AMoRE, NEOS, Isodar@Yemilab

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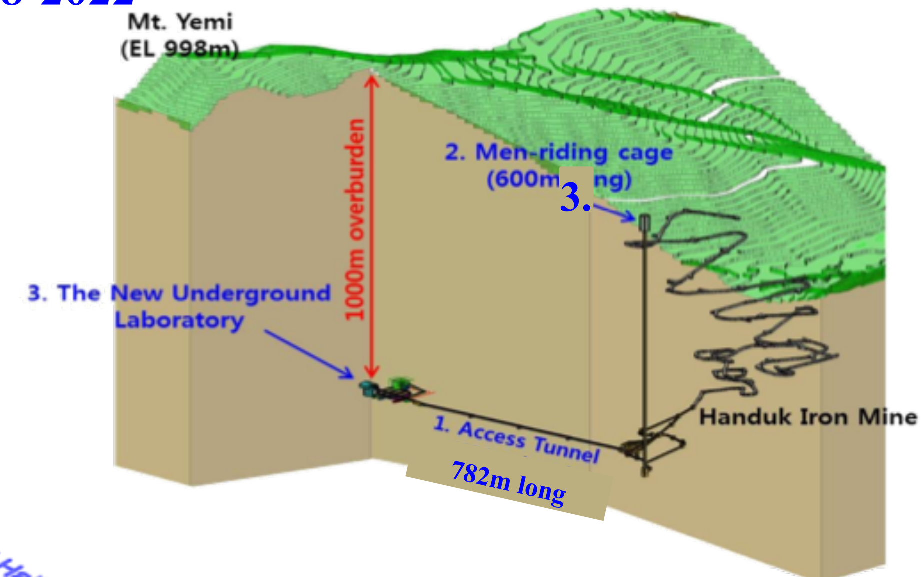
Institute for Basic Science

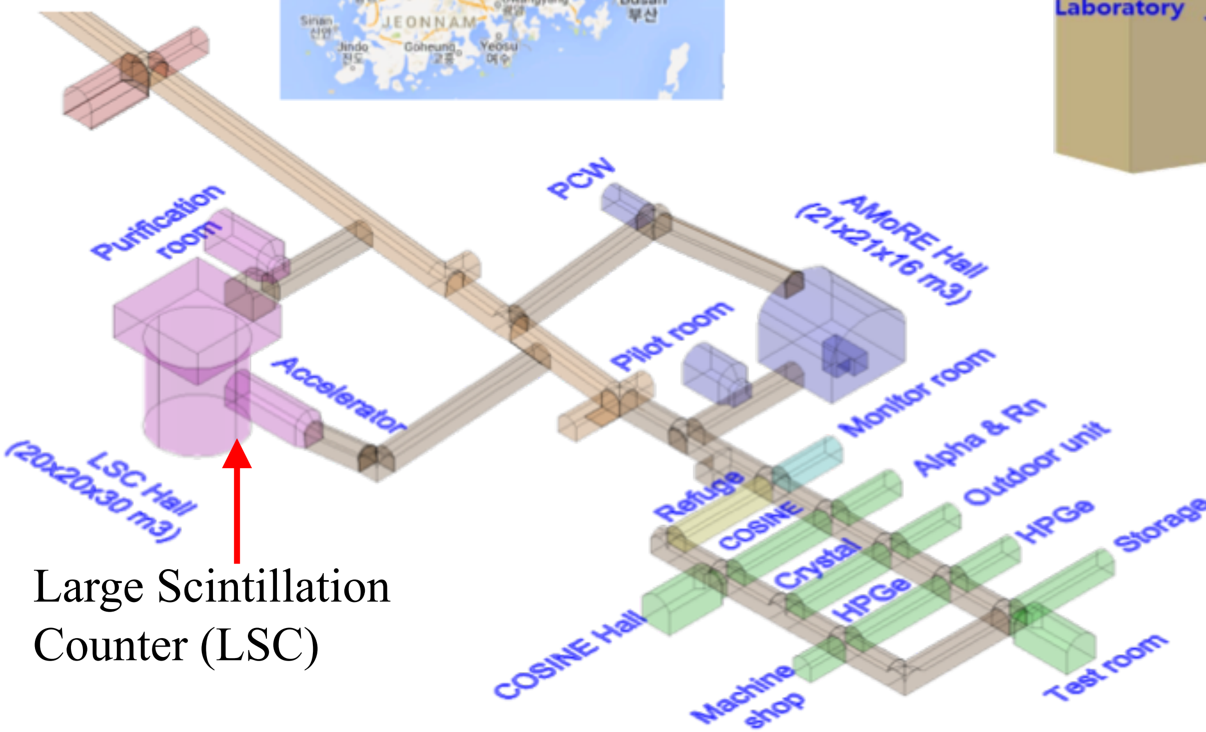
2021. 12. 18.

2021 Meeting of the Division of Particles and Fields of the Korean Physical Society

Yemilab project for new discoveries.

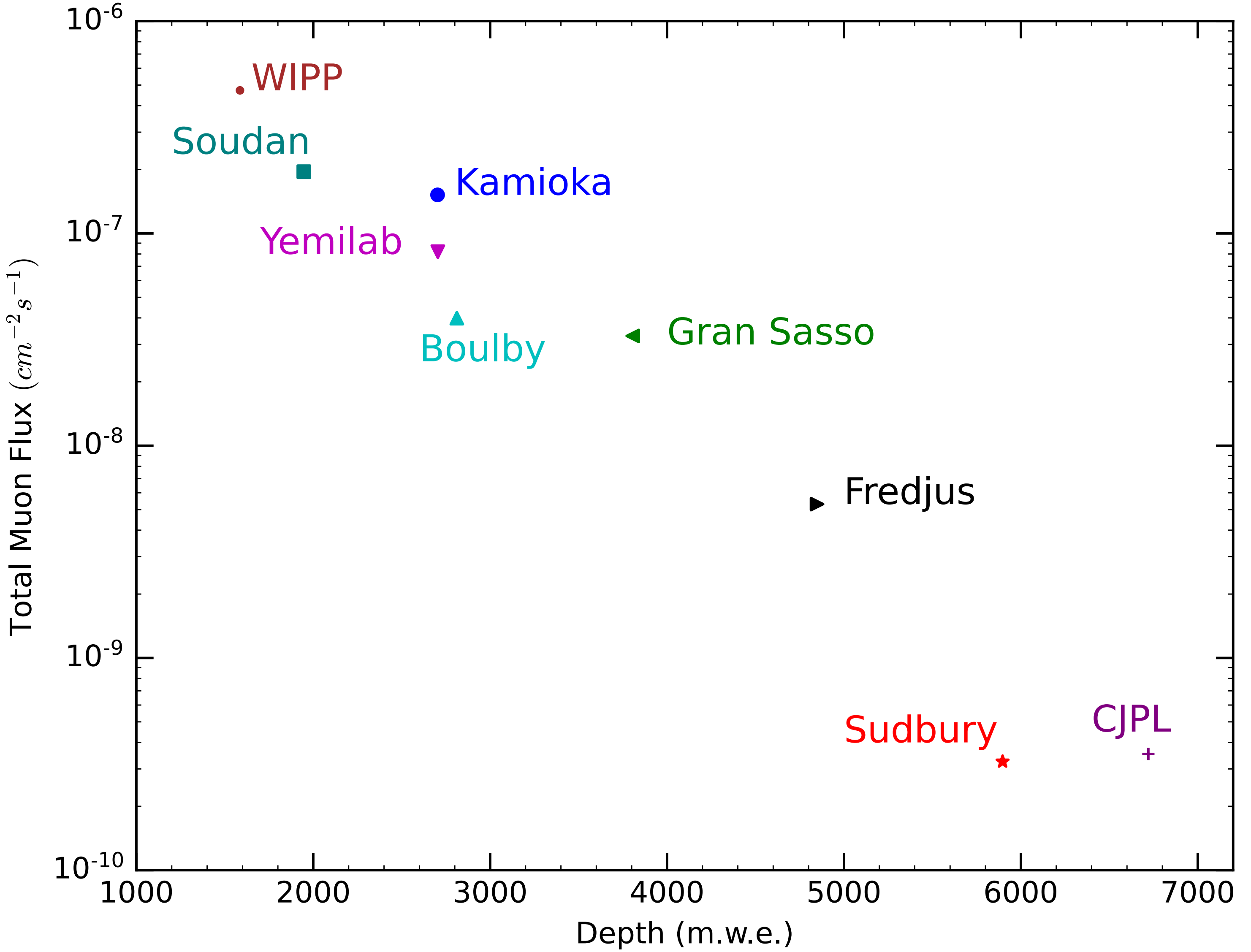
- 1000 meter underground.
- Construction cost ~30 M$
- 2018-2022





Large Scintillation Counter (LSC)

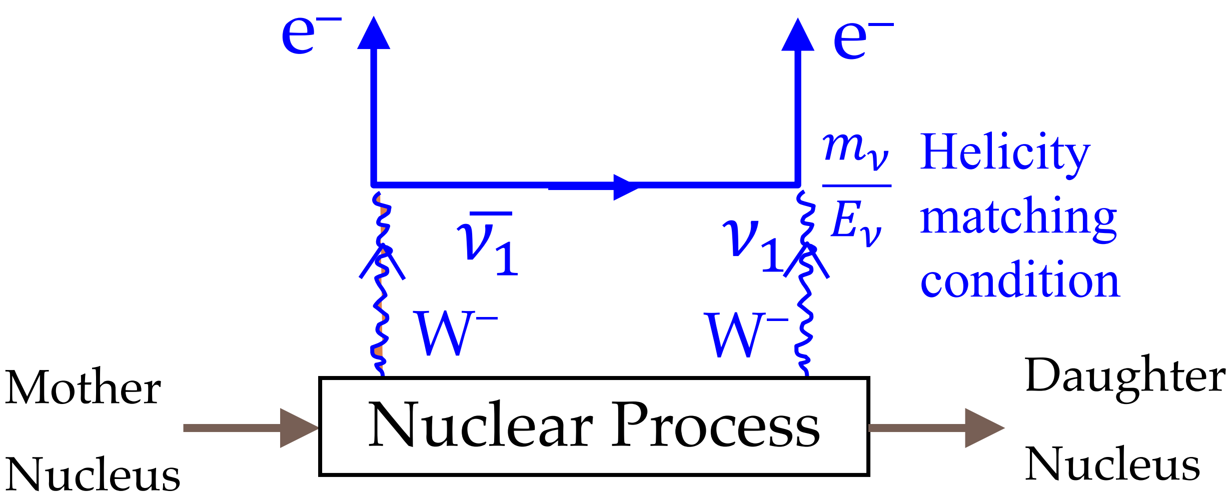
Muon flux

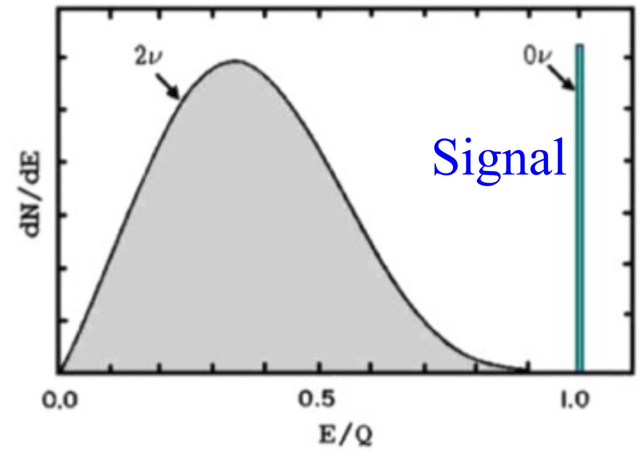


WIPP
Soudan
Kamioka
Yemilab
Boulby
Gran Sasso
Fredjus
Sudbury
CJPL
Total Muon Flux $(cm^{-2}s^{-1})$
Depth (m.w.e.)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
7000

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…

for light neutrino exchange model.

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

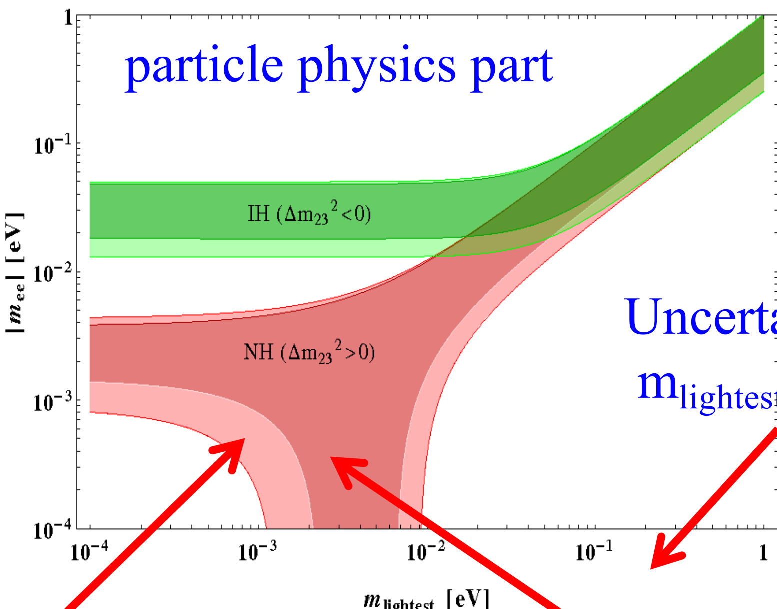
Half-life Measured — **Phase factor** — **Nuclear Matrix Element** — **Effective 0νββ Neutrino Mass**

Effective 0νββ neutrino mass is ;

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| =$$

$$\left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$

$m_{\beta\beta}$

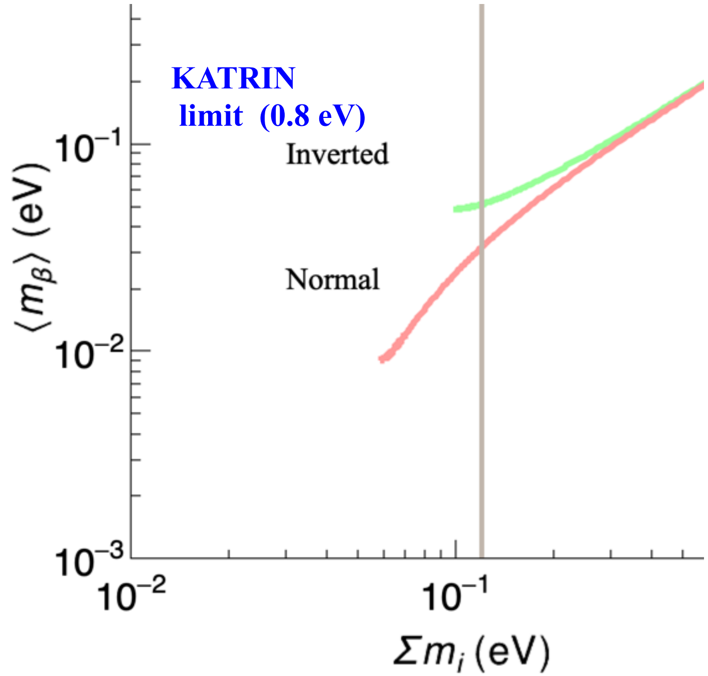


Uncertainties from $m_{lightest}$

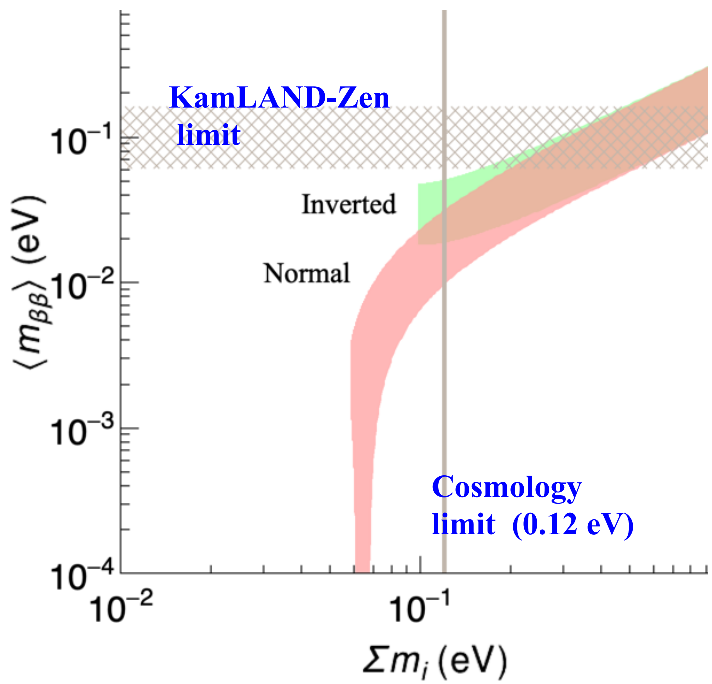
Uncertainties from mixing angles

Uncertainties from phases

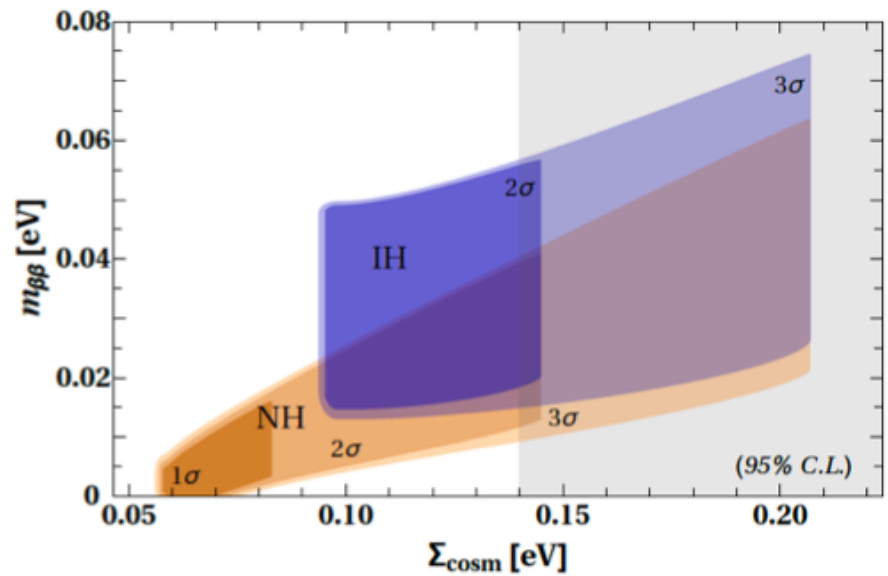
Current Mass Limits



- 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.



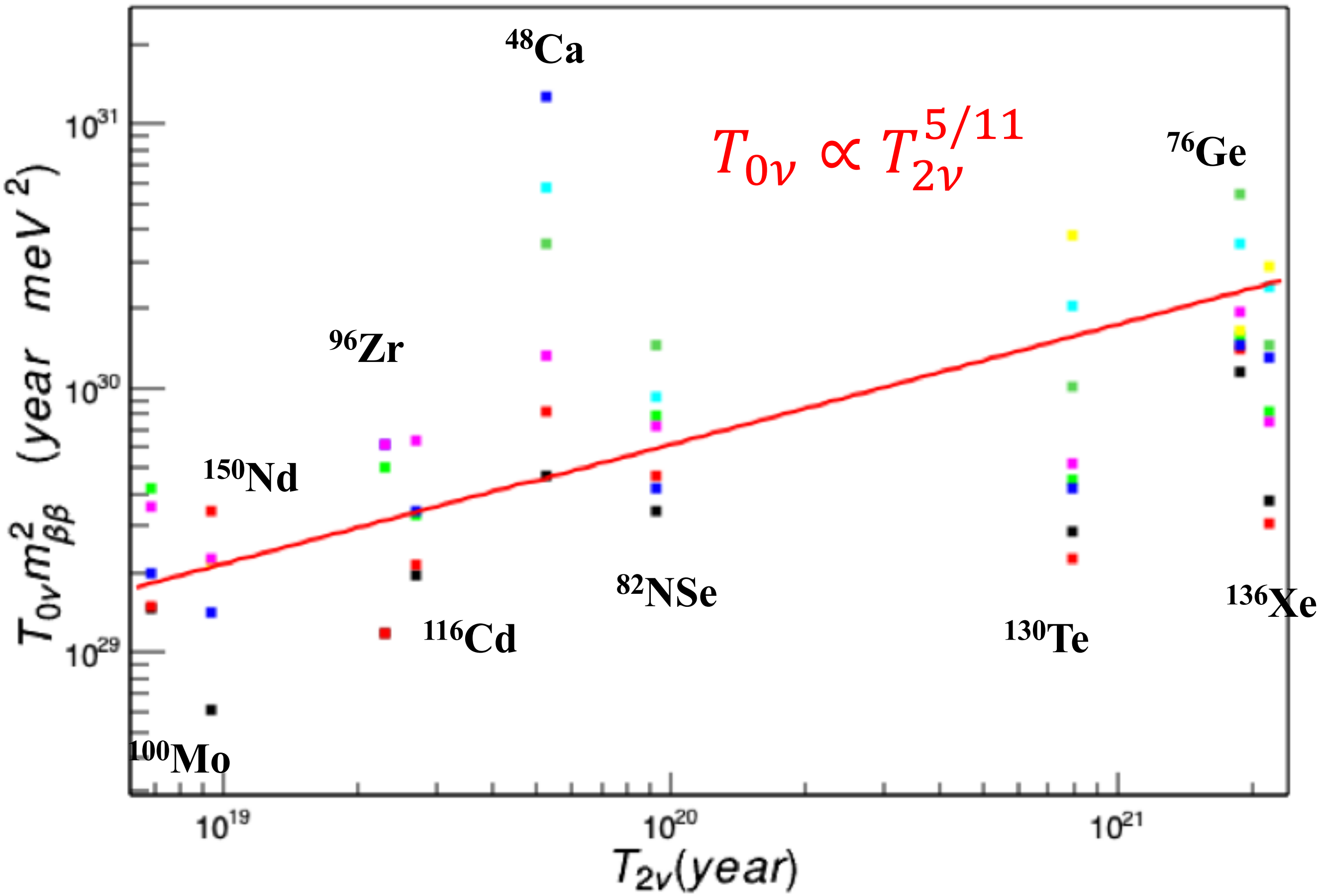
Dell'Oro et al., *JCAP* 12 (2015) 023



$0\nu\beta\beta$ vs $2\nu\beta\beta$ T(1/2) - updated

- **A correlation between** $2\nu\beta\beta$ **half-life(measured) vs** $0\nu\beta\beta$ half-life (calculated)

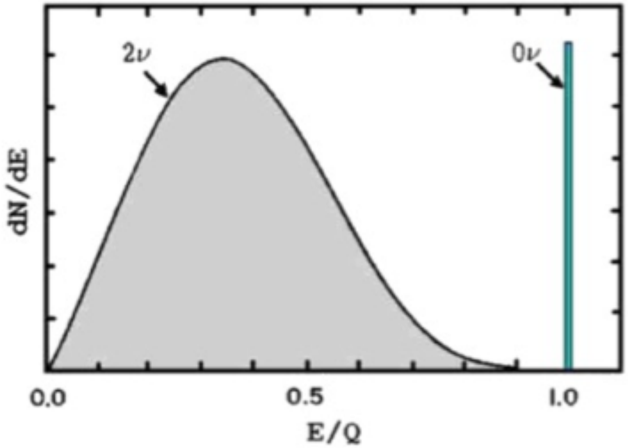
$G_{0\nu} \propto Q^5, \; G_{2\nu} \propto Q^{11}.$ H. Ejiri's comment



Now, how sensitive are the 0νββ experiments ?

- **0νββ needs a good energy resolution and extremely low backgrounds.**
- **Discovery sensitivities depend on background and exposure**

Signal : sharp peak @ Q-value

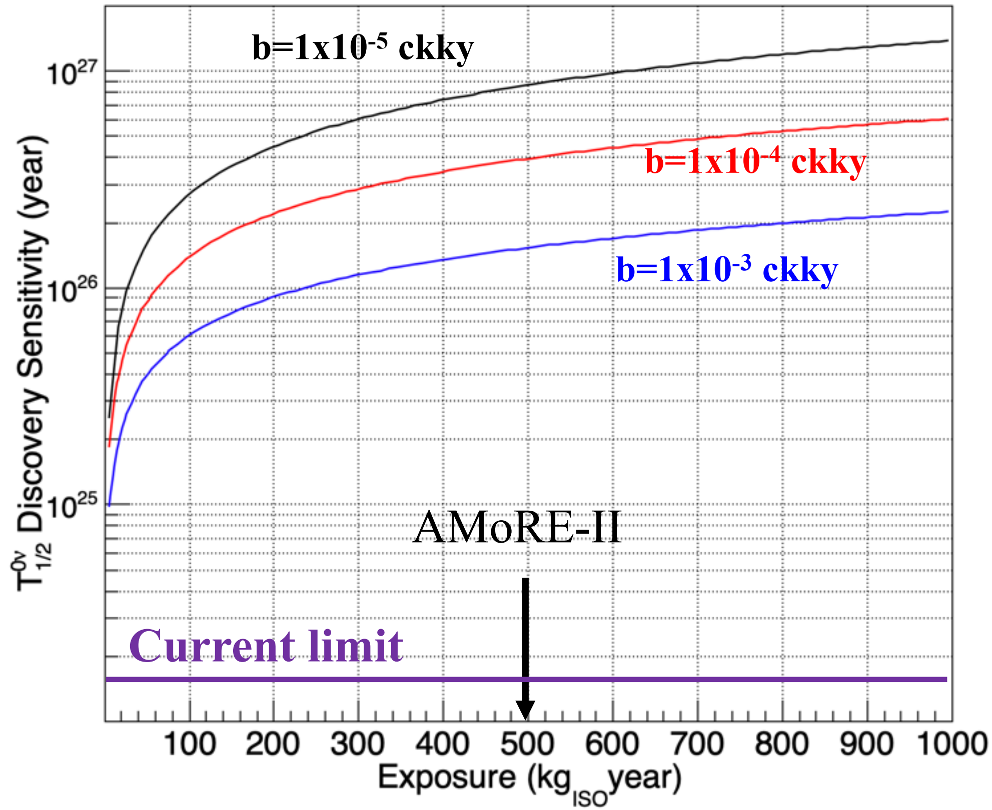


Background Unit :
ckky=counts/(keV kg year)

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

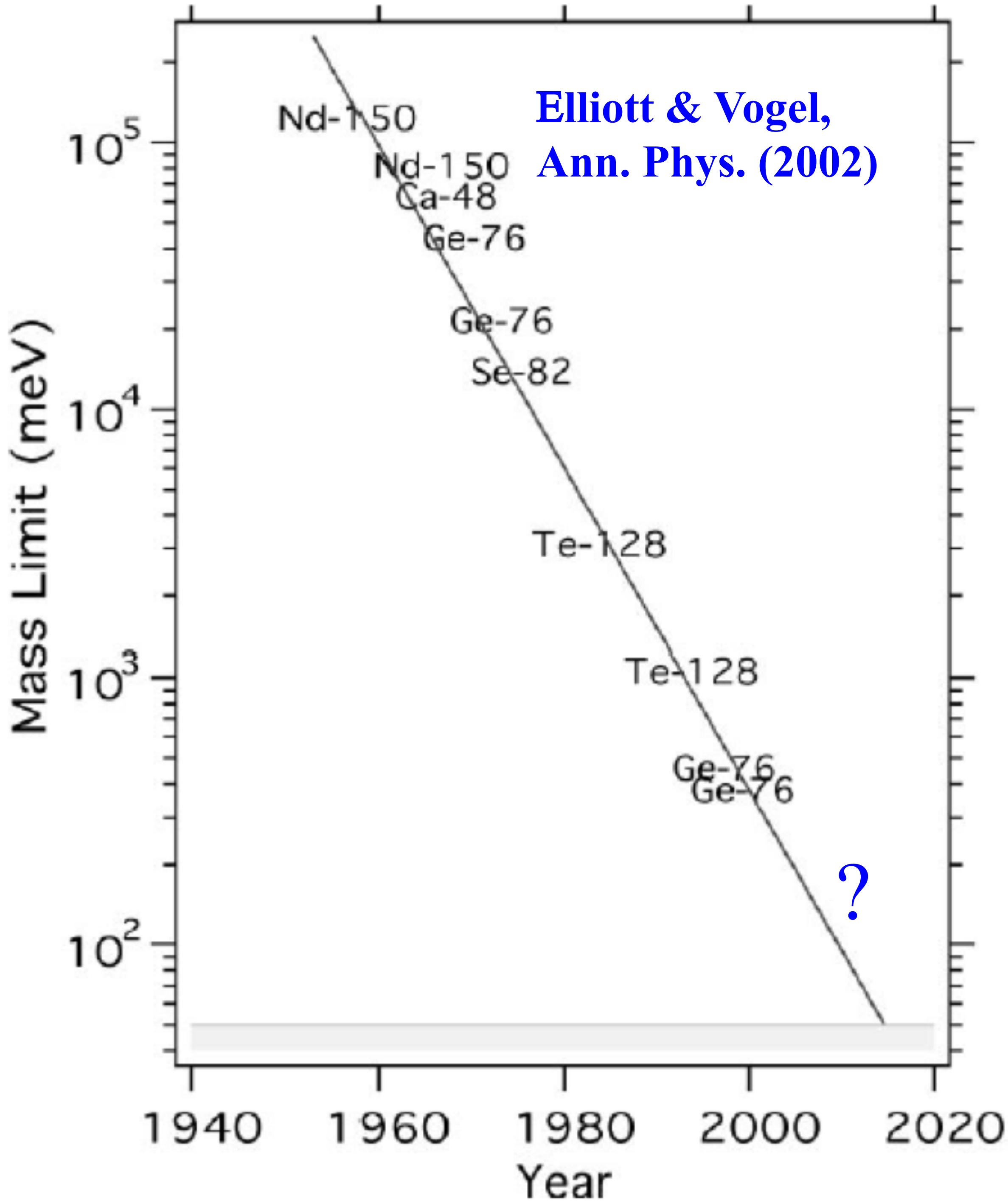
$$T_{1/2}^{0\nu} \propto MT\ (for\ \text{“0”}\ backgronds)$$

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%).



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

The history tells us….

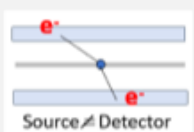


Implementation in tens of experiments

Legenda
(color code)

Completed
Data taking
Construction / Commissioning
Advanced R&D sometimes at CDR/TDR level
R&D

SuprNEMO demonstrator | Tracking + Calorimeter | ^{82}Se



TGV-2 EC/EC β^+/EC ^{106}Cd
N. Rukhadze, this conference

Large source mass, Easily scalable — Fluid embedded source

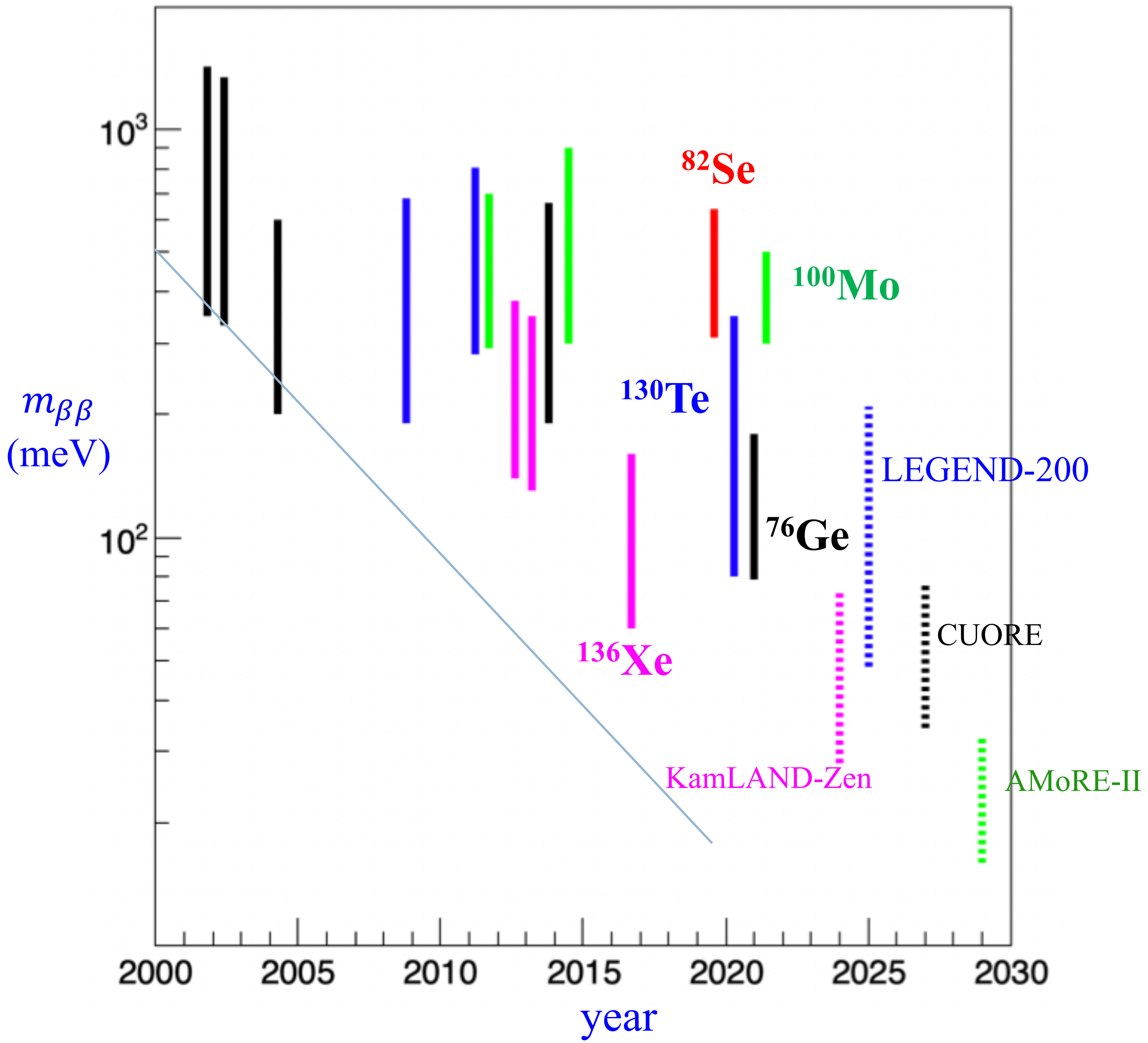
NvDEx	High pressure TPC		^{82}Se
ZICOS	Dilution in liquid scintillator+Cherenkov		^{96}Zr
SNO+	Dilution in liquid scintillator		^{130}Te
SNO+-Phase II	**Dilution in liquid scintillator**		^{130}Te
Theia	Dilution in liquid scintillator+Cherenkov		^{130}Te-^{136}Xe
KamLAND-Zen 400	Dilution in liquid scintillator		^{136}Xe
KamLAND-Zen 800	Dilution in liquid scintillator		^{136}Xe
KamLAND2-Zen 800	Dilution in liquid scintillator		^{136}Xe
EXO-200	Liquid TPC		^{136}Xe
nEXO	**Liquid TPC**		^{136}Xe
NEXT-White	High pressure TPC		^{136}Xe
NEXT-100	**High pressure TPC**		^{136}Xe
NEXT-HD / NEXT-BOLD	High pressure TPC		^{136}Xe
PANDAX-III	High pressure TPC		^{136}Xe
AXEL	High pressure TPC		^{136}Xe
DARWIN	Double-phase TPC		^{136}Xe
LZ	Double-phase TPC		^{136}Xe
R2D2	High pressure TPC	*I. Katsioulas, this conference*	^{136}Xe
LiquidO	Dilution in opaque liquid scintillator		multi

High energy resolution / efficiency — Crystal embedded source

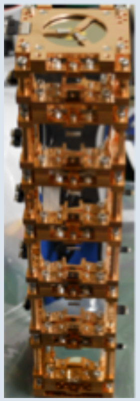
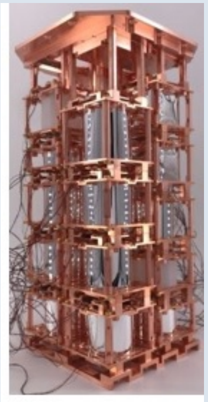
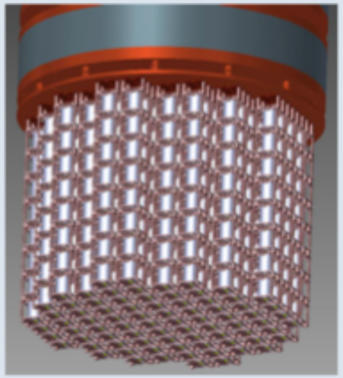
CANDLES-III	Scintillators		^{48}Ca
CANDLES-IV	Scintillating bolometers	*J. Minami, this conference*	^{48}Ca
MAJORANA DEM.	Semiconductor detectors		^{76}Ge
GERDA	Semiconductor detectors		^{76}Ge
LEGEND-200	Semiconductor detectors		^{76}Ge
LEGEND-1000	**Semiconductor detectors**		^{76}Ge
CDEX-300 / CDEX-1000	**Semiconductor detectors**	*Qian Yue, this conference*	^{76}Ge
SELENA	Semiconductor detectors		^{82}Se
CUPID-0	Scintillating bolometers		^{82}Se
CUPID-Mo	Scintillating bolometers		^{100}Mo
AMORE-I	Scintillating bolometers		^{100}Mo
AMORE-II	**Scintillating bolometers**		^{100}Mo
CUPID	**Scintillating bolometers**		^{100}Mo
CUPID Reach / CUPID-1T	Scintillating bolometers		^{100}Mo
COBRA	Semiconductor detectors		^{116}Cd
TIN-TIN	Bolometers		^{124}Sn
CUORE	Bolometers		^{130}Te
CROSS	Scintillating bolometers		^{100}Mo-^{130}Te
BINGO	Scintillating / Cherenkov bolometers		^{100}Mo-^{130}Te

A. Giulliani @ TAUP2021

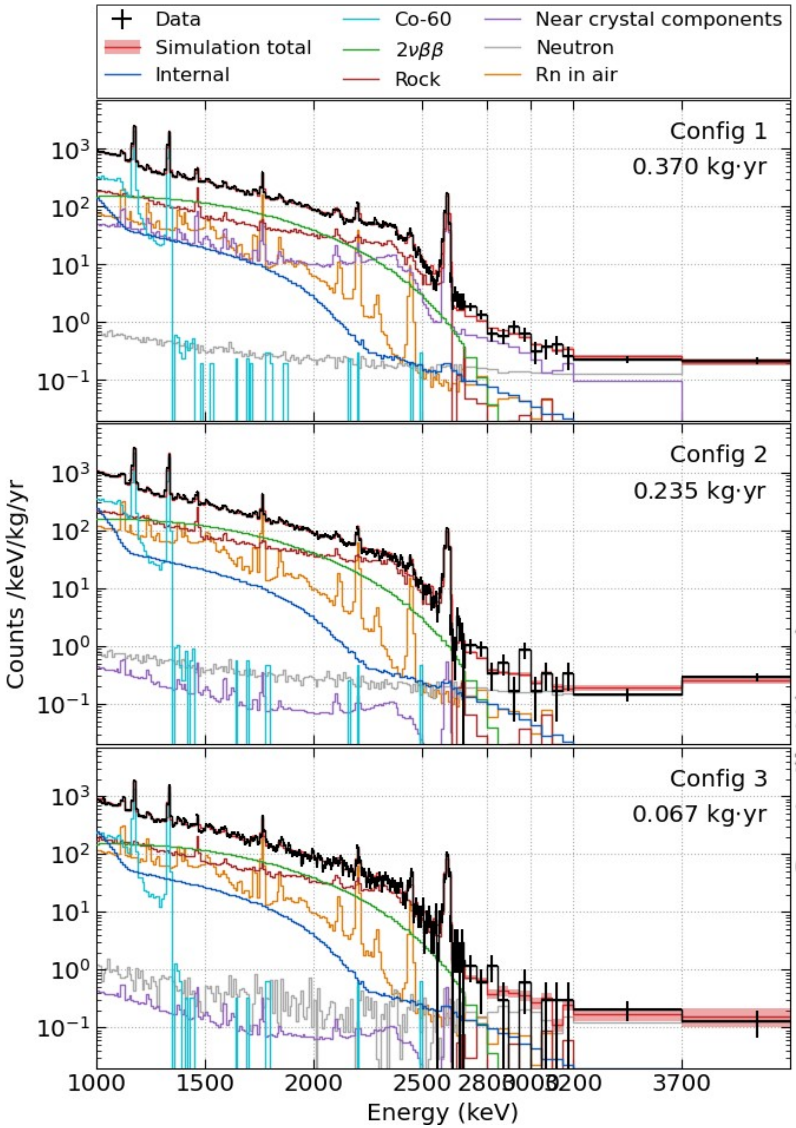
Recent Limits & Persepectives



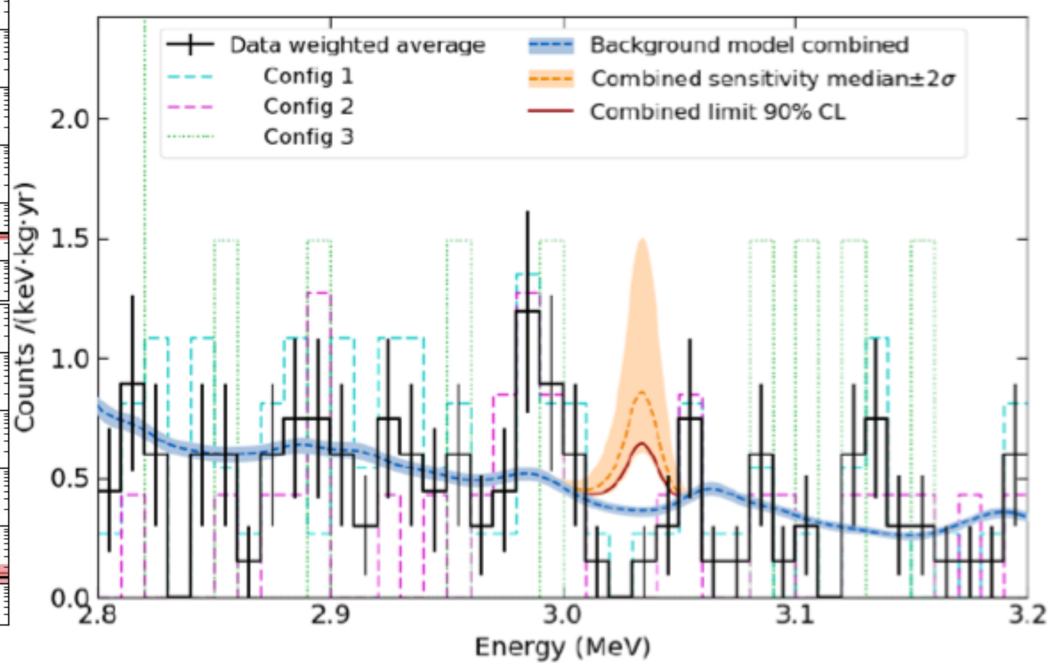
Plan of AMoRE Project

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
Backgrounds (**ckky**)	$\sim10^{-1}$	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$\sim3.0x10^{23}$	$\sim7.0x10^{24}$	$\sim8.0x10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	13-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2022	Yemilab / 2022-2027

AMoRE-pilot - finished

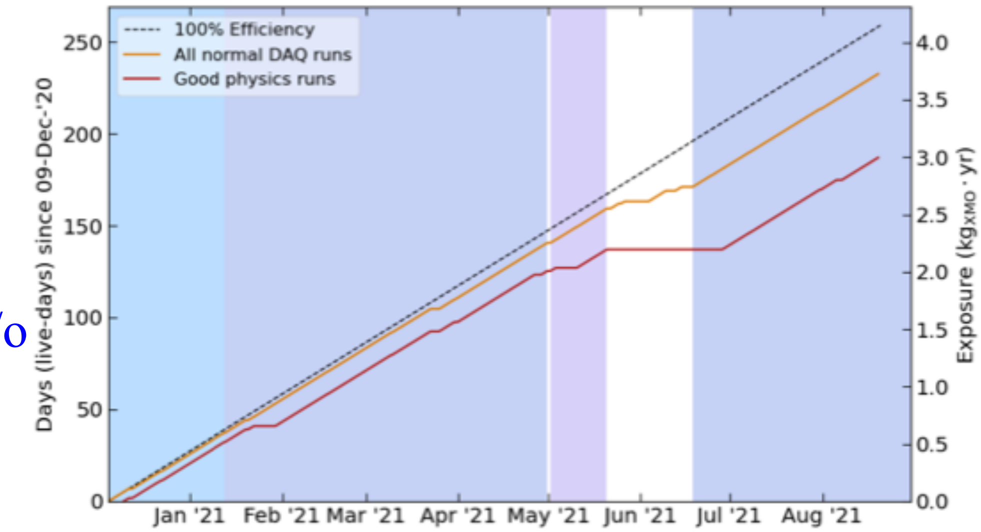


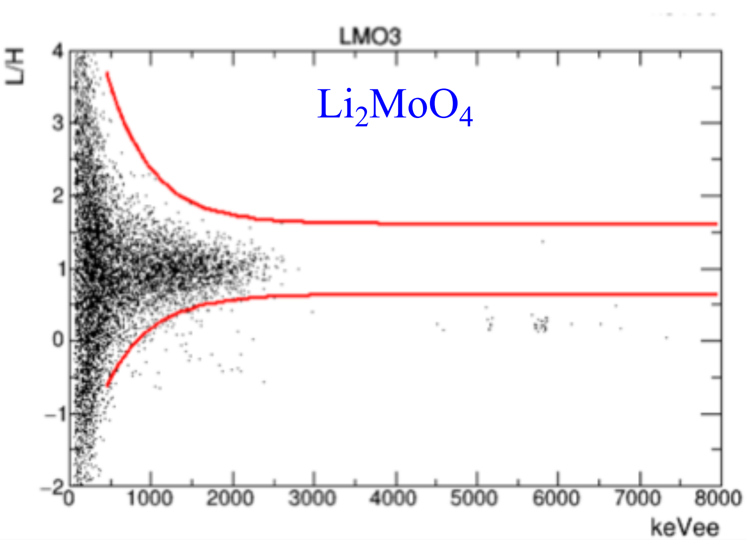
- AMoRE-Pilot experiment began in 2015 @ Y2L to demonstrate the concept.
- 6 CMO crystals are used.
- ~ 2 years of data with different configurations to reduce the backgrounds.
- Final 0νββ halflife limit is 3.43×10^{23} year.

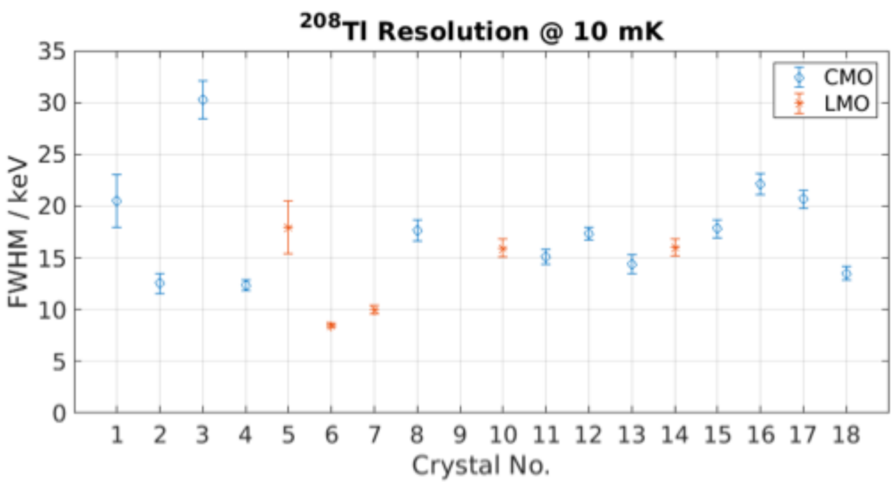


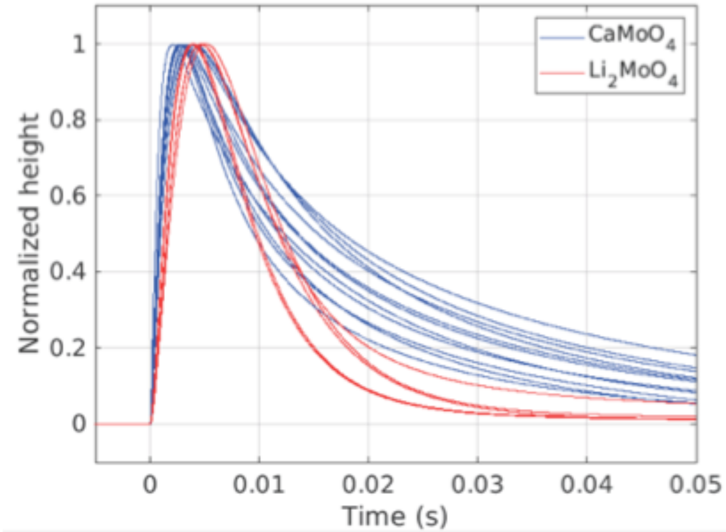
AMoRE-I - running

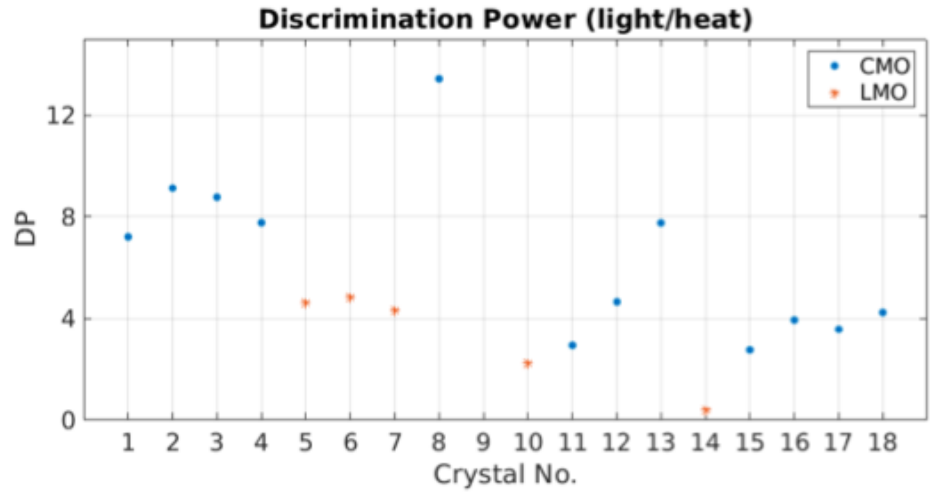
- AMoRE-I run began Aug. 2020 @ Y2L
  - Check detector performance (LMO)
  - Understand background better.
- 17 crystals (34 MMC-SQUID sensors) are stable for over 1 year w/o any noticeable change !

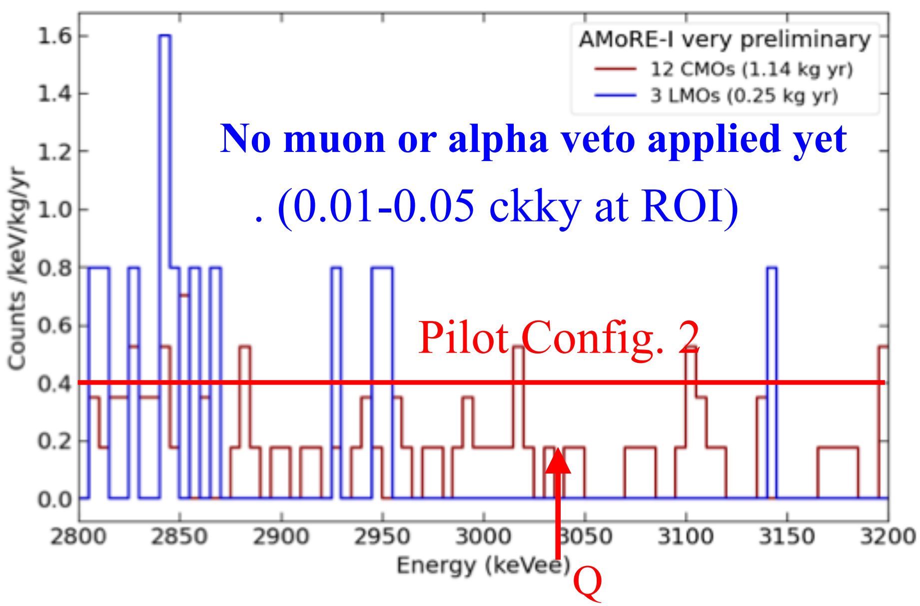










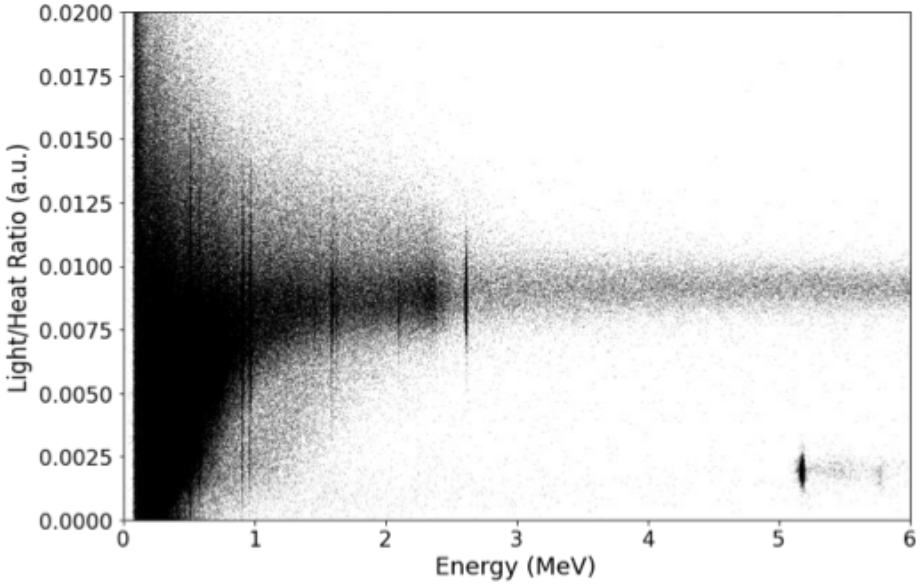


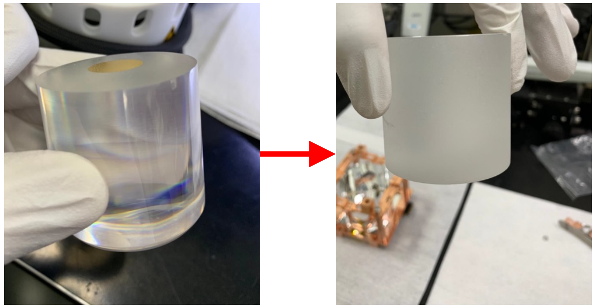
Will get the backgrounds and limits before Neutrino 2022.

AMoRE-II – under construction

- Improvement in detector performance is continuing.

(1) Polishing vs lapping(roughening)



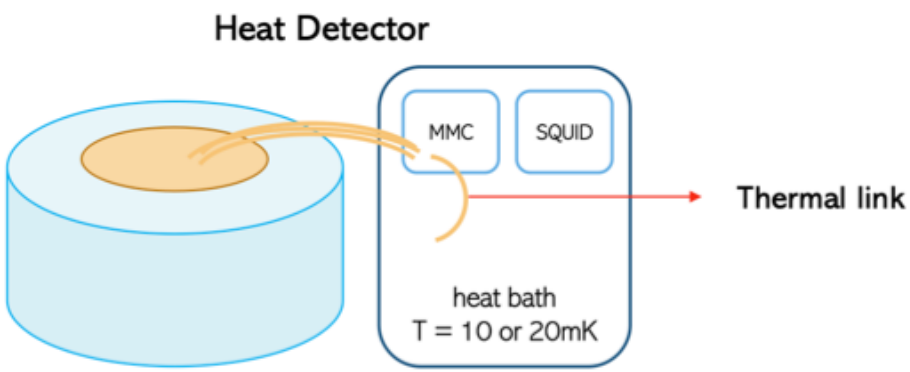


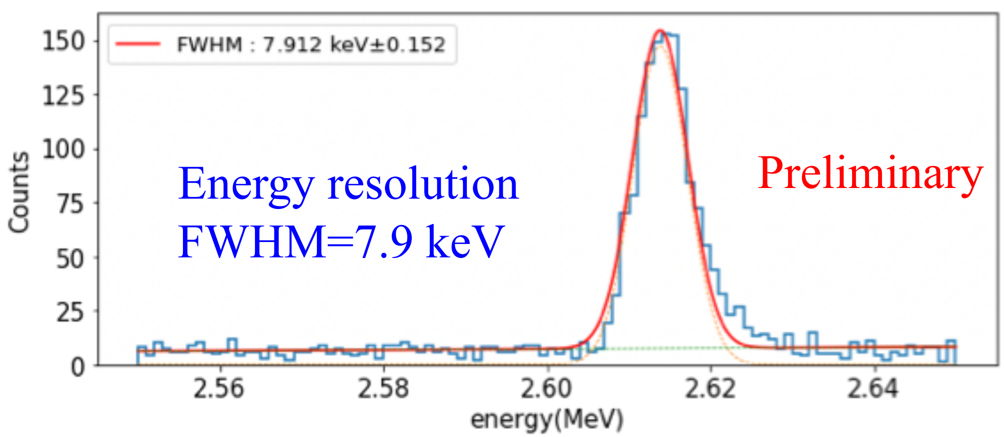
Lapping effects :

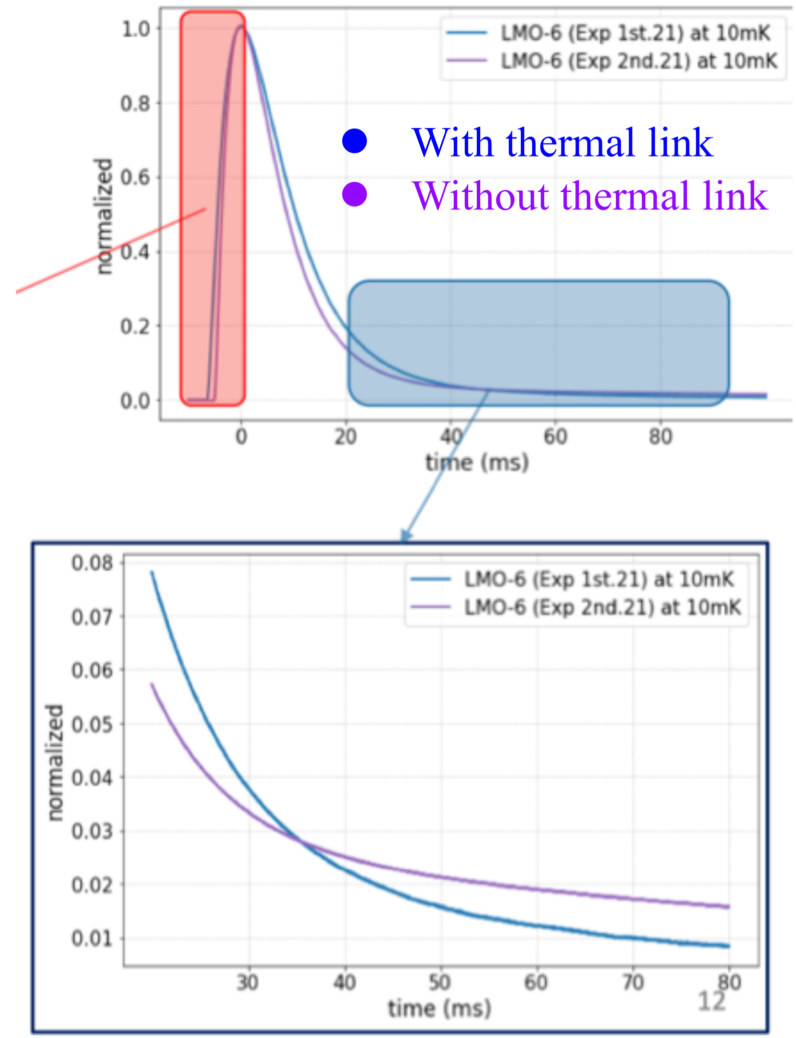
- Better energy resolution ~ 8 keV FWHM.
- Larger light output → DP factor > 10.
- Signal slower, rising time 3.2 ms → 4.8 ms. → Disadvantage of larger pileup effect, but still within AMoRE-II requirement.

(2) Thermal link to heat bath

- Tested larger (D=H=6cm) crystal to reduce channel numbers for AMoRE-II and further experiments.

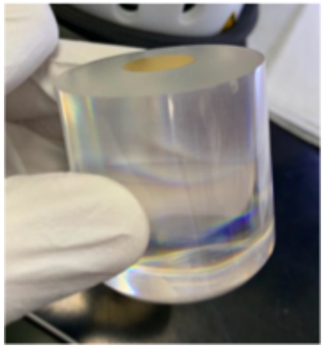




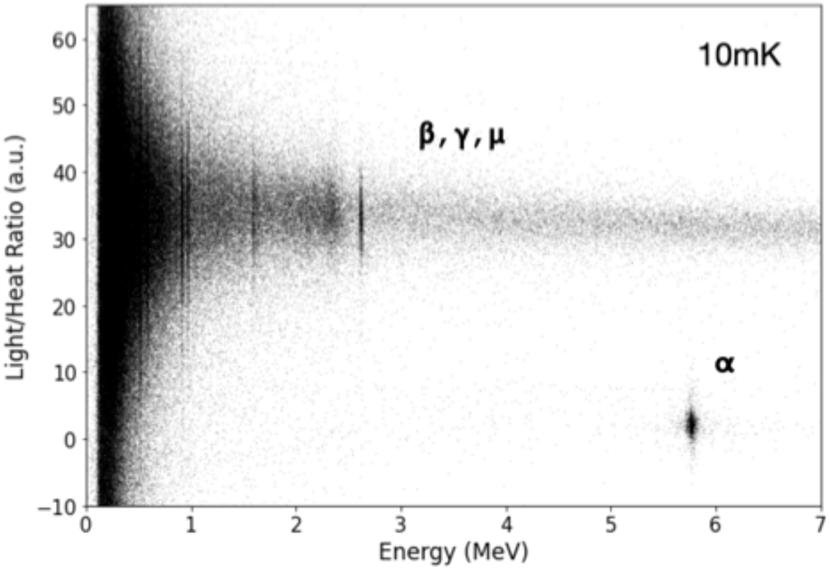


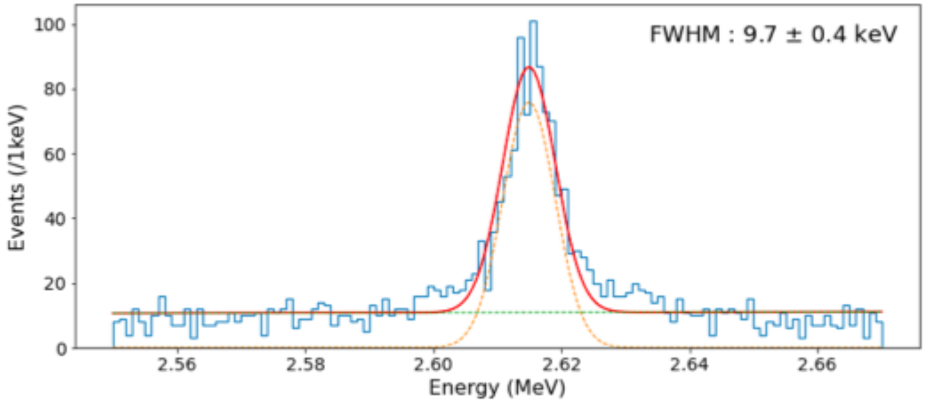
Now, AMoRE's energy resolution is close to CUPID-Mo in the test setup, which has been a task for a long time !

(3) $Na_2Mo_2O_7$ crystal

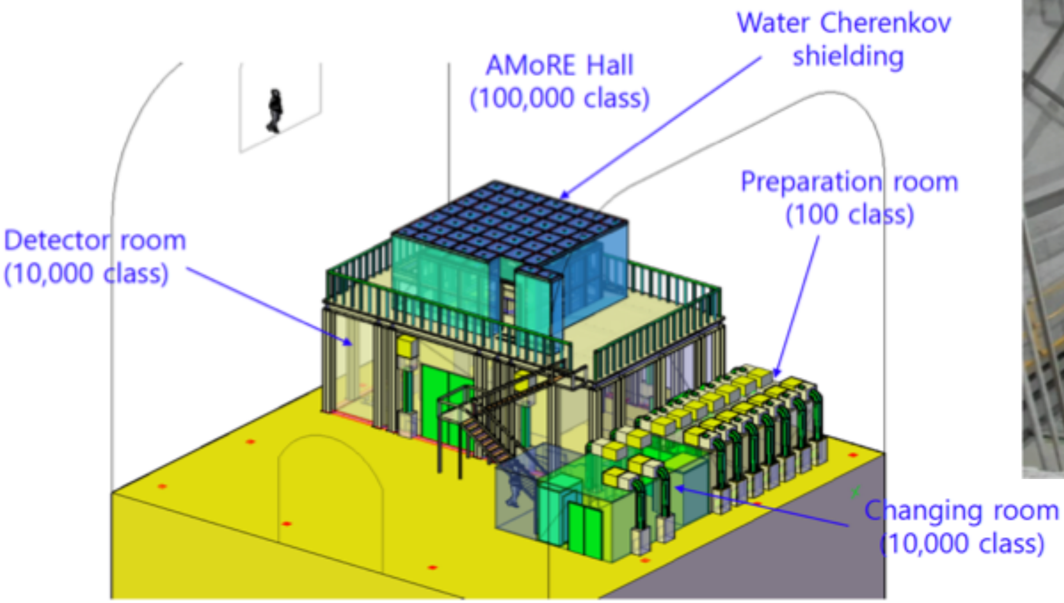


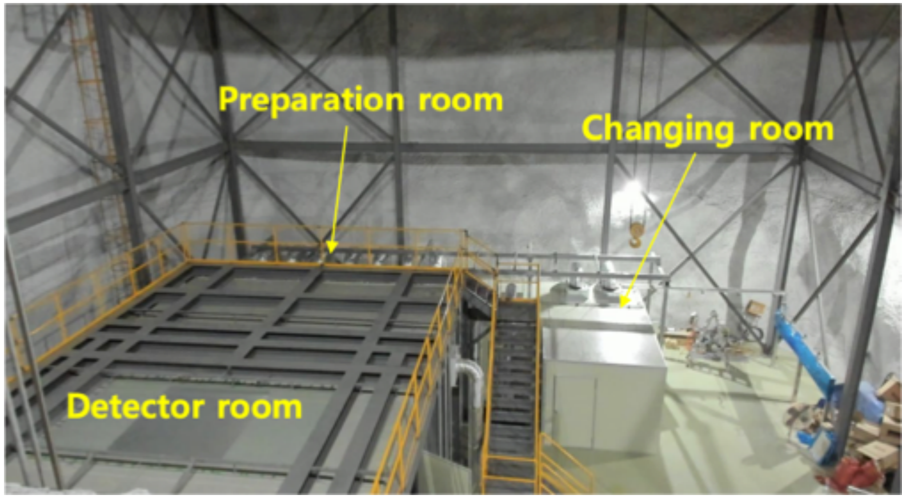
- Tested a large (D=H=4cm) $Na_2Mo_2O_7$ crystal to check it is suitable for AMoRE-II experiment.
- Slower rising time (~5.6ms @ 10mK), but good energy resolution and excellent PID.
- A candidate, but it is found difficult to grow large crystal.



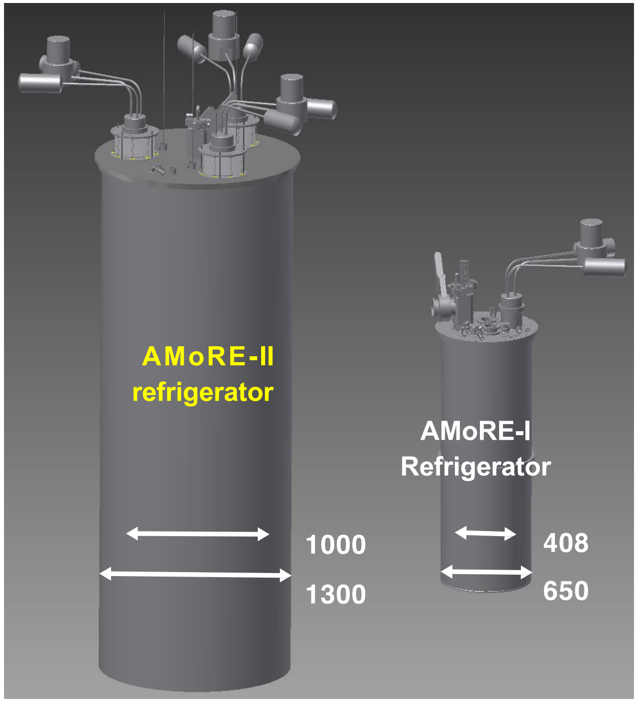


Construction is going on..





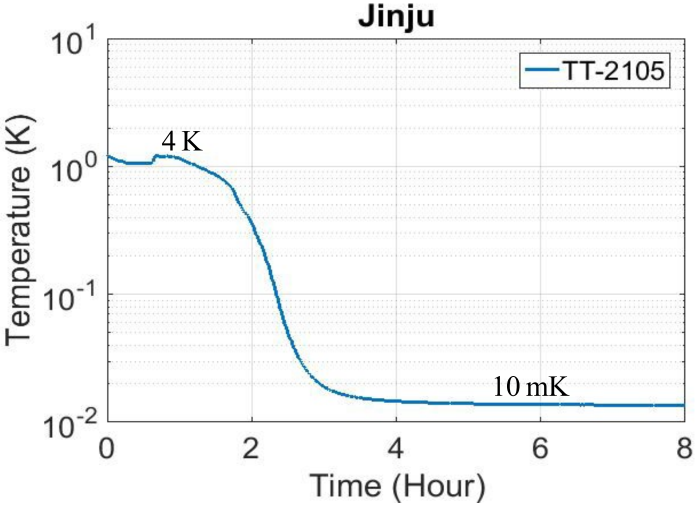
AMoRE-II refrigerator, detector tower



Large dilution Refrigerator from Leiden.

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

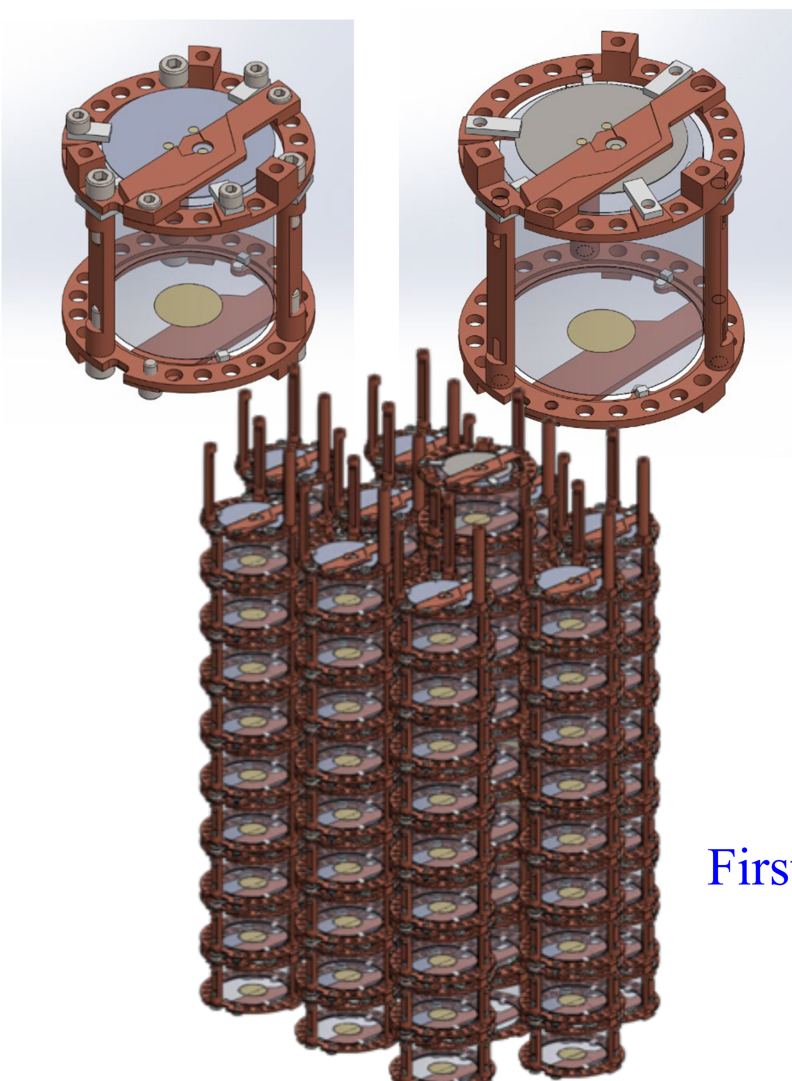
- With heavy LN2 supply, it takes 6 days to reach 4 K.
- Mass inside IVC: 900 kg (Cu) now, ~ 4 t (Cu+Pb) to be added
- ~ 3 hours to condense the mix.
- ~ 4 hours to reach 10 mK
- Mass at MC: 300 kg (Cu) now, ~ 4 t (Cu+Pb) to be added.

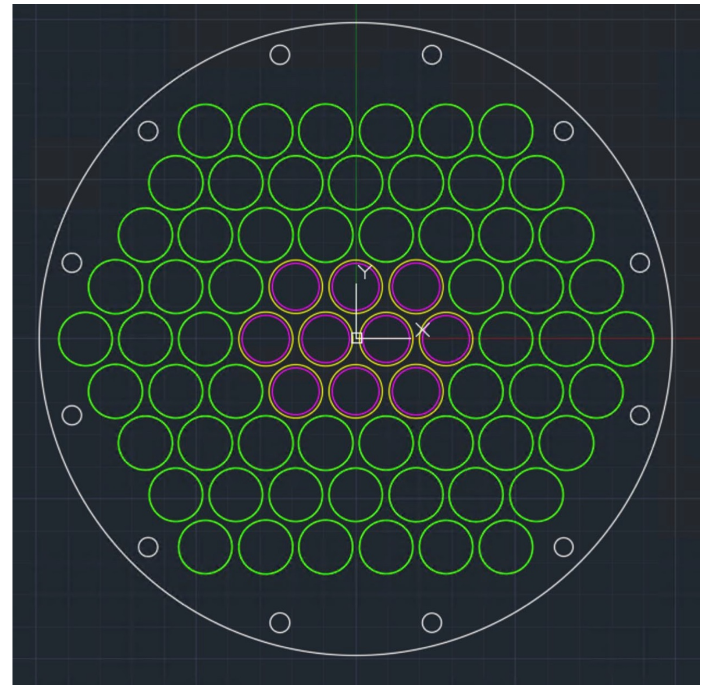


New detector module and towers

- The module designs are done for 5-cm and 6-cm LMOs

5cm module 6cm module

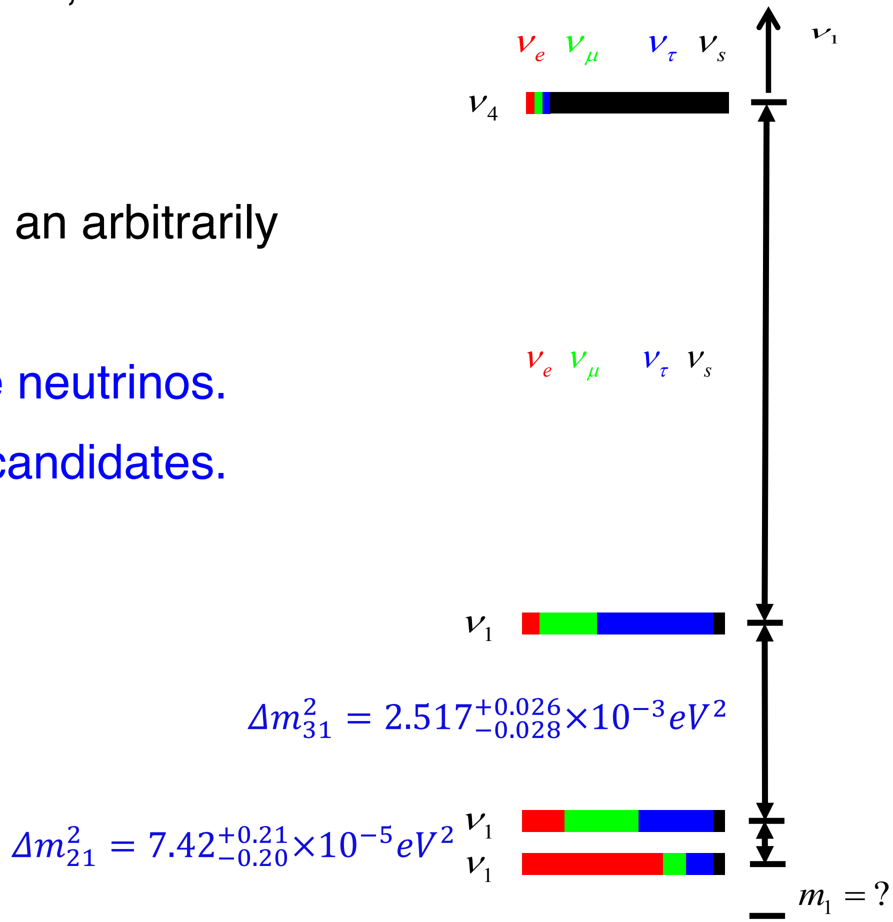




First, 90 crystals will be cooled.

Are there sterile neutrinos ?

- Three "Active" neutrinos are left-handed.
- Sterile neutrinos are right-handed neutrinos, so sterile.
  → 4th Flavor
- They can be Majorana particles.
- Being sterile, they can, in principle, have an arbitrarily mass.
- Sterile neutrinos can oscillate with active neutrinos.
- Heavy sterile neutrinos are dark matter candidates.

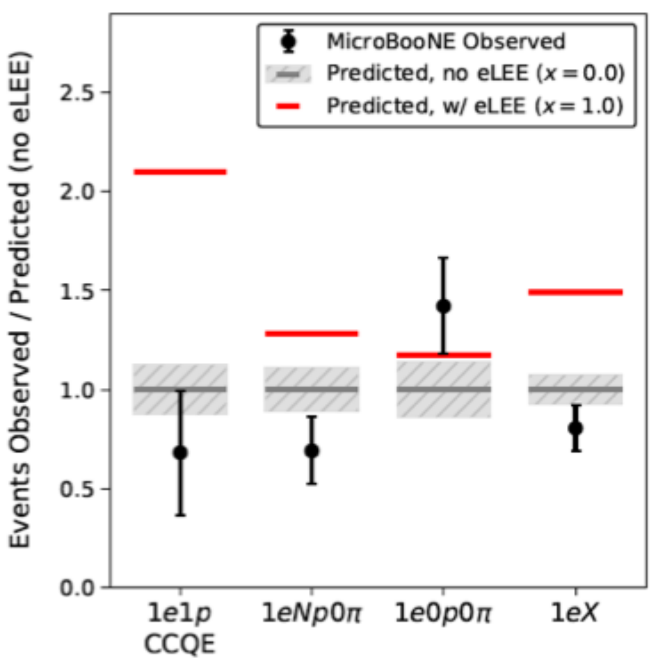


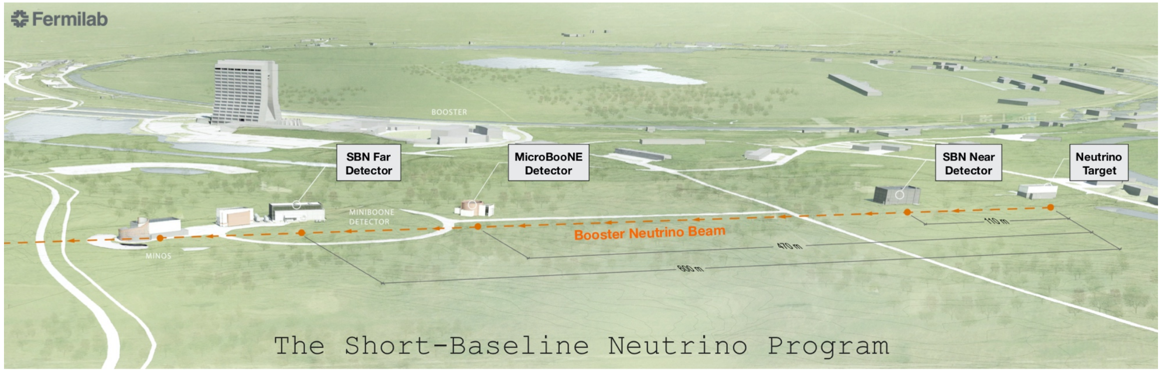
$\nu_e, \nu_\mu, \nu_\tau.$ → ν_s →ν_e, ν_μ, ν_τ

Disapperance Apperance

Microboone

- Search for Neutrino-Induced Neutral Current Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single-Photon Hypothesis, **arXiv:2110.00409**
- Search for an anomalous excess of inclusive charged-current nu_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction, **arXiv:2110.13978**
- Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using Multiple Final State Topologies, **arXiv:2110.14054**
- Search for an anomalous excess of charged-current e interactions without pions in the final state with the MicroBoNE experiment, **arXiv:2110.14065**
- Search for an anomalous excess of charged-current quasi-elastic e interactions with the MicroBooNE experiment using Deep-Learning-based reconstruction., **arXiv:2110.14080**

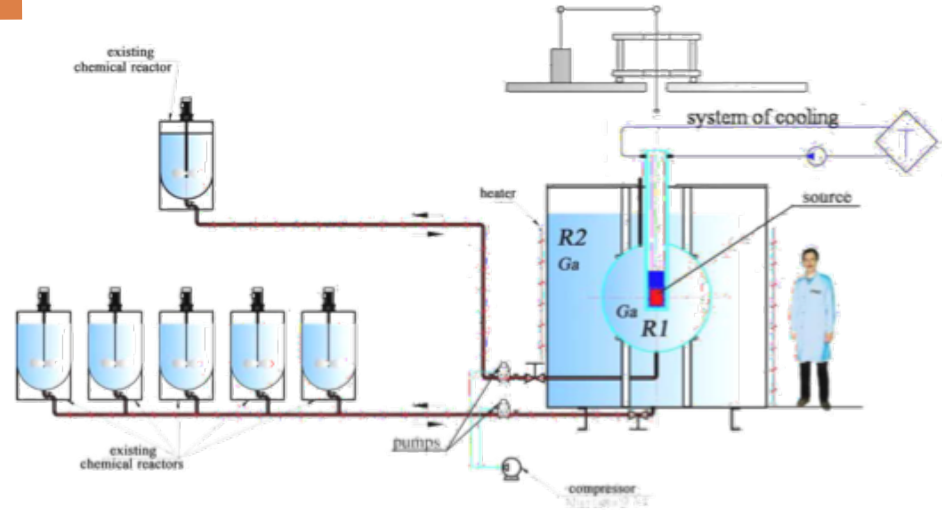




MicroBooNE rejects the hypothesis that nu_e CC interactions are fully responsible for that excess at >97% CL for both exclusive (1e1p CCQE, 1eNp0pi) and inclusive (1eX) event classes.

→ MINIBOONE's excess is not observed. Microboone is consistent with background model.

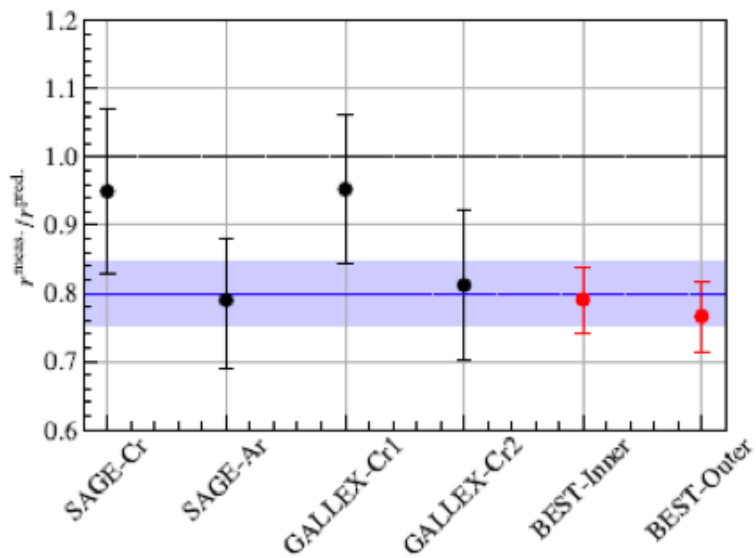
2-zone Ga experiment BEST



Slide by V.V.Gorbachev

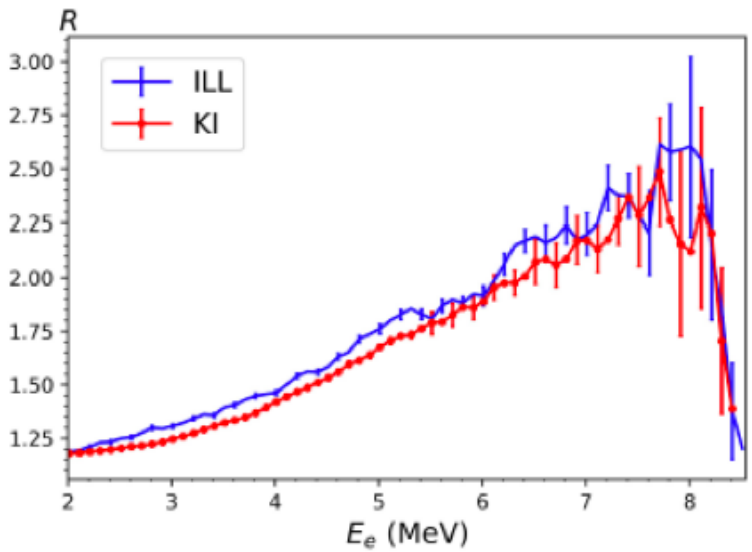
^{51}Cr+ e-⟶ ^{51}V + ν_e
Eν= 750 keV, 90% (95% captures on Ga)
430 keV, 10%

-Independent measurements in each zone with 2 baselines
-Increased target mass (48 tons instead of 13 tons)
-More active source (3.4 MCiinstead of 0.5 MCi)
-All procedures were well studied in sun runs

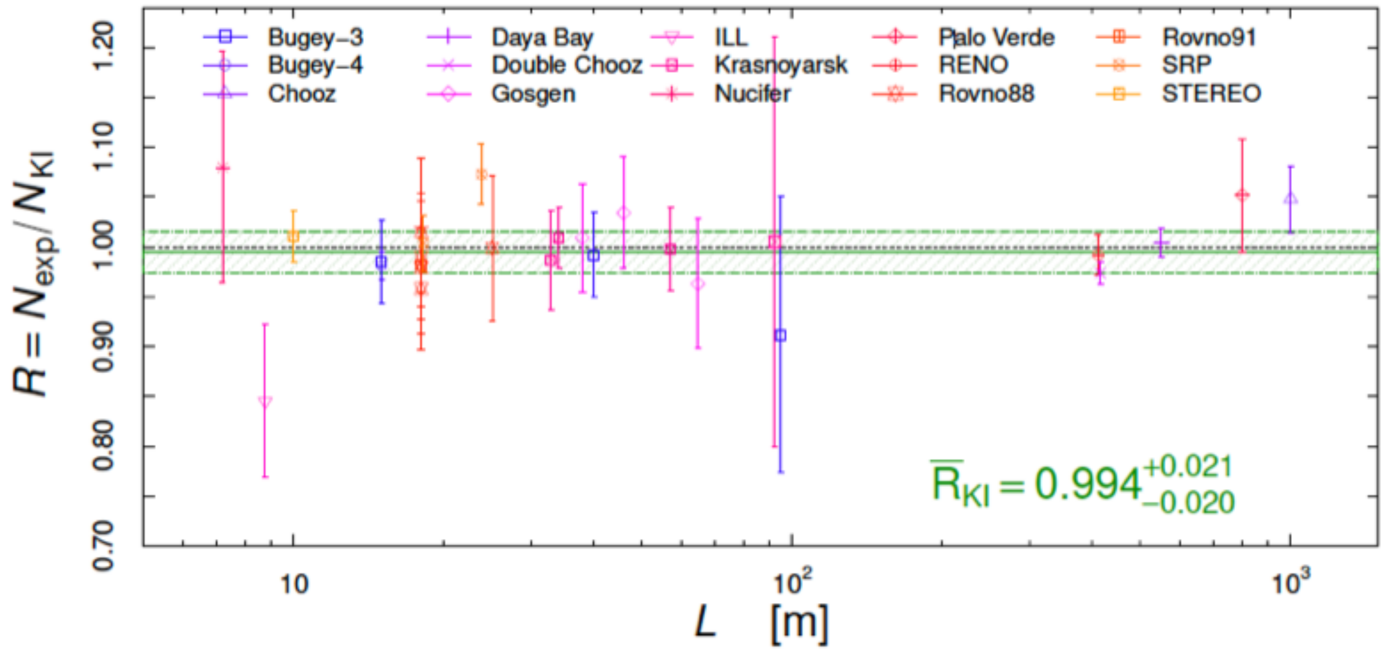


Ga anomaly confirmed and intensified

Reactor neutrino spectra revisited.

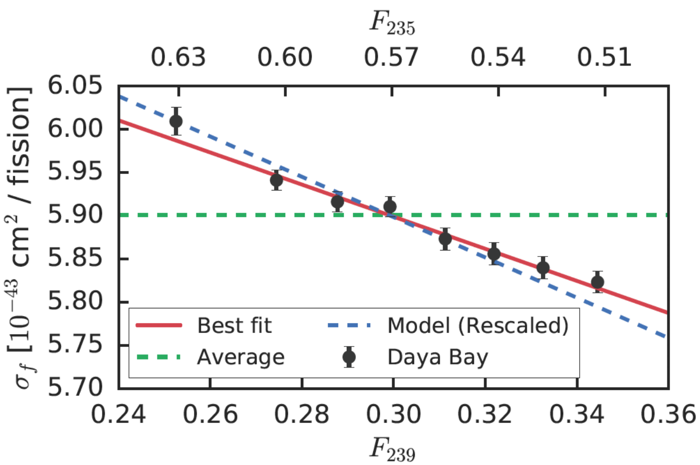


arXiv:2103.01684, Kopeikin et al.
Electron spectra measured again at Kuchatov Institute.

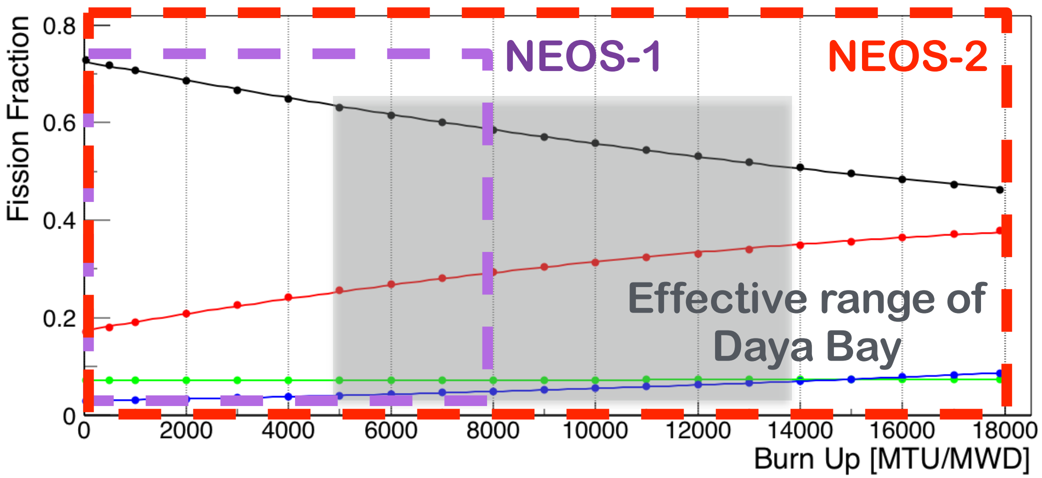


NEOS projects

- NEOS-II covered whole burn-up cycle (1.5 years data) compared to NEOS (0.5 year data).
- PI : Yoomin Oh & Sunny Seo (CUP, IBS)

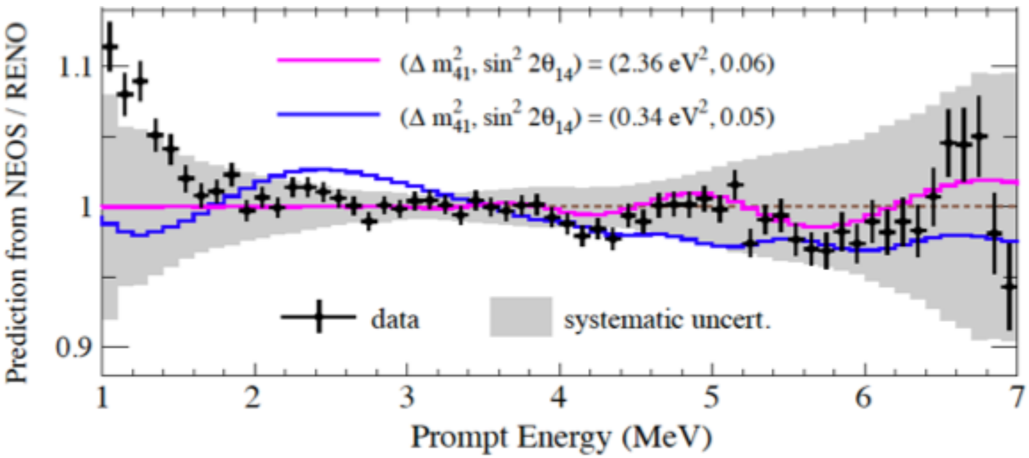


An et al., PRL 118, 251801 (2017)



RENO opened unfolded spectra.
Atif et al., arXiv:2011.00896

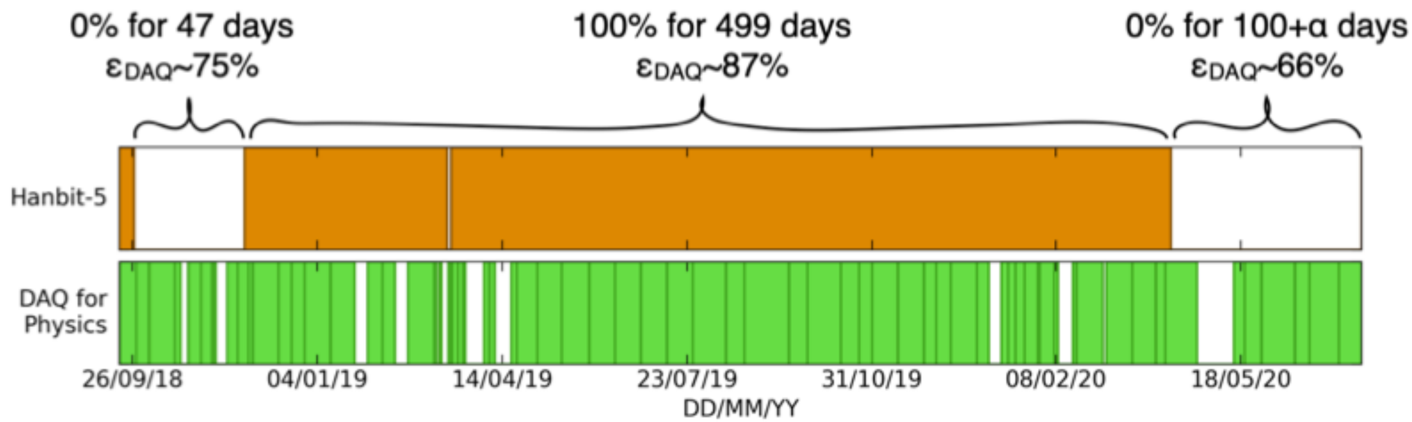
NEOS compared with RENO.



NEOS-II data taking finished

Reactor

Detector

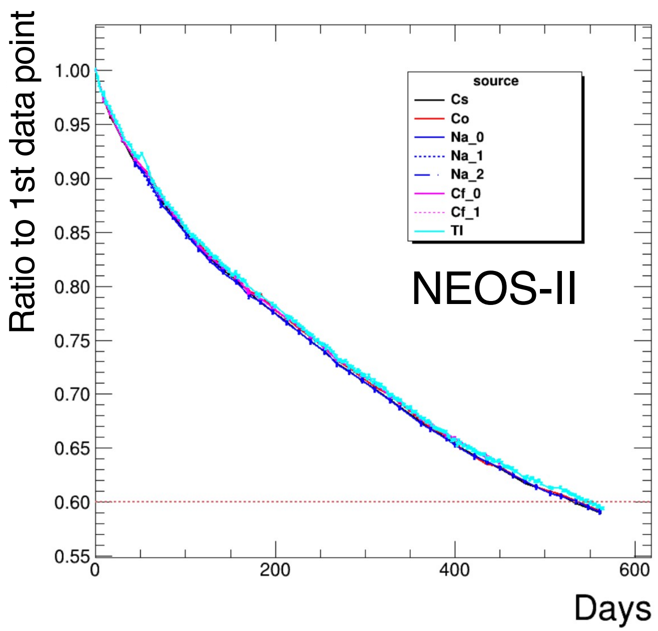


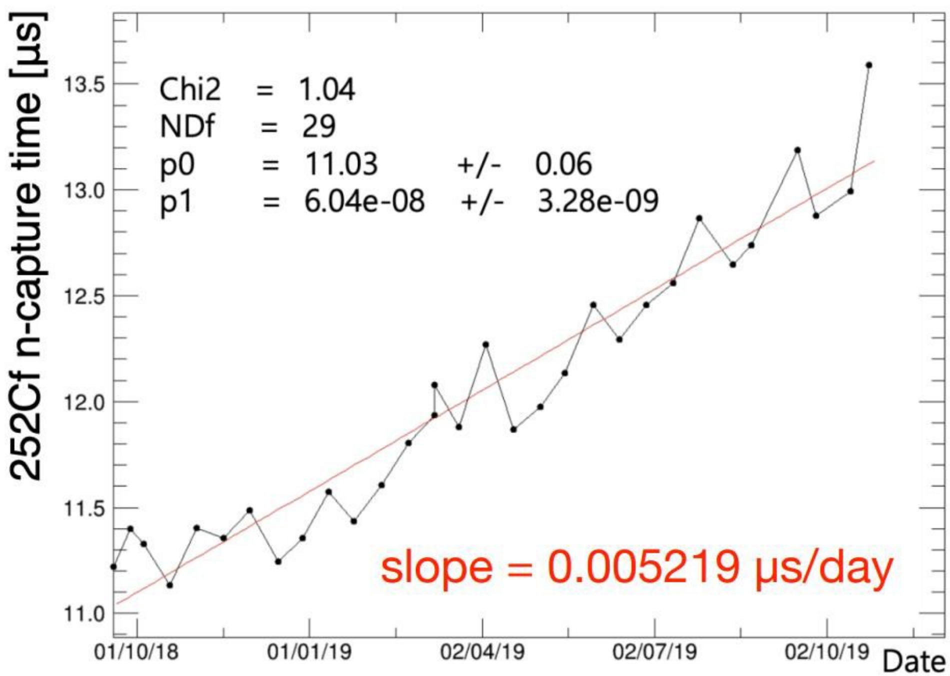
To confirm

- the wiggling pattern seen in NEOS-I
- the fuel burn-up.
- Improve sterile neutrino search.

LS stability issue in NEOS-II

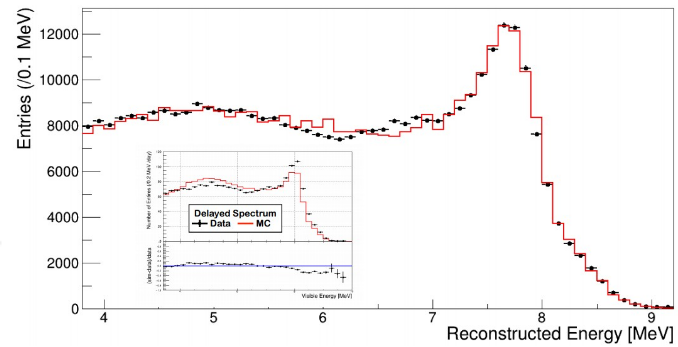
- LAB LS with 0.5% Gd loaded and 10% of DIN (UG-F) mixed; same recipe for NEOS-I & II.
- Precipitates in the LS samples → LY decreases, attenuation got worse.
- Can be controlled for analysis (YJKo @ v-2020).
- Efficiency should be studied carefully.





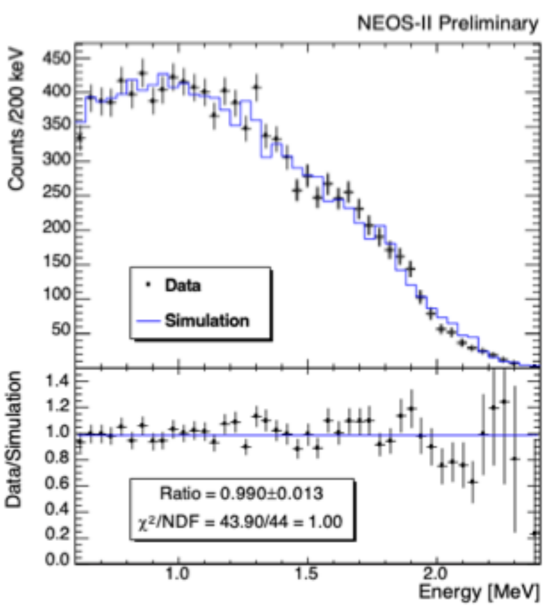
NEOS-II Simulation

- MC tuning is almost done.
- Validating MC by comparing beta spectra w/ data
- Beta spectrum for ^{12}B will be compared.

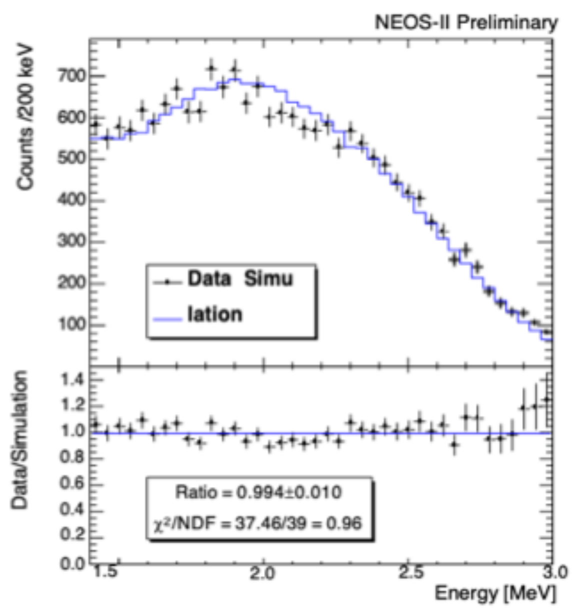


Okayama Model: [PTEP 2019 2, 023D01]

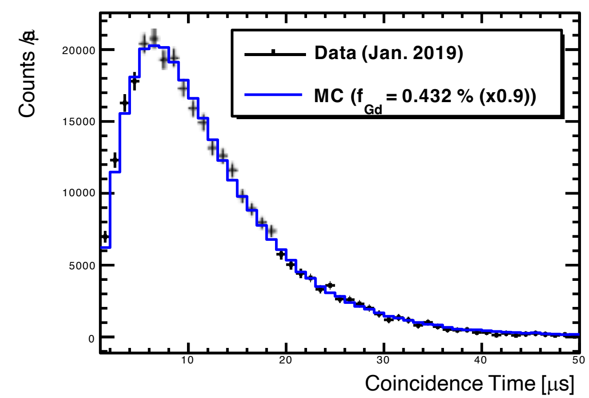
- ^{212}Bi



- ^{214}Bi

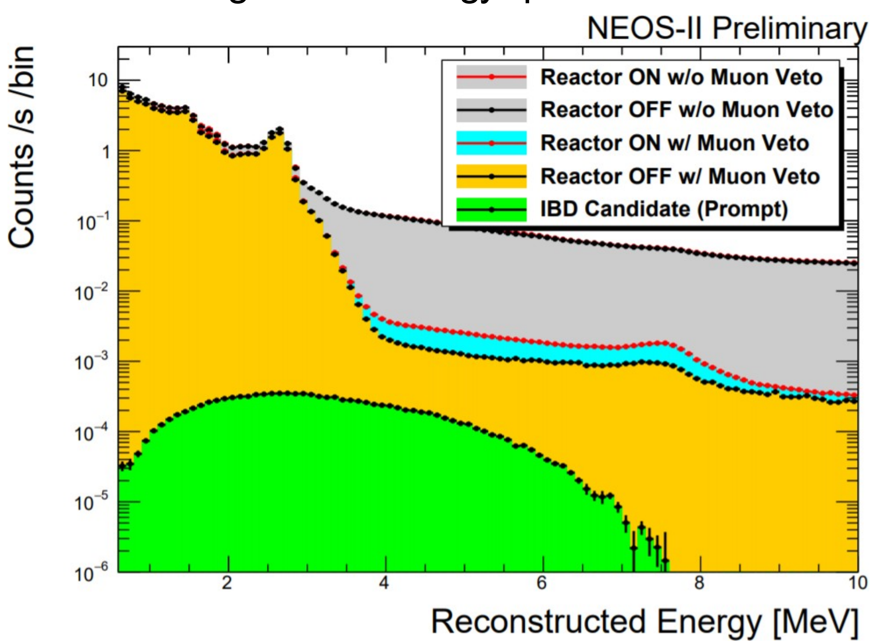


- IBD Coincidence Time

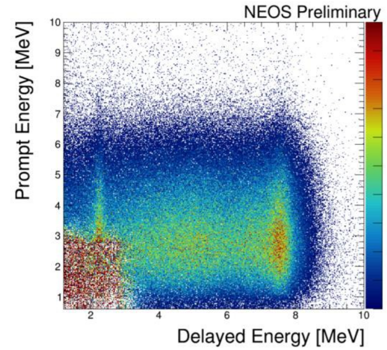


IBD reconstruction

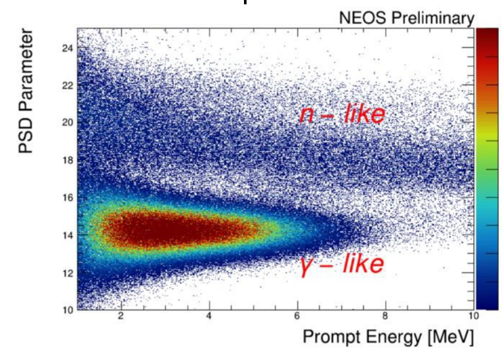
- Single event energy spectra



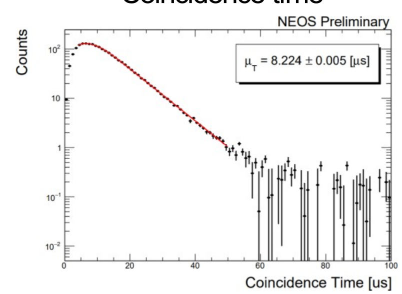
- Energy spectra



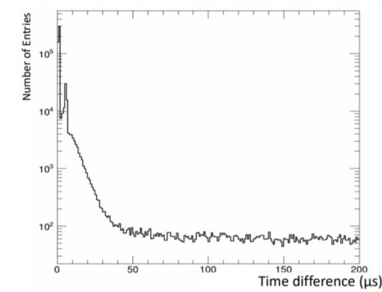
- PSD parameter



- Coincidence time



- Time difference from muon to target



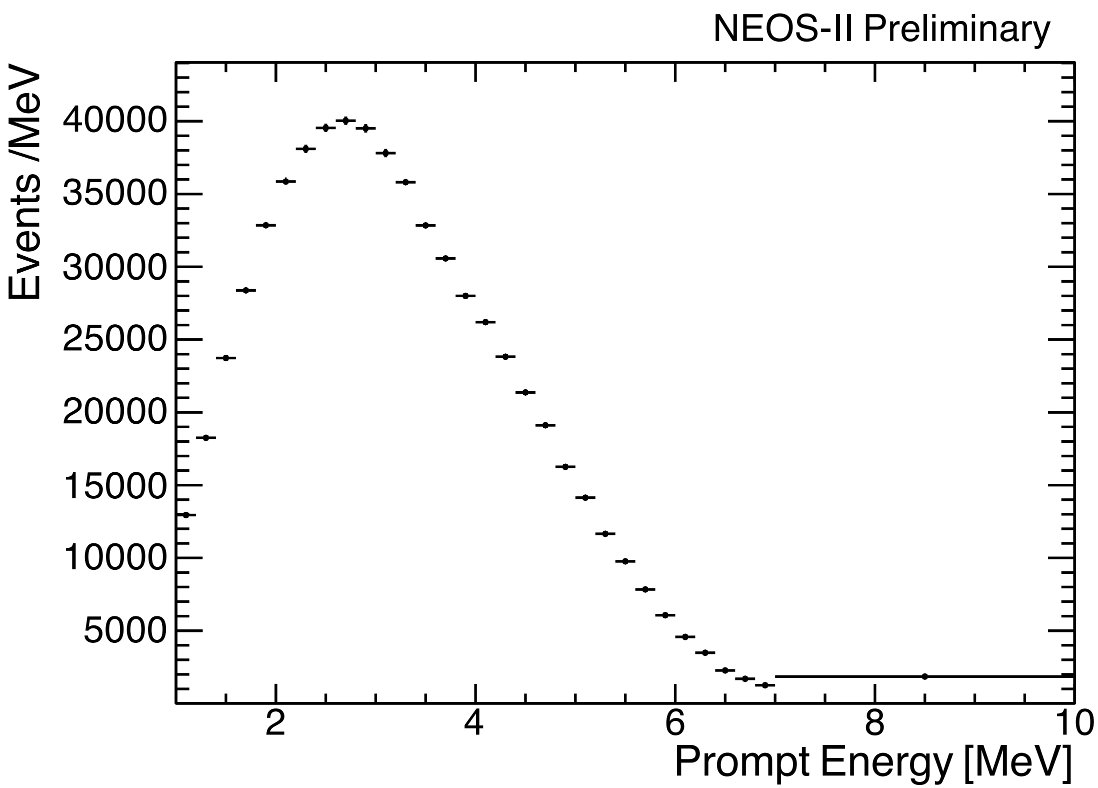
- Single event selection

- Energy cut, Exception electric noise, flasher cut

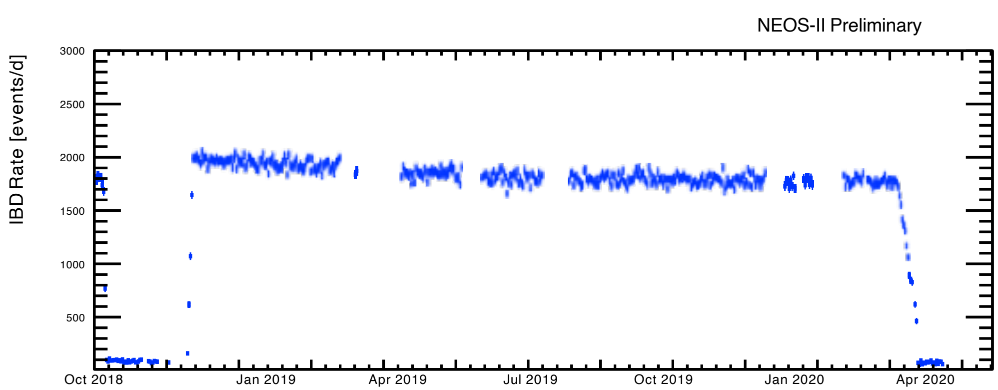
- IBD candidate

- Energy cut, muon veto, multiplicity cut, PSD parameter cut

IBD Prompt Energy Spectrum & Rate

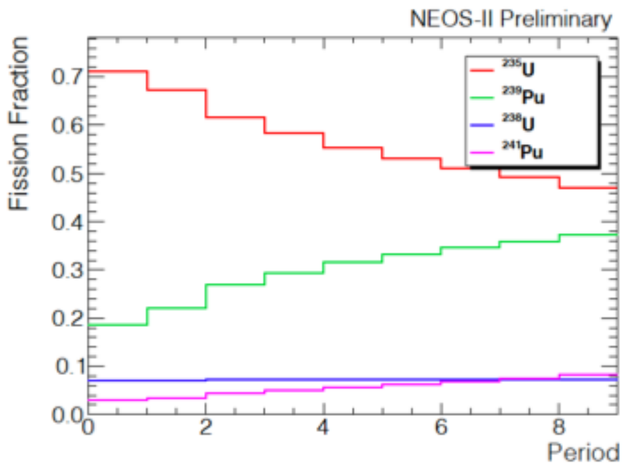


Comparison with the prediction is going on.
NEOS-II data for sterile neutrino and fuel decomposition is coming soon.

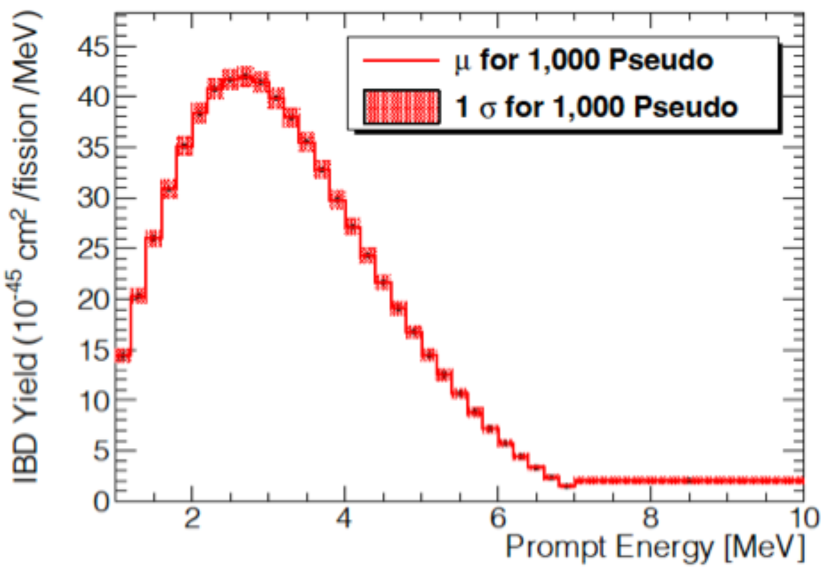


Spectrum decomposition

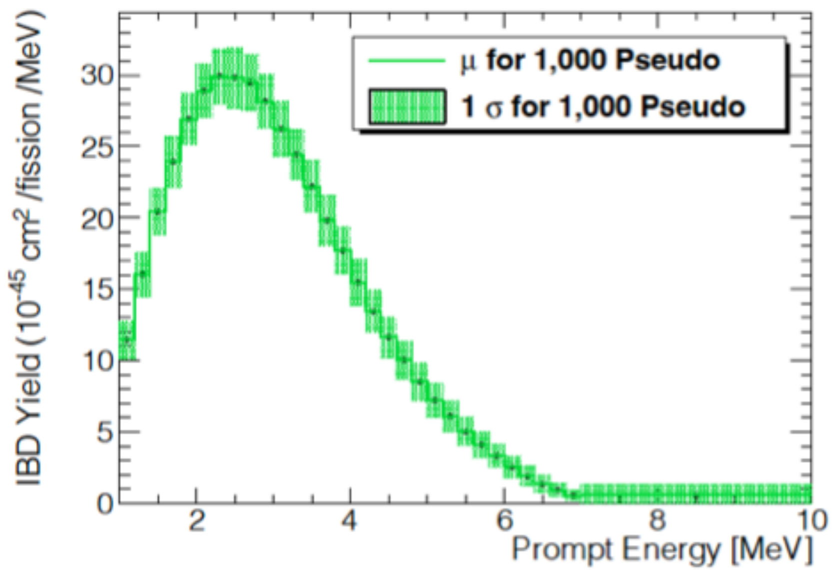
- 9 periods for reactor on time based on data run numbers.
- Generating pseudo data by using Huber-Mueller model.
- Standard deviation : 4 % & 20 % for ^{235}U & ^{239}Pu in 4 - 6 MeV.



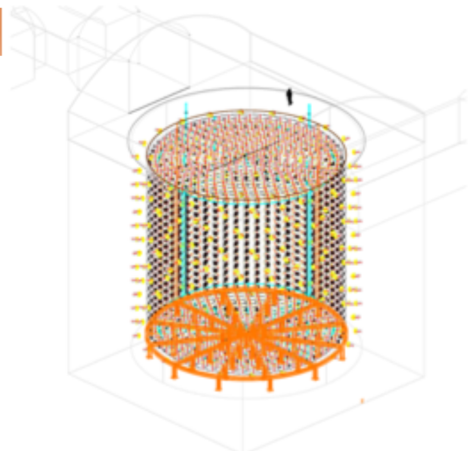
^{235}U

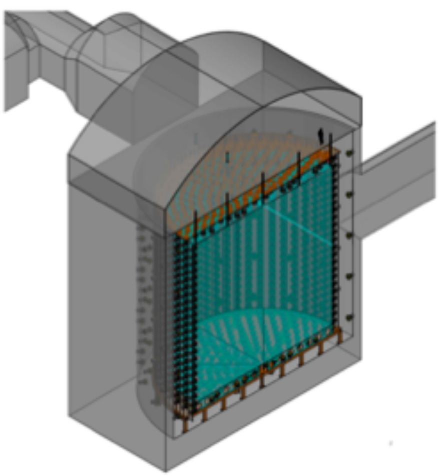


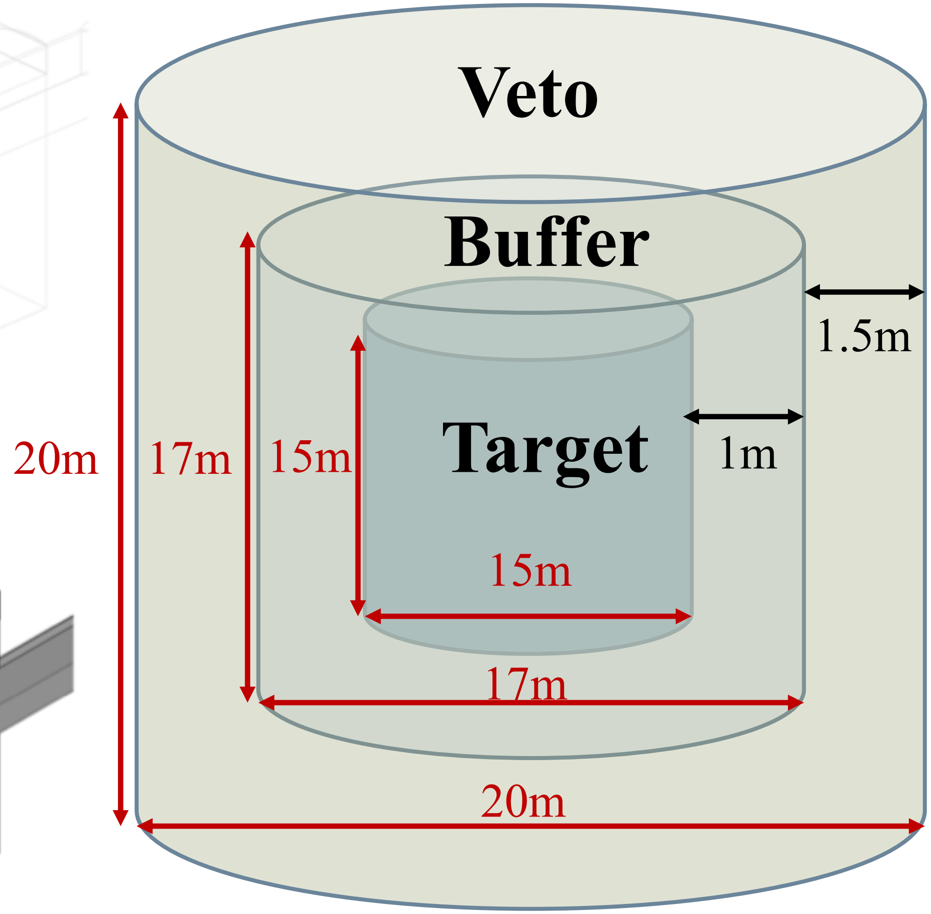
^{239}Pu



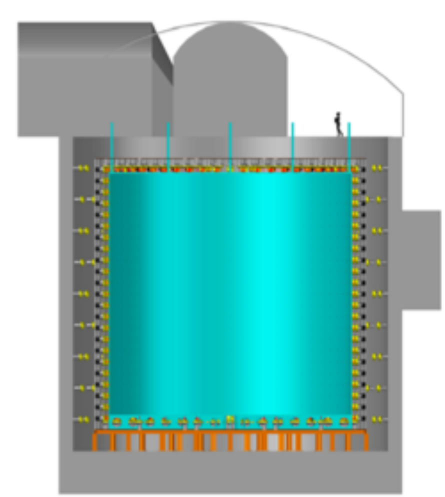
LSC @ Yemilab







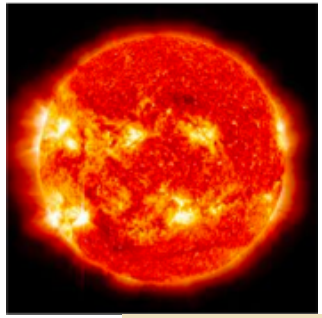
Target: 2.26 kton
Buffer: 1.14 kton
Veto: 2.41 kton



1200(1800,2400) x 20 inch PMTs = 20% (30, 40)% coverage

Broad Physics Program

Solar ν



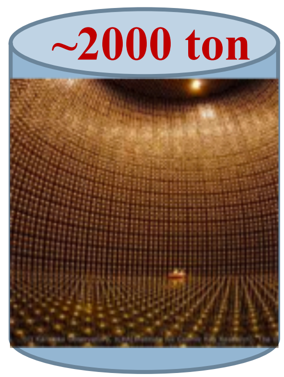
Supernova ν

DSNB

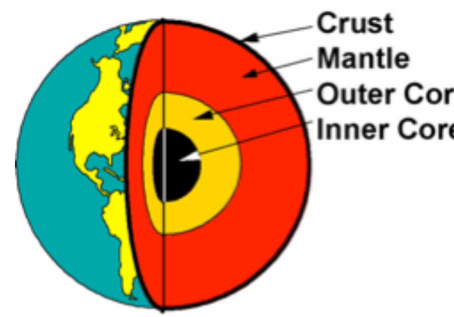
ν Telescope

e- beam

Dark Photon



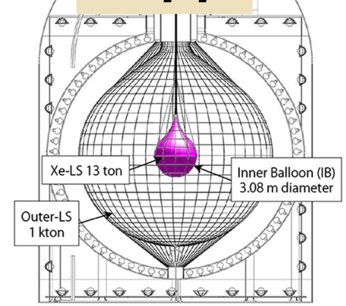
Geo ν



New step to Geo Science

Sterile ν

0νββ

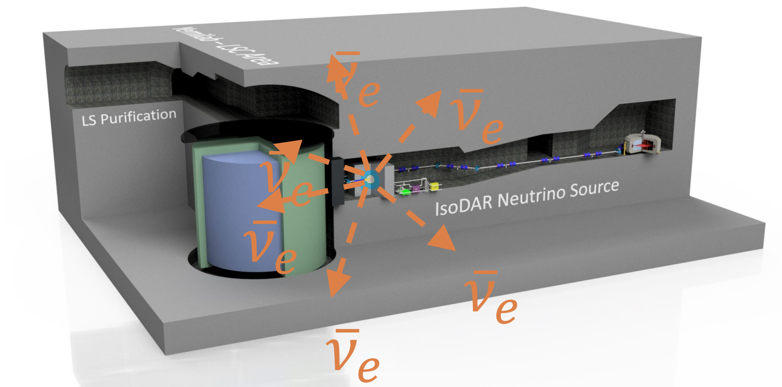


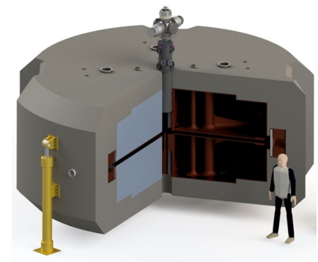
Sunny Seo, IBS

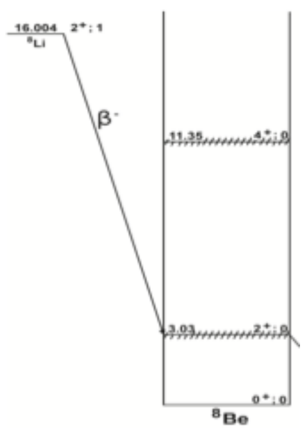
Neutrino production @ IsoDAR

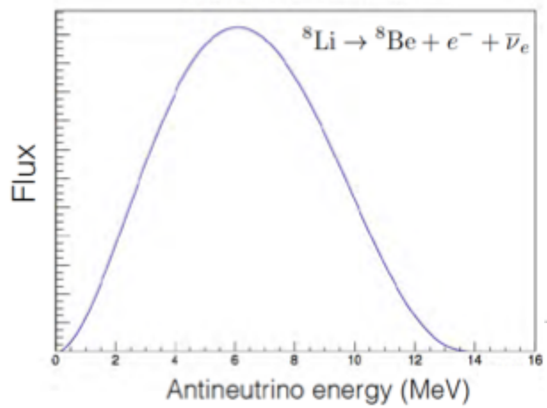
arXiv:2110.10635 : "IsoDAR@Yemilab"

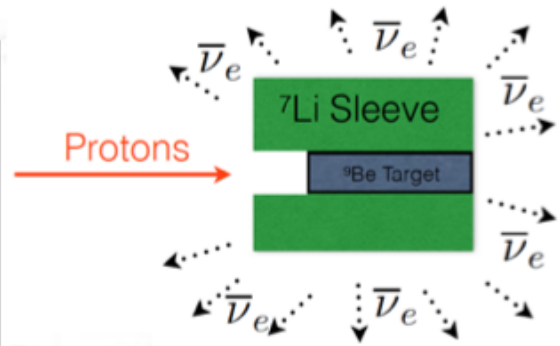
IsoDAR uses ^{8}Li Isotope Decay-at-rest











$p + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Li} + 2p$

$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$

$n + {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Li} + \gamma$

$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^- + \bar{\nu}_e$

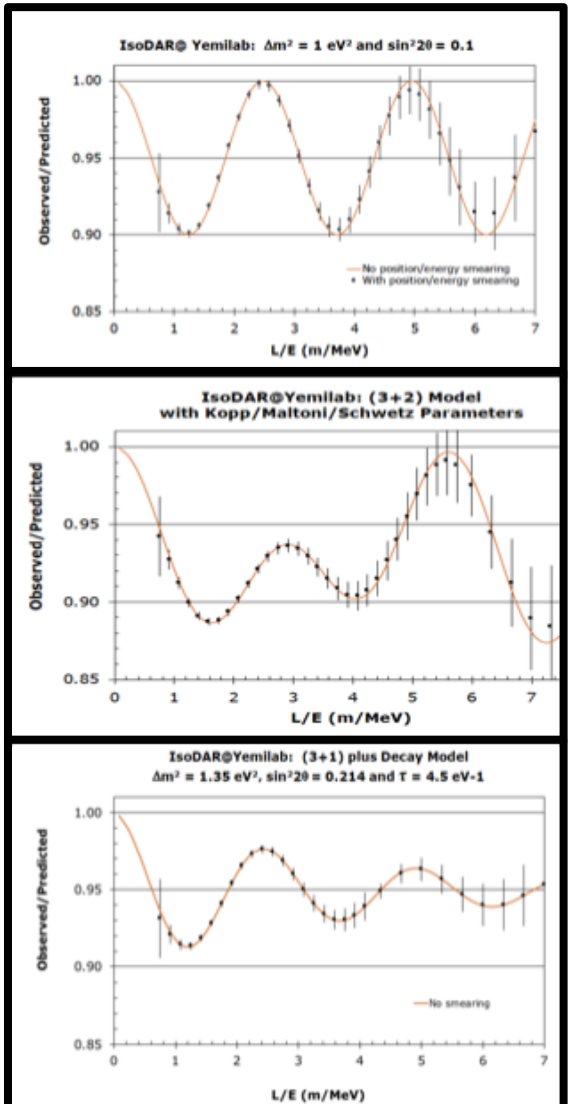
Runtime	5 calendar years
IsoDAR duty factor	80%
Livetime	4 years
Protons on target/year	$1.97 \cdot 10^{24}$
^{8}Li/proton ($\bar{\nu}_e$/proton)	0.0146
$\bar{\nu}_e$ in 4 years livetime	$1.15 \cdot 10^{23}$
IsoDAR@Yemilab mid-baseline	17 m
IsoDAR@Yemilab depth	985 m (2700 m.w.e.)

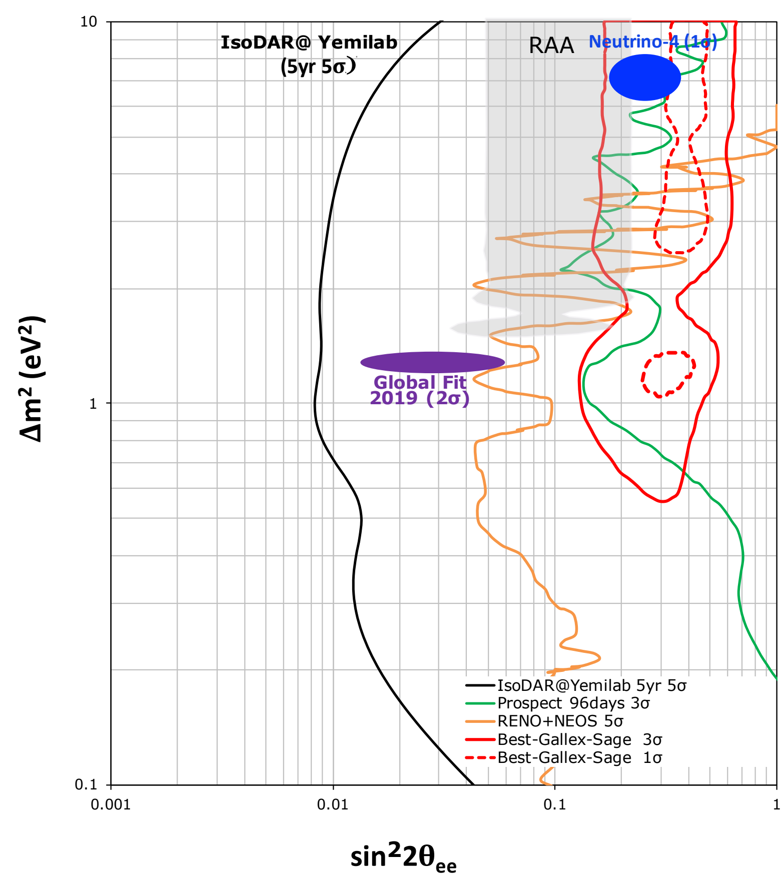
1.7x10^{6} IBD events in 5 years.
~ 1000 events/day

Expected results.

arXiv:2111.09480 : "Neutrino Physics Opportunities with the IsoDAR Source at Yemilab"

- $\bar{\nu}_e p \rightarrow e^+ n$
- Well known energy spectra and cross section unlikely with other experiments; reactor neutrinos, ~GeV neutrino-nuclear cross section, neutrino-nucleus CC interaction etc.





Other physics

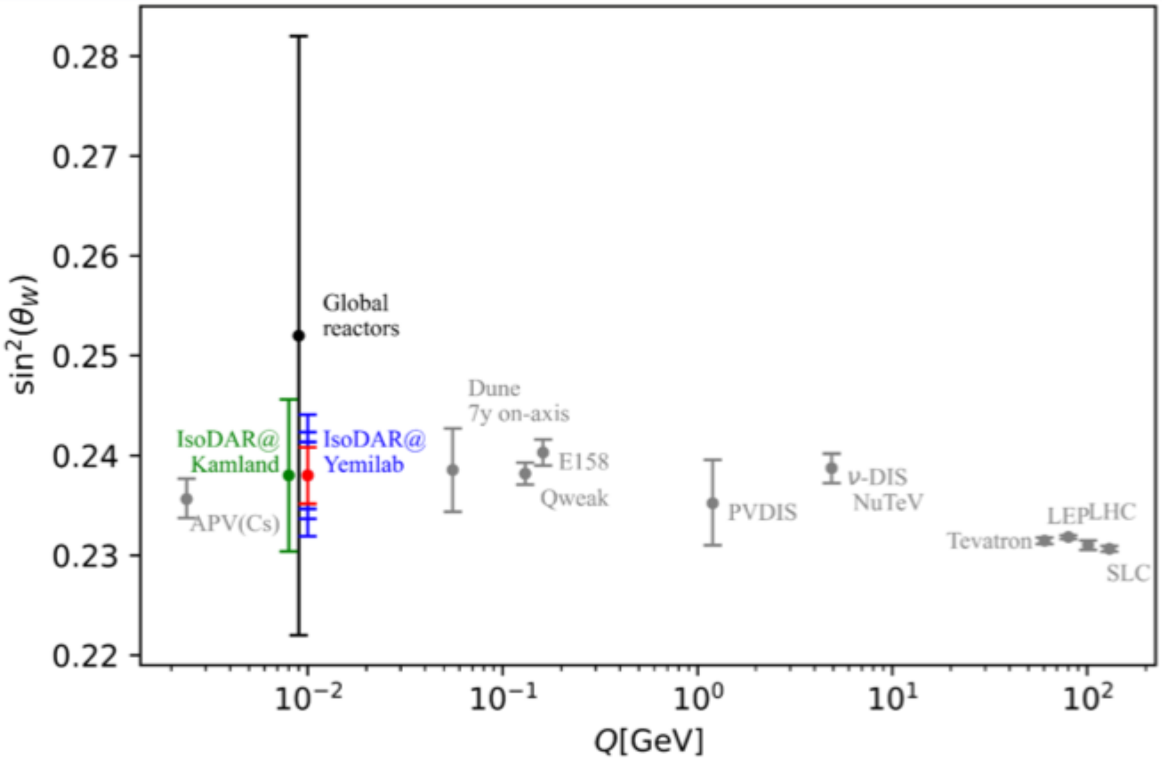
arXiv:2111.09480 : "Neutrino Physics Opportunities with the IsoDAR Source at Yemilab"

IsoDAR@Yemilab elastic scattering

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

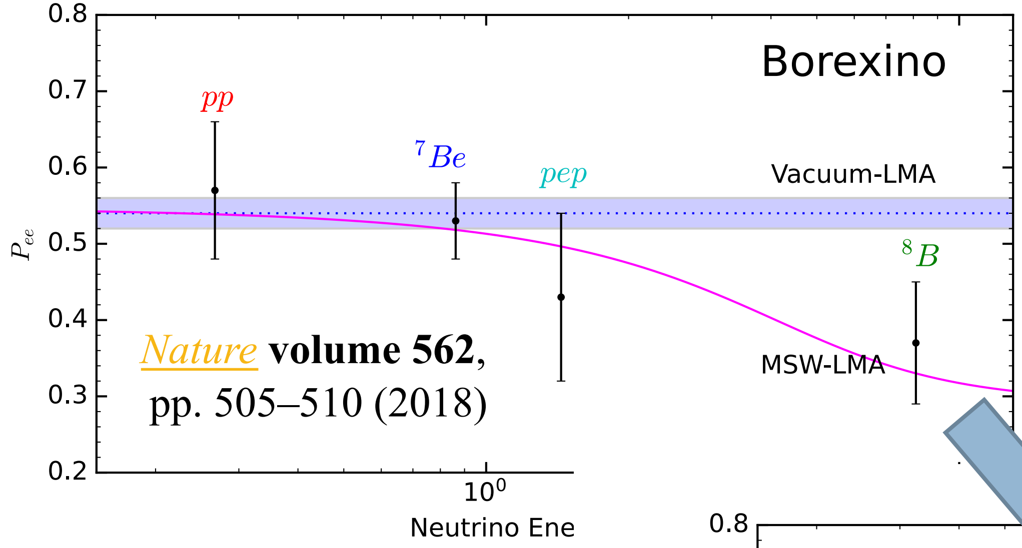
World-leading reactor measurement, TEXONO: $\sin^2\theta_W = 0.251 \pm 0.039$

Global, all-reactor analysis (PLB 761 450 2016): $\sin^2\theta_W = 0.252 \pm 0.030$



Solar Neutrinos

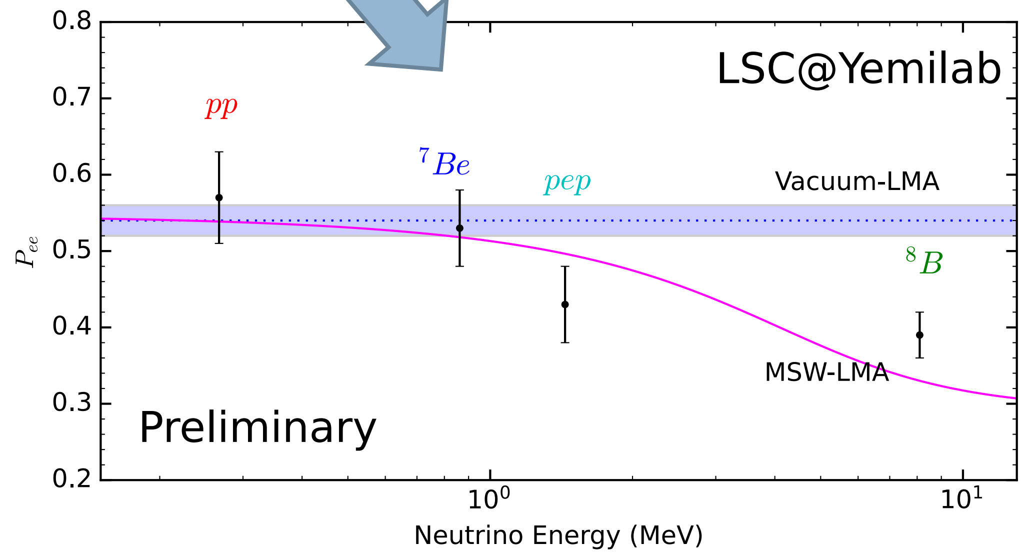
- Borexino data: **2007(2008) – 2016** @LNGS
- 300 ton LS (~2200 8" PMTs, ~6% @1MeV)
- Very low radioactive BKG



Nature **volume 562**, pp. 505–510 (2018)

5 year operation @Yemilab

2.26 kton LS



Summary

- $0\nu\beta\beta$ is one of the best probe for BSM physics.
- AMoRE experiment aims to be sensitive close to 10^{27} year range for ^{100}Mo isotope and will be installed by end of 2023 in full scale.
- AMoRE group established a unique detection system among competent leading double beta decay experiments.
- $0\nu\beta\beta$ can be discovered at anytime with new sensitivities.
- O(eV) Sterile neutrino searches are continuing with contradictory results. NEOS-II data for sterile neutrino and fuel decomposition is coming soon.
- LSC cavern will be ready soon and a white paper on LSC physics including IsoDAR@Yemilab is coming along.

Schedule for AMoRE-II

- The backgrounds will be estimated more clearly when we have first data of AMoRE-II with 90 crystals in 2022.
- Modular expansion is possible, increasing # of detectors.
- After AMoRE-II, ton scale experiment can be considered. ~ CUPID 1ton.
- CUPID & AMoRE discuss to collaborate for future combination.