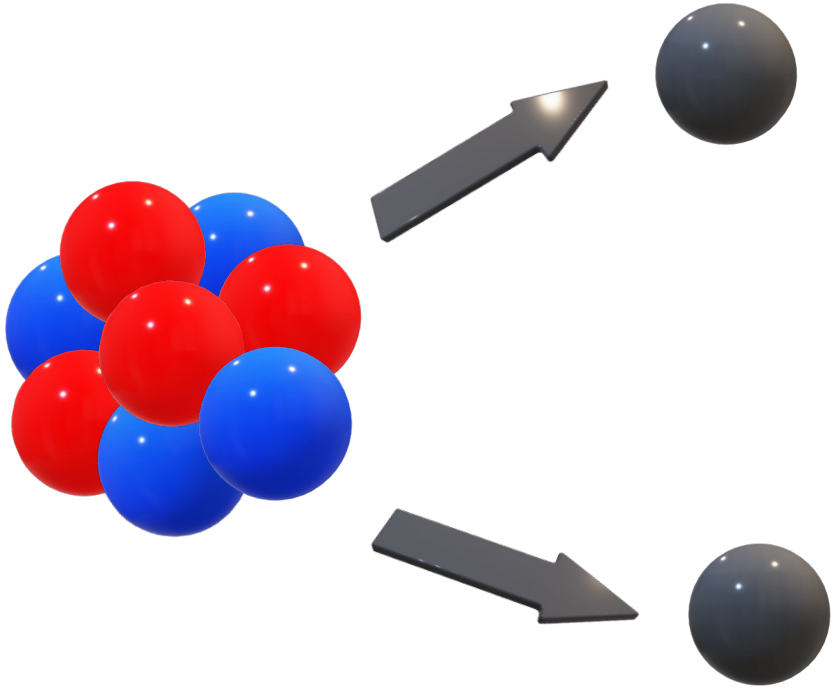
NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENTS: PRESENT AND PERSPECTIVES

NATALIA DI MARCO - GSSI & LNGS-INFN

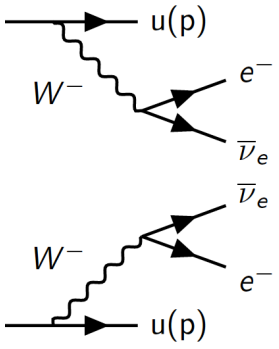


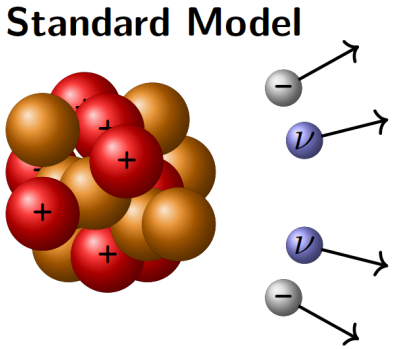
DOUBLE BETA DECAY(S)

- $2\nu\beta\beta$ Maria Goeppert-Mayer (1935)

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

Observed $T_{1/2} \sim 10^{21}$ yr

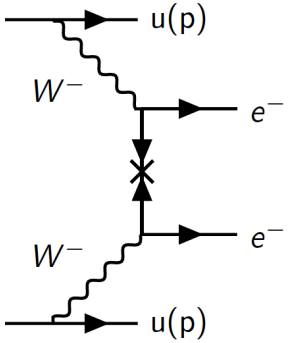


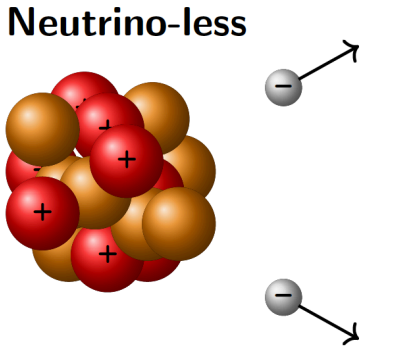


- $0\nu\beta\beta$ Wendell H. Furry (1939)

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \qquad \Delta L = 2$$

Never observed –best *limit* $T_{1/2} > 10^{26}$ yr



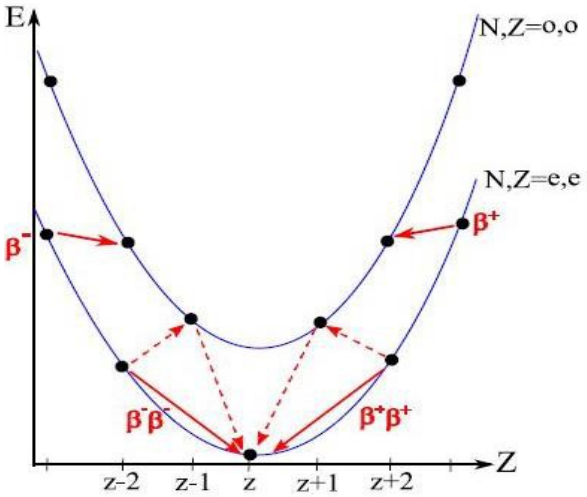


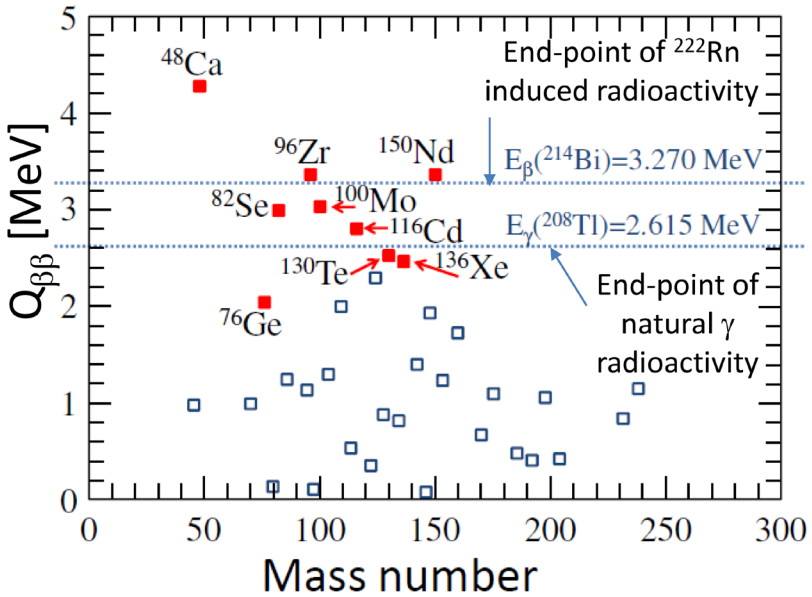
NEUTRINOLESS DOUBLE BETA DECAY

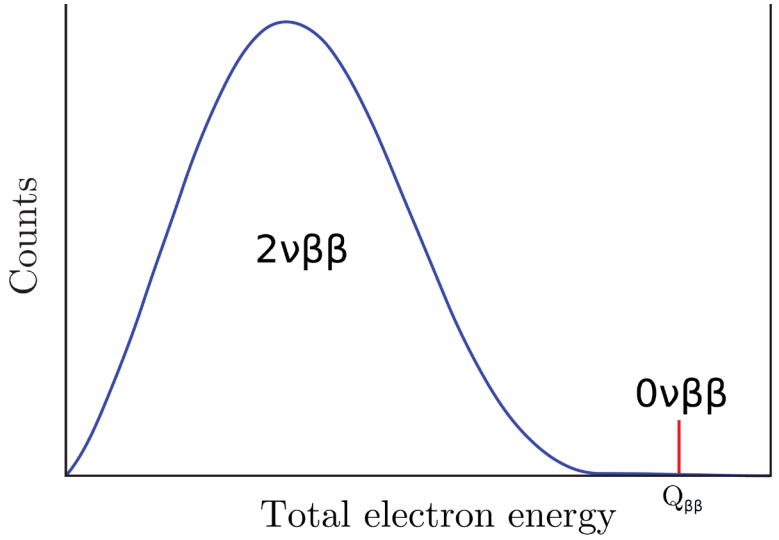
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- Lepton number violation ΔL = 2
- Standard mechanism:

  mediated by **light massive Majorana neutrinos**
- Non-standard mechanisms: **sterile ν, LNV**
- Alternative processes:
  - $0\nu\beta^+\beta^+$: $(A, Z) \rightarrow (A, Z-2) + 2e^+$
  - $0\nu\beta^+\mathrm{EC}$: $(A, Z) + e^- \rightarrow (A, Z-2) + e^+$
  - $0\nu\mathrm{ECEC}$: $(A, Z) + 2e^- \rightarrow (A, Z-2)$
- Possible for 35 nuclei (only)
- Signature: peak@$Q_{\beta\beta}$ (energy resolution!)







$0\nu\beta\beta$- HALF LIFE

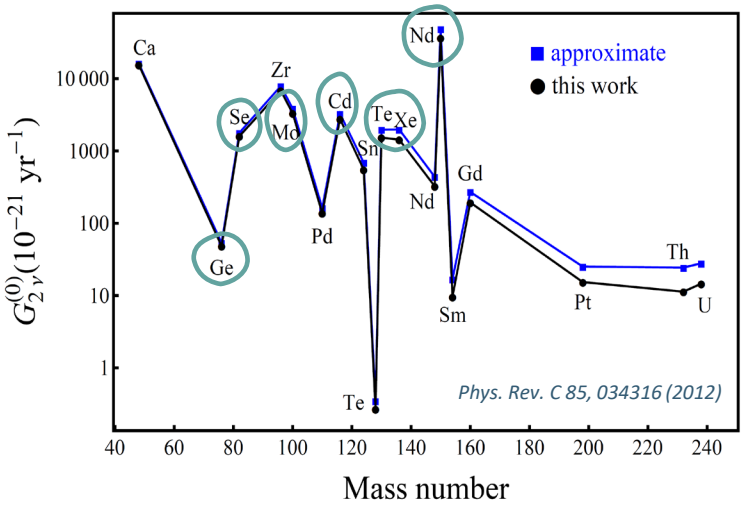
$$\Gamma^{0\nu} = \left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\, g_A^4\, |M_{nucl}|^2\ |f(m_i, U_i)|^2$$

$0\nu\beta\beta$- HALF LIFE

$$\Gamma^{0\nu} = \left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\; g_A^4\; |M_{nucl}|^2\; |f(m_i, U_i)|^2$$

Atomic physics

Phase space: $G^{0\nu} \propto {Q_{\beta\beta}}^5$

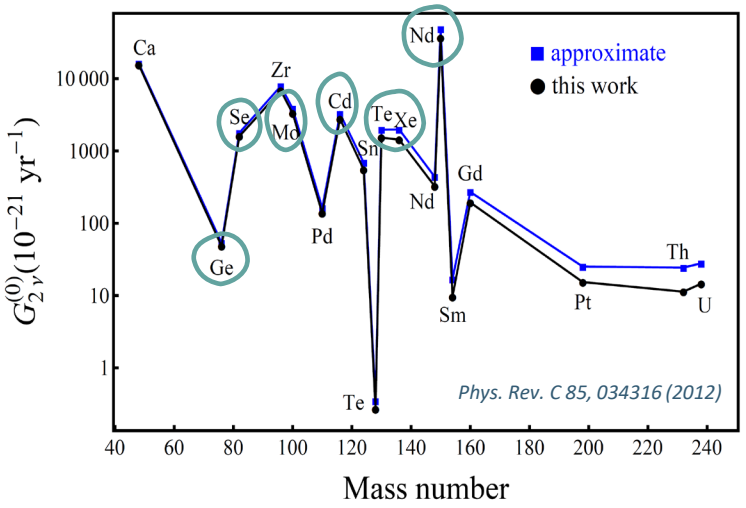


$0\nu\beta\beta$- HALF LIFE

$$\Gamma^{0\nu} = \left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\; g_A^4\; |M_{nucl}|^2\; |f(m_i, U_i)|^2$$

Atomic physics

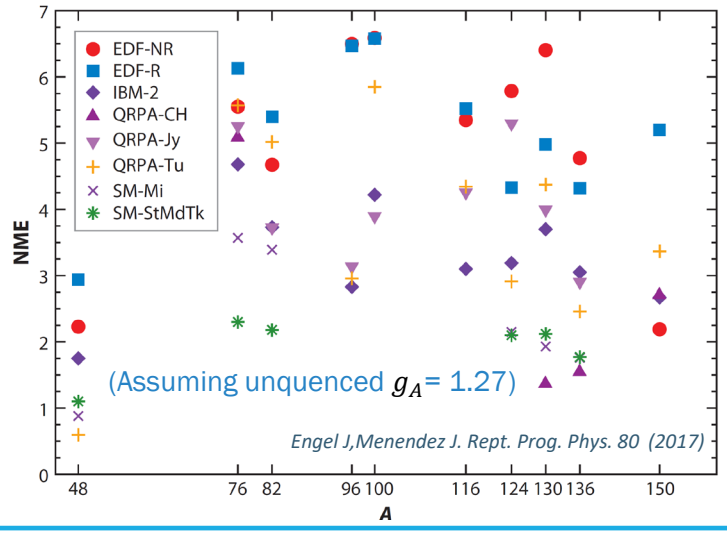
Phase space: $G^{0\nu} \propto {Q_{\beta\beta}}^5$



Nuclear physics

Nuclear matrix element (NME)

Axial coupling: g_A
- $g_{nucleon}$ = 1.269
- g_{quark} = 1
- $g_{phen.}$ = $g_{nucleon}$ x $A^{-0,18}$

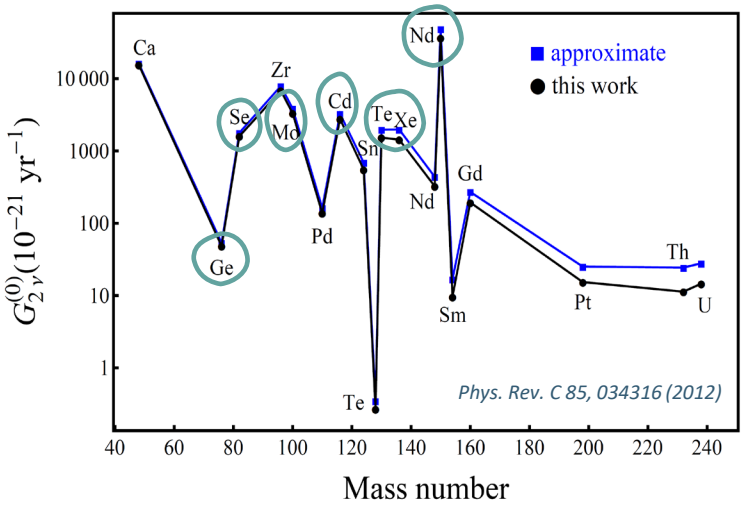


$0\nu\beta\beta$- HALF LIFE

$$\Gamma^{0\nu} = \left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\; g_A^4\, |M_{nucl}|^2\; |f(m_i, U_i)|^2$$

Atomic physics

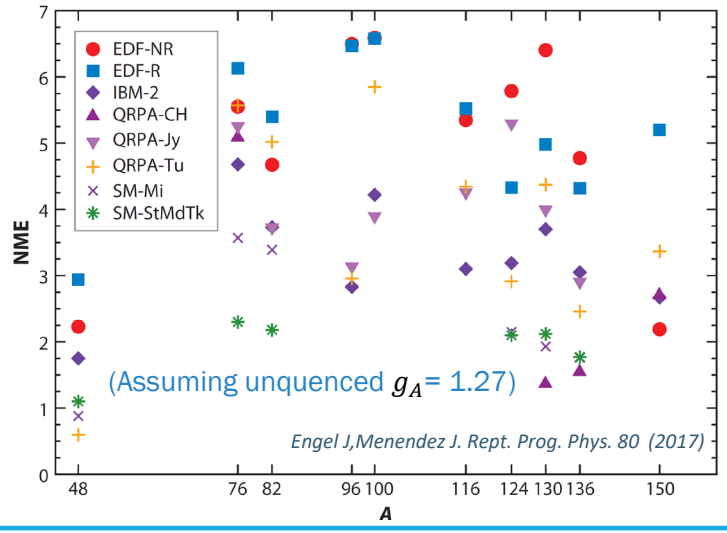
Phase space: $G^{0\nu} \propto {Q_{\beta\beta}}^5$



Nuclear physics

Nuclear matrix element (NME)

Axial coupling: g_A
- $g_{nucleon}$ = 1.269
- g_{quark} = 1
- $g_{phen.}$ = $g_{nucleon}$ x $A^{-0,18}$



Particle Physics

Light neutrino exchange:

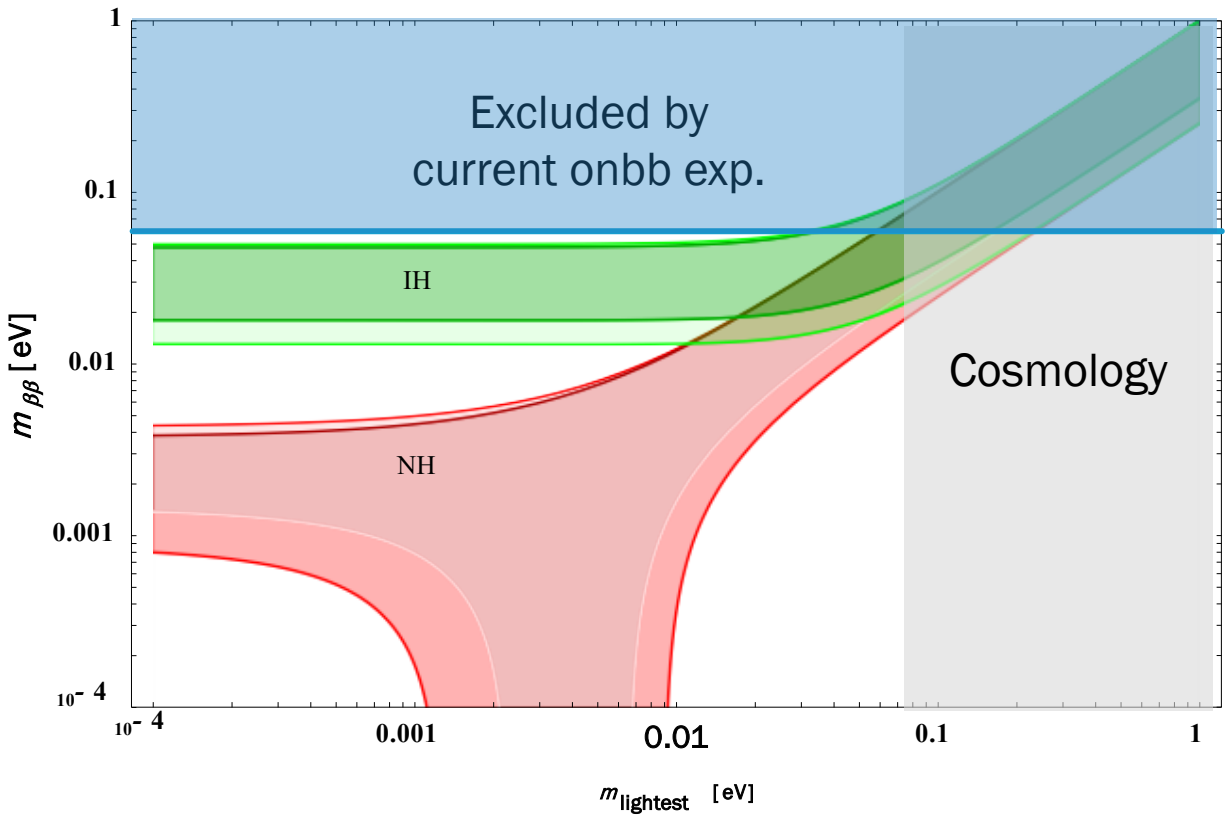
$$|f(m_i, U_i)| \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e}\left|\sum_{K=1,2,3} U_{ek}^2 m_k\right|$$

where $m_{\beta\beta}$ is the effective Majorana mass

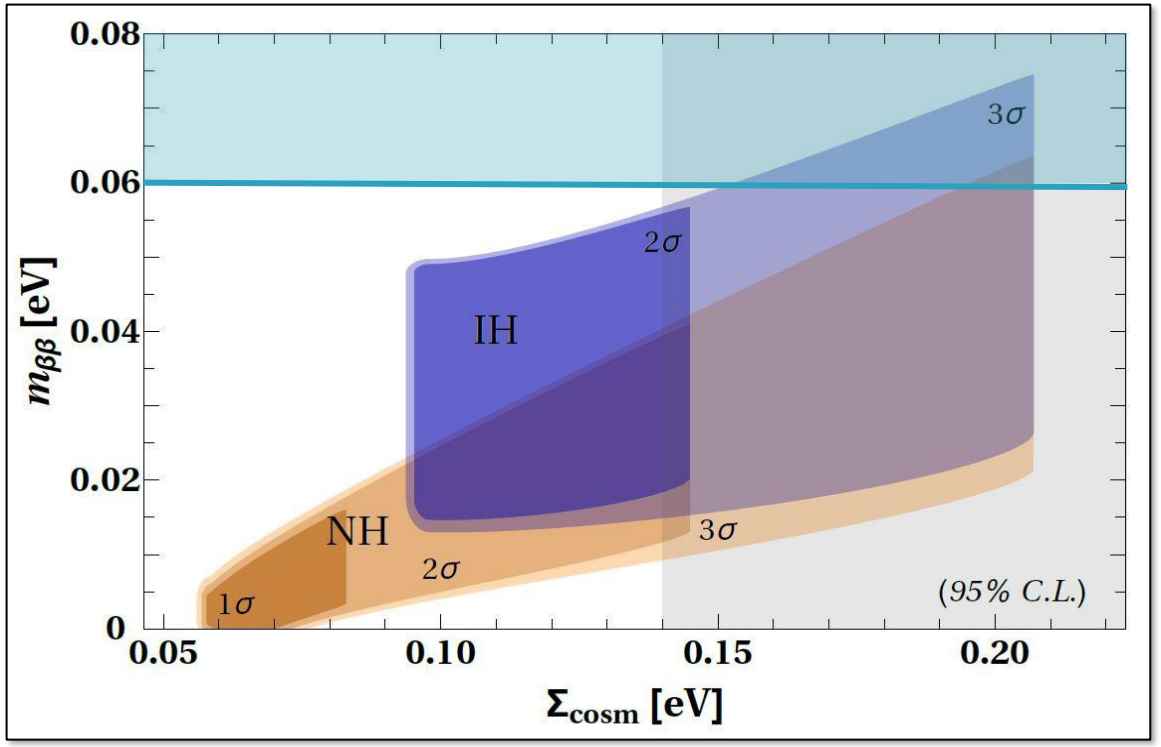
$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu 1} + s_{12}^2 c_{13}^2 m_{\nu 2} e^{i\phi_{12}} + s_{13}^2 m_{\nu 3} e^{i\phi_{13}}$$

$\phi \rightarrow Majorana\ phases$

$0\nu\beta\beta$- SENSITIVITY



Phys. Rev. D90, 033005 (2014)



Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

$0\nu\beta\beta$- SENSITIVITY

$$\mathcal{S}^{0\nu} = \ln 2 \; \mathcal{N}_A \frac{\eta \; \varepsilon}{W} \sqrt{\frac{M \; T}{\Delta E \; B}}$$

$0\nu\beta\beta$- SENSITIVITY

$$\mathcal{S}^{0\nu} = \ln 2 \; \mathcal{N}_A \frac{\eta \, \varepsilon}{W} \sqrt{\frac{M \, T}{\Delta E \, B}}$$

Detector mass

- tonne scale next generation exp. → 10^{27}nuclei
- Scalability depends on the technology employed

Live time

$0\nu\beta\beta$- SENSITIVITY

$$\mathcal{S}^{0\nu} = \ln 2 \; \mathcal{N}_A \frac{\eta \, \varepsilon}{W} \sqrt{\frac{M \, T}{\Delta E \, B}}$$

Detector mass

- tonne scale next generation exp. → 10^{27}nuclei
- Scalability depends on the technology employed

Live time

Isotopic abundance

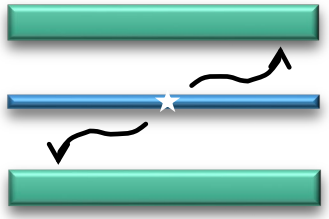
Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$0\nu\beta\beta$- SENSITIVITY

Detector efficiency

- Source ⊆ detector (bolometers,semiconductor, scintillators)

- Source ≠ detector (tracker)



Detector mass

- tonne scale next generation exp. → 10^{27}nuclei
- Scalability depends on the technology employed

Live time

Isotopic abundance

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$$\mathcal{S}^{0\nu} = \ln 2 \; \mathcal{N}_A \frac{\eta\,\varepsilon}{W} \sqrt{\frac{M\,T}{\Delta E\,B}}$$

Energy resolution

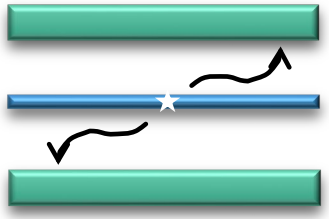
- Ge semiconductor
- Bolometer
- TPC
- Liq. scintillators

$0\nu\beta\beta$- SENSITIVITY

Detector efficiency

- Source ⊆ detector (bolometers,semiconductor, scintillators)

- Source ≠ detector (tracker)



Isotopic abundance

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$$\mathcal{S}^{0\nu} = \ln 2 \; \mathcal{N}_A \frac{\eta \; \varepsilon}{W} \sqrt{\frac{M \; T}{\Delta E \; B}}$$

Detector mass

- tonne scale next generation exp. → 10^{27}nuclei
- Scalability depends on the technology employed

Live time

Background index

- $\frac{bkg\ counts@Q_{\beta\beta}}{\Delta E \times M \times T}$ [cts/keV/kg/y]
- Next generation goal → 0 background experiment

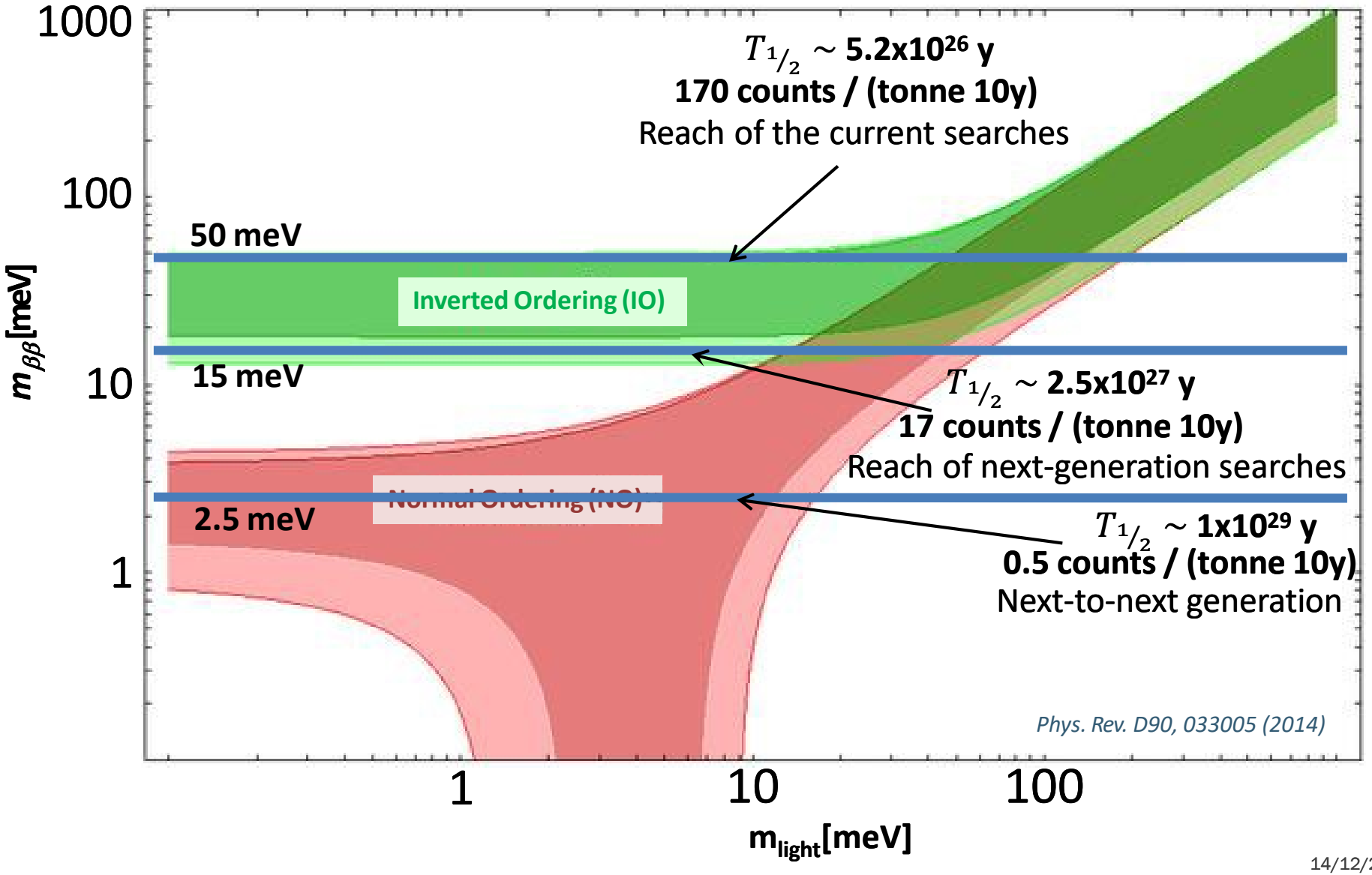
Energy resolution

- Ge semiconductor
- Bolometer
- TPC
- Liq. scintillators

$0\nu\beta\beta$- COUNTS

A. Giuliani @ TAUP2021

Example: ^{100}Mo (less favorable NME)



$0\nu\beta\beta$- BACKGROUND

Cosmic muons

- Underground lab (μ flux reduction > $10^{6)}$

$0\nu\beta\beta$- BACKGROUND

Cosmic muons

- Underground lab (μ flux reduction > $10^{6)}$

α,β,γ from natural radioactivity

- Material selection (< 1 μBq/kg required)
- Shielding

$0\nu\beta\beta$- BACKGROUND

Cosmic muons

- Underground lab (μ flux reduction > $10^{6)}$

Radiogenic and cosmogenic neutrons

- Shielding

α,β,γ from natural radioactivity

- Material selection (< 1 μBq/kg required)
- Shielding

$0\nu\beta\beta$- BACKGROUND

Cosmic muons
- Underground lab (μ flux reduction > $10^{6)}$

Radiogenic and cosmogenic neutrons
- Shielding

α,β,γ from natural radioactivity
- Material selection (< 1 μBq/kg required)
- Shielding

Cosmogenic activation
- Choice of detector materials – Storage of material underground

$0\nu\beta\beta$- BACKGROUND

Cosmic muons

- Underground lab (μ flux reduction > $10^{6)}$

α,β,γ from natural radioactivity

- Material selection (< 1 μBq/kg required)
- Shielding

+ Bkg rejection techniques

Depending on the technology:

- Particle ID
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface events
- Fiducial volume / Active shielding
- Final-state nucleus identification

Radiogenic and cosmogenic neutrons

- Shielding

Cosmogenic activation

- Choice of detector materials – Storage of material underground

$0\nu\beta\beta$- BACKGROUND

Cosmic muons
- Underground lab (μ flux reduction > $10^{6)}$

α,β,γ from natural radioactivity
- Material selection (< 1 μBq/kg required)
- Shielding

+ Bkg rejection techniques

Depending on the technology:
- Particle ID
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface events
- Fiducial volume / Active shielding
- Final-state nucleus identification

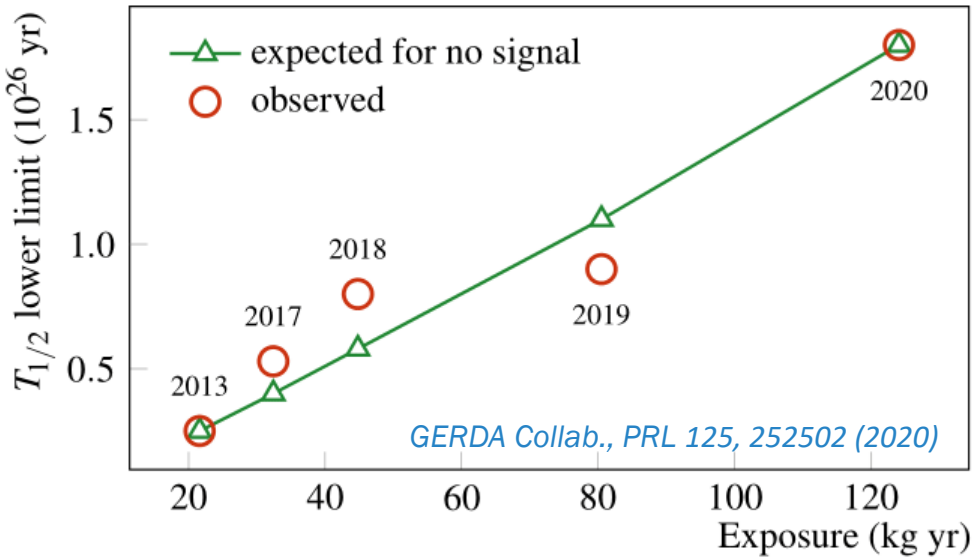
Radiogenic and cosmogenic neutrons
- Shielding

Cosmogenic activation
- Choice of detector materials – Storage of material underground

$$M \times T \times \Delta E \times n_B \leq 1$$

Zero-background approximation: less than 1 event in the region of interest (ROI) around $Q_{\beta\beta}$ for a given exposure

$$S^{0\nu} \propto MT$$



$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Bolometers

Exp.	Isotope
CUORE	^{130}Te

Phonons

Scintillation

Ionization

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Tracker det.

Exp.	Isotope
SupeNEMO	^{82}Se

$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Bolometers

Exp.	Isotope
CUORE	^{130}Te

Scintillating bolometers

Exp.	Isotope
CUPID-0	^{82}Se
CUPID-Mo AMORE CUPID	^{100}Mo

Phonons

Scintillation

Ionization

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Liquid TPC

Exp.	Isotope
EXO200/nEXO	^{136}Xe

Gas TPC

Exp.	Isotope
NEXT	^{136}Xe

Double Phase TPC

Exp.	Isotope
DARWIN / LZ	^{136}Xe

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Tracker det.

Exp.	Isotope
SupeNEMO	^{82}Se

$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Scintillating bolometers

Exp.	Isotope
CUPID-0	^{82}Se
CUPID-Mo AMORE CUPID	^{100}Mo

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Bolometers

Exp.	Isotope
CUORE	^{130}Te

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Liquid TPC

Exp.	Isotope
EXO200/nEXO	^{136}Xe

Gas TPC

Exp.	Isotope
NEXT	^{136}Xe

Double Phase TPC

Exp.	Isotope
DARWIN / LZ	^{136}Xe

$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Source embedded in a crystal

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Scintillating bolometers

Exp.	Isotope
CUPID-0	^{82}Se
CUPID-Mo AMORE CUPID	^{100}Mo

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Bolometers

Exp.	Isotope
CUORE	^{130}Te

Source embedded in a fluid

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Liquid TPC

Exp.	Isotope
EXO200/nEXO	^{136}Xe

Gas TPC

Exp.	Isotope
NEXT	^{136}Xe

Double Phase TPC

Exp.	Isotope
DARWIN / LZ	^{136}Xe

$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Source embedded in a crystal

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Scintillating bolometers

Exp.	Isotope
CUPID-0	^{82}Se
CUPID-Mo AMORE CUPID	^{100}Mo

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Bolometers

Exp.	Isotope
CUORE	^{130}Te

High energy resolution / efficiency

Source embedded in a fluid

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Liquid TPC

Exp.	Isotope
EXO200/nEXO	^{136}Xe

Gas TPC

Exp.	Isotope
NEXT	^{136}Xe

Double Phase TPC

Exp.	Isotope
DARWIN / LZ	^{136}Xe

Large source mass
Easily scalable

$0\nu\beta\beta$- TECHNIQUES

Disclaimer: not complete list!

Source embedded in a crystal

Semiconductors

Exp.	Isotope
MAJORANA GERDA LEGEND CDEX	^{76}Ge
COBRA	^{116}Cd

Scintillating bolometers

Exp.	Isotope
CUPID-0	^{82}Se
CUPID-Mo AMORE CUPID	^{100}Mo

Scint. crystal

Exp.	Isotope
CANDLES-III	^{48}Ca

Bolometers

Exp.	Isotope
CUORE	^{130}Te

Source embedded in a fluid

Liquid scint.

Exp.	Isotope
KamLAND-zen	^{136}Xe
SNO+	^{130}Te

Liquid TPC

Exp.	Isotope
EXO200/nEXO	^{136}Xe

Gas TPC

Exp.	Isotope
NEXT	^{136}Xe

Double Phase TPC

Exp.	Isotope
DARWIN / LZ	^{136}Xe

High energy resolution / efficiency

3rd option: 0-bkg by tracking or tagging

Large source mass
Easily scalable

$0\nu\beta\beta$- EXPERIMENTAL PANORAMA

A. Giuliani @ TAUP2021

Legenda (color code)

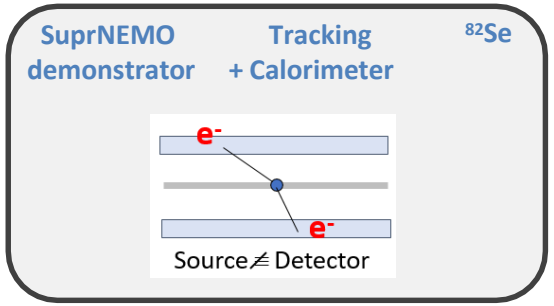
Completed

Data taking

Construction / Commissioning

Advanced R&D sometimes at CDR/TDR level

R&D



Large source mass Easily scalable **Fluid embedded source**	N DEx	High pressure TPC	^{82}Se
	ZICOS	Dilution in liquid scintillator+Cherenkov	^{96}Zr
	SNO+	Dilution in liquid scintillator	^{130}Te
	SNO+-Phase II	**Dilution in liquid scintillator**	**^{130}Te**
	Theia	Dilution in liquid scintillator+Cherenkov	^{130}Te-^{136}Xe
	KamLAND-Zen 400	Dilution in liquid scintillator	^{136}Xe
	KamLAND-Zen 800	Dilution in liquid scintillator	^{136}Xe
	KamLAND2-Zen 800	Dilution in liquid scintillator	^{136}Xe
	EXO-200	Liquid TPC	^{136}Xe
	nEXO	**Liquid TPC**	**^{136}Xe**
	NEXT-White	High pressure TPC	^{136}Xe
	NEXT-100	**High pressure TPC**	**^{136}Xe**
	NEXT-HD / NEXT-BOLD	High pressure TPC	^{136}Xe
	PANDAX-III	High pressure TPC	^{136}Xe
	AXEL	High pressure TPC	^{136}Xe
	DARWIN	Double-phase TPC	^{136}Xe
	LZ	Double-phase TPC	^{136}Xe
	R2D2	High pressure TPC	^{136}Xe
	LiquidO	Dilution in opaque liquid scintillator	multi
High energy resolution / efficiency **Crystal embedded source**	CANDLES-III	Scintillators	^{48}Ca
	CANDLES-IV	Scintillating bolometers	^{48}Ca
	MAJORANA DEM.	Semiconductor detectors	^{76}Ge
	GERDA	Semiconductor detectors	^{76}Ge
	LEGEND-200	Semiconductor detectors	^{76}Ge
	LEGEND-1000	**Semiconductor detectors**	**^{76}Ge**
	CDEX-300 / CDEX-1000	**Semiconductor detectors**	**^{76}Ge**
	SELENA	Semiconductor detectors	^{82}Se
	CUPID-0	Scintillating bolometers	^{82}Se
	CUPID-Mo	Scintillating bolometers	^{100}Mo
	AMORE-I	Scintillating bolometers	^{100}Mo
	AMORE-II	**Scintillating bolometers**	**^{100}Mo**
	CUPID	**Scintillating bolometers**	**^{100}Mo**
	CUPID Reach / CUPID-1T	Scintillating bolometers	^{100}Mo
	COBRA	Semiconductor detectors	^{116}Cd
	TIN-TIN	Bolometers	^{124}Sn
	CUORE	Bolometers	^{130}Te
	CROSS	Scintillating bolometers	^{100}Mo-^{130}Te
	BINGO	Scintillating / Cherenkov bolometers	^{100}Mo-^{130}Te

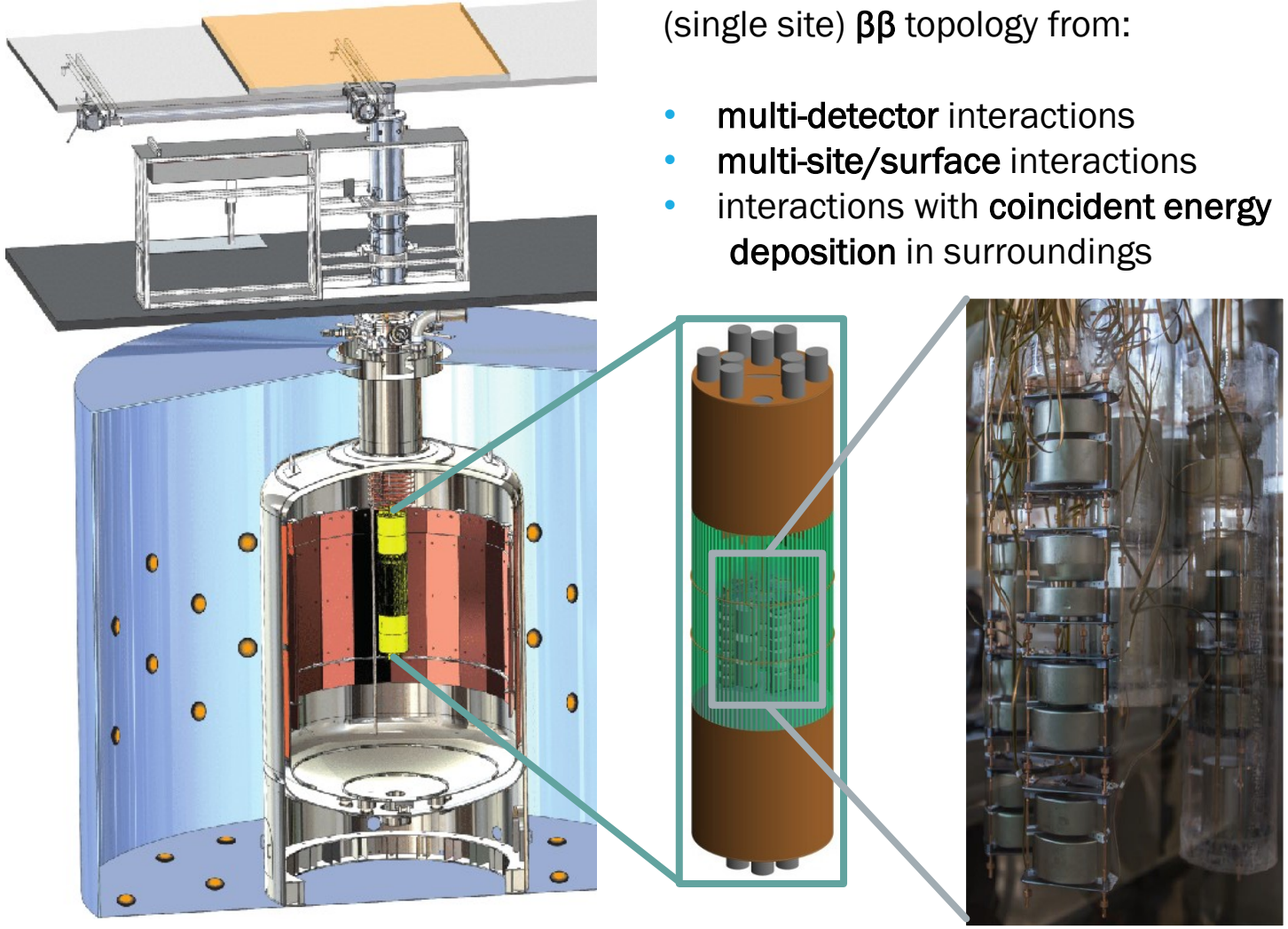
$0\nu\beta\beta$- *PRESENT* EXPERIMENTAL PANORAMA

- GERDA
  MAJORANA
- CUORE
  CUPID-Mo/0
- KamLAND-Zen 800
- EXO 200
- NEXT-WHITE

$0\nu\beta\beta$ EXPERIMENTS - *GERDA*

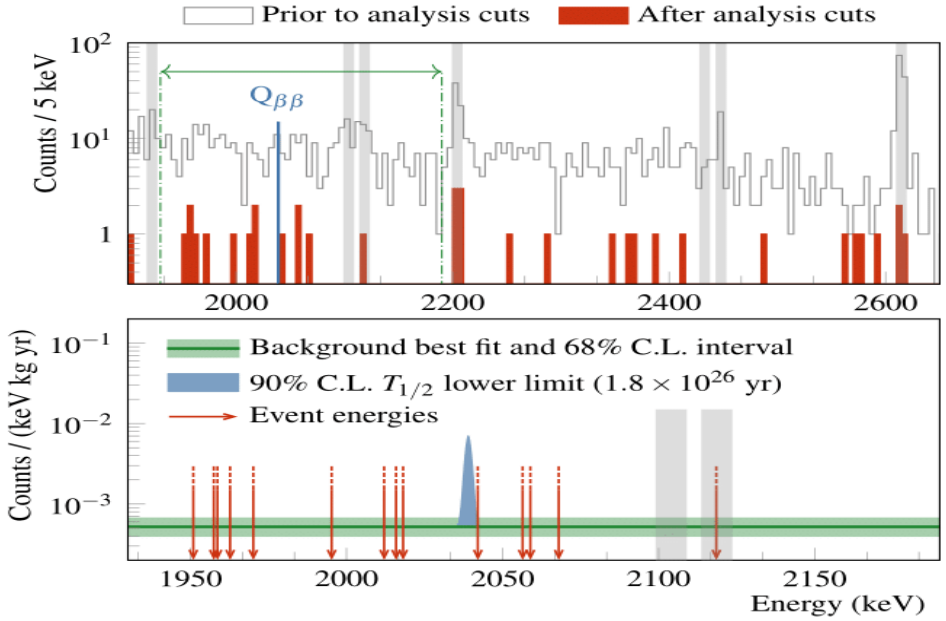
[GERDA, Phys Rev Lett **125** (2020), 252502]

@LNGS – 40 kg of Ge semiconductor detectors (enrichment up to 88% in ^{76}Ge) – 2011 → 2019



Discriminate **point like** (single site) **ββ** topology from:

- **multi-detector** interactions
- **multi-site/surface** interactions
- interactions with **coincident energy deposition** in surroundings



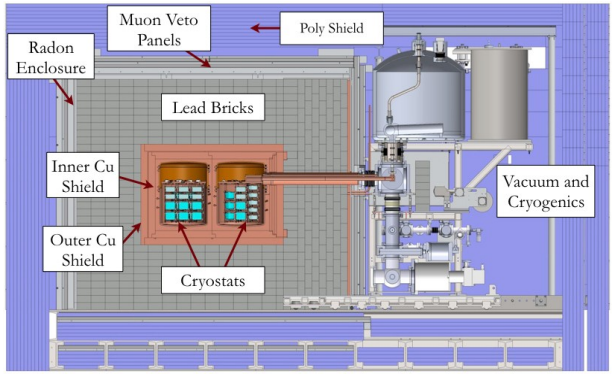
Exposure	127.2 kg yr
$\Delta E@Q_{\beta\beta}$ (FWHM)	2.6±0.2 keV (BEGe PhaseII)*
BI	$5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 1.8\times10^{26}$ yr @ 90% C.L.

Leading experiment in tems of half-life
0-background regime for the whole exposure

$0\nu\beta\beta$ EXPERIMENTS – *MAJORANA DEMONSTRATOR*

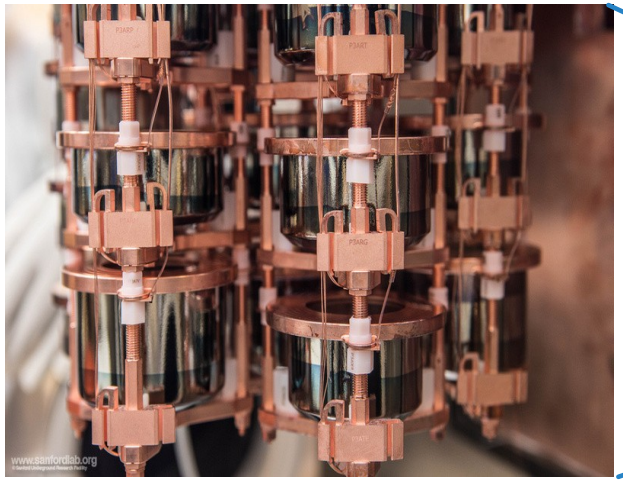
[PRC *100* 025501 (2019)]

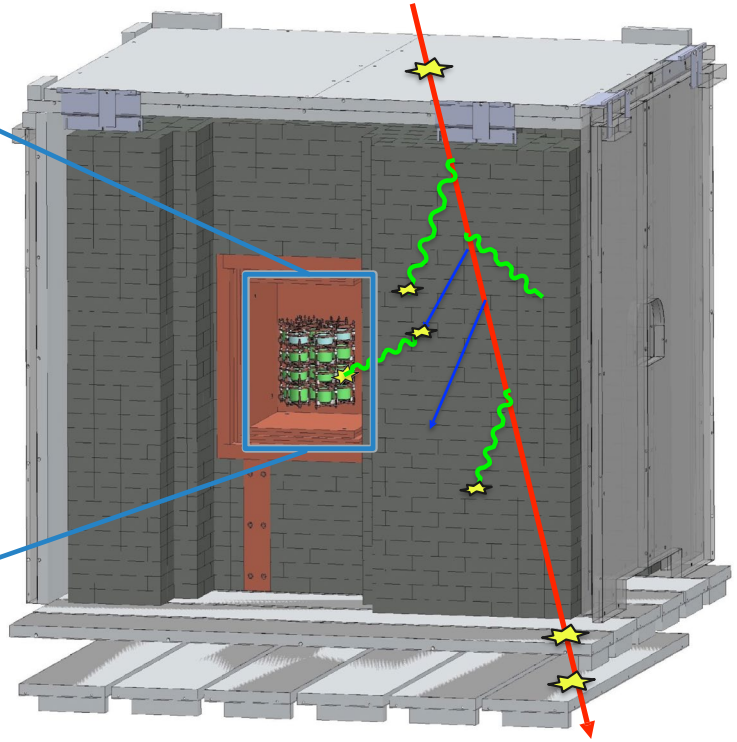
@SURF(US) – 30 kg of Ge semiconductor detectors (enrichment up to 88% in ^{76}Ge) – 2015 → 2021

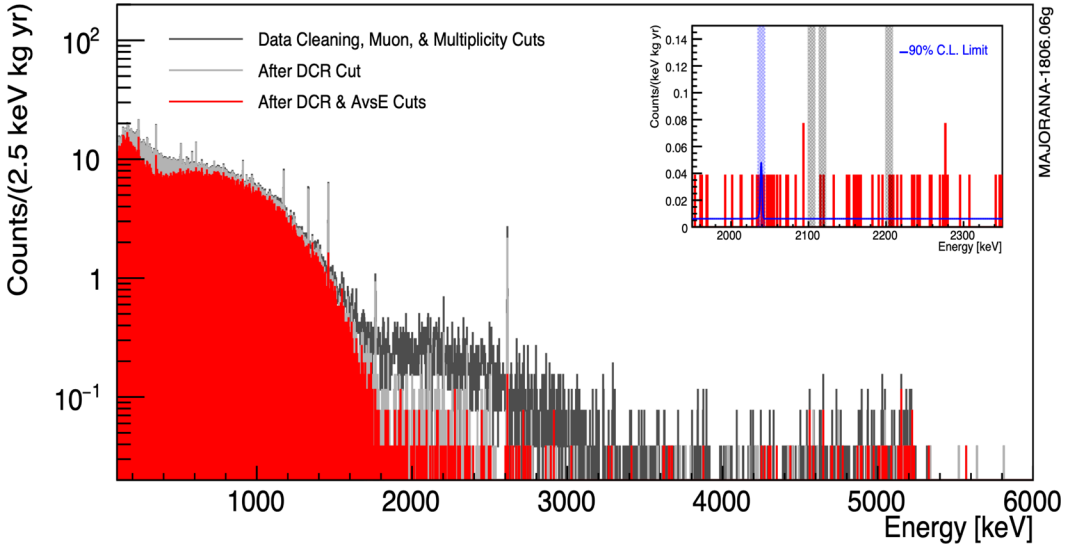


Rejection of backgrounds
Muon Veto: reject events coincident with muons Granularity: multiple detectors hit
Pulse shape discrimination:

- Reject multi-site events
- Reject surface events







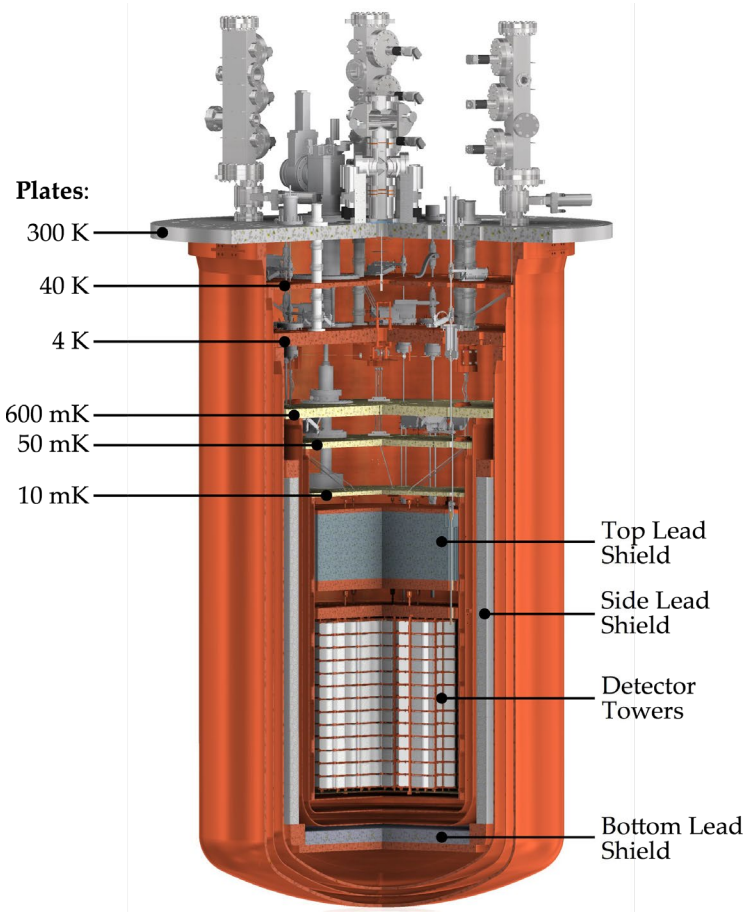
Exposure (released)	26 kg yr
$\Delta E@Q_{\beta\beta}$ (FWHM)	2.5 keV
BI	11.9 ± 2.0 cts/(FWHM t yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 2.7\times10^{25}$ yr @ 90% C.L.

Best energy resolution of all 0νββ experiments
Full data set ***65*** **kg yr** to be released

$0\nu\beta\beta$ EXPERIMENTS - *CUORE*

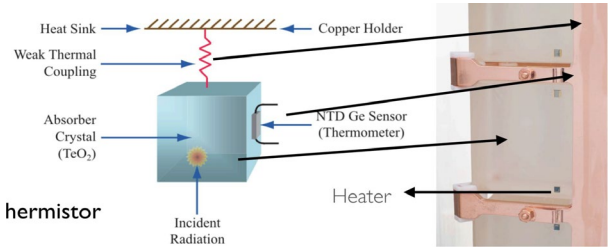
[arXiv:2104.06906]

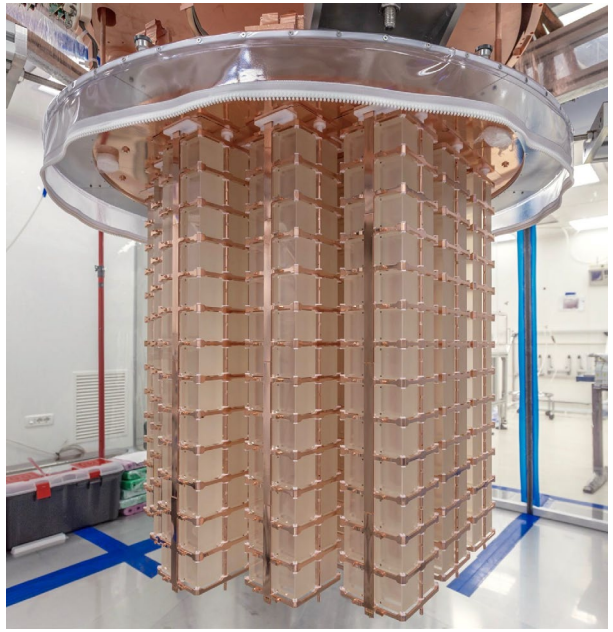
@LNGS – 988 TeO_2 crystals, arranged in 19 towers –206 kg of ^{130}Te – 2017 --> still taking data

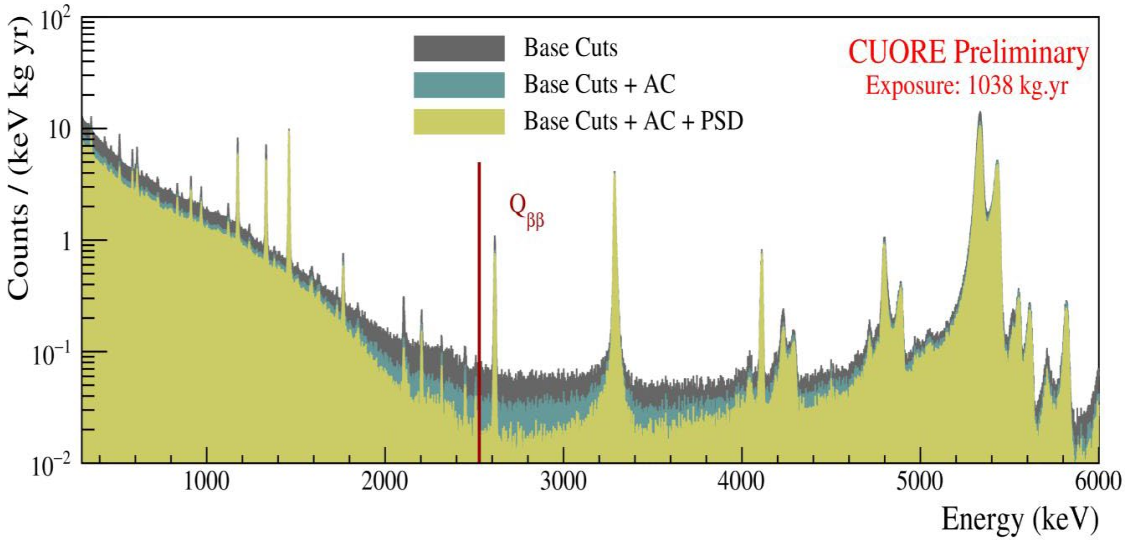


Background rejection

- Anti-coincidence cut
- PSD





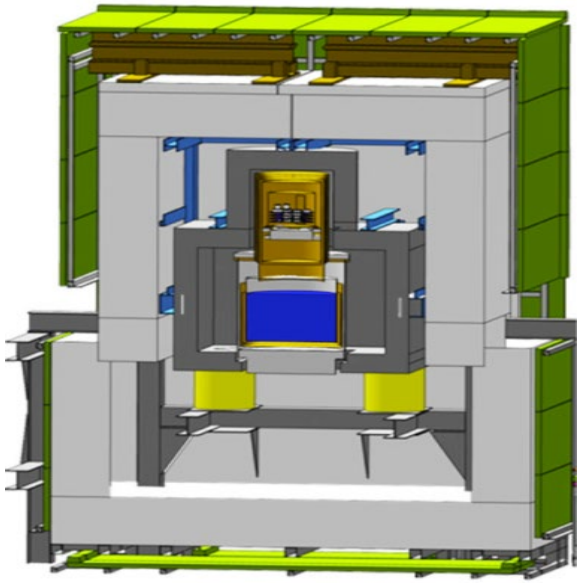


Exposure (analysed)	1038.4 kg yr
$\Delta E@Q_{\beta\beta}$ $(FWHM)$	7.8 keV
BI	1.49×10^{-2} cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 2.2\times10^{25}$ yr @ 90% C.L.

*Data taking to be continued until 3 ton*yr exposure is collected (expected end 2024) (target sensitivity* $T^{0n}_{1/2} > 9.0\times10^{25}$ yr @ 90% C.L., $m_{\beta\beta}$<50-130 meV)

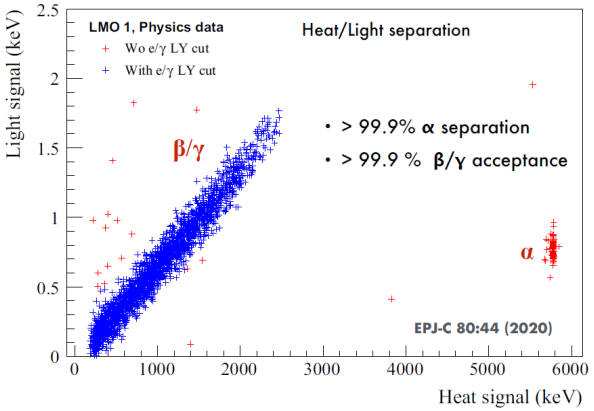
$0\nu\beta\beta$ EXPERIMENTS – *CUPID-Mo*

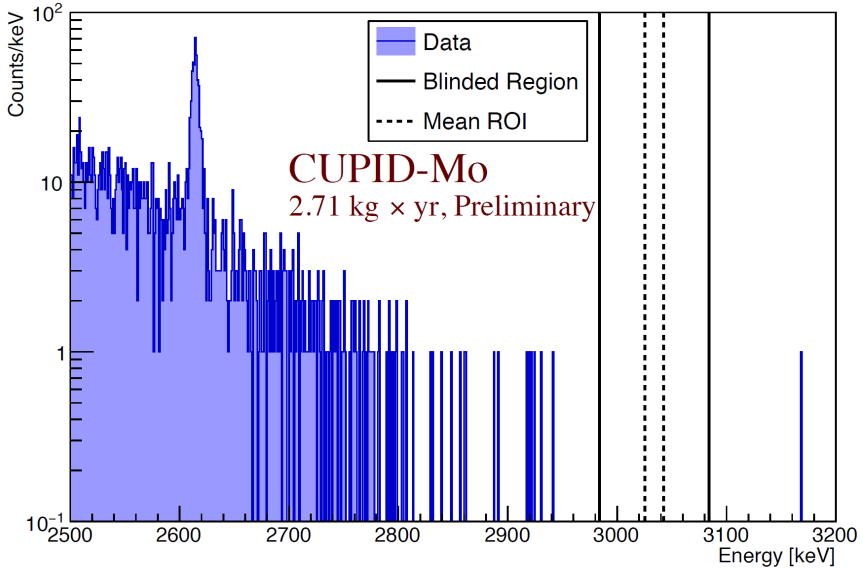
CUPID-Mo@LSM (France)– 20x ~210g $Li_2{}^{100}MO_4$ (LMO) crystals –enriched at 97% in ^{100}Mo – 2019 --> 2020

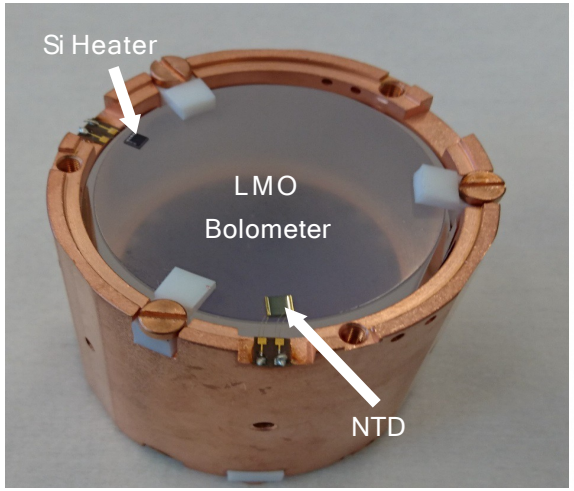


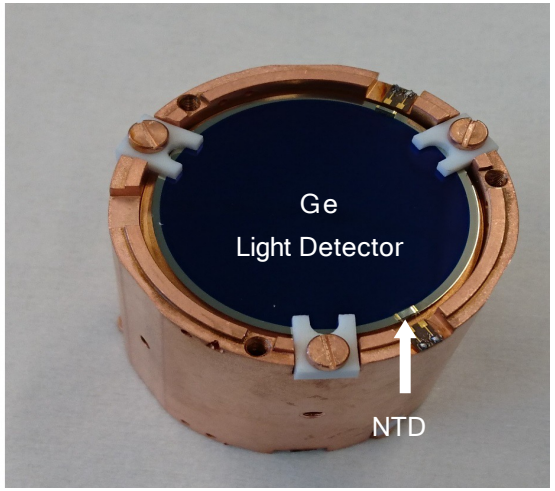
Background rejection

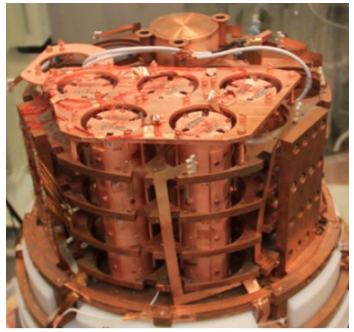
- Anti-coincidence
- Light yield for discrimination between α and β / γ events
- PSD











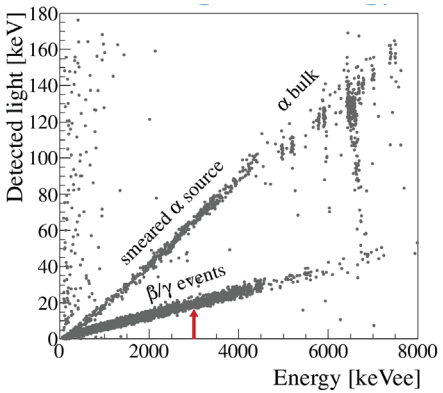
Exposure (analysed)	2.71 kg yr
$\Delta E@Q_{\beta\beta}$	~7.38 ± 0.35 keV
BI	4.68 × 10^{-3} cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2}$ > 1.8×10^{24} yr @ 90% C.L.

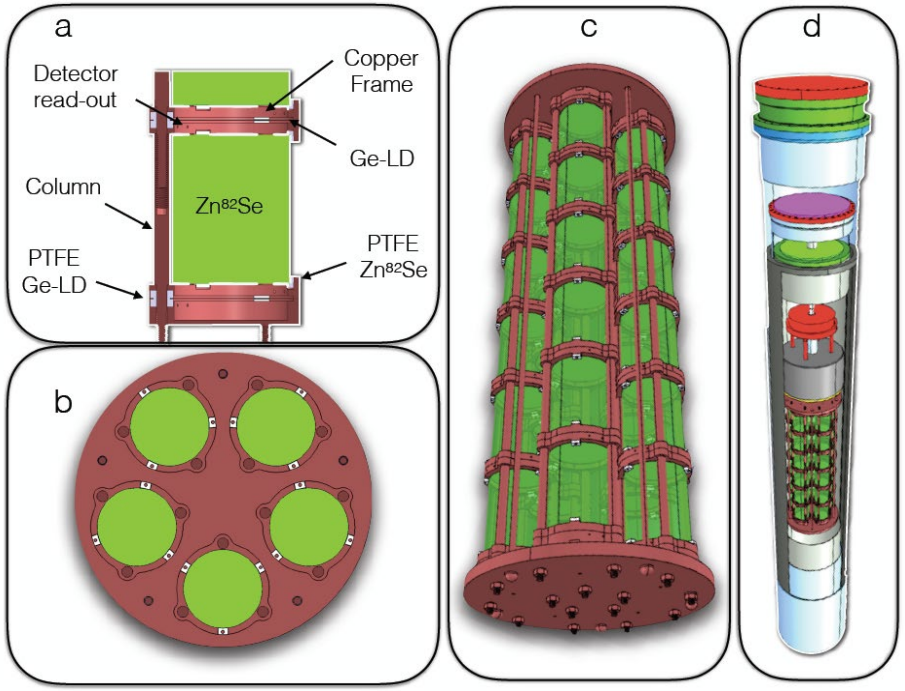
$0\nu\beta\beta$ EXPERIMENTS – *CUPID-0*

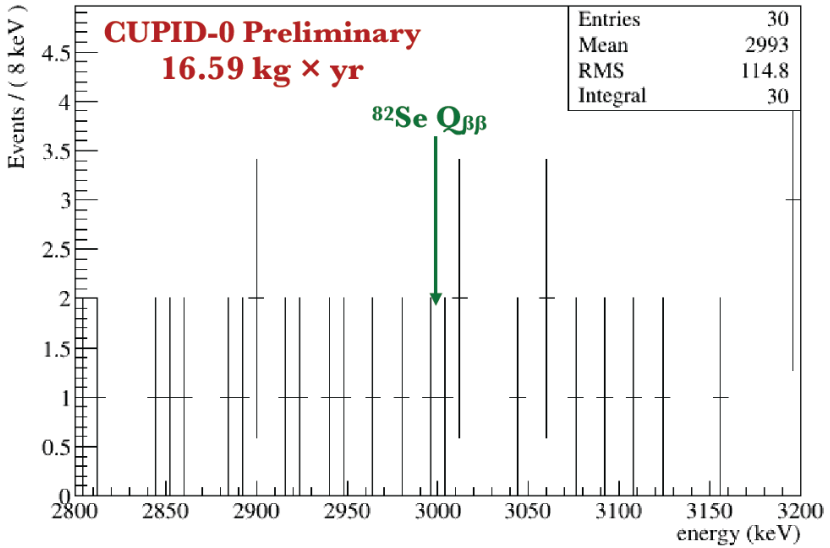
CUPID-0@LNGS - 24 ZSe crystals –enriched at 95% in ^{82}Se (5.17 kg) – 2018 --> 2020

Background rejection

- Light signal pulse shape for α / β event discrimination
- Delayed coincidences







Exposure (analysed)	16.59 kg yr
$\Delta E@Q_{\beta\beta}$	20 keV
BI	5.5×10^{-3} cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 4.7\times10^{24}$ yr @ 90% C.L.

Pilot for next generation experiment CUPID

$0\nu\beta\beta$ EXPERIMENTS – *KAMLAND-ZEN 800*

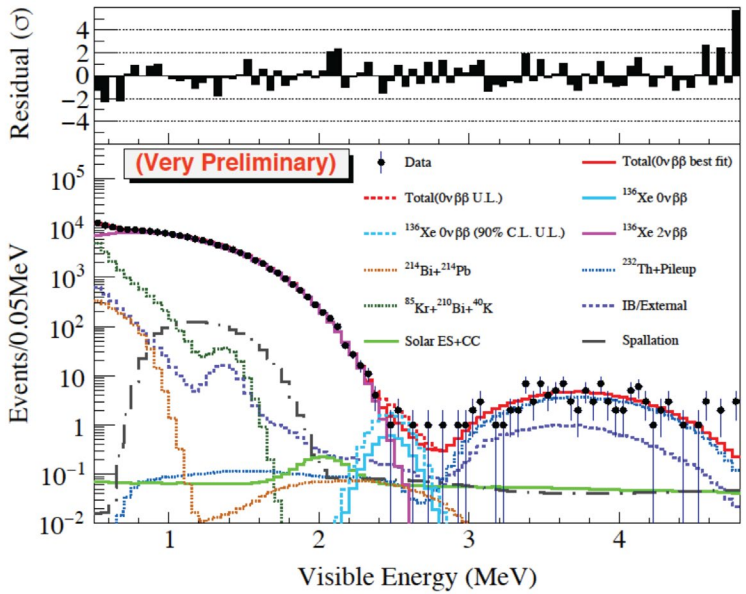
[Phys. Rev. Lett. 117, 082503, AoboLi@TAUP2021]

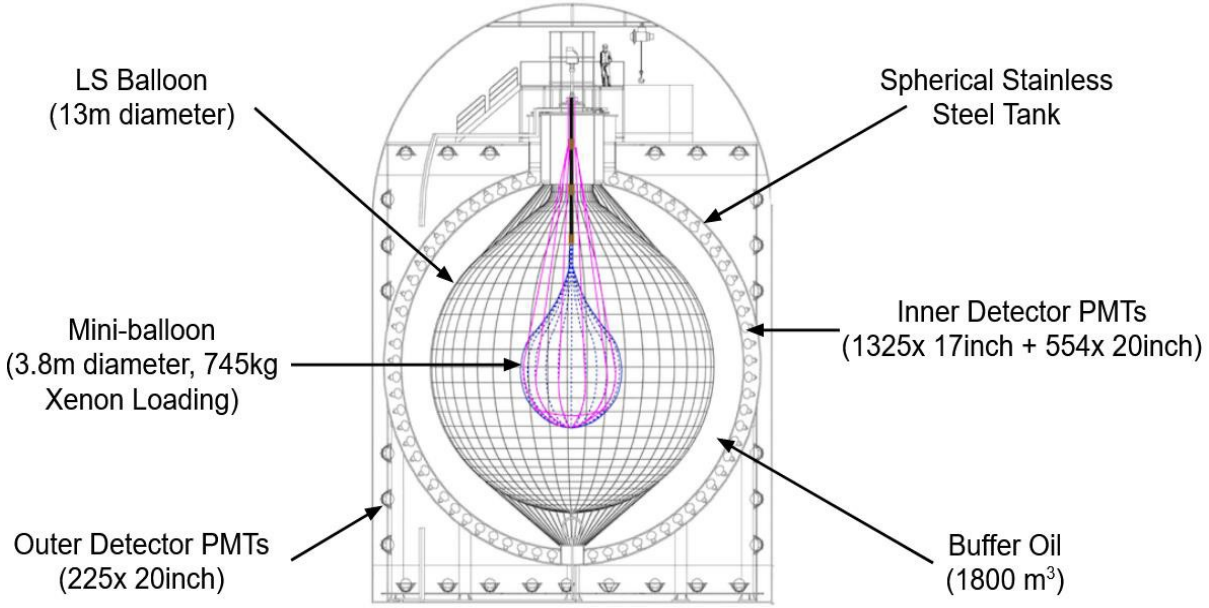
@Kamioka (JP) –91% enriched ^{136}Xe loaded in Liquid Scint.(745 kg) – 2019 --> still taking data

Previous phase:
KamLAND-Zen 400
1.07×10^{26} yrs (90% C.L.)
(Phys. Rev. Lett. 117, 082503)

Background rejection

- **240cm cut**: Select events inside and just outside of the mini-balloon
- **Rn cut**: delayed coincidence cut for ^{214}Bi – ^{214}Po and ^{212}Bi – ^{212}Po
- **Fiducial volume cut**: Further reduce backgrounds going from r < 240 cm to r < 157 cm
- **Spallation Cut**: Remove events correlated with muons
- **Triple coincidence tag**: Muon - ^{10}C - neutron capture





Exposure	246.1 kg yr
$\Delta E/E@Q_{\beta\beta}$	4.5%
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 4\times10^{25}$ yr @ 90% C.L.

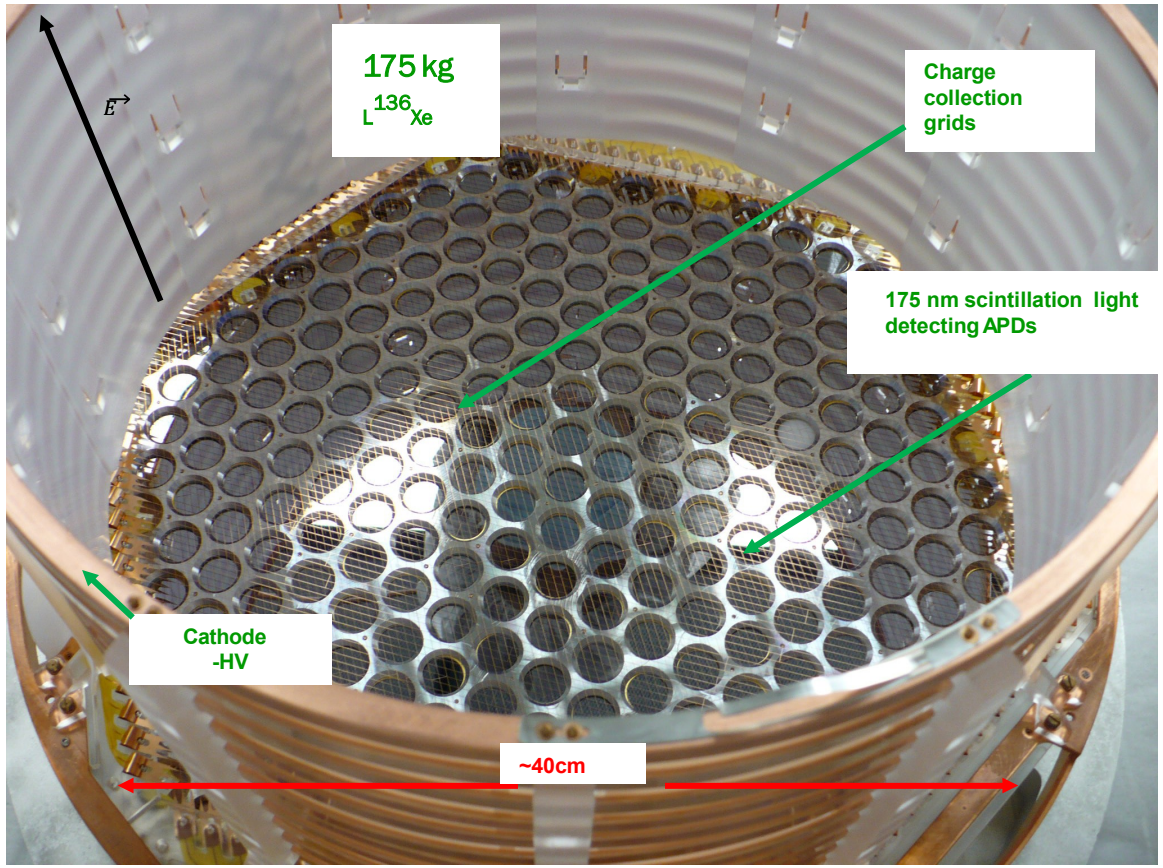
Intensive studies on backgrounds (^{136}Xe long-lived spallation products)
Twice the exposure to analyze
Goal: $T^{0n}_{1/2} > 5\times10^{26}$ yr @ 90% C.L. ($m_{\beta\beta}$ < 30 –80 meV)

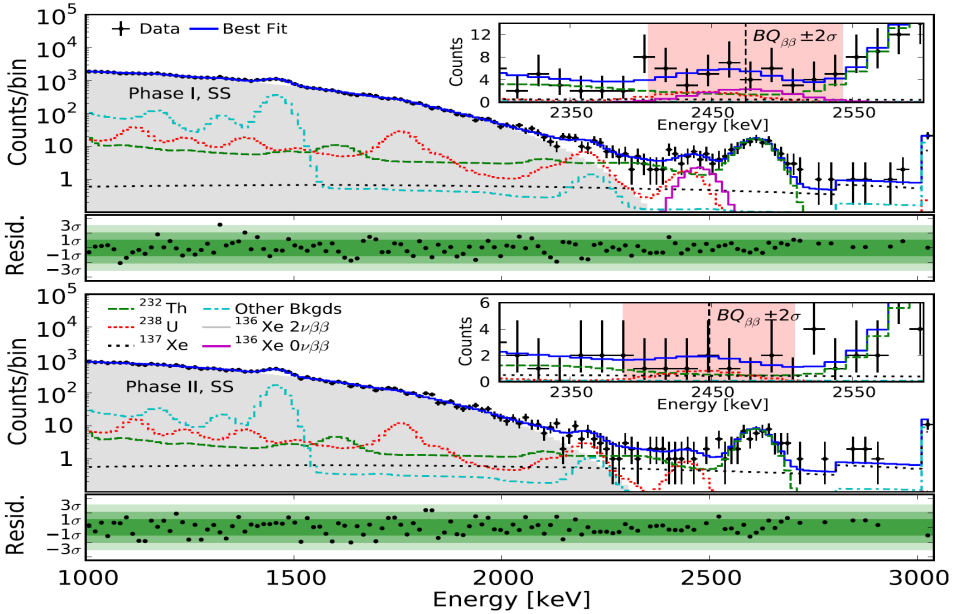
$0\nu\beta\beta$ EXPERIMENTS – *EXO 200*

[Phys. Rev. Lett. 123 (2019) 161802]

@WIPP (US) – Single phase enriched LXe TPC (150 kg of ^{136}Xe)– 2012 → 2019

Energy measured using scintillation (APDs) and ionisation (wires)





Exposure	234.1 kg yr
$\Delta E/E@Q_{\beta\beta}$ $(FWHM)$	2.8%
BI	1.5×10^{-3} cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 3.5\times10^{25}$ yr @ 90% C.L.

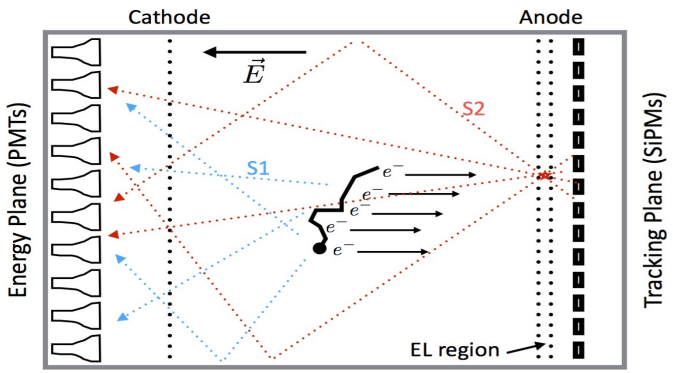
First observation of 2nbb of 136Xe (2011)

$T_{1/2}$= 2.165×10^{21}y

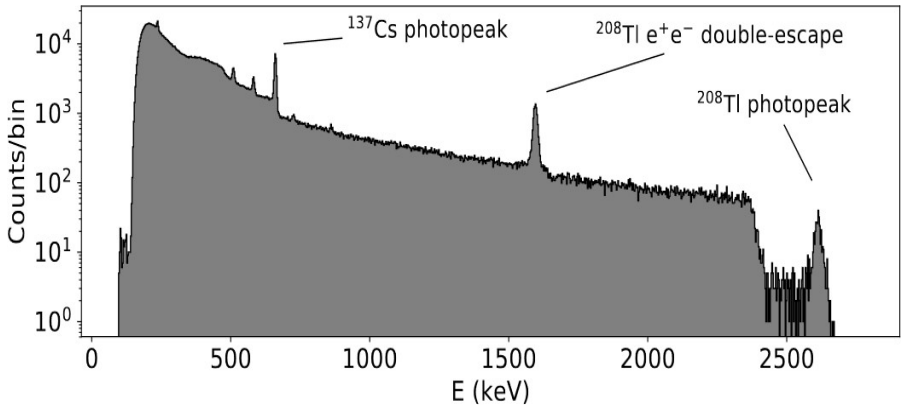
$0\nu\beta\beta$ EXPERIMENTS – *NEXT-WHITE*

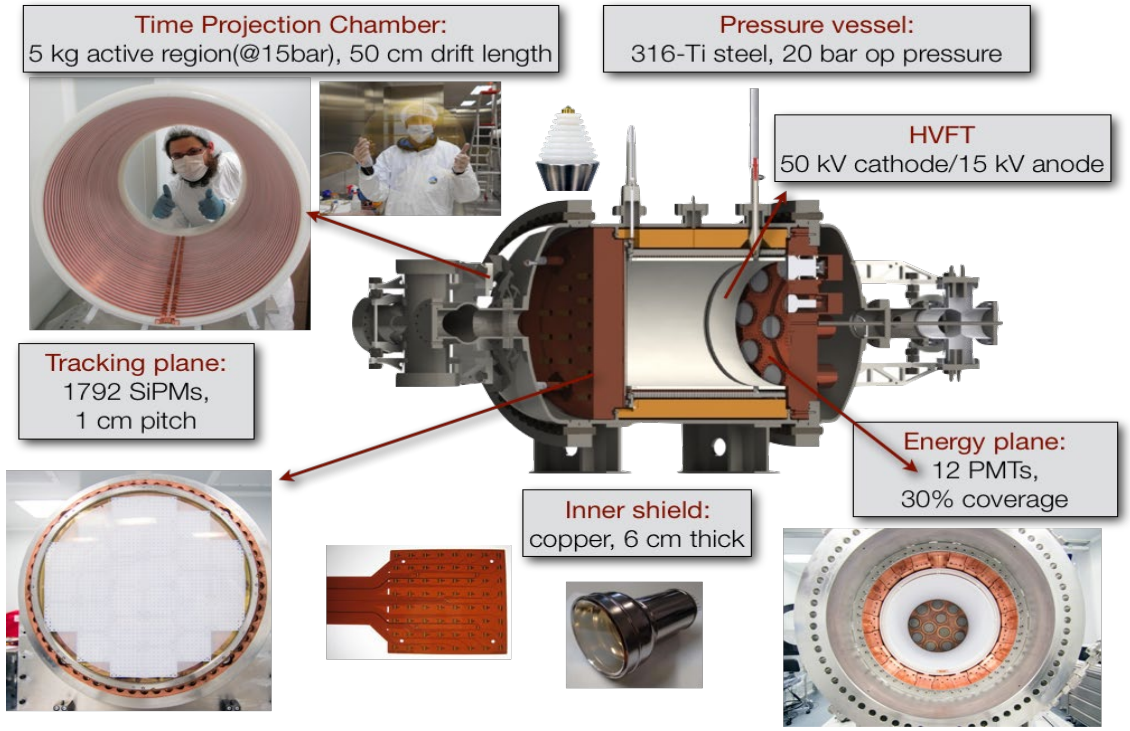
[J. High Energ. Phys.2019, 230 (2019), J. High Energ. Phys.2019, 52 (2019)]

@LSC (Spain)–High pressure enriched Xenon TPC with electroluminescence amplification of the signal (5 kg)– 2016→2021

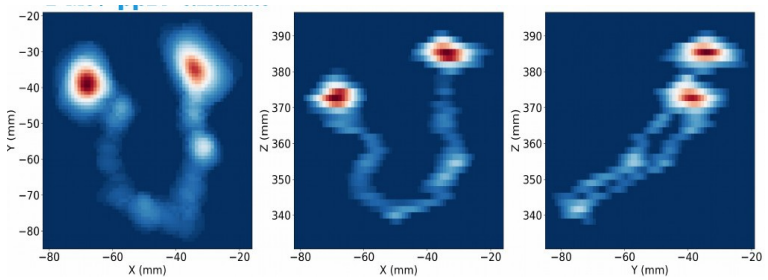


- Primary scintillation (t0→z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane)





- **Topology-based** background rejection

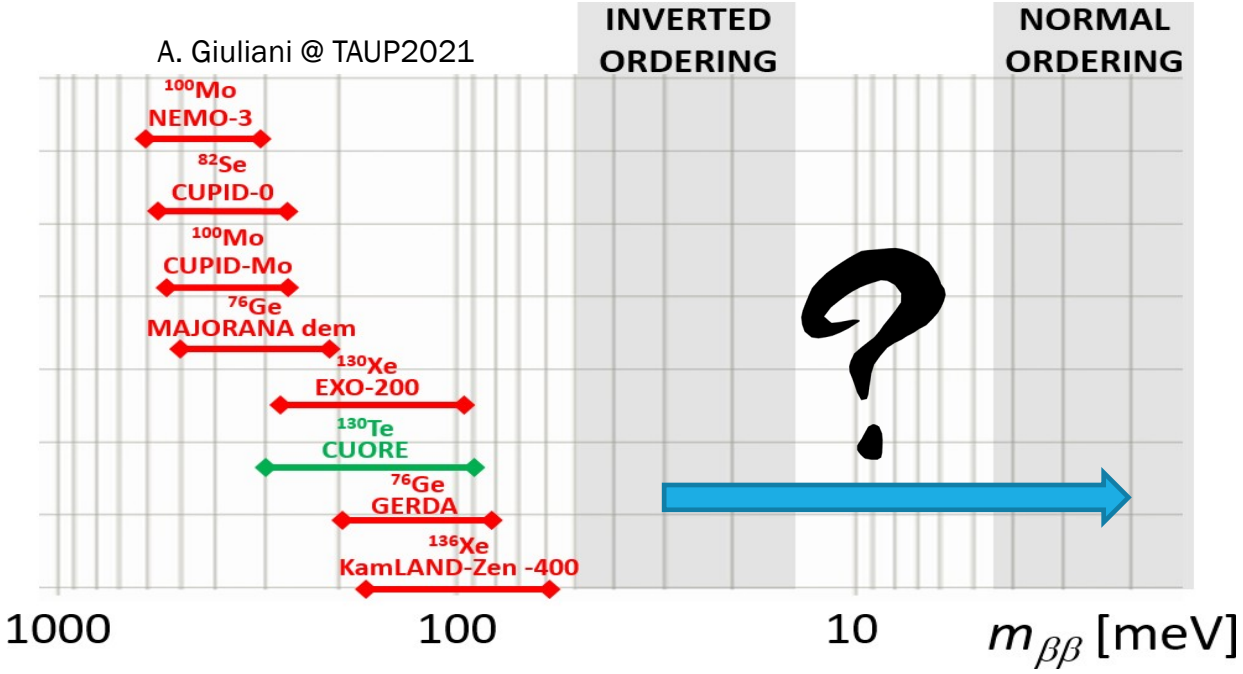


$\Delta E/E@Q_{\beta\beta}$ $(FWHM)$	1%

Proof of concept for next generation experiment

$0\nu\beta\beta$- *PRESENT* EXPERIMENTAL PANORAMA

EXPERIMENT	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$<m_{\beta\beta}>$ [meV]
GERDA	^{76}Ge	127.2	18	79-180
MAJORANA	^{76}Ge	26	2.7	200-433
CUORE	^{130}Te	1038.4	2.2	90-305
CUPID-Mo	^{100}Mo	2.71	0.18	280 – 490
CUPID-0	^{82}Se	16.59	0.47	276 – 570
KamLAND-zen 400	^{136}Xe	594	10.7	61-165
EXO200	^{136}Xe	234.1	3.5	93-286



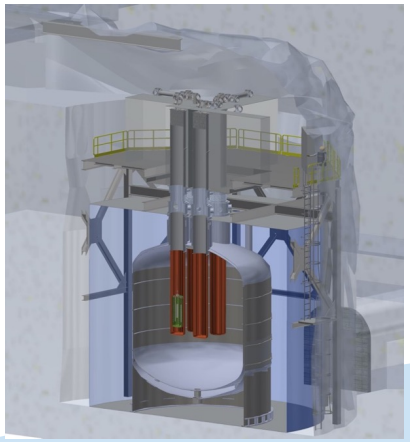
$0\nu\beta\beta$- NEXT AND NEXT-TO-NEXT GENERATION

GERDA MAJORANA	LEGEND 200	LEGEND 1000
CUORE CUPID-Mo/0	CUPID	CUPID-Reach/CUPID-1t
AMORE-I	AMORE-II	
KamLAND-Zen 800	KamLAND2-Zen	
EXO 200	nEXO	
NEXT-WHITE	NEXT-100	NEXT-HD/NEXT-BOLD
SNO+	SNO+ Phase II	… THEIA

$0\nu\beta\beta$- NEXT GENERATION - LEGEND

arXiv:2107.11462

The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years..



LEGEND-200

200 kg in upgrade of existing infrastructure at LNGS

BG goal: <0.5 c /(FWMH t y)

$T_{1/2} > 10^{27}$ yrs after 5 yrs

$m_{\beta\beta}$ = 34 −78 meV

Commissioning ongoing

LEGEND-1000

1000 kg, staged via individual payloads

Background goal <0.025 cts/(FWHM t yr)

$T_{1/2} > 10^{28}$ yrs after 10 yrs

$m_{\beta\beta}$ = 9 −21 meV

@SNOLAB

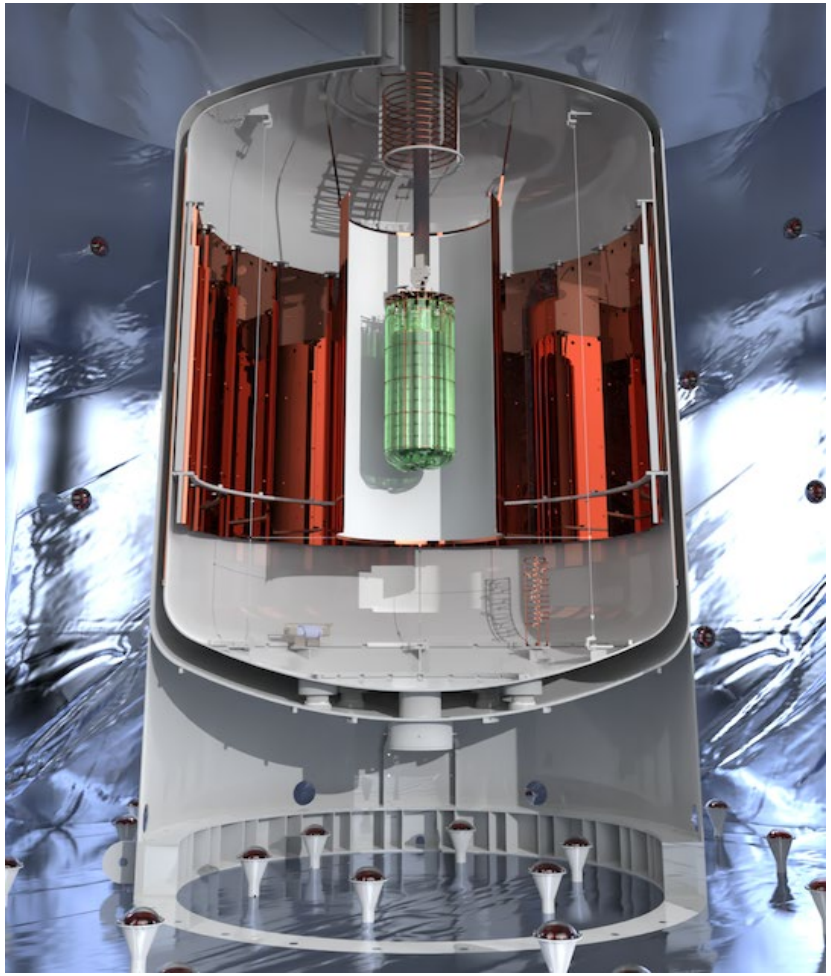
(alternative site @LNGS)

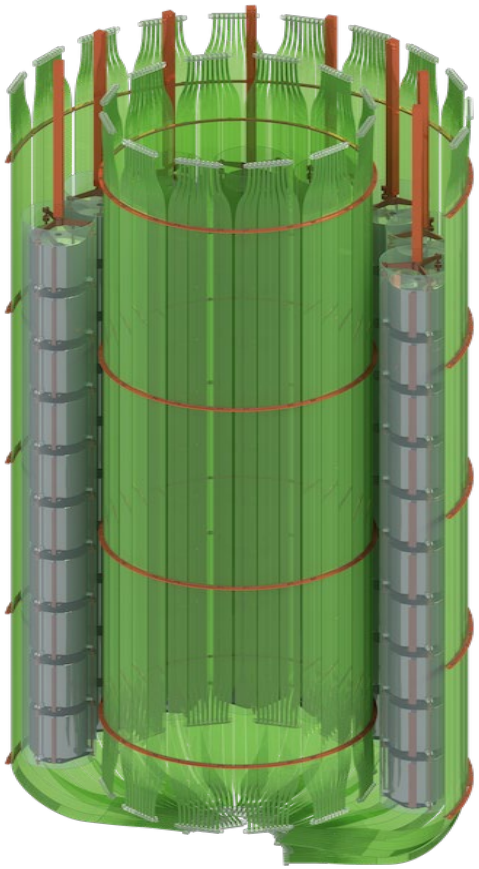
GERDA

Majorana

$0\nu\beta\beta$- NEXT GENERATION - LEGEND 200

arXiv:2107.11462





GERDA

- Bare HPGe operated in instrumented liquid argon
- Liquid argon cryostat in instrumented water shield
- Fast HPGe deployment and retrieval through lock system

MAJORANA

- Electroformed Copper
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

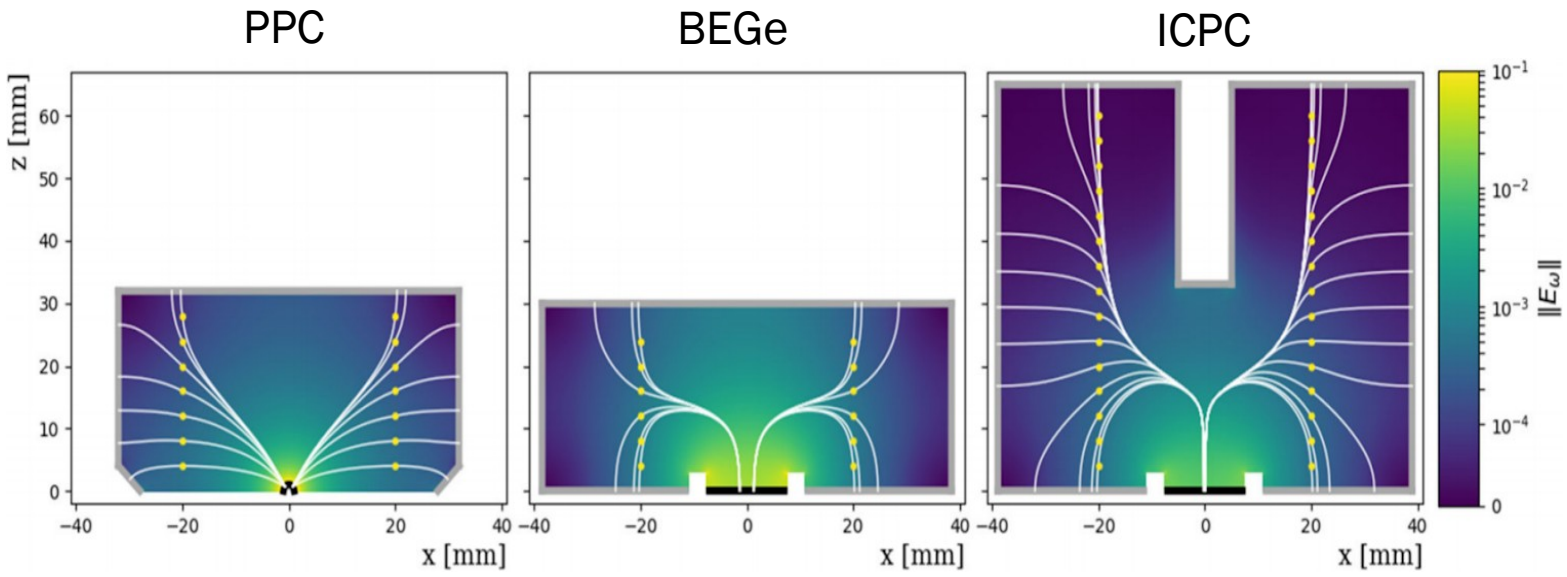
BOTH

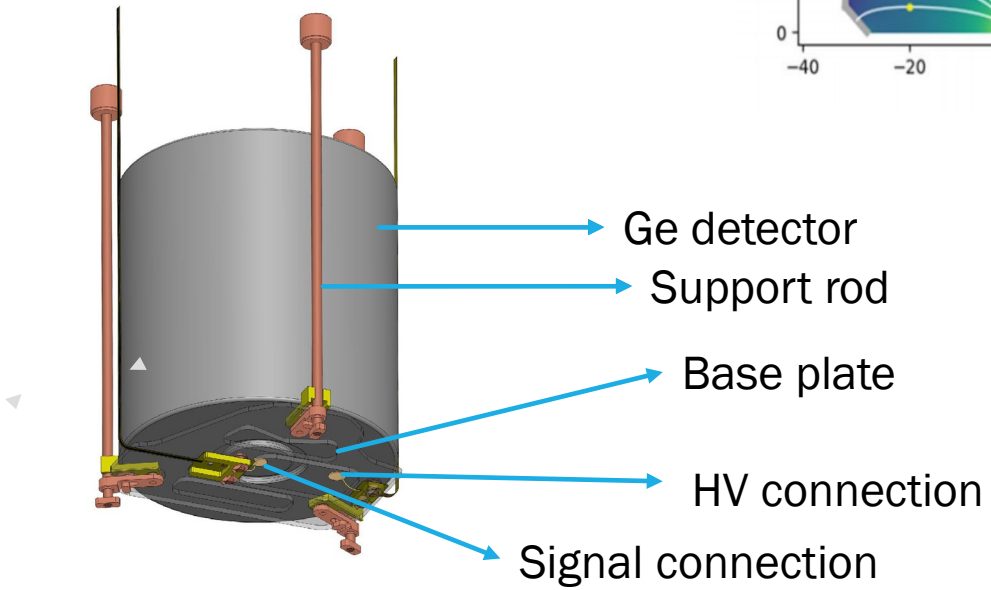
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution

$0\nu\beta\beta$- NEXT GENERATION - LEGEND 200

arXiv:2107.11462

70 kg of enriched detectors from the Majorana Demonstrator and Gerda and an additional 130 kg of newly produced **ICPC detectors**.

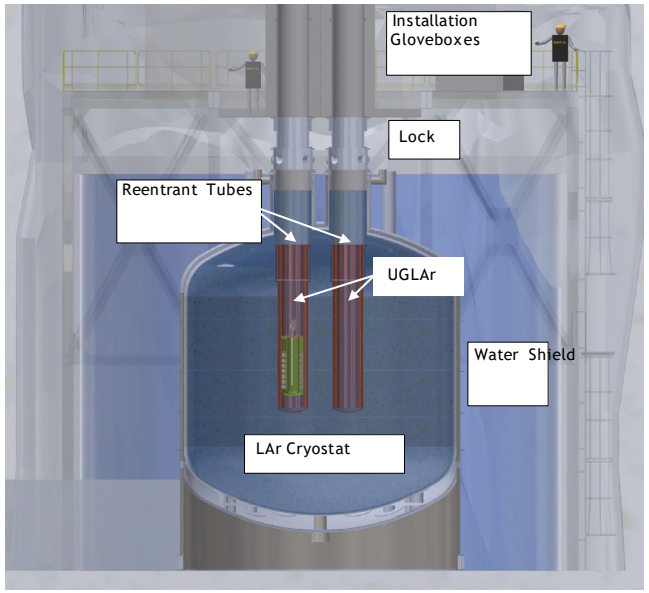


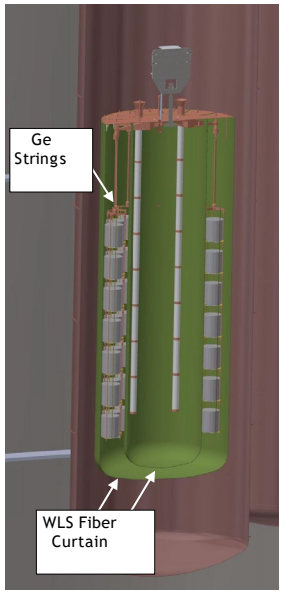


- 2.6 kg average mass
- Excellent pulse-shape performance

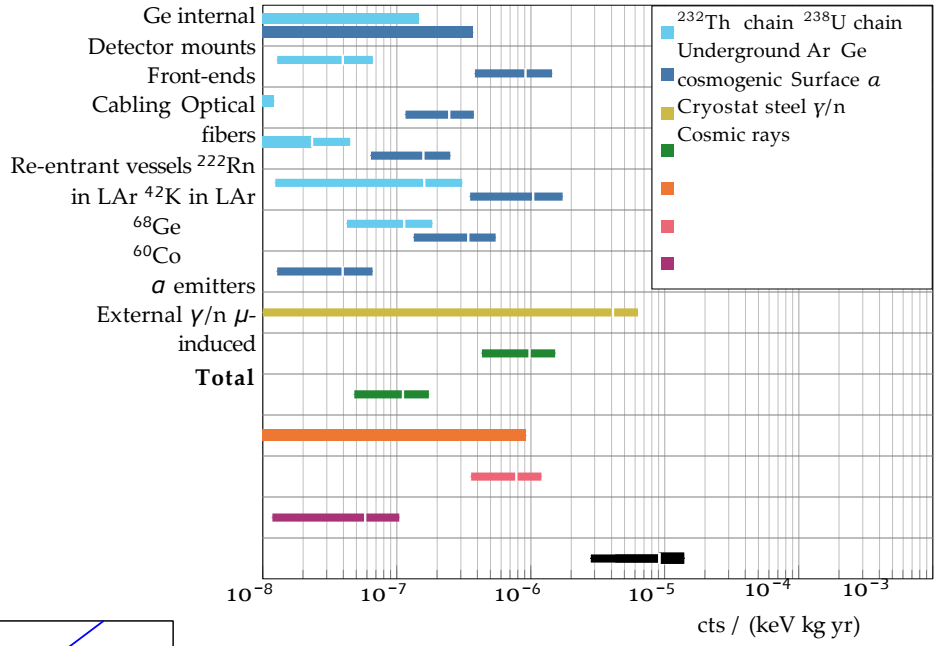
$0\nu\beta\beta$- NEXT GENERATION - LEGEND 1000

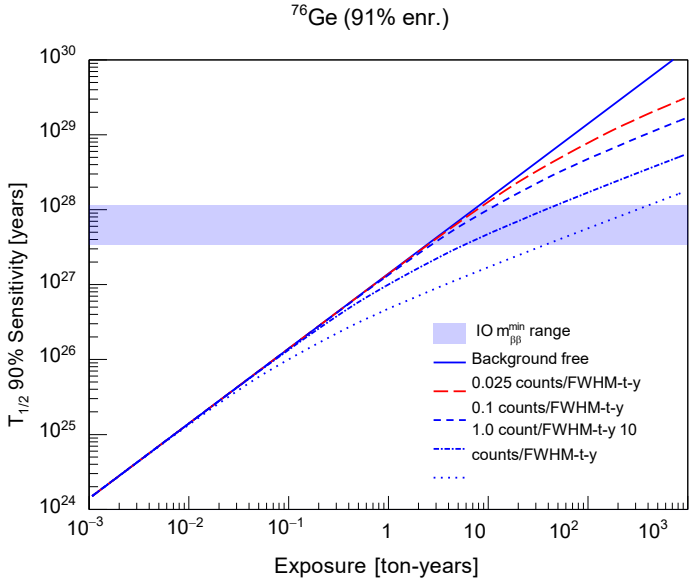
arXiv:2107.11462

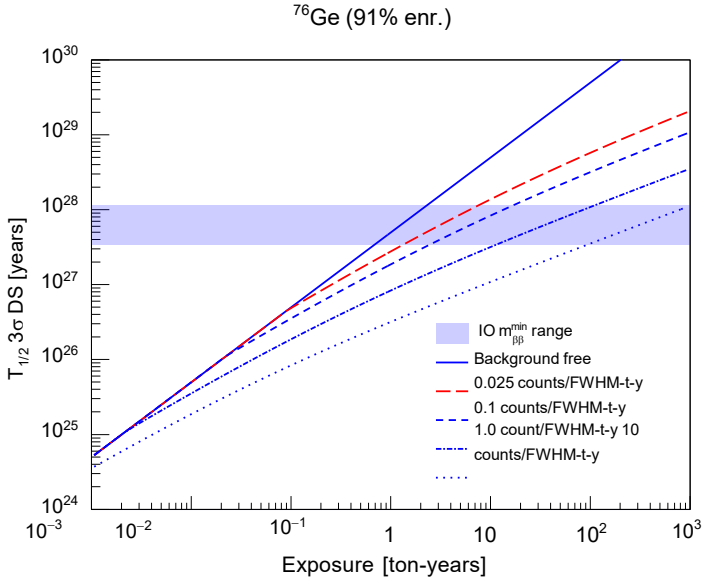




Projected background for LEGEND-1000 **0.025 cts/(FWHM t yr)** 10^{-5} cts/(keV kg yr)



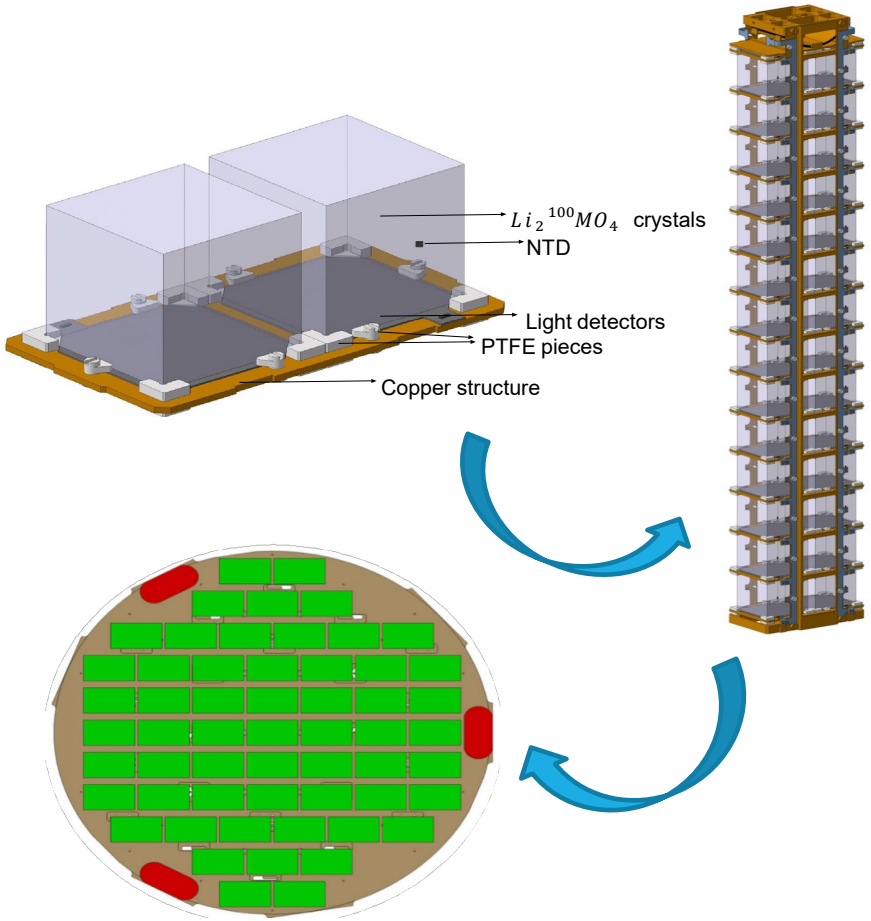




Quasi-background-free search beyond the bottom of the inverted hierarchy region

$0\nu\beta\beta$- NEXT GENERATION - CUPID

CUORE Upgrade With Particle Identification is built on successful CUPID-Mo/0 + CUORE

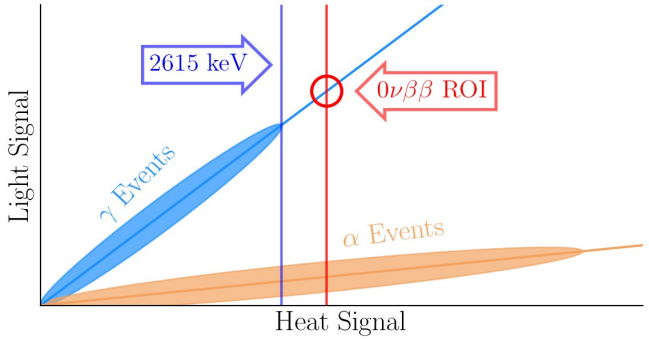


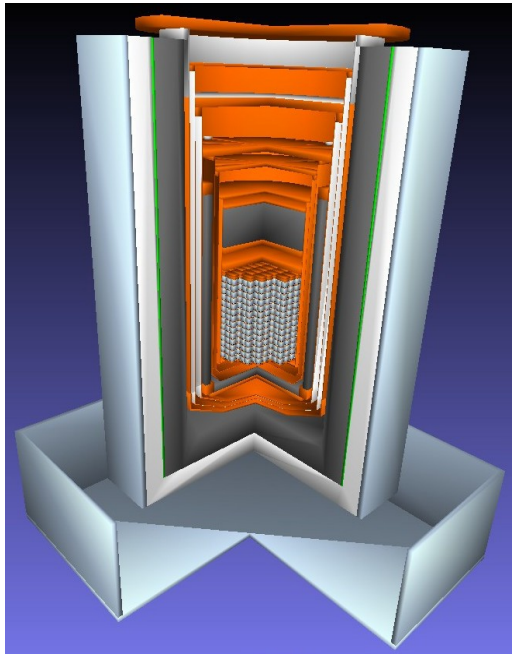
Detector

- 1596 total crystals
- 450 kg of $Li_2{}^{100}MoO_4$
- 95% enrichment in ^{100}Mo: **240 kg of ^{100}Mo**
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs.
- Ge light detectors with SiO anti-reflective coating
- Each crystal has top and bottom light detectors
- No reflecting foils
- NTD readouts for both $Li_2{}^{100}MoO_4$ crystals and Ge LDs
- Possible option of TES readouts for LDs
- Re-using CUORE cryostat

Background

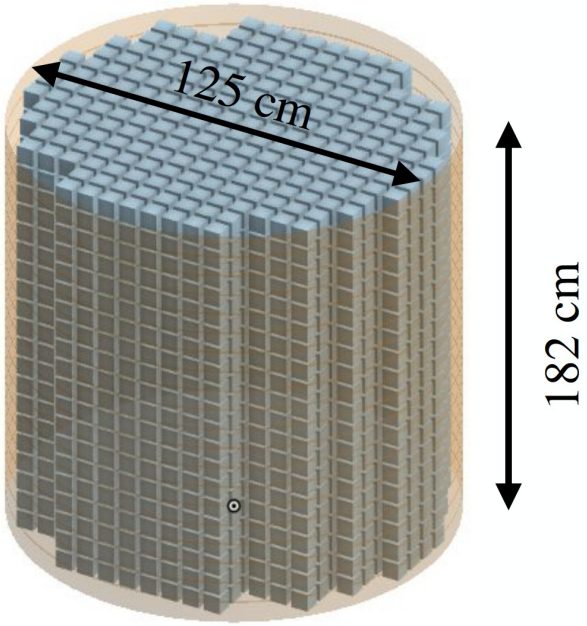
- α background effectively eliminated by PID
- β/γ backgrounds reduced to < 5×10-5 cnts/(keV·kg·yr) ▸
  - Achievable with existing material selection, parts cleaning and handling, cryostat shielding
  - Delayed coincidence cuts remove backgrounds from U/Th decay chains
- 2νββ decay pileup reduced to < 5×10-5 cnts/(keV·kg·yr)
  - Requires light detector timing resolution of ~140 μs
  - Higher sampling rate, wider bandwidth electronics, lower noise, new NTDs, machine learning techniques
  - Alternative: TES based light detectors (mature technology)
  - Muons reduced by an order of magnitude
    Muon veto system with 99% geometric efficiency

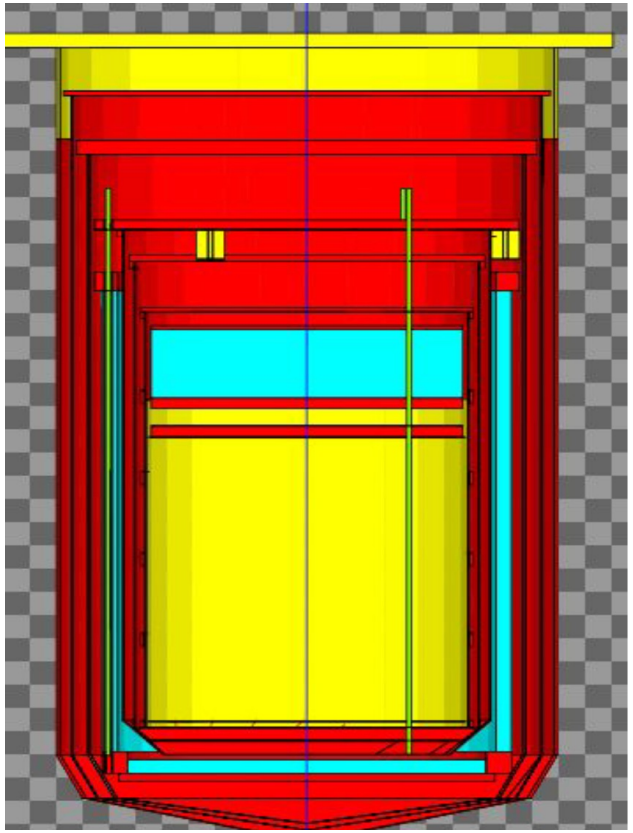




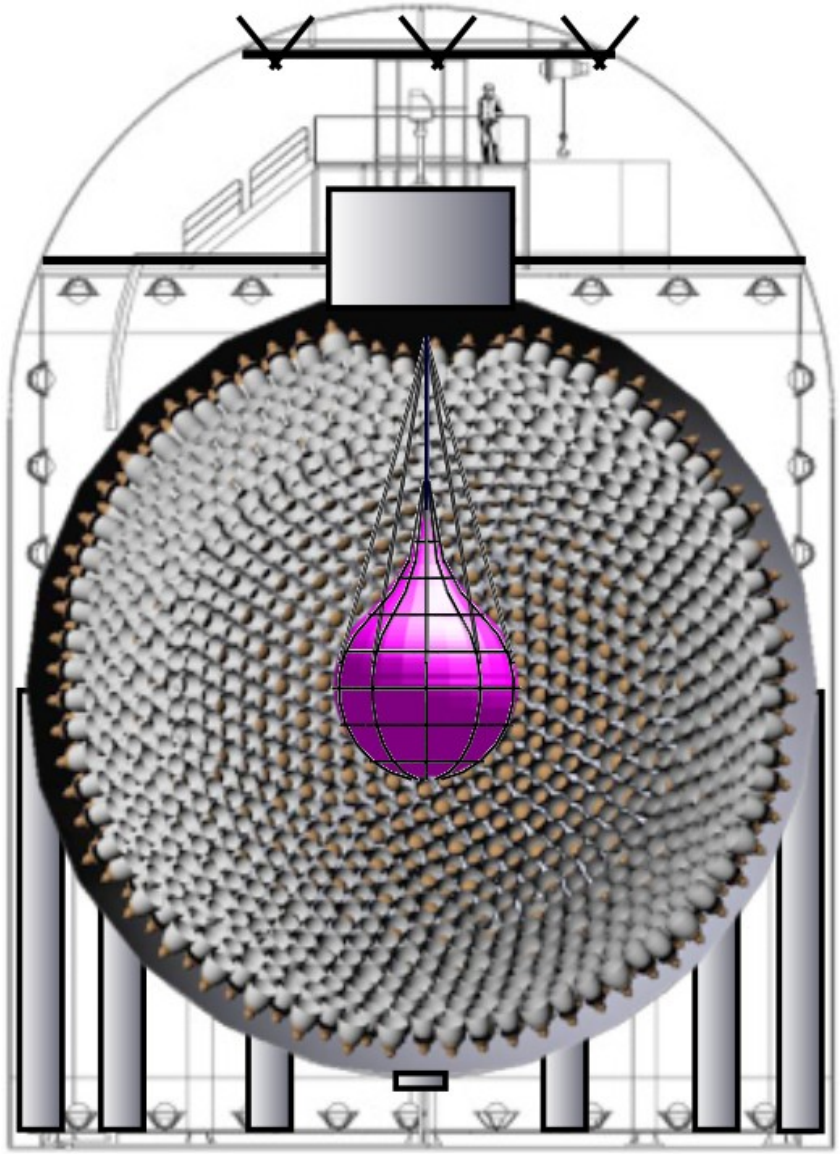
$0\nu\beta\beta$- NEXT GENERATION - CUPID

	CUPID	CUPID-Reach	CUPID – 1T
Mass [kg]	450	450	1871
^{100}Mo Mass [kg]	240	240	1000
Resolution [keV FWHM]	5	5	
BI [cts/(keV·kg·yr]	10^{-4}	2×10^{-5}	5×10^{-6}
$T^{0\nu}_{1/2}$ [90% CL]	1.4×10^{27}	2×10^{27}	9.2×10^{27}
$m_{\beta\beta}$ [meV]	10 - 17	8.4 - 14	4 - 6.9





$0\nu\beta\beta$- NEXT GENERATION – KAMLAND2-ZEN



KamLAND2-Zen:

- Xenon mass ~ 1ton
- 2X better ΔE
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

Target

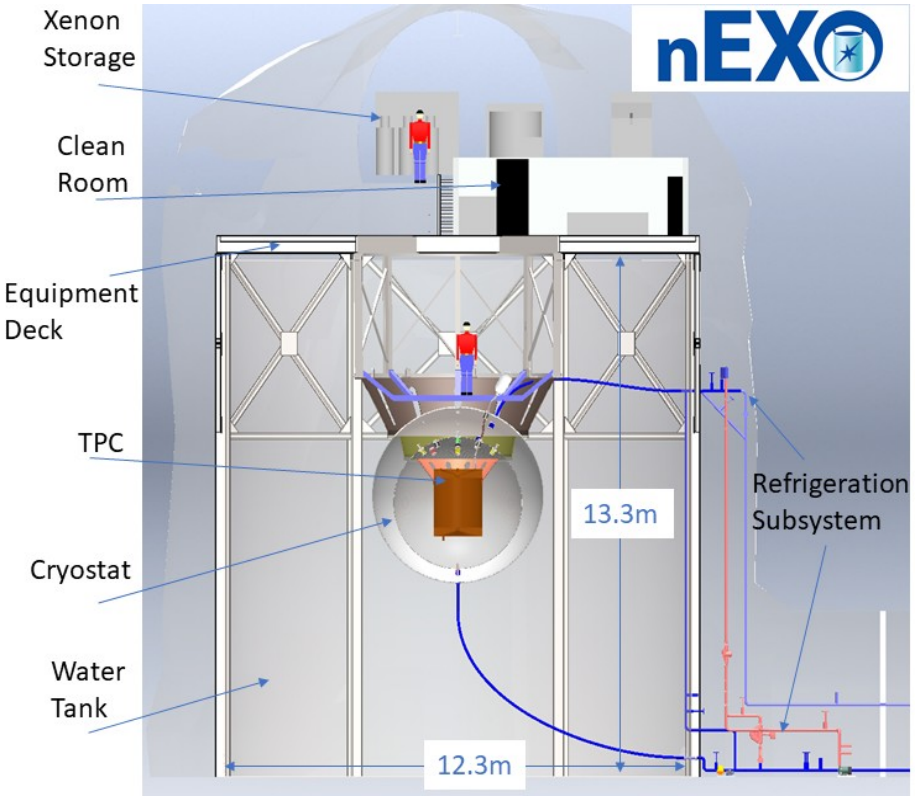
$T_{1/2} > 2 \times 10^{27}$ yr

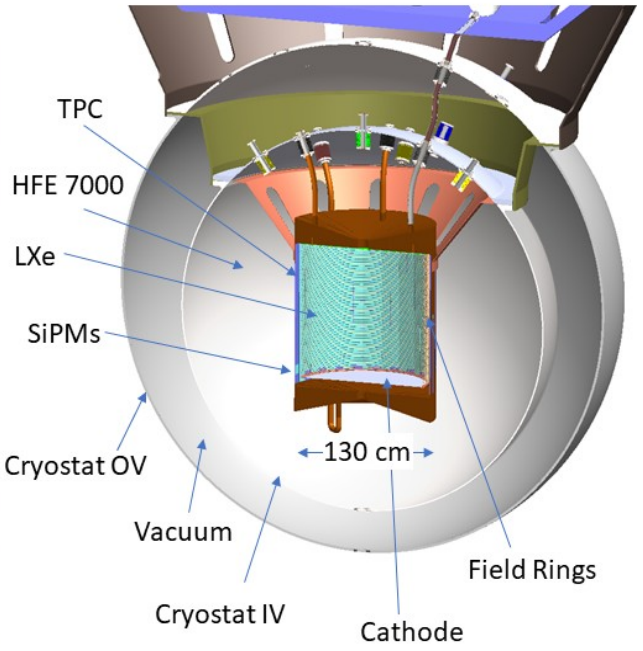
$m_{\beta\beta} < 20$ meV

R&D underway

$0\nu\beta\beta$- NEXT GENERATION –nEXO

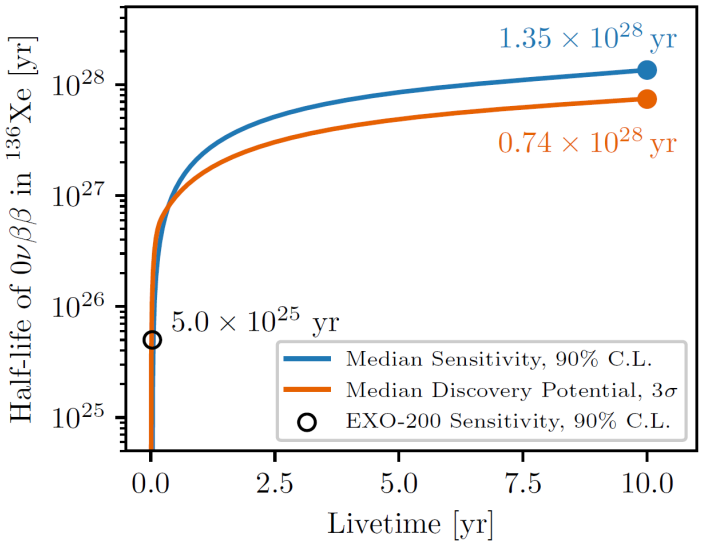
arXiv:1805.11142





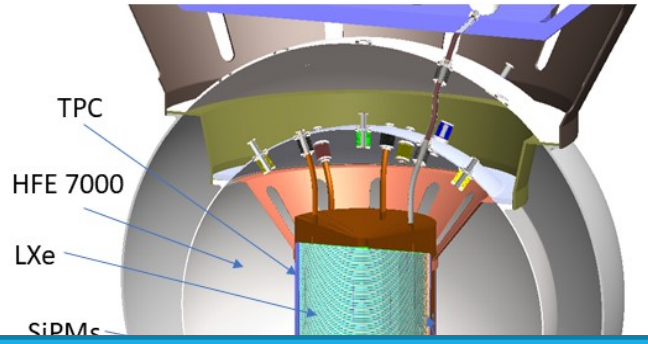
- **Single phase enriched (90%) LXe TPC (5000 kg)**
- Energy resolution **ΔE(σ) ~0.8%@$Q_{\beta\beta}$**
- Measurement of both charge and scintillation
- **Single site**(including signal) **vs. multi site events** (background)
- Multi-dimensional analysis using energy, 3D position and topology
- Active water Cherenkov veto
- @SNOLAB

TARGET:
BI: 7×10^{-5} cts/(keV kg y)
10 y sensitivity: 1.35×10^{28}y
$m_{\beta\beta}$ < 5 -15 meV



$0\nu\beta\beta$- NEXT GENERATION –nEXO

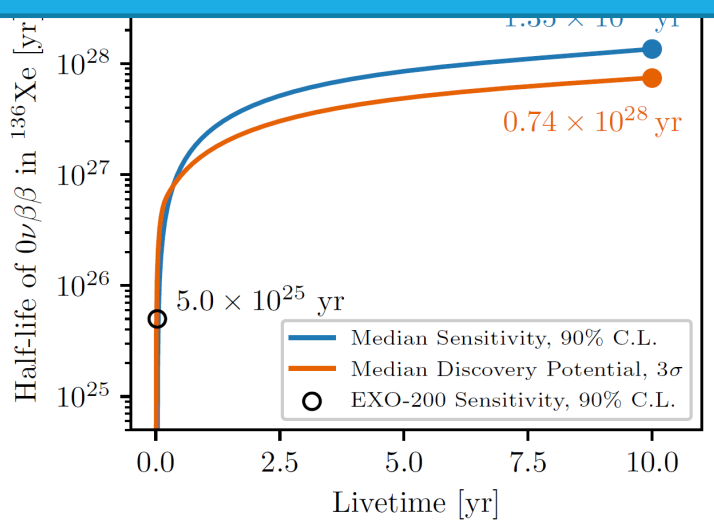
arXiv:1805.11142



- **Single phase enriched (90%) LXe TPC (5000 kg)**
- Energy resolution **ΔE(σ) ~0.8%@$Q_{\beta\beta}$**
- Measurement of both charge and scintillation
- **Single site** (including signal) **vs. multi** (background)
- analysis using
- n and topology
- enkov veto

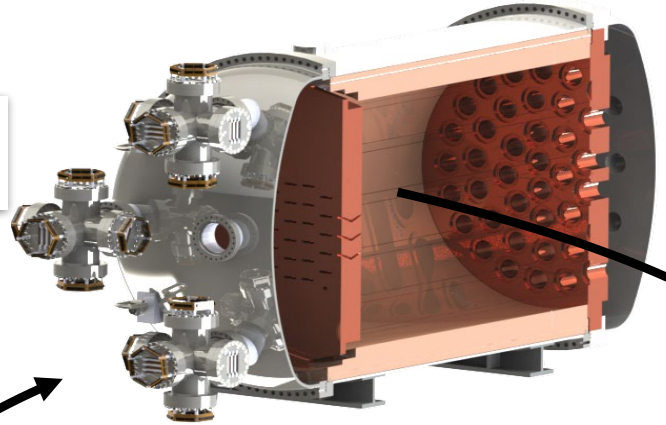
Double-phase Xe TPCs mainly conceived for direct Dark Matter detection
(DARWIN, LZ, PANDAX-4T)
can provide competitive results on $\boldsymbol{0\nu\beta\beta}$ ^{136}Xe (even with natural Xenon), but with sensitivities that are about 1-2 orders of magnitude lower than nEXO's

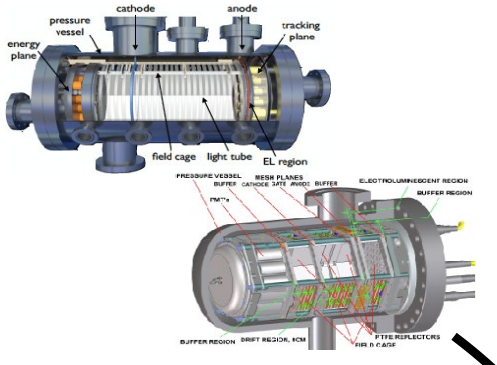
TARGET:
BI: 7×10^{-5} cts/(keV kg y)
10 y sensitivity: 1.35×10^{28}y
$m_{\beta\beta}$ < 5 -15 meV



$0\nu\beta\beta$- NEXT GENERATION – NEXT

NEXT-100 (~100 kg)
[2022 - 2026]



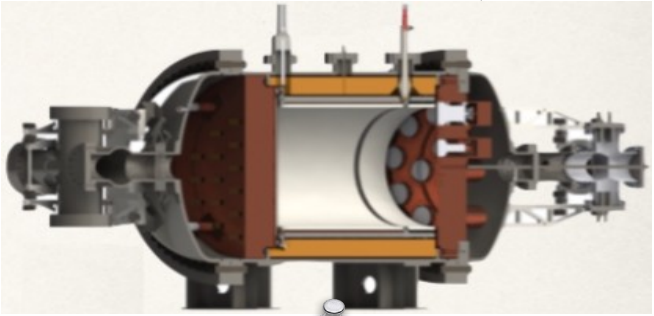


Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept

ββ0v searches (10^{26} y)
Show extrapolation to ton scale

NEXT-White (~5 kg)
[2015 - 2021]

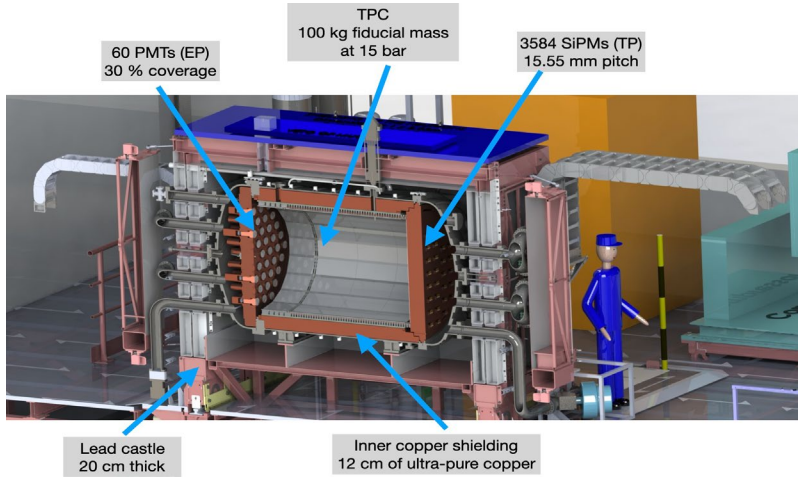


Underground and radio-pure operations, background, ββ2v

NEXT-HD/BOLD
[2026…]

ββ0v searches
(10^{27}- 10^{28} y)

$0\nu\beta\beta$- NEXT GENERATION – NEXT



NEXT-100 (funded) –**LSC, Spain**(2022-2025)

Upscaling of NEXT-White

- More isotope ~**97kg of enr Xe gas (136Xe: 90%)**
- 5 bar operation
- Same structure/technology of NEXT-White
- Larger vessel, 60x PMTs and 5600x SiPMs
- projected background index: 4×10^{-4}cts/(keV kg y)

TARGET
400 kg y sensitivity: 1×10^{26}y
$m_{\beta\beta}$ < 60 -160 meV
Main goal: **prepare future stages** of NEXT technology

NEXT-HD (High Definition) –start in 2026

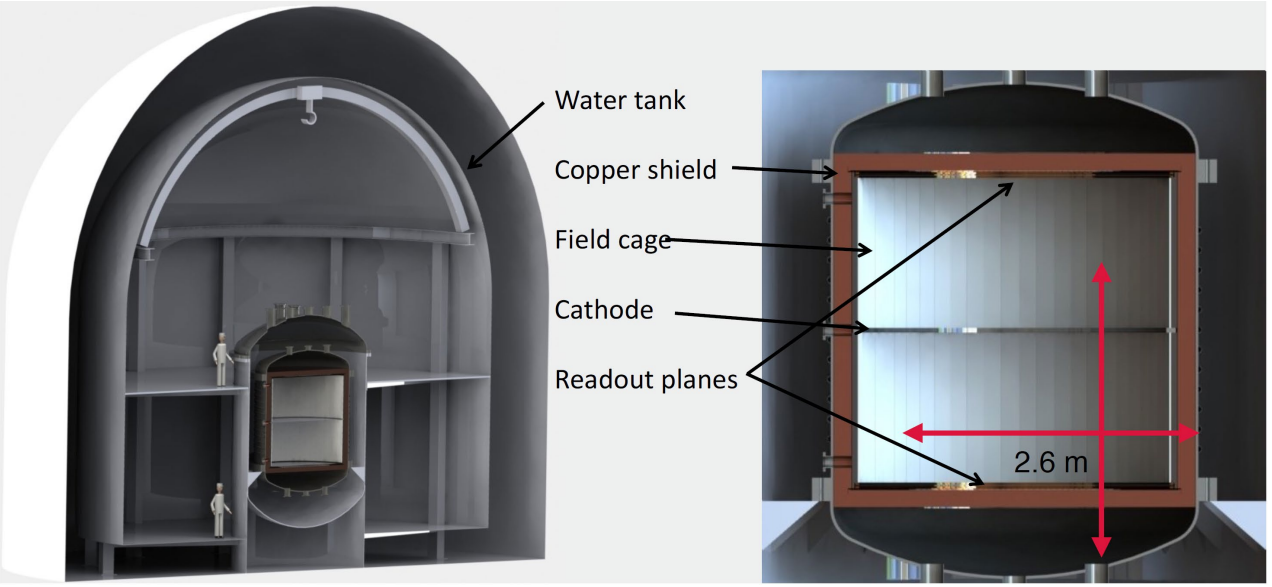
- Up to 1 ton enriched Xe gas at 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Projected background index: 5×10^{-5} cts/(keV kg y)

TARGET
2×10^{27}y

NEXT-BOLD (Barium On Light Detection)

- NEXT-HD-like module with **Ba tagging**
- Ba tagging by **SMFI** (Single Molecule Fluorescence Imaging) was proved
- R&D to adapt SMFI to the NEXT dry environment
- Background free

TARGET
6 ton y
8×10^{27}y
Phys. Rev. Lett. 120, 132504 (2018)



$0\nu\beta\beta$- NEXT GENERATION – SNO+

arXiv:2104.11687v2

SNO+ Neutrinoless Double Beta Decay with Tellurium-Loaded Liquid Scintillator

780 tonnes of LS with 0.5% Te (by weight) will contain 1,330 kg of ^{130}Te *isotope*

SNO+ → three phases

- **Pure-water phase** (from May 2017 - 2019)
  - measurement of the external background
  - physics results (8B n's, invisible nucleon decays)
  - world-leading limits on invisible nucleon decay
- **Liquid scintillator phase** without Te (completed April 2021)
  - measurement of scintillator background
  - U, Th concentration 5×10^{-17}g/g
  - Background level low enough for 0nbb
- **Te phase** (from 2022) –Study of 2nbb and 0nbb

SNO+-phase II (start in 2026)

- 3% Te concentration
- Improve transparency
- Improve light detectors

TARGET

ΔE = 190 keV FWHM

9.5 counts/y in ROI

5 y sensitivity :

1.9×10^{26}y

$m_{\beta\beta}$ < 30 -104 meV

TARGET

1.9×10^{27}y

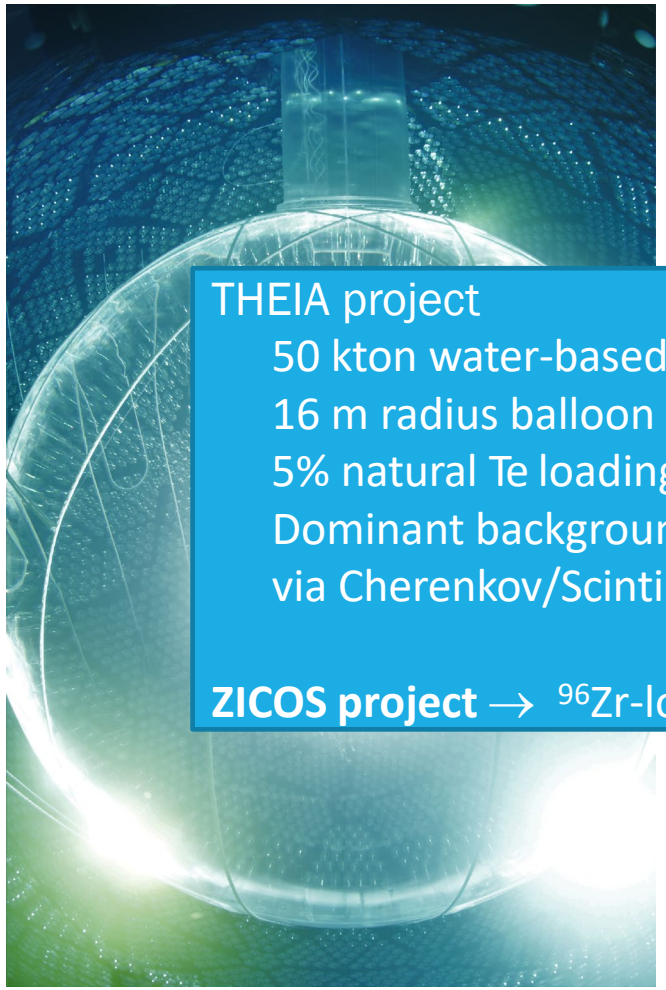
$m_{\beta\beta}$ < 13 -45 meV

$0\nu\beta\beta$- NEXT GENERATION – SNO+

arXiv:2104.11687v2

SNO+ Neutrinoless Double Beta Decay with Tellurium-Loaded Liquid Scintillator

780 tonnes of LS with 0.5% Te (by weight) will contain 1,330 kg of ^{130}Te *isotope*



SNO+ → three phases

- **Pure-water phase** (from May 2017 - 2019)
  - measurement of the external background

THEIA project

50 kton water-based liquid scintillator detector

16 m radius balloon with high-LY LS and isotope

5% natural Te loading or 3% enriched ^{136}Xe loading

Dominant background: ^{8}B solar 's → directional measurement via Cherenkov/Scintillation separation

ZICOS project → ^{96}Zr-loaded-liquid scintillator

- 3% Te concentration
- Improve transparency
- Improve light detectors

TARGET

FWHM

in ROI

vity :

^{6}y

4 meV

TARGET

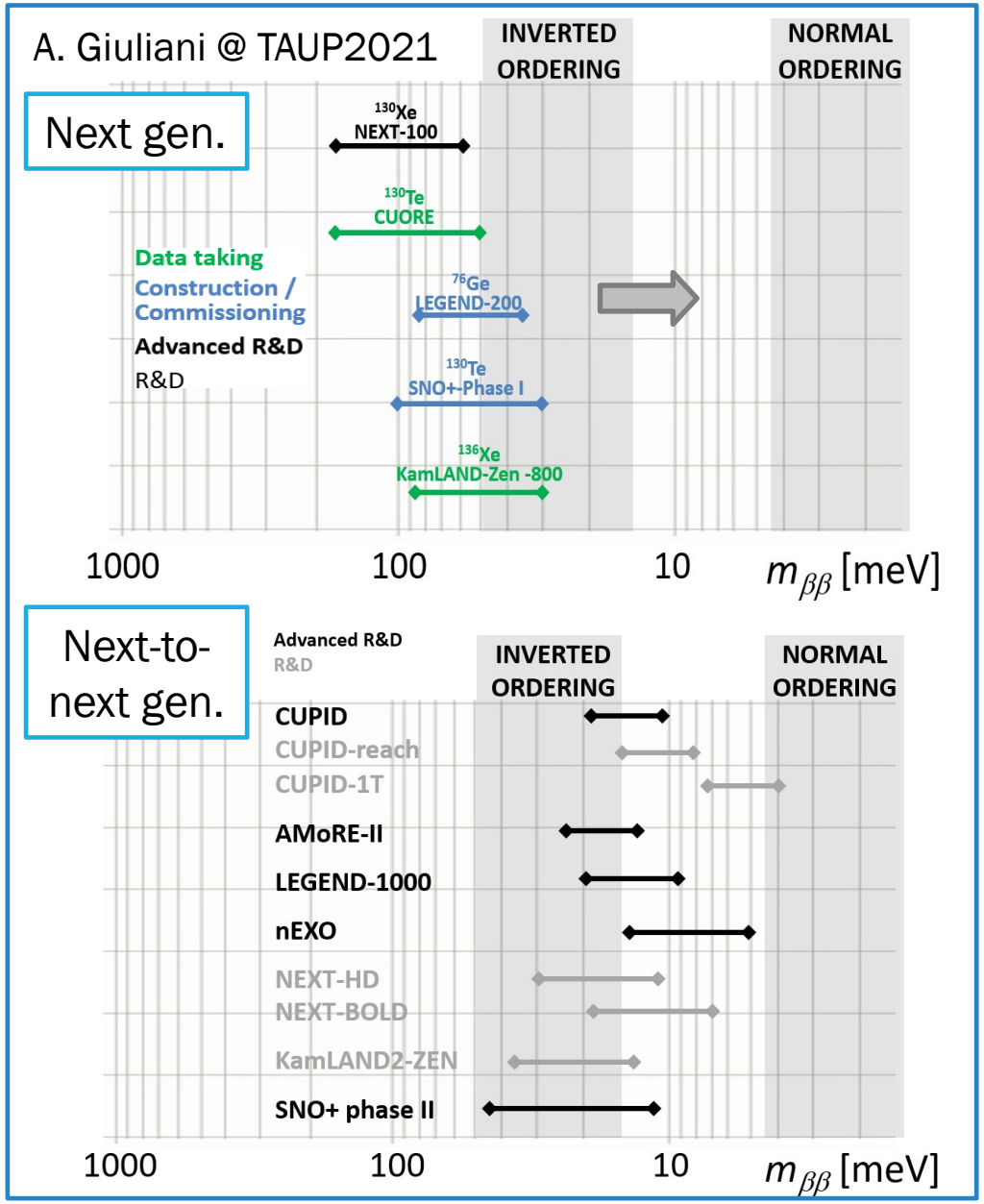
1.1×10^{28}y

T

1.9×10^{27}y

$m_{\beta\beta}$ < 13 -45 meV

CONCLUSIONS



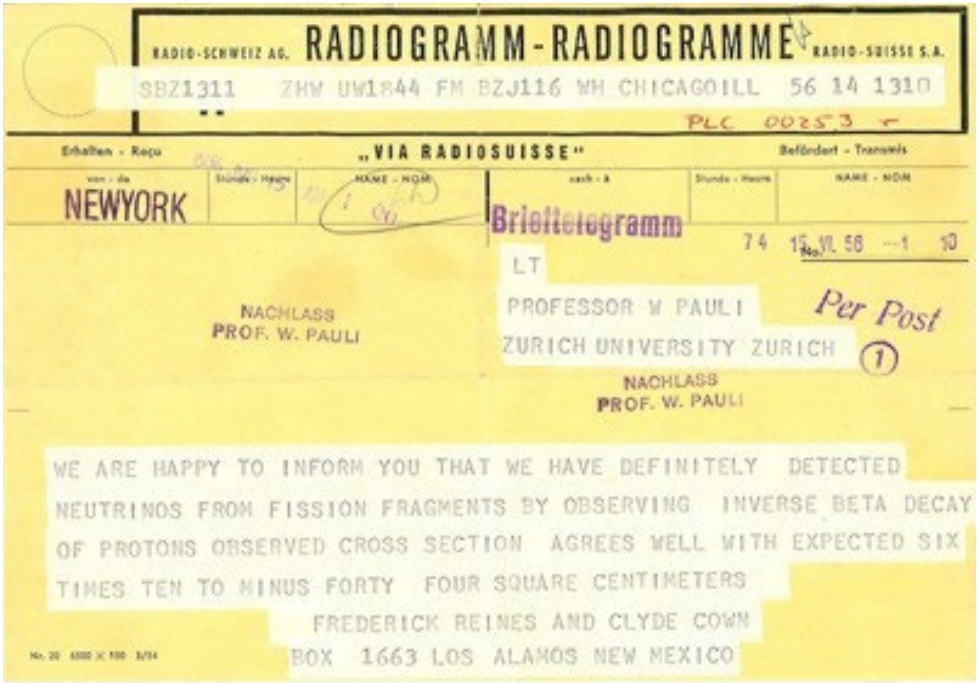
- $0\nu\beta\beta$ is a crucial process for particle physics and cosmology
- Impressive experimental program covering next (>5 y) and next-to-next (> 10y) generation of experiments
- Different technologies ''converging'' on most promising isotopes (^{76}Ge, ^{136}Xe, ^{100}Mo, ^{130}Te)
- Next-generation experiments have a good discovery potential
- Despite the efforts NH region still far to be reached (O(10^{29}y))

but…

1934

"*there is not practically possible way of detecting a neutrino*"

Bethe and Peierls



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de NEWYORK

NAME - NOM

nach - à Brieftelegramm

74 15.11.56 1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

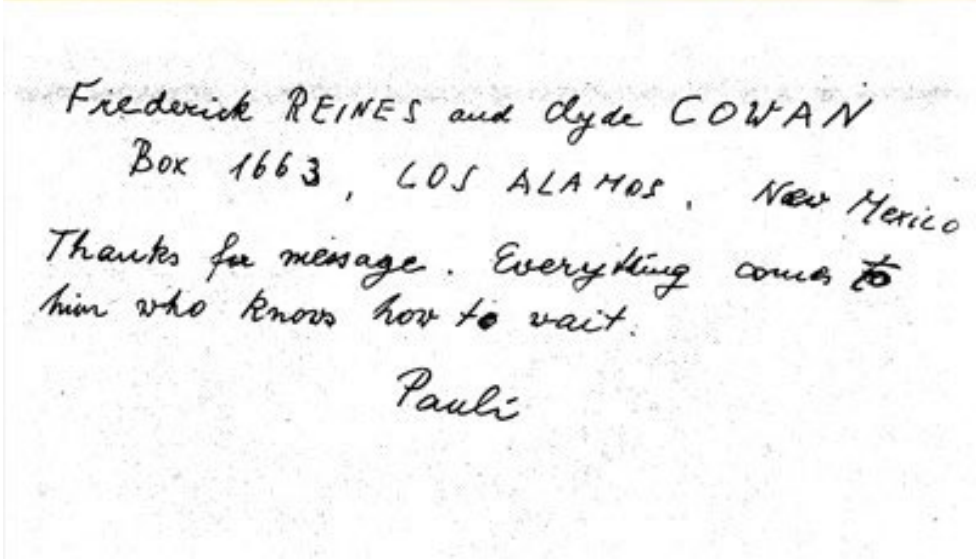
NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO



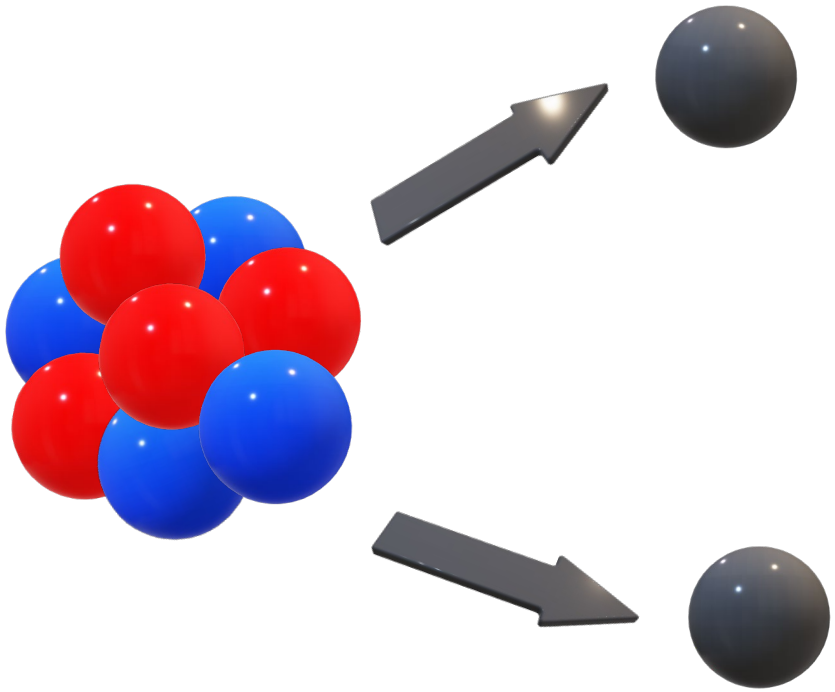
Frederick REINES and Clyde COWAN

Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

BACKUP



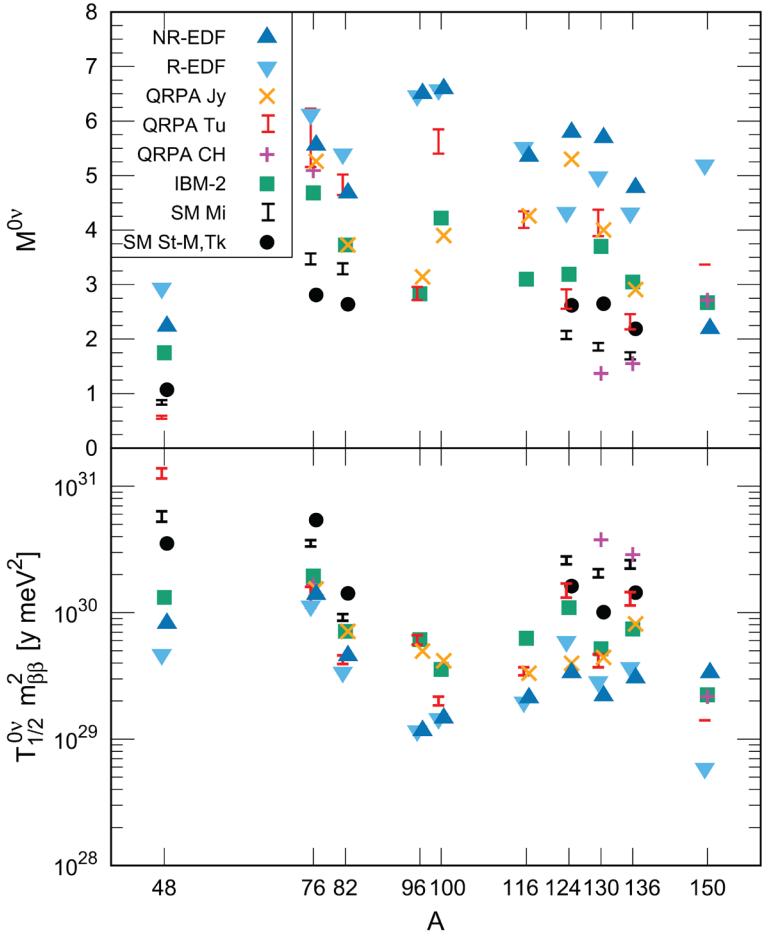
$0\nu\beta\beta$- NME(S)

- A convenient parametrization

$$M^{0\nu} = g_A^2 \left(M_{GT}^{0\nu} - \left(\frac{g_v}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu} \right)$$

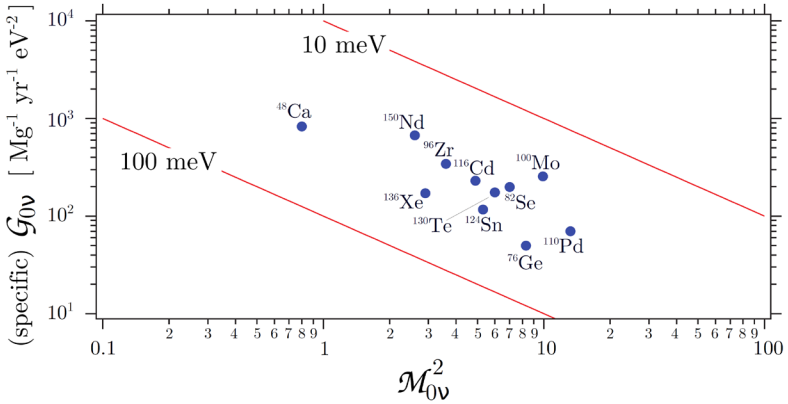
[F. Simkovic et al., Phys. Rev. C 60, 055502 (1999)]

- Factor 2 –3 uncertainty between nuclear models
- Ab-initio NMEs in lighter isotopes smaller than phenomenological NMEs
- **Observed β-decay rates in nuclei systematically smaller than for free neutrons →** Quenching of axial nucleon coupling gA?
- Gysbers et al., Nature Physics 15 (2019) 428: "our work suggests that a complete and consistent calculation without a phenomenological quenching of the axial-vector coupling g_A is called for"
- ...more on F.Deppisch, "Double Beta Decay: Theory Review" @TAUP2021



Engel J,Menendez J. Rept. Prog. Phys. 80 (2017)

Figure 5. Top panel: nuclear matrix elements ($M^{0\nu}$) for $0\nu\beta\beta$ decay candidates as a function of mass number A. All the plotted results are obtained with the assumption that the axial coupling constant g_A is unquenched and are from different nuclear models: the shell model (SM) from the Strasbourg–Madrid (black circles) [113], Tokyo (black circle in ^{48}Ca) [114], and Michigan (black bars) [82] groups; the interacting boson model (IBM-2, green squares) [109]; different versions of the quasiparticle random-phase approximation (QRPA) from the Tübingen (red bars) [115, 116], Jyväskylä (orange times signs) [81], and Chapel Hill (magenta crosses) [117] groups; and energy density functional theory (EDF), relativistic (downside cyan triangles) [118, 119] and non-relativistic (blue triangles) [120]. QRPA error bars result from the use of two realistic nuclear interactions, while shell model error bars result from the use of several different treatments of short range correlations. Bottom panel: associated $0\nu\beta\beta$ decay half-lives, scaled by the square of the unknown parameter $m_{\beta\beta}$.



Sterile Neutrinos

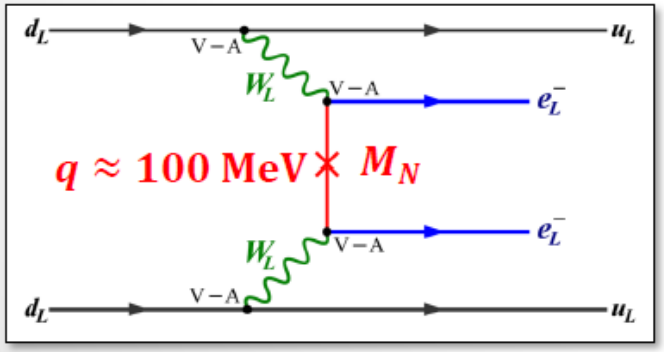
- Masses lighter than ≈ 100 MeV

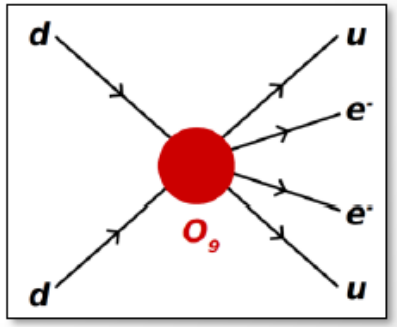
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- Masses larger than ≈ 100 MeV

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2 \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

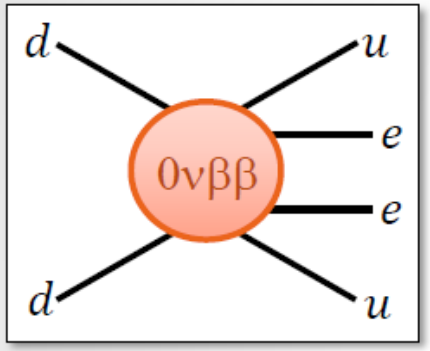
- Short-distance on nuclear scale



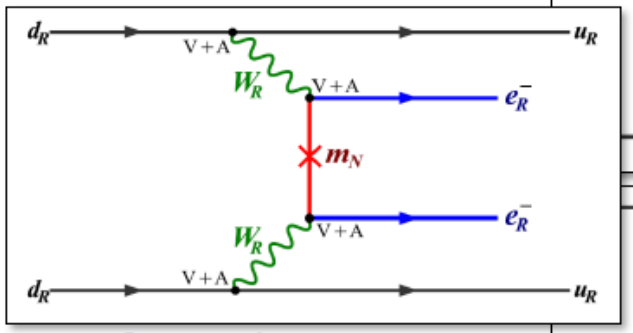


New Physics and $0\nu\beta\beta$

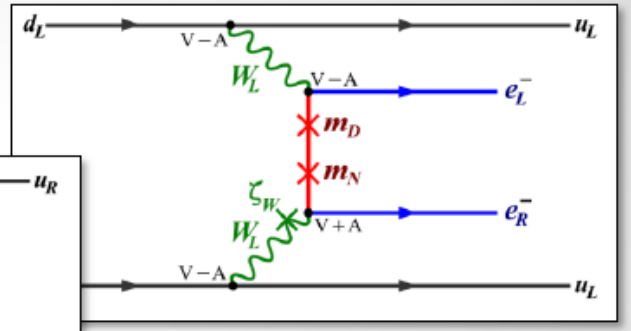
- Plethora of New Physics scenarios

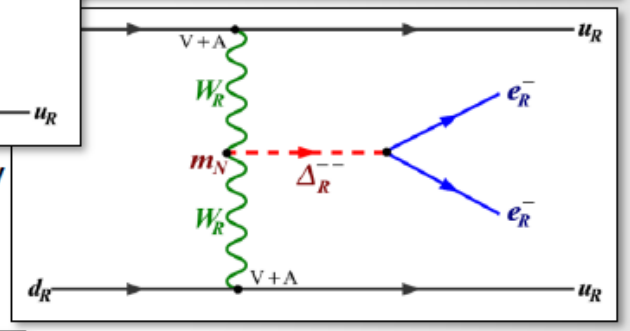


=



Left-Right Symmetry

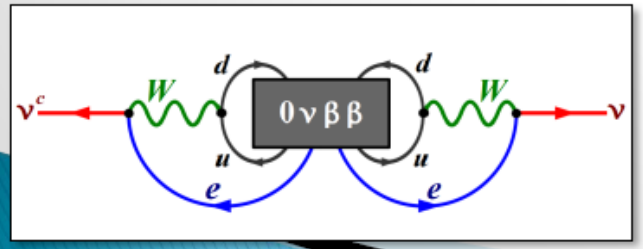


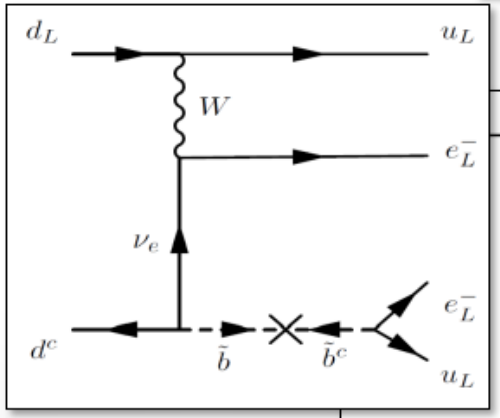


$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

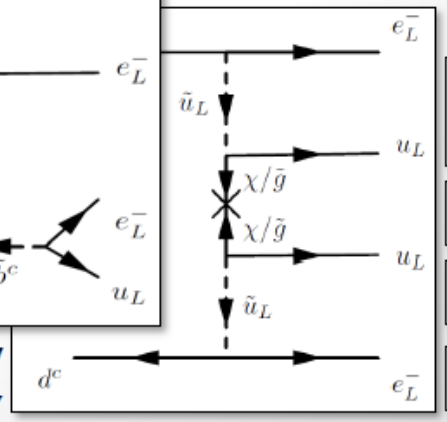
- Neutrinos still Majorana

Schechter, Valle
Phys. Rev. D25 (1982) 2951





R-Parity Violating SUSY



Extra Dimensions

Majorons

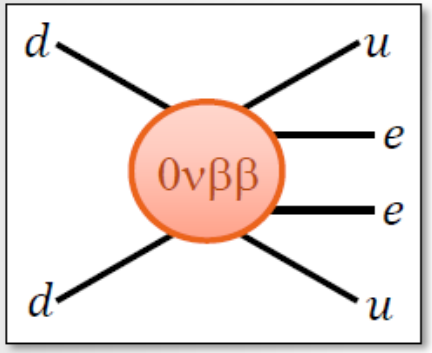
Leptoquarks

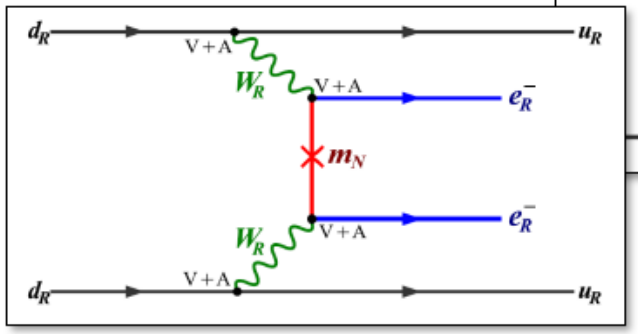
...

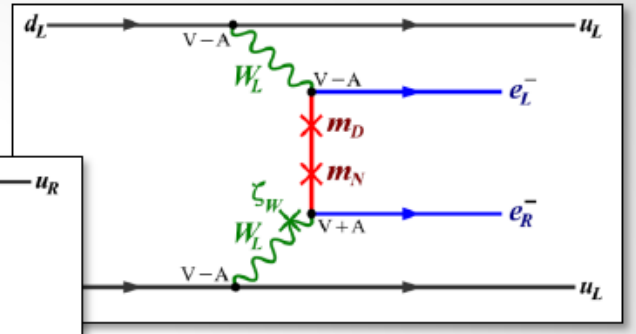
New Physics and $0\nu\beta\beta$

University College London

- Examples in Left-Right Symmetry





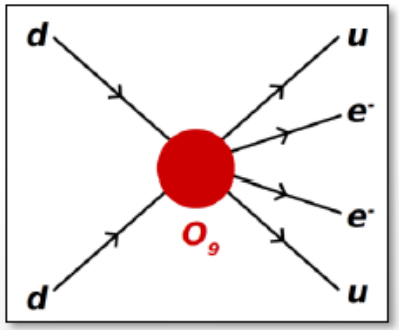


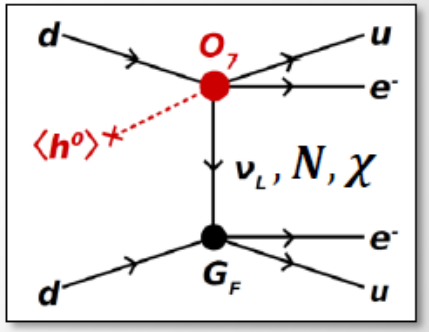
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

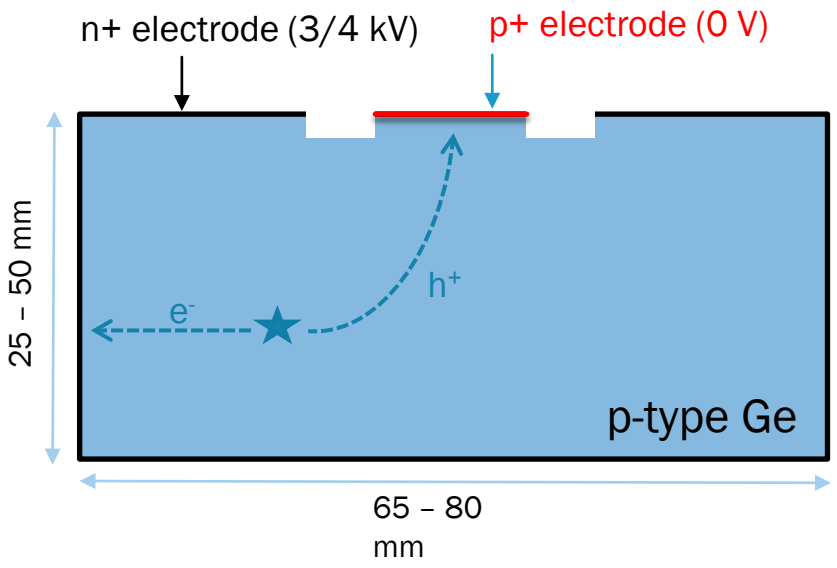
$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes LNV at the TeV scale and above



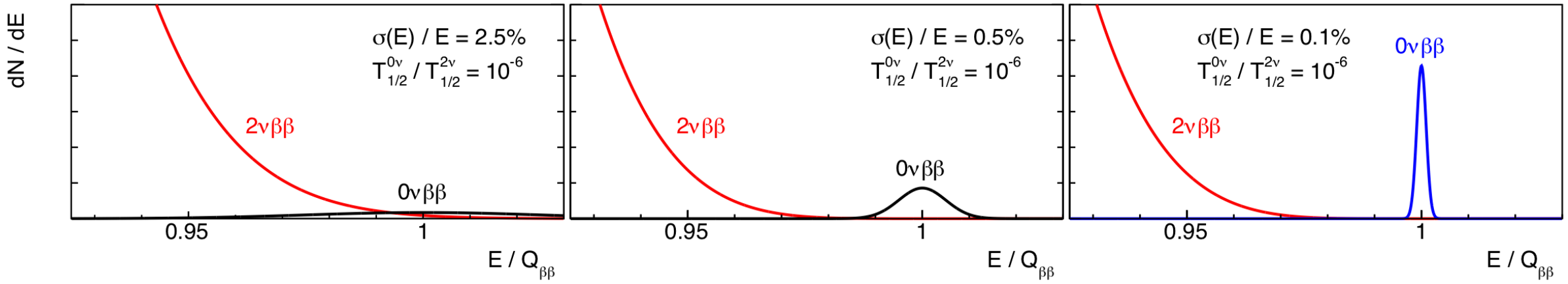


SEARCHING FOR $0\nu\beta\beta$ OF ^{76}GE

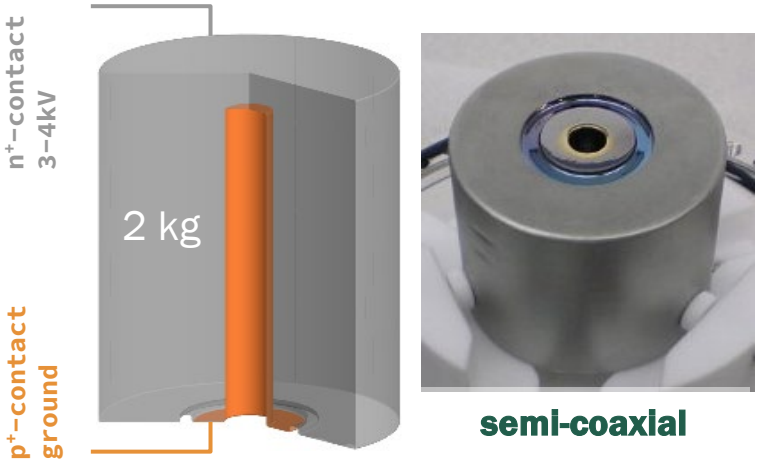


Why high purity Ge detectors?

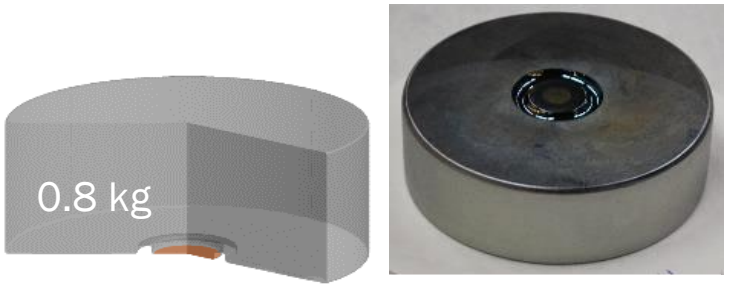
- source = detector → high efficiency
- radio-pure → no intrinsic background
  [Astropart.Phys. 91 (2017) 15-21]
- high density → e^- range of 1-2 mm
- semiconductor → $\sigma(E)/E < 0.1\%$ at $Q_{\beta\beta}$
- enrichment up to 88% in ^{76}Ge
  [Eur. Phys. J. C 79, 978 (2019)]



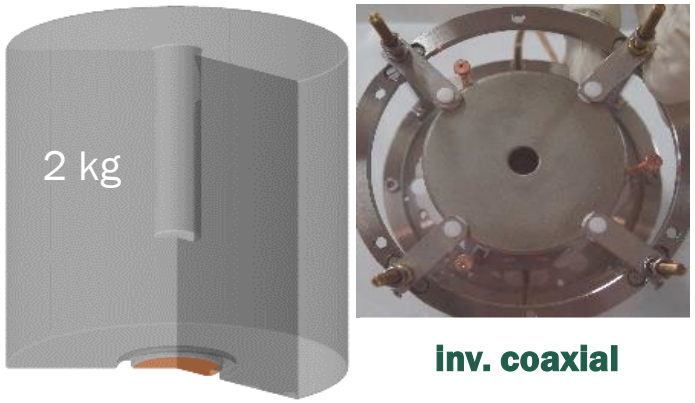
THE GERDA EXPERIMENT



semi-coaxial



BEGe



inv. coaxial

7 (*6) ^{enr}**Coax** (15.6 kg, *14.6 kg)

+30 ^{enr}**BEGe** (20 kg)
+Lar instrumentation

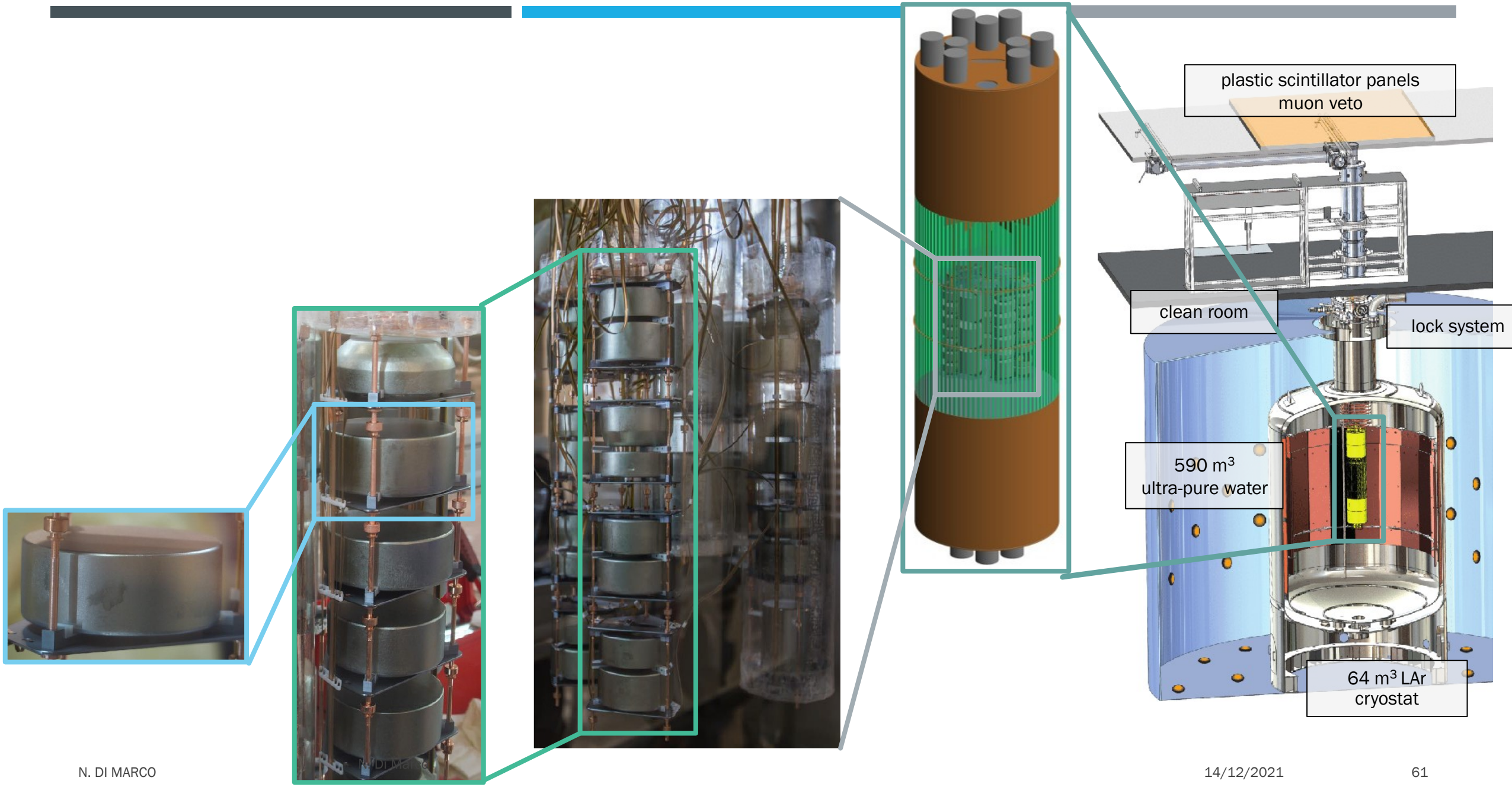
+ 5 ^{enr}**Inverted coax** (9.6 kg)
+ improved fiber geometrical coverage

Phase I

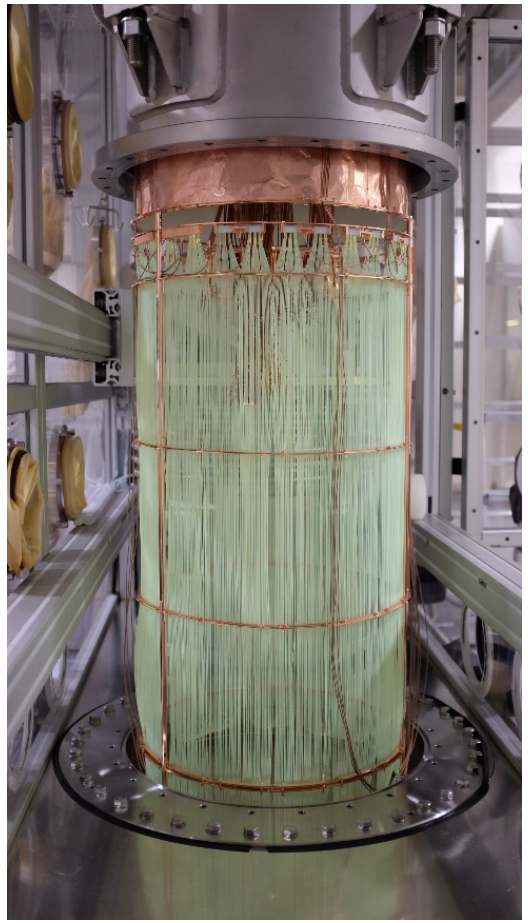
Phase II [Eur. Phys. J. C 78 (2018) 388, EPJC 75, 506 (2015)]

Phase II post 2018 upgrade (*)

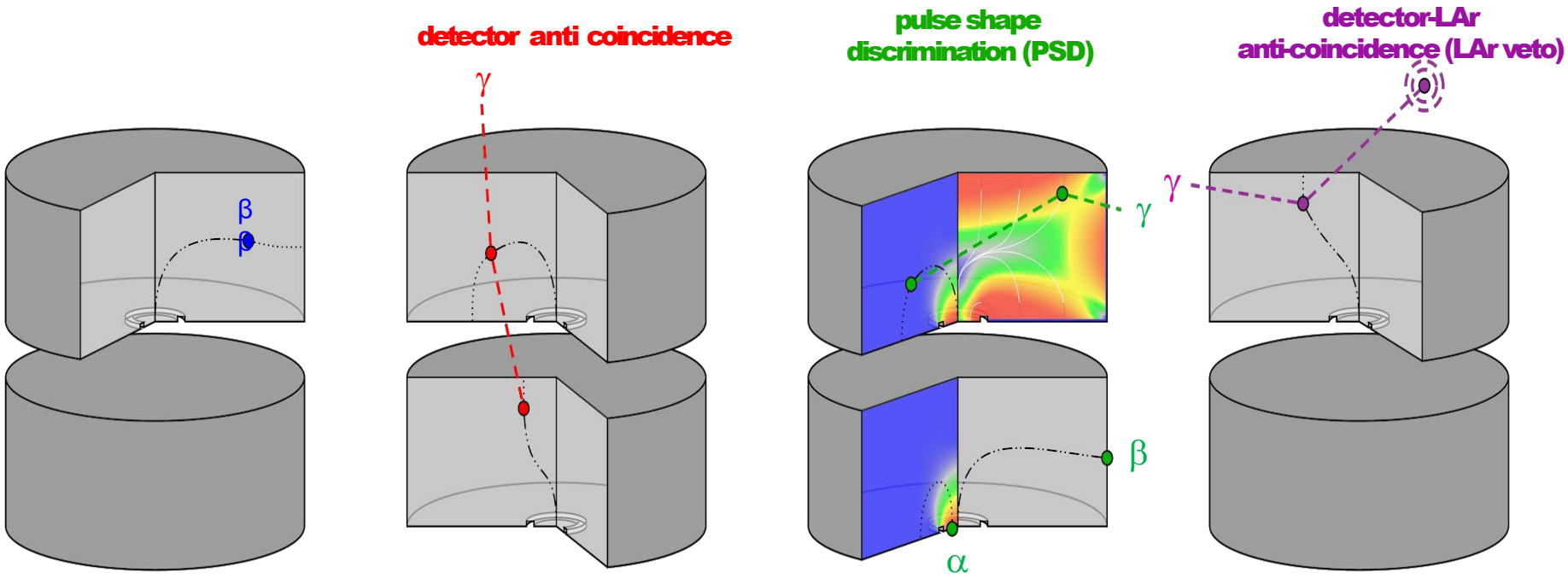
THE GERDA EXPERIMENT



THE GERDA EXPERIMENT



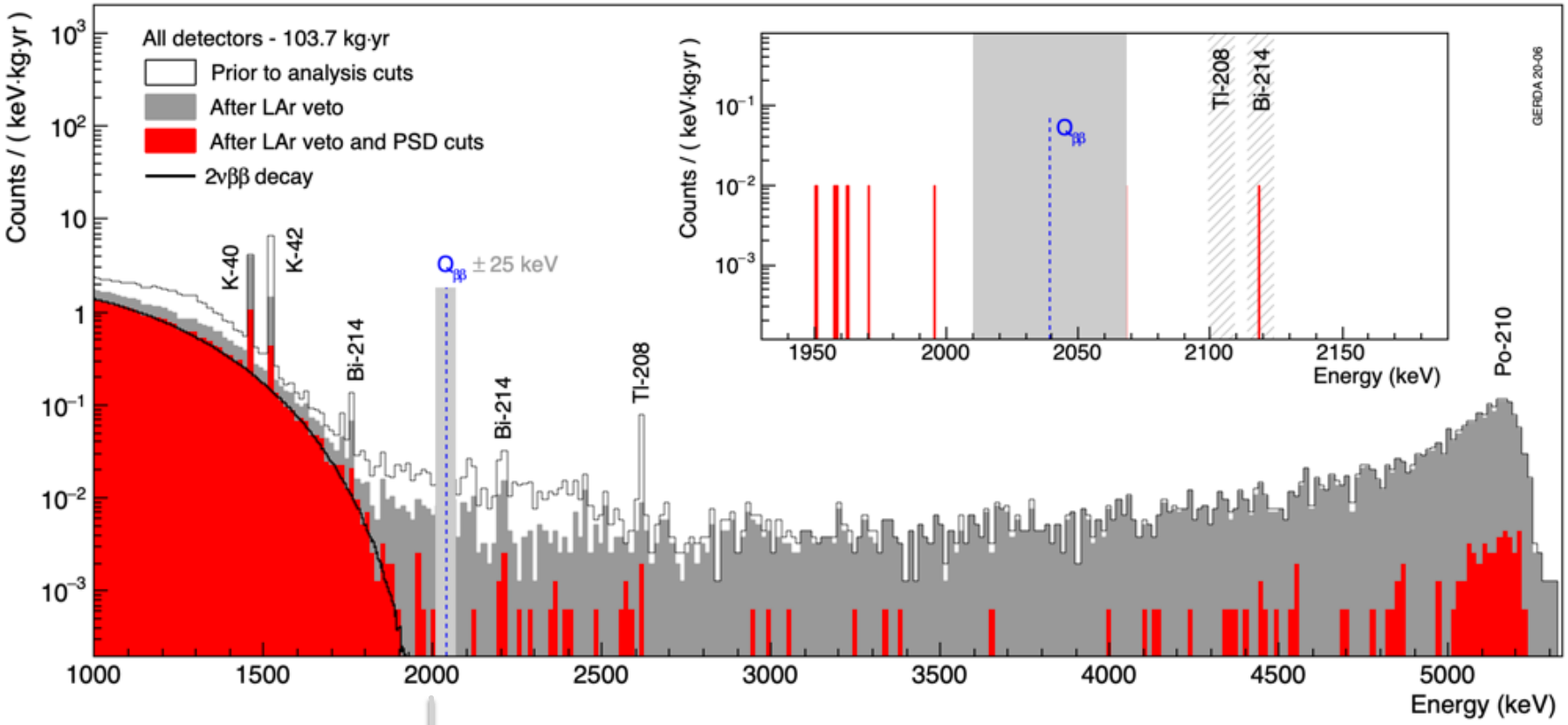
GERDA - ACTIVE BACKGROUND SUPPRESSION



Discriminate **point like** (single site) **ββ** topology from:

- **multi-detector** interactions
- **multi-site/surface** interactions
- interactions with **coincident energy deposition** in surroundings

GERDA - ACTIVE BACKGROUND SUPPRESSION – LAR&PSD



Blinded region ±25 keV @ $Q_{\beta\beta}$

GERDA - STATISTICAL ANALYSIS

ROI:
[1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP)

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

Phase II (103.7 kg yr):

$T^{0\nu}_{1/2} > 1.5 \cdot 10^{26}$ yr @ 90% C.L. (Frequentist)

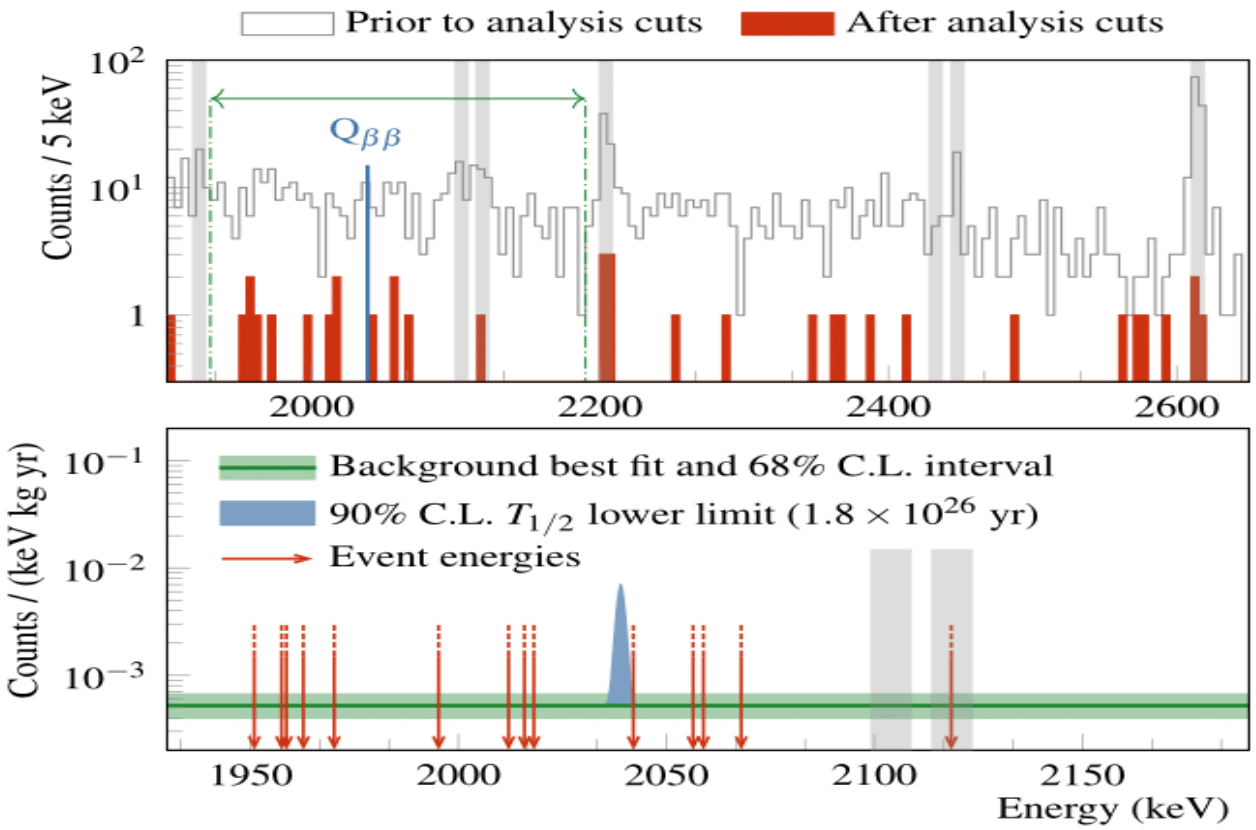
Phase I + Phase II (127.2 kg yr):

$T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr @ 90% C.L. (Frequentist)

The limit coincides with the sensitivity, defined as the median expectation under the no signal hypothesis

$T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ yr @ 90% C.L. (Bayesian)

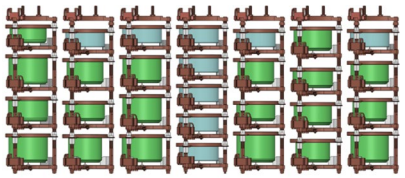
[GERDA, *Phys Rev Lett* **125** (2020), 252502]



MAJORANA RUN CONFIGURATION & TIMELINE

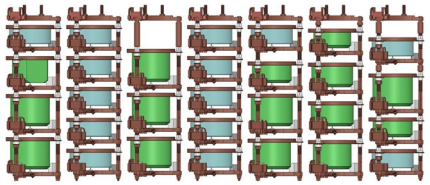
Julieta Gruszko@TAUP 2021

Jun. 2015 - Module 1:
16.8 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge



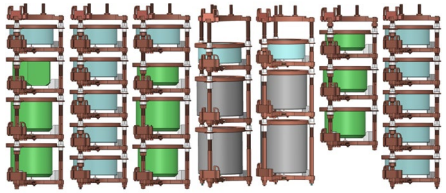
Deploy Module 1 in shield

Aug. 2016 - Module 2:
12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge



Deploy Module 2 in shield

Sept. 2020 - Module 2 Upgrade:
14.1 kg (13) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

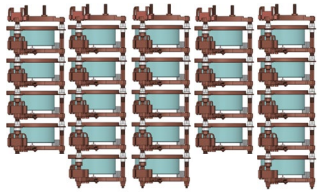


6.7 kg (4) as ICPC

Cable/Connector Upgrade of Module 2
Removed 5 PPC detectors for LEGEND Testing
Installed 4 LEGEND ICPC Detectors

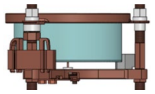
Mar. 2021:
Stopped ^{enr}Ge Operation
Removed all ^{enr}Ge for LEGEND-200

May 2021 - Module 2:
14.3 kg (23) ^{nat}Ge

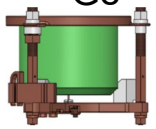


Continuing operation with natural Ge detectors

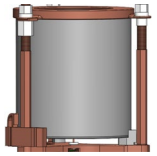
Mirion/Canberra
BEGe
^{nat}Ge



Ortec
PPC
^{enr}Ge



Ortec ICPC
^{enr}Ge



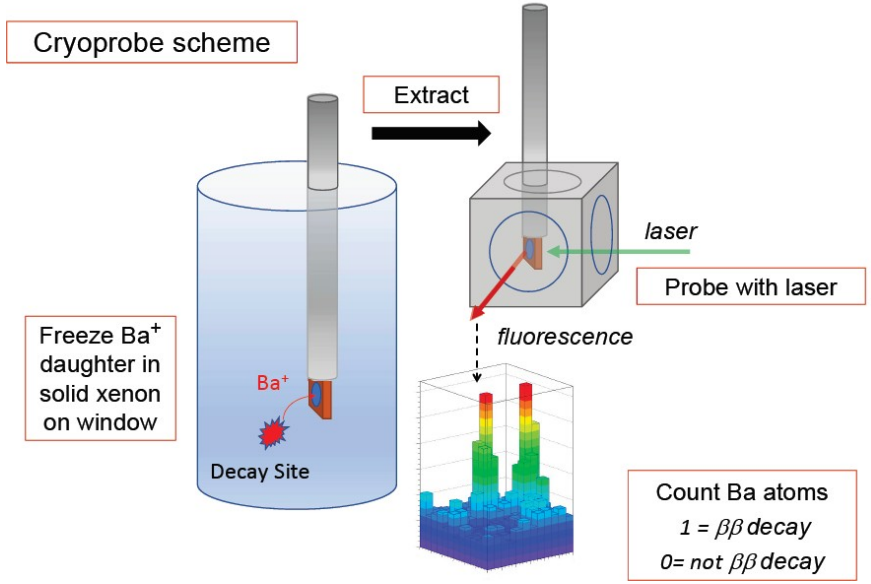
BOLD2: Barium Tagging can change the game

Imaging of single Ba atoms and ions in solid xenon for barium tagging in nEXO

James Todd, David Fairbank, and William Fairbank
Colorado State University and the nEXO Collaboration

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

Barium tagging gives potential to eliminate all but 2νββ backgrounds in neutrinoless double beta decay experiments.



Images of Ba atoms and Ba^{+} ions at few atom level

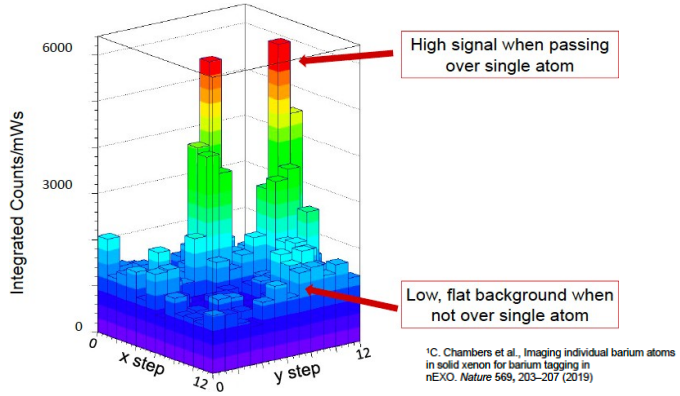
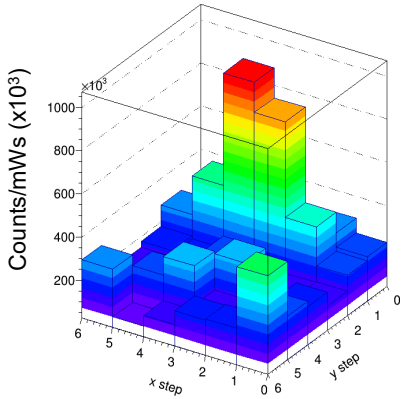
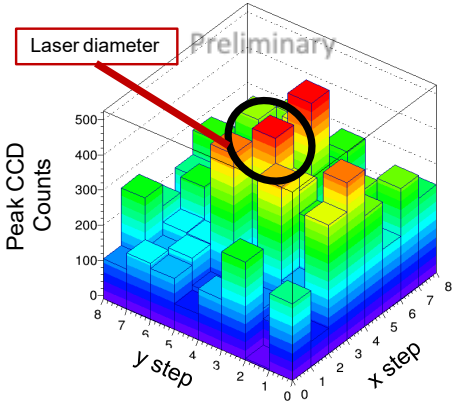


Image of two barium atoms in the single vacancy matrix site.[1]



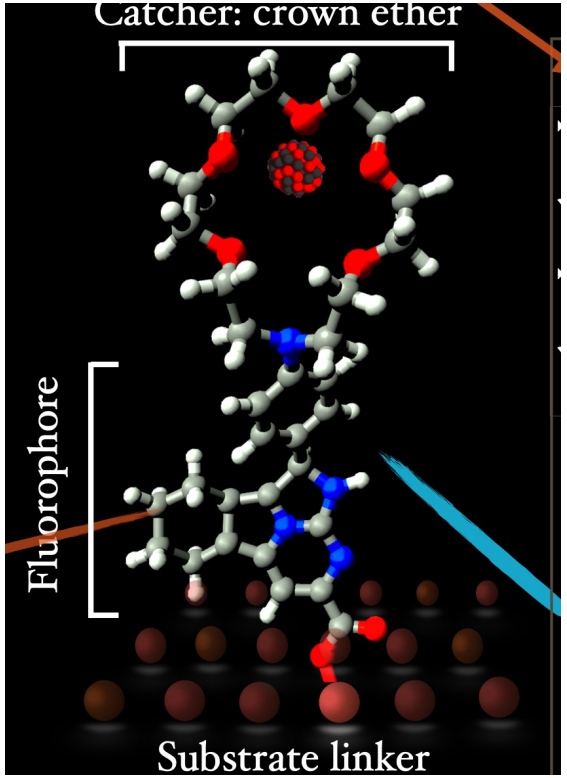
Step size: 4μm
Single Ba image in 7-vacancy site



Scan image of Ba^{+} deposit looking at 530 nm Ba^{+} emission, with ~4 Ba^{+} ions deposited in entire scan area.

https://www.nature.com/articles/s41586-019-1169-4

Barium Tagging can change the game



The **NEXT** Collaboration's Big Idea:

Exploit *single molecule fluorescent imaging (SMFI)* to visualize a single barium ion as it arrives at the TPC cathode.

For ^{136}Xe, in gas phase, the daughter is ~100% $^{136}Ba^{++}$, perfect for using SMFI techniques.

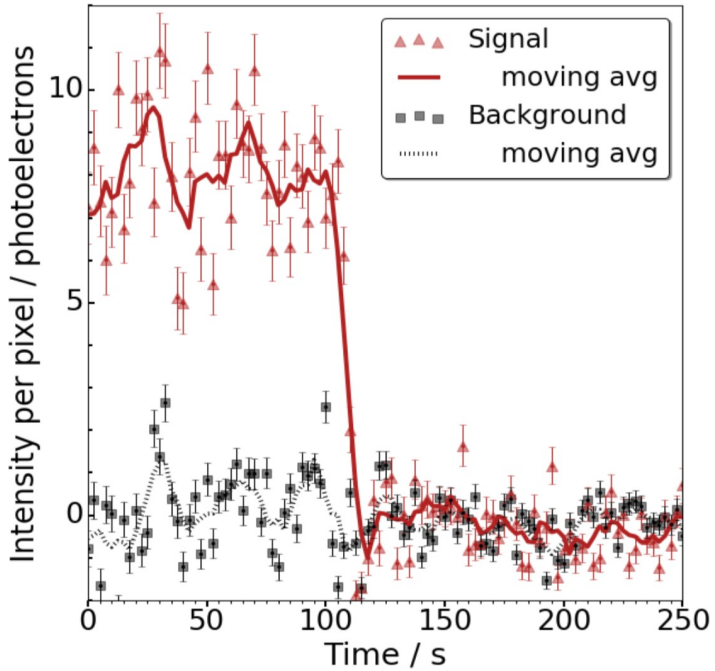
Goal: develop custom molecules that change luminous response after chelating Ba dications.

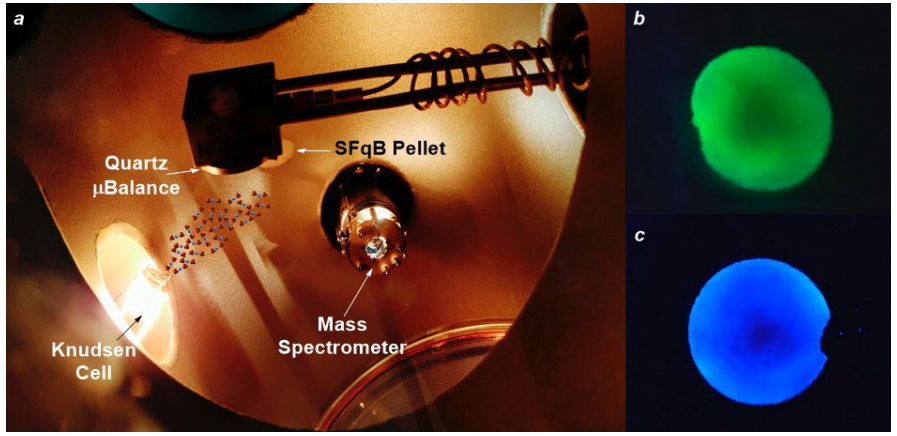
Molecules must (and do!) display high specificity to Ba^{++}

Common elements: crown ether + fluorophore + linker

Complementary approaches explored in US and Spain
Spain: molecule changes color strongly: green ➔ blue
Texas: molecule changes from non-luminous to luminous

Molecular engineering: predictive computations too!

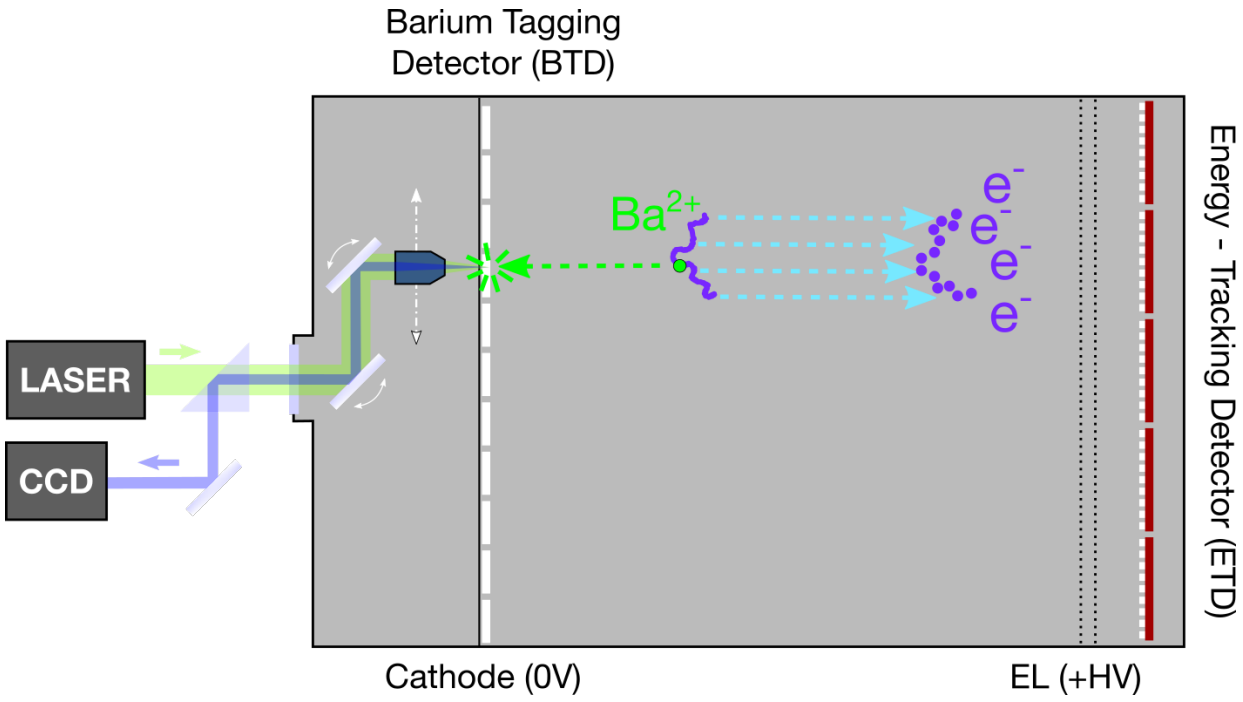


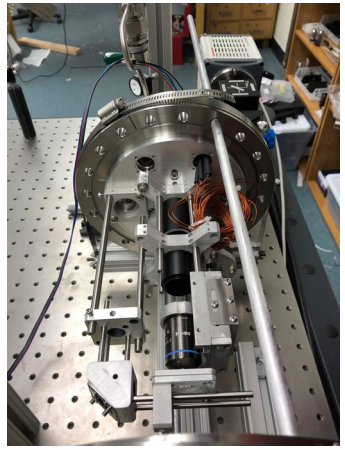


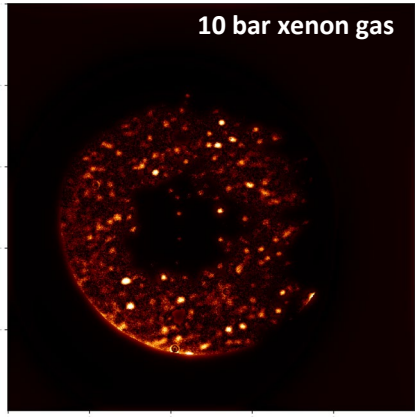
https://www.nature.com/articles/s41586-020-2431-5

https://journals.aps.org/prl/abstract/10.110 /PhysRevLett.120.132504

Barium Observation Light Detector (NEXT-BOLD)







- Predict arrival position of Ba2+ with windows of 1 cm/1ms
- Instrument full cathode or implement RF carpet
- Open gate to let Ba^{2+} pass just when it arrives to cathode. Thus coincidence between topology, energy and Ba^{2+} signal
- Unambiguous Ba^{2+} signature from color shift, photobleaching or both.

https://www.nature.com/articles/s41586-020-2431-5

https://arxiv.org/abs/2006.09494