Review of current and future neutrinoless double beta decay experiments

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8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics
Jun 11 – 13, 2022 - Villa Orlandi, Anacapri, Capri Island, Italy

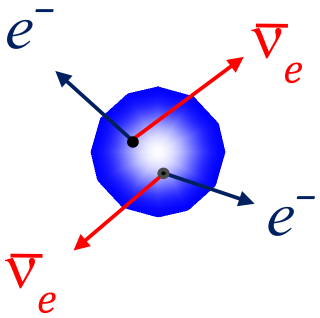
INFN

Double Beta Decay

Rare Nuclear Decay

(A,Z) → (A,Z+2) + 2e⁻ + [...]

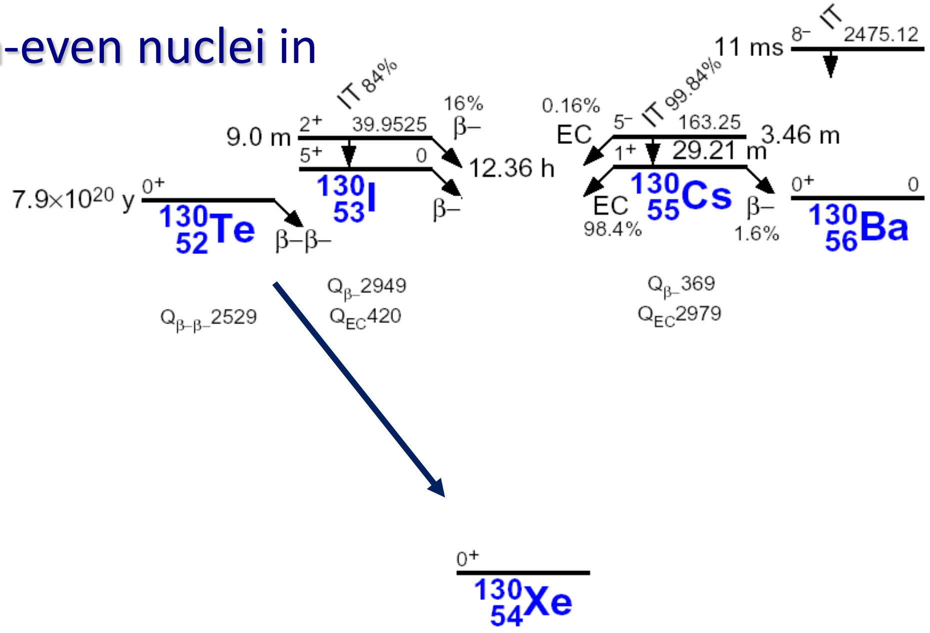
occurs in a number of even-even nuclei in *A* even multiplets



ββ-2ν: two neutrino mode

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

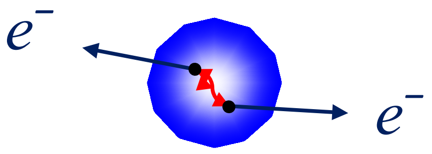
- allowed in Standard Model
- *second order weak transition*

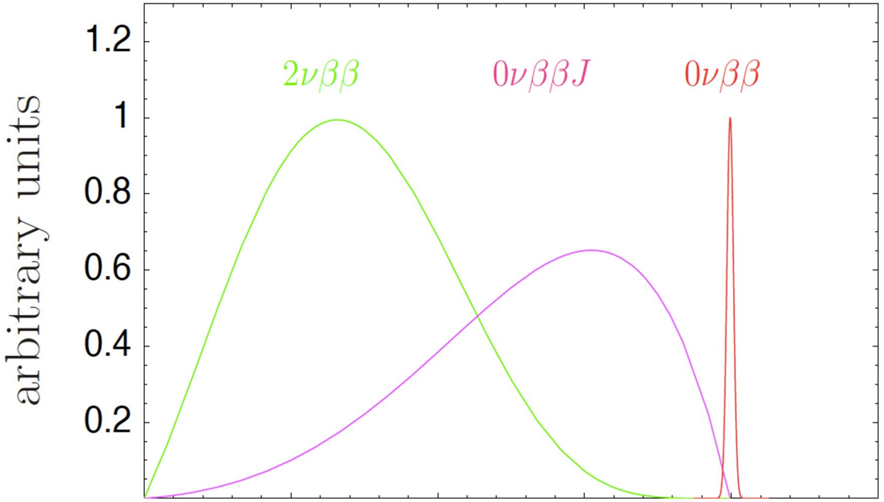


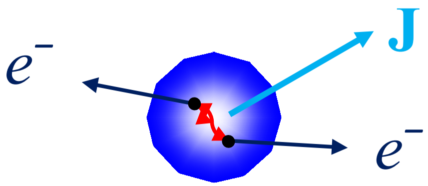
ββ-0ν: neutrinoless mode

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

- not allowed in SM (ΔL=2, B-L violation)
- neutrino is a massive Majorana particle
- Majorana phases







ββ-0ν: "exotic" modes

$(A, Z) \rightarrow (A, Z+2)$ + exotic particles

Neutrinoless Double Beta Decay Process

With a specific approach and introducing some important approximations:

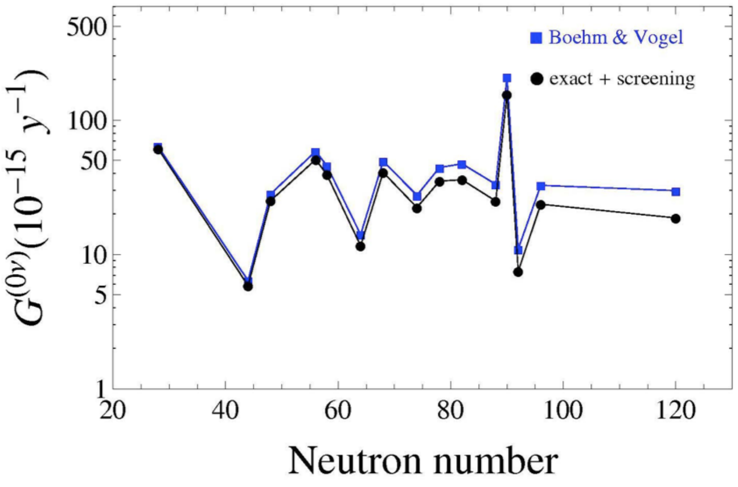
$$\Gamma^{0\nu} = G_x(Q, Z)|M_x(A, Z)|^2|\eta_x|^2$$

phase space factor
calculable precisely

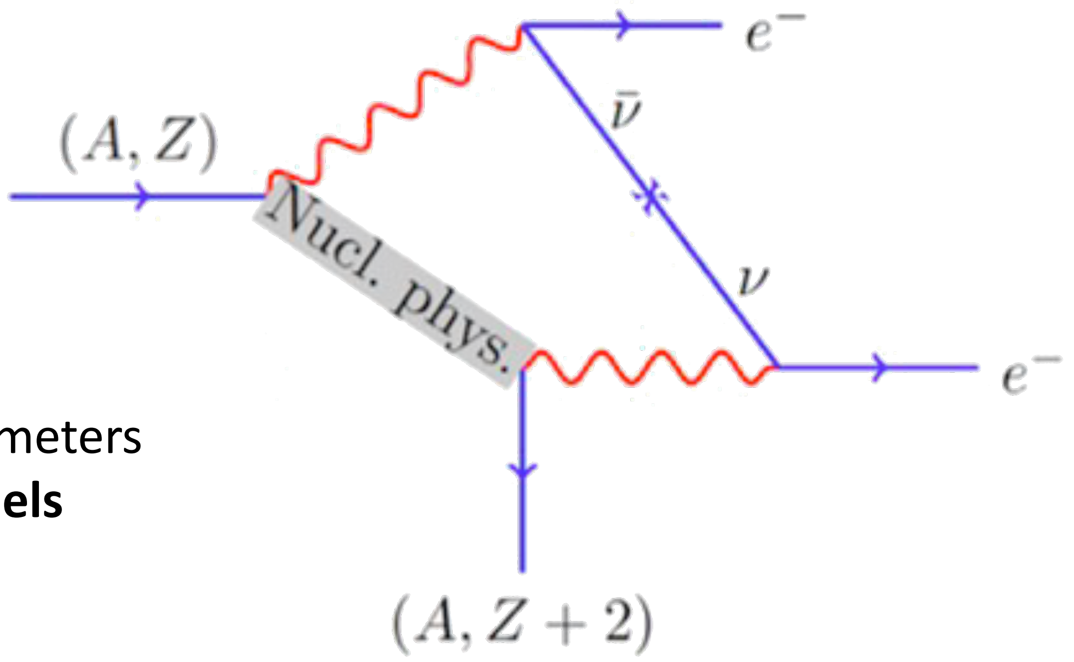
nuclear matrix element
not well established

particle physics parameters
depends on models

- massive Majorana neutrinos
- GUT's
- SUSY
- …



F. Böhm and P. Vogel, *loc. cit.*
J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



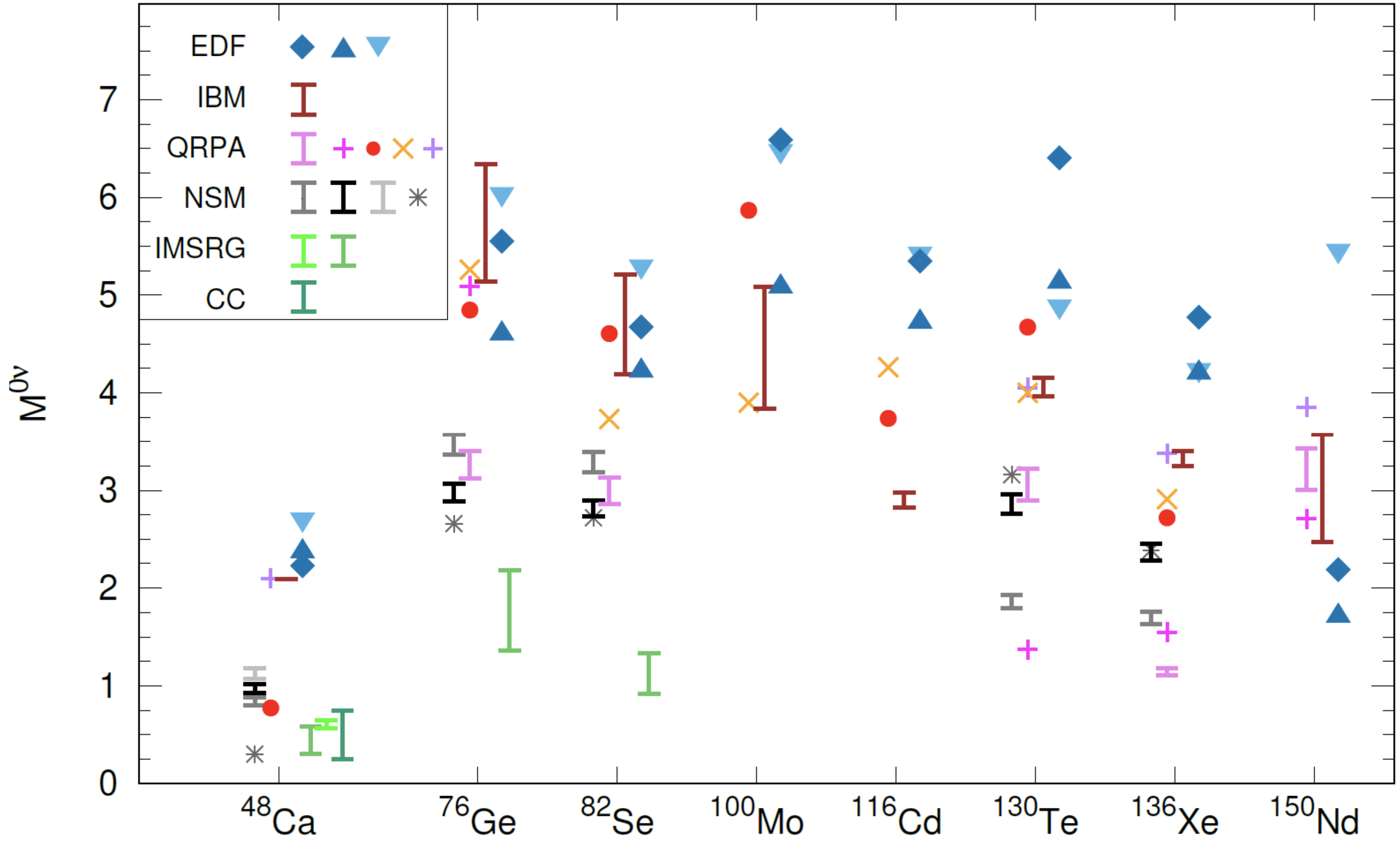
Nuclear Matrix Elements

$M_{0\nu}$ values estimated from different Nuclear Matrix calculation methods

NME calculations:
- **EDF**: large
- **QRPA**: larger spread
- **NSM**: small
- **IMSRG** ^{48}Ca ab initio: very small

- Significant differences
- Results inaccuracy

g_A quenching?



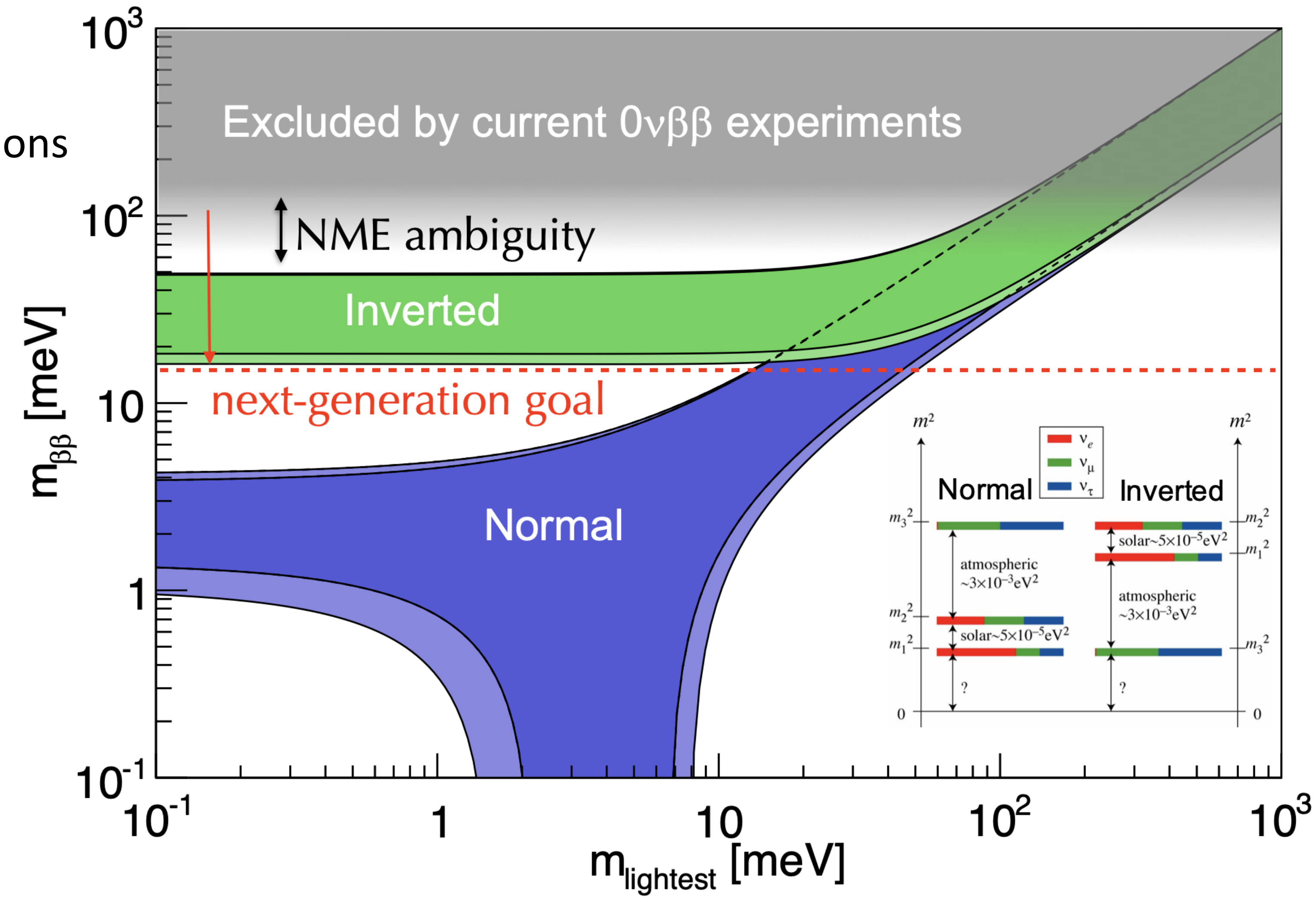
Light Majorana Neutrinos Mechanism

ββ0ν mediated by exchange of light Majorana neutrinos other mechanisms give no contributions

$$\eta_x = < m_{ee} >= \sum_k U_{ek}^2 m_k$$
$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

m_{ee} depends on three masses and two Majorana phases

- Transition amplitude is proportional to the coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations
- Oscillation experiments could identify only neutrino mass differences



Experimental Sensitivity

$$\tau^{0\nu}_{1/2} = ln2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

N_{bkg} >> 1 $$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

N_{bkg} ~ 1 $$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

Many important Parameters

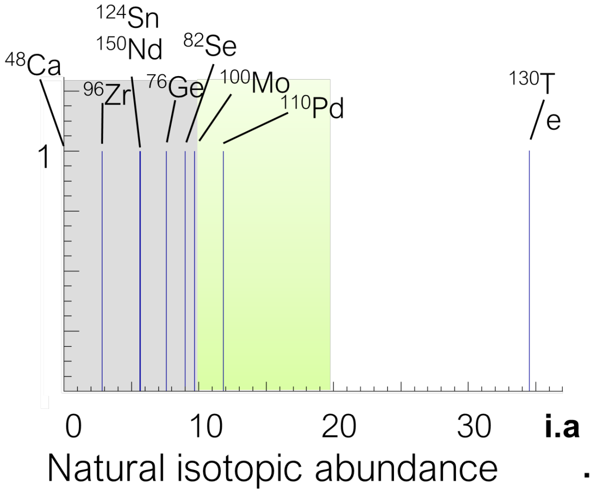
N_{nuclei}	number of active nuclei
t_{meas}	measurement time [y]
M	mass of the detector [kg]
ε	detection efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energetic resolution [keV]
bkg	background index [c/keV/y/kg]

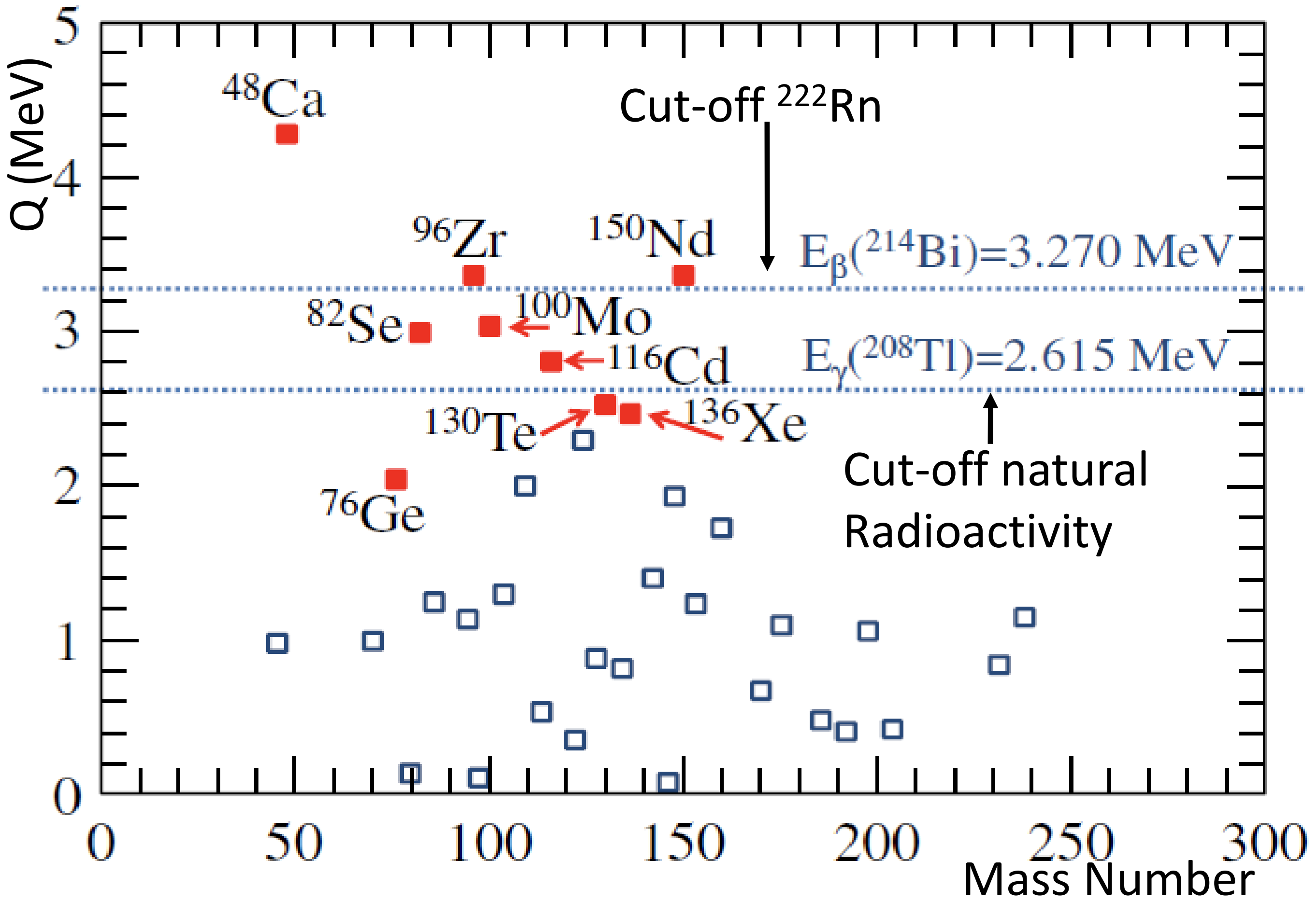
- isotope choice/enrichment
- experimental approach
- scalability
- stability
- cost

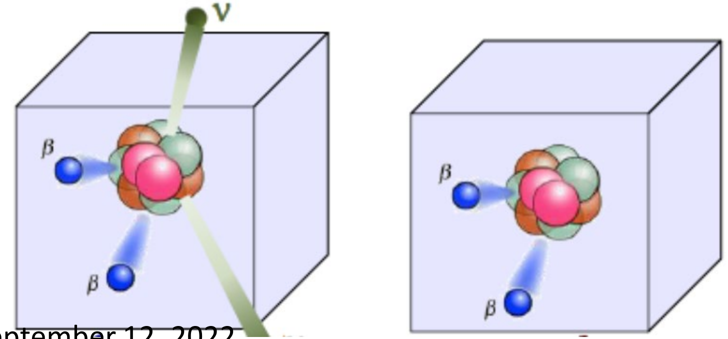
Isotope selection

From the Table of Isotopes

- 35 isotopes with double beta decay transitions
- 9 promising for sensitive measurements
- most promising candidates: $Q_{\beta\beta}$ > 2-3 MeV
- isotope enrichments are needed







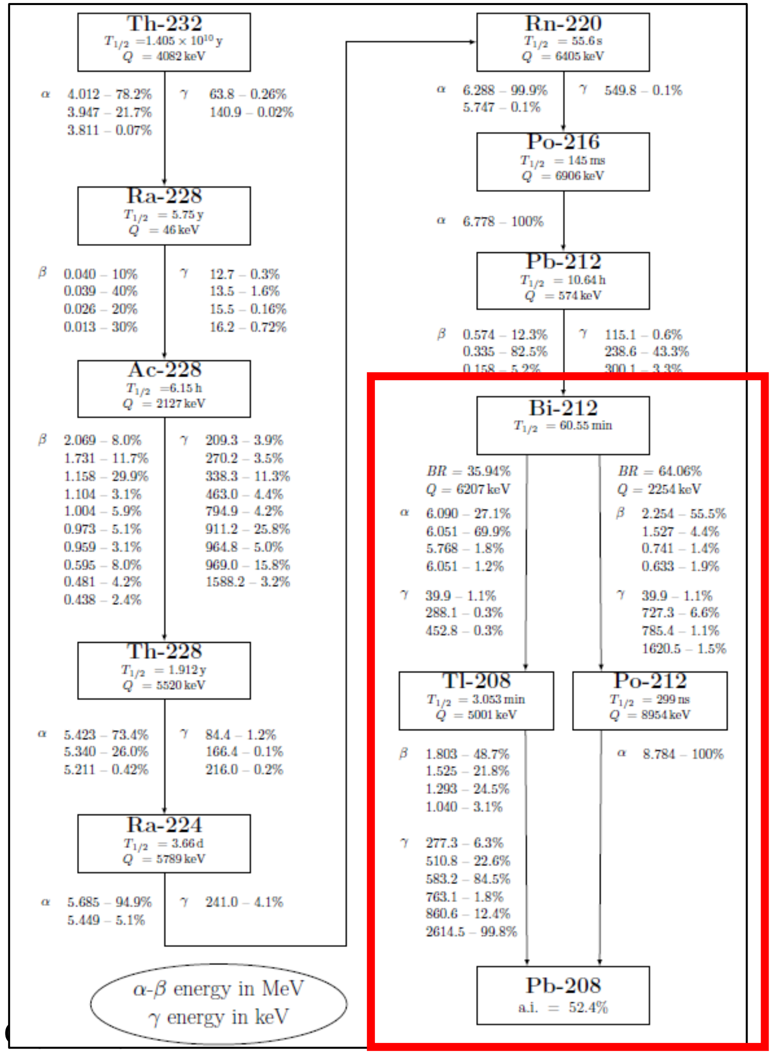
Considering a calorimetric approach (**Source == Detector**)

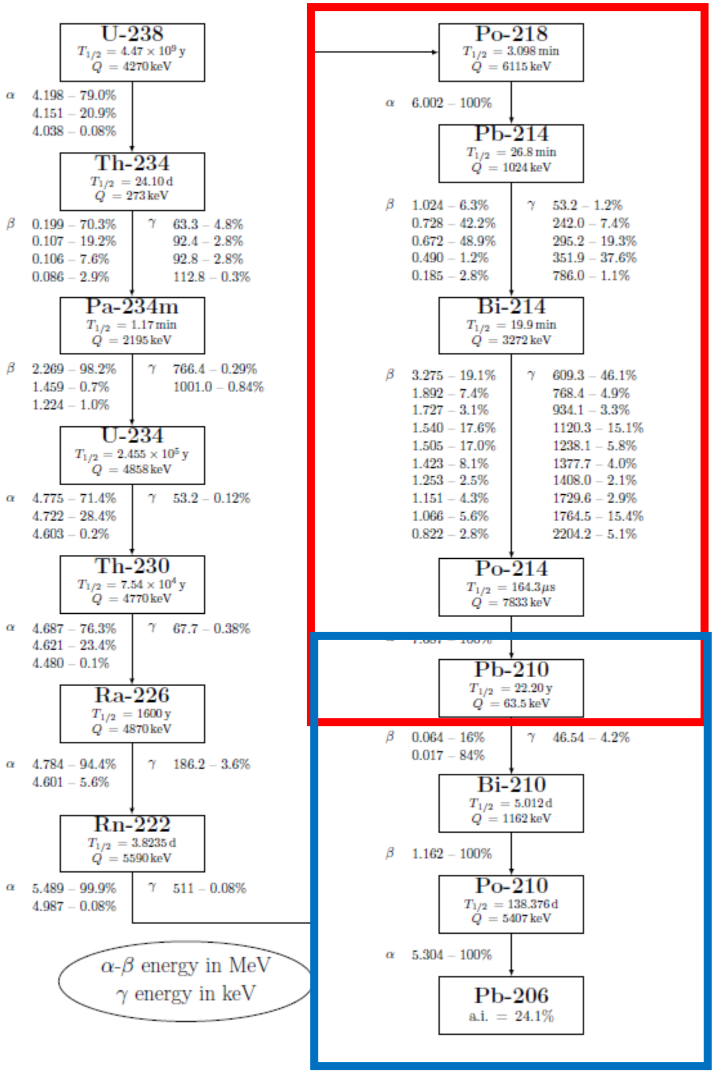
- **isotope enrichments** are needed
- **very clean materials** have to be identified

Background interferences

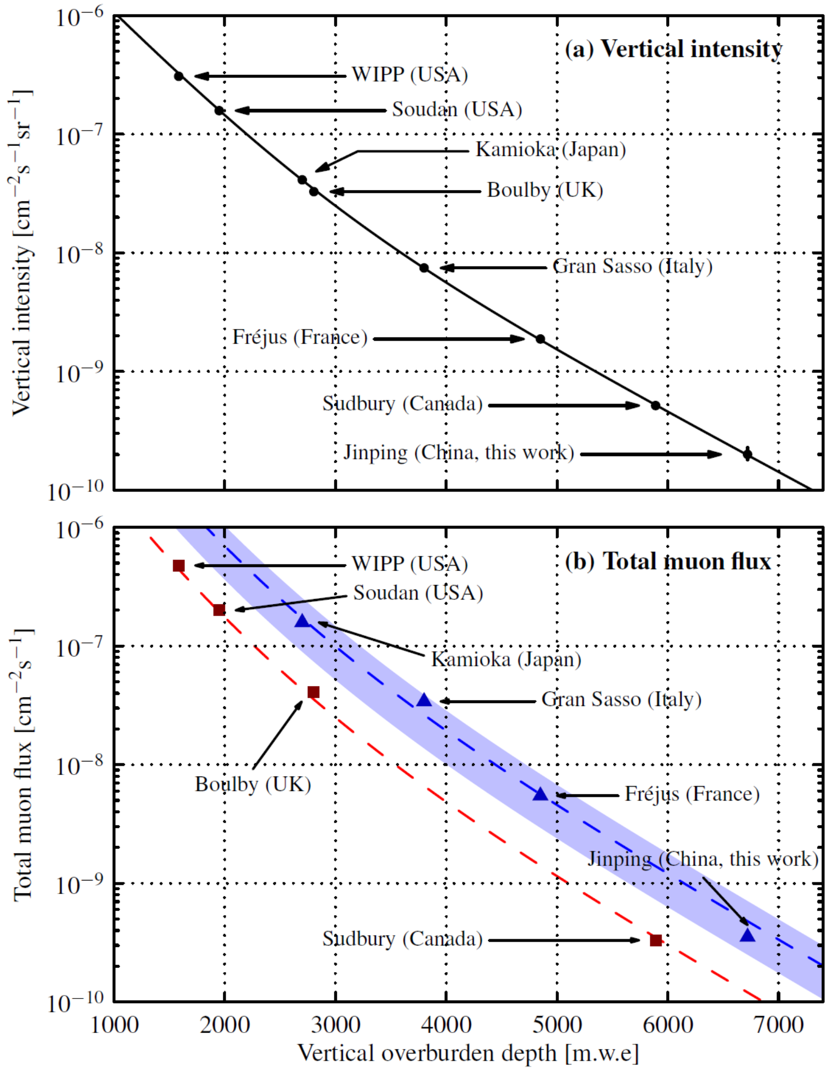
It is necessary to strongly reduce background events:

- Cosmic Rays
- Radioactivity





Guo et al., Chinese Physics **C45** (2021) 025001, arXiv:2007.15925v2



E. Previtali

Possible Calorimetric Approaches

Fluid or diluted in a fluid ← **Source** → Integral part of a crystal

- Container size
- Concentration of the source

← **Scalability** →

- Size of a single crystal
- Number of crystals

Large volumes of fluid

- Diluted source in liquid scintillatol →
  - Without balloon (SNO+)
  - With balloon (**KamLAND-Zen**)
  - With balloon+Cherenkov (Theia)
  - Opaque scintillator (LiquidO)
- TPC
  - High-pressure gas →
    - Cylindrical(Xe: Next, PandaX, Axel; SeF6:N\nuDEx)
    - Spherical(R2D2)
  - Liquid →
    - Single phase (Xe: EXO-200, **nEXO**)
    - Double phase (Xe: Darwin, LZ)

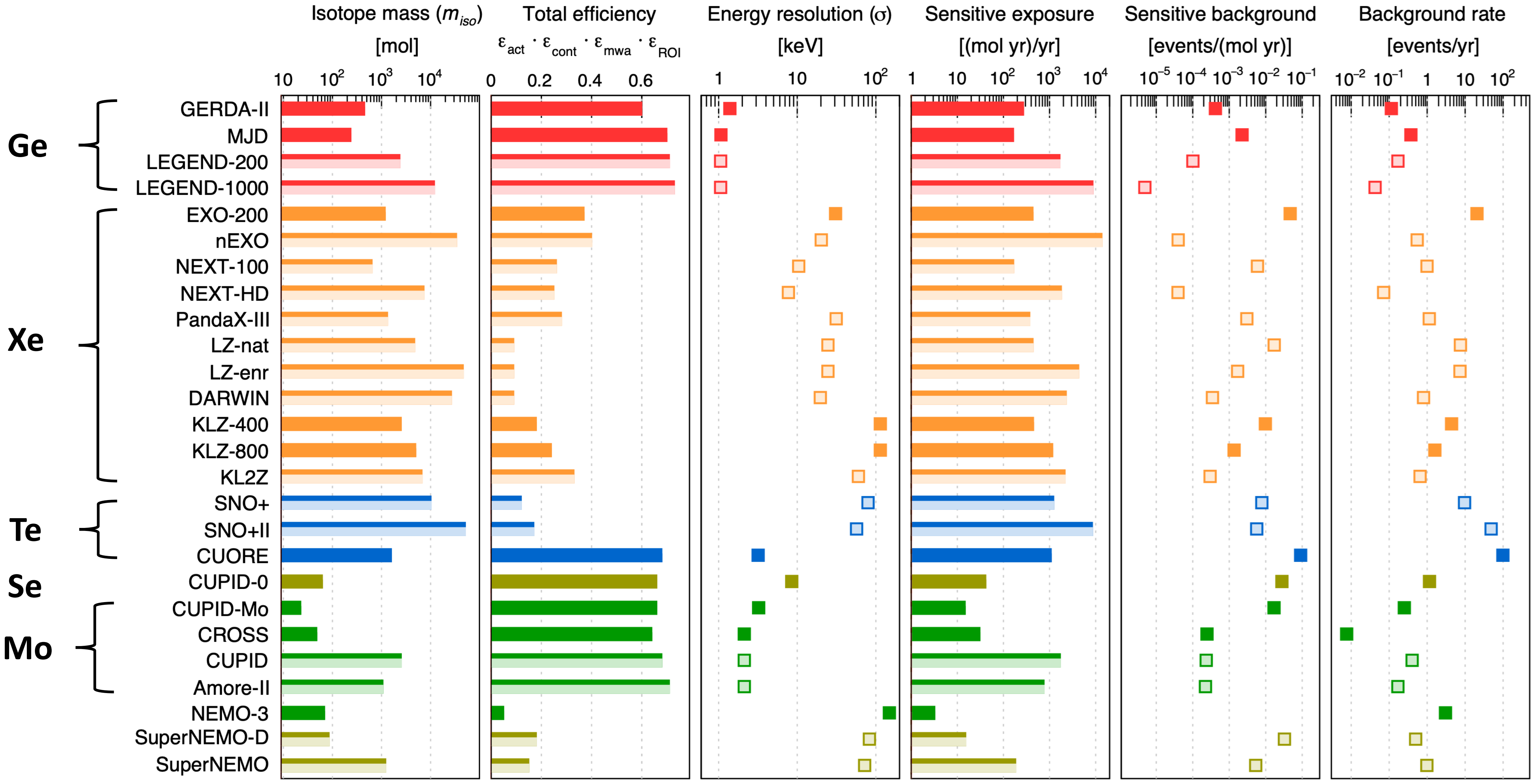
Crystal arrays

- Inorganic Scintillators (Candles)
- Semiconductor detectors
  - Germanium diodes →
    - Immersed in LAr (**GERDA, LEGEND**)
    - Conventional cryostats (MJD)
  - CCD to Se (SELENA)
  - CdZnTe (COBRA)
- Bolometers →
  - Pure bolometers (**CUORE**)
  - Scintillating bolometers (**CUPID, AMORE**)
  - PSD (CROSS)

Present and Future experiments

	Experiment	Isotope	Status	Laboratory	Moles of isotope	Isotopic abundance	B (events/kg$_{iso}$/keV/yr)	Fiducial isotope mass (kg)	Active fraction (%)	Eficiency	FWHM (keV)
High-purity Ge detectors	GERDA-II	^{76}Ge	completed	LNGS	450	0.87	6.00E-04	30	88	0.7189	3.29
	MJD	^{76}Ge	completed	SURF	240	0.88	4.74E-03	16	90	0.8099	2.585
	LEGEND-200	^{76}Ge	construction		2400	0.9	2.10E-04	166	91	0.819	2.585
	LEGEND-1000	^{76}Ge	proposed		12000	0.91	1.00E-05	839	92	0.828	2.585
Xenon TPC's	EXO-200	^{136}Xe	completed	WIPP	1200	0.81	1.99E-03	75	46	0.84	72.85
	nEXO	^{136}Xe	proposed	SNOLAB	34000	0.9	2.10E-06	2959	64	0.66	47
	NEXT-100	^{136}Xe	construction	LSC	640	0.9	4.90E-04	77	88	0.3724	23.5
	NEXT-HD	^{136}Xe	proposed		7400	0.9	5.80E-06	956	95	0.3916	18.095
	PandaX-III-200	^{136}Xe	construction	CJPL	1300	0.9	1.20E-04	136	77	0.481	72.85
	LZ-nat	^{136}Xe	construction	SURF	4700	0.09	1.22E-03	90	14	0.8	58.75
	LZ-enr	^{136}Xe	proposed	SURF	46000	0.9	1.20E-04	876	14	0.8	58.75
	Darwin	^{136}Xe	proposed		27000	0.09	4.10E-05	477	13	0.9	47
Large liquid scintillators	KLZ-400	^{136}Xe	completed	Kamioka	2500	0.91	3.80E-04	150	44	0.97	267.9
	KLZ-800	^{136}Xe	data taking	Kamioka	5000	0.91	5.30E-05	394	58	0.97	267.9
	KL2Z	^{136}Xe	proposed	Kamioka	6700	0.91	2.20E-05	729	80	0.97	141
	SNO+I	^{130}Te	construction	SNOLAB	10000	0.348	3.00E-04	272	20	0.97	188
	SNO+II	^{130}Te	proposed	SNOLAB	51000	0.348	3.00E-04	1873	27	0.97	133.95
Cryogenic calorimeters	CUORE	^{130}Te	data taking	LNGS	1585	0.348	5.38E-02	206	100	0.8096	7.52
	CUPID-0	^{82}Se	completed	LNGS	62	0.96	5.95E-03	5	100	0.6966	19.975
	CUPID-Mo	^{100}Mo	completed	LSM	23	0.97	7.82E-03	2.3	100	0.6916	7.52
	CROSS	^{100}Mo	construction	LSC	48	0.96	1.71E-02	5	100	0.675	4.935
	CUPID	^{100}Mo	proposed	LNGS	2500	0.96	1.70E-04	250	100	0.711	4.935
	AMORE	^{100}Mo	proposed	Yemilab	1100	0.96	1.70E-04	110	100	0.7462	4.935
Tracking calorimeters	NEMO-3	^{100}Mo	completed	LSM	690	0.9	2.18E-03	69	100	0.11	347.8
	SuperNEMO-D	^{82}Se	construction	LSM	850	0.9	1.10E-04	70	100	0.28	195.05
	SuperNEMO	^{82}Se	proposed	LSM	1200	0.9	3.20E-05	98	100	0.28	169.2

Present and Future Experiments



Matteo Agostini, Giovanni Benato, Jason A. Detwiler, Javier Menéndez, Francesco Vissani - arXiv:2202.01787

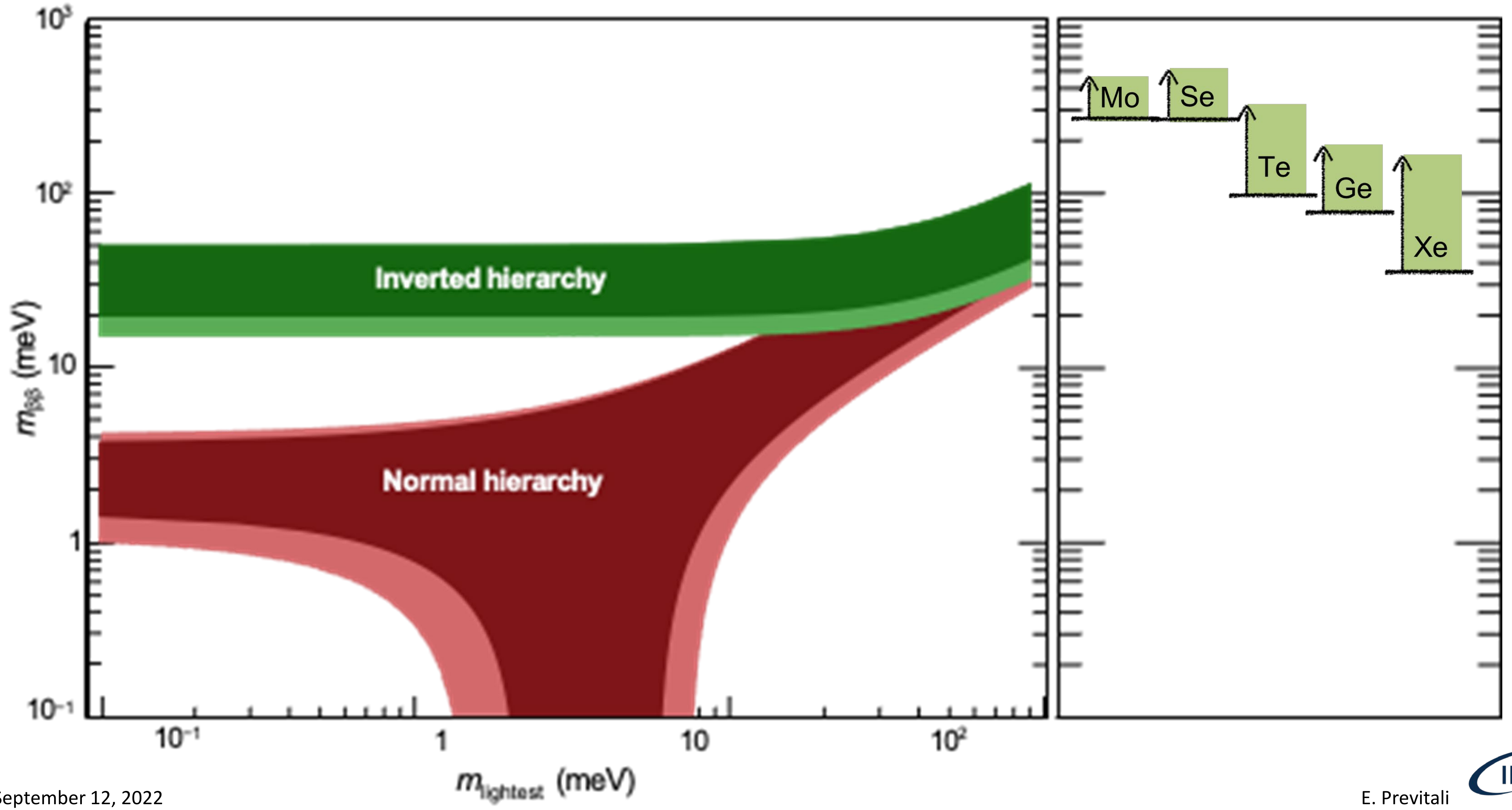
Present Experimental Sensitivities

Isotope	Daughter	Q	f_{nat}	f_{enr}	T(2)	T(0)
^{48}Ca	^{48}Ti	4267.98(32)	0.187(21)	16	$(6.4^{+0.7}_{-0.6}$ (stat)$^{+1.2}_{-0.9}$ (syst)) 10^{19}	> 5.8 10^{22}
^{76}Ge	^{76}Se	2039.061(7)	7.75(12)	92	(1.92±94) 10^{21}	> 1.8 10^{26}
^{82}Se	^{82}Kr	2997.9(3)	8.82(15)	96.3	(8.60±0.03 (stat)$^{+0.19}_{-0.13}$ (syst)) 10^{19}	> 3.5 10^{24}
^{96}Zr	^{96}Mo	3356.097(86)	2.80(2)	86	(2.35±0.14 (stat) ± 0.16 (syst))10^{19}	> 9.2 10^{21}
^{100}Mo	^{100}Ru	3034.40(17)	9.744(65)	99.5	$(7.12^{+0.18}_{-0.14}$ (stat) ± 0.10 (syst)) 10^{18}	> 1.5 10^{24}
^{116}Cd	^{116}Sn	2813.50(13)	7.512(54)	82	$2.63^{+0.11}_{-0.12}$ 10^{19}	> 2.2 10^{23}
^{130}Te	^{130}Xe	2527.518(13)	34.08(62)	92	$(7.71^{+0.08}_{-0.06}$ (stat)$^{+0.12}_{-0.15}$ (syst)) 10^{20}	> 2.2 10^{25}
^{136}Xe	^{136}Ba	2457.83(37)	8.857(72)	90	(2.165 ±0.016 (stat) ±0.059 (syst))10^{21}	> 1.1 10^{26}
^{150}Nd	^{150}Sm	3371.38(20)	5.638(28)	91	(9.34±0.22(stat)$^{+0.62}_{-0.60}$(syst)) 10^{18}	> 2.0 10^{22}

NEUTRINO 2022 updates

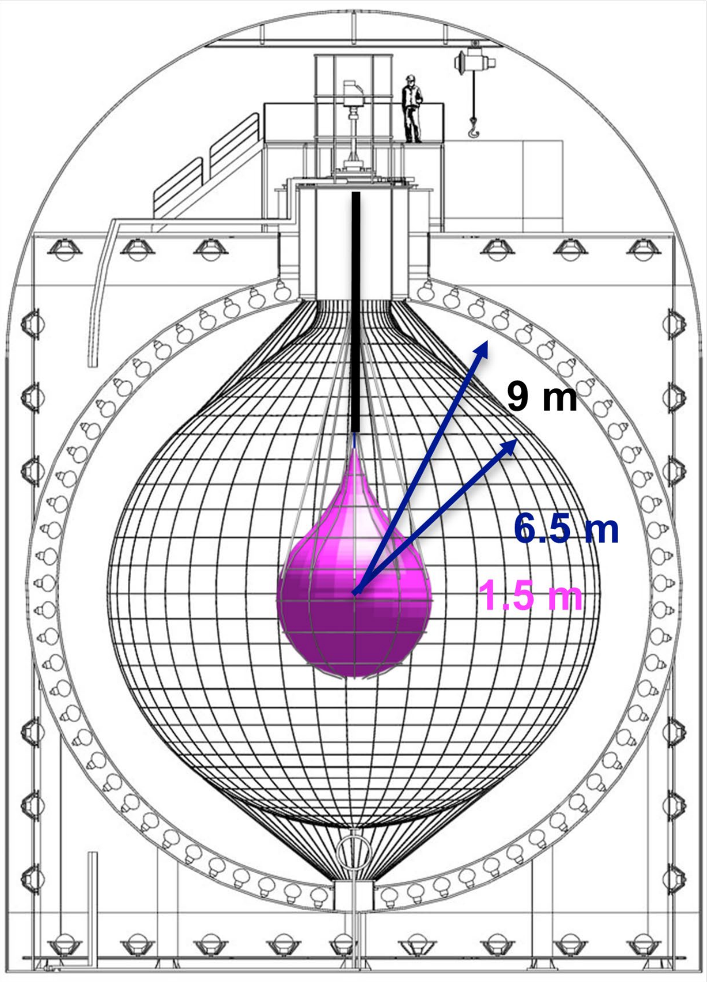
Experiment	Isotope	Limit $T_{1/2}$ (yr)	BI (10^{-3} ckky)	BI (10^{-3} $ckk_{iso}yr$)	FWHM (keV)	Exposure (kg_{iso}·yr)	$m_{\beta\beta}$ (meV)	
AMORE-I	^{100}Mo	$1.2\cdot10^{24}$	39	72.8	10	1.67	343-600	Y. Oh
GERDA	^{76}Ge	$1.8\cdot10^{26}$	0.5	6.8	3	103.7	79-180	J. Gruszko
MJD	^{76}Ge	$8.3\cdot10^{25}$	6	6.8	2.85*	64.5	113-269	J. Gruszko
CUORE	^{130}Te	$2.2\cdot10^{25}$	14.9	52.7	7.8	288.6	90-305	I.Nutini
CUPID-0	^{82}Se	$4.7\cdot10^{24}$	3.5	5.4	20	8.8	276-570	A. Zolotarova
CUPID-Mo	^{100}Mo	$1.8\cdot10^{24}$	3.0	5.6	7.4	2.7	280-490	A.Zolotarova
KL-ZEN-800	^{136}Xe	$2.3\cdot10^{26}$*		0.06	268	605	36-156	A. Nando

Sensitivities on Light Neutrino Majorana Mass



KamLAND-Zen

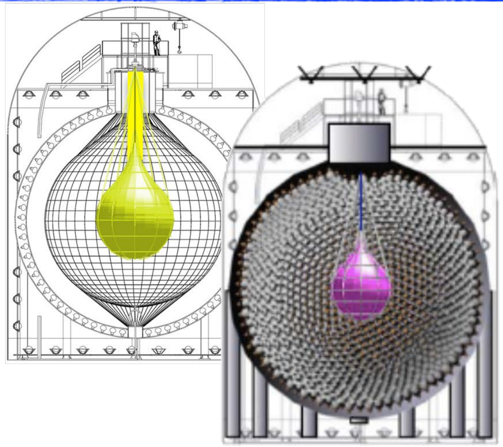
Large Liquid Scintillator Detector



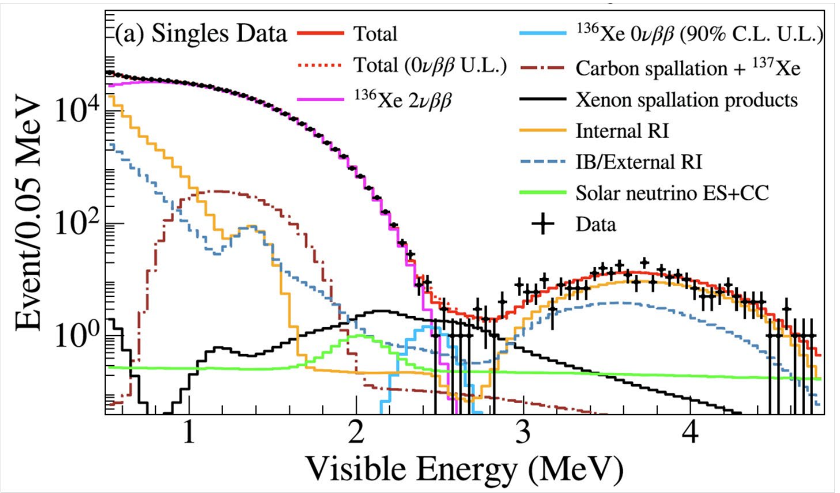
Phase-2: 2013/12/11 - 2015/10/27: **534.5 days (504 kg-yr)**

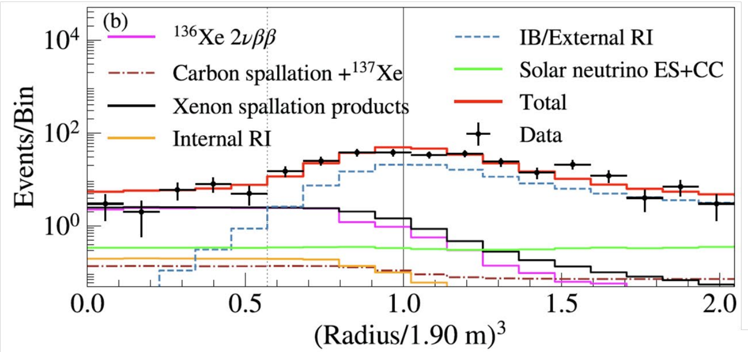
- Sensitivity:
  > 5.6·10^{25} yr (90% C.L.)
- Fit:
  > 9.2·10^{25} yr (90% C.L.)
- Phase I + II:
  > 1.07·10^{26} yr (90% C.L.)

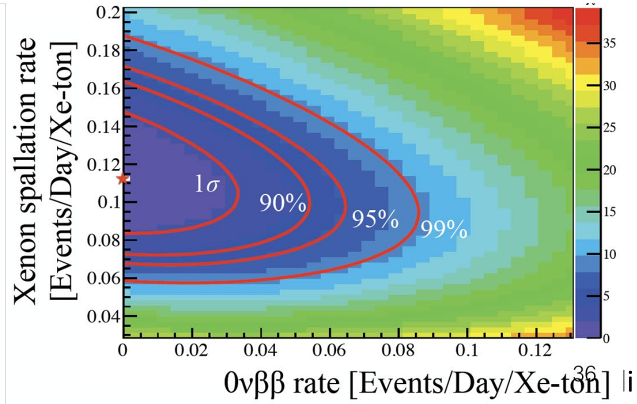
- KL-Zen-800: data taking started in **January 2019** with 750 kg ^{enr}Xe (new balloon)



- KamLAND2-Zen with 1000 kg (proposed)







GERDA

High purity germanium diodes immersed in LAr
- ΔE < 3 Kev FWHM @ $Q_{\beta\beta}$
- Pulse shape analysis: multi/single site vs.
- anticoincidence with LAr
  - scintillating fibers (WLS) coupled to SIPMS
  - PMT above and below the detector

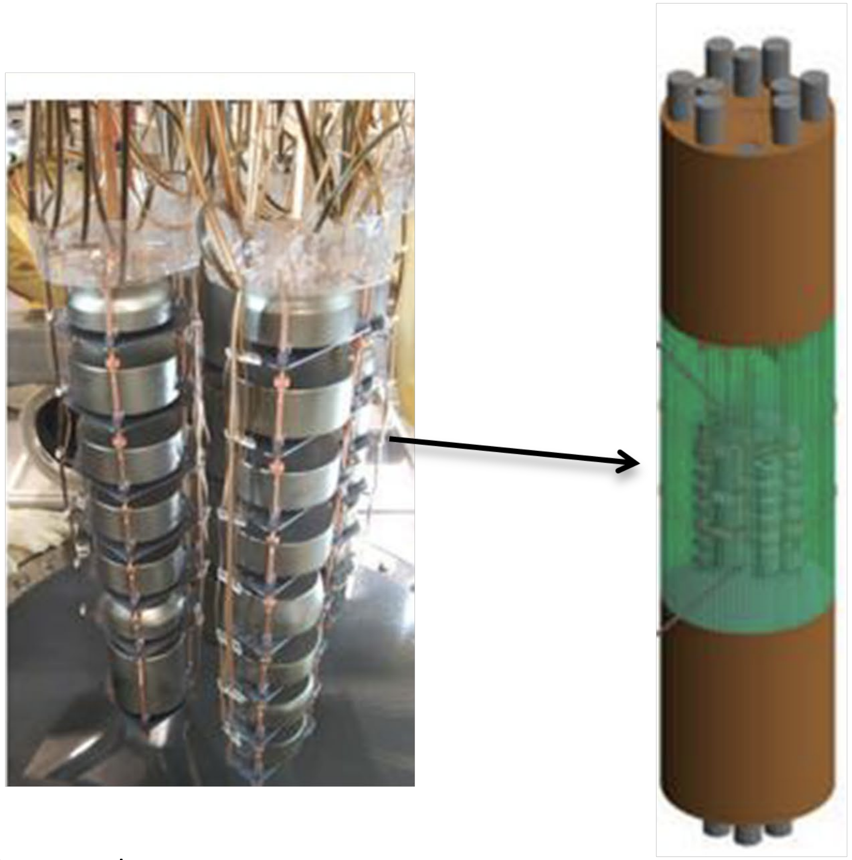
- 37 germanium HP detectors
- 35 kg of ^{76}Ge
- LNGS: Hall A
- Exceptional background level

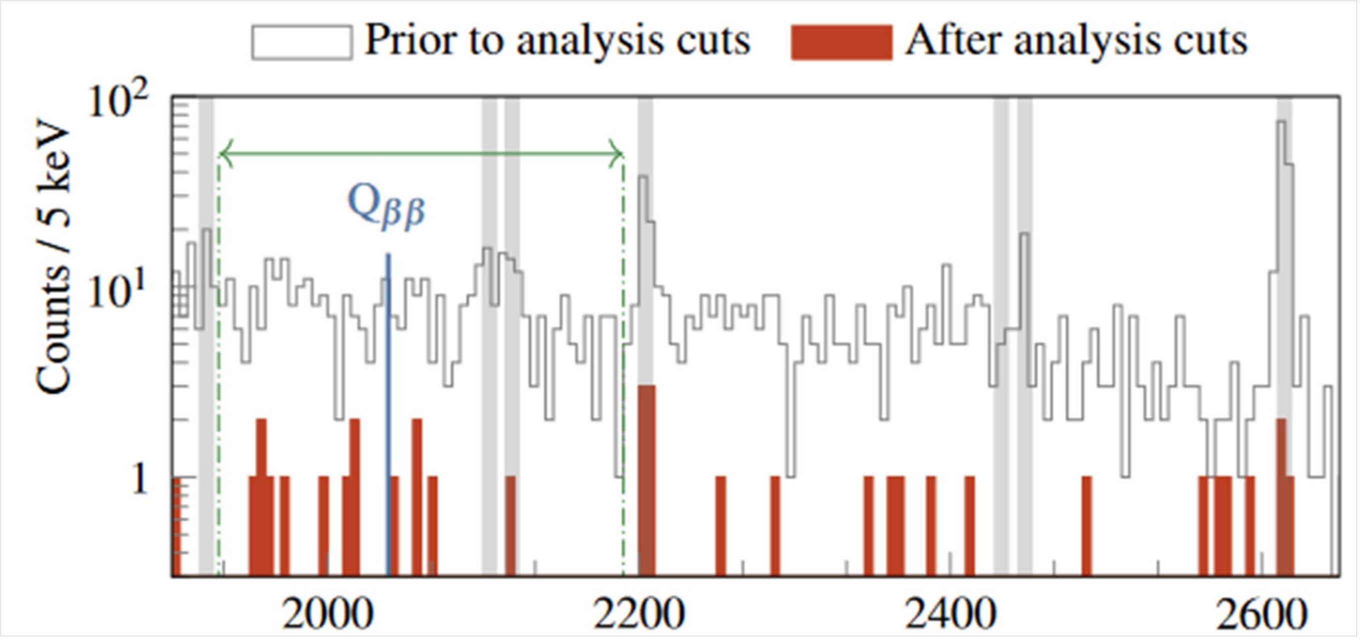
$$5.2^{+1.6}_{-1.3} \times 10^{-4}\ \text{cont/(keV kg yr)}$$

- Best limit on average lifetime

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

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

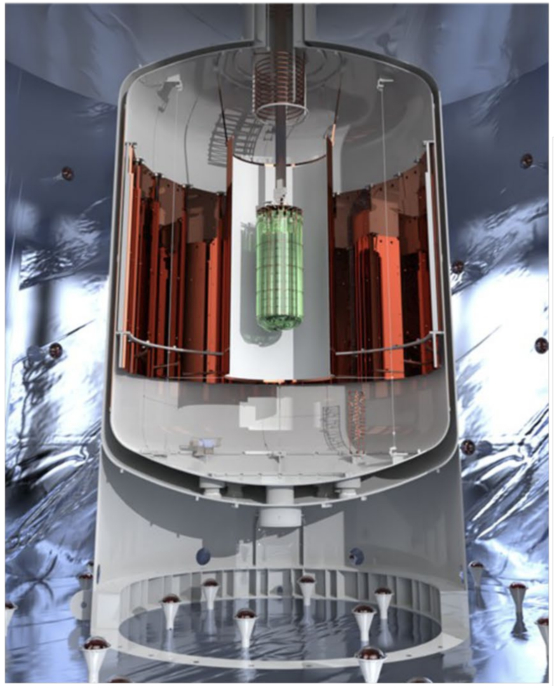


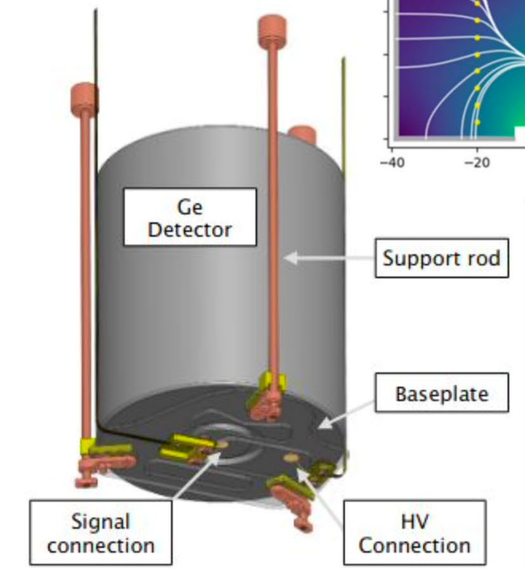


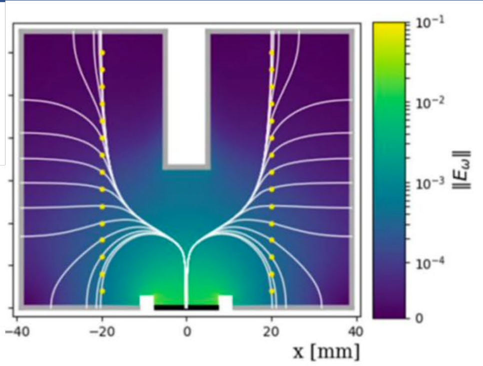
Phys. Rev. Lett. 125, 252502 (2020)

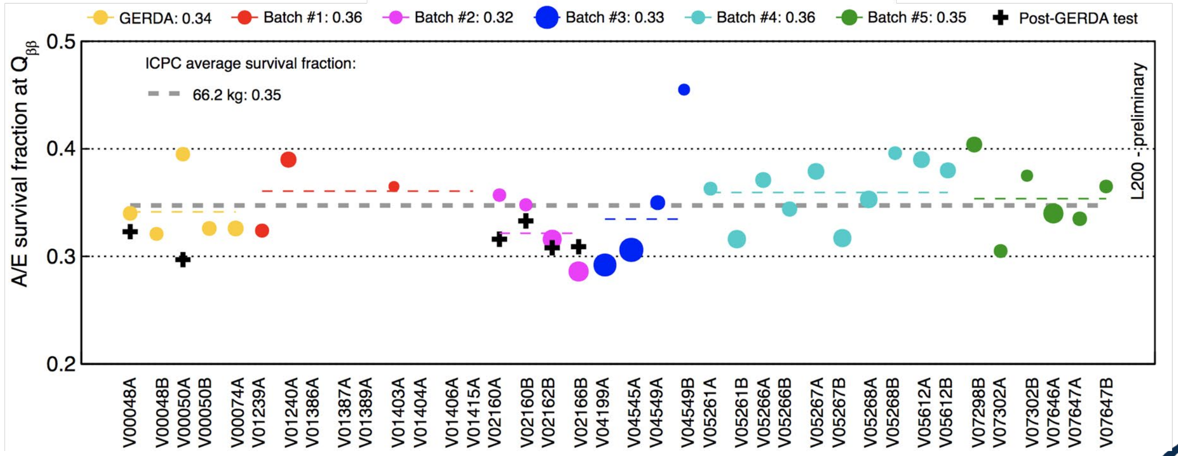
LEGEND-200

- Natural evolution of the GERDA principle
- Combines the best of Gerda and MJD
  - from GERDA:
    - detector configuration
    - infrastructure@ LNGS
    - system improvements
  - from MJD
    - selection of radio-pure materials
    - electronics
    - low threshold1
- ^{76}Ge:
  - 35 kg from GERDA
  - 30 kg from MJD
  - 140 kg new materials
- New type of detector, already tested in GERDA
  - ICPC m > 2 kg (0.7-0.9 kg previously)
  - same energy resolution and PSD capability







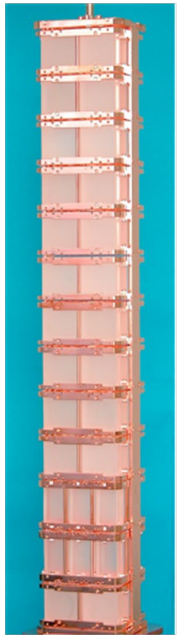


- Infrastructure upgrade: February 2020
- Detector commissioning: September 2021
- Data taking: start in 2022

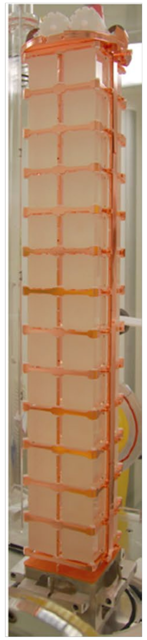
CUORE

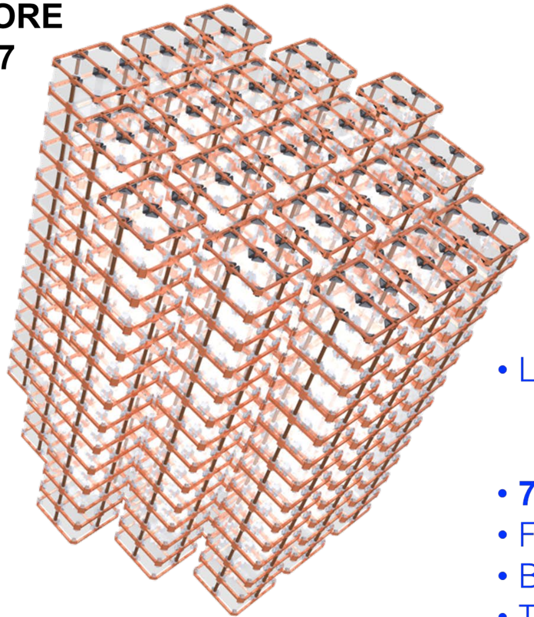
Largest cryogenic particle detector ever realized

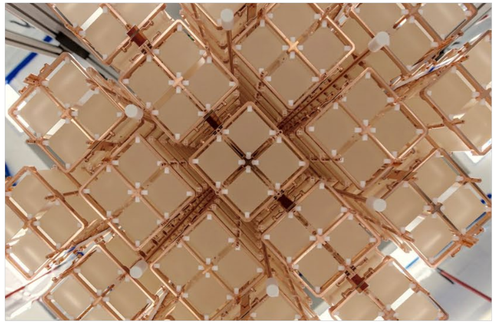
Cuoricino 2003

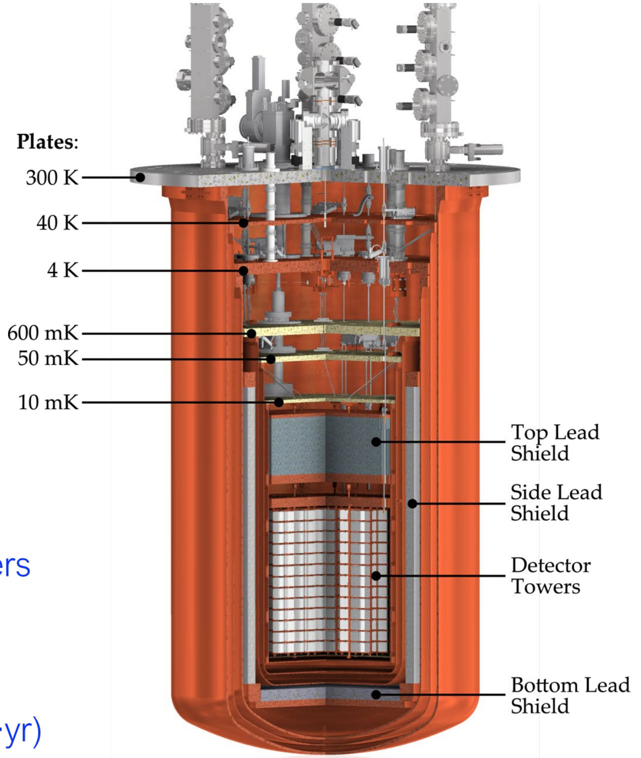


CUORE-0 2012

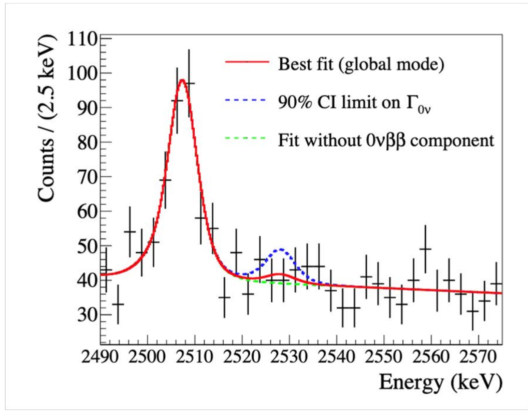








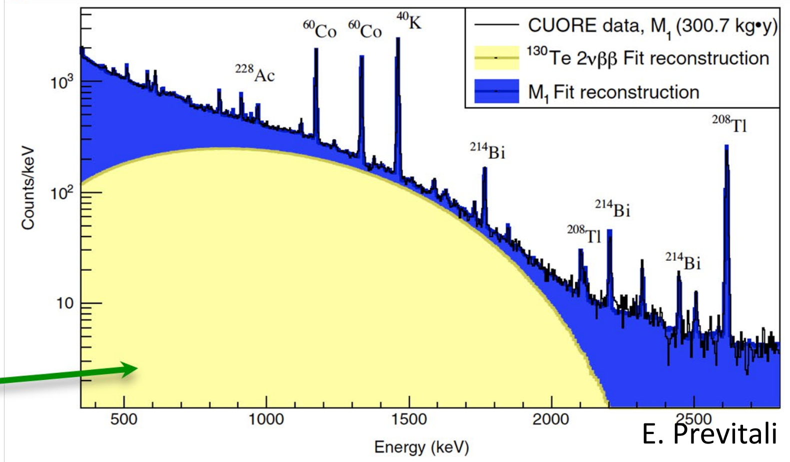
- LNGS
  - 988 TeO_2 crystals arranged on 19 towers
  - dedicated "dry" cryostat
- **742 kg** di $^{natural}TeO_2$ (206 kg of ^{130}Te)
- FWHM: **7.7 keV** FWHM (ROI)
- Background: **(1.4 ± 0.2)·10^{-2}** cnts/(keV·kg·yr)
- Total exposure: 1.8 tonne (TeO_2)·yr



- $\beta\beta0\nu$ result (1038.4 kg yr TeO_2, 288 kg yr ^{130}Te): :
  - **$T_{1/2}(0\nu) > 2.2\cdot10^{25}$ yr (90%C.L.)**
  - **$m_{\beta\beta}$ < 90−305 meV**

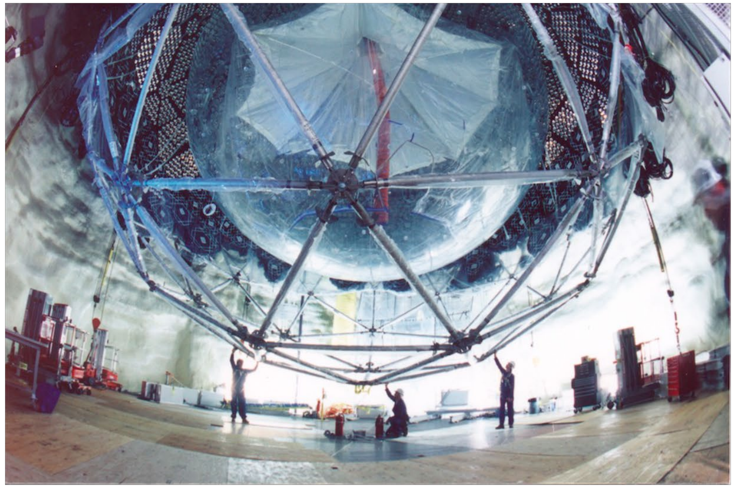
Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58
https://www.nature.com/articles/s41586-022-04497-4

- $T_{1/2}(2\nu) = [7.71(^{+0.08}_{-0.06}(stat.)^{+0.12}_{-0.15}(syst.)]\cdot10^{20}$ yr

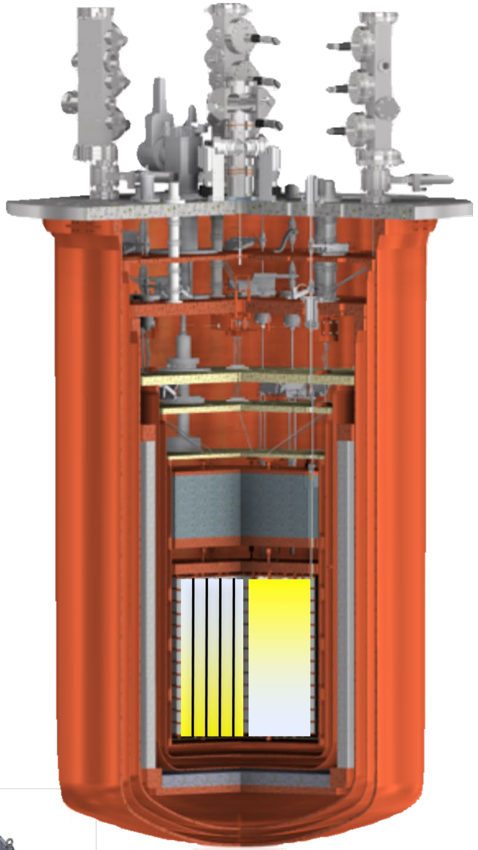


Next Generation Experiments

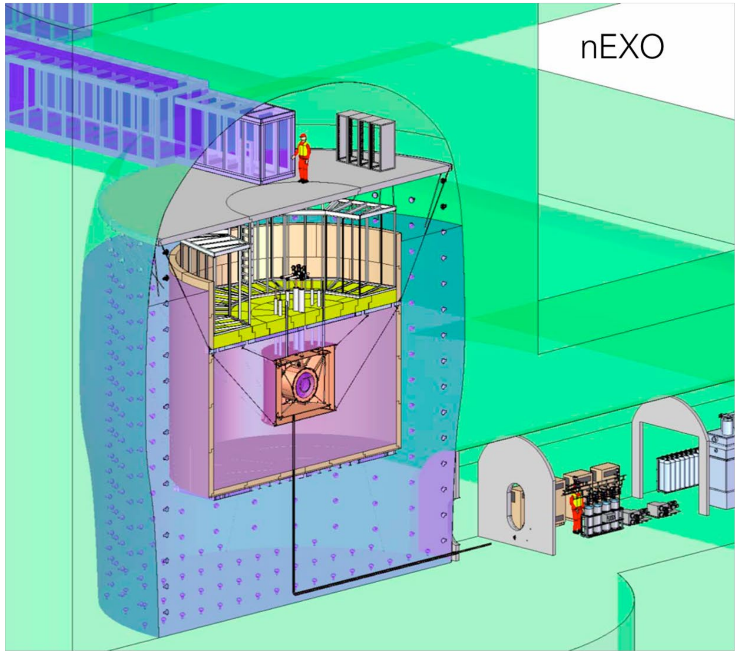
SNO+



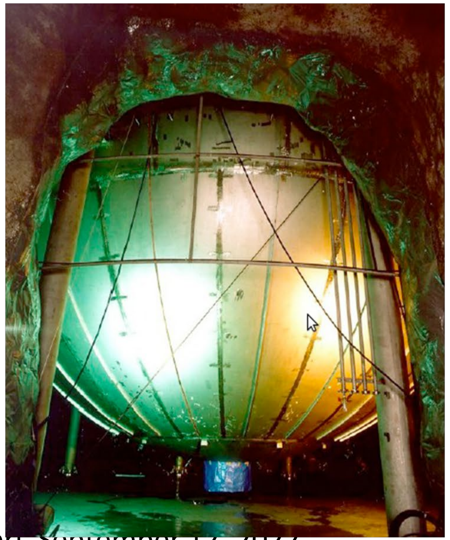
CUPID



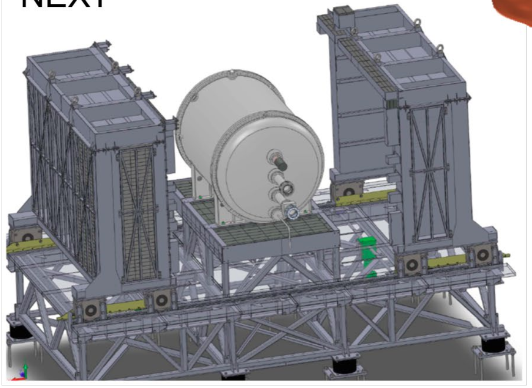
nEXO



KamLAND-ZEN



NEXT



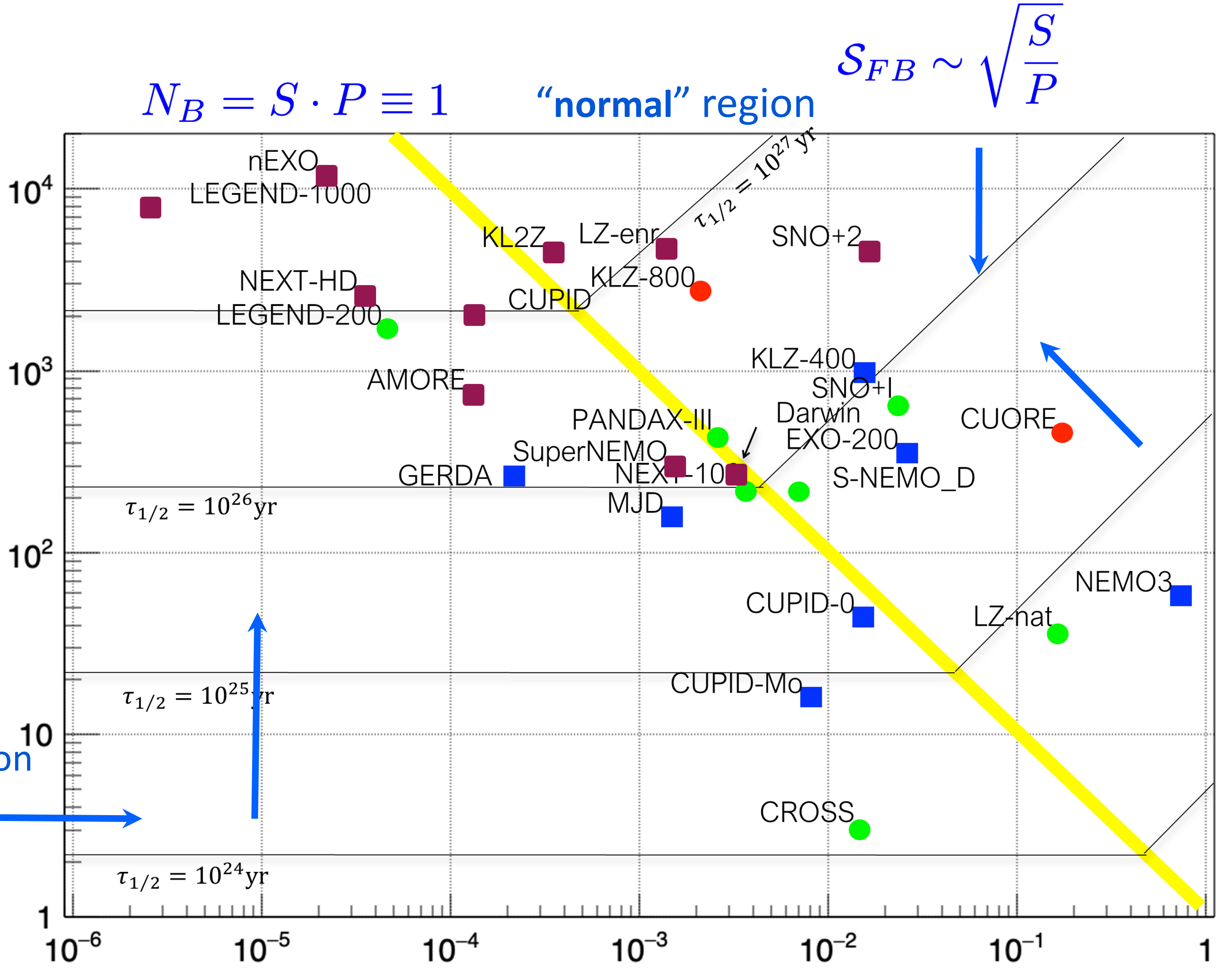
LEGEND

Sensitivity Plot: Present and Future

$$N_B = S \cdot P \equiv 1$$

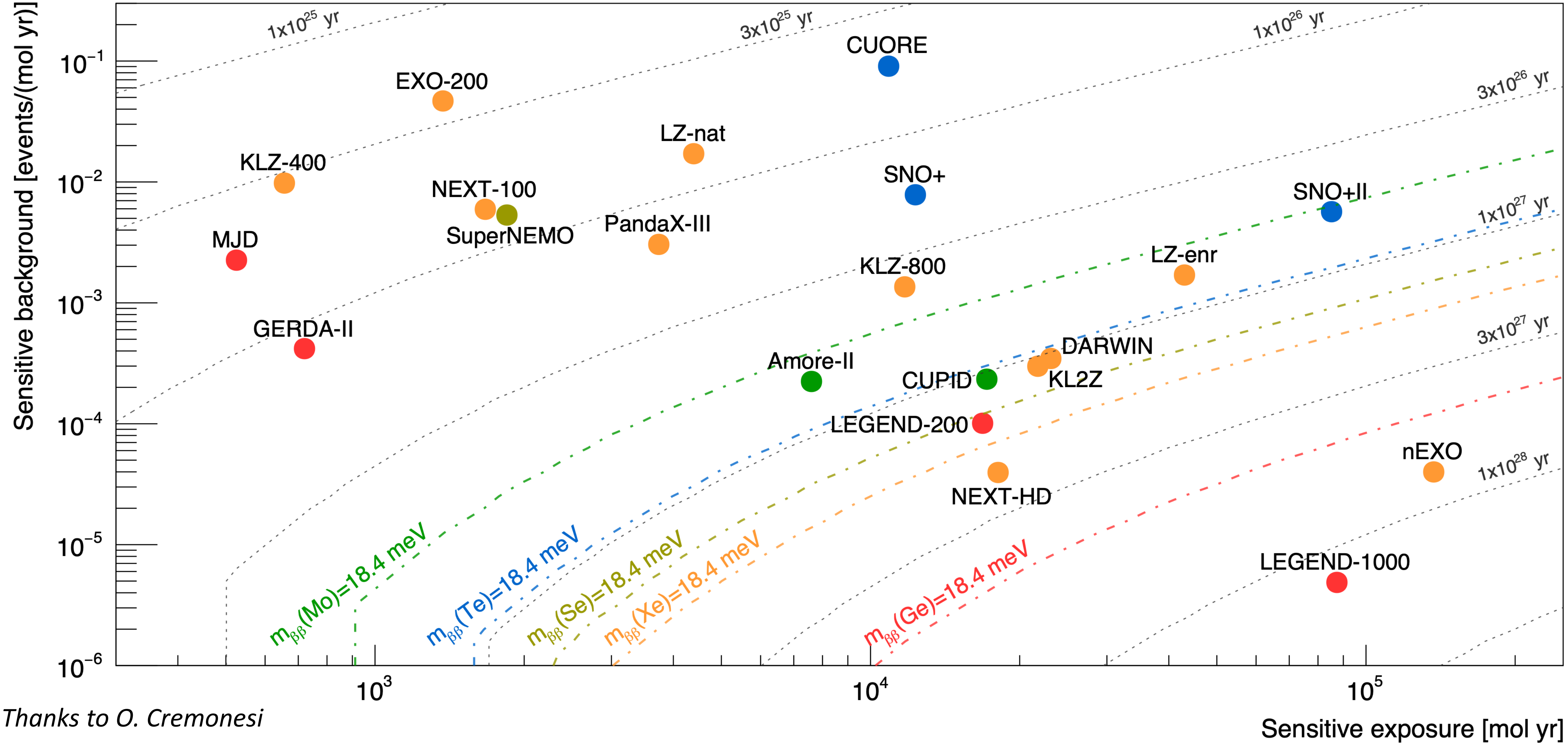
$$\mathcal{S}_{FB} \sim \sqrt{\frac{S}{P}}$$

$$\mathcal{S}_{ZB} \sim S$$



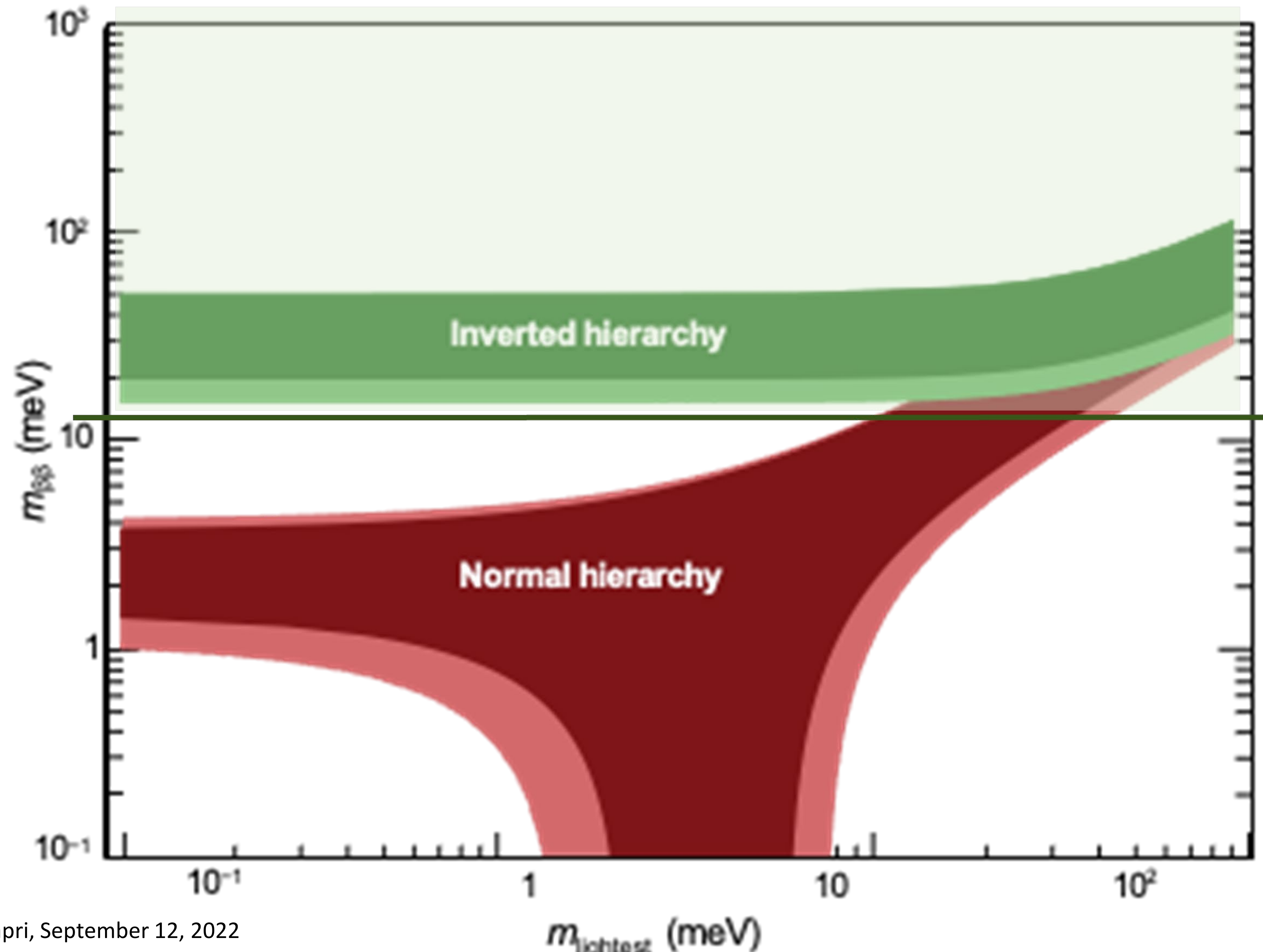
Biassoni e Cremonesi, arXiv:1310.3870 - Prog. Part. Nucl. Phys. 114 (2020) 103803

Sensitivities: a different view



Thanks to O. Cremonesi

Future Sensitivity

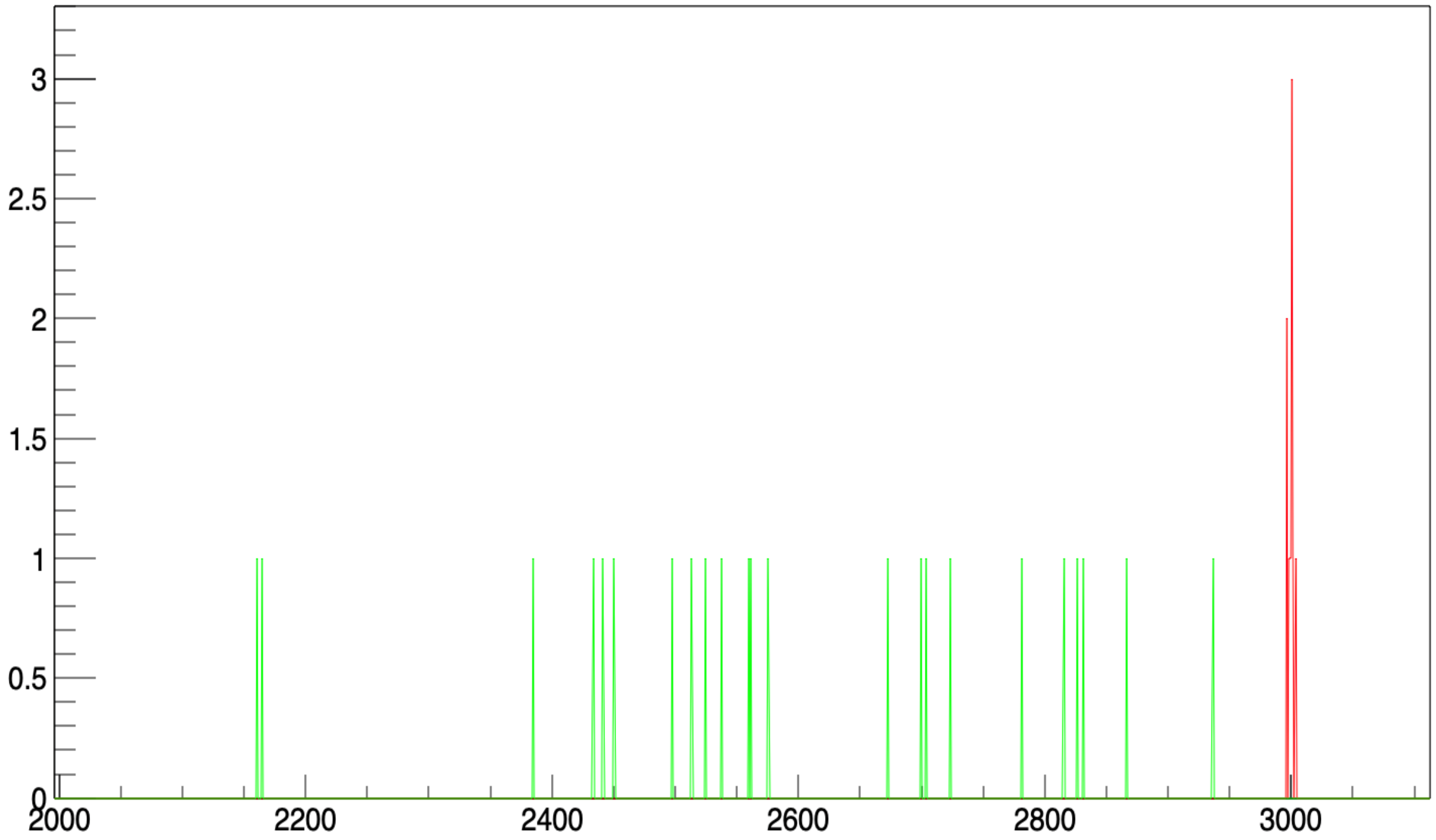


CUPID, LEGEND,KamLAND-ZEN,nEXO,…

$\tau_{0\nu} > 10^{27}$-10^{28} y

Discovey Potential

If will we see a peak @ ββ decay energy?

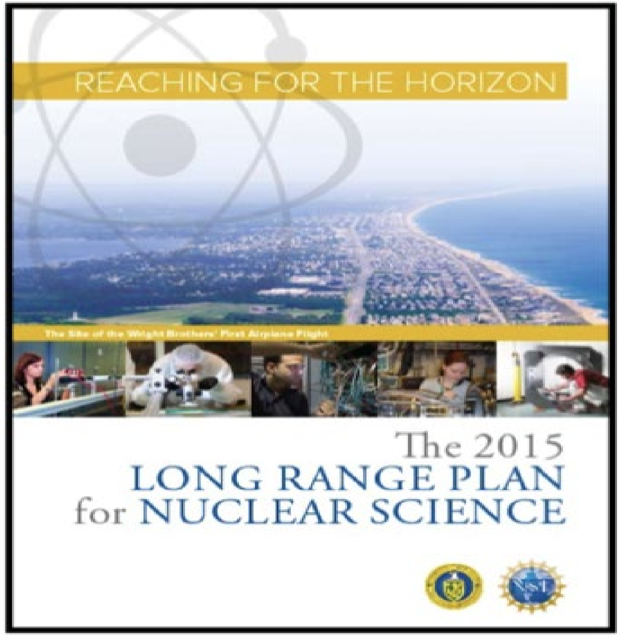


There are some important aspects:

- Few isotopes are needed
- High energy resolution detector crucial
- Nuclear matrix element determined
- Clear evaluation of possible interferences
- ……

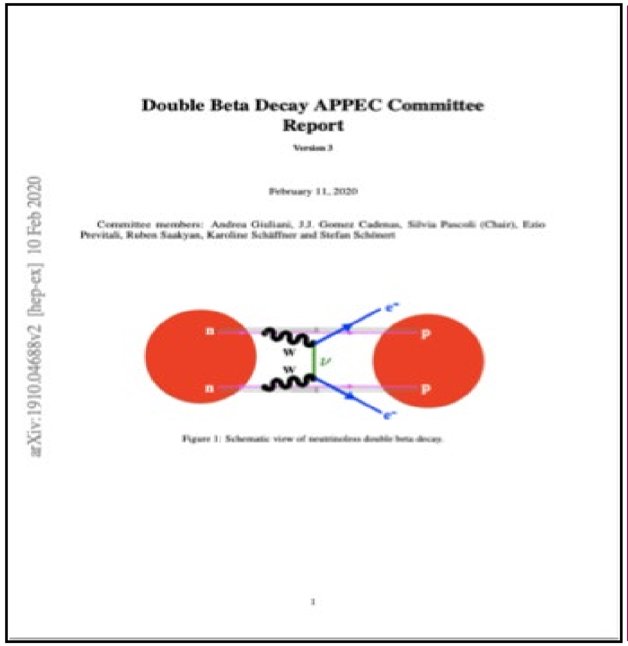
In that sense a discovery potential sensitivity for each experiment is important

Complicated Strategy for the Future



https://science.osti.gov/np/nsac

"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."



arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

1

https://arxiv.org/abs/1910.04688

- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental program in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

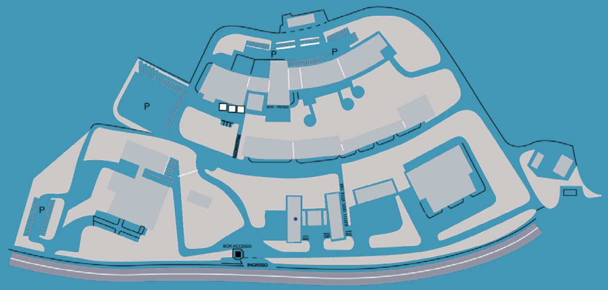
DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

- Outcome: Realize international portfolio **LEGEND-1000, nEXO and CUPID with European partners**
- Open discussion in september 2021 @ LNGS.

https://agenda.infn.it/event/27143/

"The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign **with more than one large ton-scale experiment** implemented in the next decade, **with one ton scale experiment in Europe and the other in North America.** "

INFN LNGS



Thank you