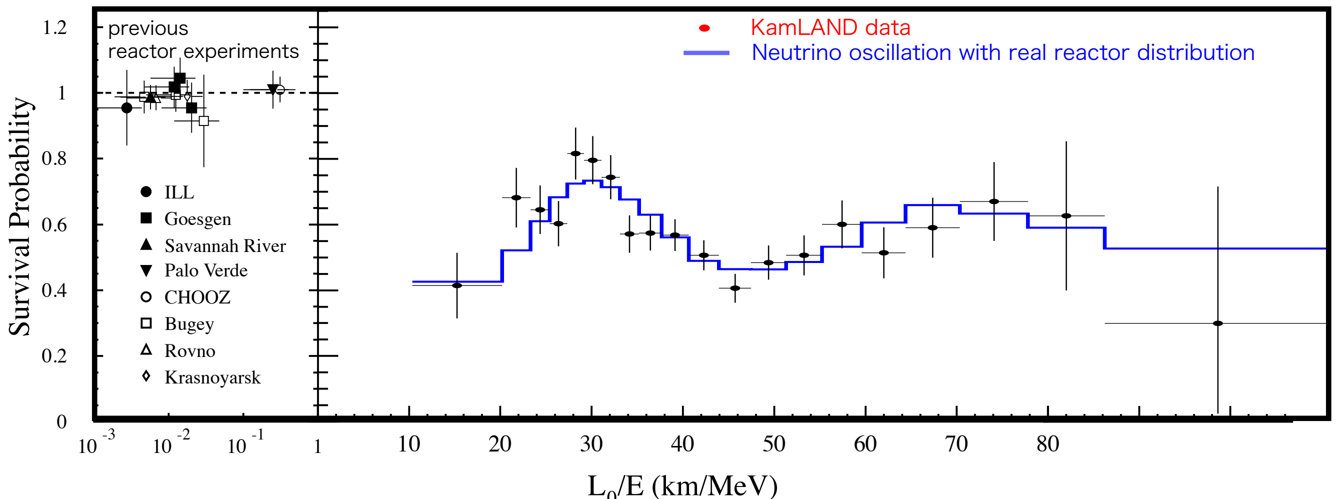
International Workshop on Next Generation Nucleon Decay and Neutrino Detectors
Vancouver

Review of Double Beta Decay Experiments

Azusa Gando
RCNS, Tohoku University
Nov. 2, 2018

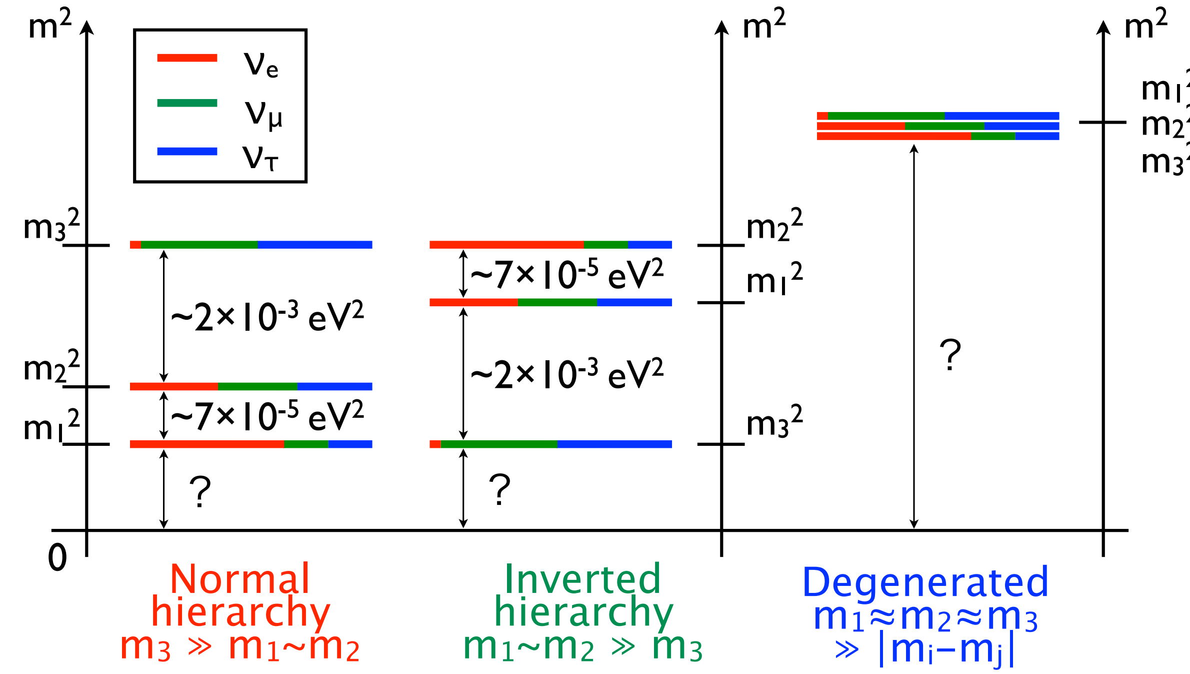
Neutrino

- Originally $m_\nu=0$ in standard model
- **$m_\nu \neq 0$** from oscillation experiment



$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right), \quad \Delta m^2_{ij} = m_i^2 - m_j^2$$

Q. Absolute mass scale?
Mass hierarchy ?



Q. Dirac or Majorana particle?

Dirac neutrino

$$\nu \neq \bar{\nu}$$

Same mass for right and left-handed
All leptons except for neutrino is Dirac type

Majorana neutrino

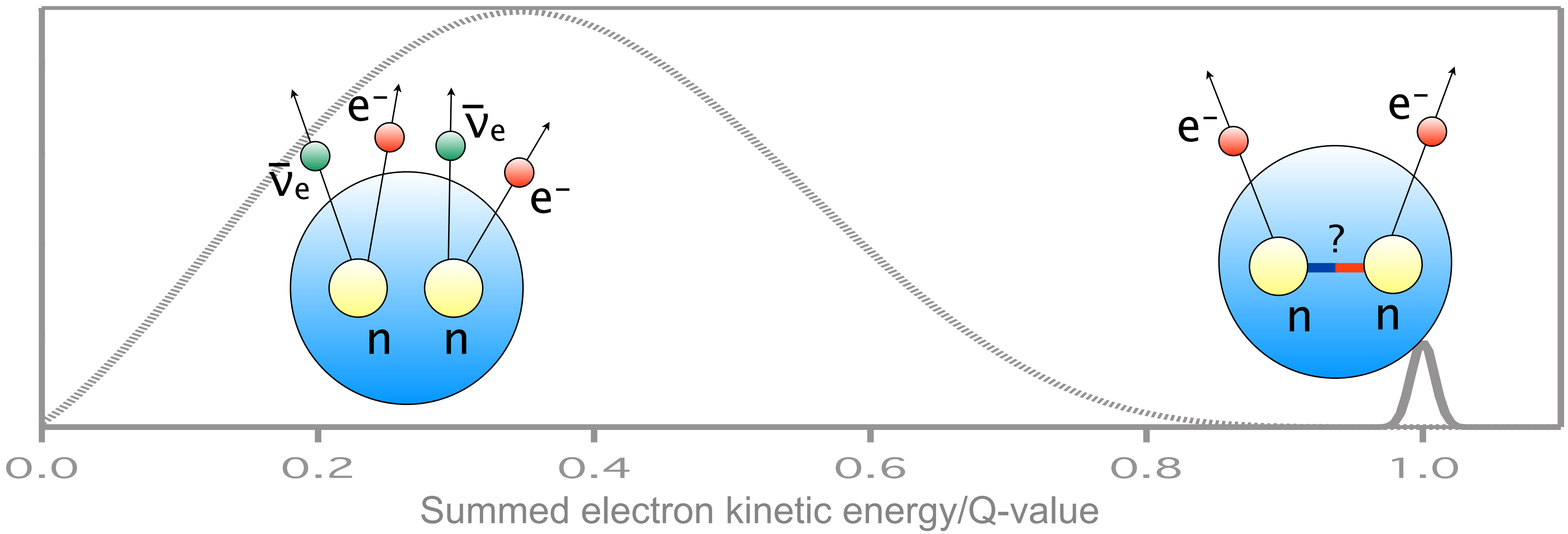
$$\nu = \bar{\nu}$$

Lepton number violation ($\Delta L = 2$)
Can be different mass for right and left-handed neutrino

Experiment Search for neutrinoless double beta ($0\nu\beta\beta$) decay

Double beta decay

- Two decay modes



2νββ decay

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

- Second order weak process
- Continuous spectrum
- Occurs on tens of isotopes
- Observed half-life $T_{1/2} \sim 10^{18\text{-}24}$ yr

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

phase space factor Nuclear matrix element

0νββ decay

(A,Z)→(A,Z+2) + $2e^-$

- Massive Majorana neutrino
- Lepton number violation
- Mono-energetic peak at Q value (widen by the energy resolution)
- It has never been observed
- Limit on half-life $T_{1/2} \sim 10^{24\text{-}26}$ yr

Neutrinoless double beta decay

In the framework of light Majorana neutrino exchange…

Decay rate of 0νββ ⟺ Effective neutrino mass

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

→ Hint for absolute mass scale

→ Neutrino mass hierarchy

Phase space factor

Calculable

phase space ∝ Q^5

Nuclear matrix element

Theoretical calculation.

Biggest uncertainty to estimate effective neutrino mass.

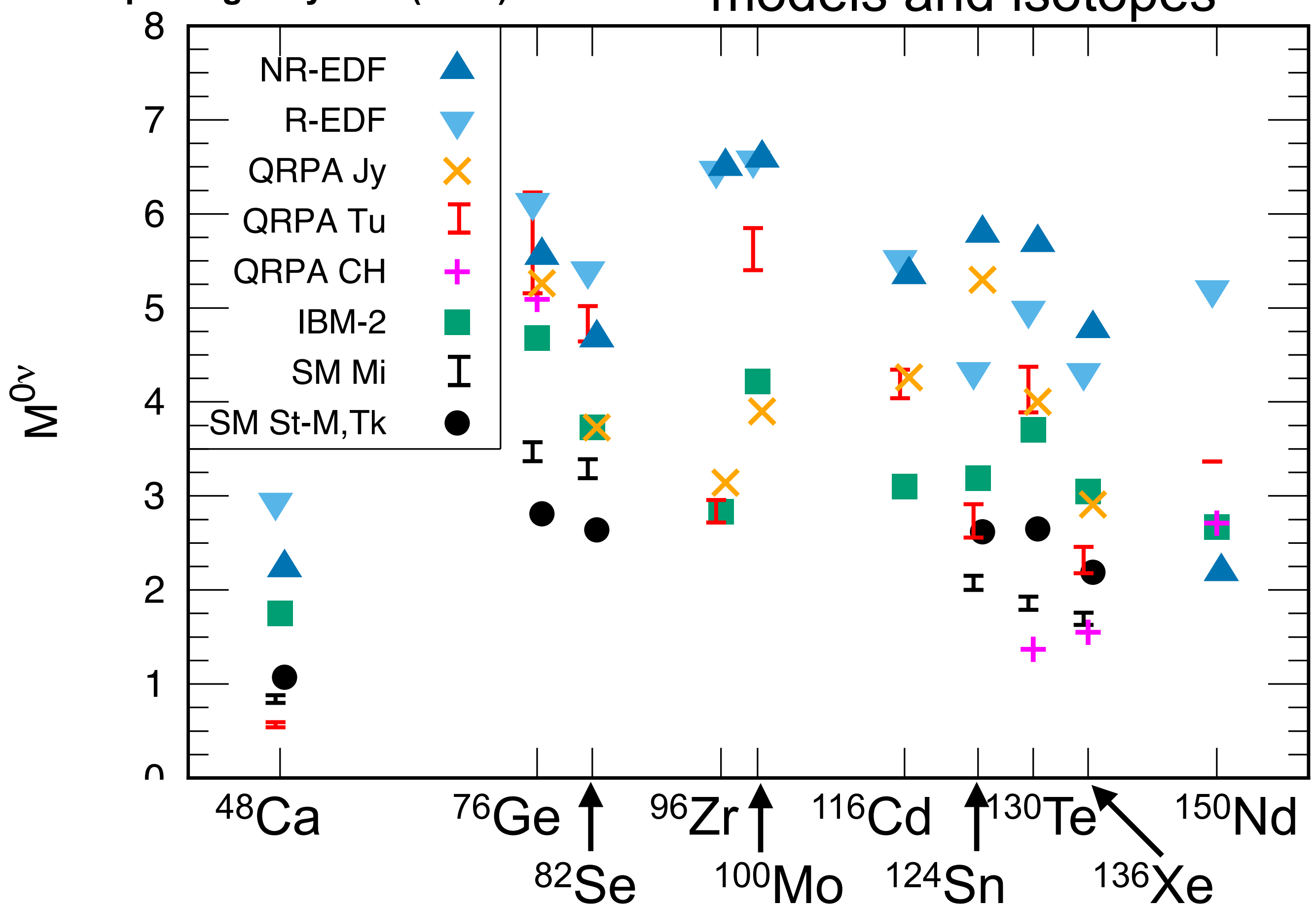
Effective neutrino mass

$$\langle m_\nu\rangle \equiv \left||U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2 e^{i\phi_2} + |U^L_{e3}|^2 m_3 e^{i\phi_3}\right|$$

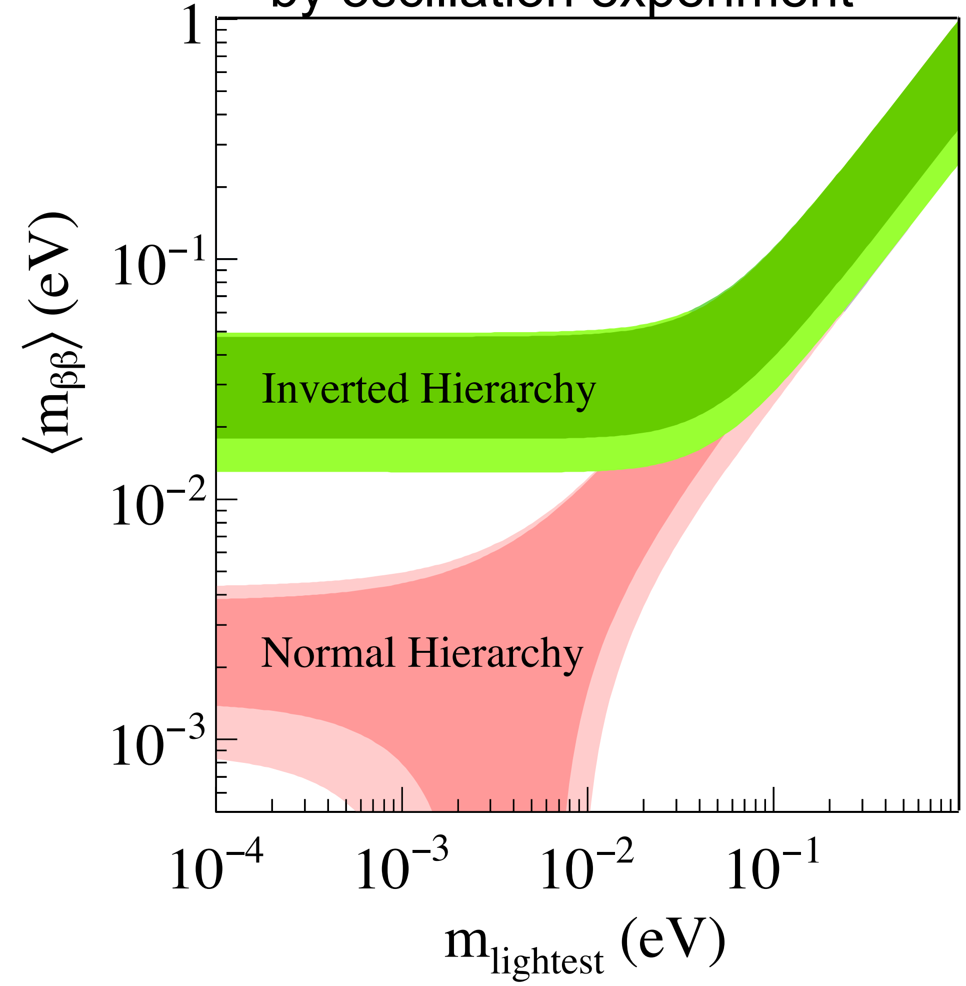
U: PMNS matrix, m_i: neutrino mass, φ: Majorana phase

J. Engel and J. Menendez Rep. Prog. Phys. 80 (2017)

2-5 times difference depend on models and isotopes



Allowed region of $\langle m_\nu \rangle$ by oscillation experiment



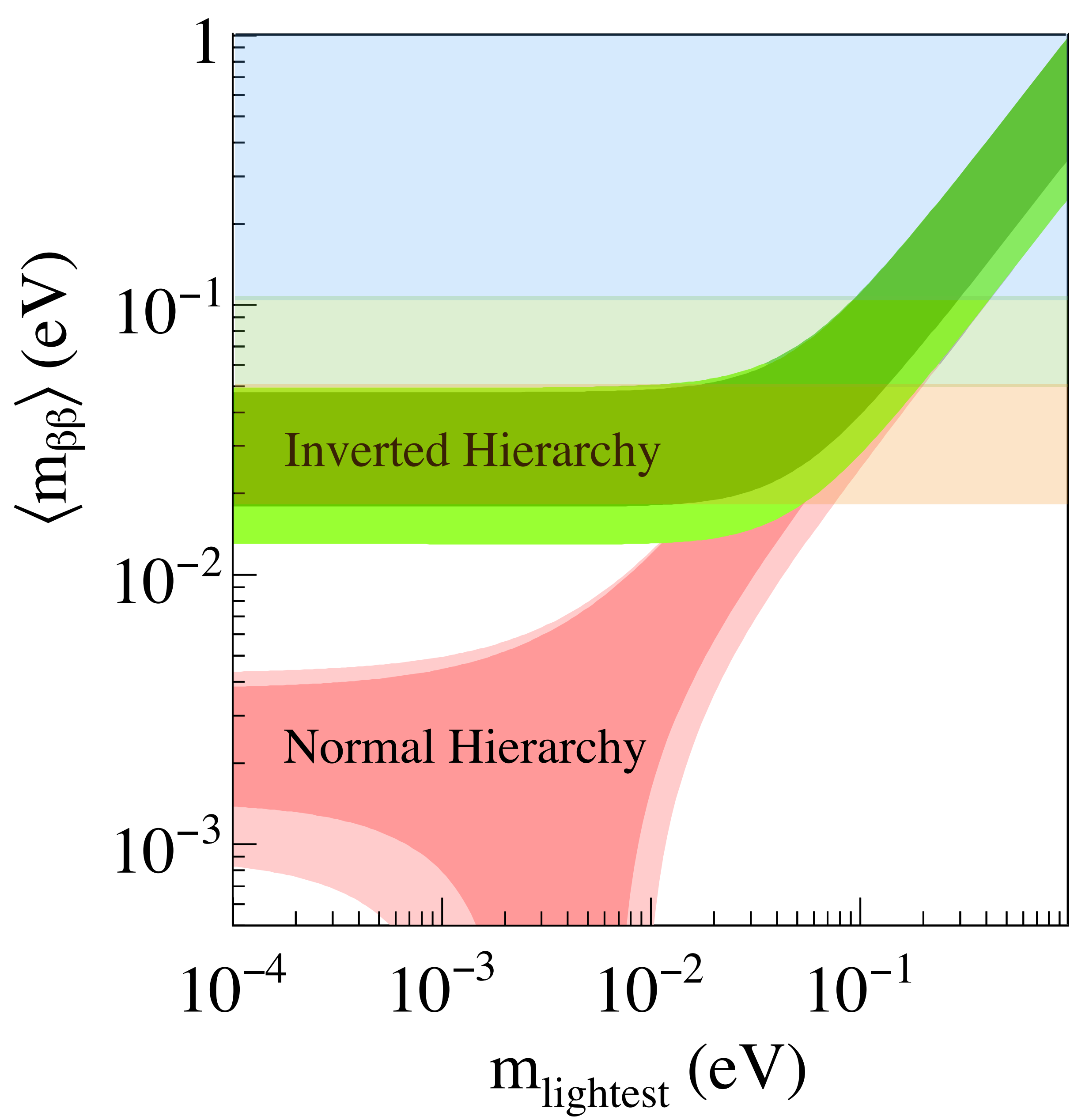
Experimental sensitivity

Decay rate of 0νββ ⟺ Effective neutrino mass

→ Hint for absolute mass scale

→ Neutrino mass hierarchy

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



	Half life	Mass of isotopes
Past & present ~100meV →	10^{25}~10^{26}y	10~10^{2}kg
Near future ~50meV →	10^{26}~10^{27}y	10^{2}~10^{3}kg
Future ~20meV →	10^{27}~10^{28}y	10^{3} kg~

Experiment needs
- capacity of large isotope mass
- low background
- high efficiency
- good energy resolution

Isotopes for double beta decay (Q-value > 2MeV)

- No perfect isotope for double beta decay

Isotope	Q-value (keV)	N.A. (%)	$T_{1/2}^{2\nu}$ (year) measurement from PDG2018 (latest value)	Pros & Cons
^{48}Ca	$\boxed{4273.6 \pm 4}$	0.19	$(6.4\pm^{0.7}_{0.6}\pm^{1.2}_{0.9}) \times 10^{19}$	Q-value **biggest**, N.A. **small**, enrichment **difficult**
^{76}Ge	2039.006 ± 0.050	7.6	$(1.926\pm0.094) \times 10^{21}$	enrichment **~90%**
^{82}Se	2995.50 ± 1.87	8.7	$(9.6\pm0.3\pm0.1) \times 10^{19}$	enrichment **>90%**
^{96}Zr	3347.7 ± 2.2	2.8	$(2.35\pm0.14\pm0.16) \times 10^{19}$	
^{100}Mo	3034.40 ± 0.17	9.4	$(6.90\pm0.15\pm0.37) \times 10^{18}$	enrichment **>90%**
^{110}Pd	2017.85 ± 0.64	7.5	-	
^{116}Cd	2813.50 ± 0.13	7.5	$(2.74\pm0.04\pm0.18) \times 10^{19}$	enrichment **80~90%**
^{124}Sn	2287.80 ± 1.52	5.8	-	
^{130}Te	2527.01 ± 0.32	$\boxed{34.2}$	$(8.2\pm0.2\pm0.6) \times 10^{20}$	N.A. **high**
^{136}Xe	2457.83 ± 0.37	8.9	$(2.165\pm0.016\pm0.059) \times 10^{21}$	enrichment **~90%**
^{150}Nd	3317.38 ± 0.20	5.7	$(9.34\pm0.22\pm^{0.62}_{0.60}) \times 10^{18}$	enrichment **difficult**

Experiments

source = detector

		Present		Future → time
Scalability	LS based	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
	Crystal	CANDLES III (UG)		
	LXe TPC	EXO-200		nEXO
	gas Xe TPC	NEXT-10 PandaX prototype	NEXT-100 PandaX-III 200kg	NEXT-2.0 PandaX-III 1t
High ΔE	HPGe	GERDA MJD	LEGEND 200	LEGEND 1000
	Bolometer	CUORE CUPID-0, CUPID-Mo		CUPID
		AMORE pilot	AMORE I	AMORE II

source ≠ detector

Tracker	SupreNEMO demonstrator		SupreNEMO

adapted from Andrea Giuliani NEUTRINO2018

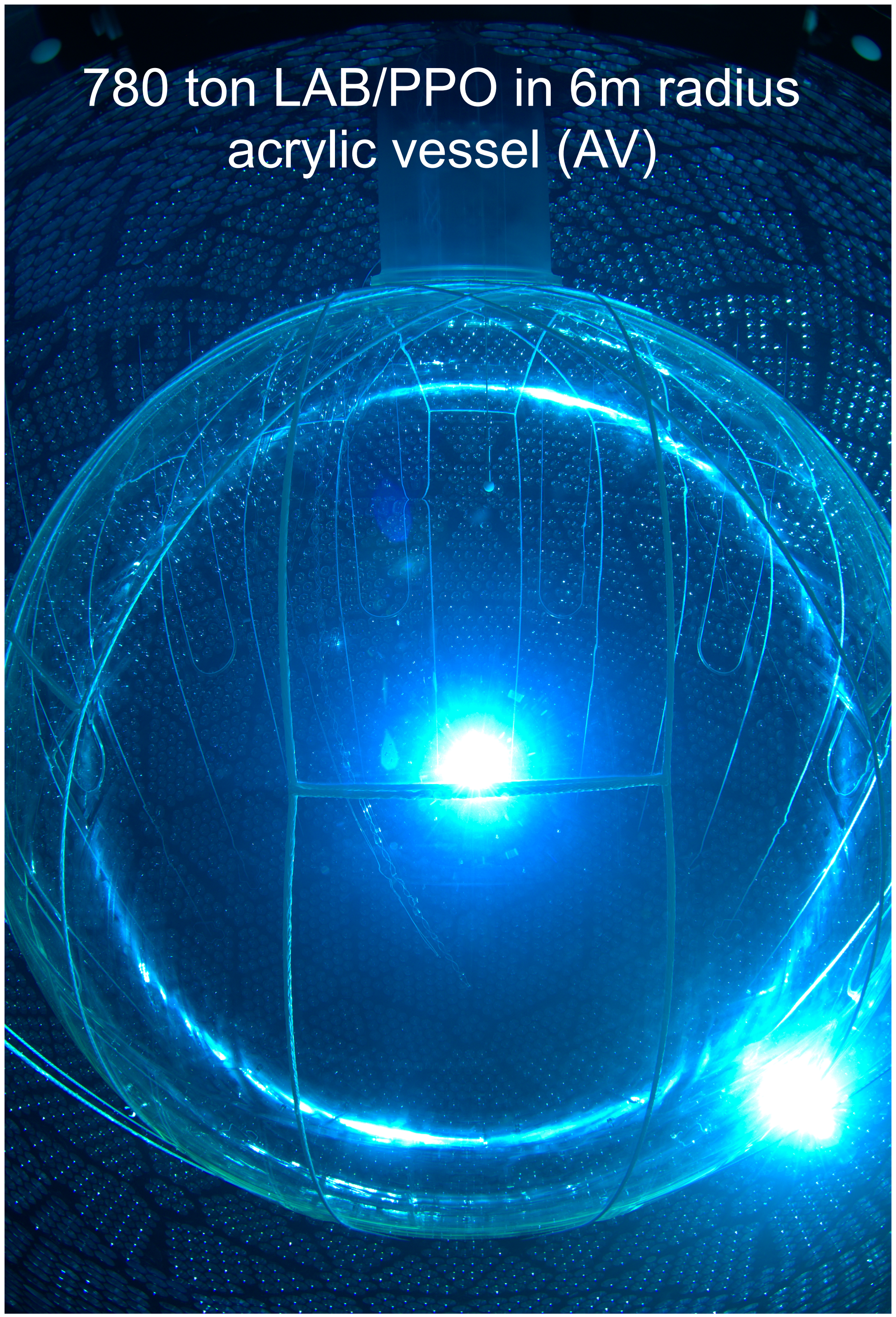
Experiments

source = detector		Present		Future → time
Scalability	LS based	**KamLAND-Zen 800** **SNO+ phase I**		**KamLAND2-Zen** SNO+ phase II
Scalability	Crystal	CANDLES III (UG)		
Scalability	LXe TPC	**EXO-200**		**nEXO**
Scalability	gas Xe TPC	NEXT-10 PandaX prototype	NEXT-100 PandaX-III 200kg	NEXT-2.0 PandaX-III 1t
High ΔE	HPGe	**GERDA** **MJD**	**LEGEND 200**	**LEGEND 1000**
High ΔE	Bolometer	**CUORE** **CUPID-0, CUPID-Mo**		**CUPID**
High ΔE	Bolometer	AMORE pilot	AMORE I	AMORE II
source ≠ detector	Tracker		SupreNEMO demonstrator	SupreNEMO

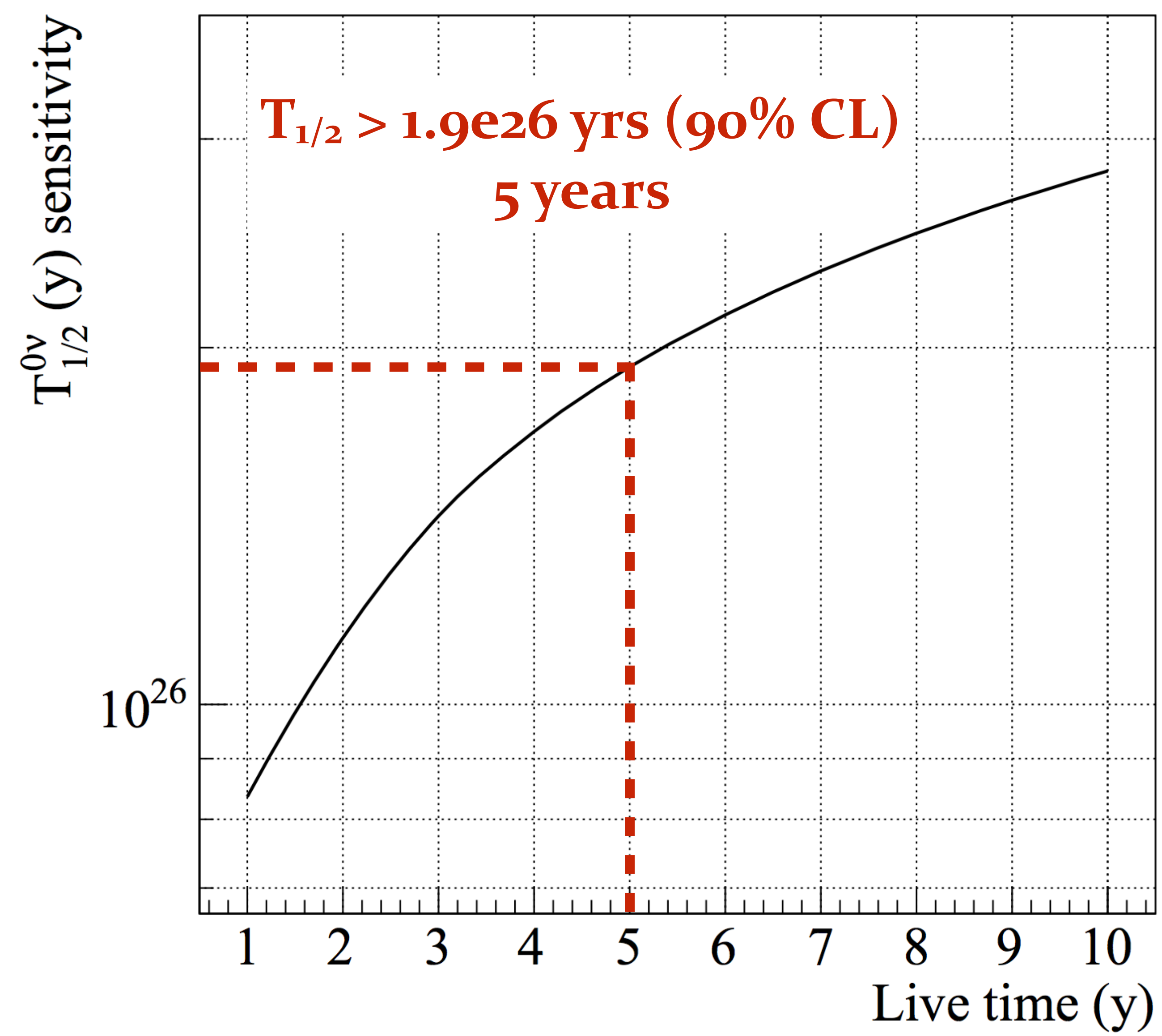
adapted from Andrea Giuliani NEUTRINO2018

SNO+ Phase I

- ^{130}**Te** (N.A. 34.2%, Q-value 2527keV). Located at SNOLab (Canada), ~5890 m.w.e.
- ^{130}**Te loaded liquid scintillator** (LAB/PPO with 0.5% $_{nat}$Te).

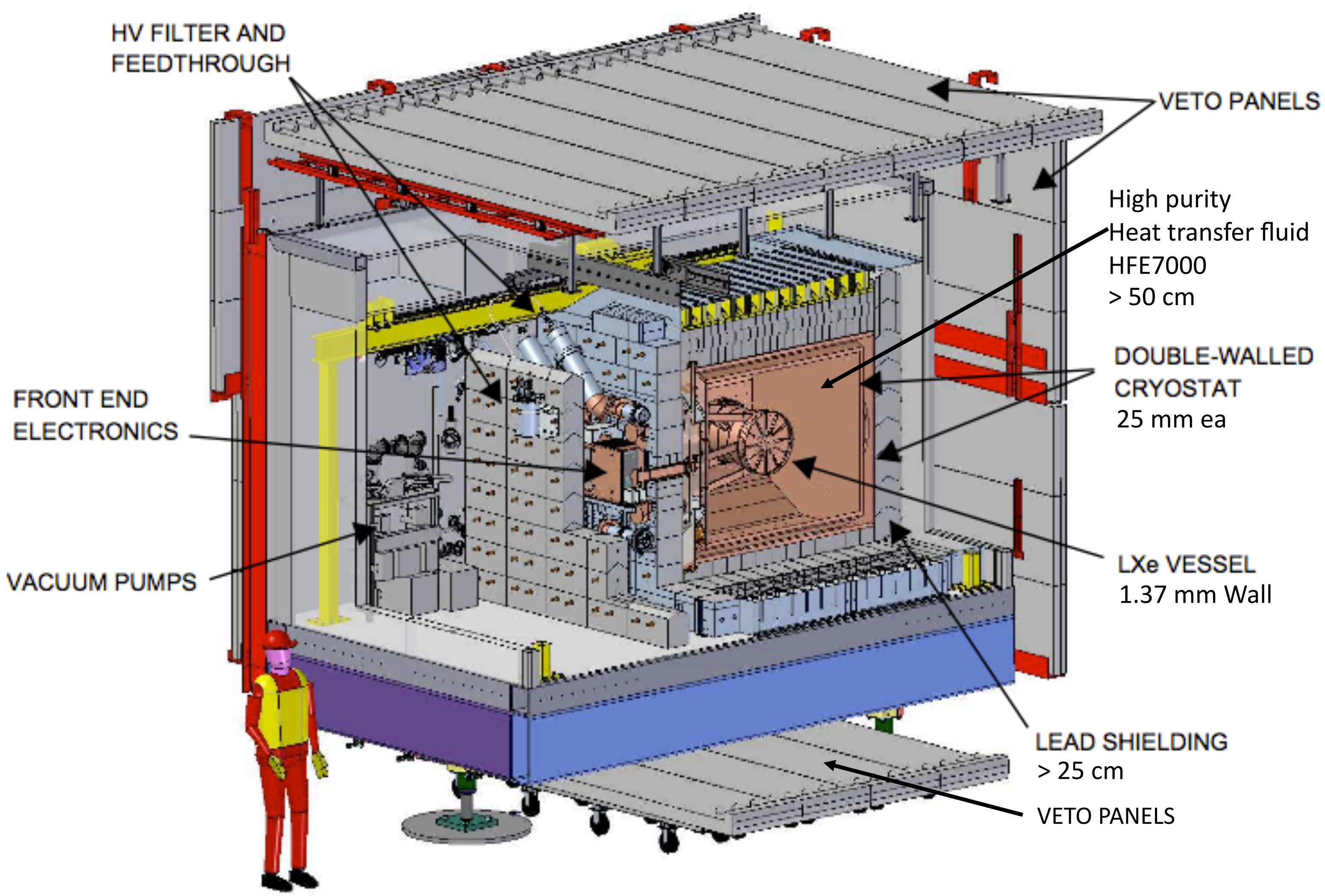


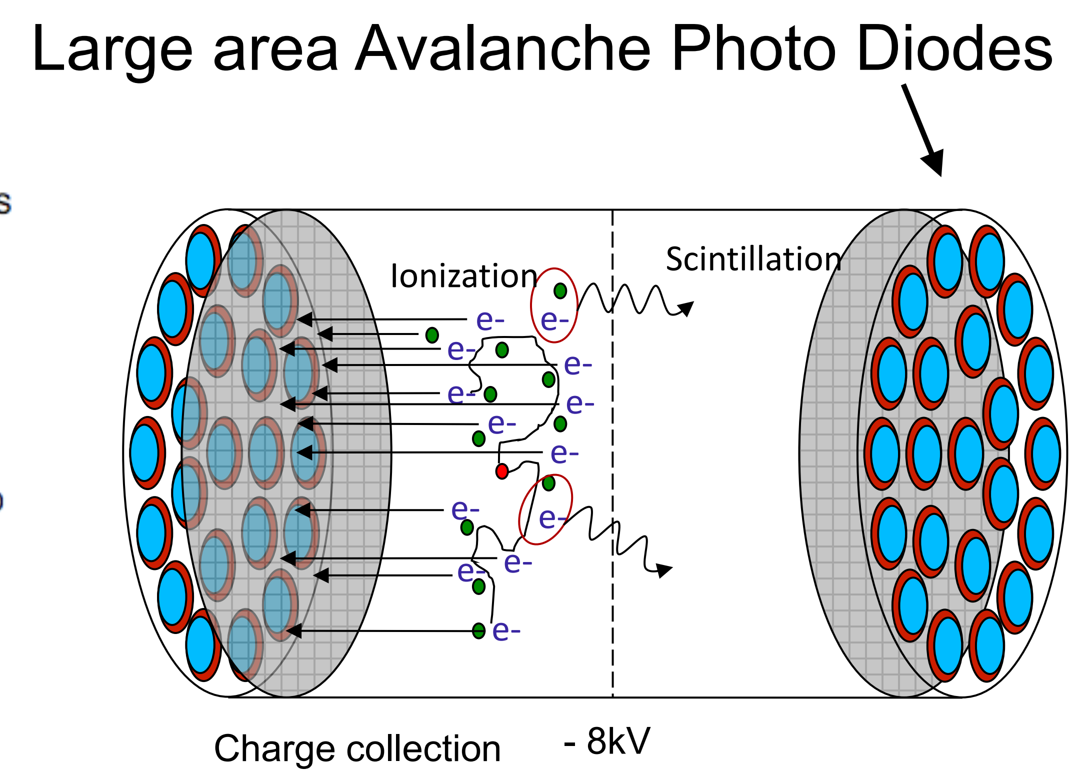
- Water phase analysis → see M. Askins's talk
- LS filing has started
- Te loading in 2019



EXO-200

- ^{136}Xe (N.A. 9.6%, Q-value 2458 keV). Located at WIPP (U.S.), ~1600 m.w.e.
- ~175 kg of **liquid Xe** (80.6% enriched) in a **time projection chamber**
- Energy resolution ~1.2% FWHM after electronic upgrade





Example of TPC schematics (EXO-200)

40cm

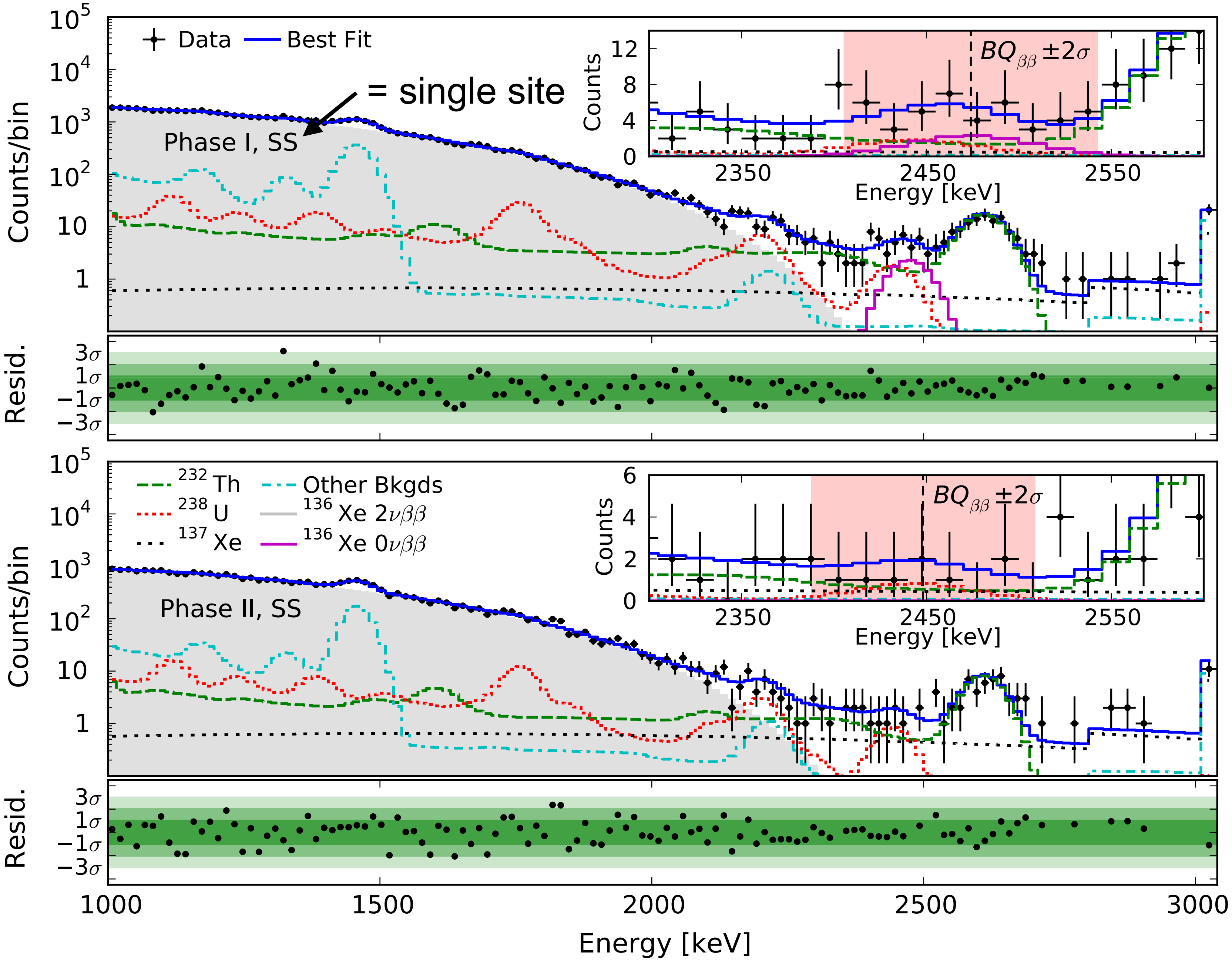
- Scintillation collected by APDs
- Amount and position of charge collected by 2 wire grids

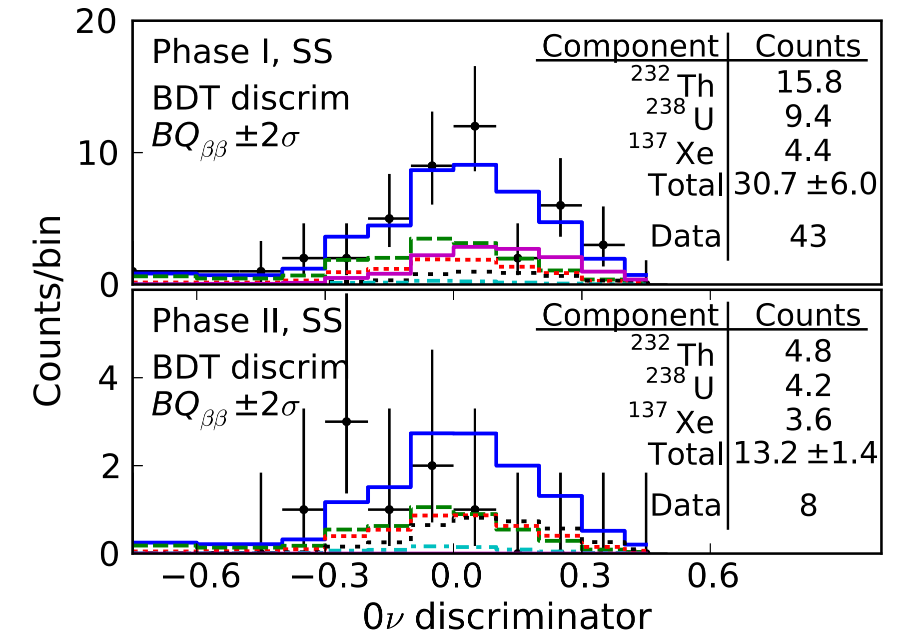
Topological classification of event (single site/multi site) → signal/background discrimination

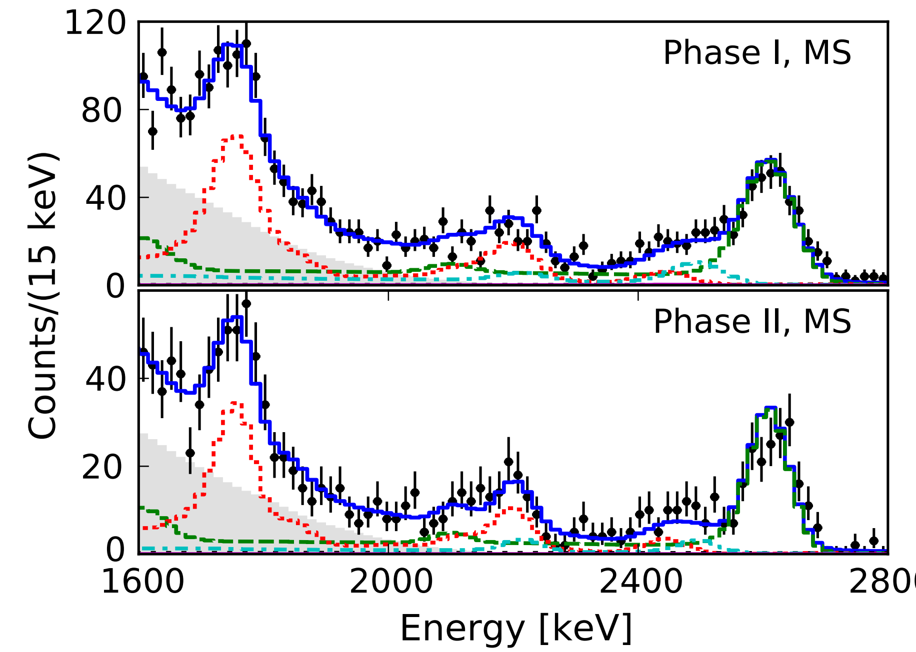
EXO-200 | Recent result

Phys. Rev. Lett. **120**, 072701

- Phase I Sep. 2011 -2014 (122 kg yr), Phase II 2016-2018 (55.6 kg yr).







EXO-200 Limit (90% C.L.)

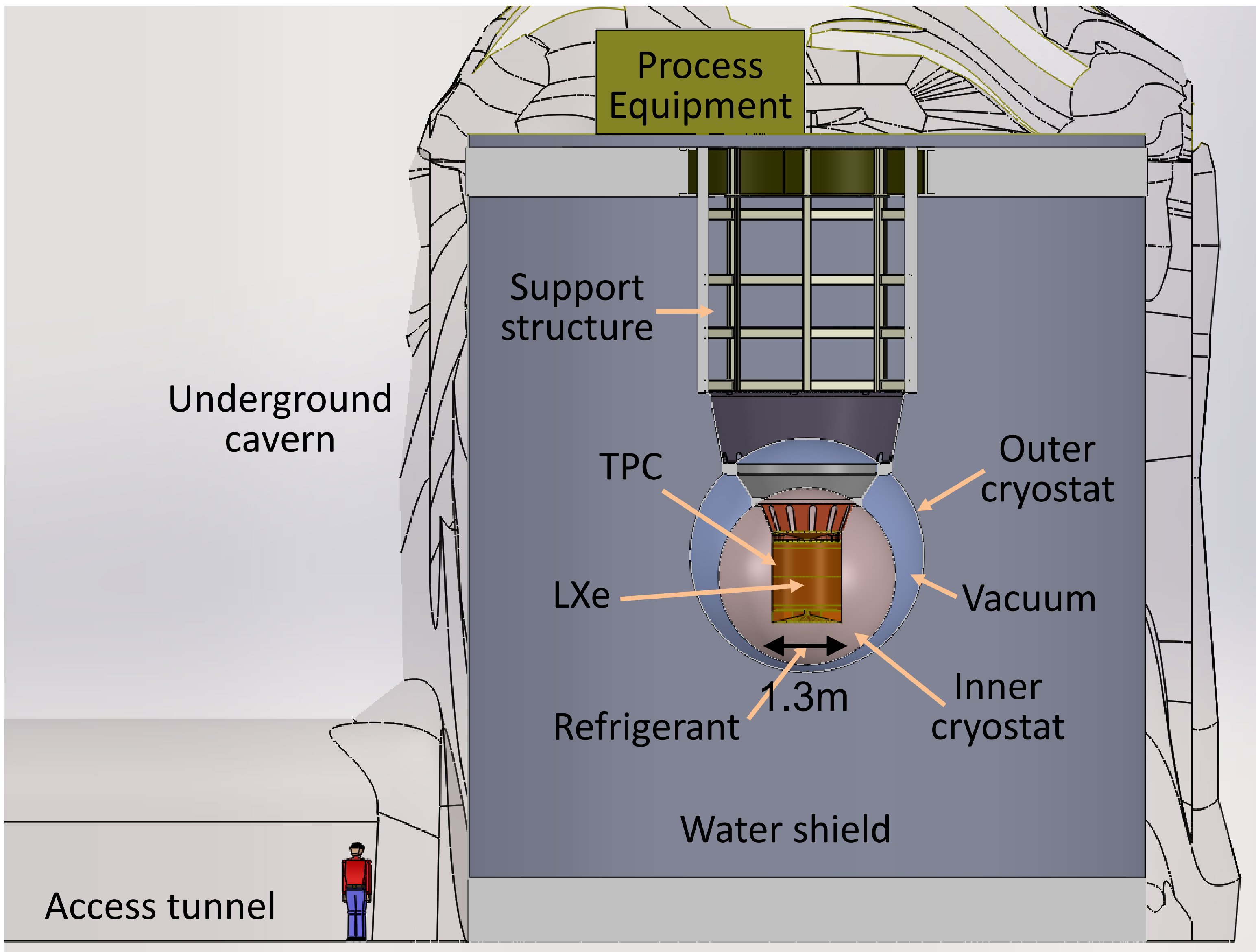
$T^{1/2} > 1.8 \times 10^{25}$ yr (Sensitivity 3.7×10^{25} yr)

$m_{\beta\beta} < 147 – 398$ meV

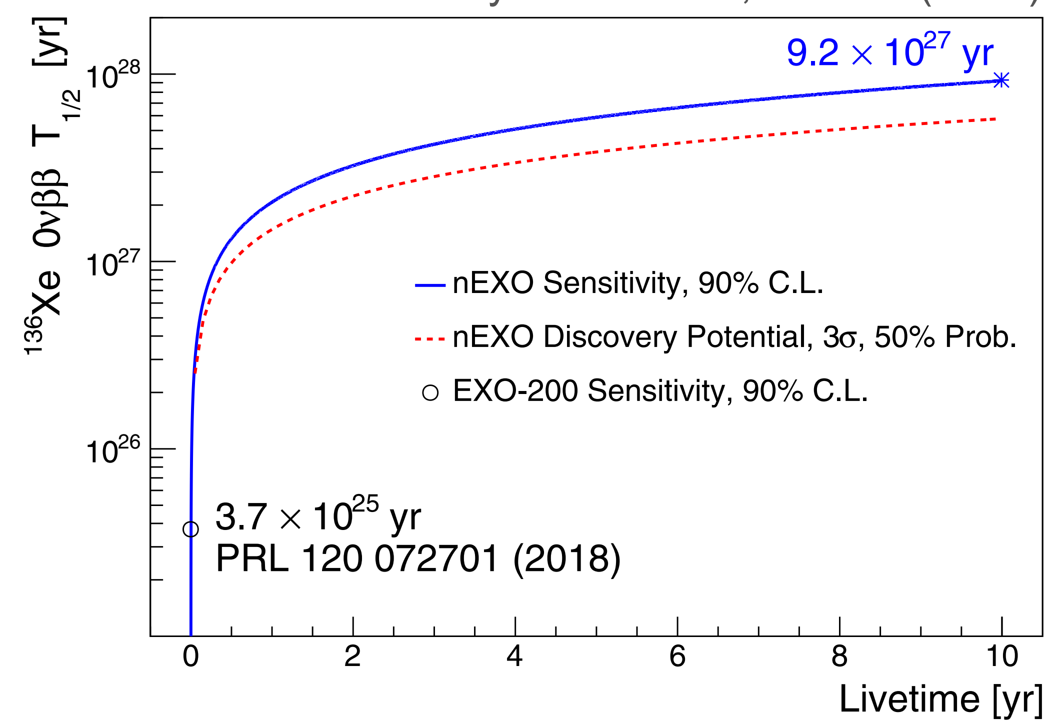
- Operation will end in Dec. 2018

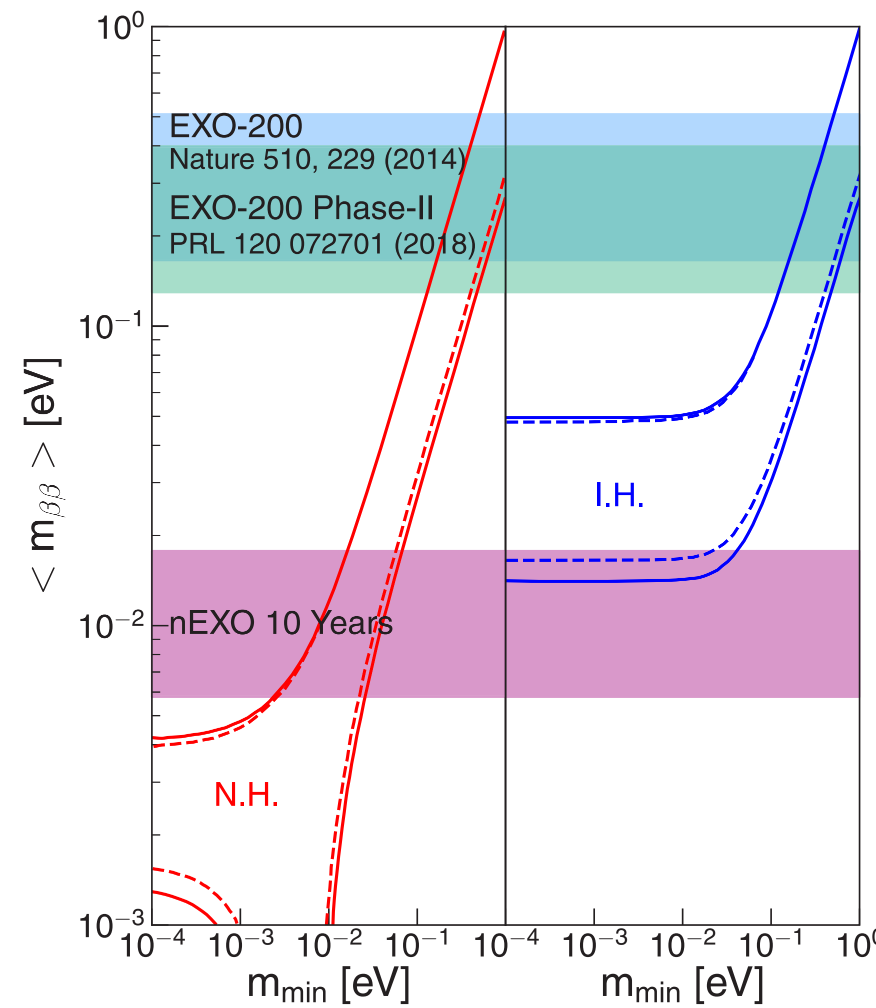
nEXO

- ~5 ton of Xenon
- Sensitivity ~ 9.2×10^{27} yr with 10 yrs livetime



Phys. Rev. C **97**, 065503 (2018)



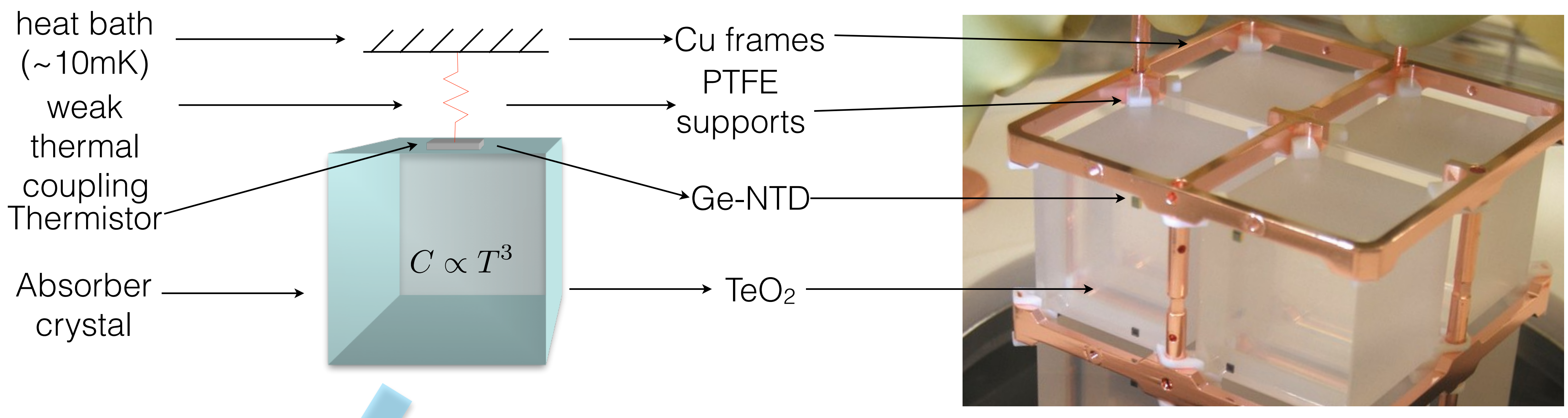


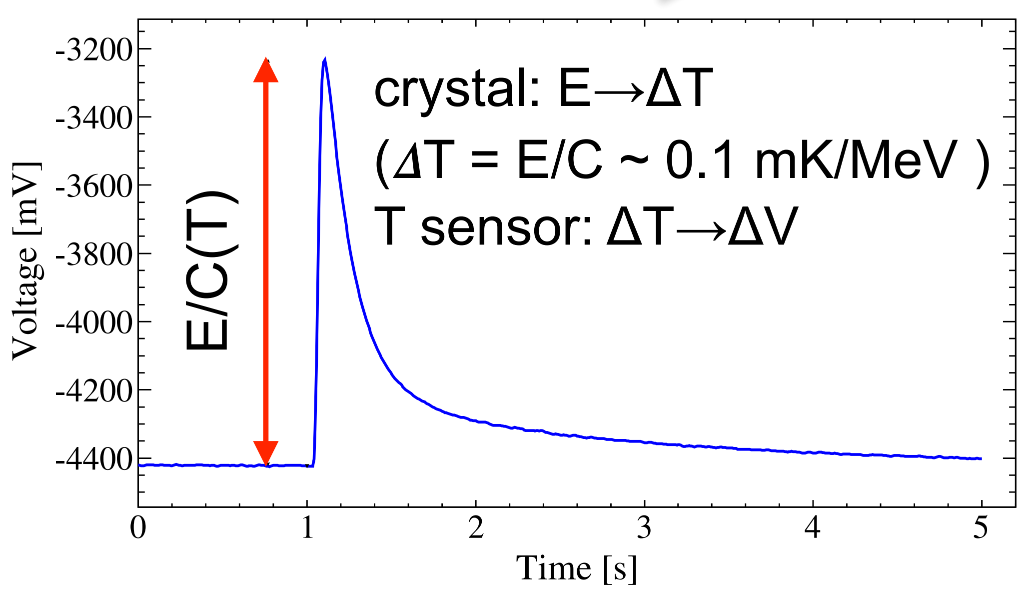
- R&D on Ba tagging ongoing

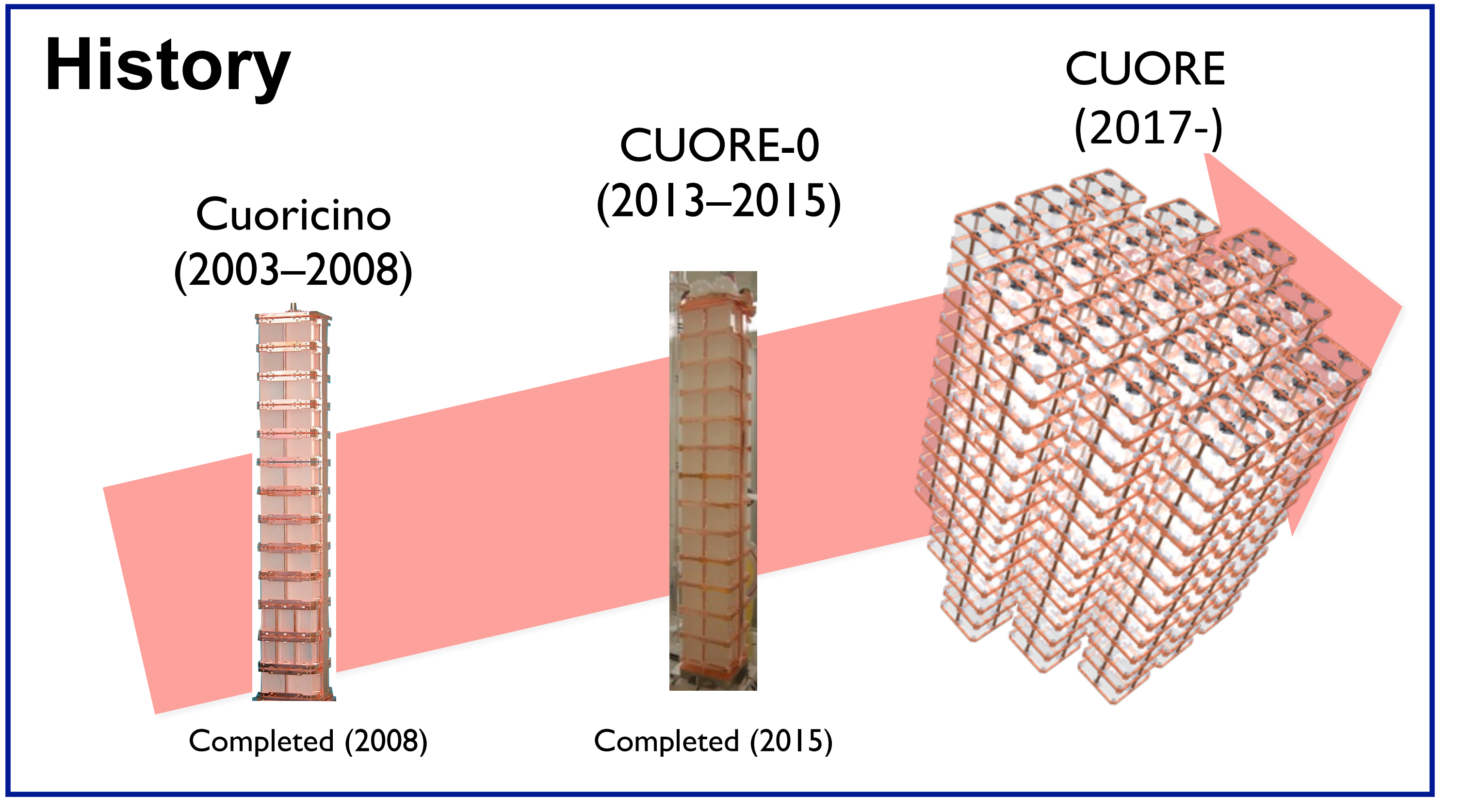
$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$

CUORE

- ^{130}Te (N.A. 34.2%, Q-value 2527keV). Located at LNGS (Italy), ~3600 m.w.e.
- **TeO_2 bolometers** (988 crystals in 19 towers), a total mass of ^{130}Te = 206 kg
- Operated at ~15mK (7mK as lowest). Energy resolution ~0.2% FWHM

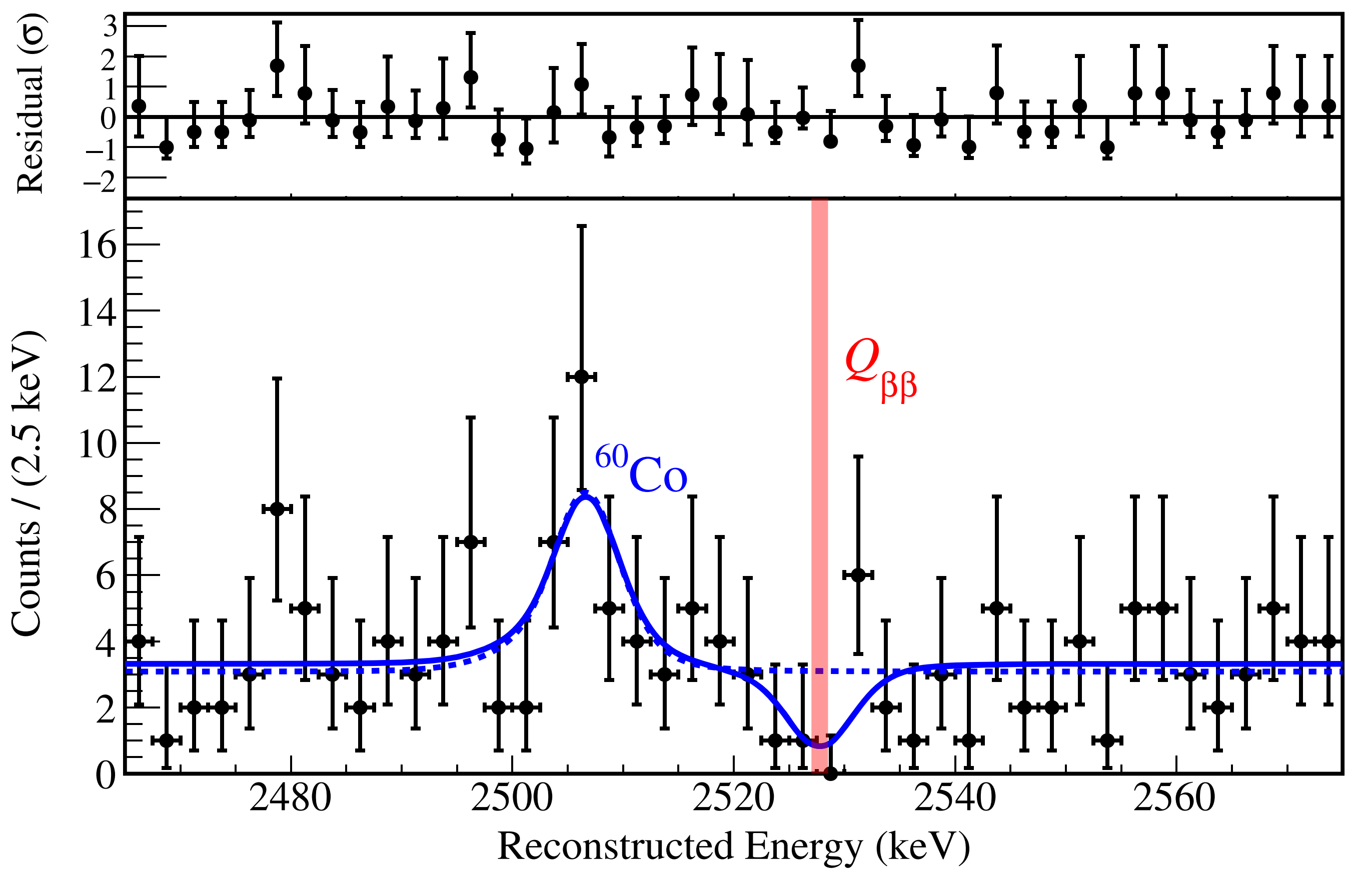




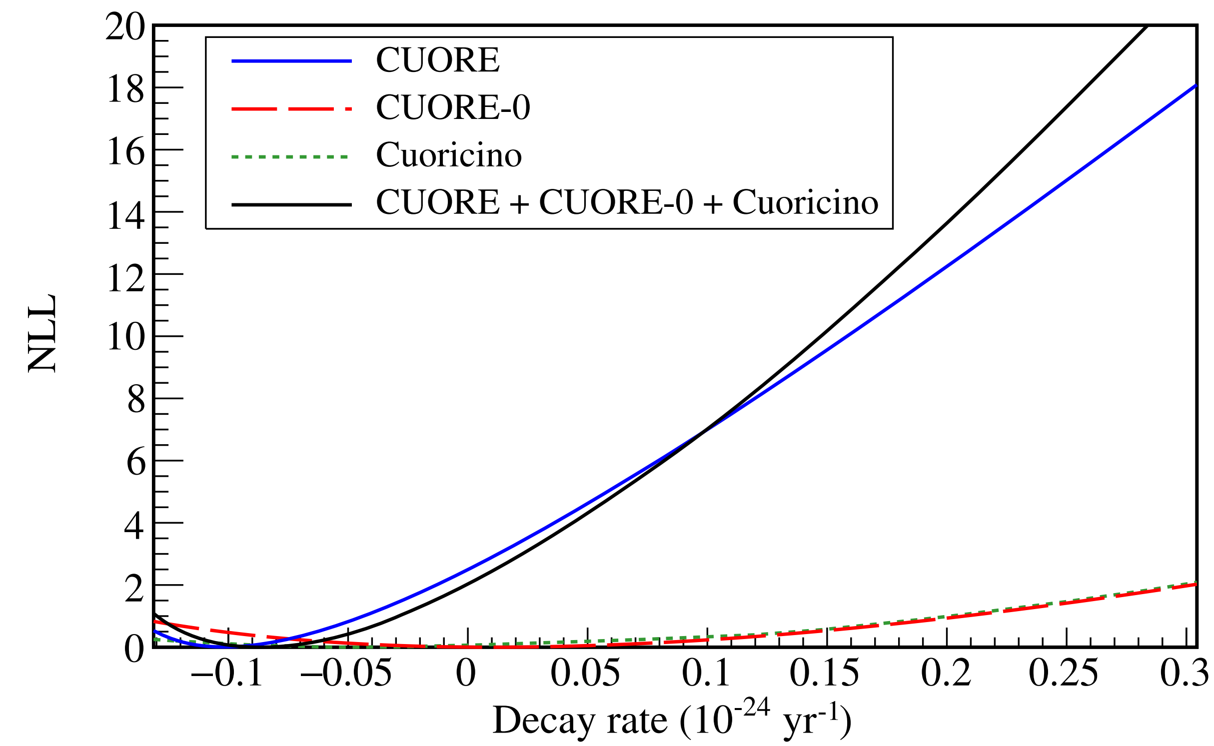


CUORE | Recent result

- Data collected in summer 2017 (7 weeks)
- Exposure: 86.3 kg·yr (24 kg·yr of ^{130}Te)



Phys. Rev. Lett. **120**, 132501



CUORE First Limit (90% C.L.)

$T^{1/2} > 1.3 \times 10^{25}$ yr (syst. included)

sensitivity 7.0×10^{24} yr

Combining the limit with Cuoricino and CUORE-0

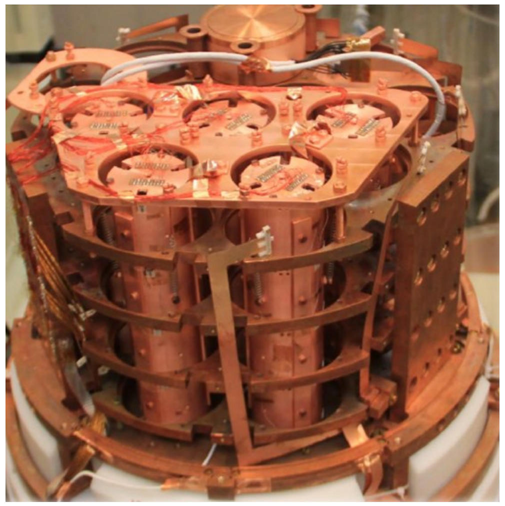
$T^{1/2} > 1.5 \times 10^{25}$ yr (90% C.L.)

$m_{\beta\beta} < 110 – 520$ meV

- Restarted physics data taking in 2018 May
- Projected sensitivity: 9×10^{25} yr in 5yrs live time, $m_{\beta\beta} < 50 – 200$ meV

CUPID (Cuore Upgrade with Particle ID)

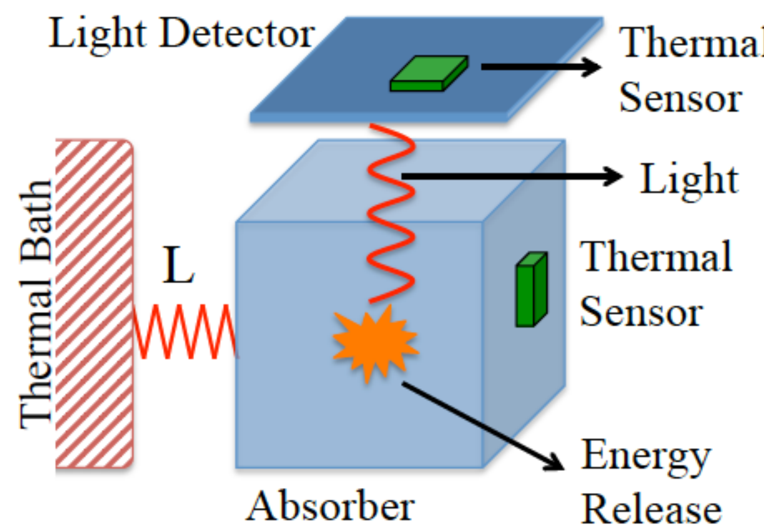
- Target: fully cover the inverted hierarchy
- Baseline target isotope ^{100}Mo (Q value 3034 keV) in $Li_2{}^{100}MoO_4$ (scintillating bolometer)
- Viable alternative ^{130}Te in $^{130}TeO_2$ (bolometer with Cherenkov readout)



CUPID-Mo at Modane

$Li_2{}^{100}MoO_4$

Phase I under commissioning

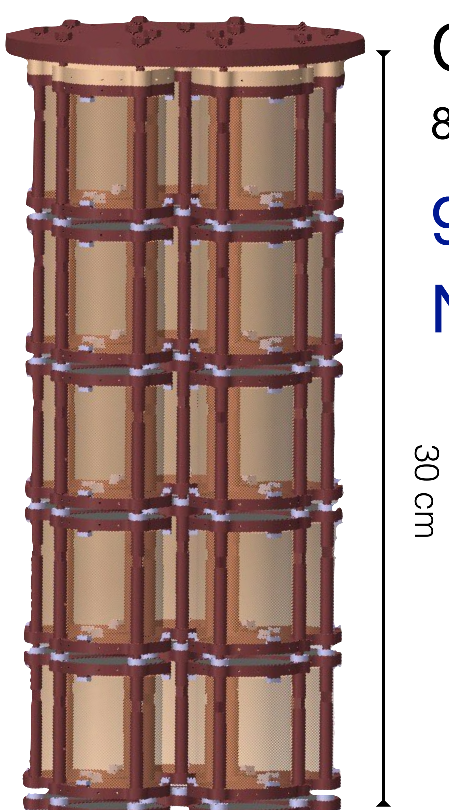


Target sensitivity @ 90% C.L.

^{100}Mo 2×10^{27} yr, 9-15meV

^{130}Te 5×10^{27} yr, 6-28meV

- Other demonstrators for R&D



LUCIFER

CUPID-0 (the first enriched bolometer)

^{82}Se (N.A. 8.7%, Q-value 2998keV)

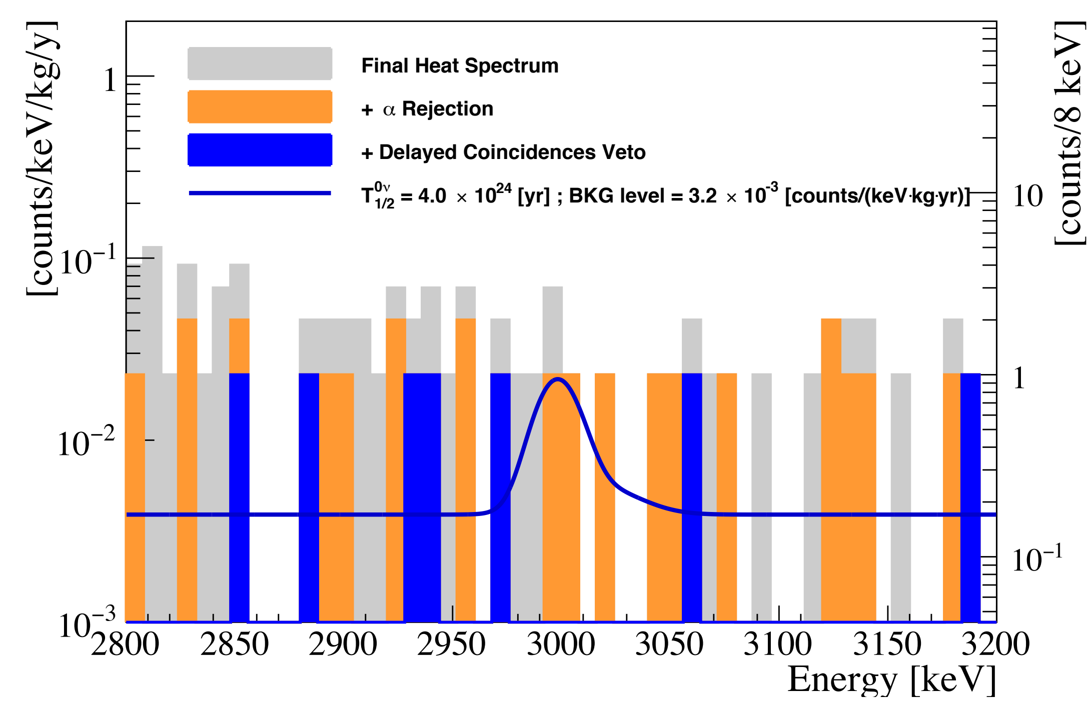
95% enriched $Zn^{82}Se$ bolometer

Now operating at LNGS

Exposure 5.46kg yr of ZnSe

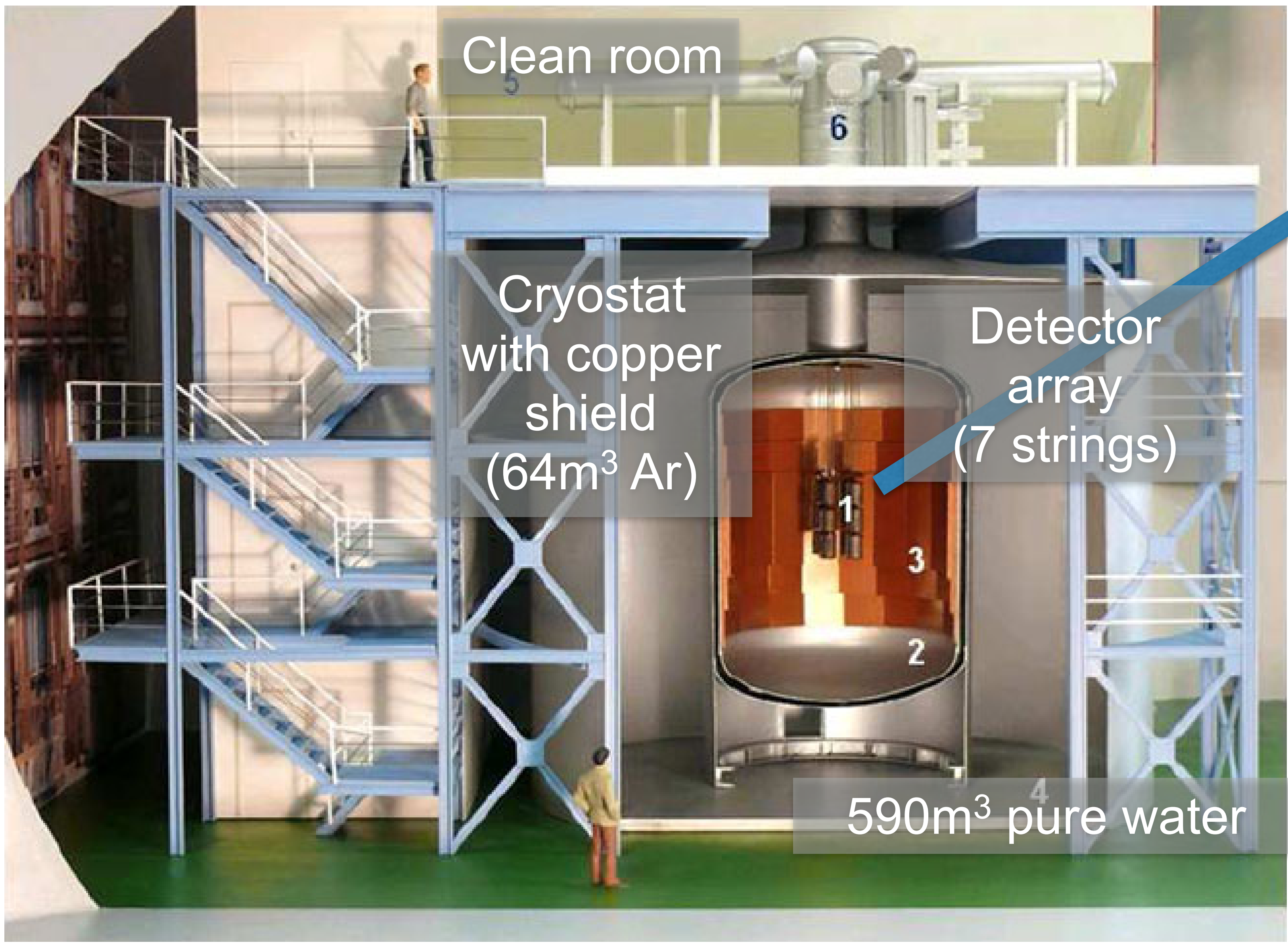
$T^{1/2} > 4.0 \times 10^{24}$ yr (90% C.L.)

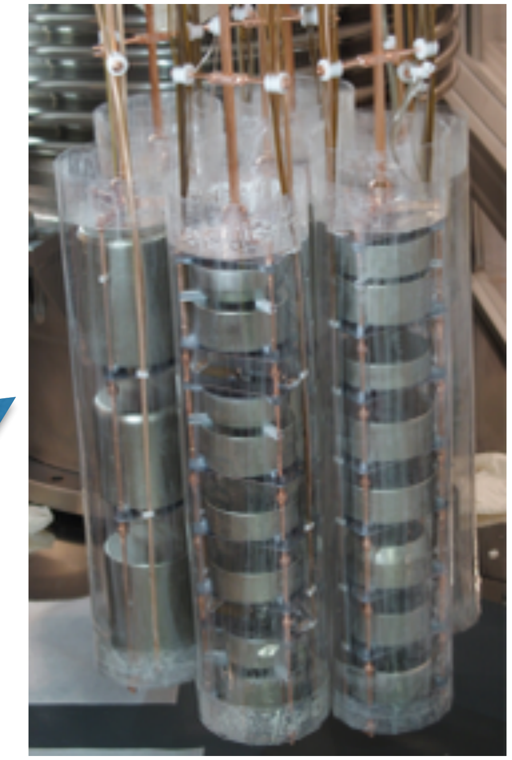
$m_{\beta\beta} < 290 – 596$ meV



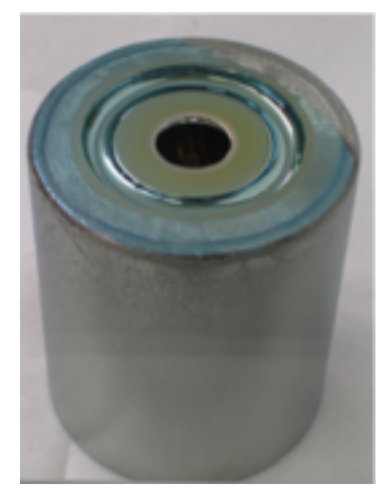
GERDA

- **^{76}Ge** (N.A. 7.6%, Q-value 2039 keV). Located at LNGS (Italy), ~3600 m.w.e.
- **HPGe detector array** in copper shielding filled with LAr
- Excellent energy resolution O(0.1)%@Qvalue





Coaxial



Enriched(~87%) × 7
15.6 kg
Natural × 3
7.6 kg

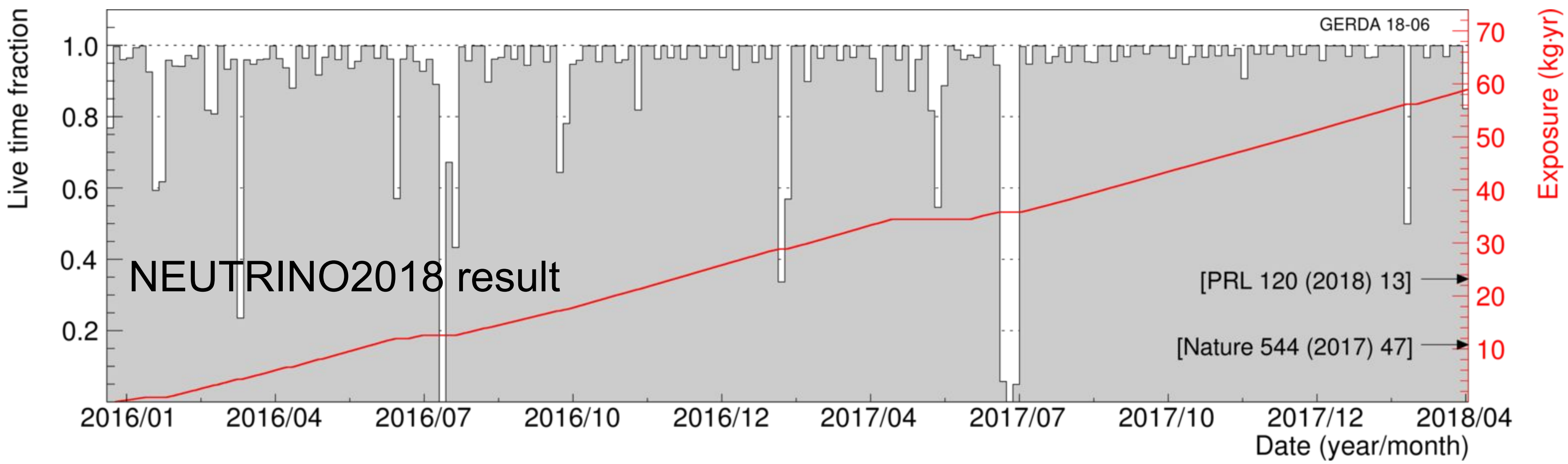
+

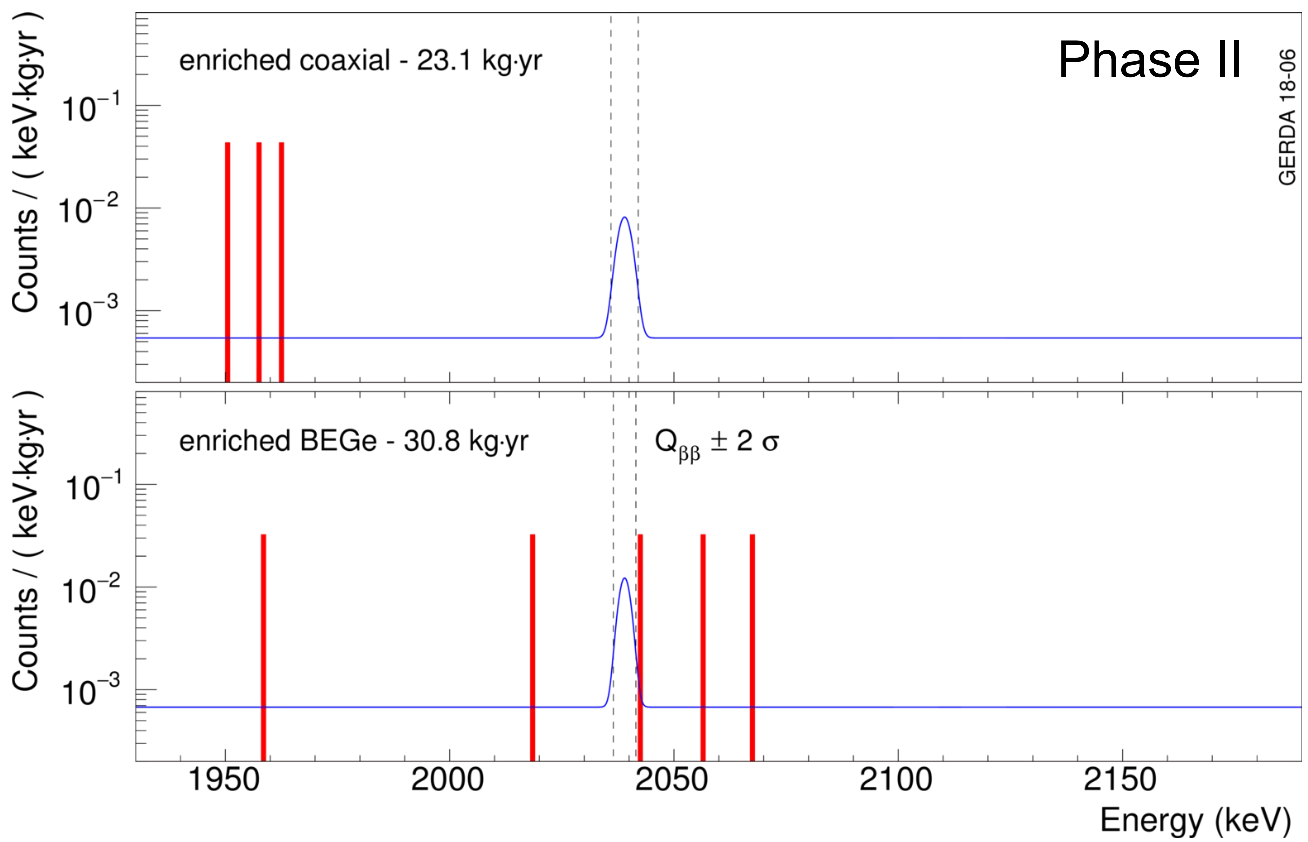
BEGe

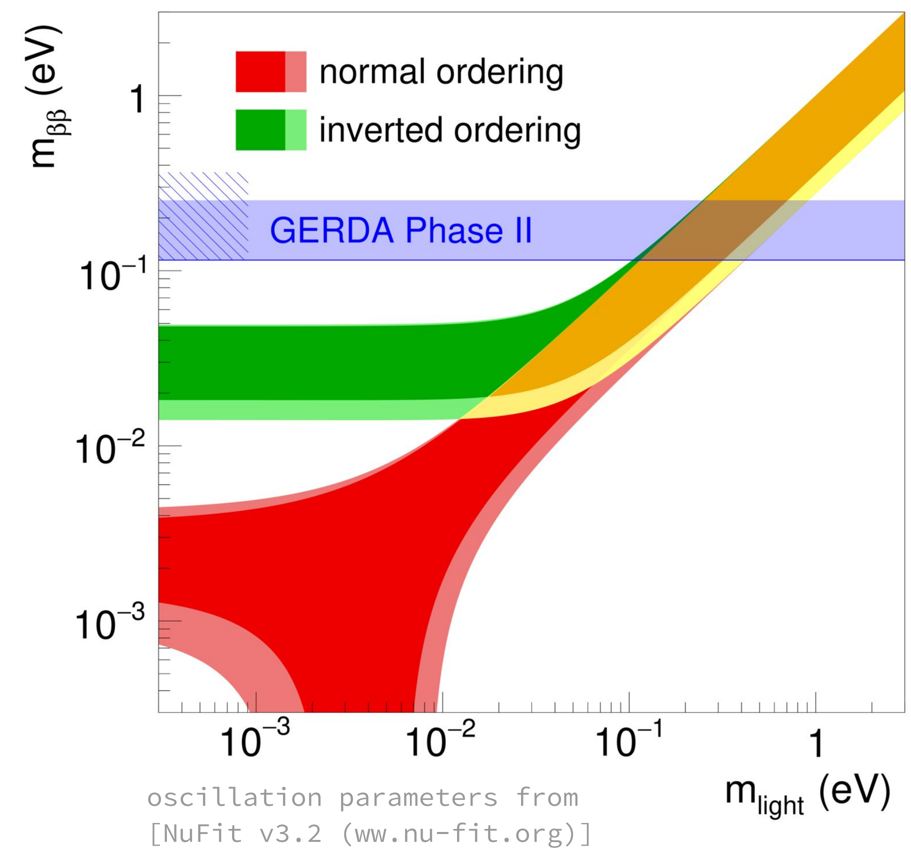
Enriched × 30
20.0 kg

GERDA | Recent Result

- Phase II Dec. 2015 - Apr. 2018, 58.9 kg yr exposure (82.4 kg yr in total)





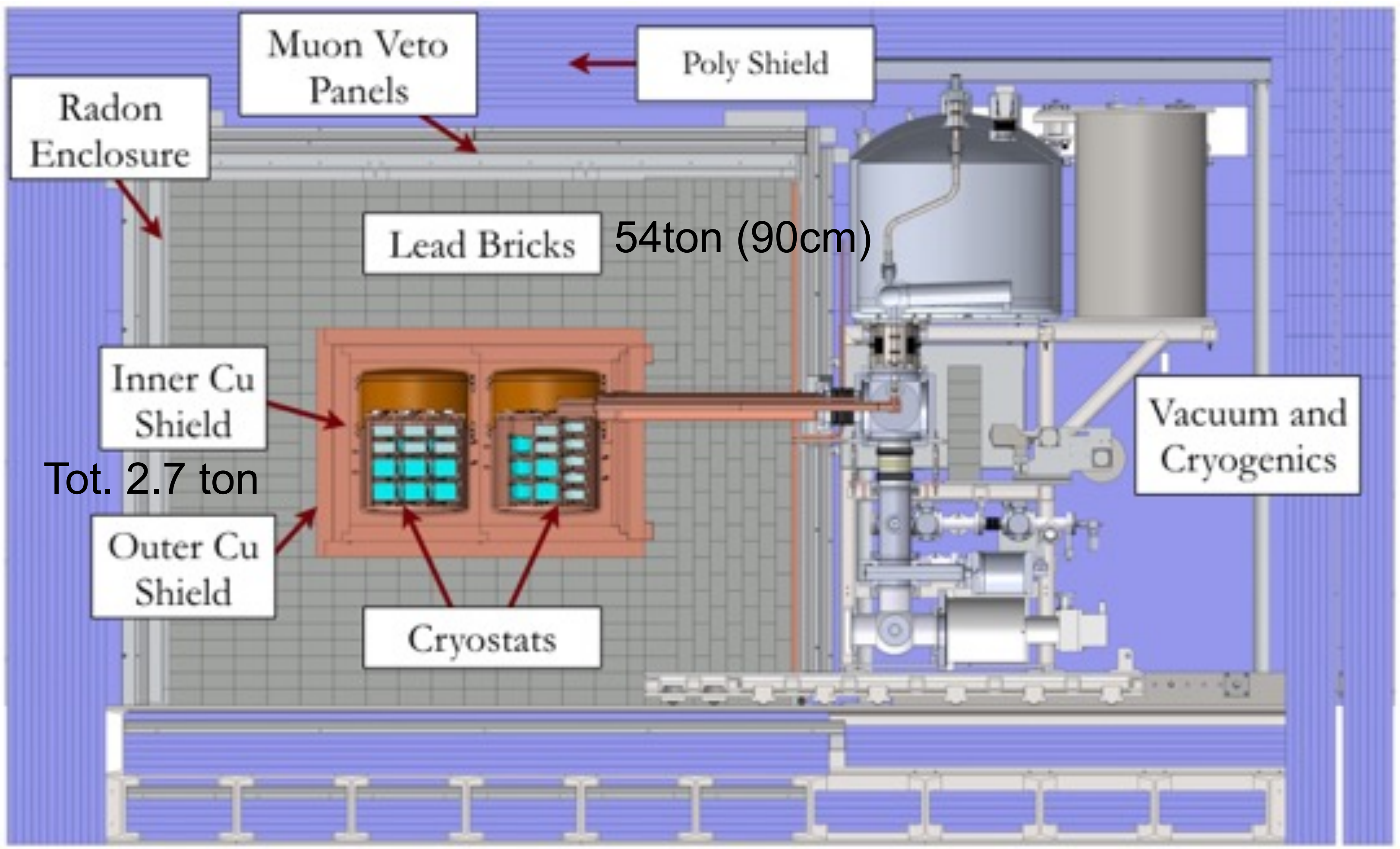


GERDA Limit (90% C.L.)

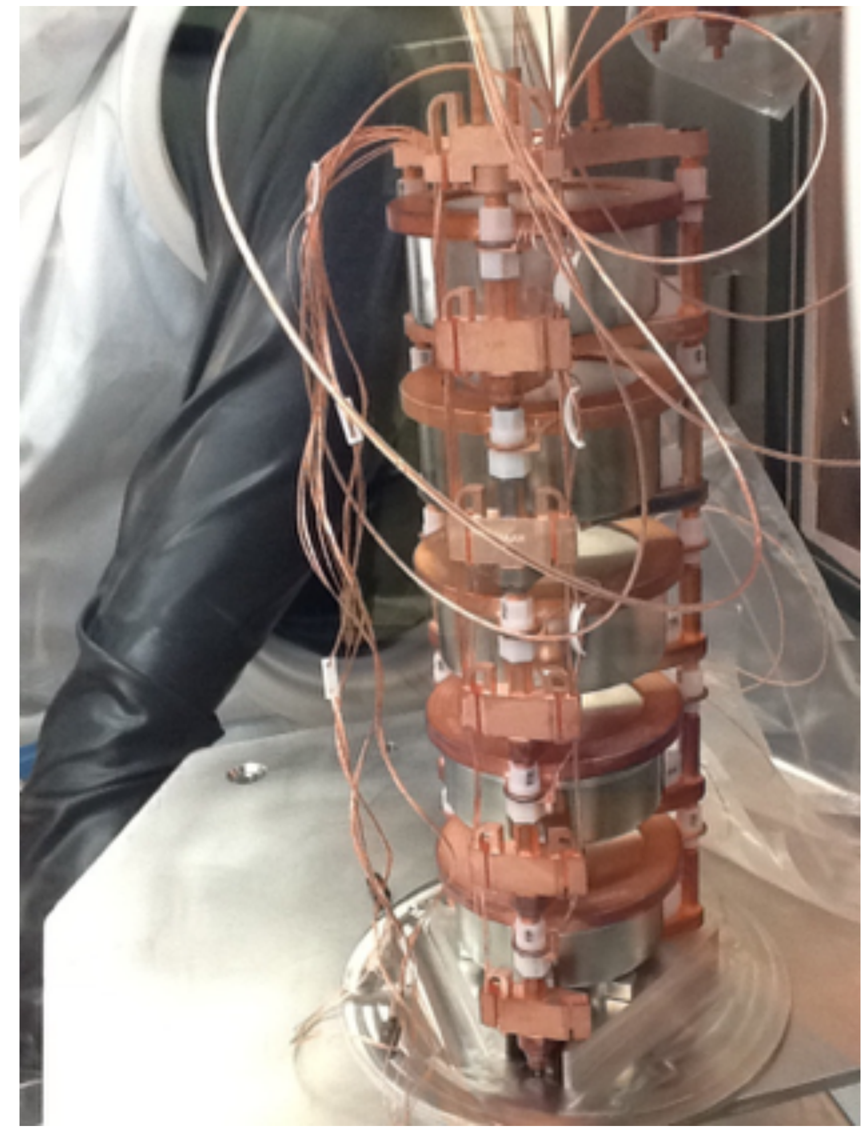
$T^{1/2} > 0.9 \times 10^{26}$ yr (sensitivity 1.0×10^{26} yr) $m_{\beta\beta} < 0.11$-0.26 eV

MAJORANA Demonstrator

- **^{76}Ge** (N.A. 7.6%, Qvalue 2039 keV). Located at SURF (USA), ~4300 m.w.e.
- **HPGe detector array** in 2 independent cryostat
- Best energy resolution: 2.5 keV FWHM@Qvalue



[N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)]

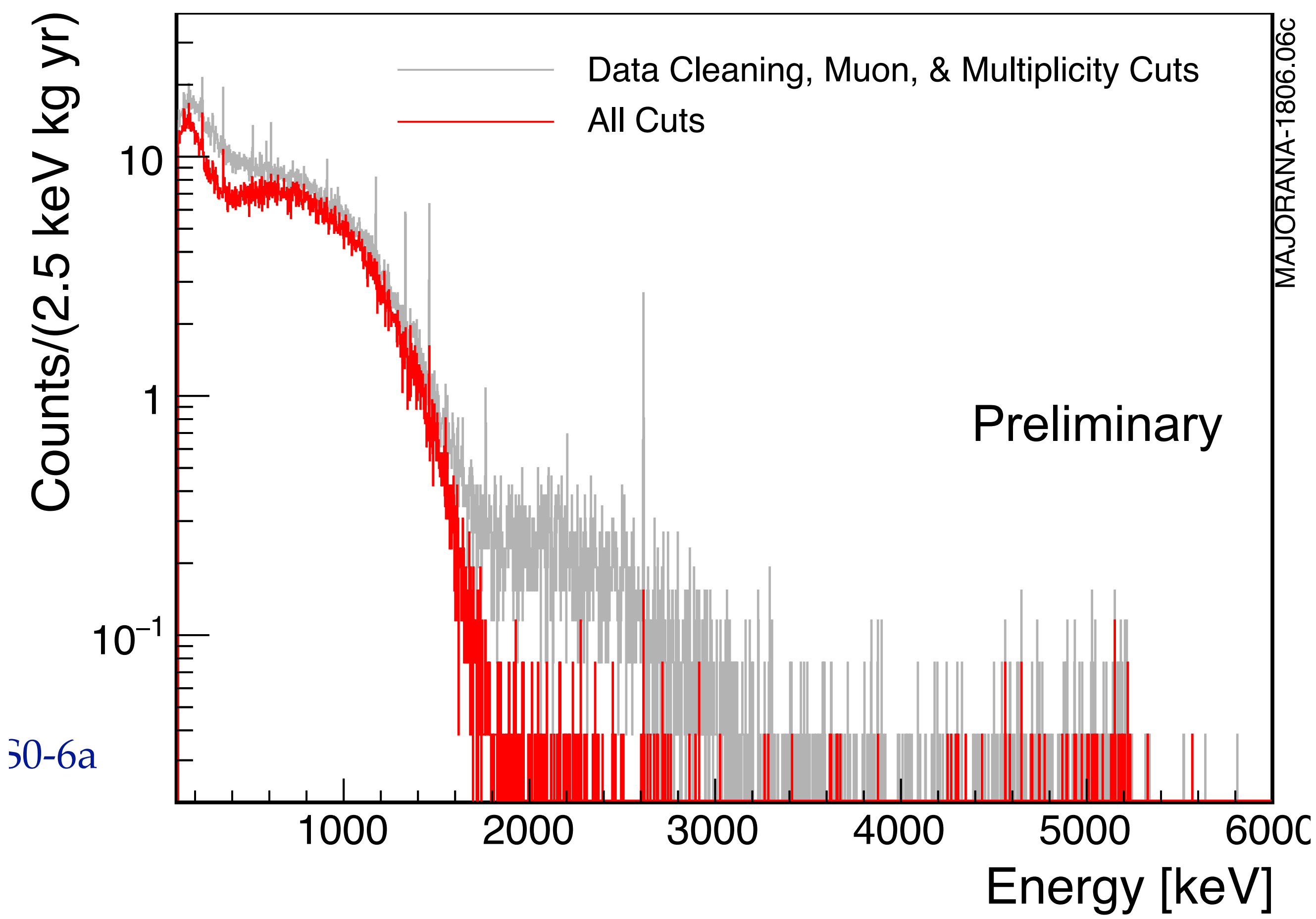


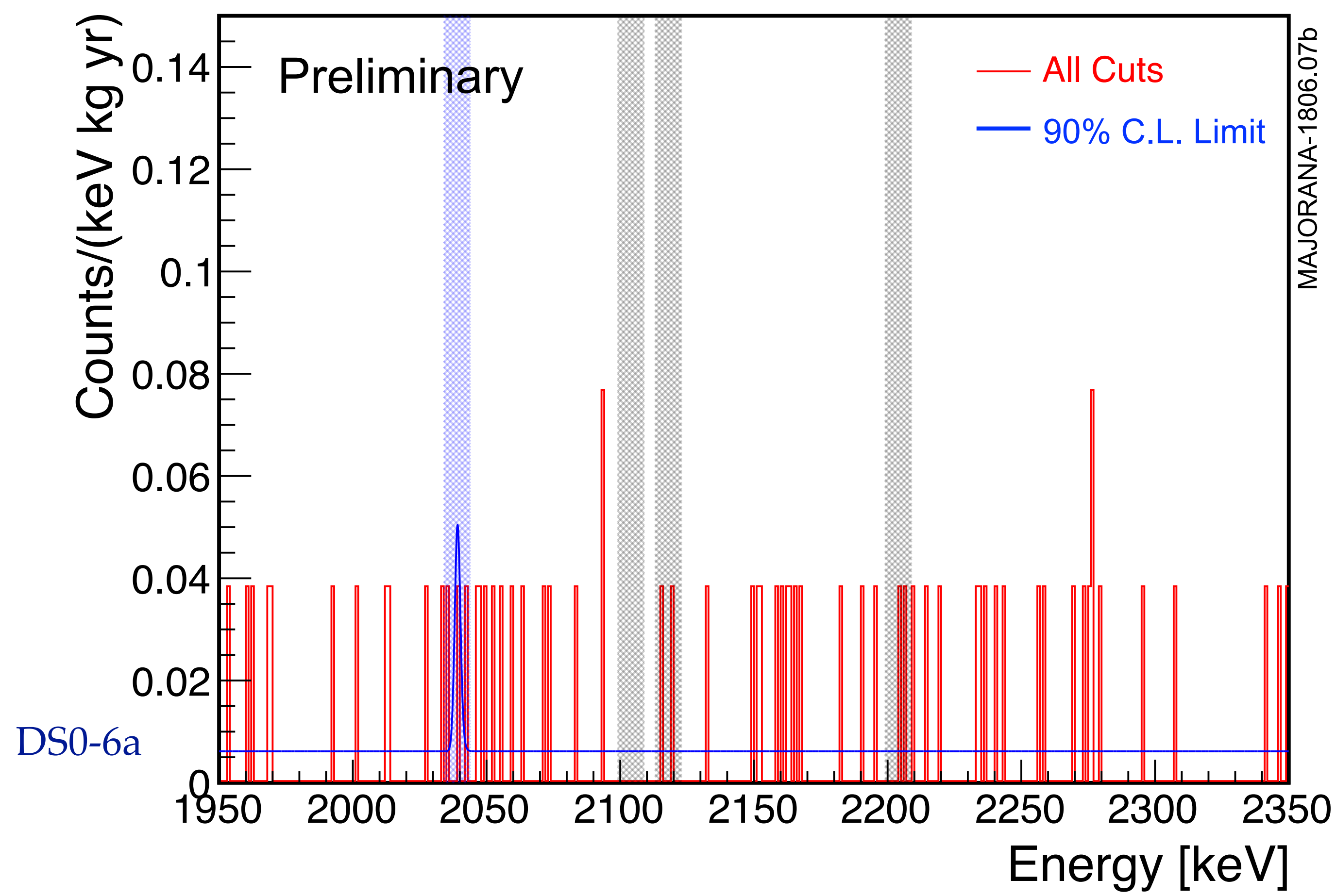
- 29.7 kg of 88% enriched ^{76}Ge crystals.
- 14.4 kg of natural Ge.

MJD | Recent Result

- Jun. 2015 - Apr. 2018, 26 kg yr exposure

NEUTRINO2018 result





MJD Limit (90% C.L.)

$T^{1/2} > 2.7 \times 10^{25}$ yr (sensitivity 4.8×10^{25} yr)

$m_{\beta\beta} < 200\text{-}433$ meV

- Half-life sensitivity will be in the range of 10^{26} yr with 50-70 kg-yr exposure

LEGEND

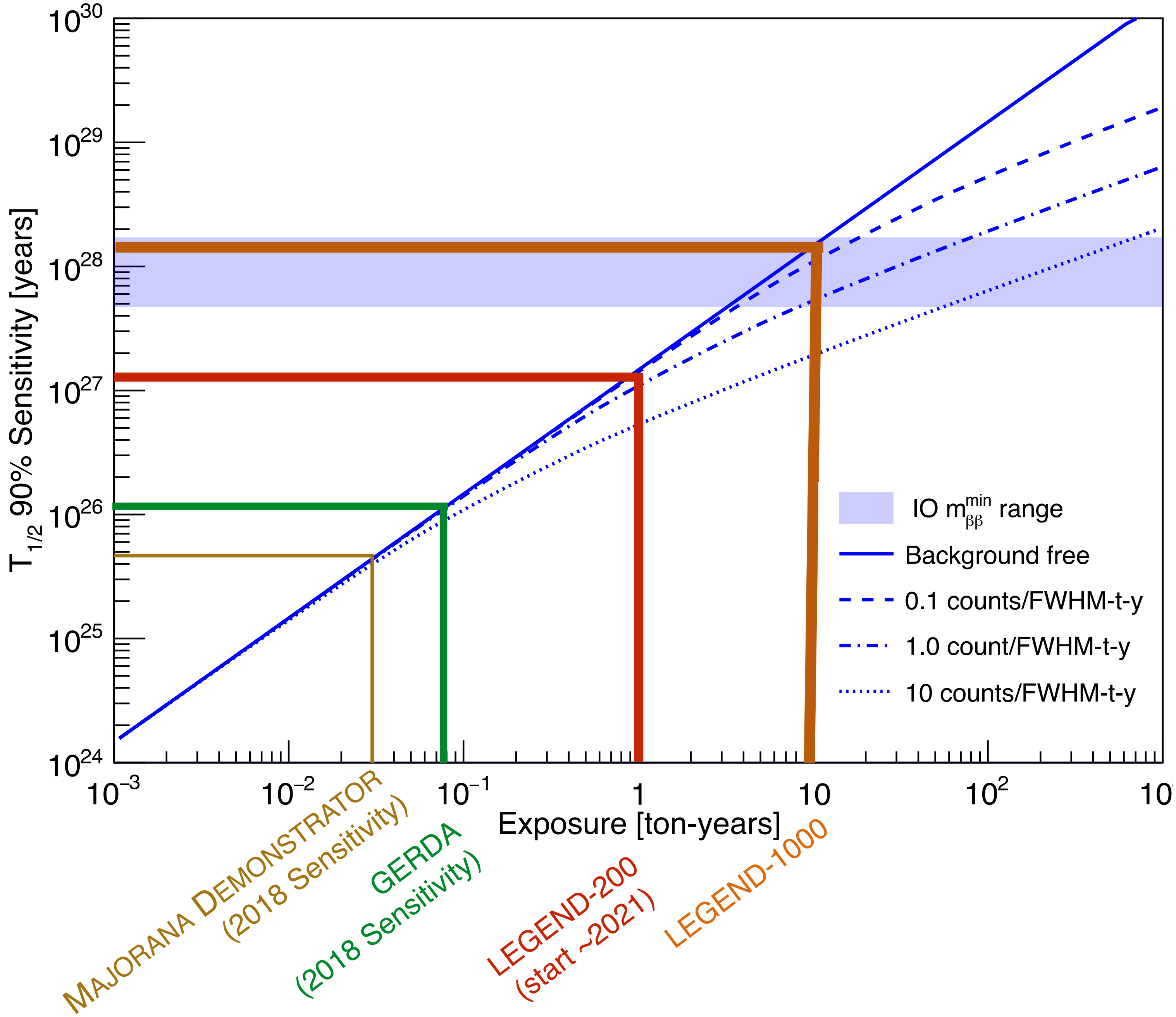
- Best of MJD + GERDA

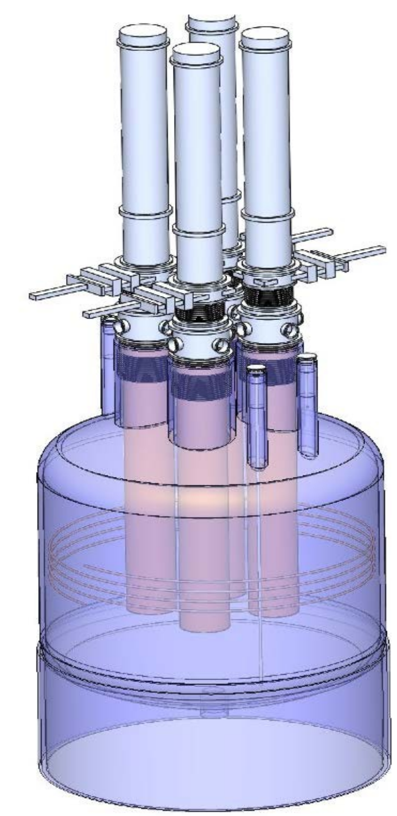
LEGEND-200 (approved by LNGS)

- (Up to) 200kg of enriched Ge
- Infrastructure at LNGS, modification of GERDA
- BG goal: 0.6 cts/FWHM t yr
- Start in 2021

LEGEND-1000

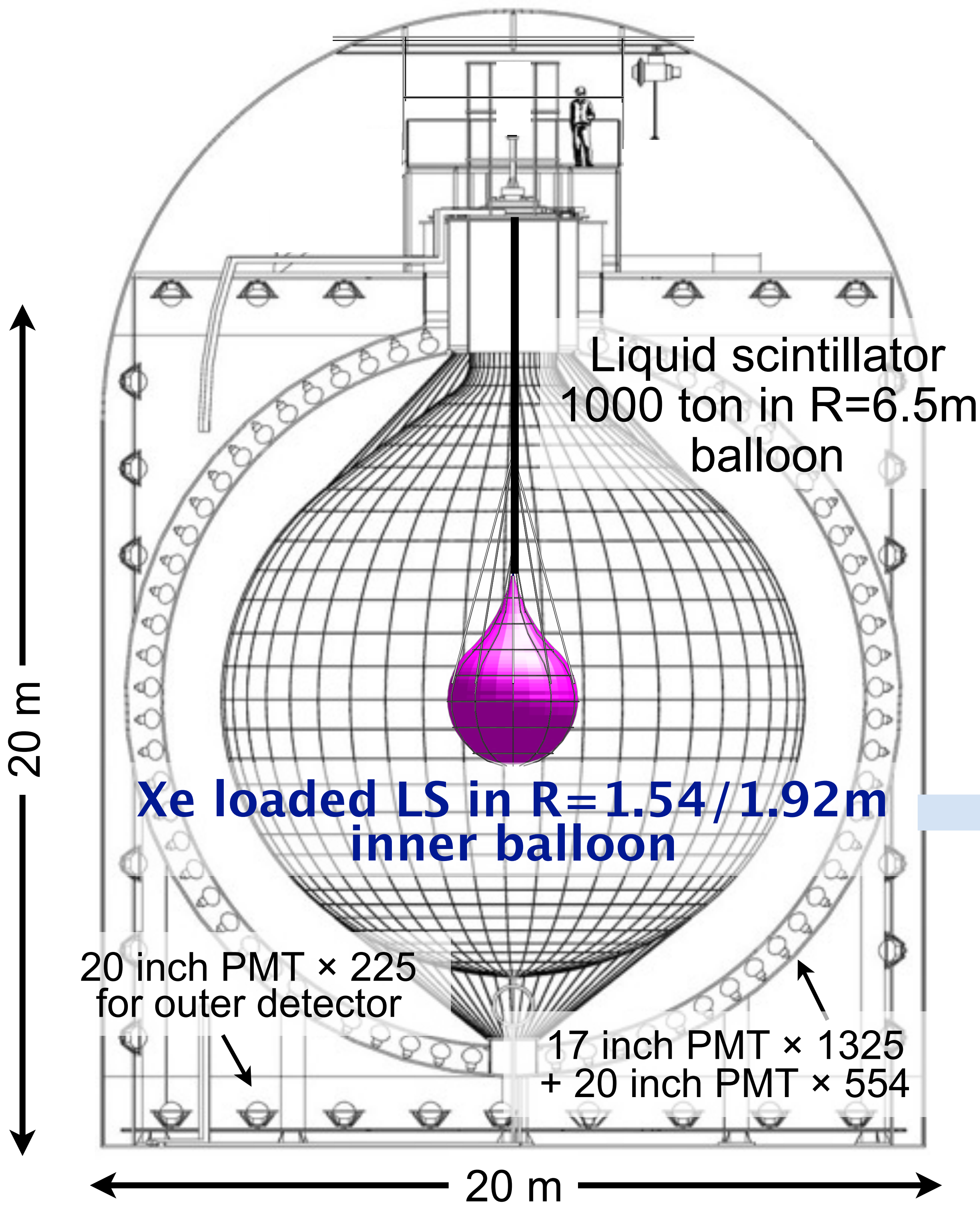
- 1000kg of enriched Ge
- Location TBD
- BG goal: 0.1 cts/FWHM t yr
- Start in mid 2020s





KamLAND-Zen 400/800

- ^{136}**Xe** (N.A. 9.6%, Q-value 2458 keV). Located in Kamioka (Japan), 2700 m.w.e.
- Modification of KamLAND (ν detector), **^{136}Xe loaded liquid scintillator**
- Largest isotope mass



Advantage

- Running detector
  Well known detector response
- Low background
  U, Th are at $10^{-17 \sim -18}$ g/g level
- Big detector → high scalability
  Ton order isotopes

Made of 25-um-thick clean nylon by welding (no glue) at class-1 clean room

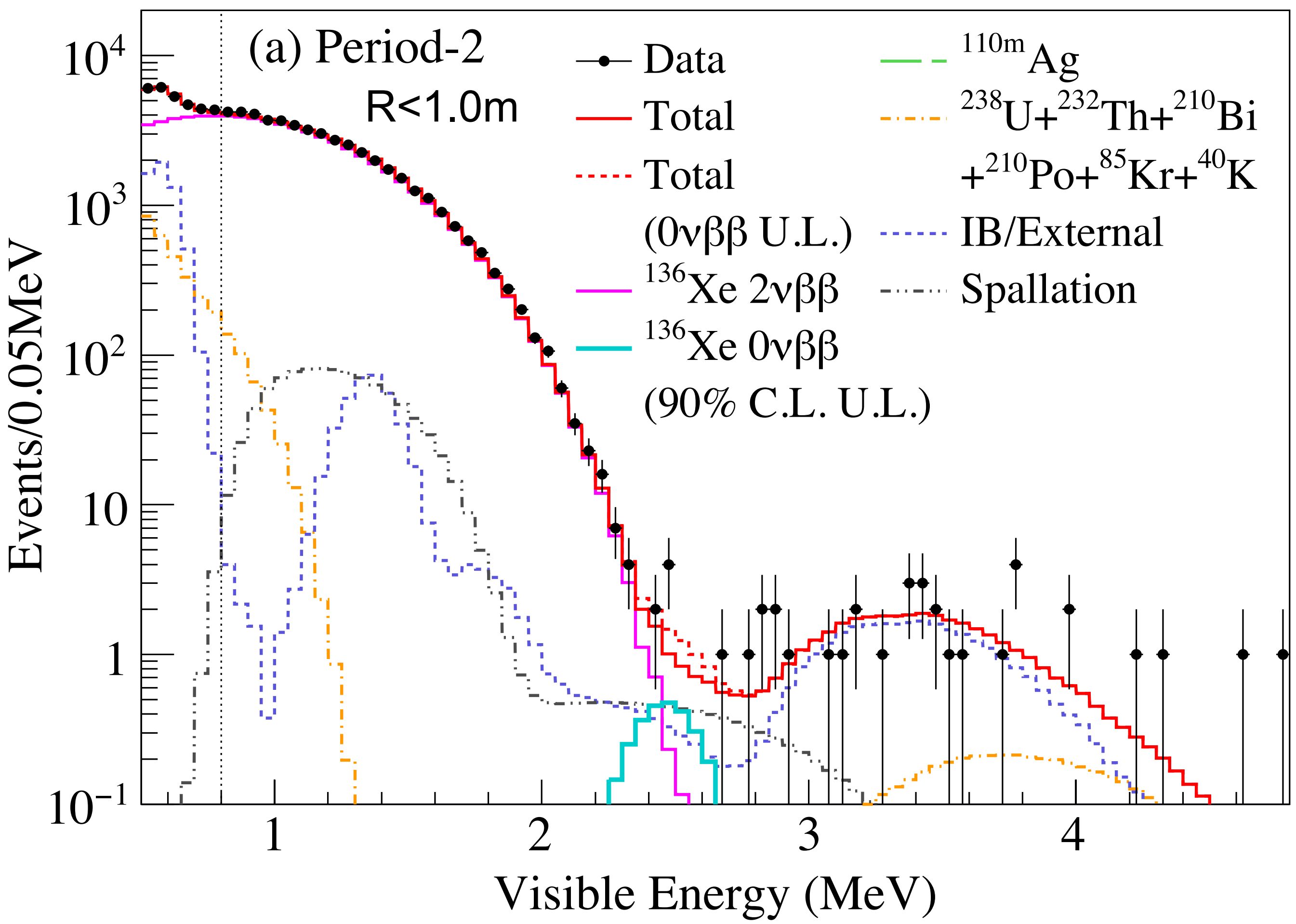
KamLAND-Zen 400 result

PRL 117, 082503 (2016)

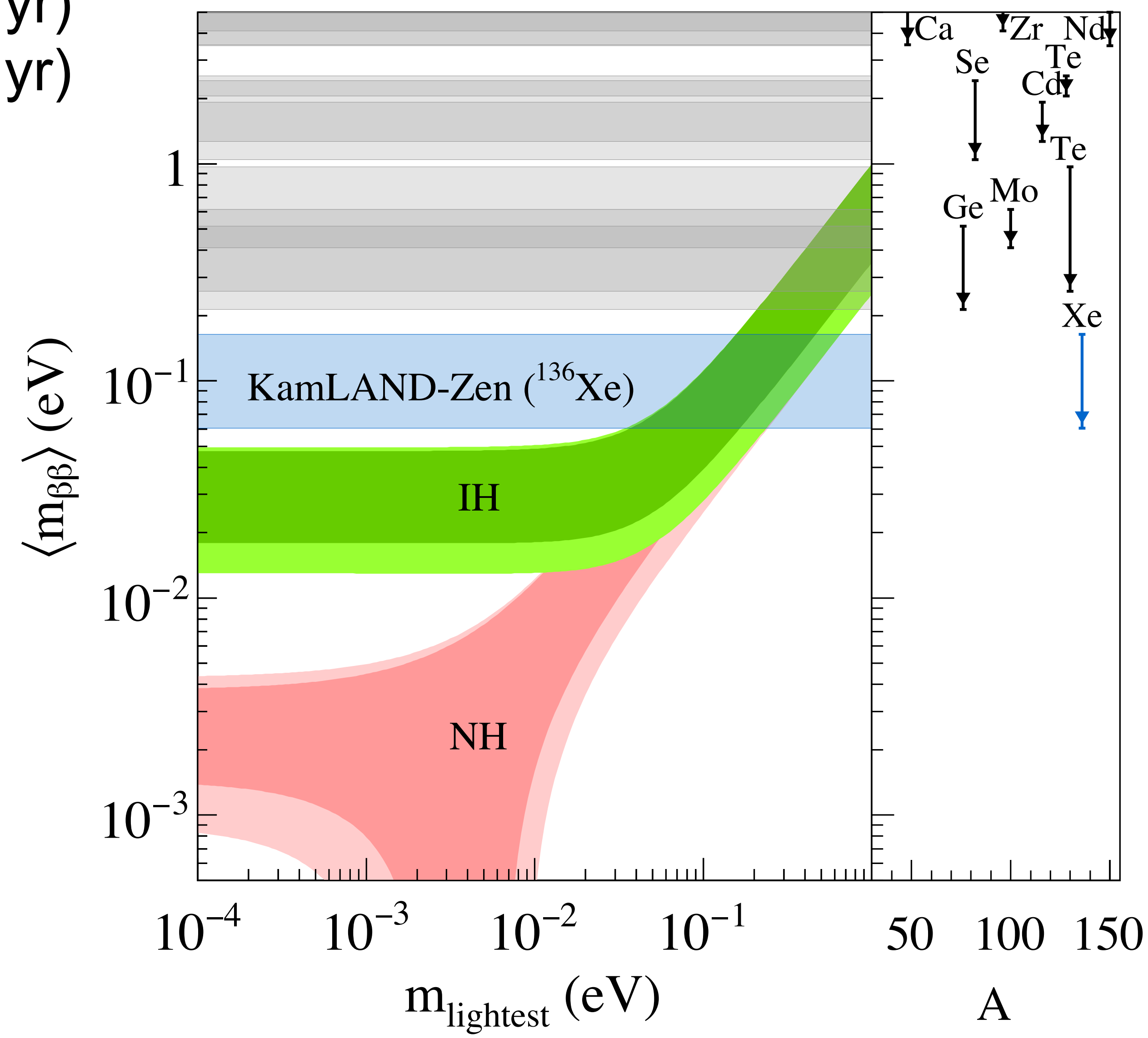
- Phase I 2011-2012, Phase II 2013-2015

^{136}Xe Half-life limit

Phase-1: $T^{1/2} > 1.9\times10^{25}$ yr (Sensitivity 1.0×10^{25} yr)
Phase-2: $T^{1/2} > 9.2\times10^{25}$ yr (Sensitivity 5.6×10^{25} yr)



Limit for effective neutrino mass



Combined result

$T^{1/2} > 1.07\times10^{26}$ yr (90% C.L.)

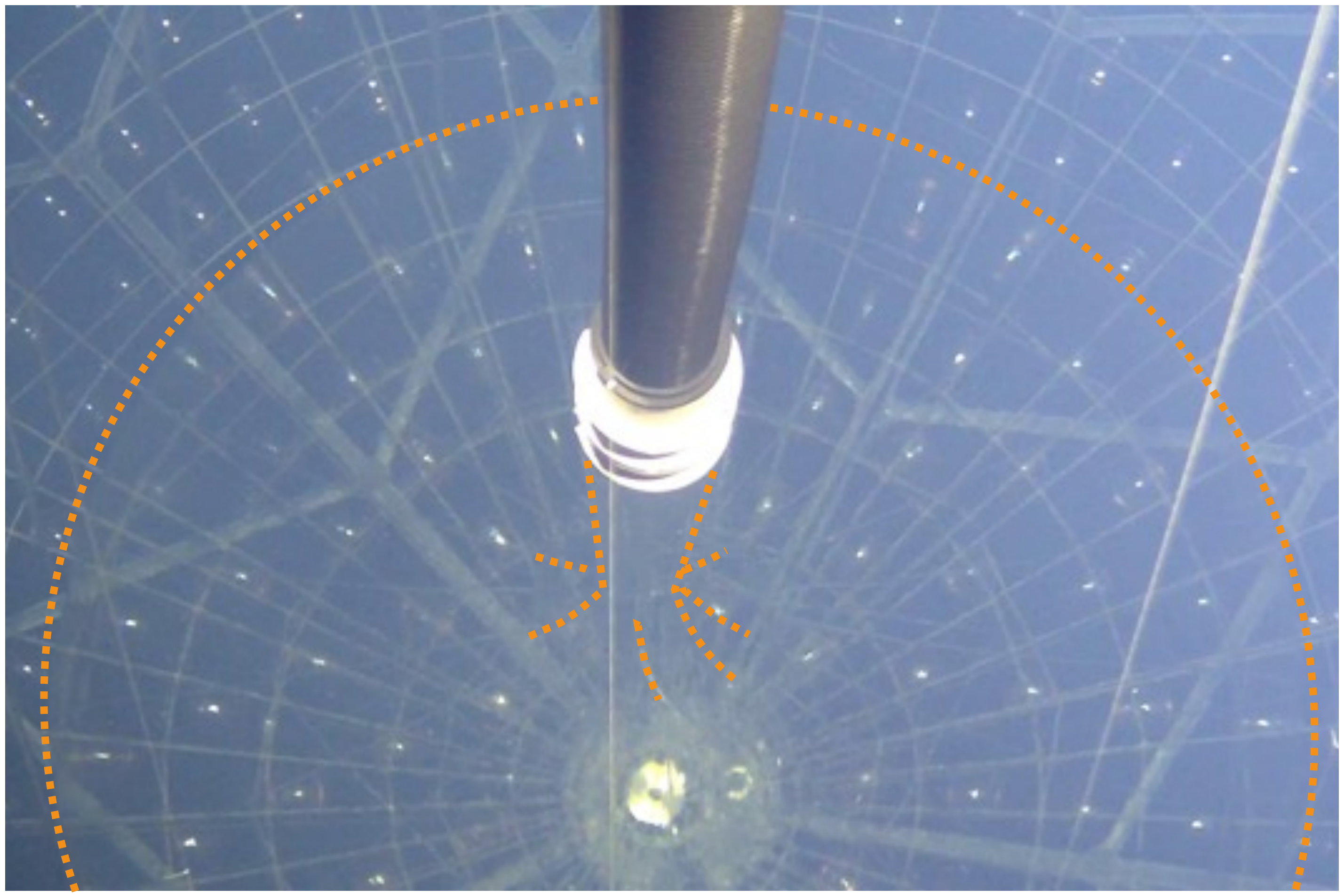
$\langle m_{\beta\beta}\rangle$ < 61-165 meV

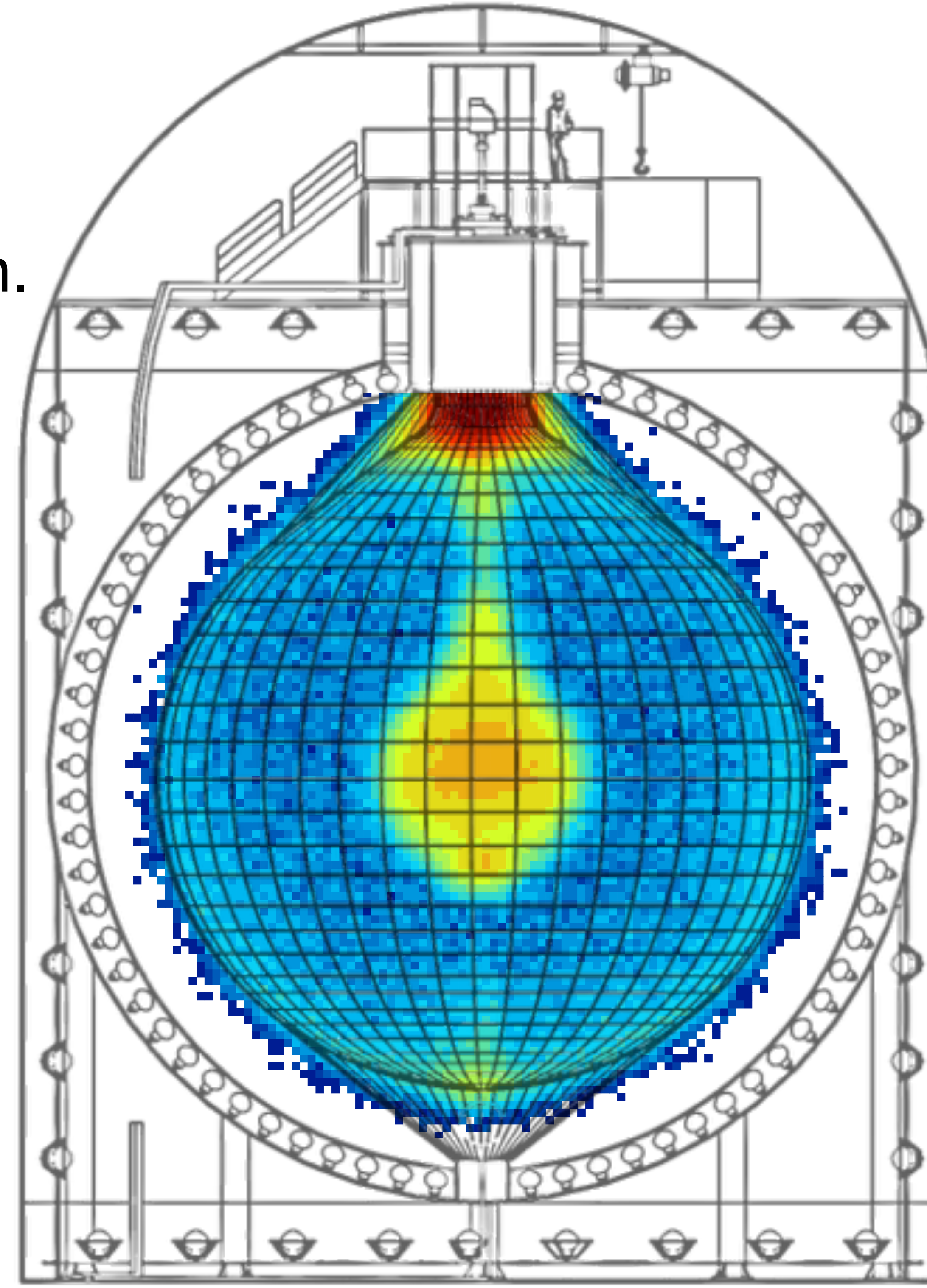
It reaches below 100 meV!

KamLAND-Zen 800

- 750kg of Xenon (90% enriched)
- Sensitivity ~40meV in 5yrs

- Filled with 30.5m^3 of dummy LS on May 19th.





No indication of leakage observed

Camera, Weight, Natural RI events,
LS composition measurement by GC-analysis

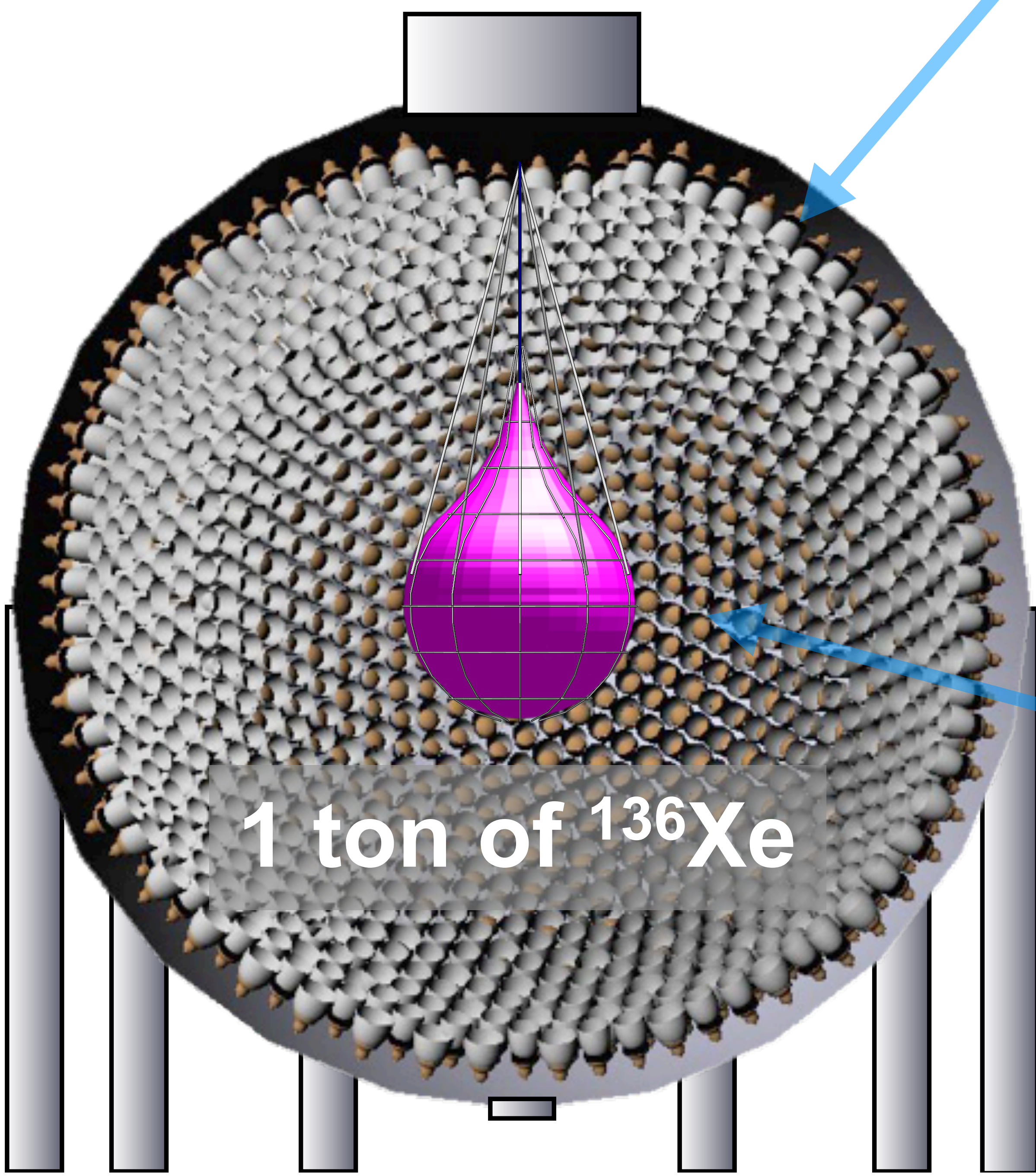
LS monitored by ^{222}Rn coming from pipe line emanation

Xe-loading after the purification. Physics run start: this winter.

KamLAND2-Zen

KamLAND → KamLAND2

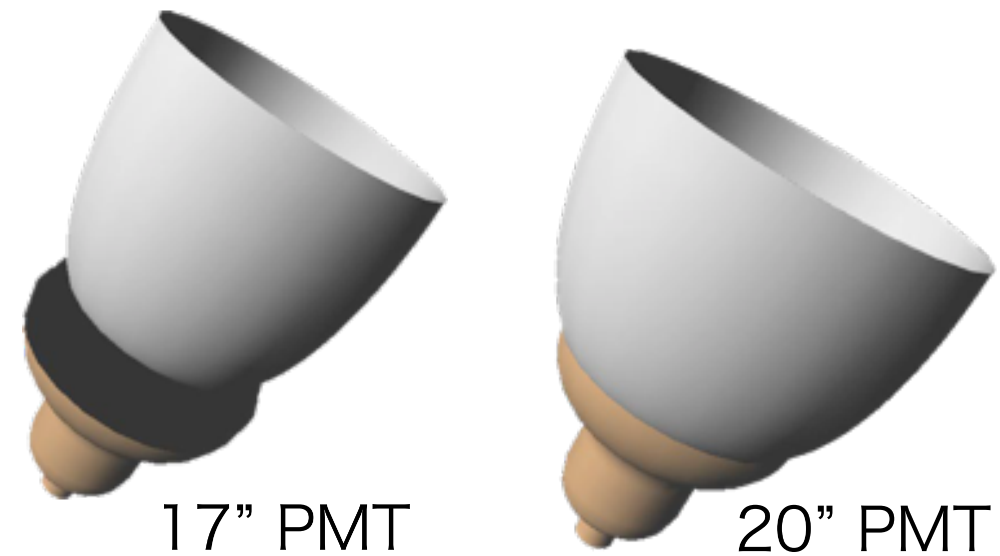
- Enlarge opening
- General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



R&D to improve the energy resolution

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage **×1.9**



17” PMT   20” PMT

Brighter LS

×1.4

Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

σ(2.6MeV)=4% → < 2.5%
Target ⟨$m_{\beta\beta}$⟩ ~20meV in 5 yrs

Launch around 2027

Summary

Neutrinoless double beta decay is a key to search for physics beyond the Standard Model.

Very active field: various isotopes and technologies.

Present experiment half life limit: $10^{25\text{-}26}$ yr with a few ten to hundreds kg of isotopes.

Next target: to explore inverted hierarchy ($10^{26\text{-}27}$ yr).