二重ベータ崩壊核行列要素に関する実験理論合同研究会@大阪大学RCNP

ニュートリノレス二重ベータ崩壊の世界情勢

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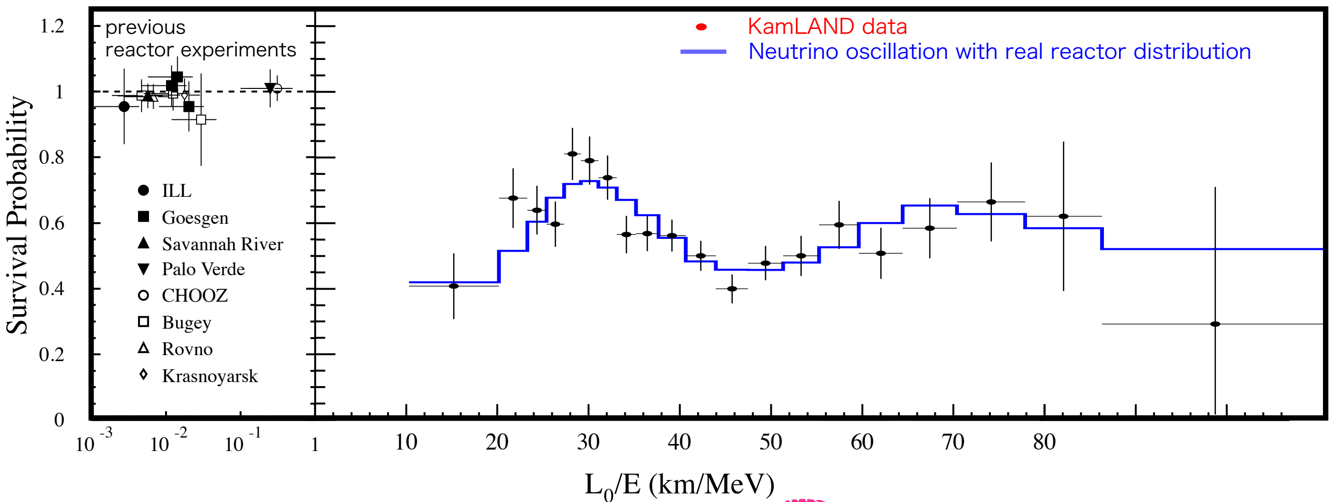
2022年10月3日

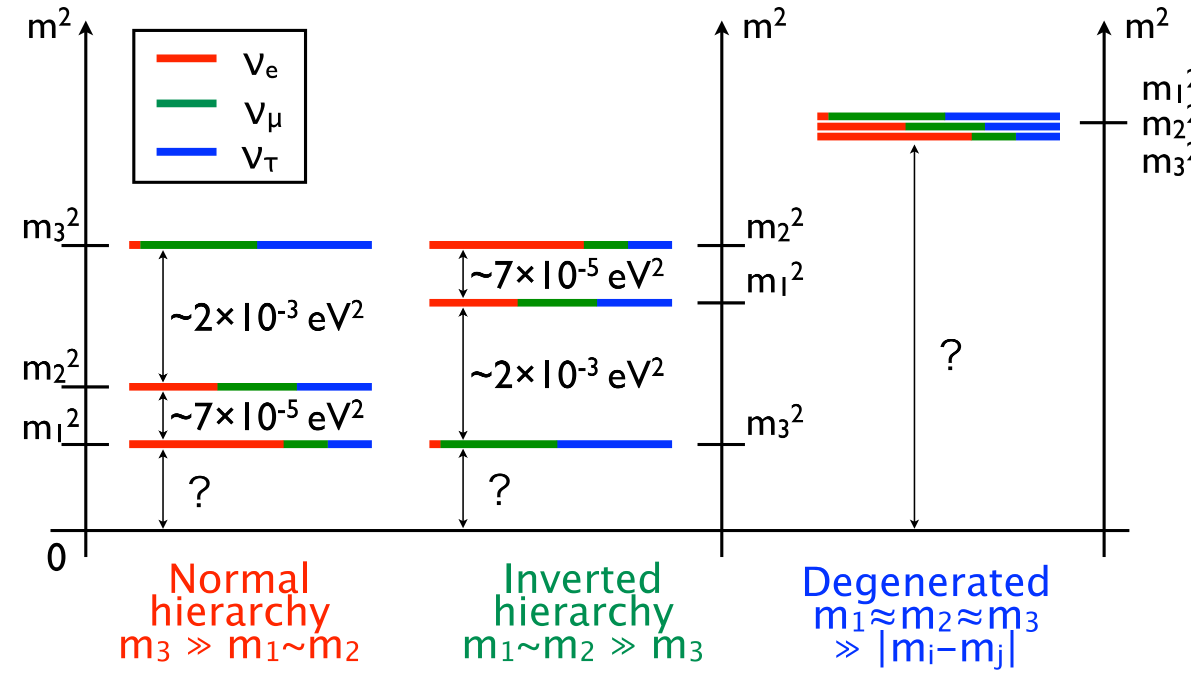
Introduction

- 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

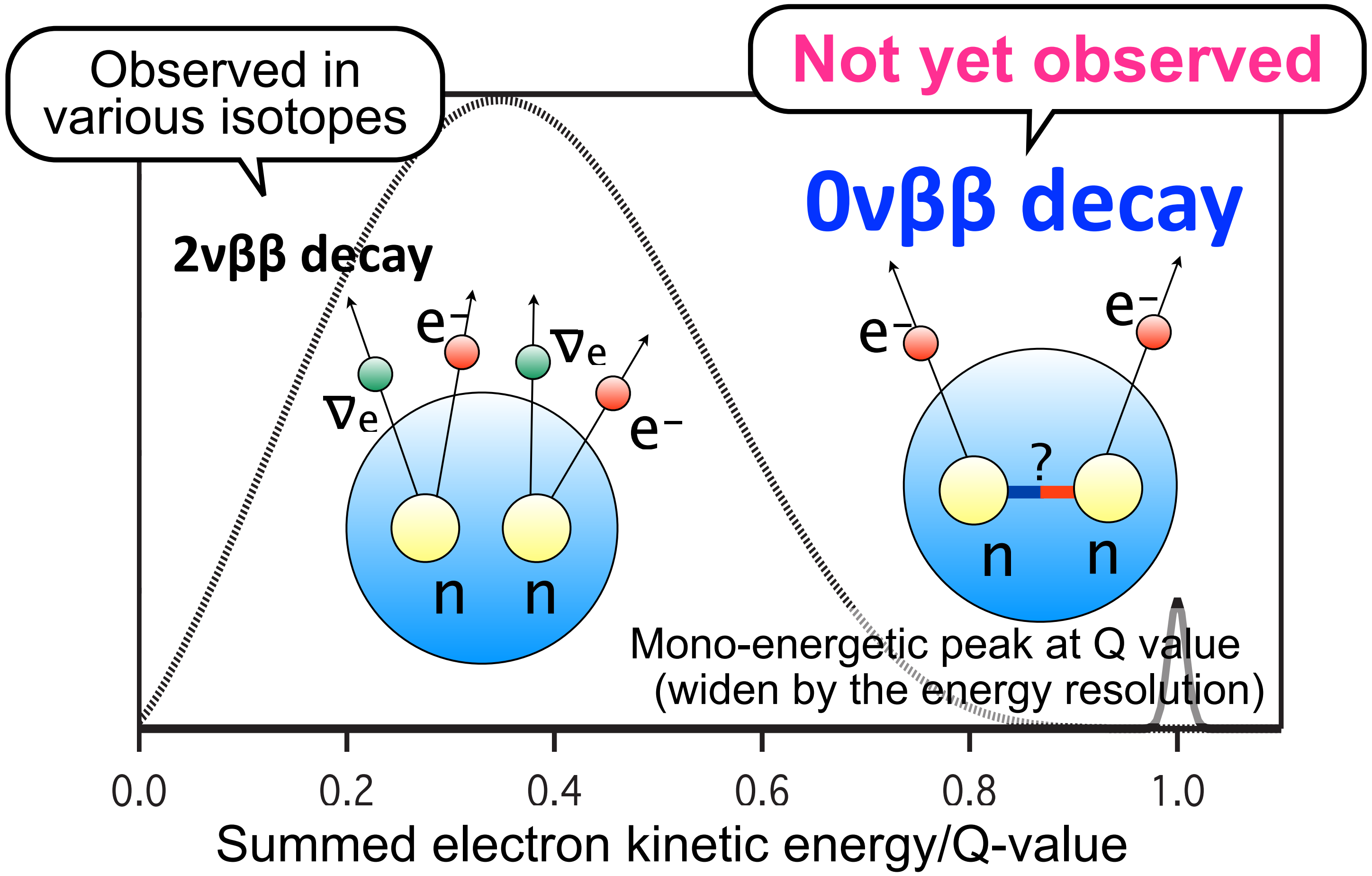
Majorana neutrino

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

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

Neutrinoless double beta decay



If 0νββ decay observed

→ **Majorana particle** (ν=ν̄)

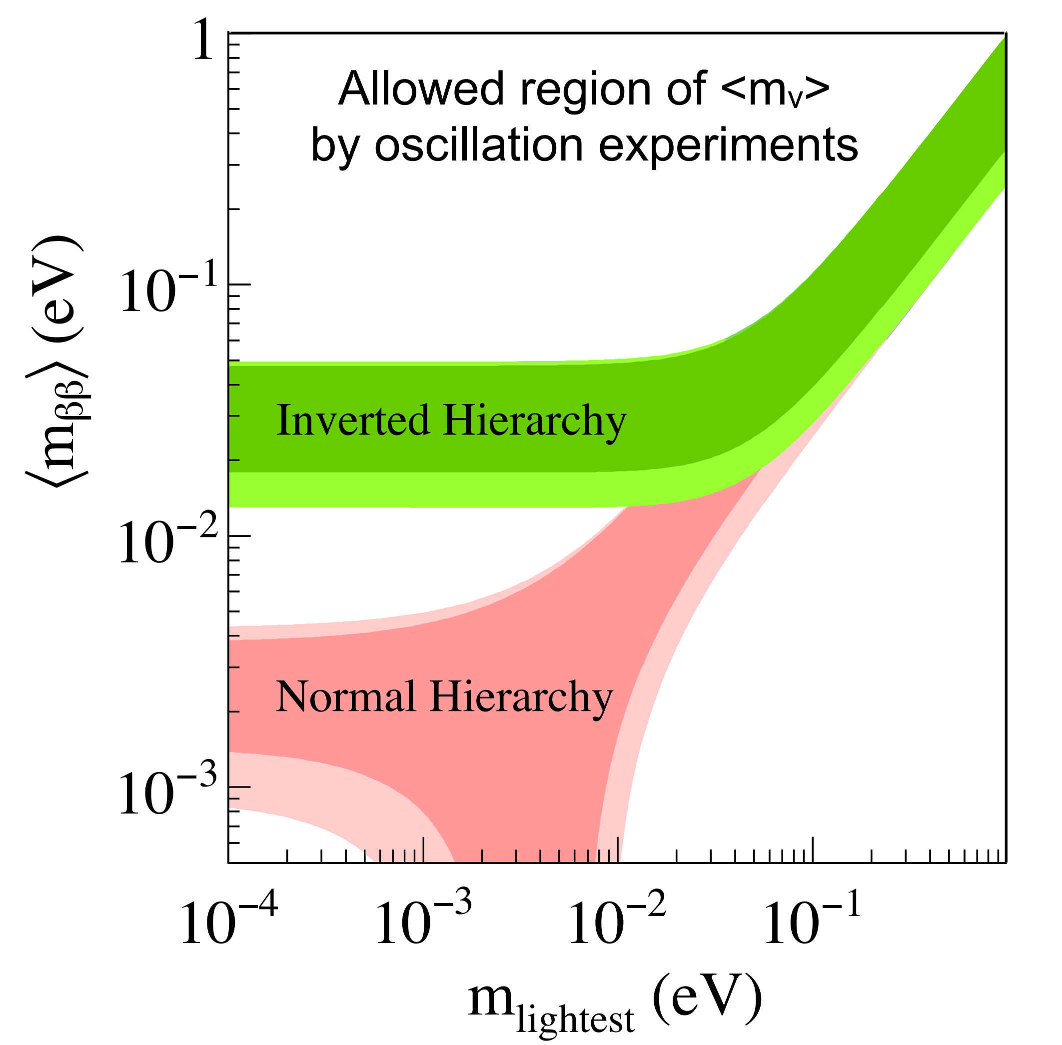
→ see-saw mechanism ? leptogenesis ?

→ lepton number violation

→ Neutrino mass hierarchy

→ Neutrino effective mass

→ hint for neutrino (absolute) mass



What we measure: decay rate

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

Theme of this workshop

G: phase space factor,

M: nuclear matrix element

$\langle m_\nu \rangle$: effective neutrino mass

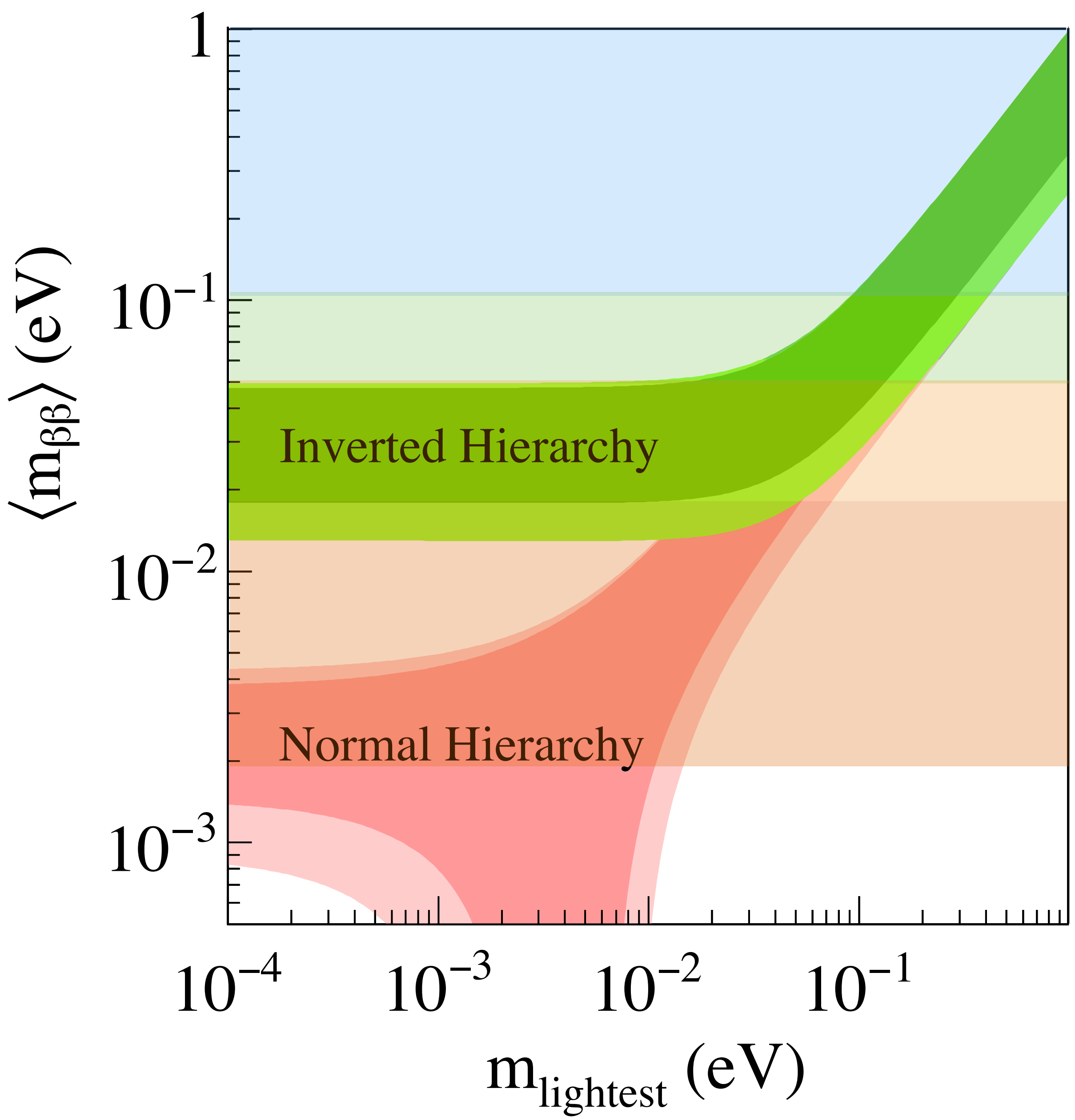
$$\langle m_\nu\rangle \equiv \left| |U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2 e^{i\phi_2} + |U^L_{e3}|^2 m_3 e^{i\phi_3}\right|$$

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

Experimental sensitivity

Decay rate of 0νββ ⟺ Effective neutrino mass

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



	Half life	Mass of isotopes
Past ~100 meV →	~10^{25} yr	10~10^2 kg
Present ~50 meV →	~10^{26} yr	10^2~10^3 kg
Near future ~20 meV →	~10^{27} yr	10^3 kg~
Future ~10 meV or less	~10^{28} yr	a few 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 experiment

TABLE II Target isotopes currently being pursued by leading $0\nu\beta\beta$-decay experiments. The reported $2\nu\beta\beta$-decay half-life values are the most precise available in literature. The $0\nu\beta\beta$-decay half-life values are the most stringent 90% C.L. limits.

Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]	$T_{1/2}^{2\nu\beta\beta}$ [d] [yr]	$T_{1/2}^{0\nu\beta\beta}$ [e] [yr]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16	$\left(6.4^{+0.7}_{-0.6}(\text{stat})^{+1.2}_{-0.9}(\text{syst})\right) \cdot 10^{19}$	$> 5.8 \cdot 10^{22}$
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92	$(1.926 \pm 94) \cdot 10^{21}$	$> 1.8 \cdot 10^{26}$
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3	$\left(8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})\right) \cdot 10^{19}$	$> 3.5 \cdot 10^{24}$
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86	$(2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst})) \cdot 10^{19}$	$> 9.2 \cdot 10^{21}$
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5	$\left(7.12^{+0.18}_{-0.14}(\text{stat}) \pm 0.10(\text{syst})\right) \cdot 10^{18}$	$> 1.5 \cdot 10^{24}$
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82	$2.63^{+0.11}_{-0.12} \cdot 10^{19}$	$> 2.2 \cdot 10^{23}$
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92	$\left(7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst})\right) \cdot 10^{20}$	$> 2.2 \cdot 10^{25}$
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90	$(2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})) \cdot 10^{21}$	$> 1.1 \cdot 10^{26}$
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91	$\left(9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})\right) \cdot 10^{18}$	$> 2.0 \cdot 10^{22}$

[a] Values from (Alanssari *et al.*, 2016b; Fink *et al.*, 2012; Kolhinen *et al.*, 2010; Kwiatkowski *et al.*, 2014; Lincoln *et al.*, 2013; Mount *et al.*, 2010; Rahaman *et al.*, 2008; Rahaman, S. and Elomaa, V. V. and Eronen, T. and Hakala, J. and Jokinen, A. and Kankainen, A. and Rissanen, J. and Suhonen, J. and Weber, C. and Äystö, J., 2011; Redshaw *et al.*, 2009, 2007).

[b] Values from (Meija and other, 2016).

[c] Values from (Abgrall *et al.*, 2021; Artusa *et al.*, 2017; Barabash *et al.*, 2014, 2011; Dafinei *et al.*, 2017; Gando *et al.*, 2012; JSC Isotope, last accessed: Sep. 2020a,l,l; Kishimoto, 2018). Enrichment is performed via gas centrifuge for all isotopes except for ^{48}Ca, for which the unpublished report in (Kishimoto, 2018) used electrophoresis (Kishimoto *et al.*, 2015). For ^{96}Zr, 86% is commercially available (JSC Isotope, last accessed: Sep. 2020a), however a 91% enrichment was achieved at smaller scale (Finch, 2015). For ^{116}Cd, 82% is the highest value used in a $0\nu\beta\beta$-decay experiment(Barabash *et al.*, 2011), however enrichment up to 99.5% is possible(JSC Isotope, last accessed: Sep. 2020d). For ^{150}Nd, 91% is the highest value used in a $0\nu\beta\beta$-decay experiment(Barabash *et al.*, 2018), however enrichment up to 98% is possible(JSC Isotope, last accessed: Sep. 2020c).

[d] Values from (Agostini *et al.*, 2015; Albert *et al.*, 2014; Alduino *et al.*, 2017b; Argyriades *et al.*, 2010; Armengaud *et al.*, 2019b; Arnold *et al.*, 2016a,b; Azzolini *et al.*, 2019b; Barabash *et al.*, 2018).

[e] 90% C.L. limits from (Adams *et al.*, 2021b,c; Agostini *et al.*, 2020b; Argyriades *et al.*, 2010; Armengaud *et al.*, 2021; Arnold *et al.*, 2016a; Azzolini *et al.*, 2019d; Barabash *et al.*, 2018; Gando *et al.*, 2016; Umehara *et al.*, 2008).

“Toward the discovery of matter creation with neutrinoless double-beta decay”, arXiv:2202.01787v1 [hep-ex]

Experiments from arXiv:2202.01787v1 [hep-ex]

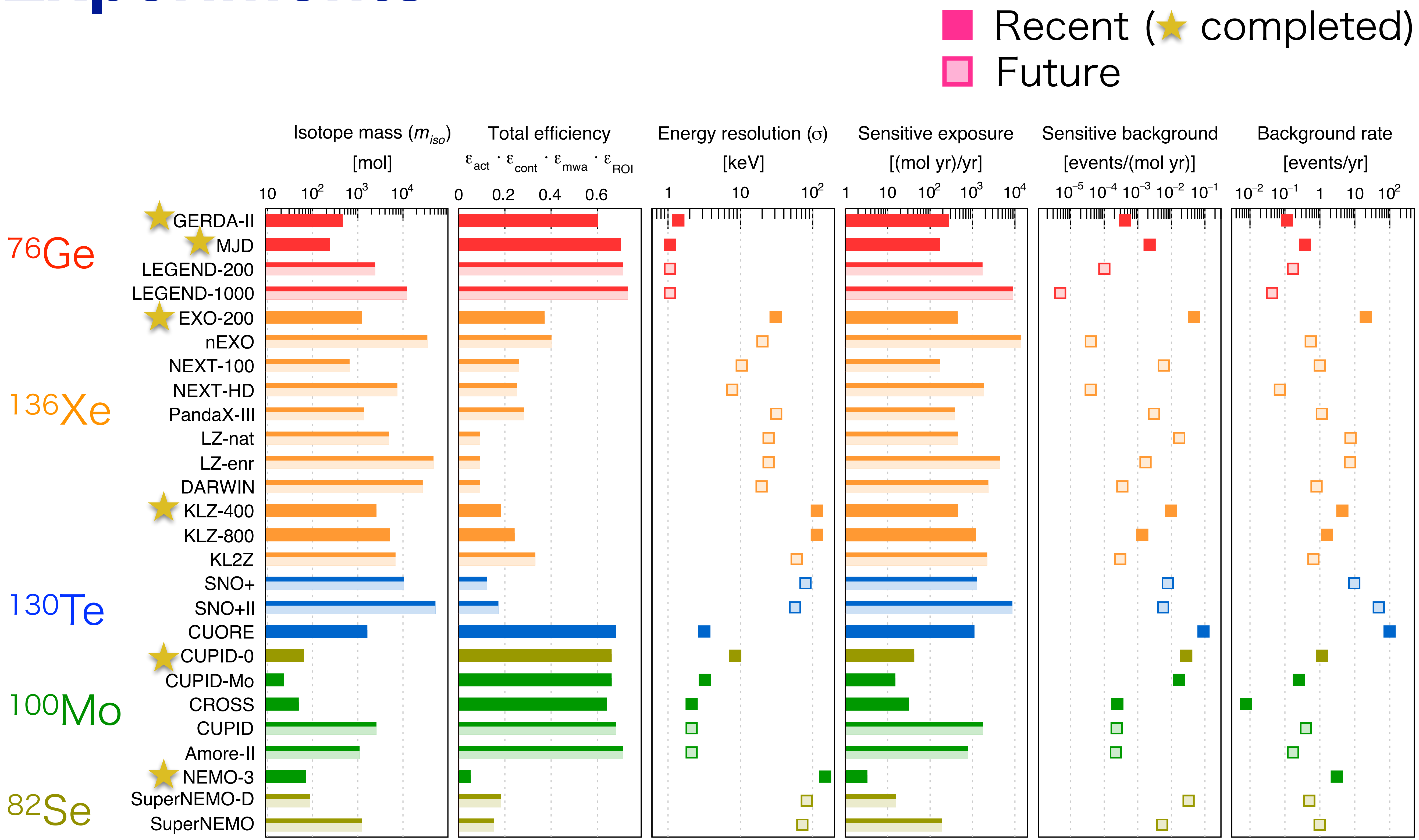


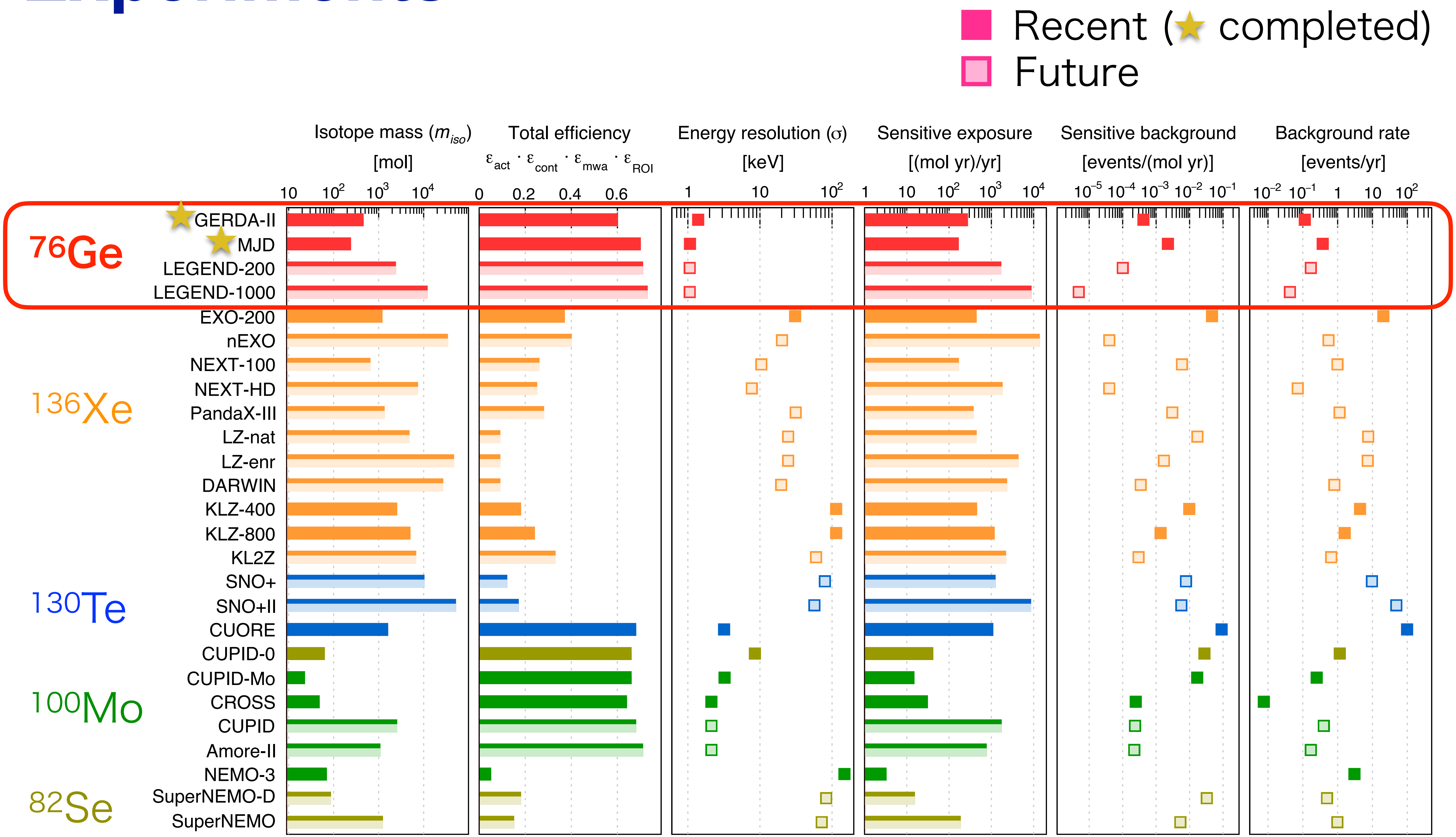
FIG. 16 Fundamental parameters driving the sensitive background and exposure, and consequently the sensitivity, of recent and future phases of existing experiment. Red bars are used for ^{76}Ge experiments, orange for ^{136}Xe, blue for ^{130}Te, green for ^{100}Mo, and sepia for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency by gas and liquid detectors, or with small mass but high resolution and efficiency by solid state detectors. The sensitive exposure is computed for one year of livetime. Ligher shades indicate experiments which are under construction or proposed.

Experiments from arXiv:2202.01787v1 [hep-ex]

TABLE IX Other detector concepts. Existing experiments are marked with a dagger.

Project	Isosope(s)	Detector technology, main features, and references
CANDLES†	^{48}Ca	Array of scintillator crystals suspended in a volume of liquid scintillator. Possible operation as cryogenic calorimeters. Ajimura *et al.* (2021) and Yoshida *et al.* (2009)
COBRA†	^{70}Zn, ^{114,116}Cd, ^{128,130}Te	CdZnTe semiconductor detector array. Room temperature; multi-isotope; high granularity. Arling *et al.* (2021); Ebert *et al.* (2016a,b); and Zuber (2001)
Selena	^{82}Se	Amorphous $^{\rm enr}$Se high resolution, high-granularity CMOS detector array. 3D track reconstruction ($O(10\mu m)$ resolution); room temperature; minimal shielding. Chavarria *et al.* (2017)
NνDEx	^{82}Se	High-pressure gaseous ^{82}SeF$_6$ ion-imaging TPC. $\lesssim 1\%$ energy resolution; precise signal topology; possible multi-isotope. Mei *et al.* (2020) and Nygren *et al.* (2018)
R2D2	^{136}Xe	Spherical TPC. Single readout channel; inexpensive infrastructure. Bouet *et al.* (2021)
AXEL	^{136}Xe	High-pressure TPC operated in proportional scintillation mode. High energy resolution; possible positive ion detection. Obara *et al.* (2020)
JUNO	—	Isotope loaded liquid scintillator. 20 ktons of scintillator; multi-isotope; multi-purpose. Abusleme *et al.* (2021) and Zhao *et al.* (2017)
NuDot	—	Liquid scintillator with quantum dots or perovskites as wavelength shifter for Cherenkov light. Discriminate directional backgrounds; multi-isotope. Gooding *et al.* (2018); Graham *et al.* (2019); Winslow and Simpson (2012); Aberle *et al.* (2013)
ZICOS	^{96}Zr	Zr-loaded liquid scintillator. Topology and particle discrimination via Cherenkov light readout. Fukuda (2016) and Fukuda *et al.* (2020)
THEIA	—	Water-based loaded liquid scintillator with Cherenkov light readout. Topology and particle discrimination; multi-isotope; multi-purpose; 25 ktons of water. Askins *et al.* (2020)
LiquidO	—	Opaque isotope-loaded liquid scintillator with wavelength shifting fibers for event topology. Room temperature; multi-isotope; multi-purpose. Buck *et al.* (2019) and Cabrera *et al.* (2019)

Experiments from arXiv:2202.01787v1 [hep-ex]



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Germanium detector

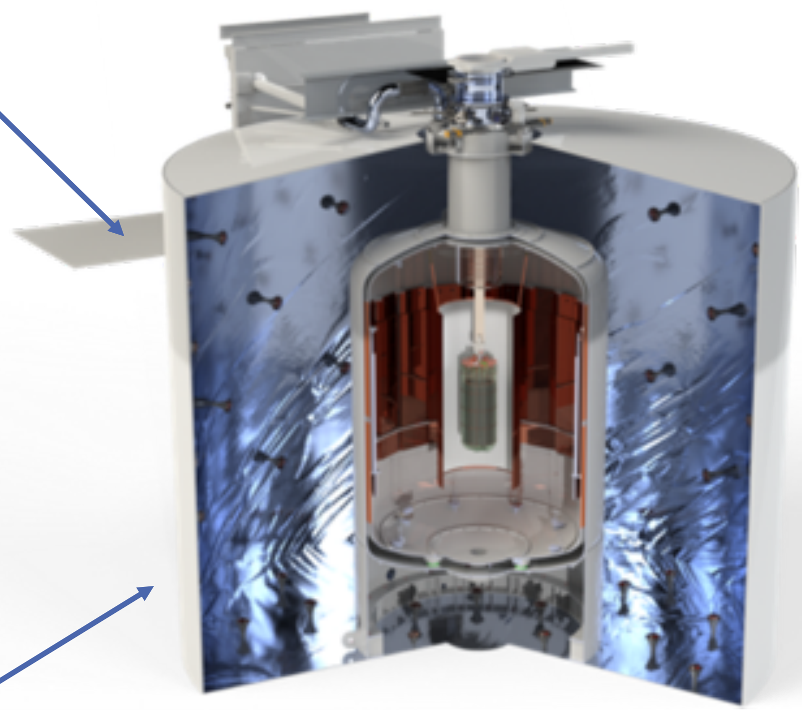
- **^{76}Ge** (N.A. 7.6%, Q-value 2039 keV). Enriched material is available.
- Excellent energy resolution O(0.1)%@Qvalue
- **HPGe detector array**

From the Current Generation to the Ton Scale

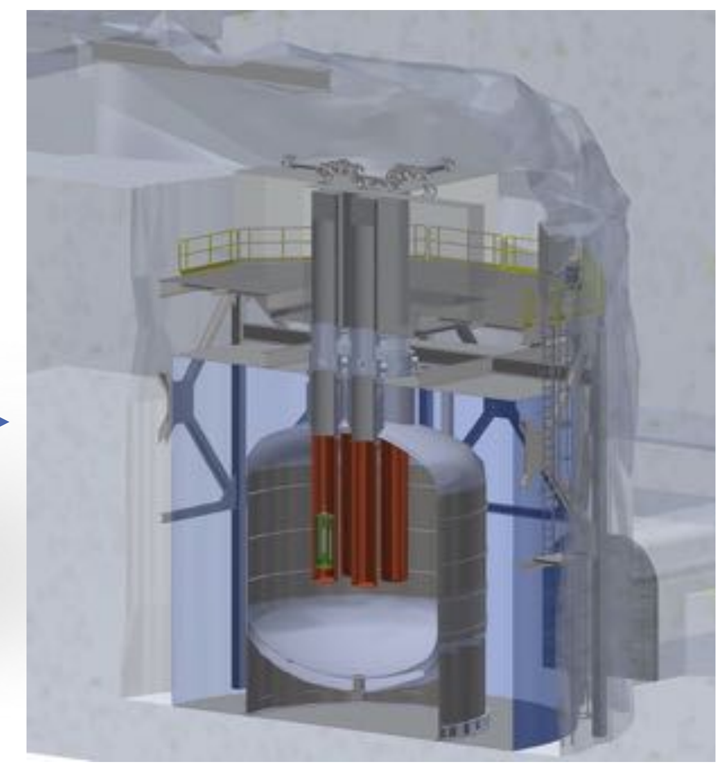
MJD: New final exposure results

GERDA: Final 0νββ results published

PRL 125, 252502 (2020)



LEGEND-200: Now in commissioning



LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462

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※Neutrino2022: ニュートリノ業界で一番大きい国際会議. 2年に一度開催. すべてplenary talk.

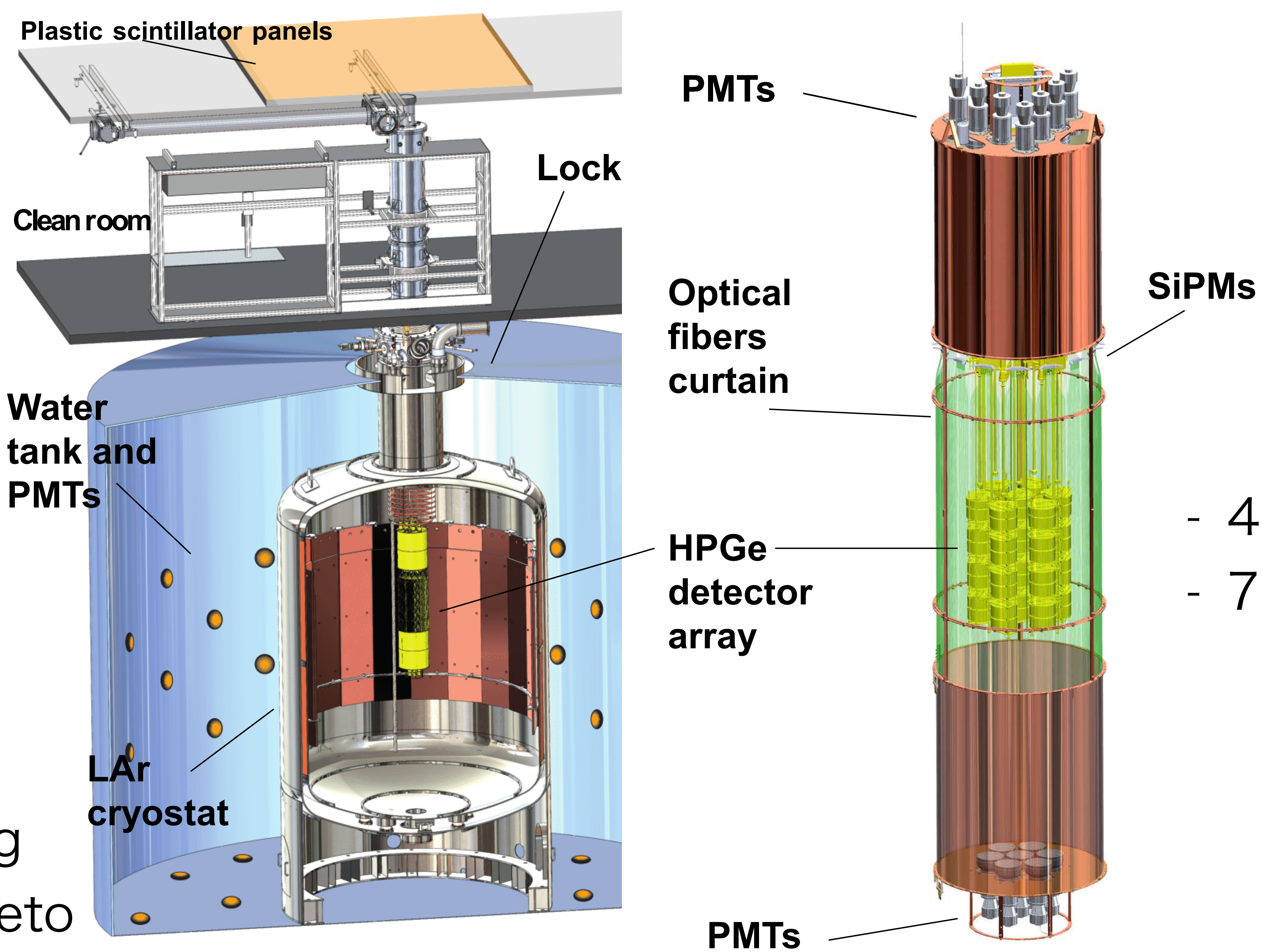
GERDA (GERmanium Detector Array)

Completed

- Located at Laboratori Nazionali del Gran Sasso (Italy), ~3600 m.w.e.
- 44.2 kg of up to 87% enriched ^{76}Ge crystals
- Energy resolution: ~3 keV FWHM @ 2039 keV

- 590 m^3
- Cherenkov detection

- 64 m^3
- cooling
- shielding
- active veto



- 41 detectors
- 7 strings

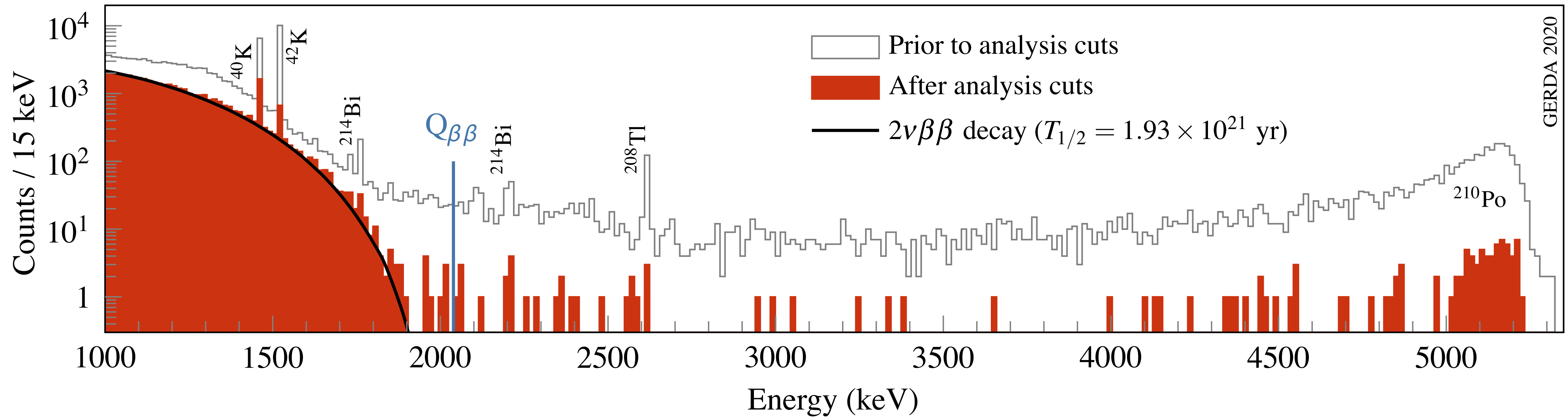
Figure 6. Schematic view of the GERDA setup. Figure published by Nature, 2017 [62].

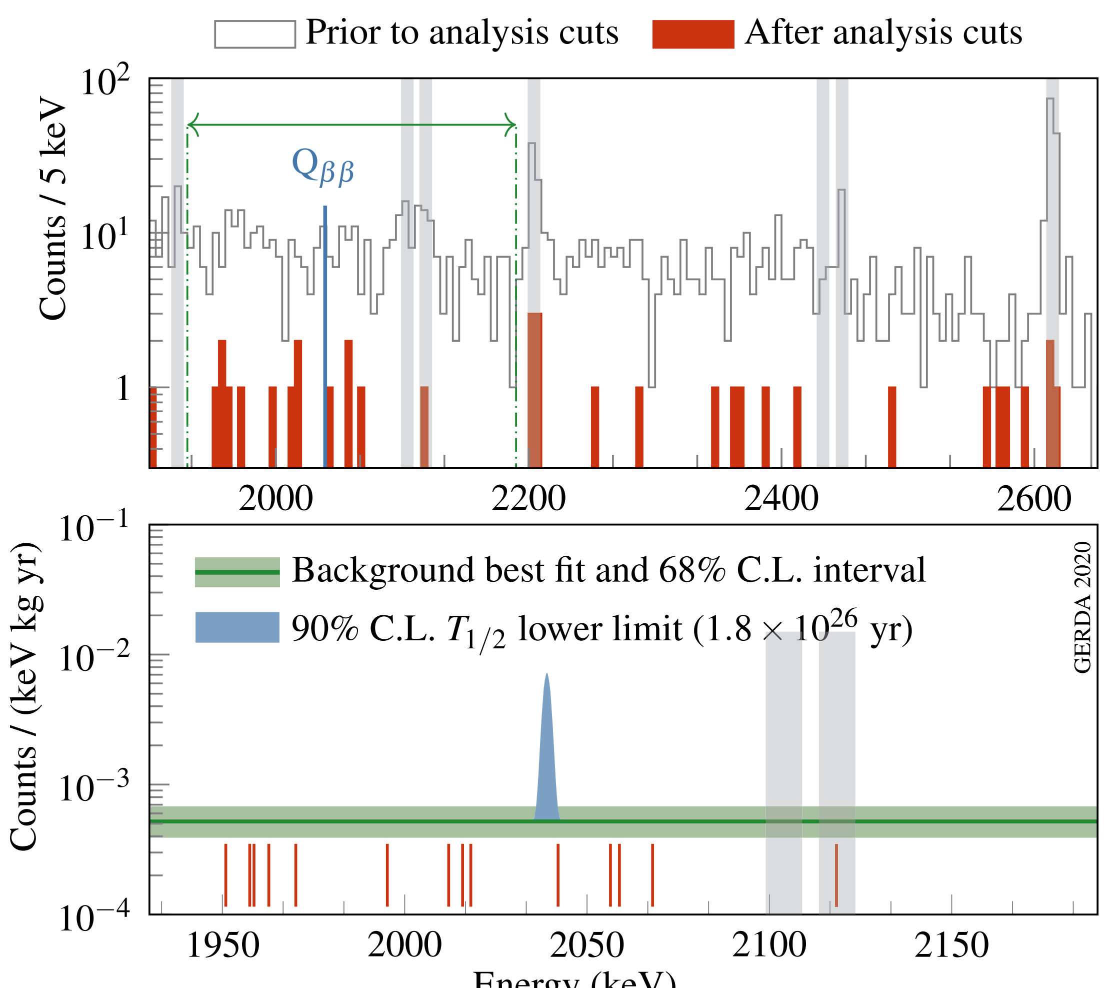
arXiv:2109.07575v1 [hep-ex] 15 Sep 2021

Latest result of GERDA

- Phase II: 2015-2021, 103.7 kg-yr exposure

Phys. Rev. Lett. 125, 252502 (2020)





BI: $5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV·kg·yr)

Best value for Ge detector

GERDA Phase I + II

Exposure: 127. 2 kg yr

Limit (90% C.L.)

$T_{1/2} > 1.8 \times 10^{26}$ yr

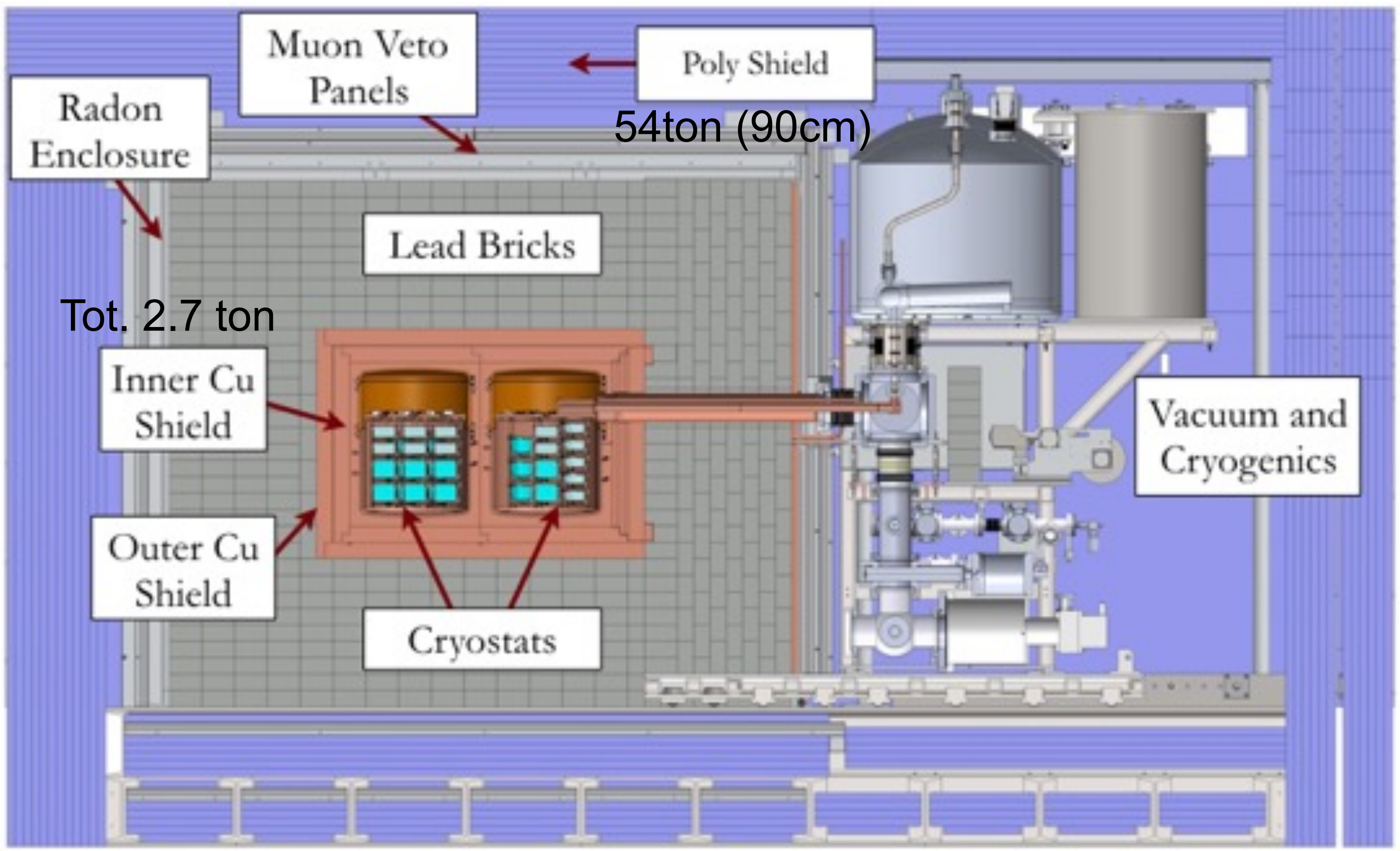
$m_{\beta\beta} < 79 - 180$ meV

assuming $g_A \sim 1.27$

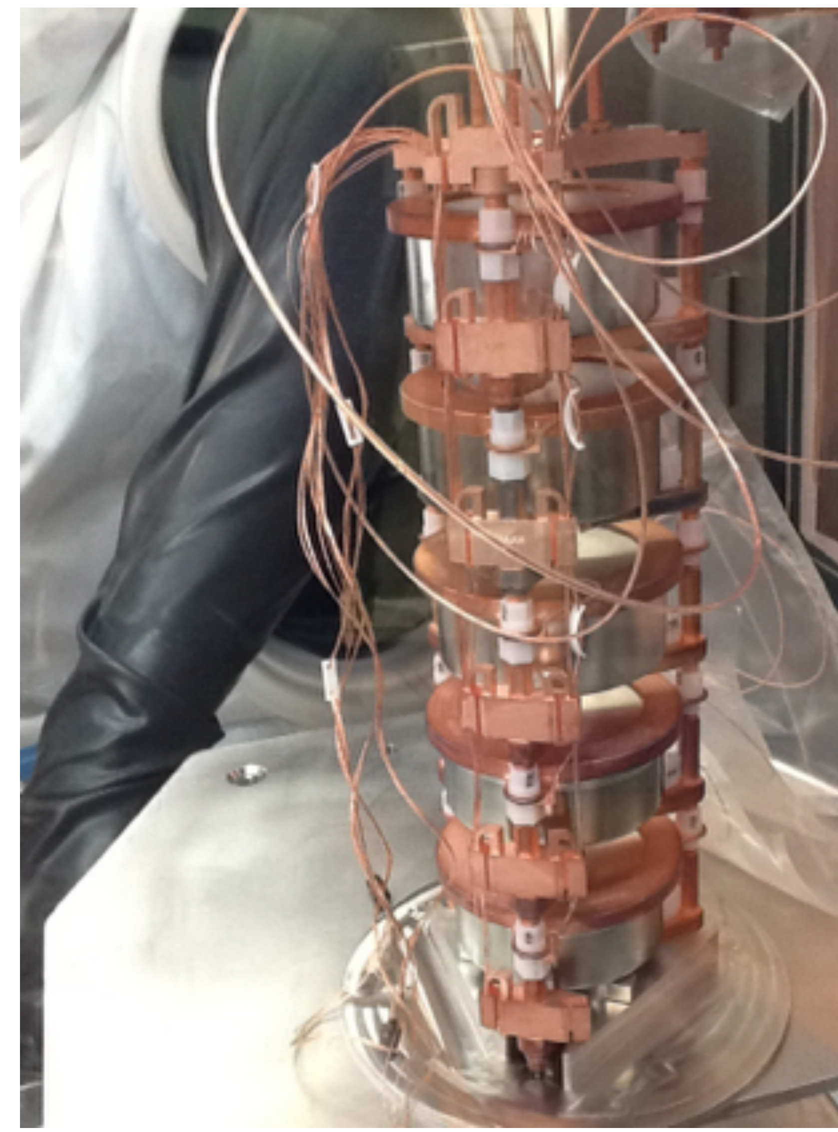
MAJORANA Demonstrator

DBD search: Completed

- Located at Sanford Underground Research Facility (USA), ~4300 m.w.e.
- 29.7 kg of 88% enriched ^{76}Ge + 14.4 kg natural Ge detectors
- Energy resolution: **2.5 keV** FWHM @ 2039 keV
- Low noise electronics



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



Latest result of MAJORANA Demonstrator

- 2015-2021, 65 kg-yr exposure

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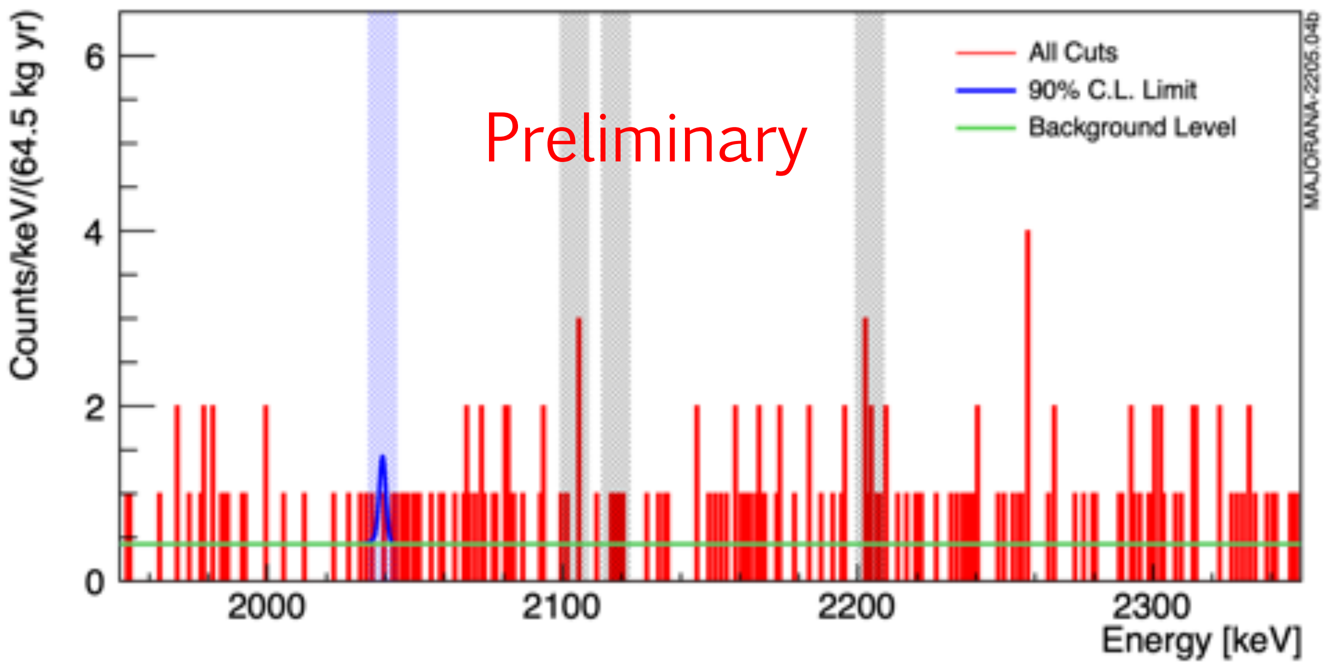
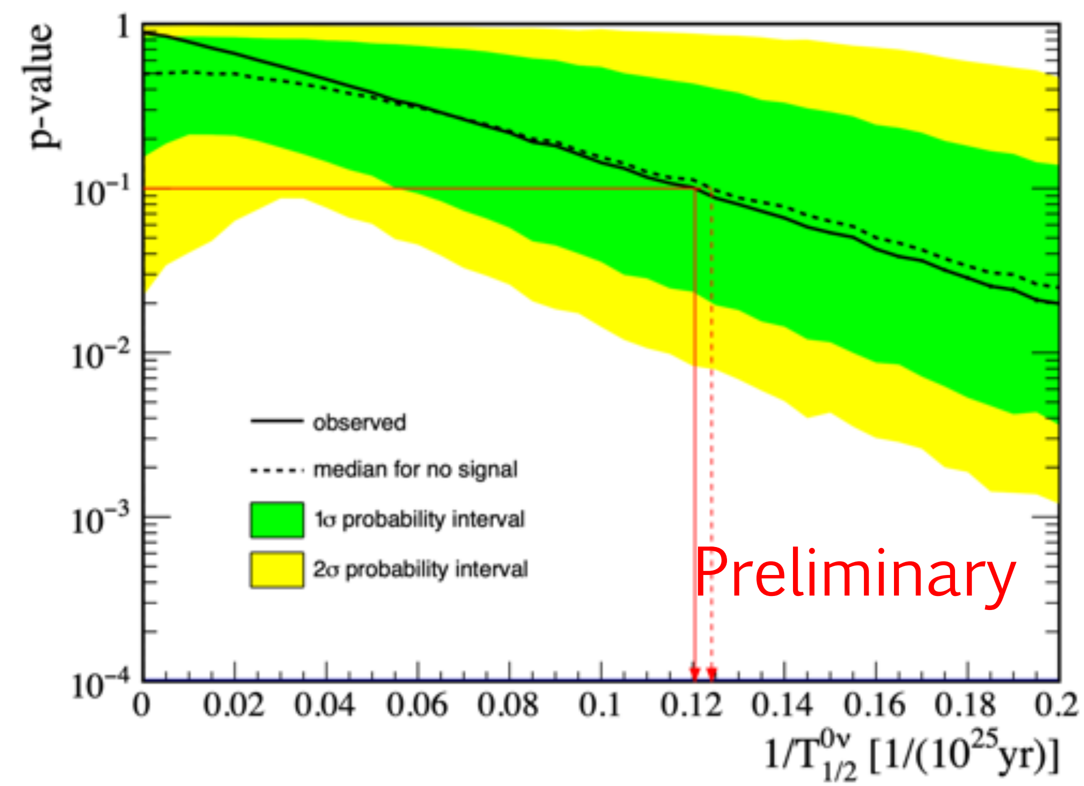
Results





Background Index: $(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)

65 kg-yr Exposure Limit: **$T_{1/2} > 8.3 \times 10^{25}$ yr** (90% C.I.)

Bayesian Limit: (flat prior on rate)

65 kg-yr Exposure Limit: **$T_{1/2} > 7.0 \times 10^{25}$ yr** (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

LEGEND

Target sensitivity for LEGEND-200: > 10^{27} yr (IO), LEGEND-1000: > 10^{28} yr (NO)

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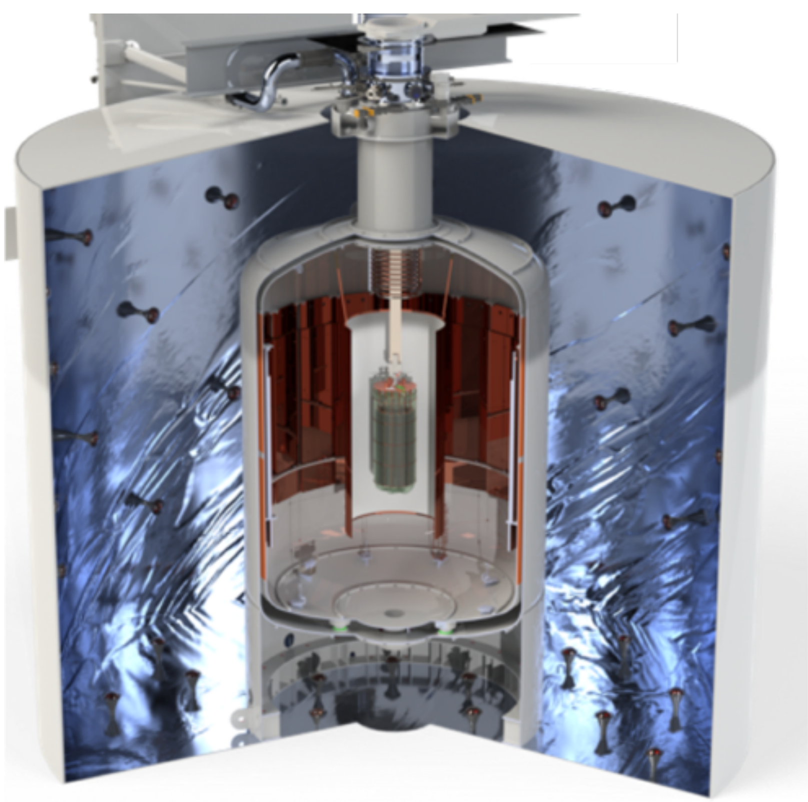
LEGEND Approach: Phased Deployment



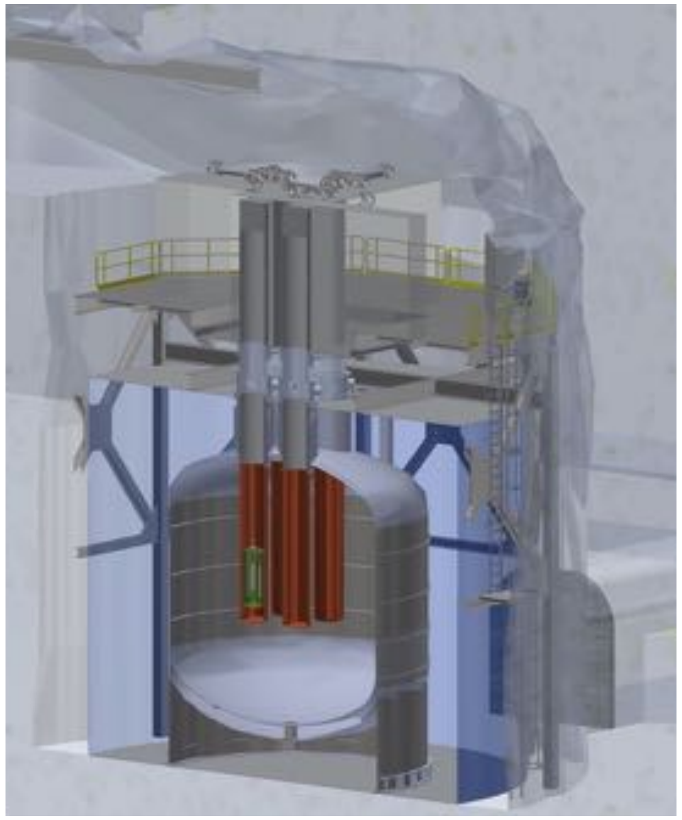
arXiv: 2107.11462

LEGEND-200:

- 200 kg, upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal

  < 0.6 cts/(FWHM t yr)

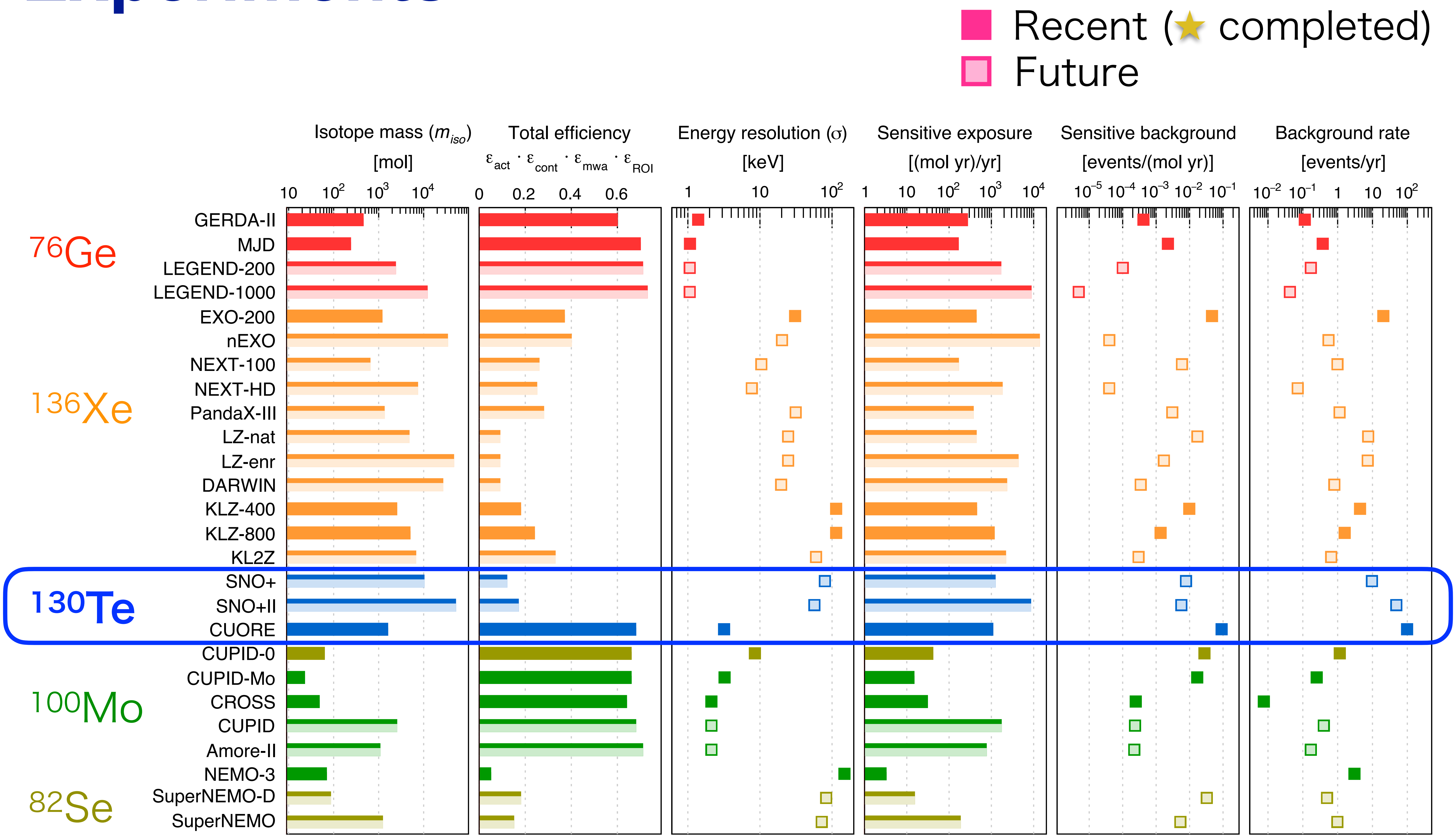
  < 2×10^{-4} cts/(keV kg yr)
- Now in commissioning, physics data starting in 2022



LEGEND-1000:

- 1000 kg, staged via individual payloads (~400 detectors)
- Timeline connected to review process
- Background goal <0.025 cts/(FWHM t yr),<1×10^{-5} cts/(keV kg yr)
- Location to be selected

Experiments from arXiv:2202.01787v1 [hep-ex]



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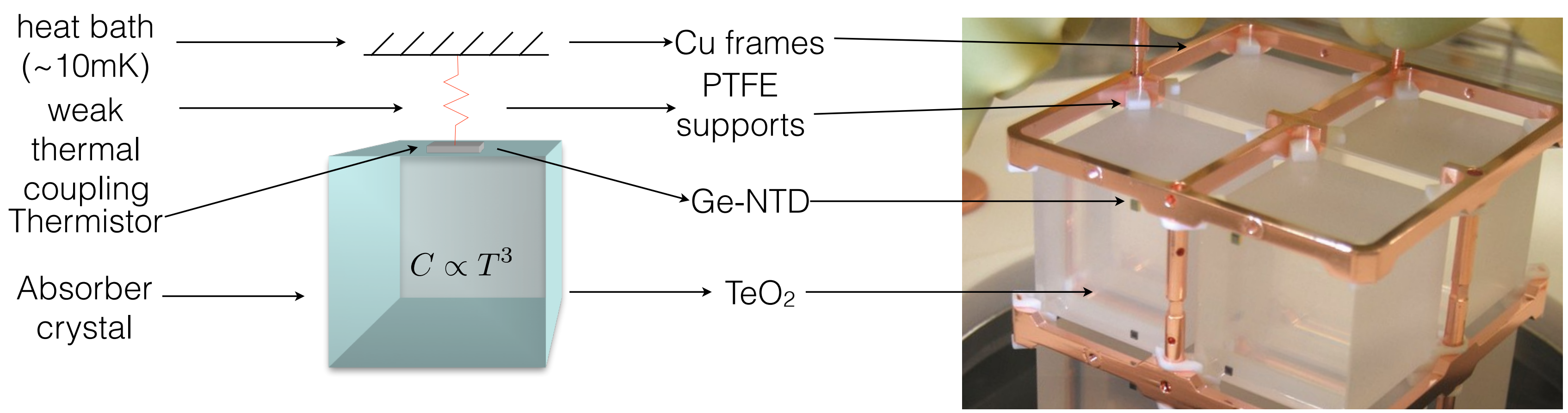
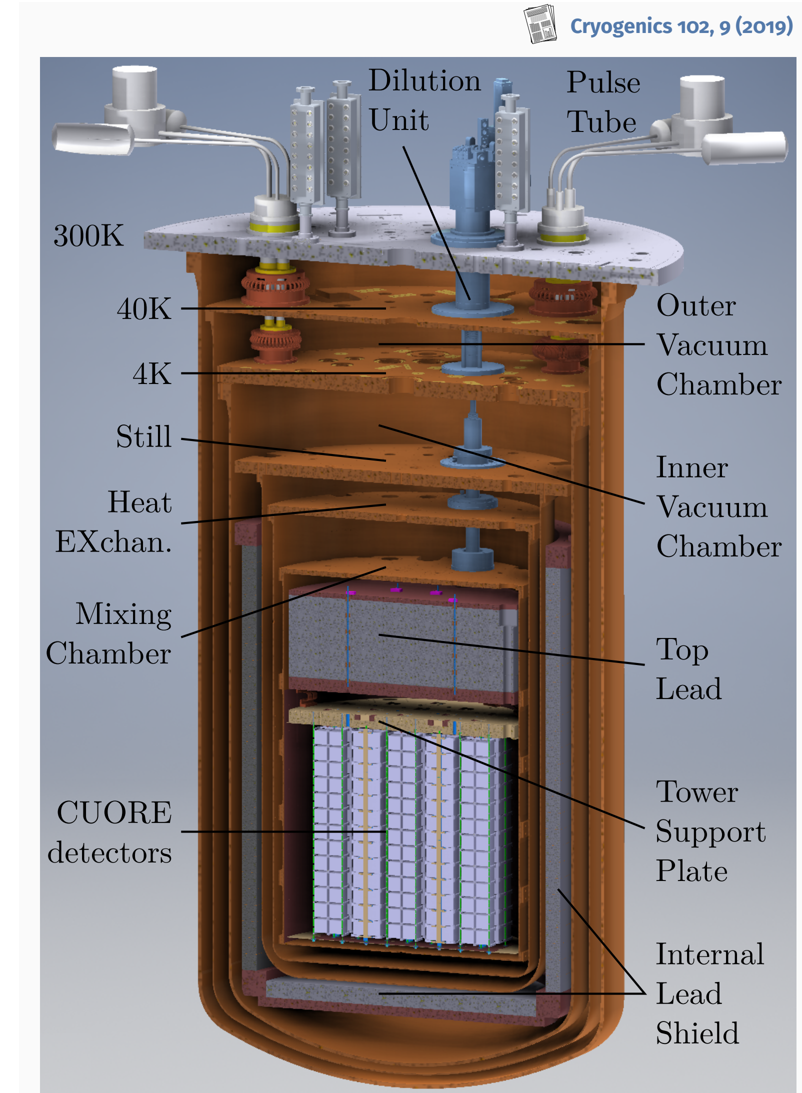
CUORE (Cryogenic Underground Observatory for Rare Events)

Running

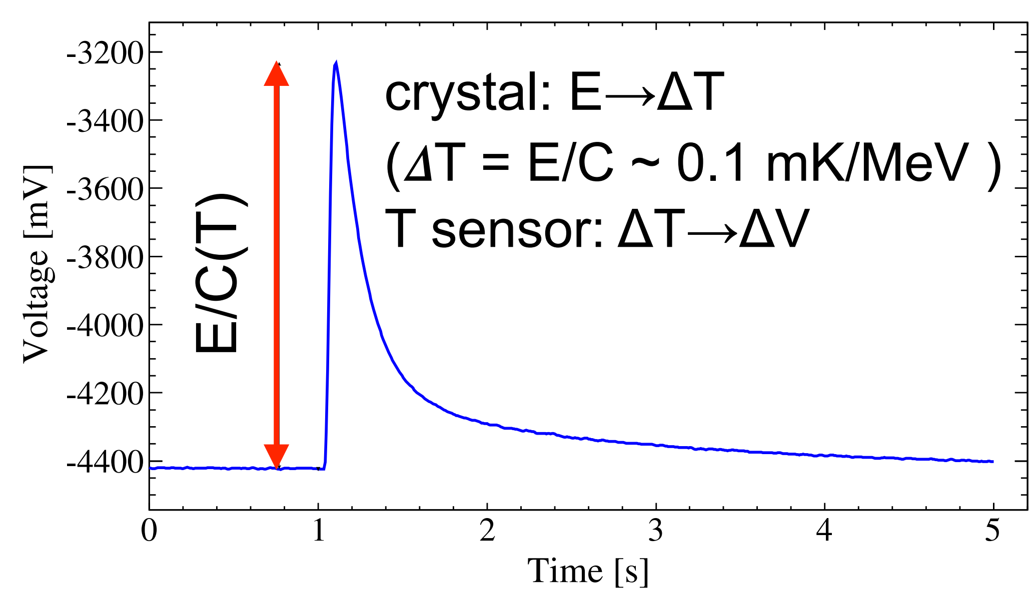
- **^{130}Te** (N.A. 34.2%, Q-value 2527keV).
- Located at LNGS (Italy), ~3600 m.w.e.
- **TeO_2 bolometers** (988 crystals in 19 towers, 742 kg),
- a total mass of ^{130}Te = 206 kg, 188 kg of ^{128}Te
- Energy resolution ~8 keV FWHM @ Q-value



↑
5×5×5 cm^3



Operated at ~10 mK (7mK as lowest).



- Start DAQ in Apr. 2017
- Goal of exposure: 3 t yr of TeO_2 (~1 ton yr of ^{130}Te)

Latest result of CUORE

^{130}Te 0νββ decay search

CUORE

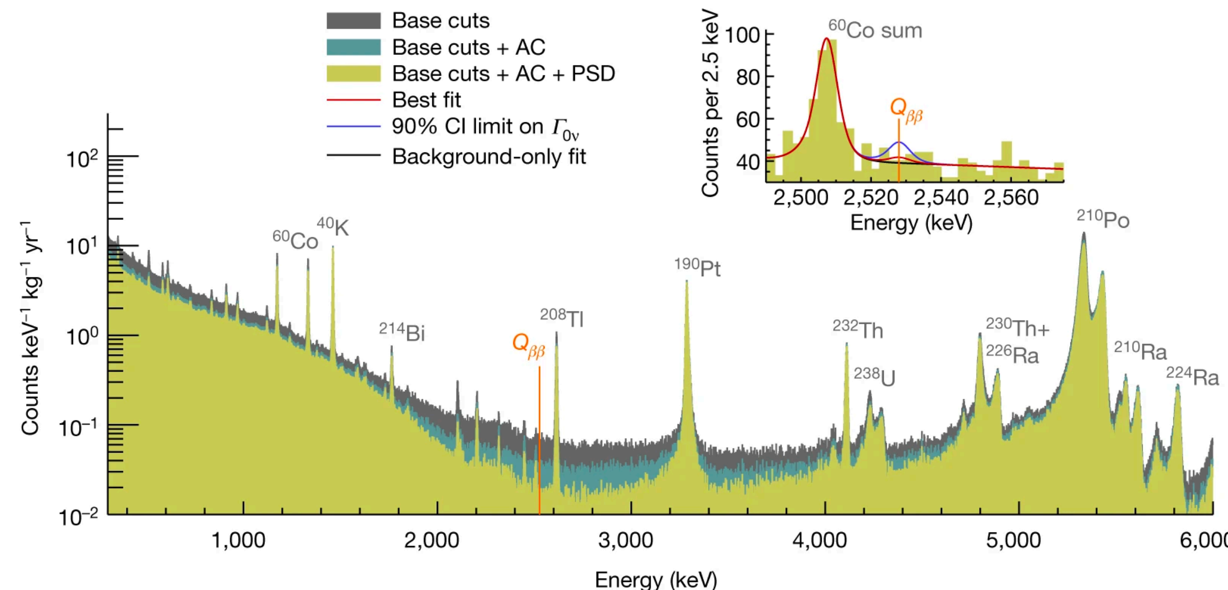
Total exposure:
1038.4 kg yr TeO_2, 288 kg yr ^{130}Te
Selection efficiencies: 92.4(2)%

^{130}Te $Q_{\beta\beta}$= 2527.5 keV

Reconstructed energy resolution at $Q_{\beta\beta}$:

7.8(5) keV FWHM

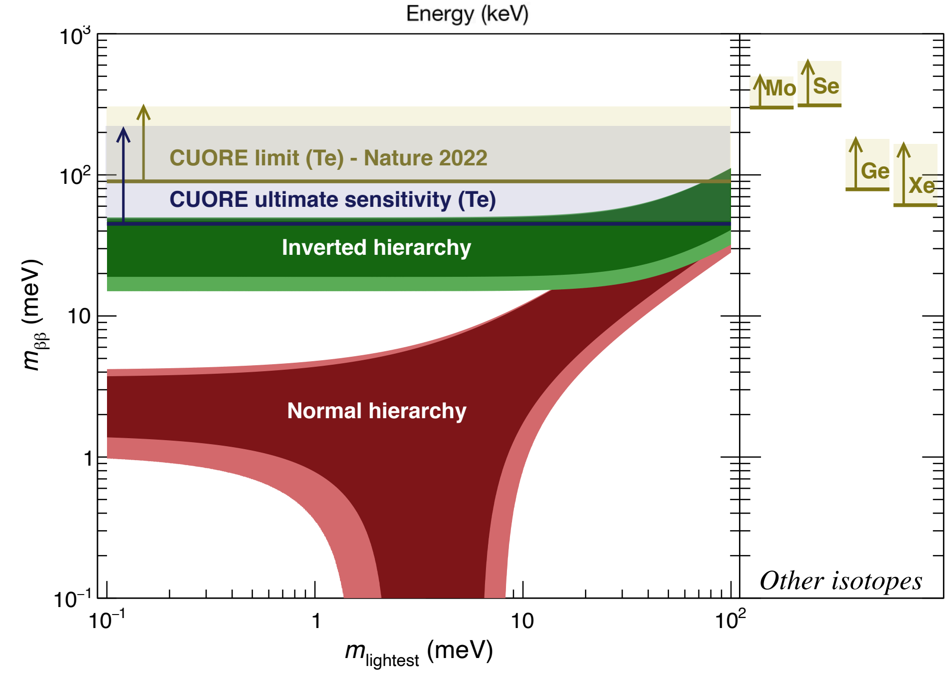
ROI background index (B)
~ 1.49(4) × 10^{-2} c/(keV·kg·yr)



0νββ analysis

Half-life limit for 0νββ in ^{130}Te (90%C.I. including syst.)
$T_{0\nu}^{1/2}$ (^{130}Te) > 2.2 x 10^{25} yr

$m_{\beta\beta}$ < 90 - 305 meV



Result published on Nature (2022)!

Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

SNO+ Phase I ~780 ton LS

Soon

Original: Neutrino oscillation experiment with heavy water, SNO. Nobel prize in 2015

- ^{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).
- Target sensitivity for Phase I: IO (~ 4 ton), Phase II: NO (~20 ton)

ICHEP 2022, Weinheimer

WWU MÜNSTER

SNO+

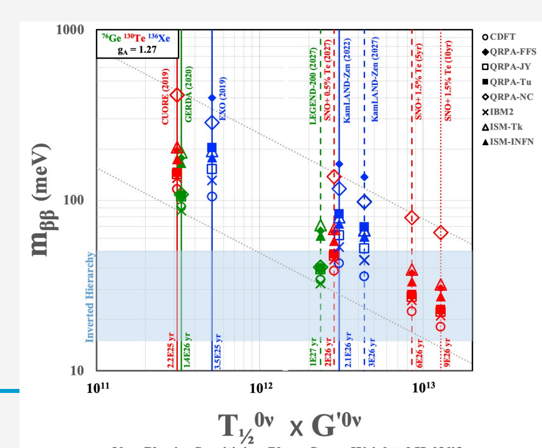
SNO+ is an operating neutrino detector at SNOLab with 780 t of liquid scintillator (2.2 g/L PPO in LAB)

Water Phase: completed
- set world-leading limits on invisible nucleon decay
- measured the ^{8}B solar neutrino flux with very low backgrounds

Pure Scintillator Phase: now
- detecting low energy ^{8}B solar neutrinos
- detecting reactor (and geo) antineutrinos to independently measure Δm^2_{12}
- supernova neutrino live

Double Beta Decay Phase:
- add up to 4,000 kg of ^{130}Te to the detector
- with sensitivity in the IM Ordering parameter space
- Tellurium systems are built ready for operation: Full-scale test batches in 2022 and 2023
- Goal: Begin loading Te in the detector in 2024

courtesy: Christine Kraus



Christian Weinheimer – Neutrino Mass and Nature – ICHEP 2022

Experiments
from arXiv:2202.01787v1 [hep-ex]

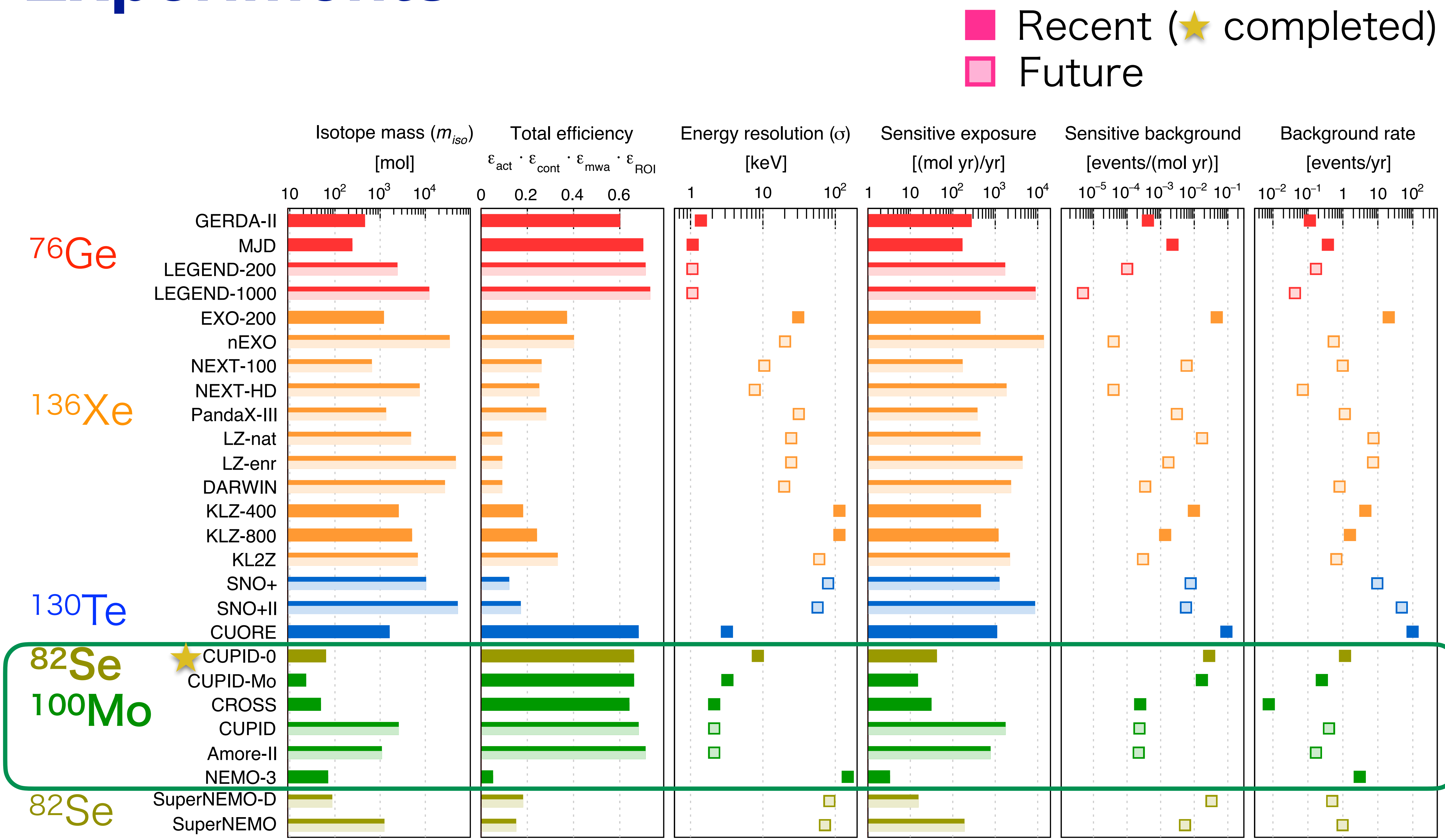
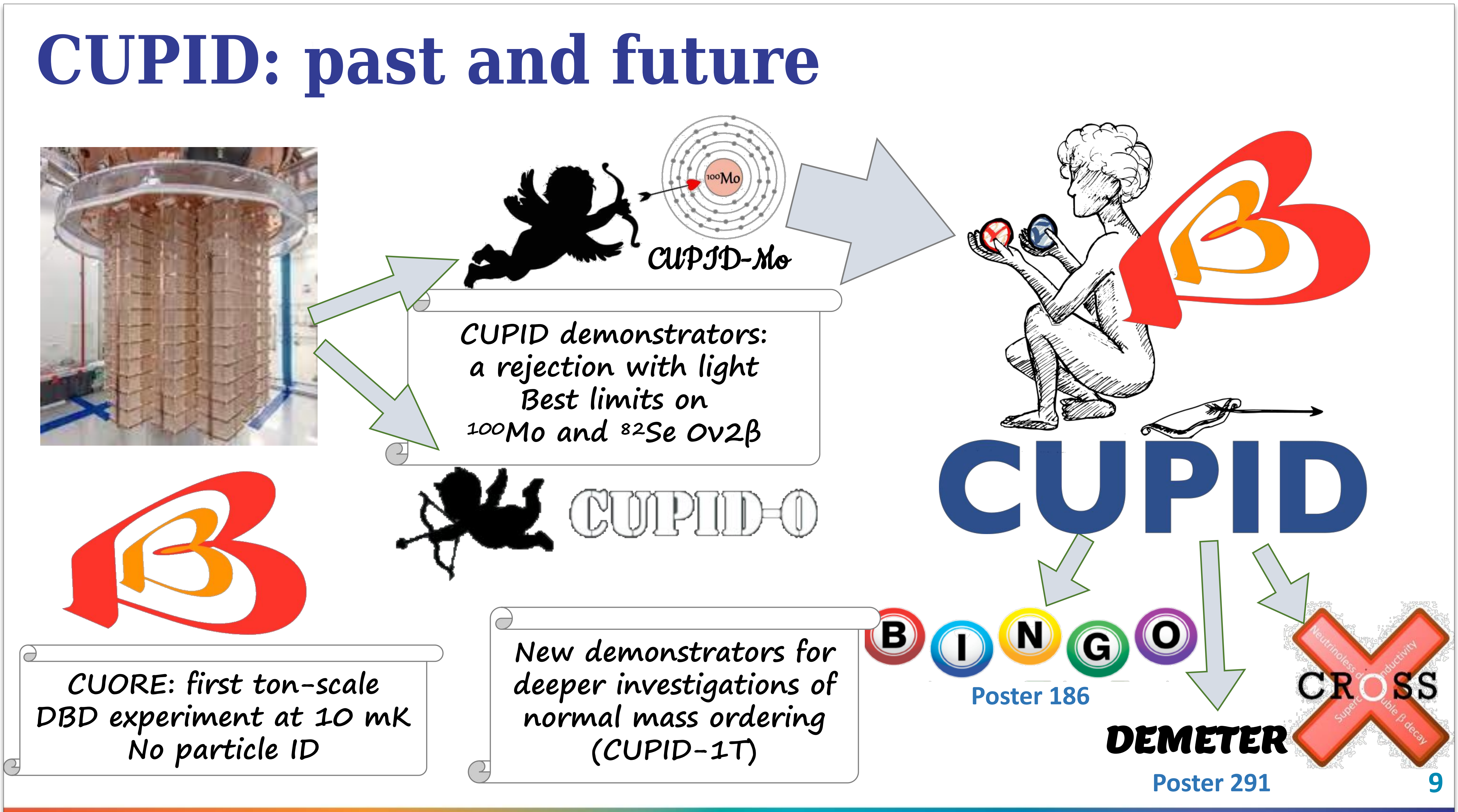


FIG. 16 Fundamental parameters driving the sensitive background and exposure, and consequently the sensitivity, of recent and future phases of existing experiment. Red bars are used for ^{76}Ge experiments, orange for ^{136}Xe, blue for ^{130}Te, green for ^{100}Mo, and sepia for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency by gas and liquid detectors, or with small mass but high resolution and efficiency by solid state detectors. The sensitive exposure is computed for one year of livetime. Ligher shades indicate experiments which are under construction or proposed.

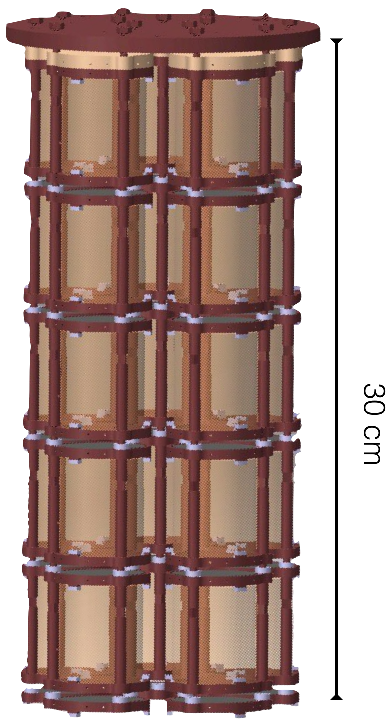
CUPID (Cuore Upgrade with Particle ID)

- CUORE's BG: from alpha particles (~90%)
- Background rejection with PID -> Scintillating bolometer
- Target sensitivity: 12 - 20 meV



CUPID-0 (First pilot detector for CUPID)

Completed



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

95% enriched Zn^{82}Se bolometer

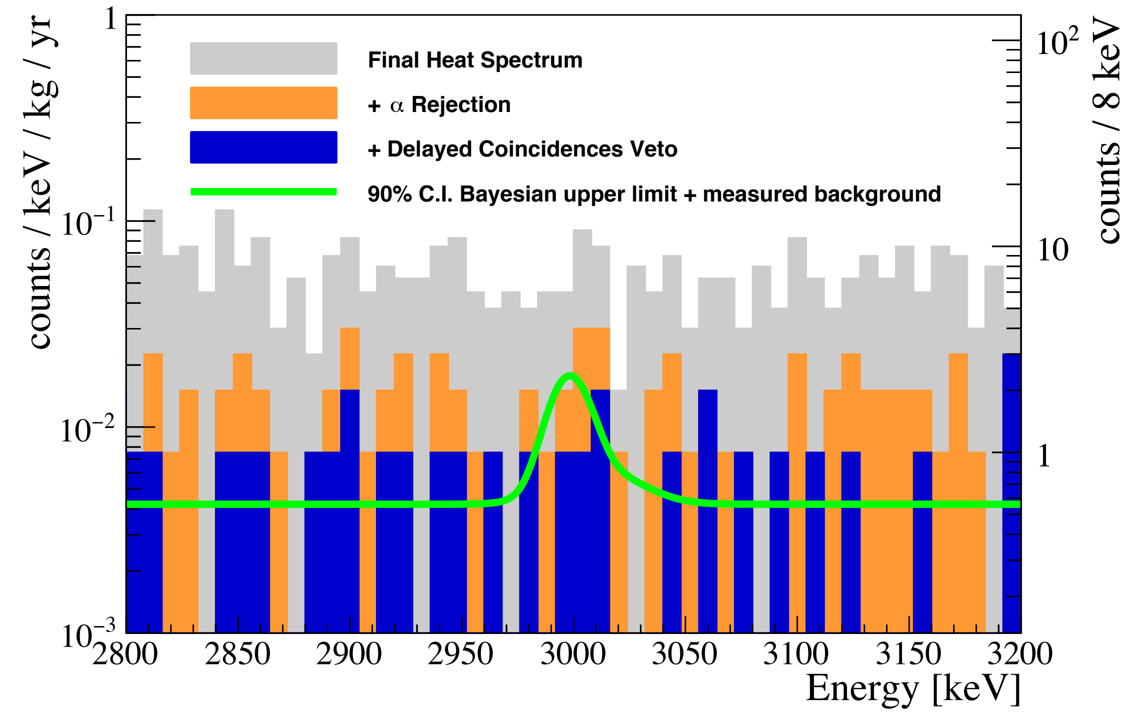
Operated at LNGS

Exposure 16.59 kg yr

$T^{1/2} > 4.6 \times 10^{24}$ yr (90% C.L.)

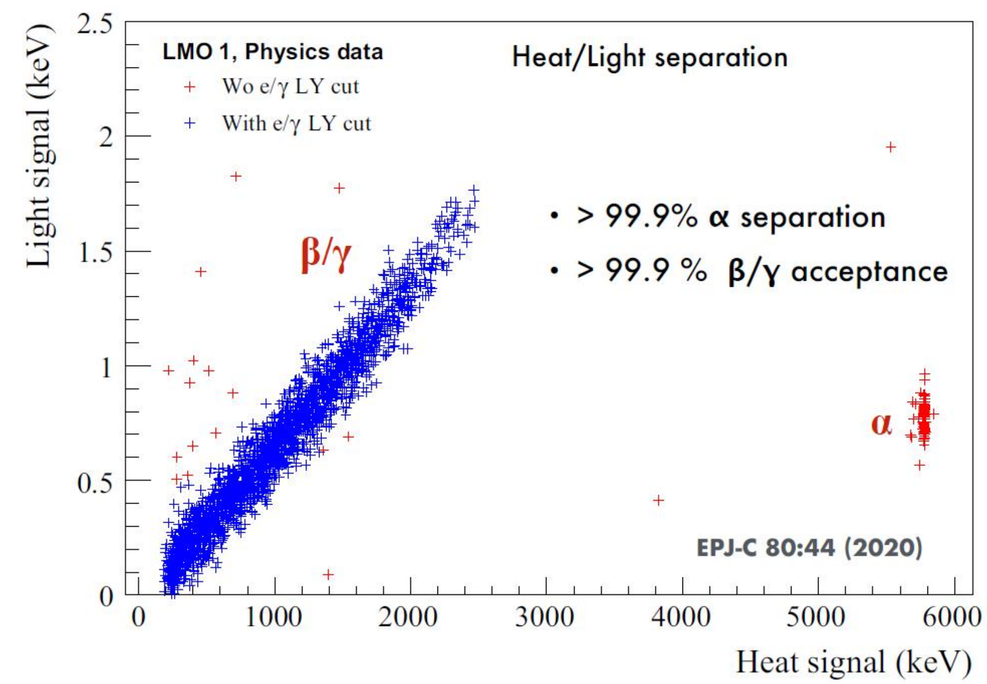
$m_{\beta\beta} < 263 – 545$ meV

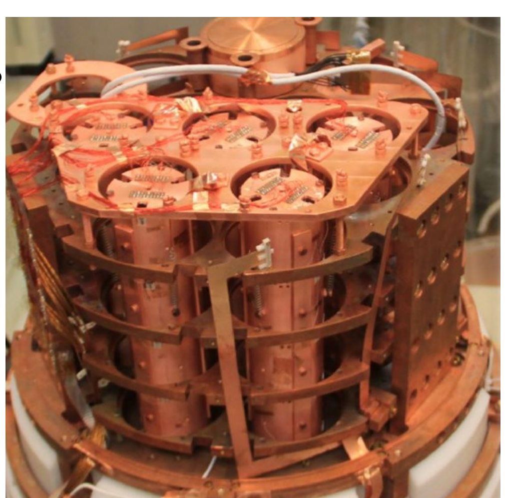
arXiv:2206.05130 [nucl-ex]



CUPID-Mo

- A demonstrator for CUPID
- Target isotope ^{100}Mo (Q-value 3034 keV) in $Li_2{}^{100}MoO_4$ (scintillating bolometer)
- Total of 2.26 kg of ^{100}Mo





- Higher energy resolution (7.4 vs 20 keV)
- Low radioimpurity (ZnSe crystals ~30 times higher U/Th contamination)
- Easier crystal growth

Exposure (^{100}Mo) 1.17 kg yr

$T^{1/2} > 1.5\times10^{24}$ yr,

$m_{\beta\beta} < 0.31 - 0.54$ eV

Phys. Rev. Lett. 126, 181802

Experiments from arXiv:2202.01787v1 [hep-ex]

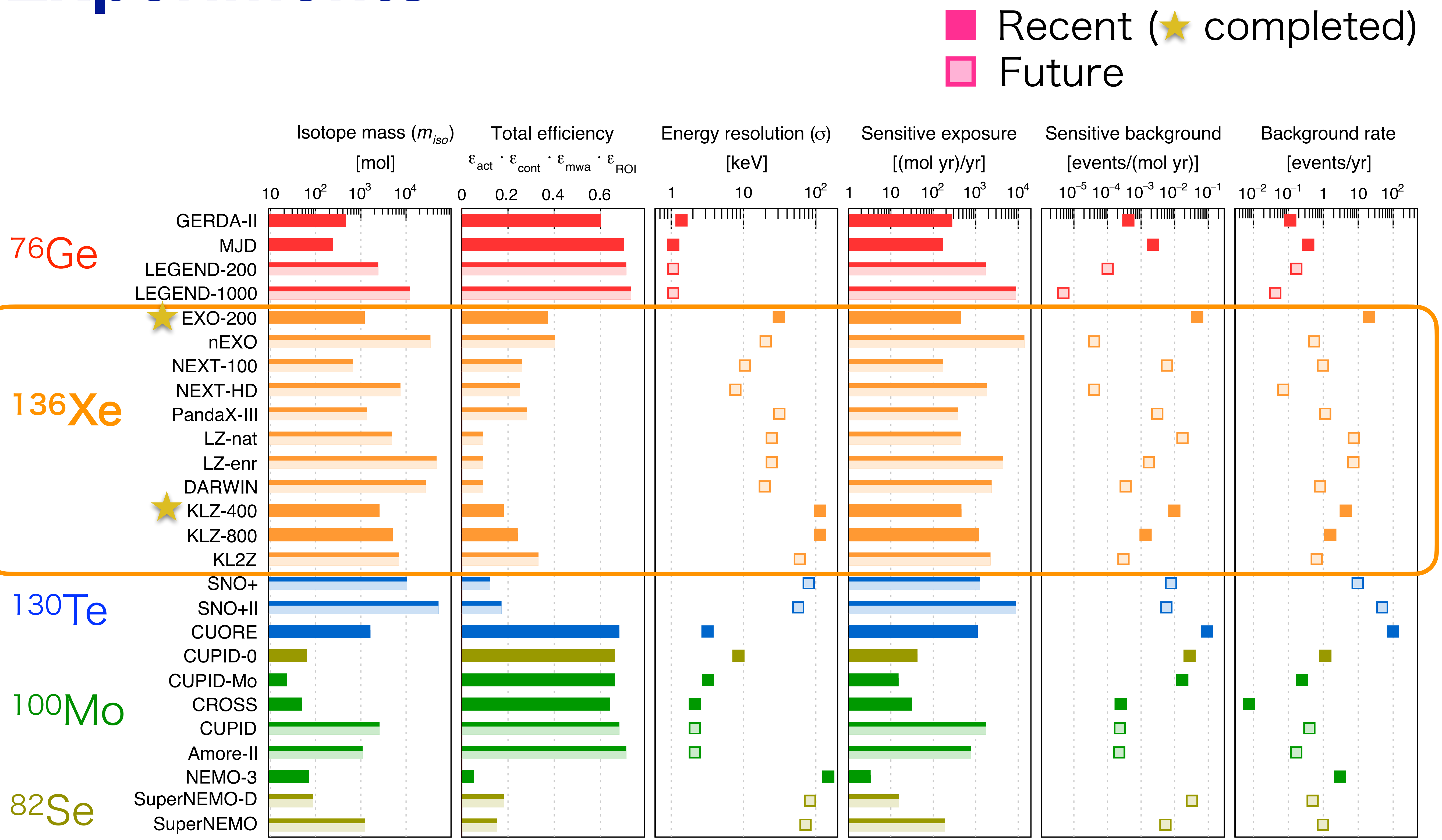
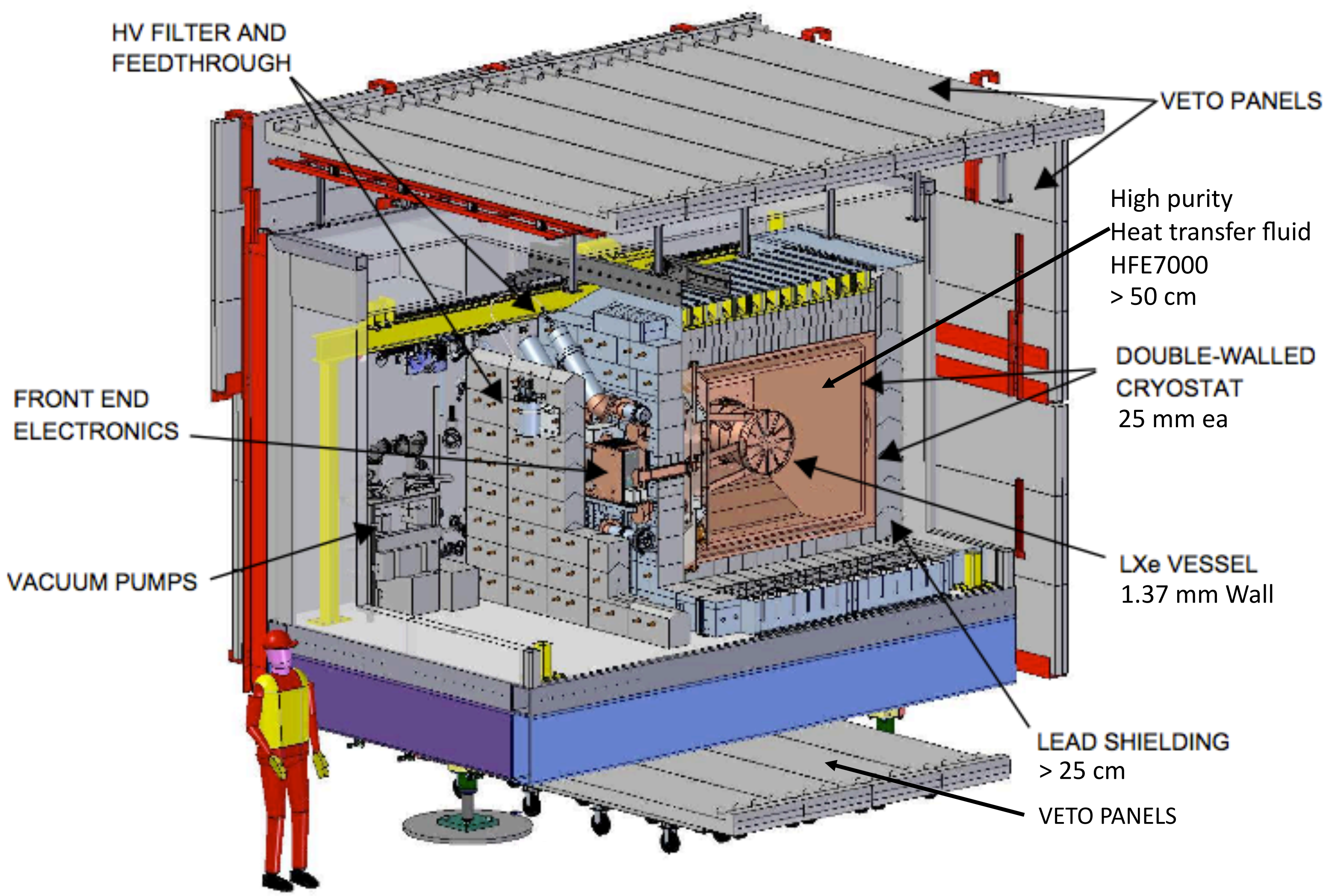


FIG. 16 Fundamental parameters driving the sensitive background and exposure, and consequently the sensitivity, of recent and future phases of existing experiment. Red bars are used for ^{76}Ge experiments, orange for ^{136}Xe, blue for ^{130}Te, green for ^{100}Mo, and sepia for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency by gas and liquid detectors, or with small mass but high resolution and efficiency by solid state detectors. The sensitive exposure is computed for one year of livetime. Ligher shades indicate experiments which are under construction or proposed.

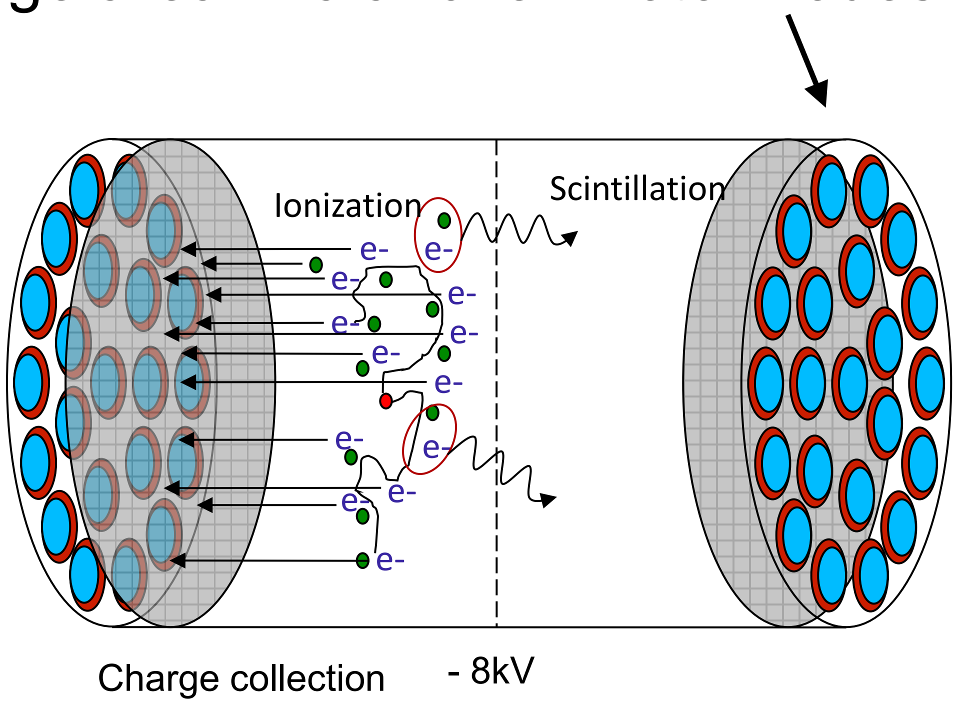
EXO-200

Completed

- ^{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



Large area Avalanche Photo Diodes



Example of TPC schematics (EXO-200)

40cm

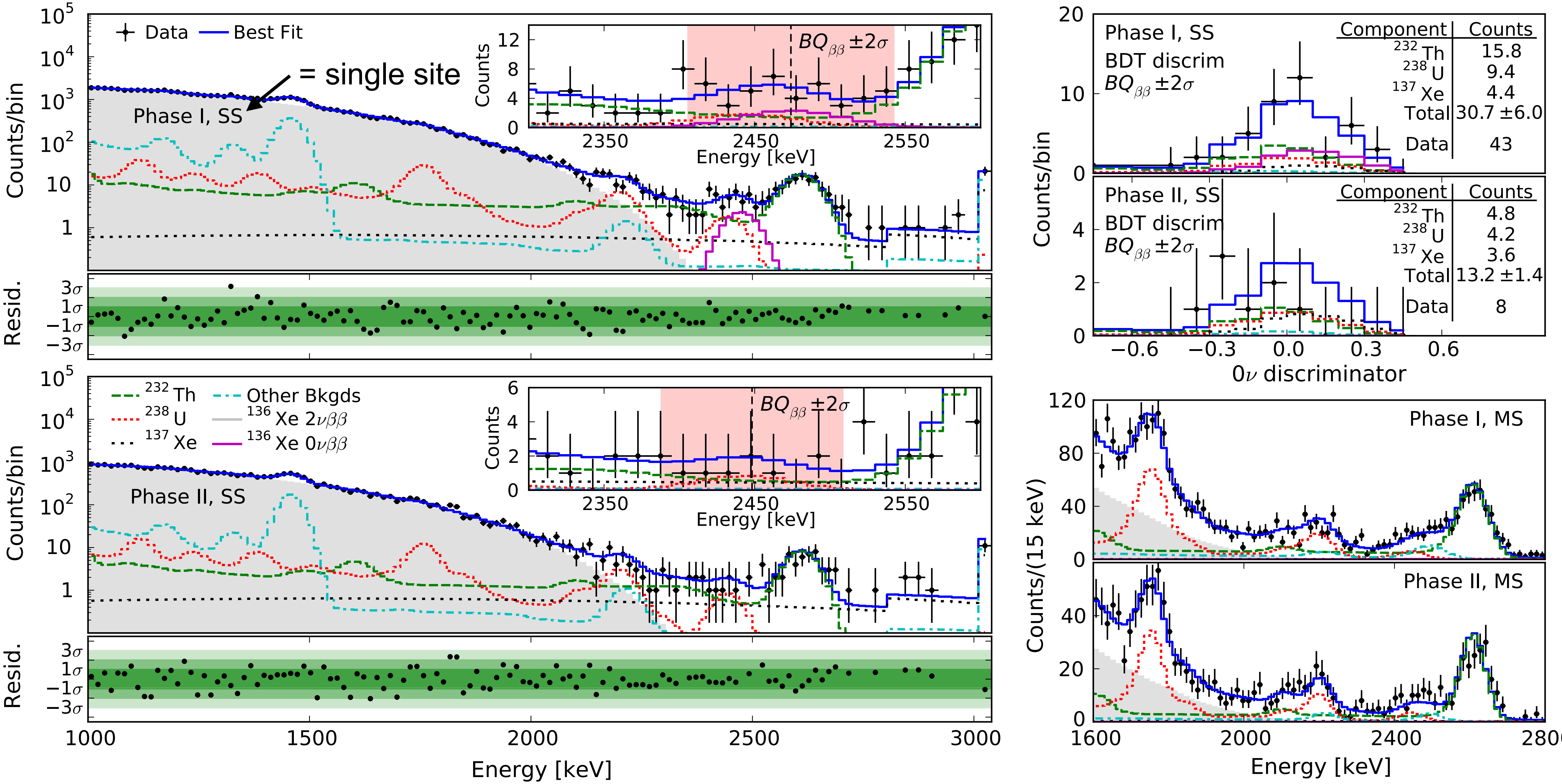
- Scintillation collected by APDs
- Amount and position of charge collected by 2 wire grids

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

Final result of EXO-200

Phys. Rev. Lett. **123,** 161802 (2019)

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



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

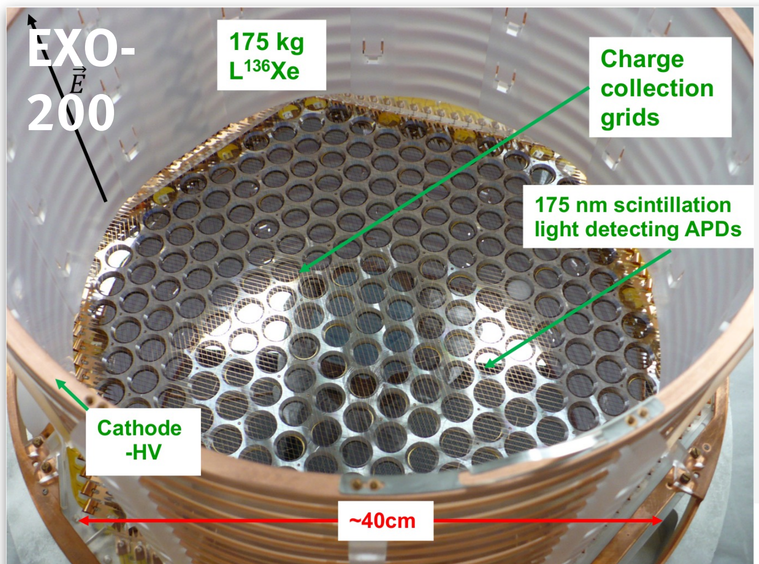
$T^{1/2} > 3.5 \times 10^{25}$ yr

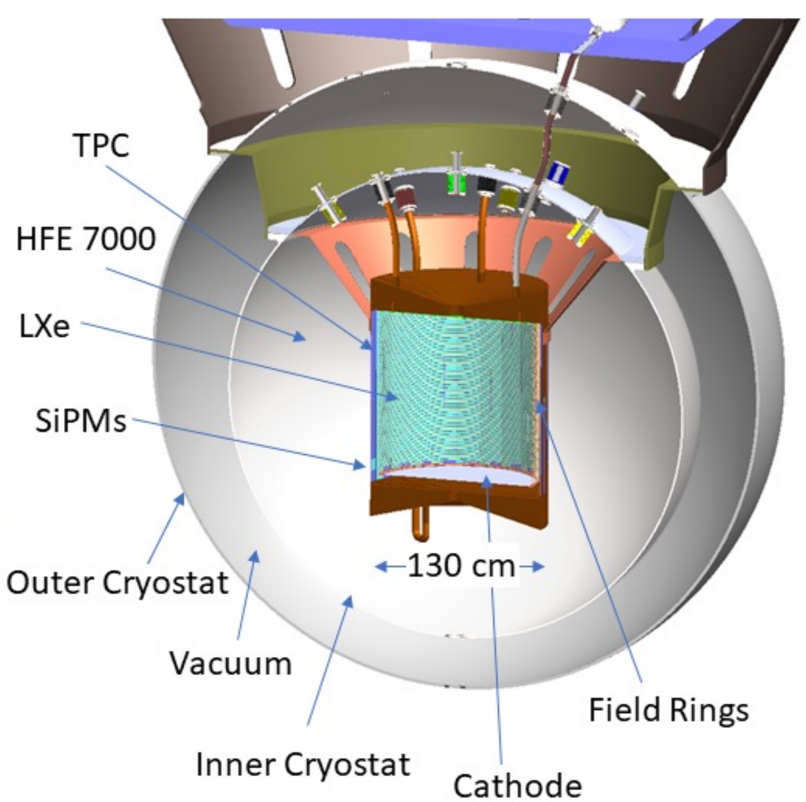
$m_{\beta\beta} < 93 - 286$ meV

nEXO

- ~5 ton of Xenon
- Target energy resolution: ~46 keV FWHM @ Q-value
- Target sensitivity ~ 1.35×10^{28} yr, 5-20 meV (10yr)

ICHEP 2022, Weinheimer





nEXO: a single phase ^{136}Xe-enriched LXe TPC

talk by Zepeng Li

nEXO: LXe TPC

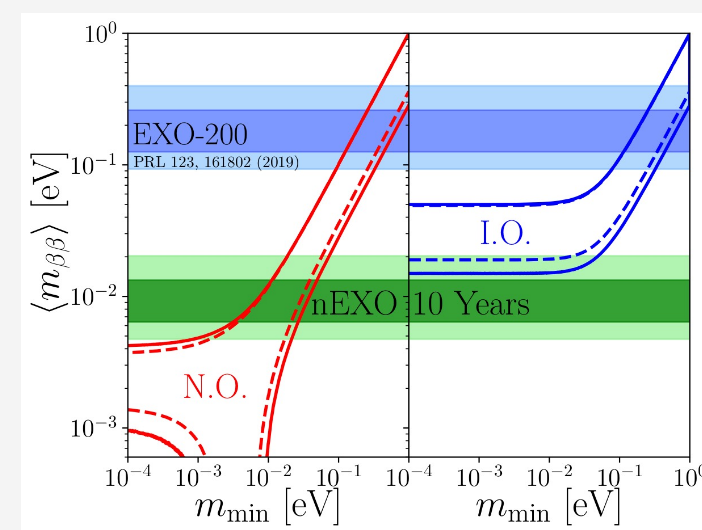
enriched ^{136}Xe: 5 t
energy resolution: ≈ 46 keV (FWHM)
background index: $B = 7 \cdot 10^{-5}$ counts/(FWHM kg yr)

→ expected sensitivity (10 yr): $T^{0\nu}_{1/2} > 1.35 \cdot 10^{28}$ yr (90% C.L.)

→ expected sensitivity (10 yr): $m_{\beta\beta} < 5 - 20$ meV

G Adhikari et al. (nEXO Coll.) J. Phys. G: 49 (2022) 015104

	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e- lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons



courtesy Giorgio Gratta

KamLAND-Zen

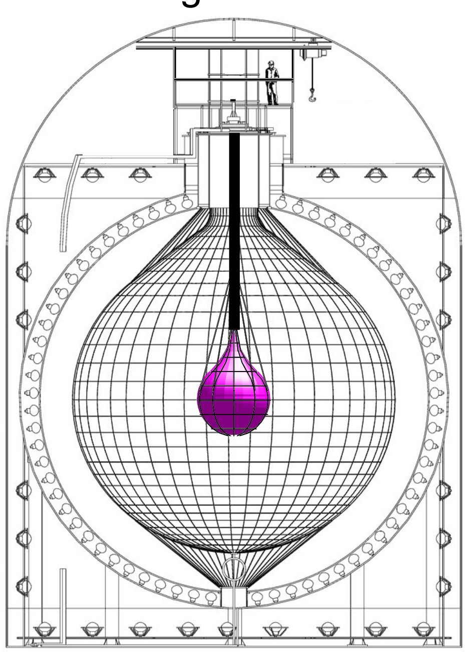
1000 ton LS
Modification of KamLAND (reactor-, geo-, solar-, astro-nu etc)

Double beta decay isotope: ^{136}Xe

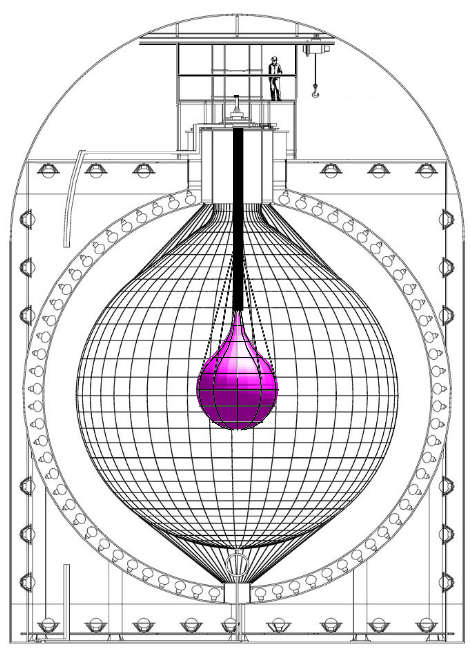
- Q-value 2.458 MeV
- Dissolved into LS ~3% by weight
- Enrichment ~90%
- Half life of $2\nu\beta\beta$ decay is long (~10^{21} yr)

^{136}Xe loaded liquid scintillator
into KamLAND center
with inner balloon

Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015

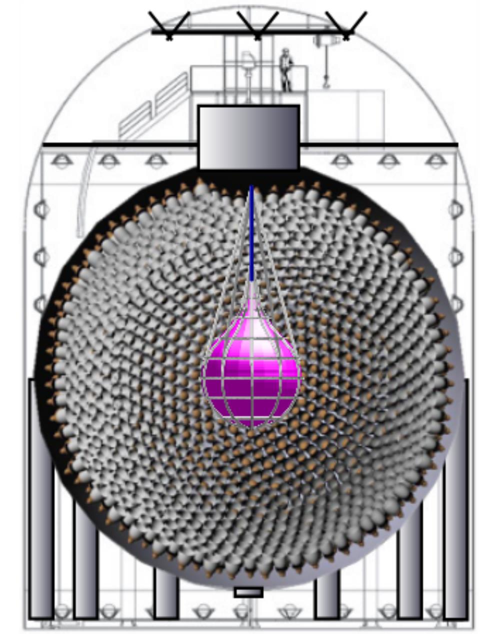


Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019



- Double amount of Xe
- Bigger, cleaner Xe-LS container
- Improved spallation rejection method
- Simultaneous fitting of single event and long-lived products

Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution

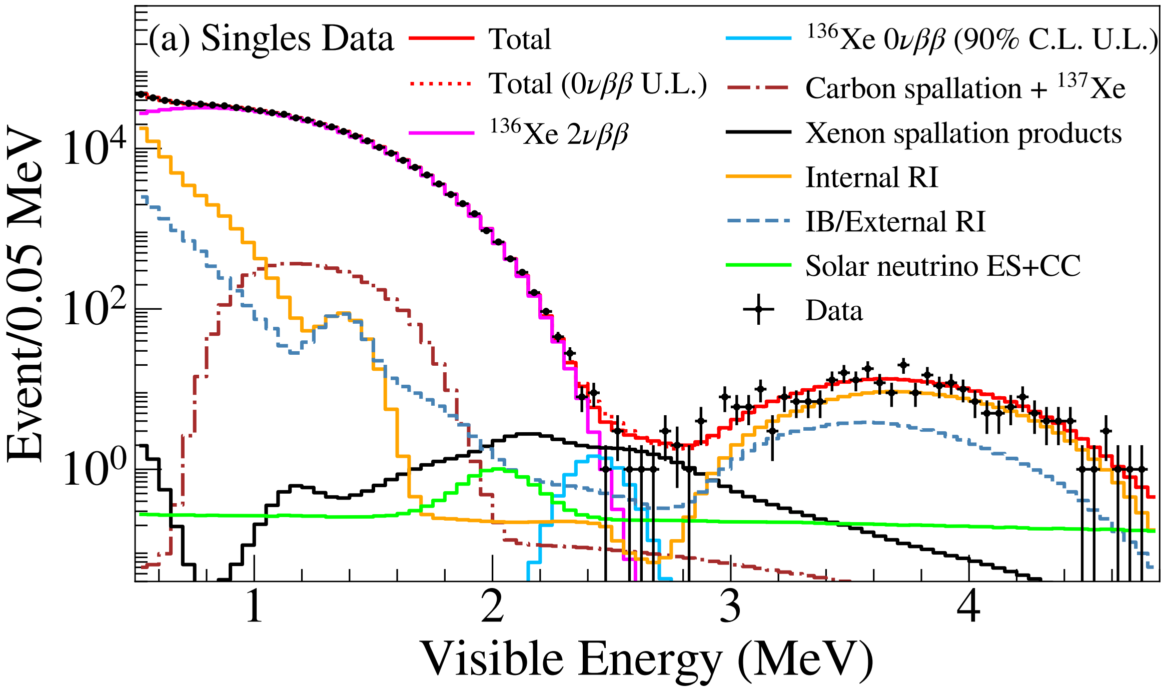


Reanalysis —combined (next page)→ **1st result** $T^{1/2} > 2.0\times10^{26}$ yr (Feb. 2019 - May 2021)

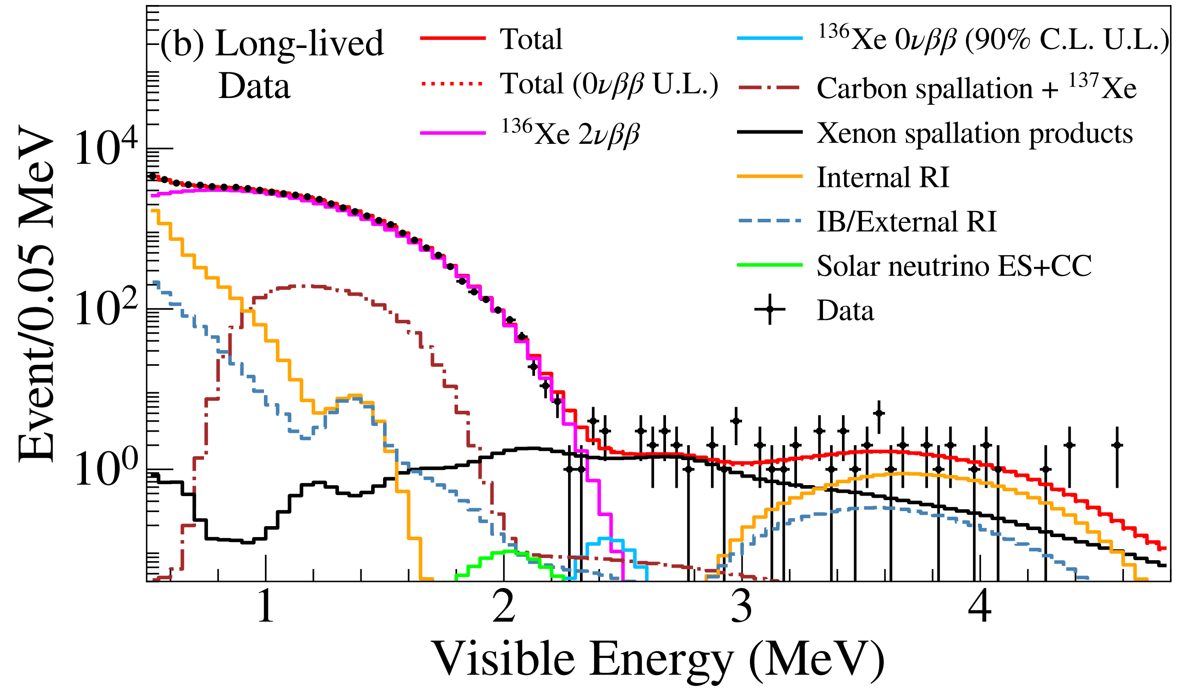
^{136}Xe Half-life limit (KL-Zen 800)

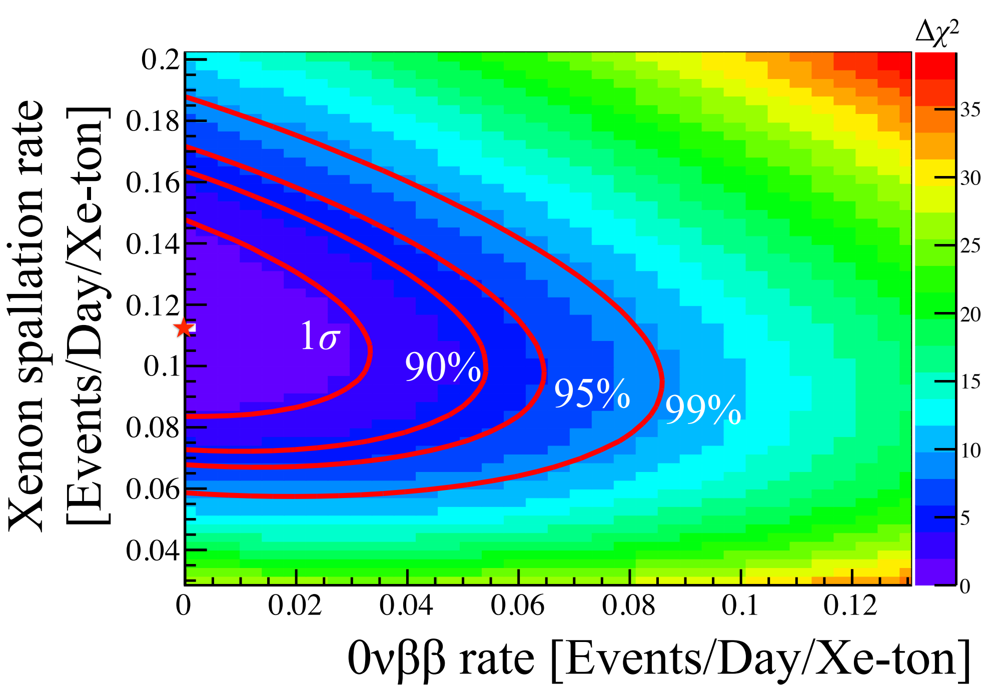
Internal 10 volume bins (1.57-m-radius spherical volume) × 3 time bins

Singles data
(sensitive to 0νββ rate)
Livetime = 523.4 days



Long-lived product data
(used to constrain the LL rate)
Livetime = 49.3 days

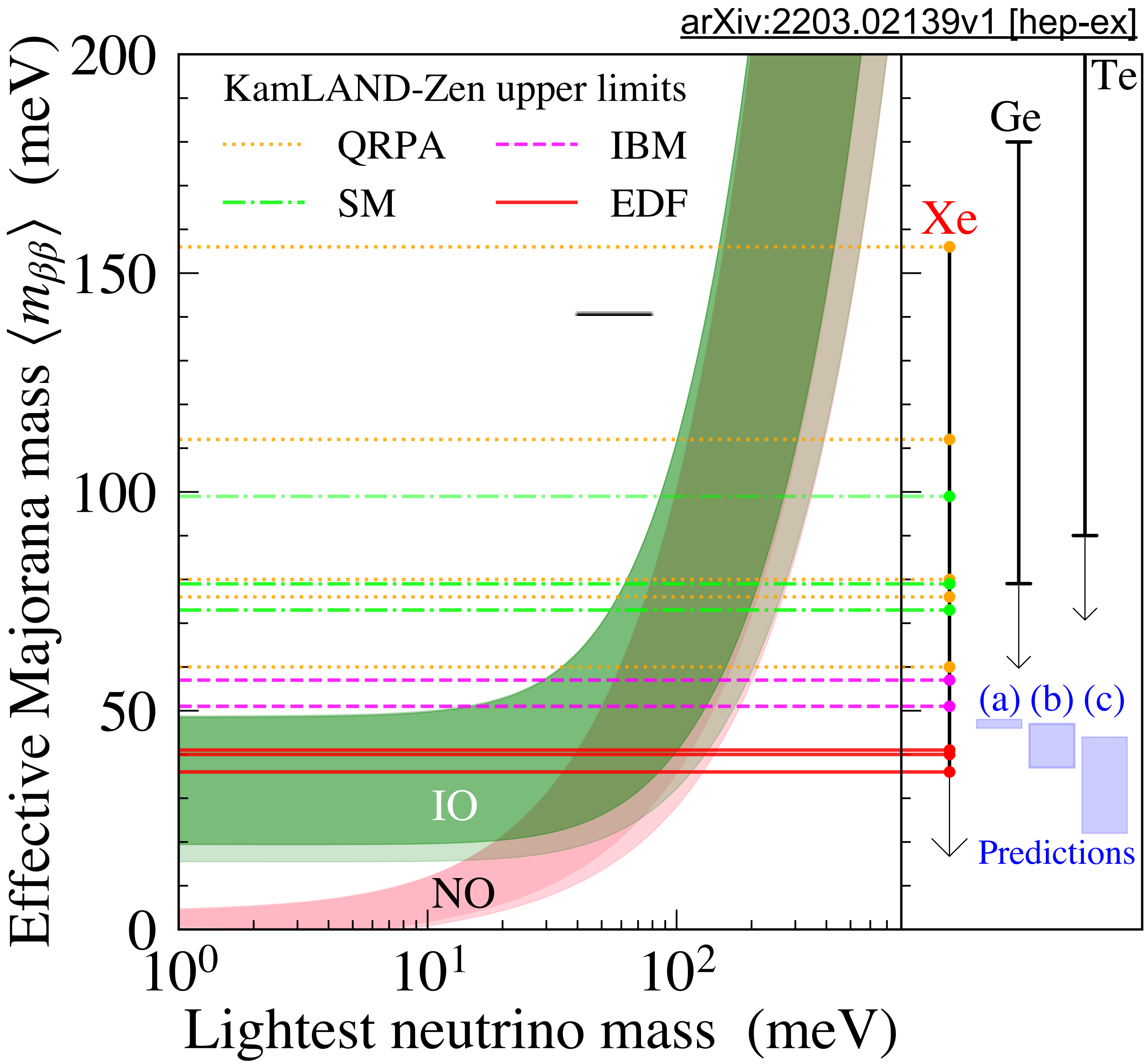




^{136}Xe 0νββ decay rate for KamLAND-Zen 800
Best fit: 0
Upper limit (90% C.L.): < 7.9 events/Xe-LS(30.5 m^3)

$T^{1/2}$ > 2.0×10^{26} yr (90% C.L.)

Limit on the effective neutrino mass



KL-Zen 400 + 800 limit

(90% C.L.)

$T^{1/2}$ > 2.3×10^{26} yr

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

NME ($M^{0\nu}$) : 1.11–4.77

assuming gA ~ 1.27

⟨$m_{\beta\beta}$⟩ < 36-156 meV

First search for inverted mass ordering

Experimental limit for Ge & Te:
(Ge) GERDA: Phys.Lett. **125** 252502
(Te) CUORE: arXiv: 2104.06906v1

Theoretical predictions:
(a) Phys. Rev. D 86, 013002
(b) Phys. Lett. B 811, 135956
(c) Euro. Phys. J. C 80, 76

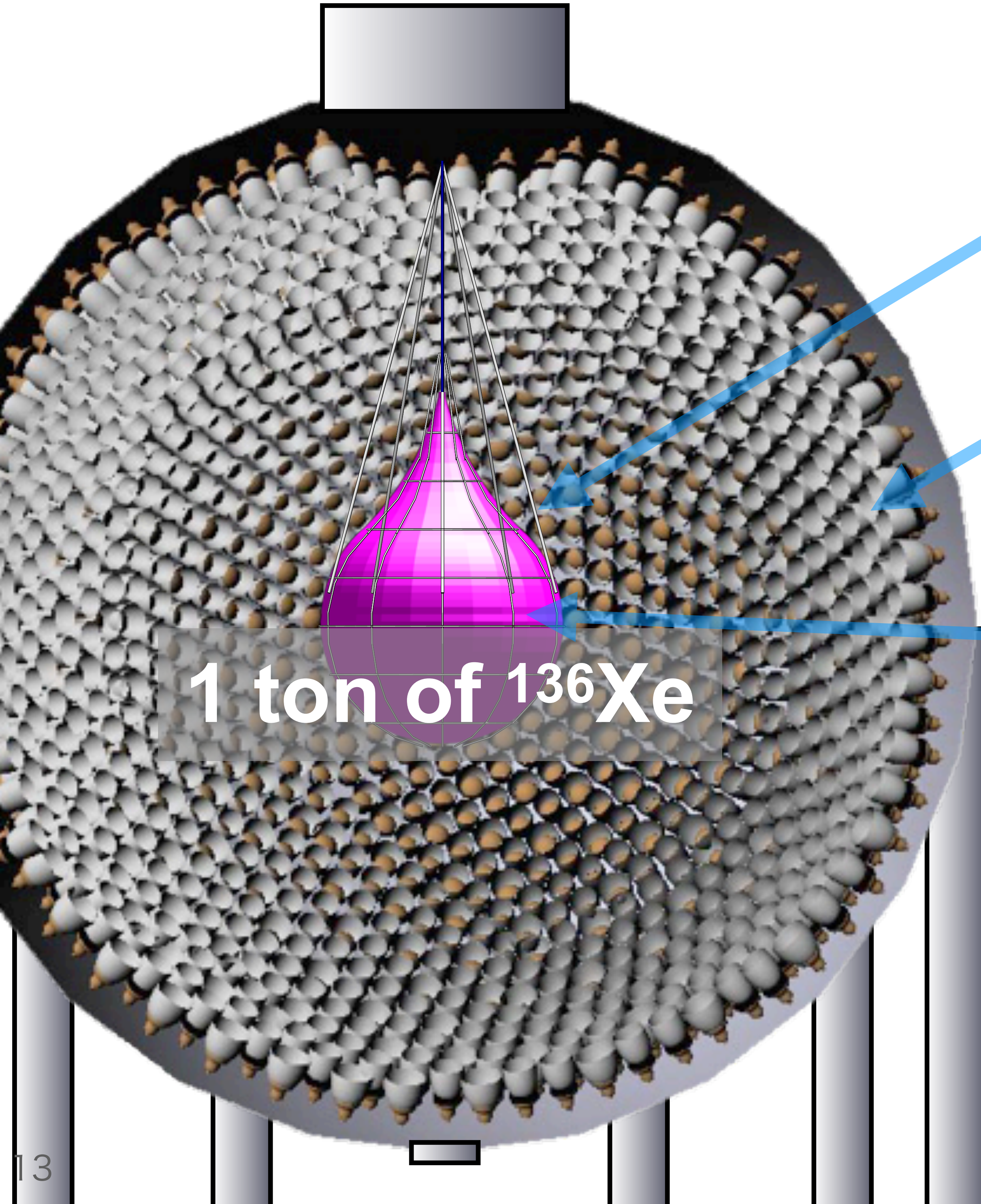
Near future improvement

- Upgraded electronics
- PID with neural networks

KamLAND2-Zen KamLAND → KamLAND2

Enlarge opening

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



New electronics

To improve background suppression. Tagging long lived isotope from cosmic ray spallation.

Scintillation inner balloon

BG reduction from Xe-LS container

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage

Brighter LS

Current LS ~8,000 photon/MeV

LAB based new LS ~12,000 photon/MeV

σ(2.6MeV) = 4% → ~2%

Target $\langle m_{\beta\beta} \rangle$ ~20 meV in 5 yrs

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).