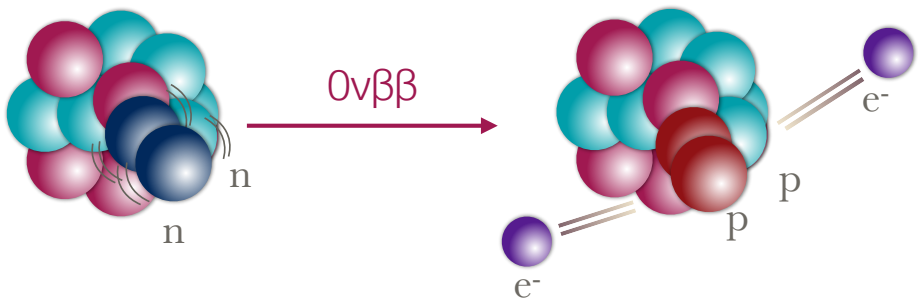
NOW 2024

Neutrino Oscillation Workshop



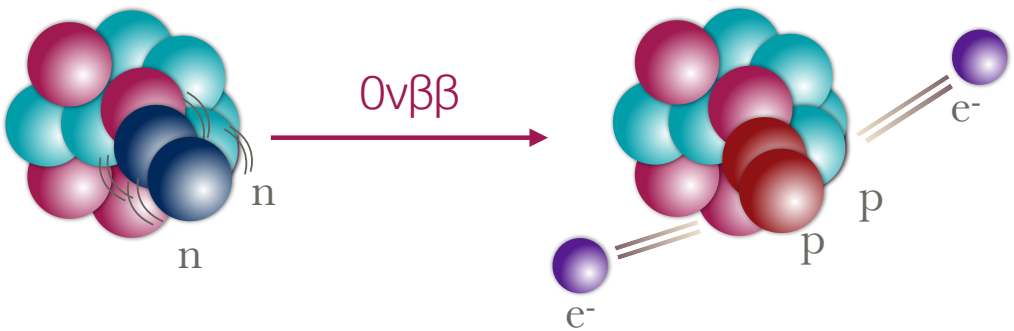
Neutrinoless Double Beta Decay Towards ton-scale experiments

SAPIENZA UNIVERSITÀ DI ROMA

Fabio Bellini

INFN Istituto Nazionale di Fisica Nucleare

0νββ decay

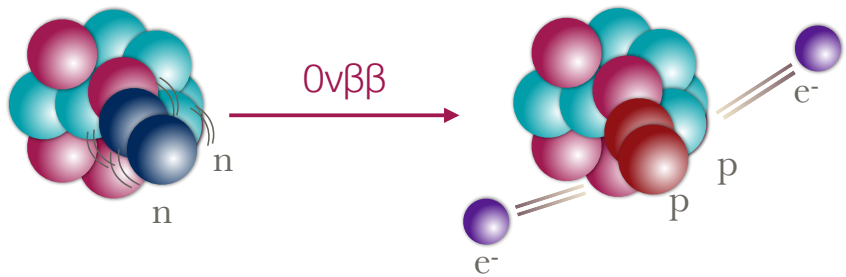


- Forbidden in Standard Model
  - L and B-L violated: $\Delta L=2$ $\Delta(B-L)=-2$
  - Matter creation in LAB: the physics that matters but doesn't antimatter :)
- Different BSM diagrams can contribute
  - If discovered ν has a Majorana mass component
  - Dim-5 operator model: exchange light-mass Majorana neutrinos
- $T^{0\nu}_{1/2} \gtrsim 10^{25/26}$yr

See Wednesday morning session

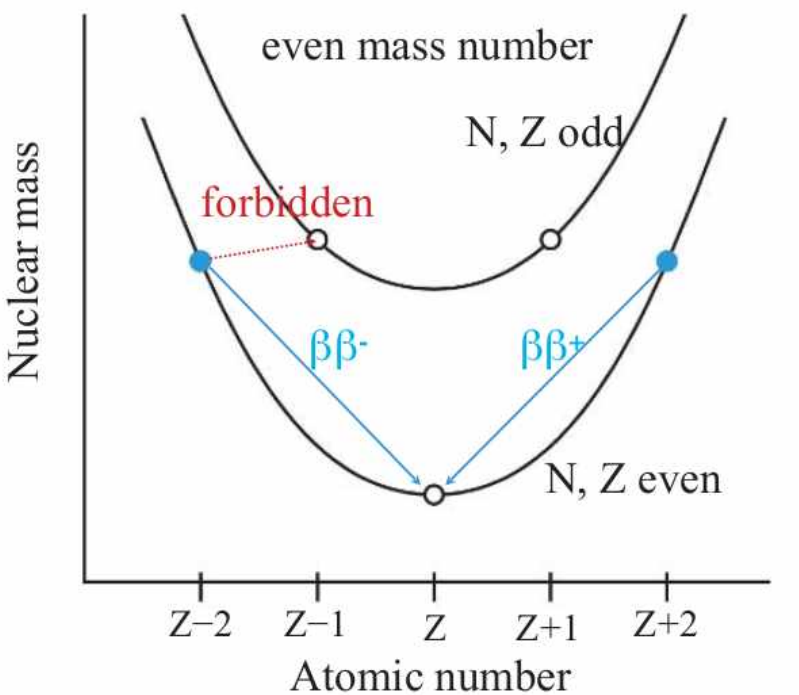
Experimental aspects

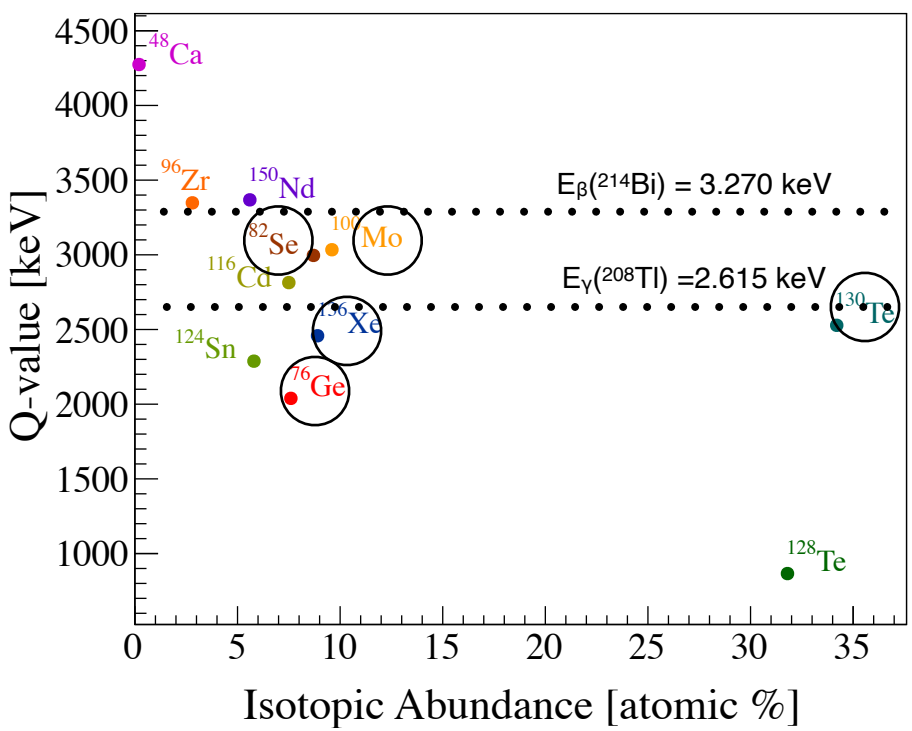
$(A,Z) \rightarrow (A,Z+2) + 2e^-$



- Experimental signature
  - One daughter ionized isotope + 2 e^-
  - e^- summed kinetic energy = monochromatic line at $Q_{\beta\beta}$ (~2-3 MeV)

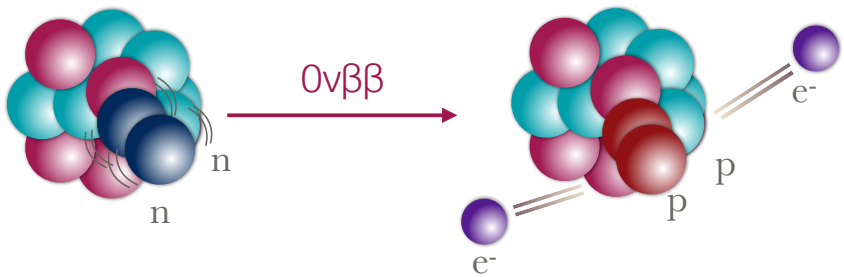
Single Beta decay must be forbidden





Experimental aspects

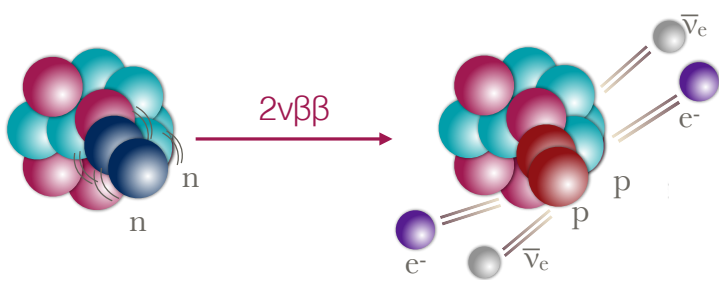
$(A,Z) \rightarrow (A,Z+2) + 2e^-$



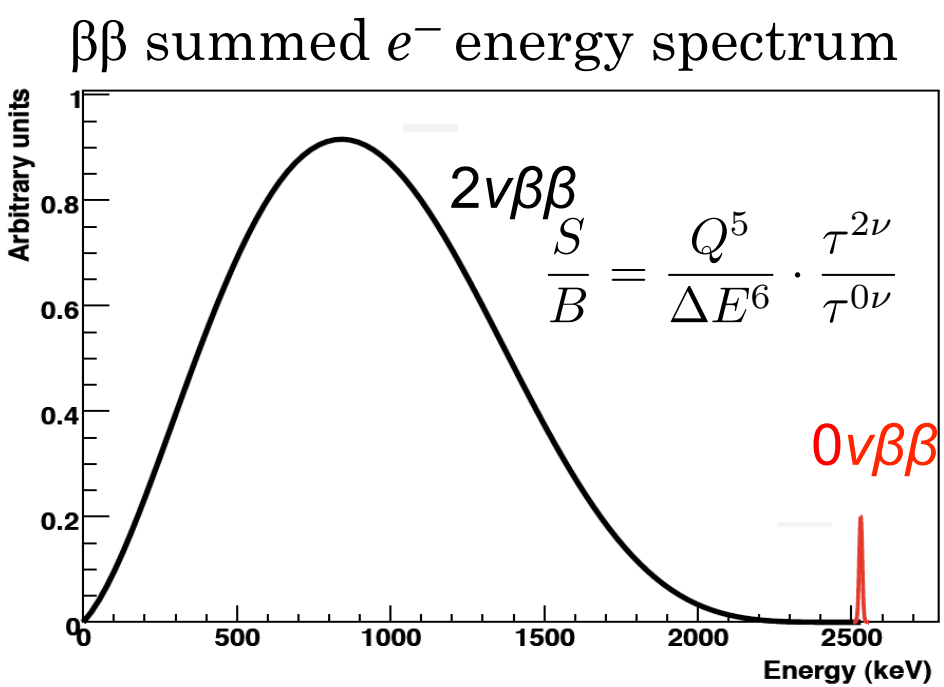
- Experimental signature
  - One daughter ionized isotope + 2 e^-
  - e^- summed kinetic energy = monochromatic line at $Q_{\beta\beta}$ (~2-3 MeV)

Irreducible background

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



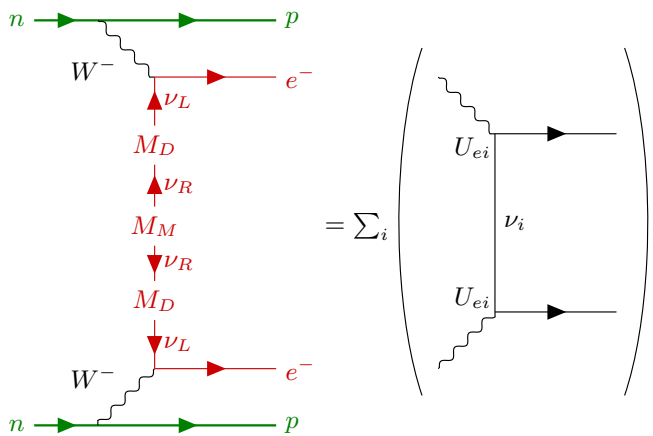
- 2nd order weak process in SM
- measured at a few % precision
- $T^{2\nu}_{1/2} > 10^{18}$ yr



$0\nu\beta\beta \Leftrightarrow \nu$ mass

- Assume exchange of light Majorana ν

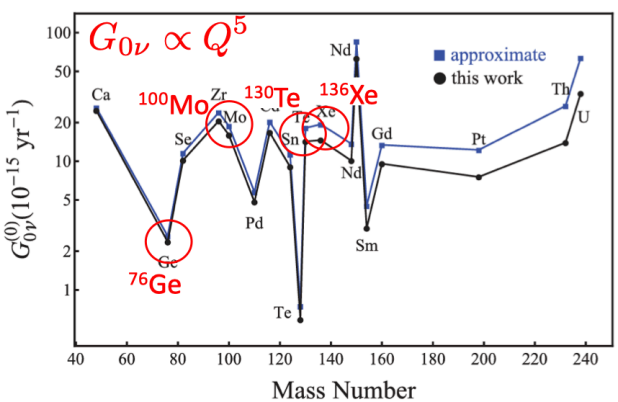
$$\frac{\Gamma^{0\nu}}{\ln 2} = (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\, g_A^4\, |M^{0\nu}|^2\, \frac{\langle m^2_{\beta\beta}\rangle}{m_e^2}$$



Rev. Mod. Phys. 95, 025002, 2023

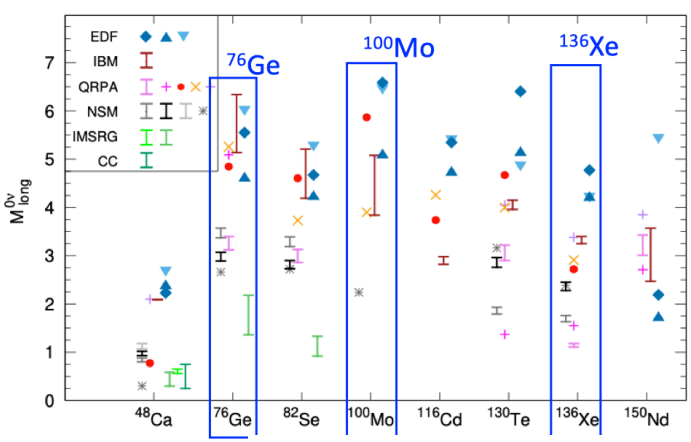
see J. Holt's talk

Phase space
(accurately calculated):



Phys. Rev. C 85, 034316 (2012)

Nuclear Matrix Element
(significant theory uncertainty):



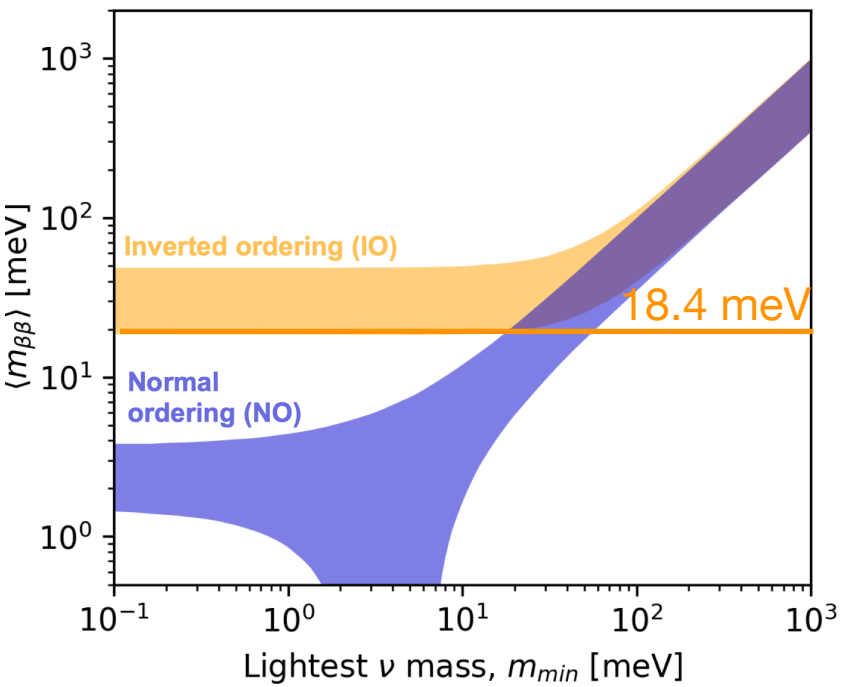
Effective Majorana Mass
(assumes "standard" mechanism):

$$\langle m_{\beta\beta}\rangle = \left|\sum |U_{ei}|^2 e^{i\phi_i} m_i\right|$$
$$= \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}\right|$$

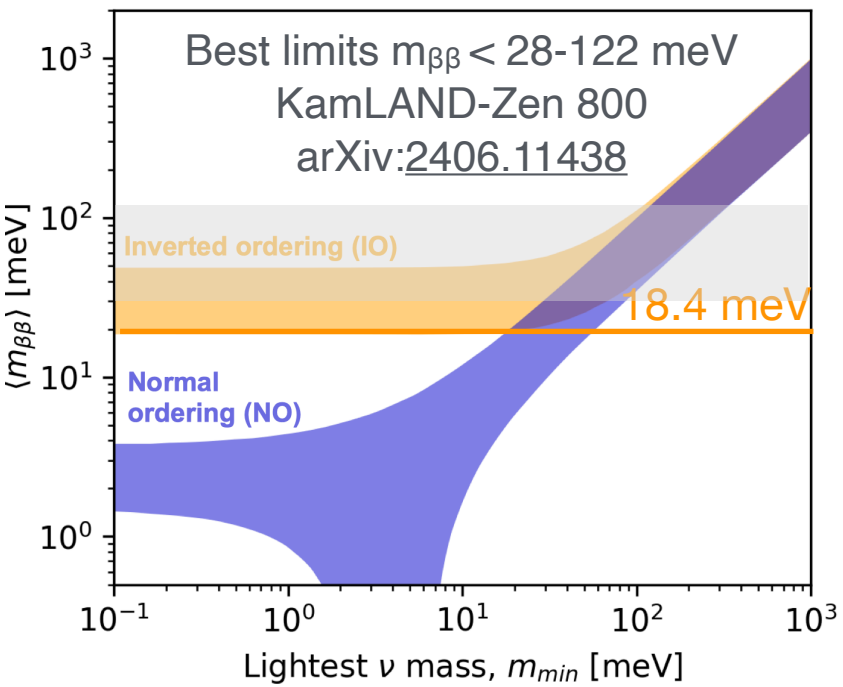
α, β are unknown Majorana phases
- *Not measurable in oscillation experiments*

This is only one model -- other LNV physics also possible!

The parameter space



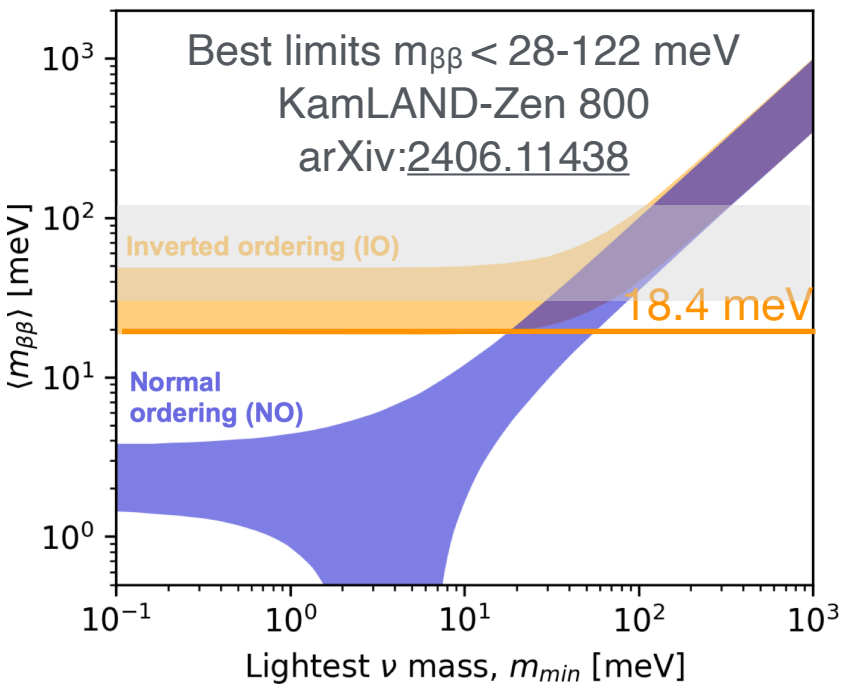
The parameter space



The parameter space

$$\langle m^2_{\beta\beta} \rangle \propto (T^{0\nu}_{1/2})^{-1}$$

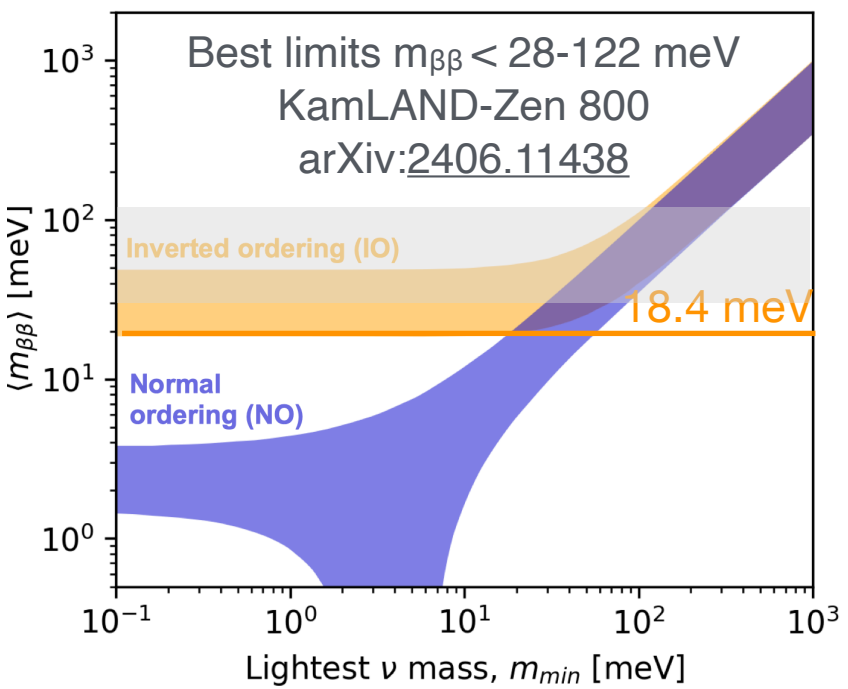
- Bkgd free operation mode → $T^{0\nu} \propto \varepsilon m^{FV}_{iso} t$ (sensitivity exposure)

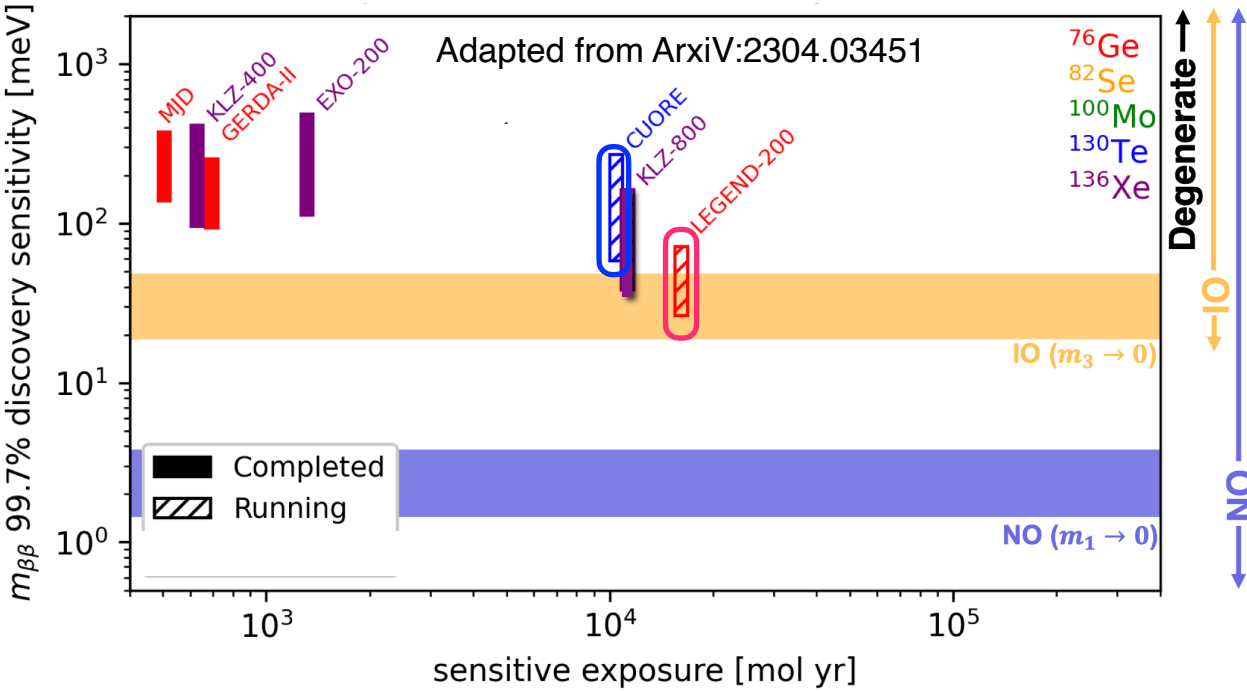


The parameter space

$$\langle m^2_{\beta\beta} \rangle \propto (T^{0\nu}_{1/2})^{-1}$$

- Bkgd free operation mode → $T^{0\nu} \propto \varepsilon m^{FV}_{iso} t$ (sensitivity exposure)



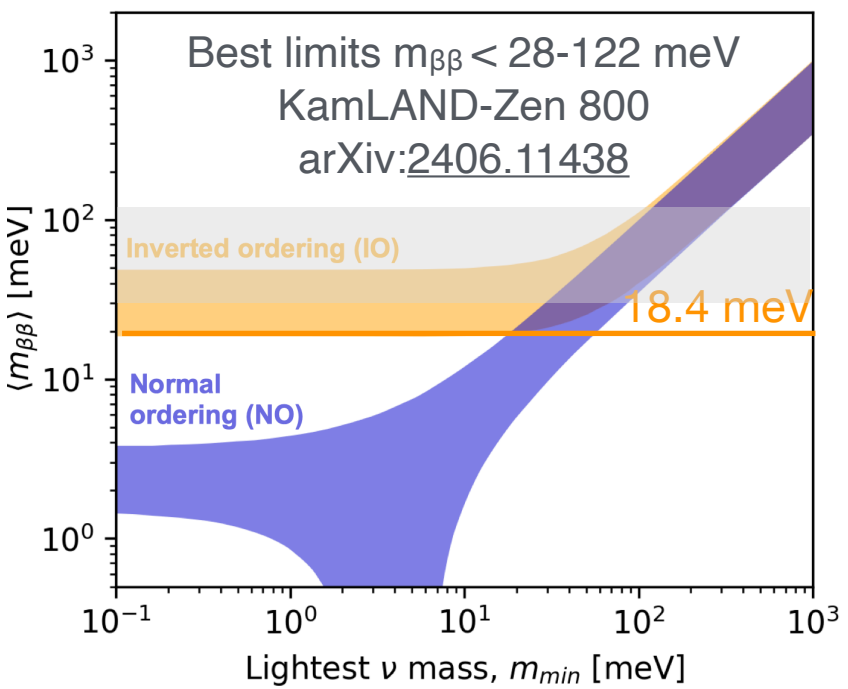


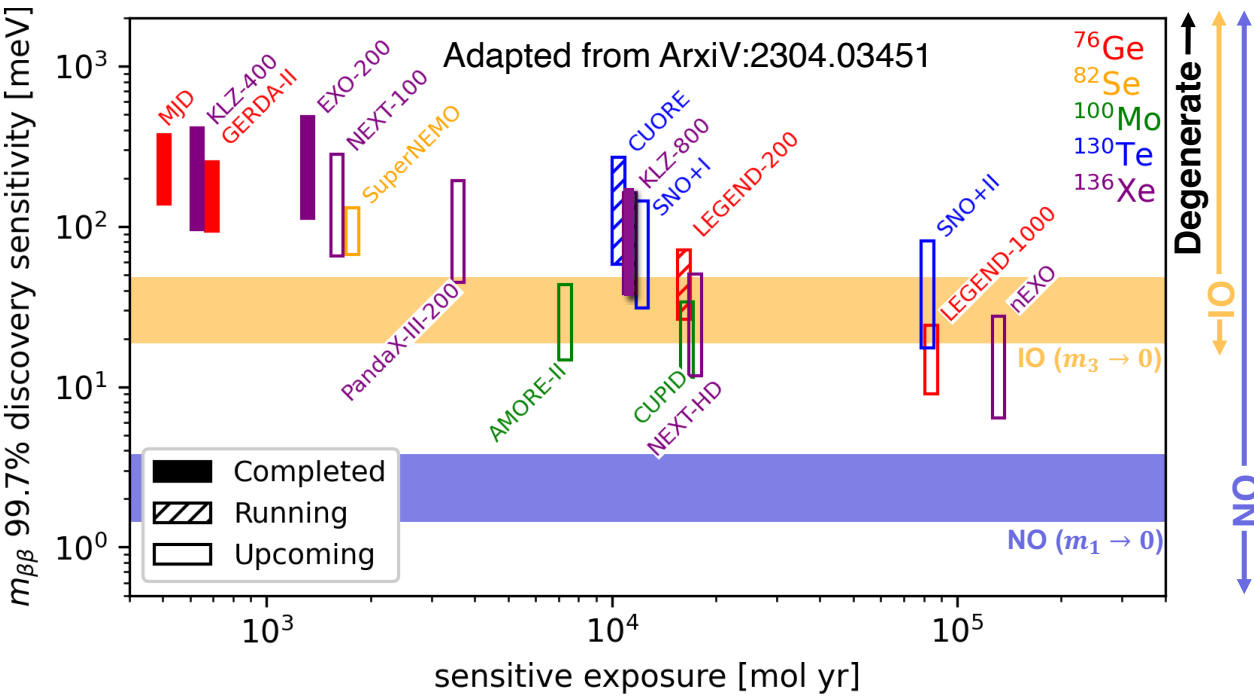
- CUORE: Ton · yr scale sen. exp. but bkgd dominated
- LEGEND-200: bkgd free mode, will reach Ton scale sen. exp. in 5 yr

The parameter space

$$\langle m^2_{\beta\beta} \rangle \propto (T^{0\nu}_{1/2})^{-1}$$

- Bkgd free operation mode → $T^{0\nu} \propto \varepsilon m^{FV}_{iso} t$ (sensitivity exposure)



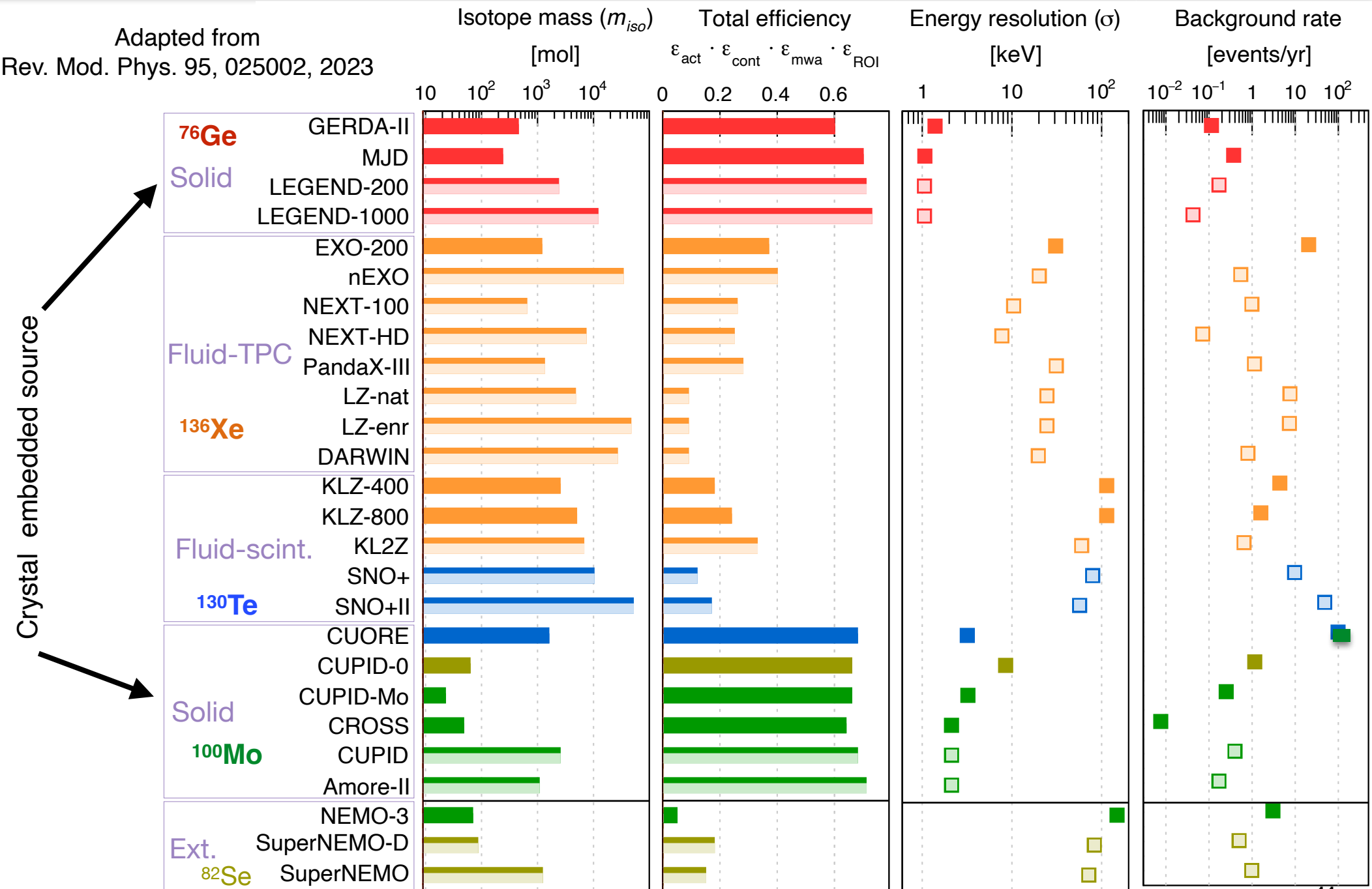


- CUORE: Ton · yr scale sen. exp. but bkgd dominated
- LEGEND-200: bkgd free mode, will reach Ton scale sen. exp. in 5 yr

Next experiments designed for discovery in I.O. region → need 10 Ton · yr

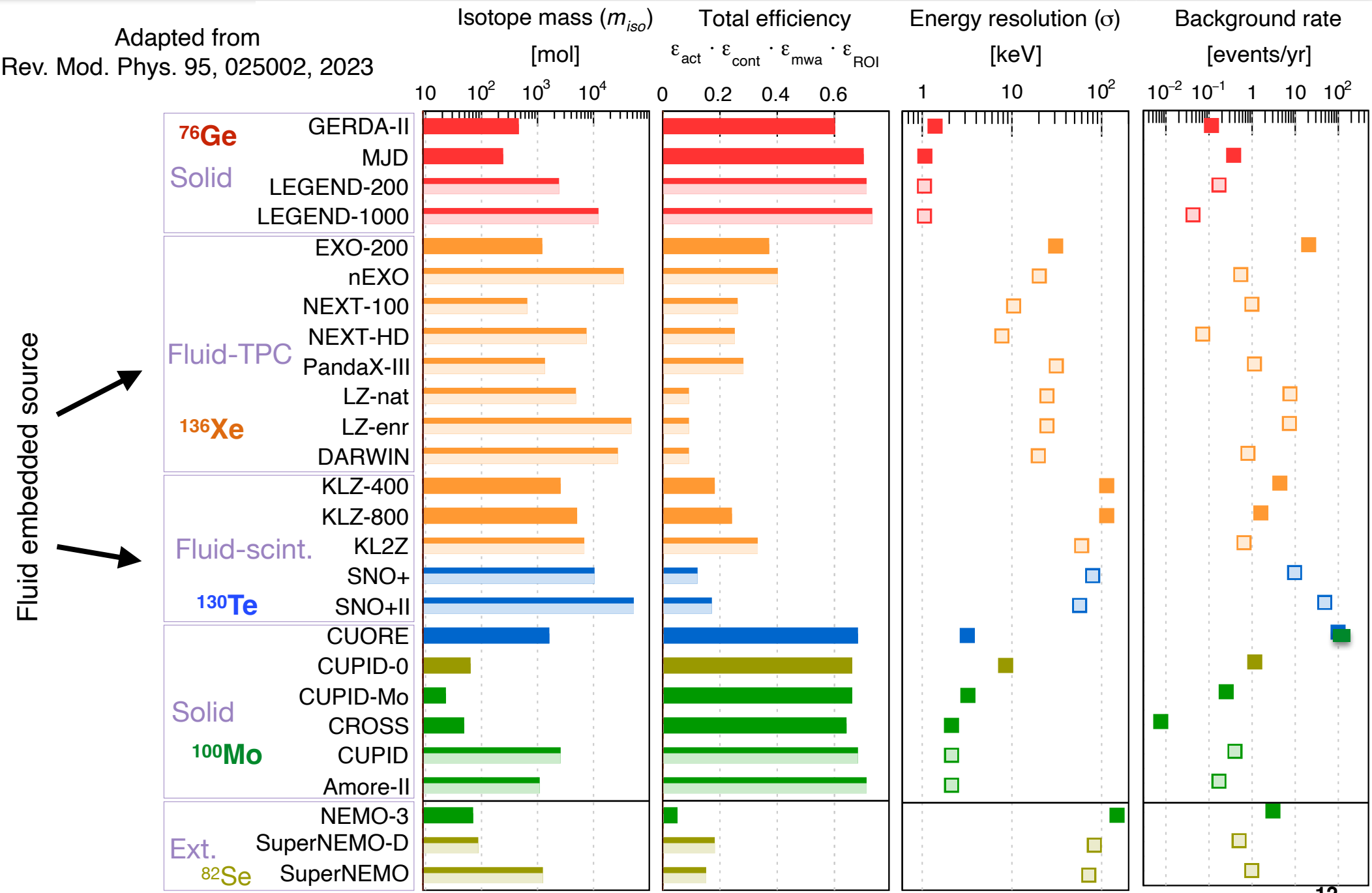
Synopsis

Adapted from
Rev. Mod. Phys. 95, 025002, 2023



Synopsis

Adapted from
Rev. Mod. Phys. 95, 025002, 2023

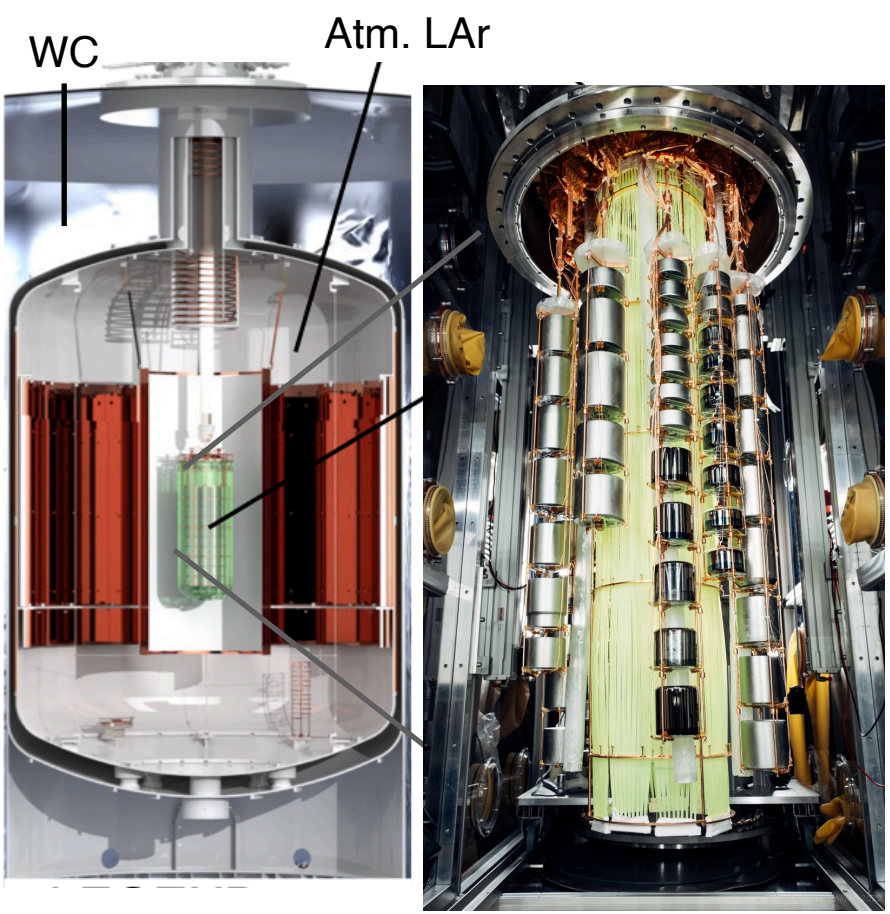


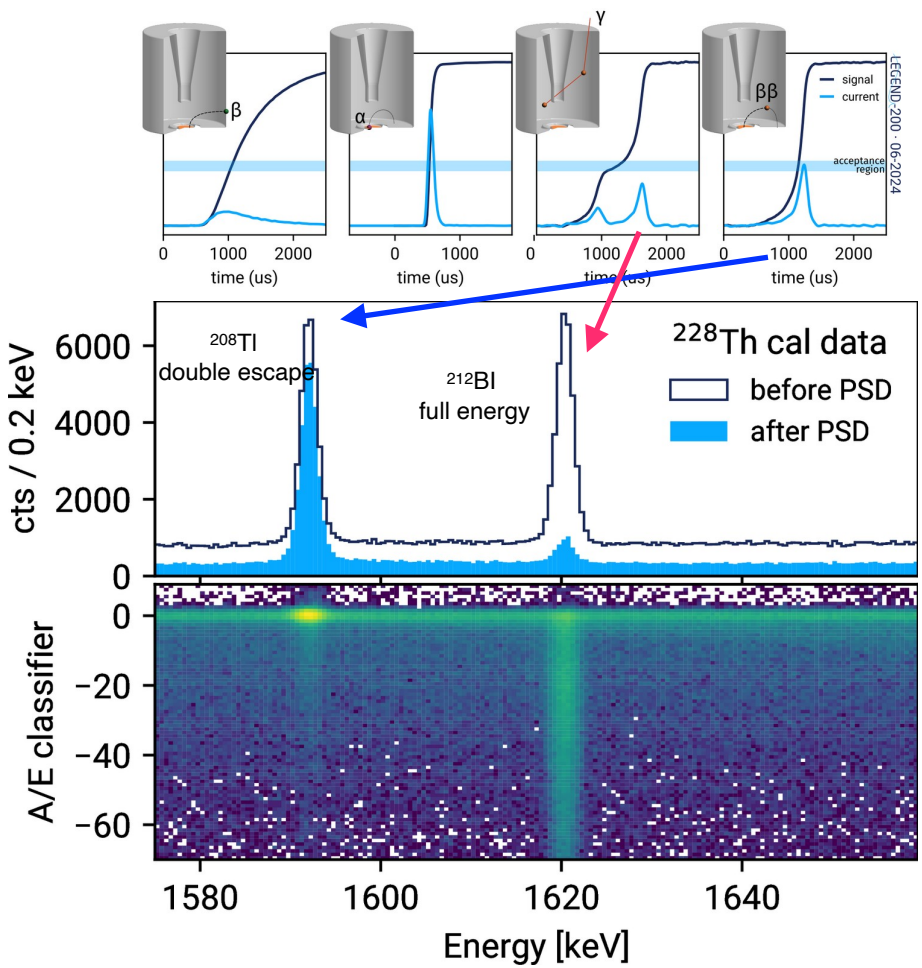
Crystal embedded source

LEGEND-200

LNGS

- Bare HPGe detectors ~90%-enr. ^{76}Ge in LAr instrumented as active veto
- Upgraded GERDA infrastructure + 200 kg ^{76}Ge (75 new 2kg Inverted Coaxial Point Contact HPGe)
- Outstanding ΔE_{FWHM} @ $Q_{\beta\beta}$~0.1%
- Almost zero background regime: $2 \cdot 10^{-4}$ ckky (cts/keV·kg·yr)
- Goal: in 5 year $T^{0\nu}_{1/2}$>1.9 10^{27} yr $m_{\beta\beta}$: [34-78] meV

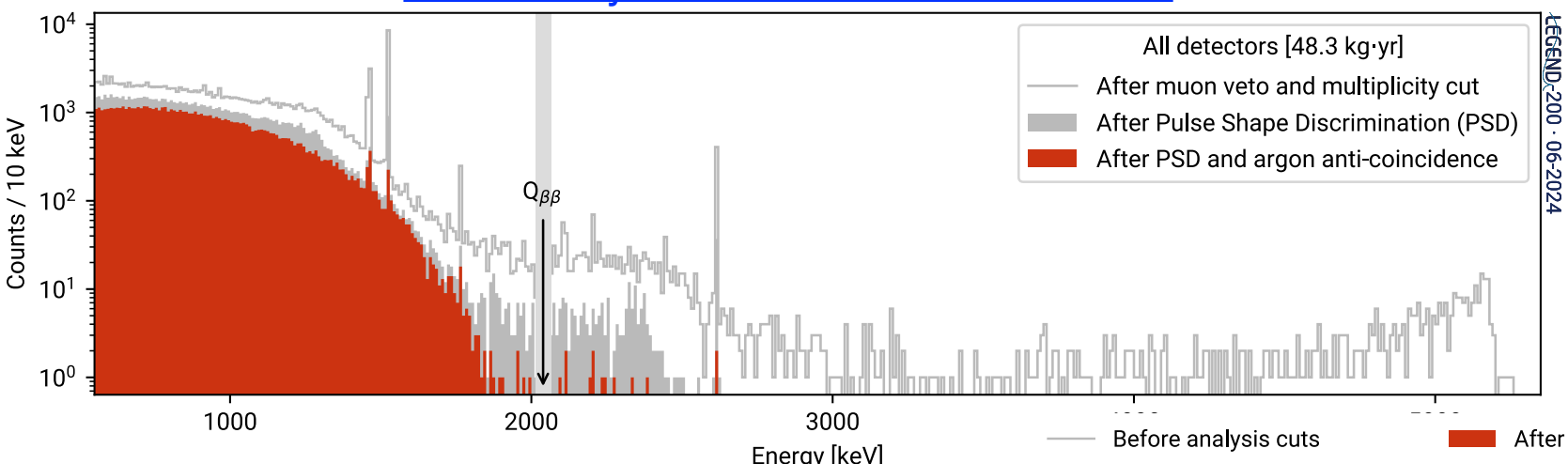


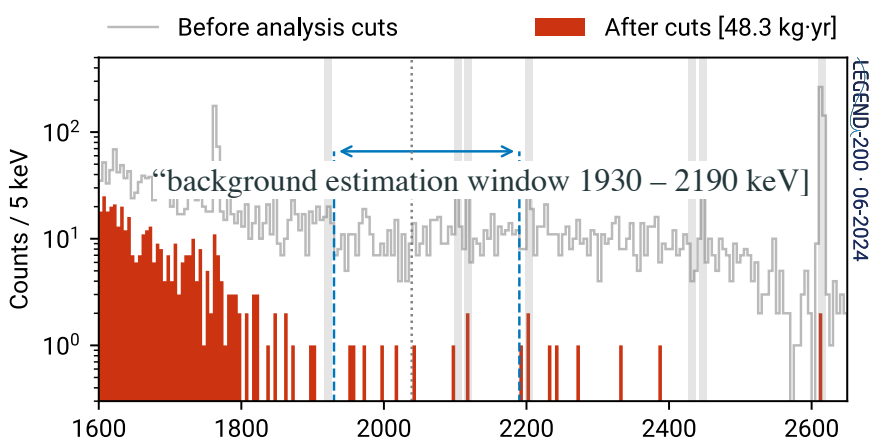


LEGEND-200: first results

- First year with 142 kg ^{76}Ge installed (130 kg operational due to hardware issues)
- 76.2 kg · yr for bkgd and performance characterisation + 48.3 kg · yr for physics data
- Performances as expected, overall efficiency ~60%

Preliminary results from Neutrino 2024





Bkgd = (5.3±2.2) · 10^{-4} ckky

(GERDA world-leading level)

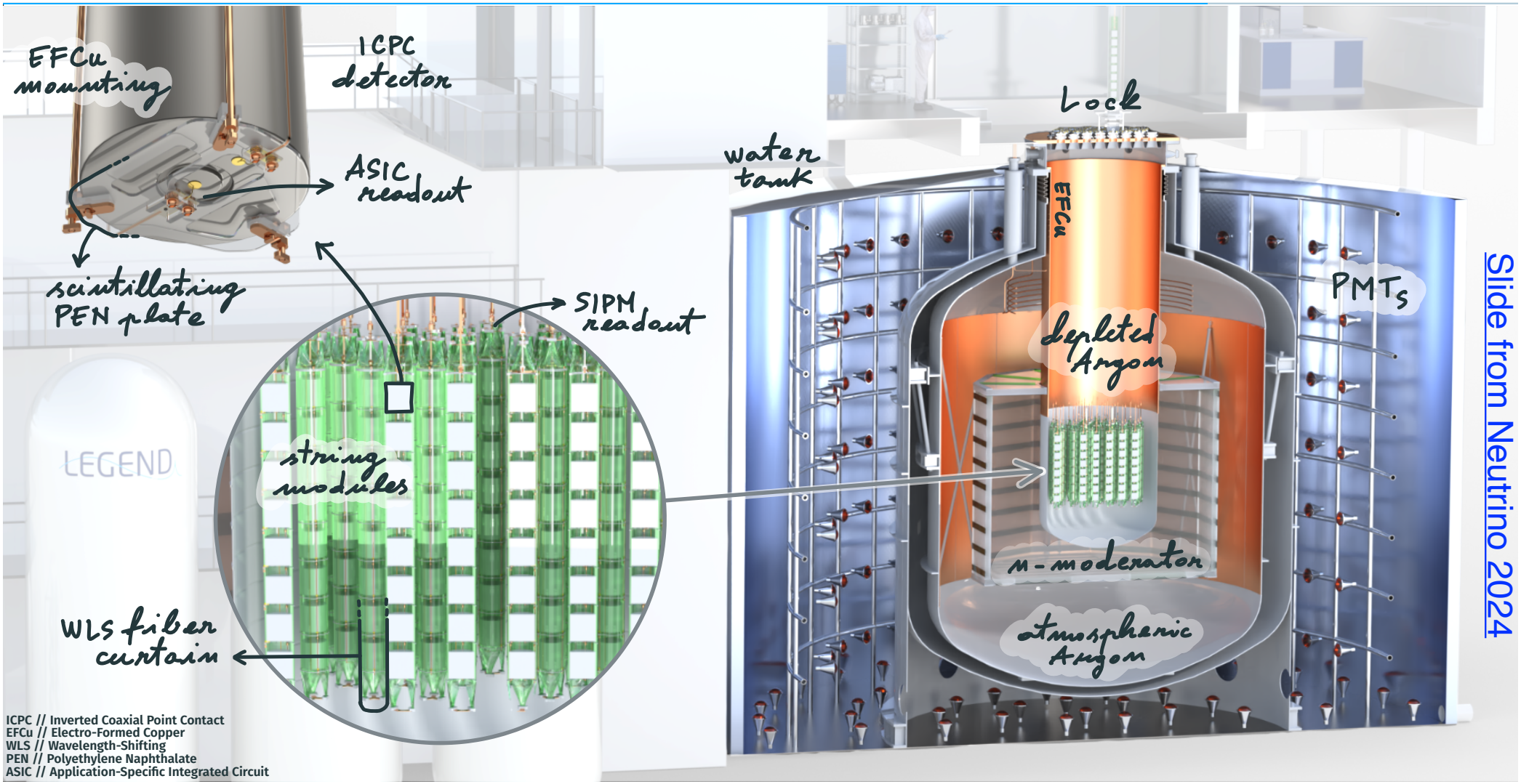
^{228}Th contribution higher then expected

Combined fit with GERDA: $T^{0\nu}_{1/2} > 1.9\ 10^{26}$ yr (90 C.L.)

LEGEND-1000

LNGS

1Ton HPGe detectors, ~90% enr ^{76}Ge in underground LAr in new infrastructure



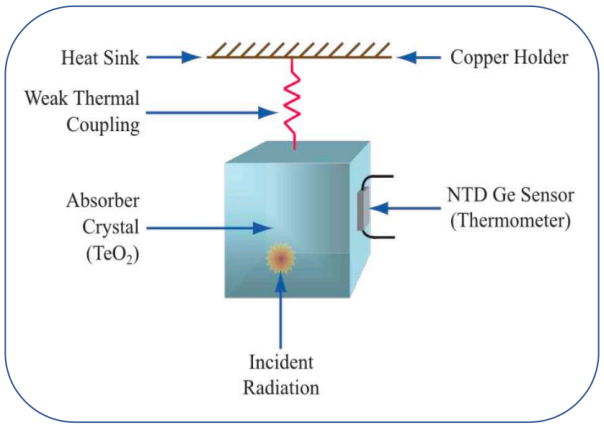
Slide from Neutrino 2024

bkgd goal: 10^{-5} ckky In 10 yr $T^{0\nu}_{1/2} \sim 10^{28}$ yr $m_{\beta\beta}$: [9-21] meV arXiv:2107.11462

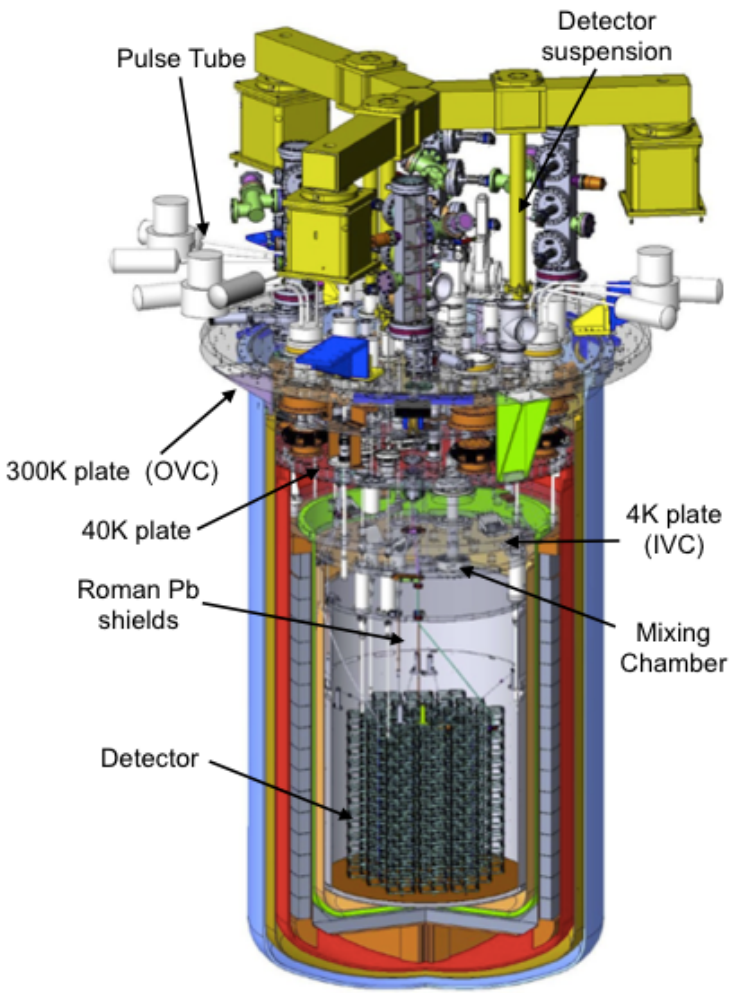
CUORE

LNGS

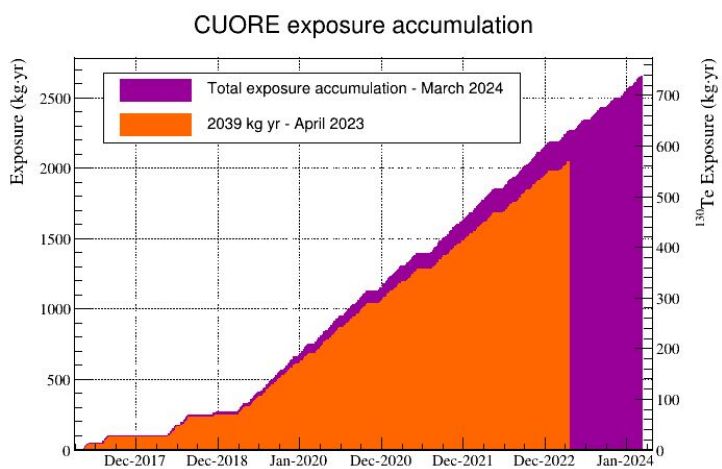
- Larger bolometric detector ever built
  - 988 $^{nat}TeO_2$ crystals at 10 mK
  - 742 kg of TeO_2, 206 kg ^{130}Te



ΔE_{FWHM} @ $Q_{\beta\beta}$ ~0.2/0.3 %



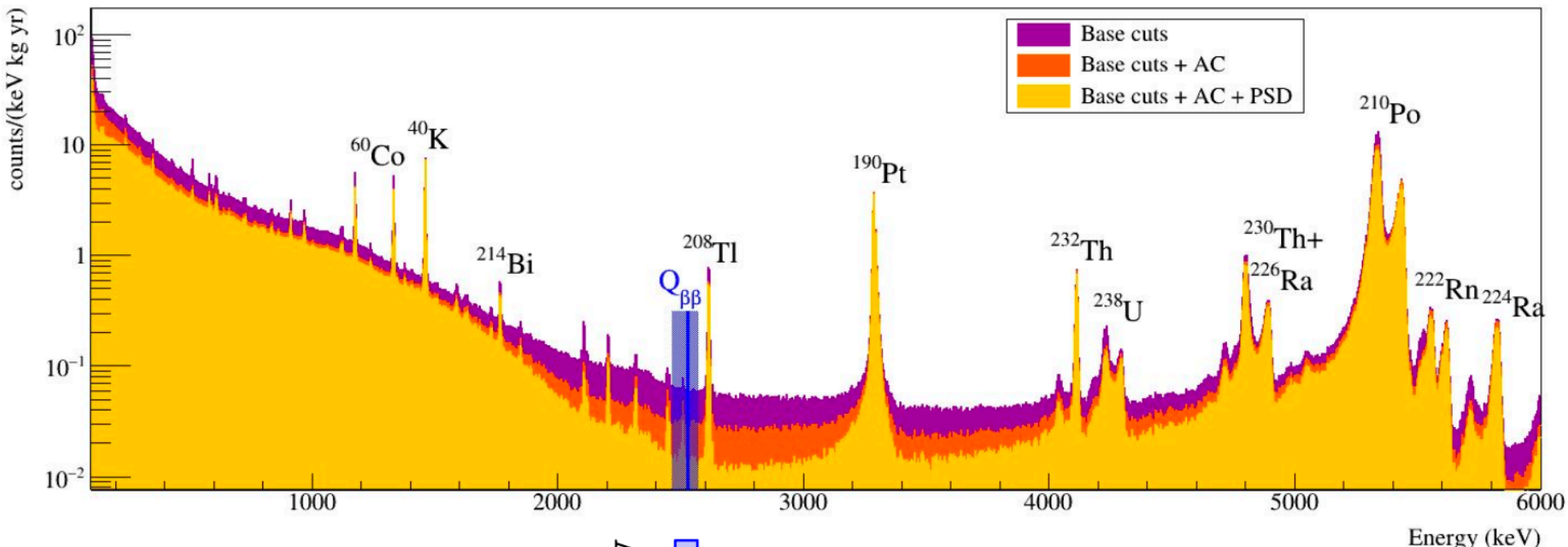
- Continuous physics data taking with high duty cycle and stable performances since 2019



  - Collected ^{130}Te exposure ~750 kg · yr

CUORE Results

ArXiv:2404.04453



Analysed ^{130}Te exposure 567 kg · yr

bkgd: ~1.4 10^{-2} ckky

$T^{0\nu}_{1/2}$>3.8 10^{25} yr (90 C.I.)

$m_{\beta\beta}$: [70-240] meV (90 C.I.)

ROI = (2465, 2575) keV

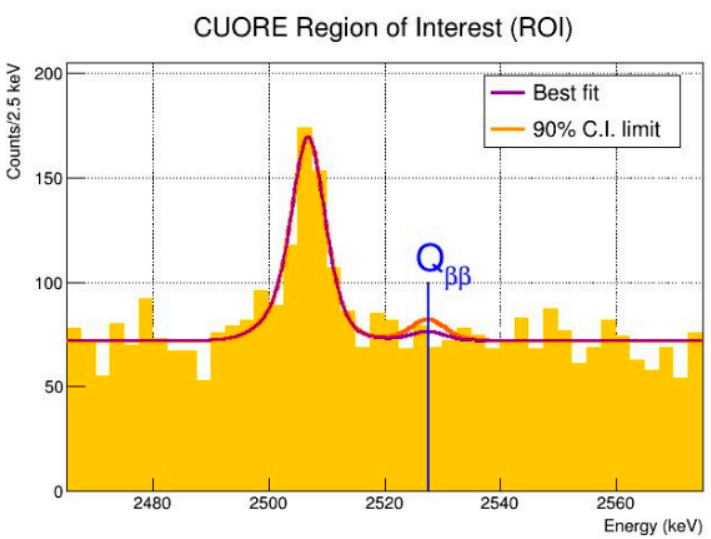


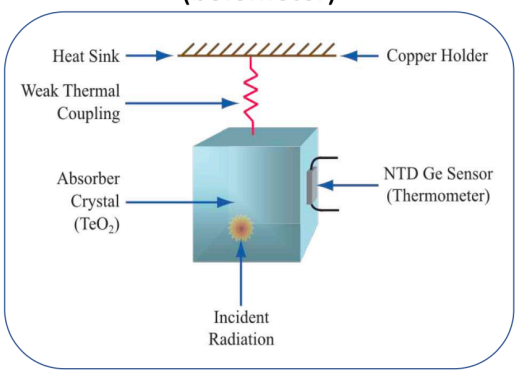
Figure from Quitadamo's talk this afternoon

CUPID

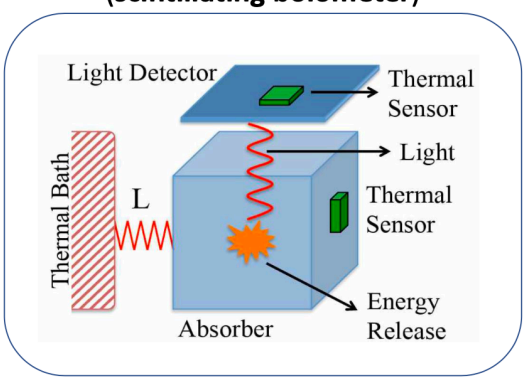
- Builds on CUORE and CUPID0/CUPID-Mo success
- Re-use CUORE infrastructure + 1600 $Li_2{}^{100}MoO_4$ (240 kg ^{100}Mo)

arXiv:1907.09376

CUORE ^{130}Te
pure thermal detector
(bolometer)



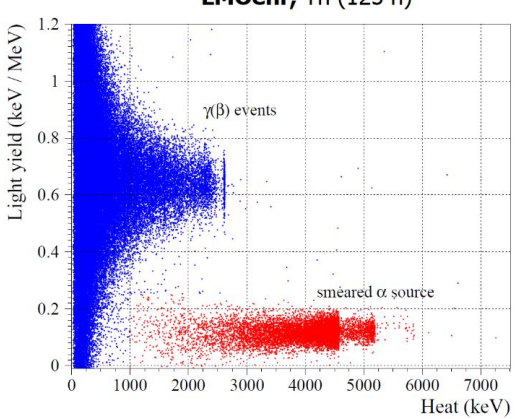
CUPID ^{100}Mo
heat + light
(scintillating bolometer)



No PID
Q = 2527 keV **< 2615 keV**

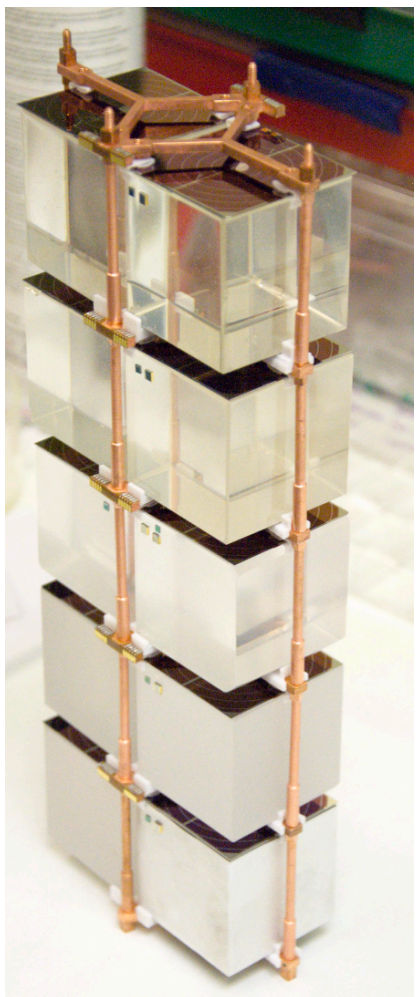
PID

LMOenr, Th (125 h)



~~α background~~
~~γ background~~

Q = 3034 keV **> 2615 keV**



Data driven background model: 10^{-4} ckky in 10 yr $T^{0\nu}_{1/2} \sim 10^{27}$ yr $m_{\beta\beta}$: [12-20] meV

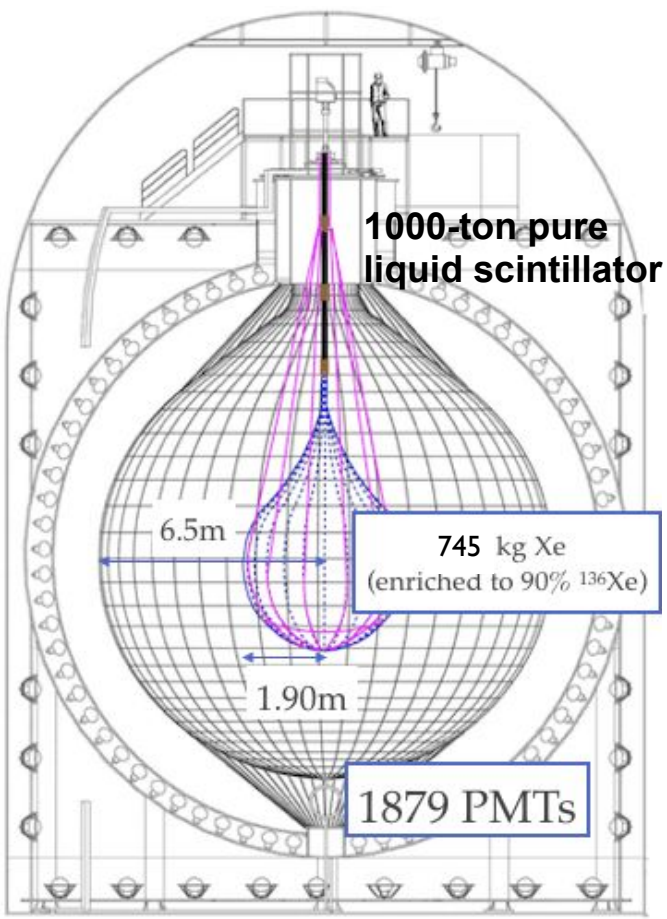
Fluid embedded source

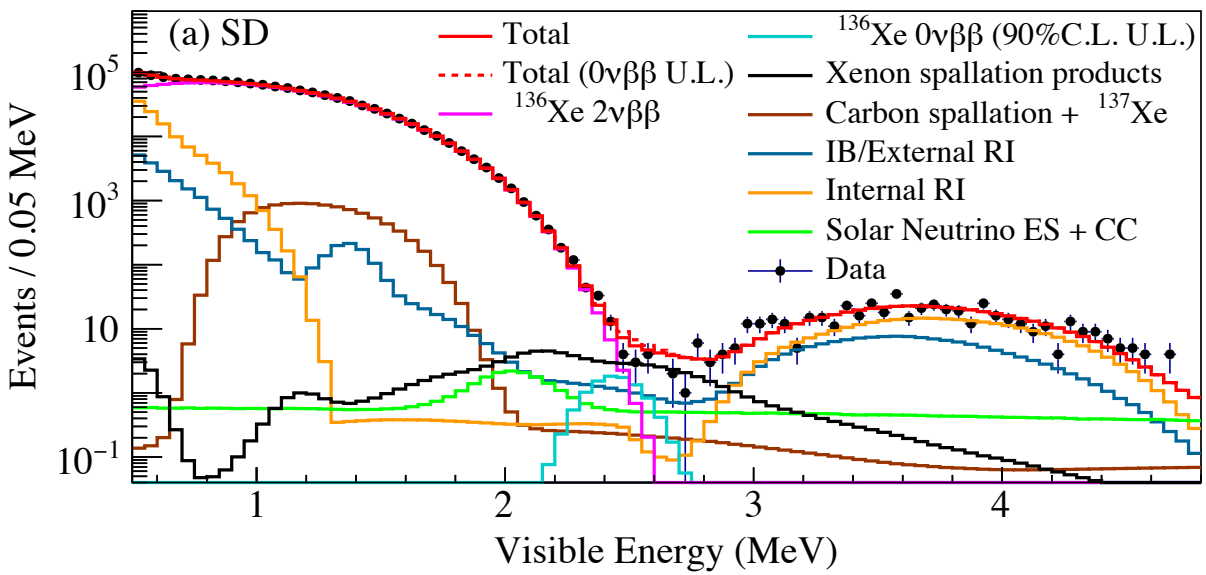
KamLAND-Zen 800 Kamioka

- 745 kg 90% enr. ^{136}Xe diluted in liquid scintillator in IB deployed in KamLAND

Final Results: arXiv:2406.11438

ΔE_{FWHM} @$Q_{\beta\beta}$: 250 keV (10%)





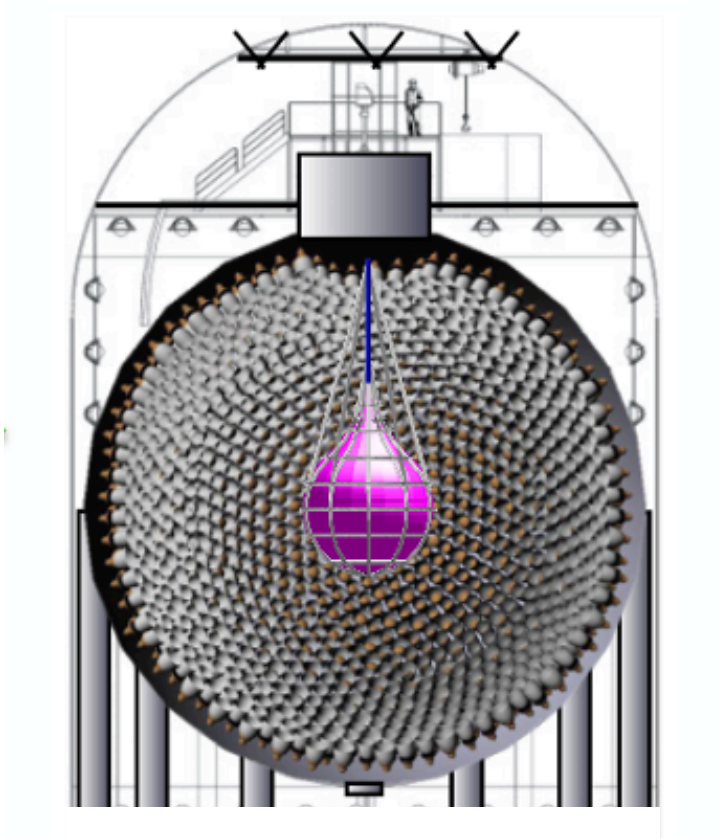
Main bkgd: 2νββ, long lived μ induced Xe spallation

Combined with KamLAND-Zen 400
Total exposure ~2.5 Ton yr

$T^{0\nu}_{1/2} > 3.8\ 10^{26}$ yr (90% C.L.) $m_{\beta\beta} < 28\text{-}122$ meV

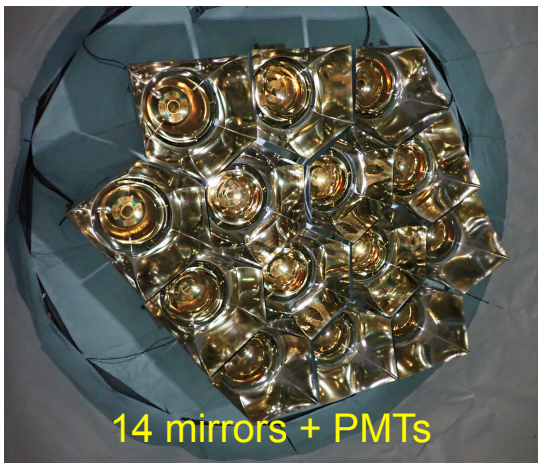
KamLAND2-Zen

- A major upgrade: larger source x 5 brighter → x 2 better ΔE



Kamland2-Zen

- 1000 kg of enriched Xe
- 100% photo coverage:
  Winston cone (x 1.8)
  new PMT (x1.9)
  new LS (x 1.4)
  - improve energy resolution
    ΔE_{FWHM} @$Q_{\beta\beta}$: 120 keV



- Pen scintillation balloon film
  - identify BiPo events in the balloon tagging α with scintillator film
- Improve tagging for long lived isotopes (new electronics)

Ultimate bkgd: ^{8}B solar ν elastic scattering

In 10 yr $T^{0\nu}_{1/2} \sim 10^{27}$ yr,

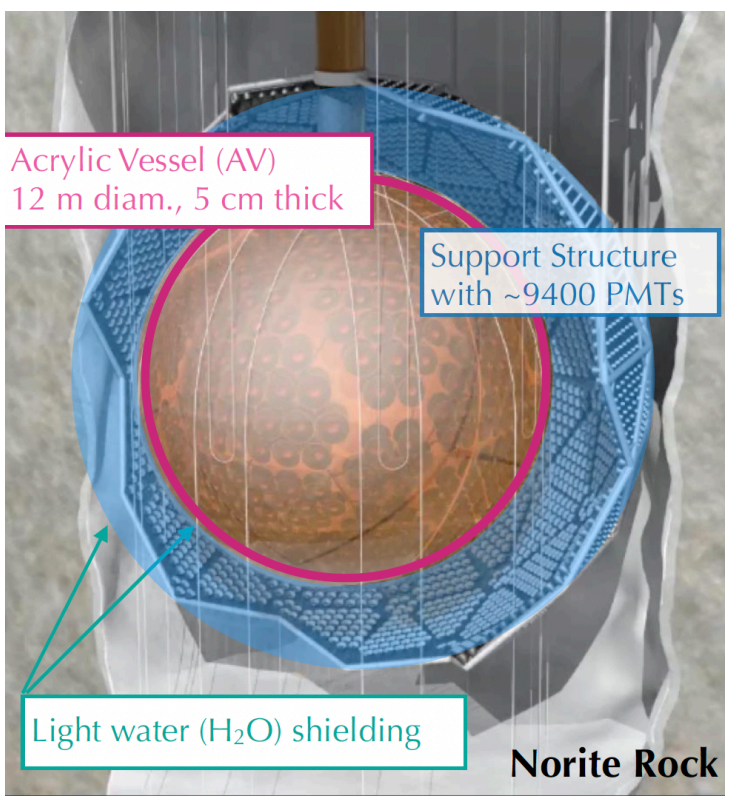
$m_{\beta\beta}$: [17-71] meV

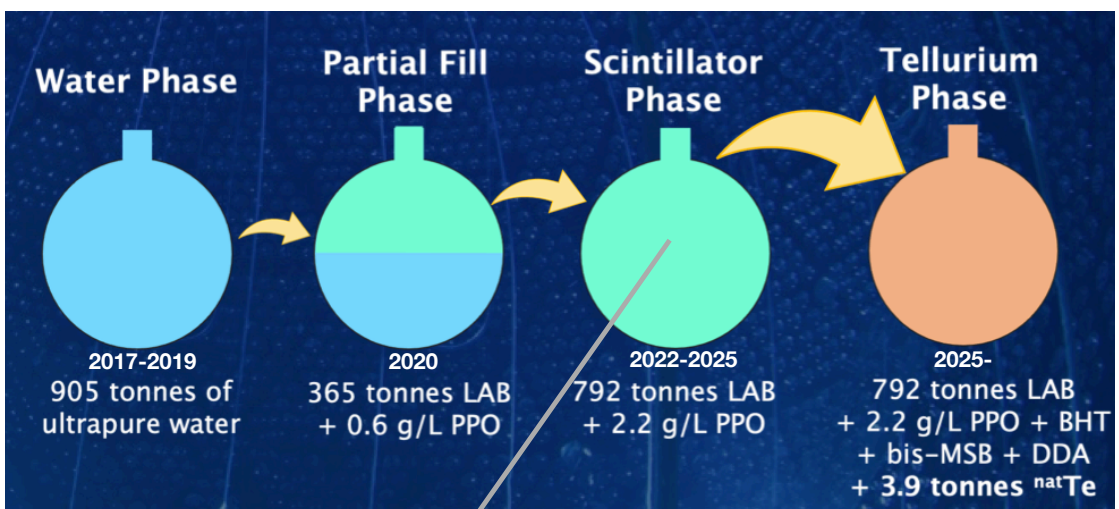
Aggressive time schedule: start data taking in 2027

SNO+

SNOLAB

- Re-use SNO light readout system + acrylic vessel filled 780 Ton ^{nat}Te loaded liquid scintillator
  - Scintillation purification system (a few 10^{-17} g/g U/Th) + novel metal loading technique
  - Phase 1: 0.5% mass loading →1.3 Ton of ^{130}Te, ΔE_{FWHM} @$Q_{\beta\beta}$: 190 keV
  - Phase 2: 0.5% →3%
  - Residual bkgd: solar ν and 2νββ





Great advantage to study backgrounds without the target

Phase	Ton ^{130}Te	$T^{0\nu}_{1/2}$	$m_{\beta\beta}$
SNO+ I	1.3	2 10^{26} yr in 3yr	31-144
SNO+ II	6.6	5.7 10^{27} yr in 10yr	17-81

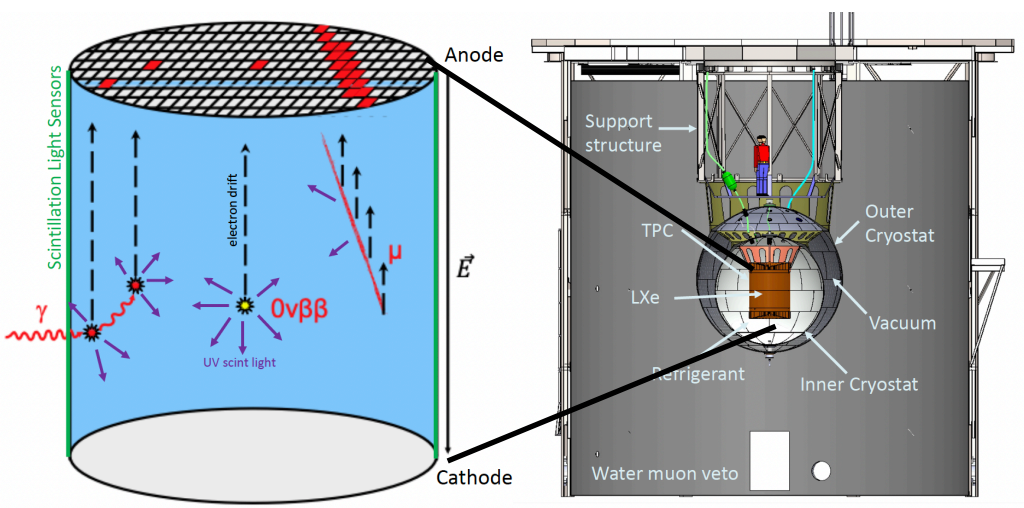
nEXO

SNOLAB

- Builds on successful EXO-200 predecessor — Phys. Rev. Let. 123 (2019) 16, 161802
- 5 Ton (90% enr. ^{136}Xe) LXe single-phase TPC with double read-out
  - 3D topology for multi/single-site discrimination + ΔE_{FWHM} @ $Q_{\beta\beta}$: 2%
  - Self shielding: dominant external bkgds exponentially attenuated in central region

Major upgrade wrt EX0-200

- X 25 mass isotope
- Improvement in light sensor (APD→ SiPM)
- Increased light collection
- Improvement in radiopurity (electroformed Cu)
- Cold electronics



Reduced by 10^3 wrt EXO-200

Bkgd: 2 10^{-6} ckky

J.Phys.G 49 (2022) 1, 015104

Tagging of individual $^{136}Ba^{++}$ daughter demonstrated by fluorescent in solid Xe

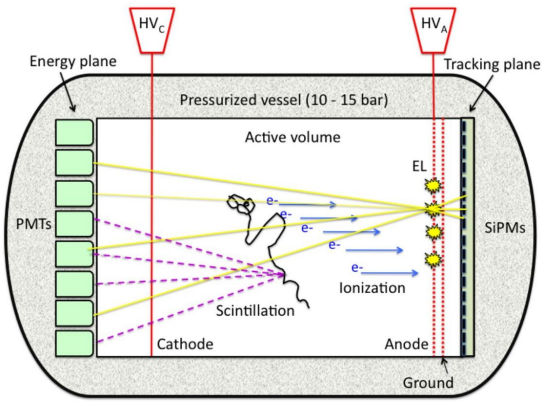
In 10 yr $T^{0\nu}_{1/2} \sim 7\ 10^{27}$ yr, $m_{\beta\beta}$: [6-27] meV

arXiv:2407.00285

NEXT-100

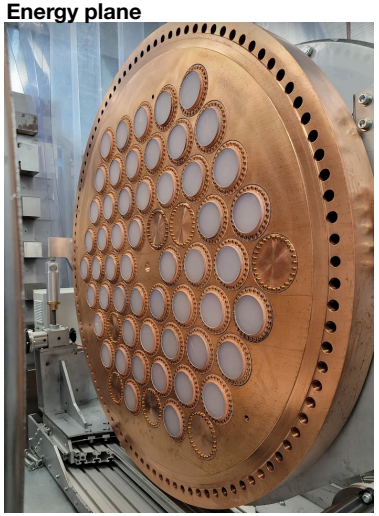
LSC

- 95 kg 90% enr. ^{136}Xe High Pressure (15 bar) gas TPC with Electroluminescence amplification:
  - Primary scintillation z coordinate + EL for tracking (SiPM) and energy resolution (PMT)
  - ΔE_{FWHM} @ $Q_{\beta\beta}$ ~1% + topological separation

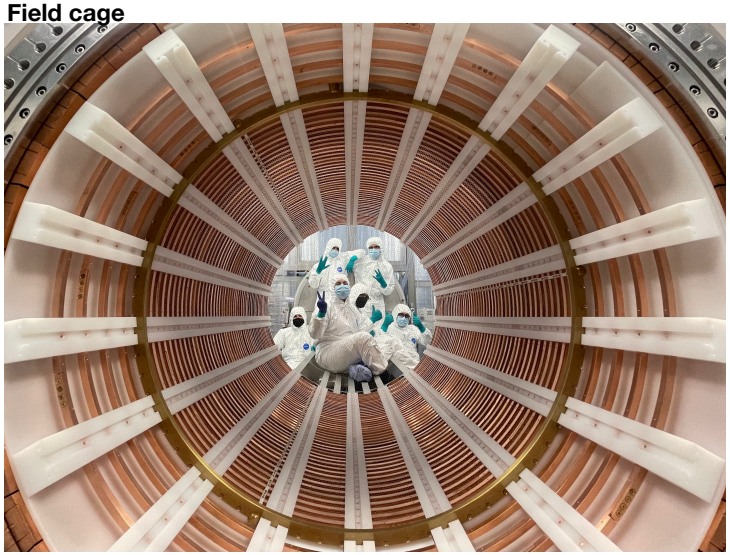


- Detector under commissioning with Ar since May 2024
  - bkgd: 4 10^{-4} ckky $T^{0\nu}_{1/2}$ ~7 10^{25} yr $m_{\beta\beta}$: [66-281] meV
  - demonstrator for future stages

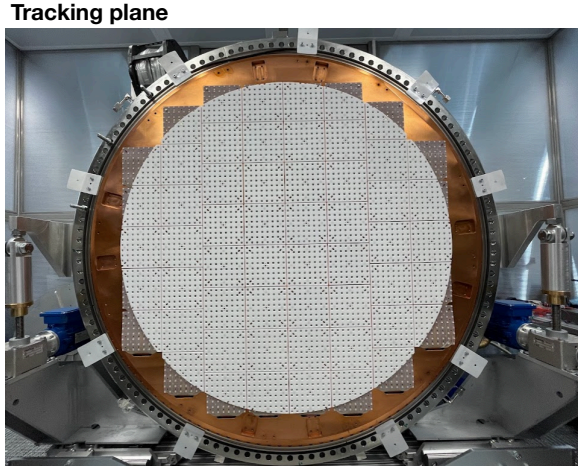
Energy plane



Field cage



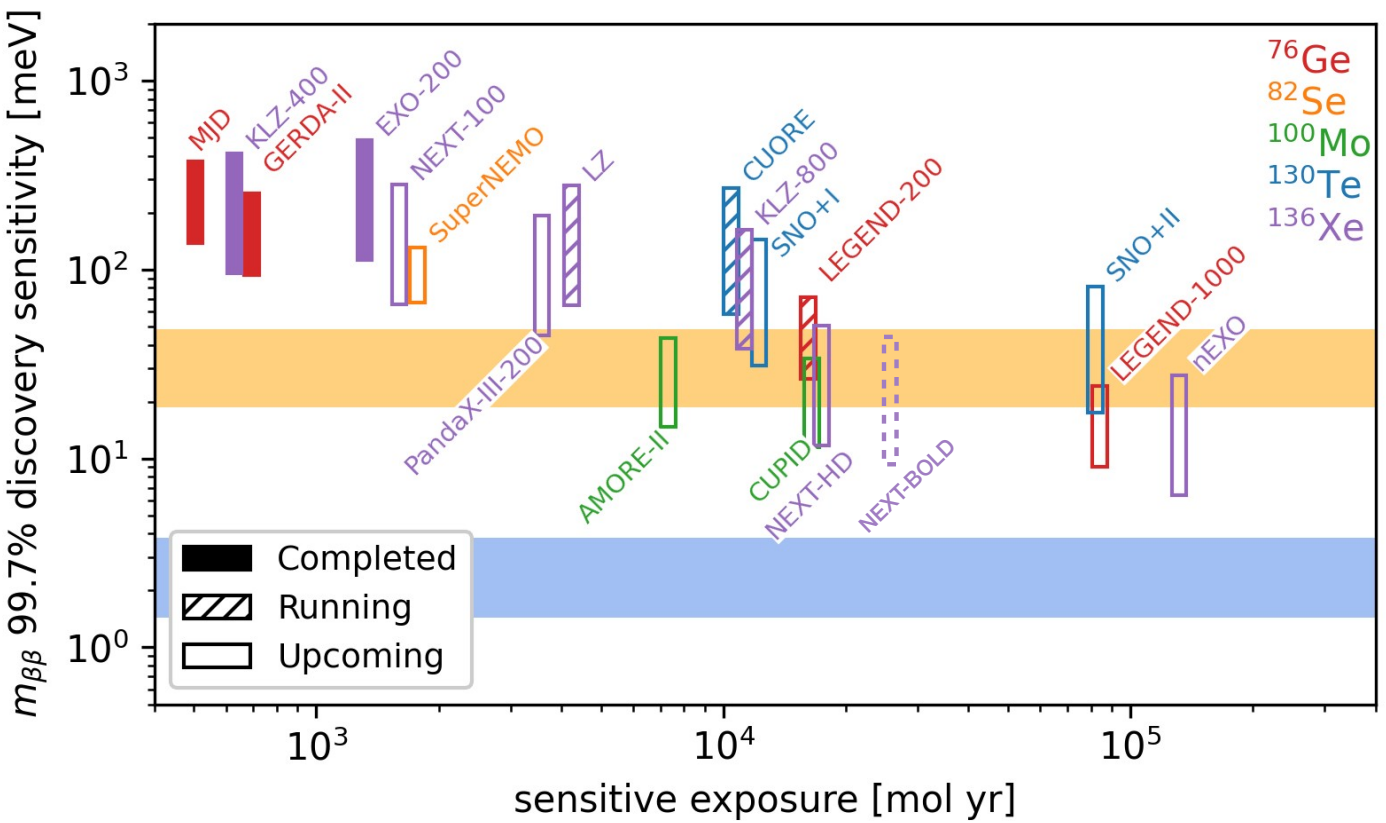
Tracking plane



- NEXT-HD: 1 Ton central cathod symmetric + SiPM readout+barrel fiber detector
  bkgd: 5 10^{-5} ckky + ΔE_{FWHM}~0.5% in 10 yr $T^{0\nu}_{1/2}$ ~2 10^{27} yr $m_{\beta\beta}$: [12-50] meV
- NEXT-BOLD(Barium iOn Light Detector): NEXT-HD + Ba^{++} tag. Fluorescence Imaging of Individual Ions and Molecules in Pressurized Noble Gases (arXiv: 2406.15422) in 10 yr $T^{0\nu}_{1/2}$ ~8 10^{27} yr, $m_{\beta\beta}$: [6-27] meV

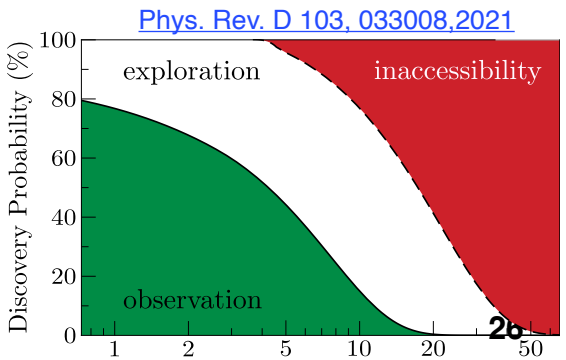
Summary

- Worldwide experimental effort pursuing a number of technologies at ton scale
- Fully explore the Inverted Ordering in the next 15 yr



Adapted from ArxiV:2304.03451
(NSAC Long Range Plan)

- Also non negligible fraction of Normal Ordering explored



Backup

Accessing Normal Ordering

- The problem could be the signal rather than the background

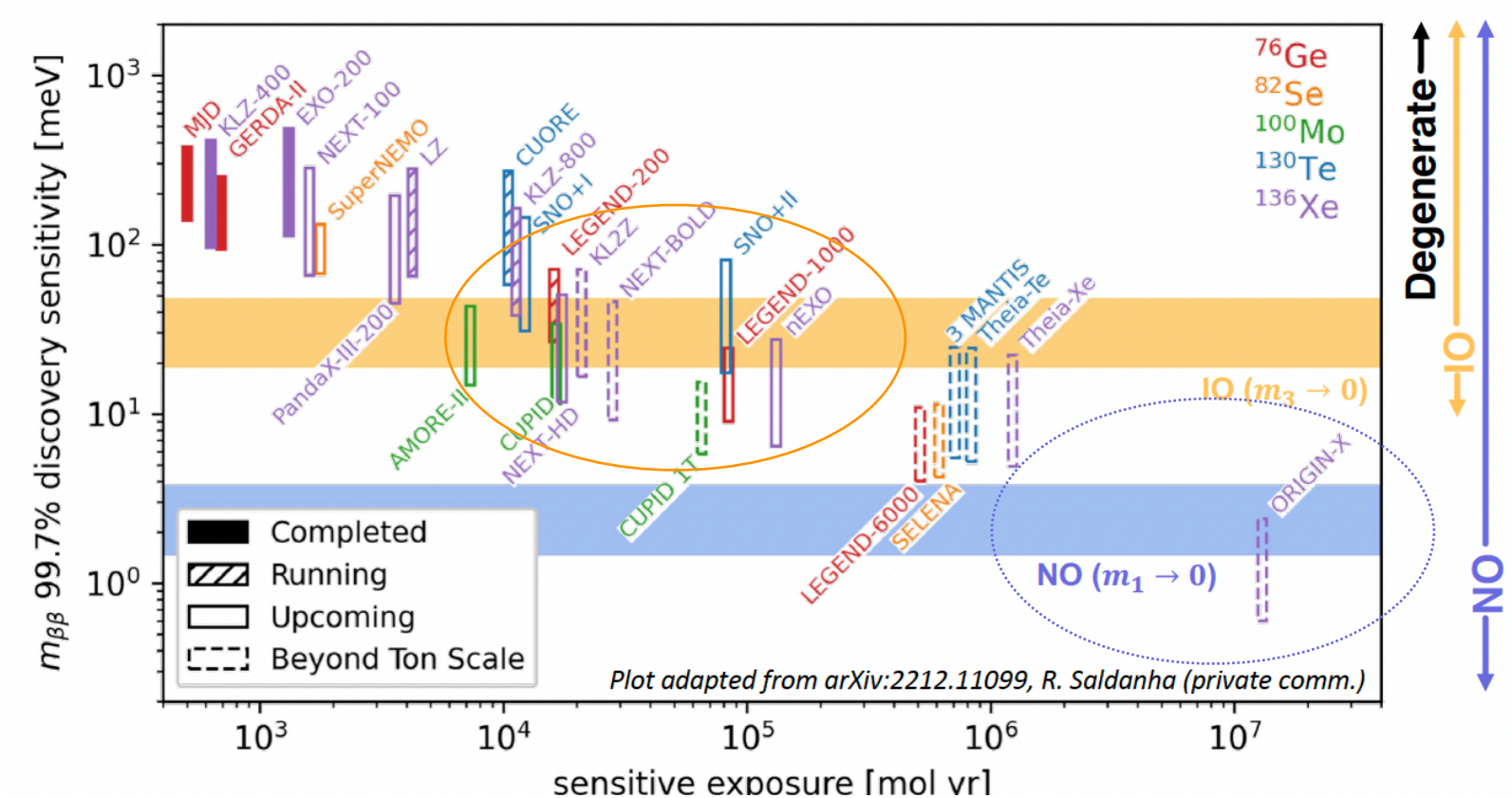
Phys.Rev.D 87 (2013) 7, 071301

Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched at $20/g ($M)	$0\nu/2\nu$ rate [2][8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^{8}	2.6	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^{6}	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^{5}	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^{4}	0.81	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^{5}	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^{4}$	11	269	0.024

- Need dedicated enrichment international facility or new enrichment technologies
- Underground lab facilities for radio purity assays and low bkgd instrumentation development→ synergy with DM experiments
- Currently negligible bkgd matter: 2vββ spillover + pile-up, ^{8}B v from sun, neutron, cosmogenic
- Extension of present technologies and/or new ones need adequate R&D

Accessing Normal Ordering

- The problem could be the signal rather than the background



$T^{0\nu}_{1/2} \sim 10^{29} - 10^{30}$ y

- Need dedicated enrichment international facility or new enrichment technologies
- Underground lab facilities for radio purity assays and low bkgd instrumentation development→ synergy with DM experiments
- Currently negligible bkgd matter: 2vββ spillover + pile-up, ^{8}B v from sun, neutron, cosmogenic
- Extension of present technologies and/or new ones need adequate R&D