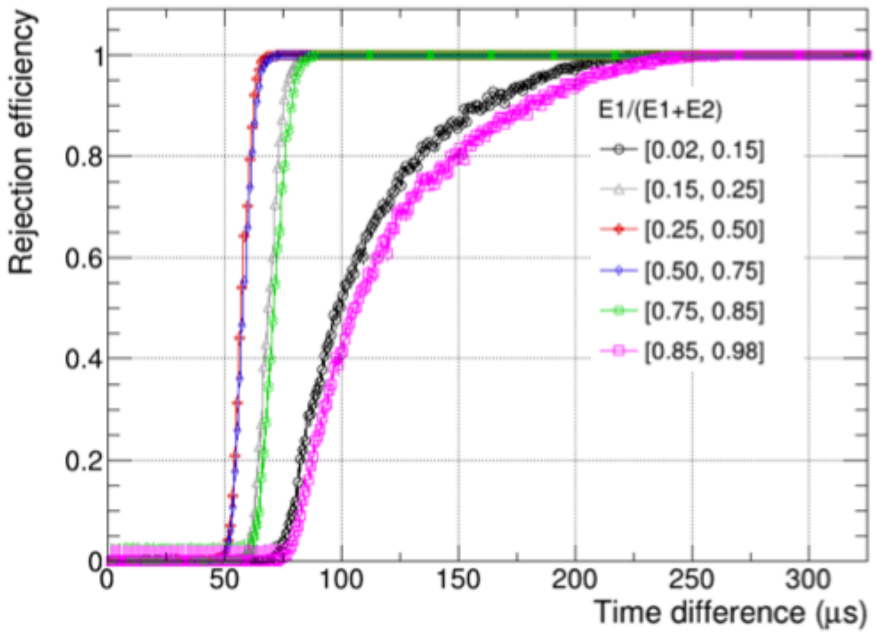
Dell'Oro et al., *JCAP* 12 (2015) 023

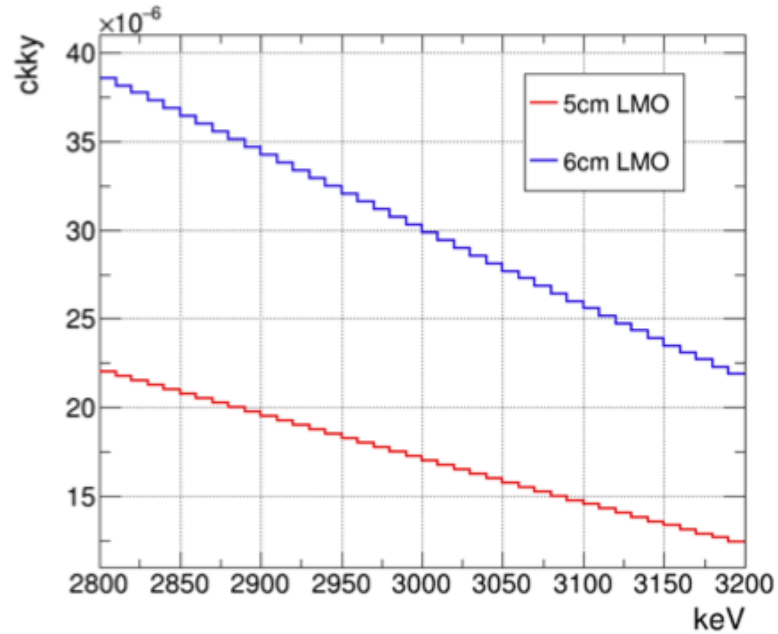


$$\Sigma < 84\,\text{meV} \qquad (1\sigma\ \text{C.L.})$$
$$\Sigma < 146\,\text{meV} \qquad (2\sigma\ \text{C.L.})$$
$$\Sigma < 208\,\text{meV} \qquad (3\sigma\ \text{C.L.})$$

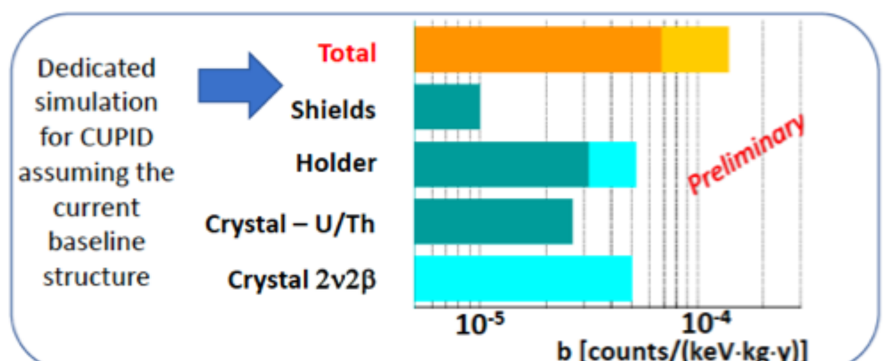
Pileup background estimation

- A realistic estimation assuming real spectra and noise data from AMoRE-pilot
- Crystal size is important – pile up event rate is proportional to square of single rates.
- 6cm crystal is acceptable.



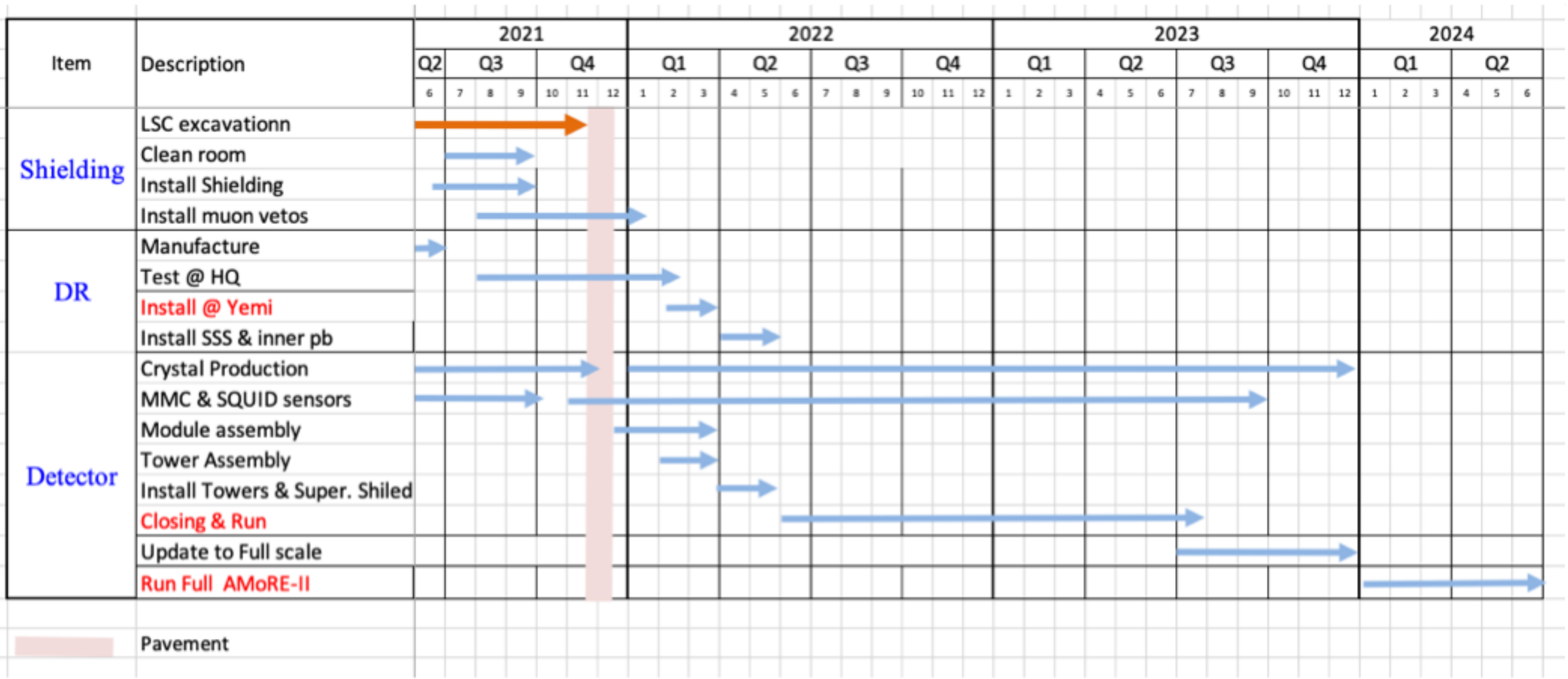


Compare with CUPID-Mo

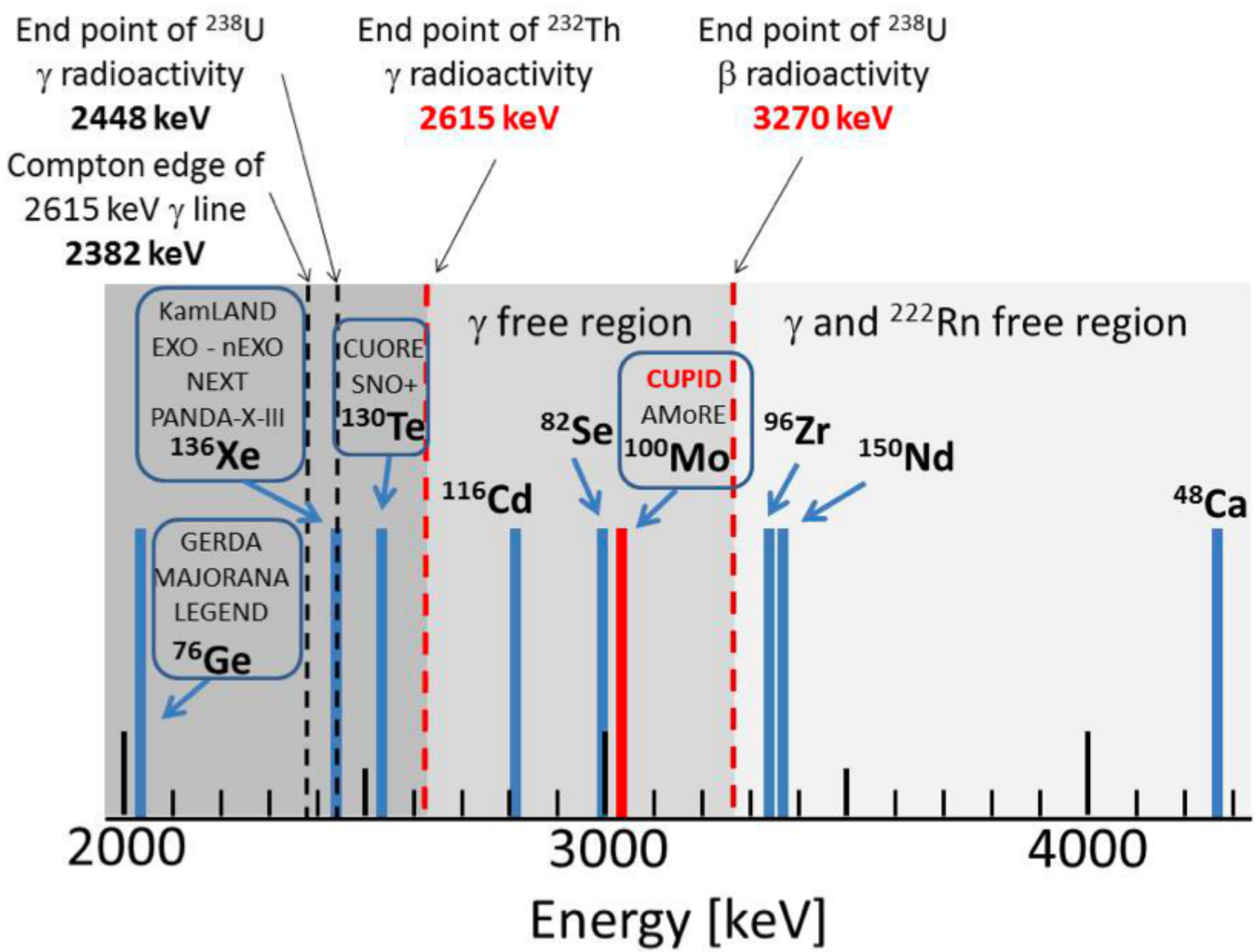


Schedule

- Construct AMoRE-II until Dec. 2021, and Upgrade to 100 kg of ^{100}Mo by 2023.
- Crystal growing takes time.



Q value vs backgrounds



Current best results for 0νββ

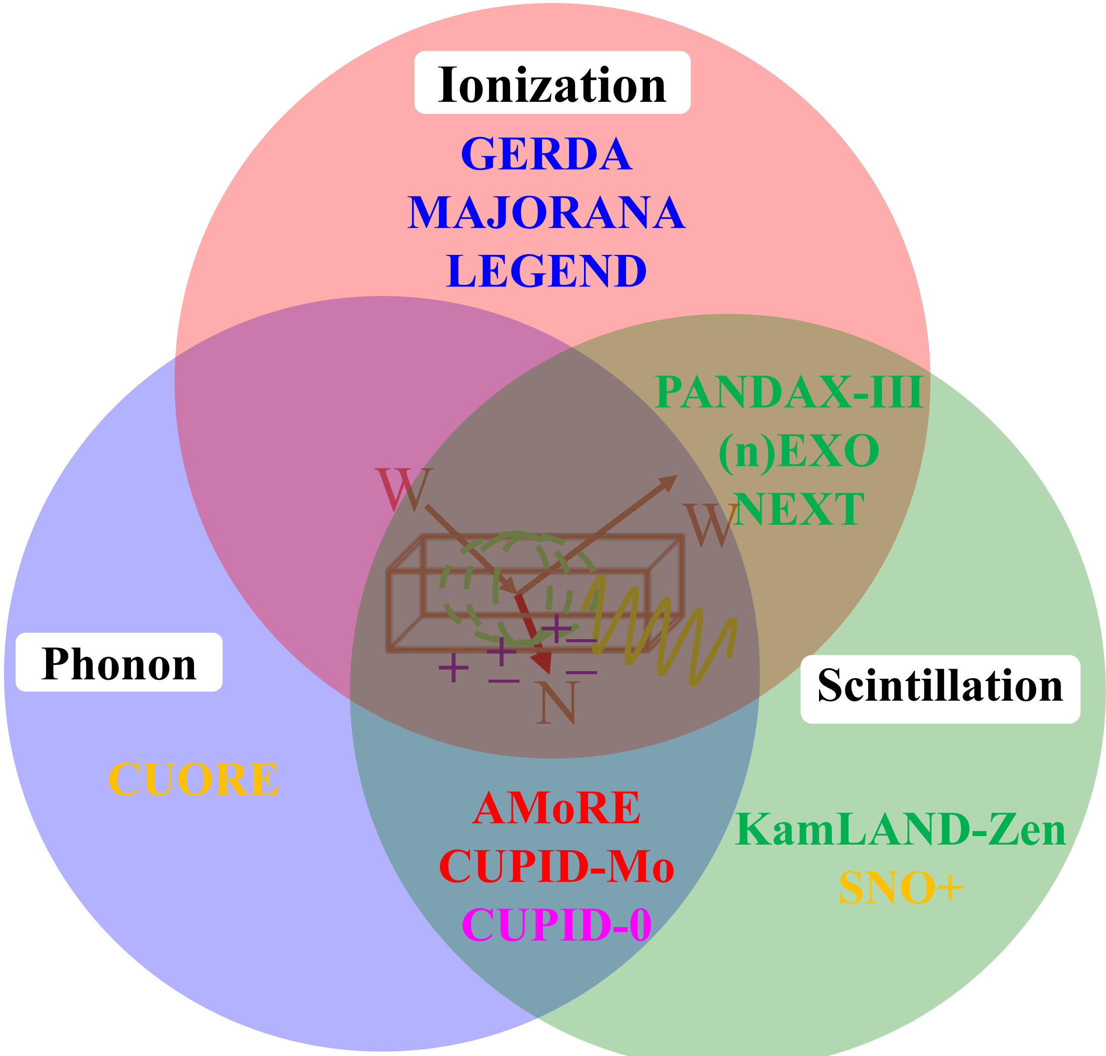
2021. 4. 10

Nucl.	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T^{0\nu}_{1/2}$ (10^{24} Y)	M (eV)	Ref.
^{48}Ca	4270.0	0.187	0.53(0.1)	CANDLES	> 0.058	<3.1-15.4	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	18.8(0.8)	GERDA-II	>180	<0.079-0.18	PRL125, 252502 (2020)
^{82}Se	2997.9	9.2	0.93(0.05)	CUPID-0	> 2.4	<0.38-0.77	PRL120, 232502 (2018)
^{100}Mo	3034.4	9.6	0.0688(0.0025)	CUPID-Mo	>1.5	<0.3-0.5	arXiv:2011.13243(2020)
^{116}Cd	2813.4	7.6	0.269(0.009)	AURORA	> 0.19	<1-1.8	nulc-ex/1601.05578.
^{130}Te	2527.5	34.5	7.91(0.21)	CUORE	> 32	<0.08-0.35	PRL124, 122501 (2020)
^{136}Xe	2458.0	8.9	21.8(0.5)	KamLAND-Zen	> 107	<0.06-0.16	PRL117, 082503 (2016)
^{150}Nd	3371.4	5.6	0.0934(0.0065)	NEMO-3	> 0.02	<1.6-5.3	PRD 94 072003 (2016)

Bolometer, Scintillation, Ionization

Detector Techniques for 0νββ

Similar techniques are used as direct dark matter experiments



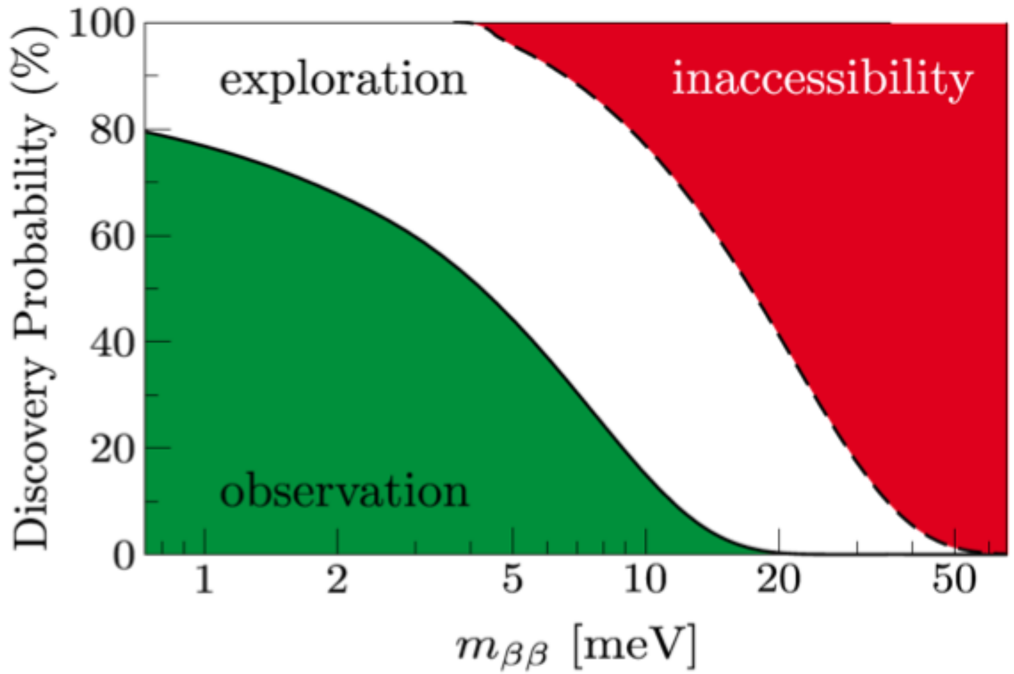
^{76}Ge
^{82}Se
^{136}Xe
^{100}Mo
^{130}Te

Discovery potential for 0νββ

“Discovery probabilities of Majorana neutrinos based on cosmological data”,

M. Agostini et al. *PRD* 103 (2021) 3, 033008

- Normal Ordering assumed.
- Planck cosmological limit imposed.



Experiments with sensitivities of the order of 10 meV → discovery power bet ween 20 and 80%.

A prediction for the decade of the 20'

1. We'll learn that m_3 is the heaviest and $\theta_{23} > 45^o$.
2. Cosmological measurements of the sum of neutrino masses will have interesting upper and non-zero lower limits.
3. The value of δ_{CP} will not be zero or π.
4. The MiniBooNE low E excess will be explained.
5. The LSND excess will not be explained.
6. DUNE will mostly be on time.
7. $0\nu\beta\beta$ limits will improve but there will not be a signal.
8. At least one of these predictions will be wrong.

\- Murray Goodman –

In "Long-Baseline Neutrino Oscillation Newsletters"

Review

- If total background in ROI <1, the sensitivity is

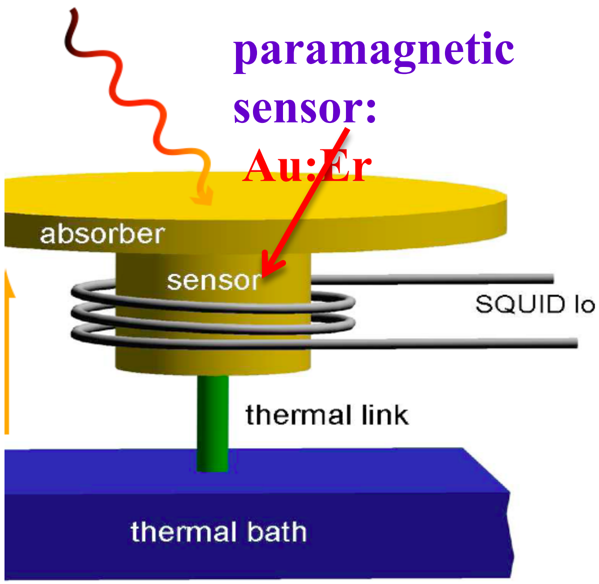
$$S_{0\nu} \propto MT,$$

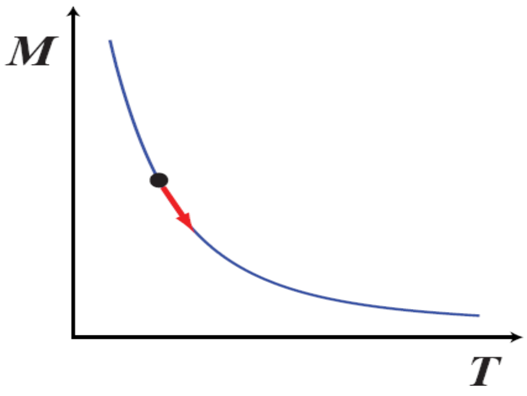
Background = $MT(\Delta E)$B <1 → MT<$\frac{1}{(\Delta E)\text{B}}$: *Exposure for "0" background.*

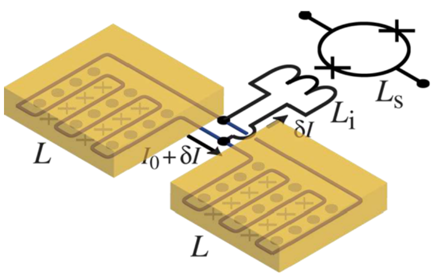
Exp	(ΔE)(keV)	B (ckty)	MT (t y)	T1/2(year)
LEGEND-200	3	$2\text{x}10^{-1}$	1.7	$\sim 5\text{x}10^{27}$
KAMLamd2-Zen	200	0.01	0.5	$\sim 2\text{x}10^{27}$
CUPID	5	0.1	2	$\sim 10^{27}$
nEXO	25	$1.4\text{x}10^{-2}$	3	$\sim 10^{28}$
AMoRE	10	0.1	1	$\sim 8\text{x}10^{26}$

Low temperature MMC sensor

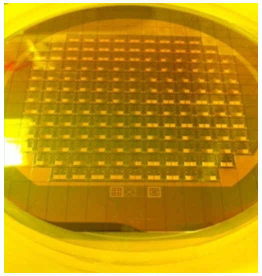
MMC (Metallic Magnetic Calorimeter)







MMC: Metallic Magnetic Calorimeter



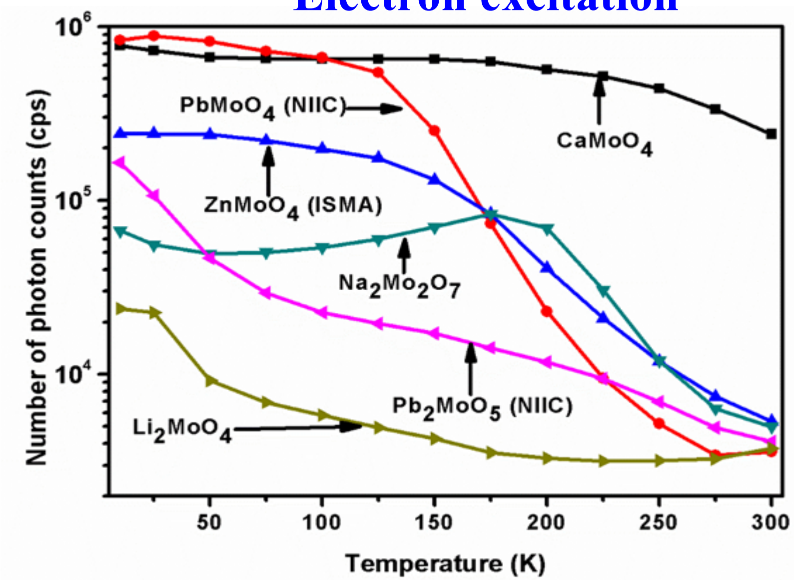
- All fabrication can be done at CUP, IBS

Total = 157

(Au:Er one sided + Au:Er both sided + test pattern(33))

AMoRE-II Crystal Decision

Electron excitation

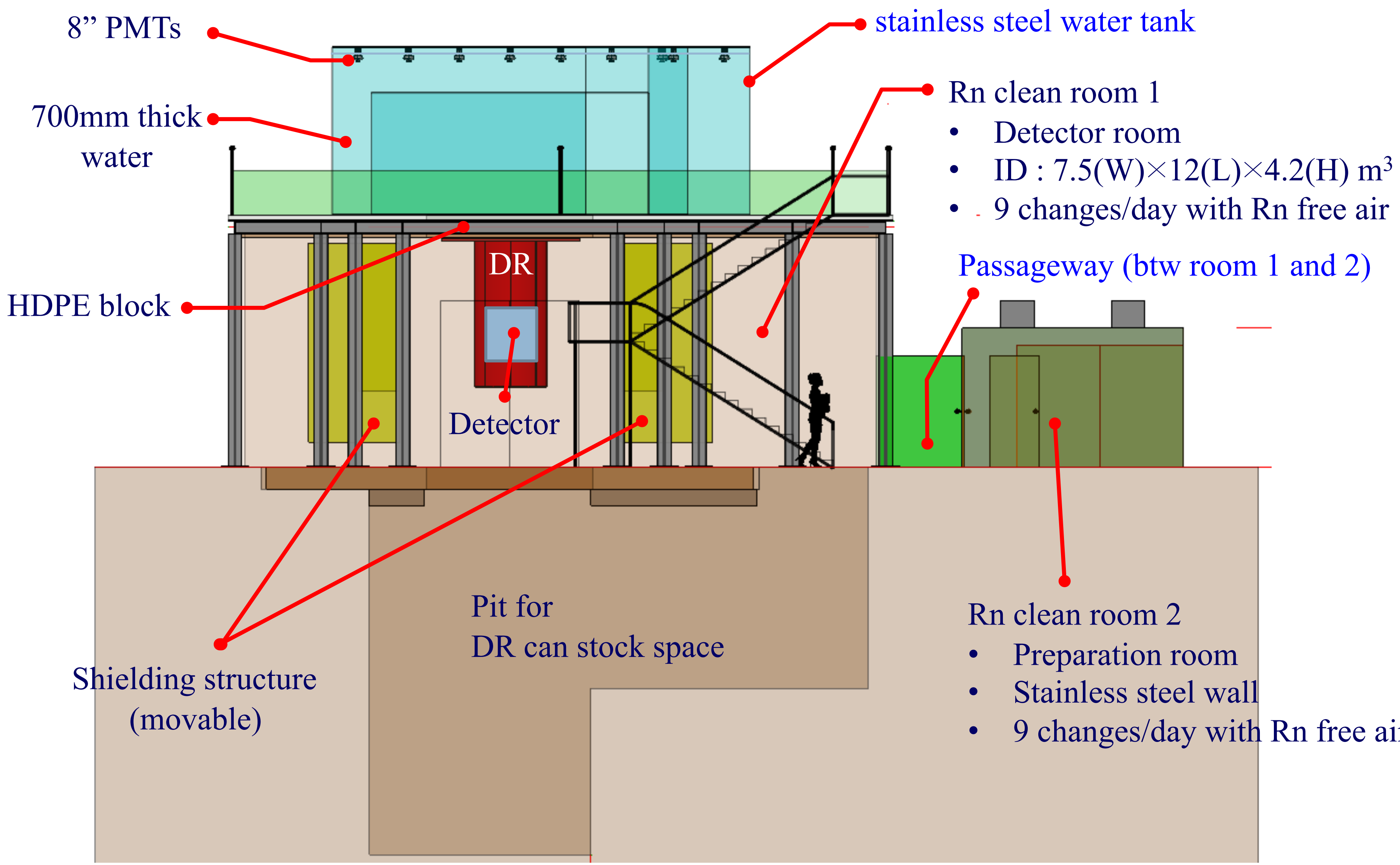


H.J. Kim et al., Crystal Research & Technology, Nov. 2019

- LMO has light output smaller than CMO by a factor larger than 10.
- But, DP is similar between these two crystals.
- LMO crystal is chosen for AMoRE-II
- Crystal growing is easier

Crystals	Scintillation				Mechanical		Thermal		Pro Con
	λ_{em} (nm)	Eg (eV)	τ (μs) @10K	E_{scin} (Rel.)	Dens. (g/cc)	Mo Fraction	T_D (K)	T_M (C)	
CMO (CARAT)	540	3.78[1]	240	100	4.32	0.49	446	1445	High light out High melt T, difficult growing, high bkg, 48Ca
NMO-I (NIIC)	663	3.50	750	9	3.62	0.558			Good light out Cleavage plane
LMO (CUP)	535	4.26.[2]	23	5	3.03	0.562	765	705	Low melt. T, easy growing, low bkg, high T_D Low light, hygroscopic
$PbMoO_4$	592	3.20[4]	20	105	6.95	0.269			High light out Low Mo fraction, higher bkg

Transparent front view of dry & radon clean room



Near future experiments

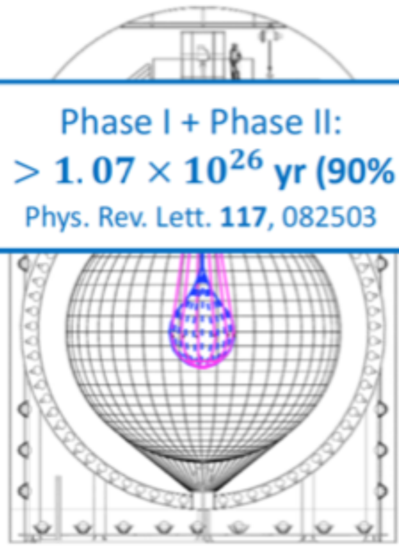
Evolution of KamLAND-Zen

Past

Phase I + Phase II:

$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)

Phys. Rev. Lett. **117**, 082503



KamLAND-Zen 400

Mini-balloon Radius = 1.54 m

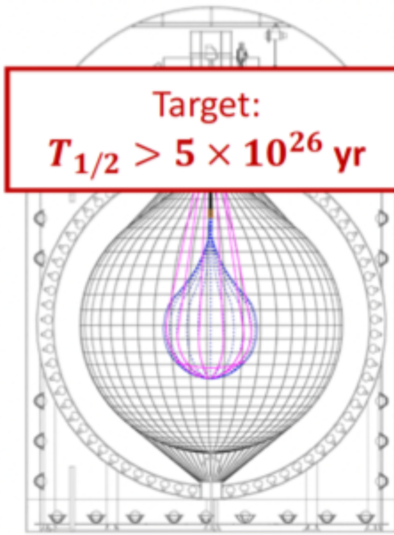
Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current

Target:

$T_{1/2} > 5 \times 10^{26}$ yr



KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

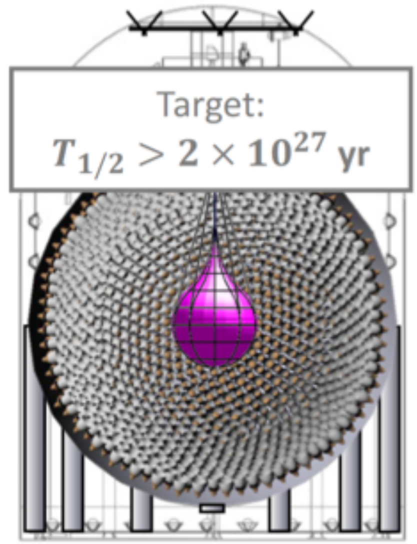
Xenon mass = 745 kg

Started January 2019

Future

Target:

$T_{1/2} > 2 \times 10^{27}$ yr



KamLAND2-Zen

Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film

What is the origin of neutrino mass ?

Dirac Masses

Balantekin, Ann.Rev.Nucl.Part.Sci. 68 (2018) 313

- Standard model (SM) has only left-handed neutrinos and right-handed antineutrinos.
- Lepton # : $\mathrm{L}(\nu) = 1, \mathrm{L}(\bar{\nu}) = -1 \rightarrow L\ is\ conserved.$
- A Dirac neutrino mass can be generated with the same Higgs mechanism giving masses to quarks and charged leptons.
- Need to extend SM to add right-handed neutrinos, ν_R.

$$L_D = -m_D(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R)$$

If $\nu \equiv \nu_L + \nu_R, \quad L_D = -m_D\bar{\nu}\nu$

$$m_D = y^\nu \langle H^0 \rangle_0$$

$\langle H^0 \rangle_0$: vacuum expectation value of H^0, 174GeV

y^ν: *Yukawa Coupling* $\sim 10^{-12}$

No explanation why Higgs-neutrino Yukawa coupling is so small.

Majorana Masses

- Once a right-handed neutrino, ν_R, is introduced, “right-handed Majorana mass term can be ;

$$L_R = -m_R/2\left[\overline{(\nu_R)^c}\nu_R + \overline{\nu_R}(\nu_R)^c\right]$$

If $\nu \equiv \nu_R + (\nu_R)^c$, $\quad L_R = -(m_R/2)\bar{\nu}\nu +$ h.c.

Here, $(\nu)^c = \nu \rightarrow$ Majorana particle

$$\mathcal{L}_R = -\frac{m_R}{2}\overline{(\nu_R)^c}\,\nu_R + h.c. \quad ,$$

See-Saw Mechanis...

- If we add both Dirac and Majorana mass terms, two mass eigenstates are obtained. Both are Majorana particles.

$$m_1 \simeq \frac{m_D^2}{m_R}$$

$$m_2 \simeq m_R$$

For, $m_D = m_\mu = 10^2 MeV$

$$m_1 = 0.1\ eV$$

$\rightarrow m_R = 10^8$ GeV