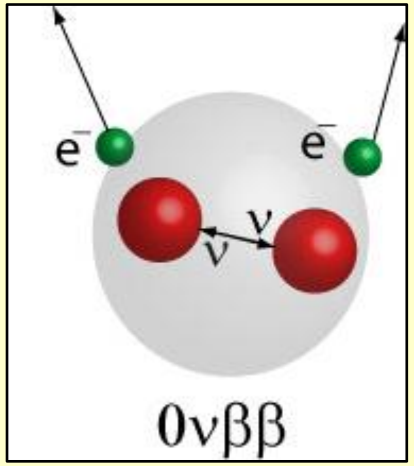
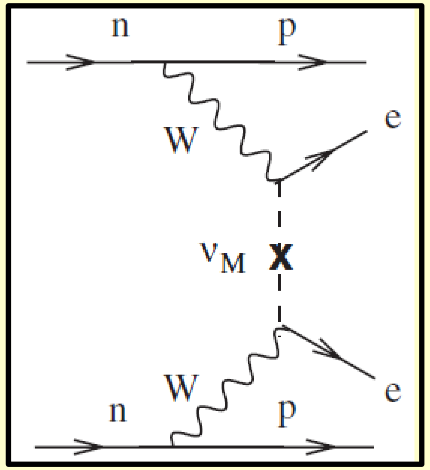
Probing the Nature of Neutrino

Vandana Nanal

Tata Institute of Fundamental Research

Mumbai, India

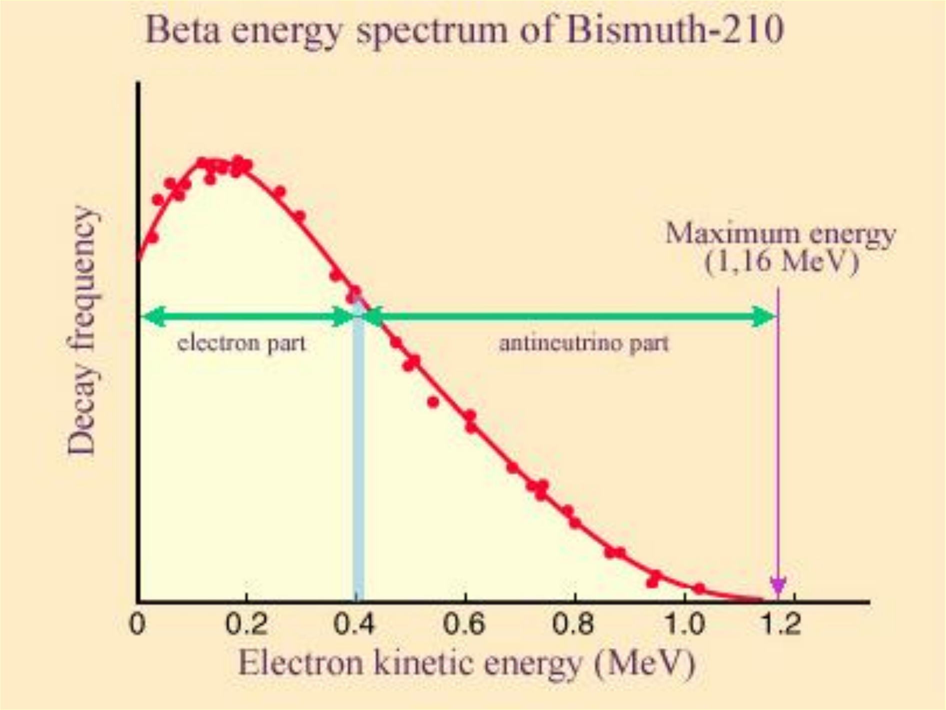




Plan

- What is Neutrinoless Double Beta Decay (NDBD)
- Experimental challenges
- Some recent results
- Indian effort – *TIN.TIN*
- Summary

Beta decay & birth of Neutrino

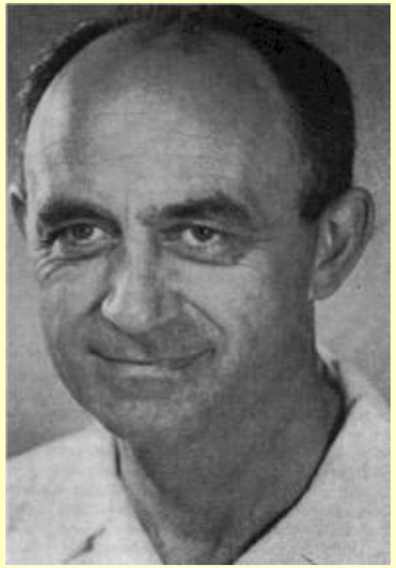


The puzzle of continuum spectra in beta decay

$$\boldsymbol{n \rightarrow p + e^{-} + ?\ + 0.78MeV}$$

$$\boldsymbol{(T_{1/2} \sim 10min)}$$

postulated by W. Pauli in 1930 mass-less spin ½ neutral particle



named as neutrino by E. Fermi (1933)
theory for β-decay (beginning of the standard model)

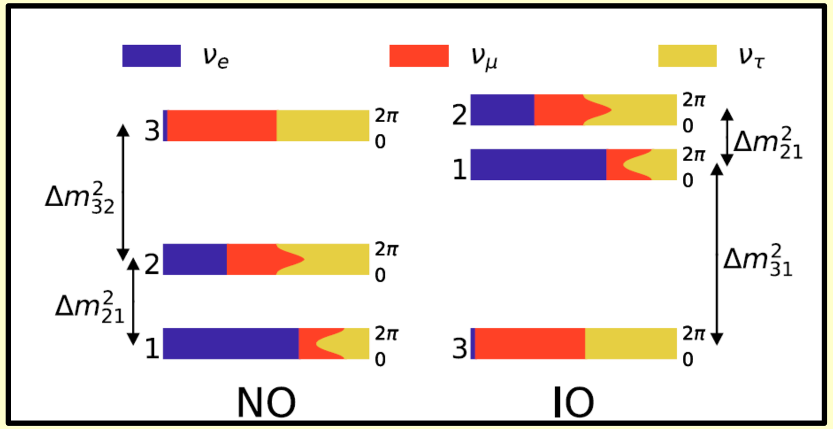
1956 :The first direct observation of the electron antineutrino from a nuclear reactor by F. Reines and C. Cowan

What we know about neutrino

- Mass eigen states (ν_1, ν_2, ν_3) and flavour eigen states (ν_e, ν_μ, ν_τ) are different
- Oscillation data → neutrino has nonzero mass
- Mass square differences Δm^2_{sol}, Δm^2_{atm}

What we don't know ….

Neutrino mass orderings



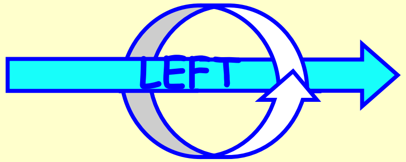
https://doi.org/10.3389/fspas.2018.00036.
arXiv:1806.11051 [hep-ph]

- Are ν their own antiparticles?
- Absolute mass of neutrino and mass ordering ?
- How many types of ν exist (more than 3)?

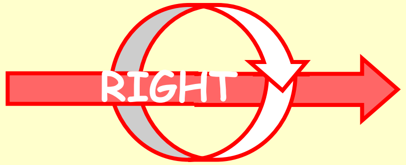
↳ *Physics beyond standard model ….*

Is neutrino a Majorana or Dirac particle ??

ν:

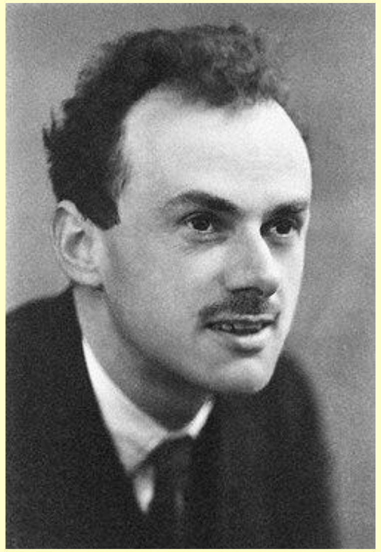


$\bar{\nu}$:



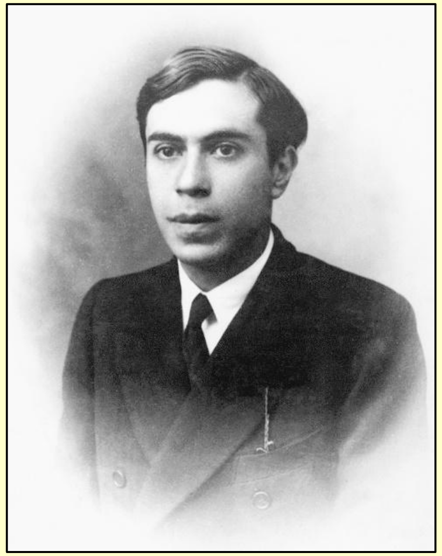
$\nu \neq \bar{\nu}$

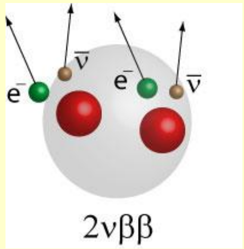
Dirac



$\nu = \bar{\nu}$

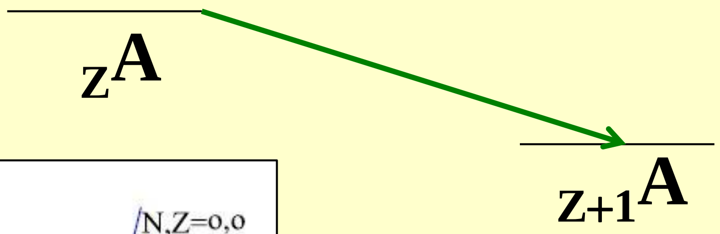
Majorana

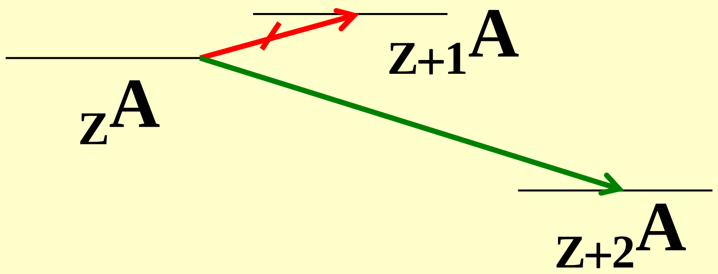


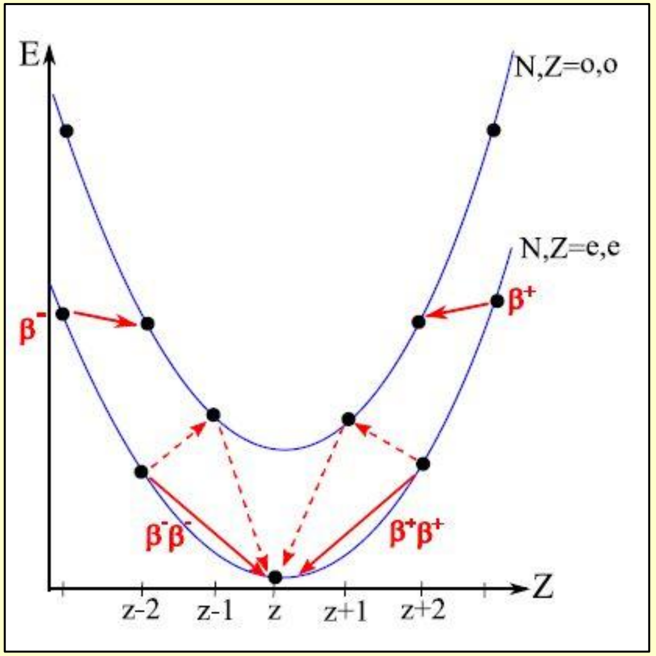


Nuclear Double Beta Decay early history

$n \rightarrow p + e + \bar{\nu}$







2nd order weak interaction normal beta decay ($\beta\nu$) suppressed by Q-value or J^{π}

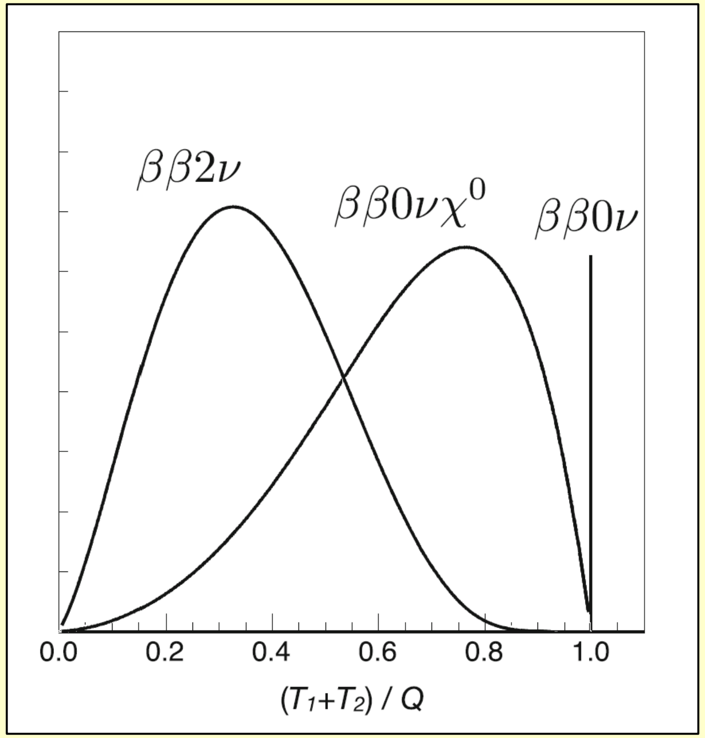
- First suggested by Maria Goeppert-Mayer (1935) $T_{1/2} \sim 10^{17}$ yrs
- Possible in only 35 even-even nuclei

- First geochemical observation of DBD $T_{1/2}$ (^{130}Te) ~1.2x 10^{21} yrs (Ingram & Reynolds, 1950)
- First DBD Experimental evidence in laboratory: ^{82}Se (Elliot et al. 1987)
- ***Seen in 13 cases till date ($T_{1/2} \sim 10^{18}$ to 10^{24} years)***

Neutrinoless Double Beta Decay

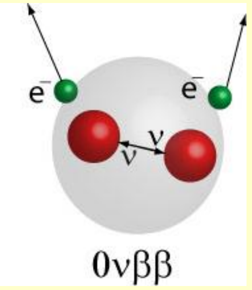
0νββ :

- Lepton number violating process
- occurs if neutrinos have mass and are their own antiparticles

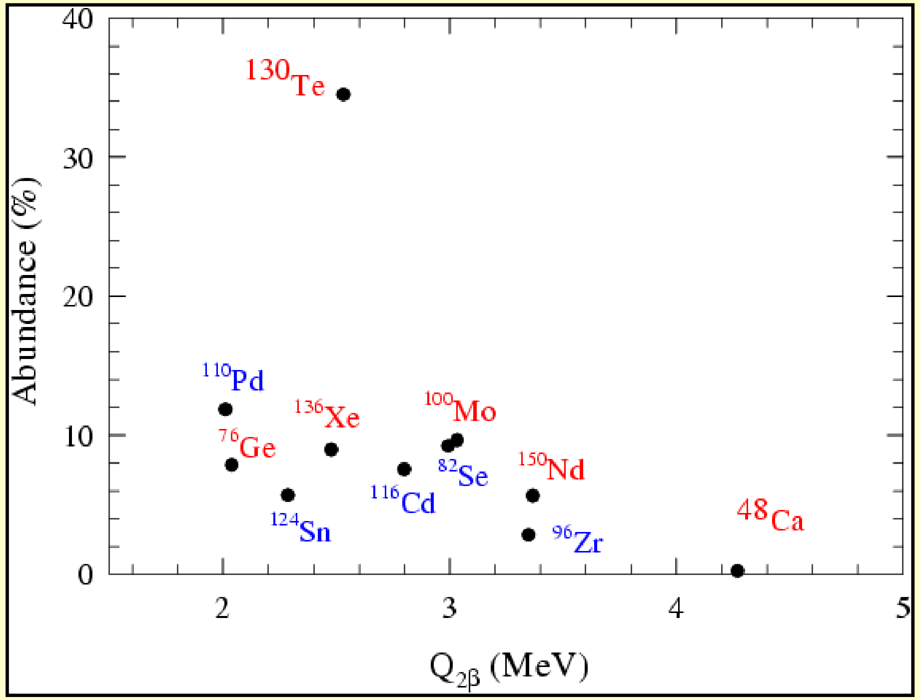


- **test the true nature of neutrino** *Dirac/Majorana*
- **the measurement of effective neutrino Majorana mass.**

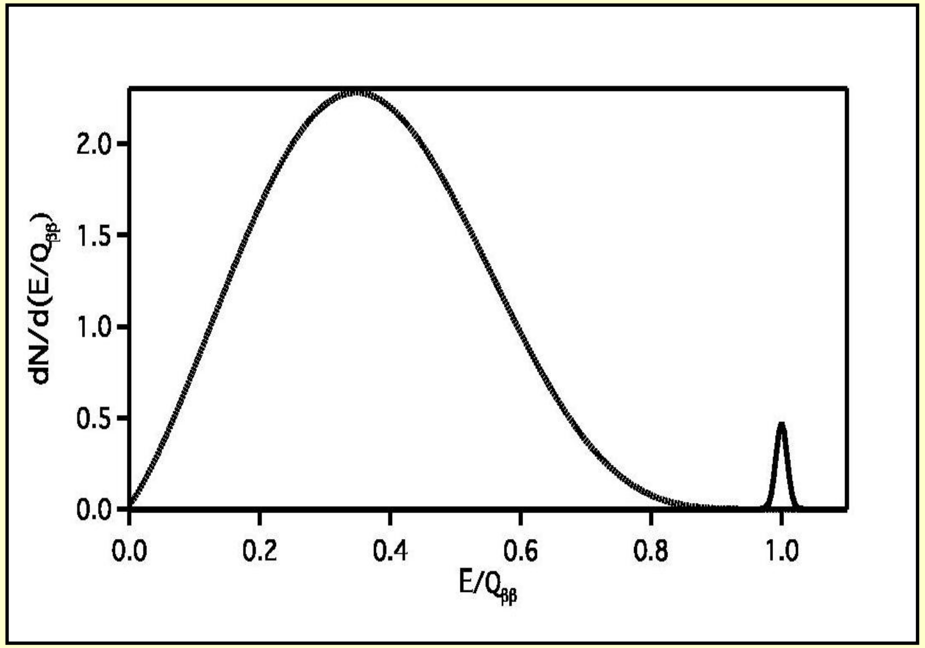
$$\Gamma_{0\nu2\beta} \propto [\text{phase-space } (\propto Q^5)] \times [\text{Nuclear ME}]^2 \times |\langle m_\nu \rangle|^2$$



How to Search for NDBD



High $Q_{2\beta}$ & abundance desirable



- Simultaneous emission of two electrons
- Constancy of the sum energy of the two emitted electrons

} Identification experiments

Sum energy peak ⇨ High resolution

Extremely low event rates ⇨ very large sources and detector

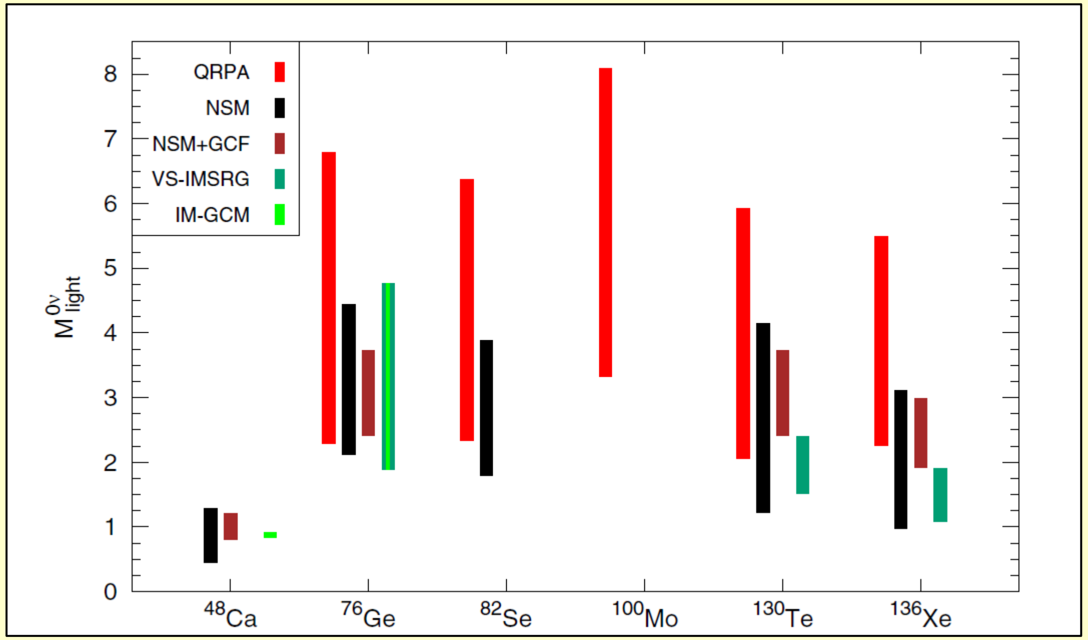
For a conclusive proof, 0νββ measurement in several isotopes is essential

Nuclear Matrix Elements

- Several nuclear models to calculate the NTME
  - Shell-model and variants , QRPA and extensions, Alternative models
- The NTME ($M_{2\nu}$) is sensitive to details of the nuclear structure
  - Spectroscopic properties of the initial and final nucleus
  - Pairing and Deformation

Observed physical properties of nuclei: ***Test of nuclear models***

Charge exchange reactions, transfer reactions, Neutrino cross section, EM transitions to IAS etc.



Experiments to constrain NTME are essential

Uncertainty in estimated neutrino mass can be large due to uncertainty in NTMEs.

J. J. Gómez-Cadenas et al.
https://doi.org/10.1007/s40766-023-00049-2

Experimental Considerations

- *Active source (DBD nuclei integral part of the detector)*
- *Passive Source (DBD source external to the detector)*

$$T_{1/2} \sim \frac{\ln 2 \bullet N_A \bullet M \bullet i \bullet \varepsilon \bullet t}{A(B\Delta E t)^{1/2}}$$

B :background (cts/keV/yr)
ΔE : energy resolution of the detector
t : data taking period
i : isotopic abundance of the element
ε : detection efficiency

$$N_{bkg} = B(c/kev/t) \bullet \Delta E \bullet t$$

$$N_{0\nu\beta\beta} \sim \sqrt{N_{bkg}}$$

Present Status

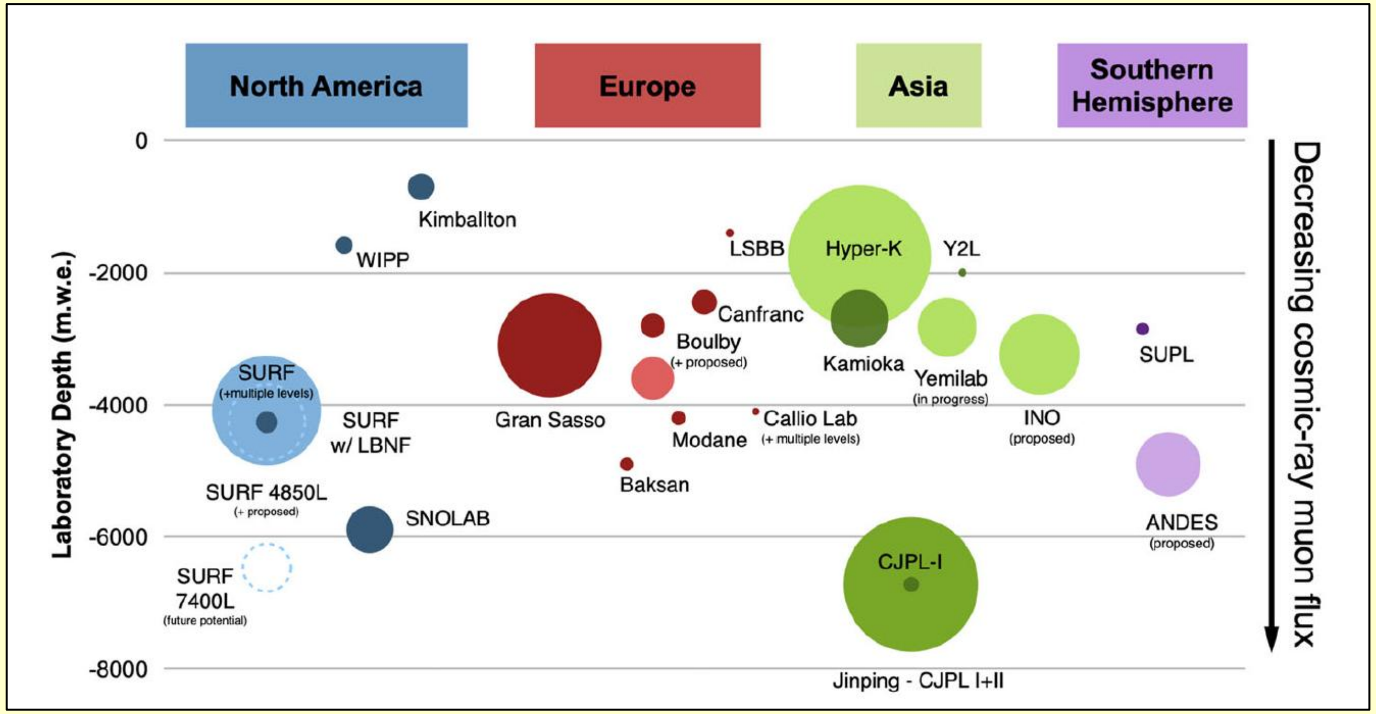
•2νββ detected in several (~13) nuclei, half life measured.
•Improvement in sensitivity possible by background reduction in some cases
•No 0νββ observed

Several experiments ~10-100 kg; $T_{1/2} \sim 10^{24}$- 10^{25} years, $\langle m_\nu \rangle \sim 0.75$ eV
Many new experiments (~ton scale) are planned/proposed, R&D in progress

Experimental Considerations

Background reduction

- Underground location (reduce cosmic ray background)



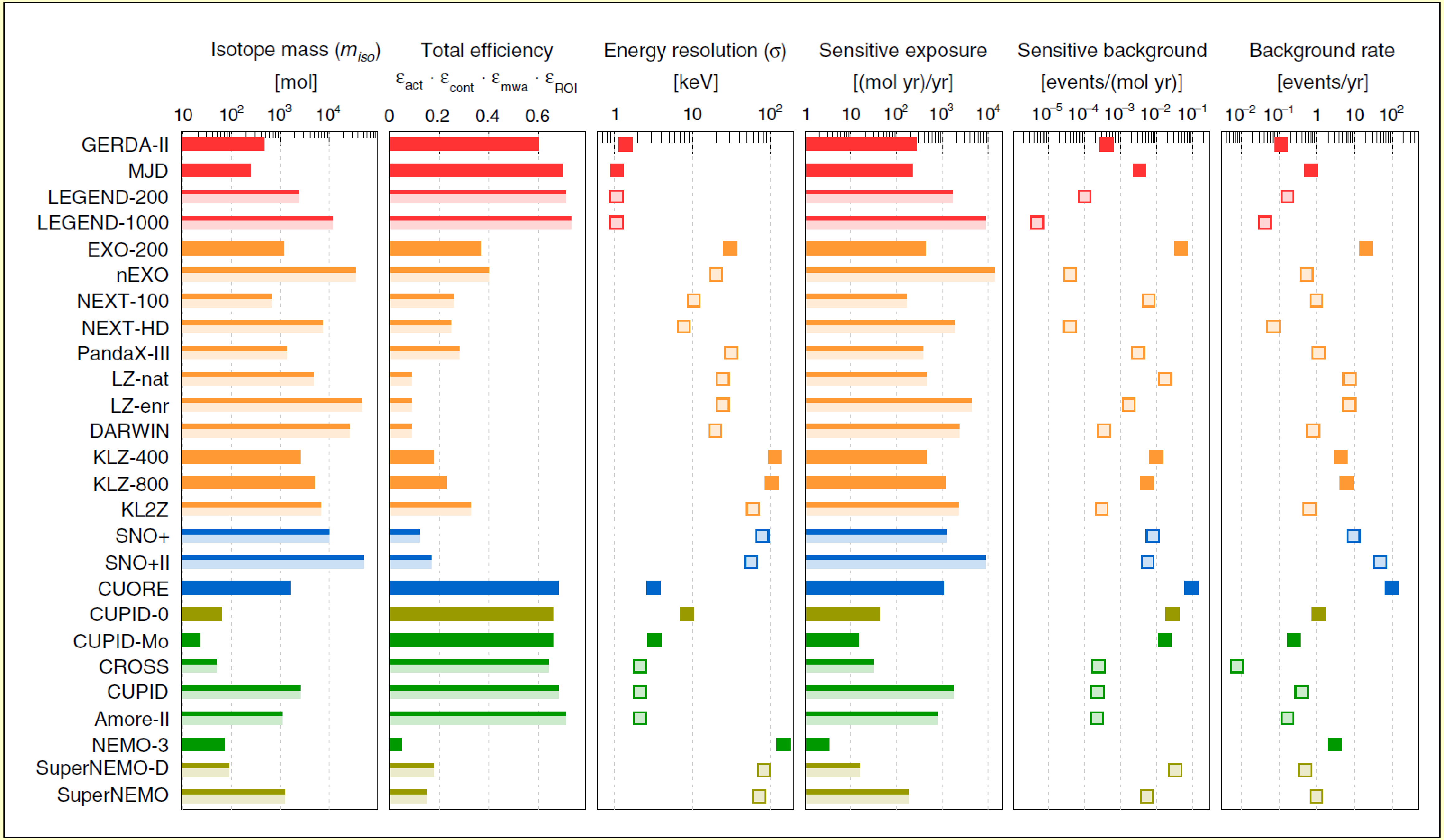
J. J. Gómez-Cadenas et al. https://doi.org/10.1007/s40766-023-00049-2

- Careful choice of materials (detector & environs- $^{235,238}U$, ^{232}Th,^{40}K, radiative impurities) and shielding

  Natural radioactivity $T_{1/2}$~ 10^9- 10^{10} yrs

- Electronic rejection of background events
- Neutron background minimization (U/Th induced and muon induced)

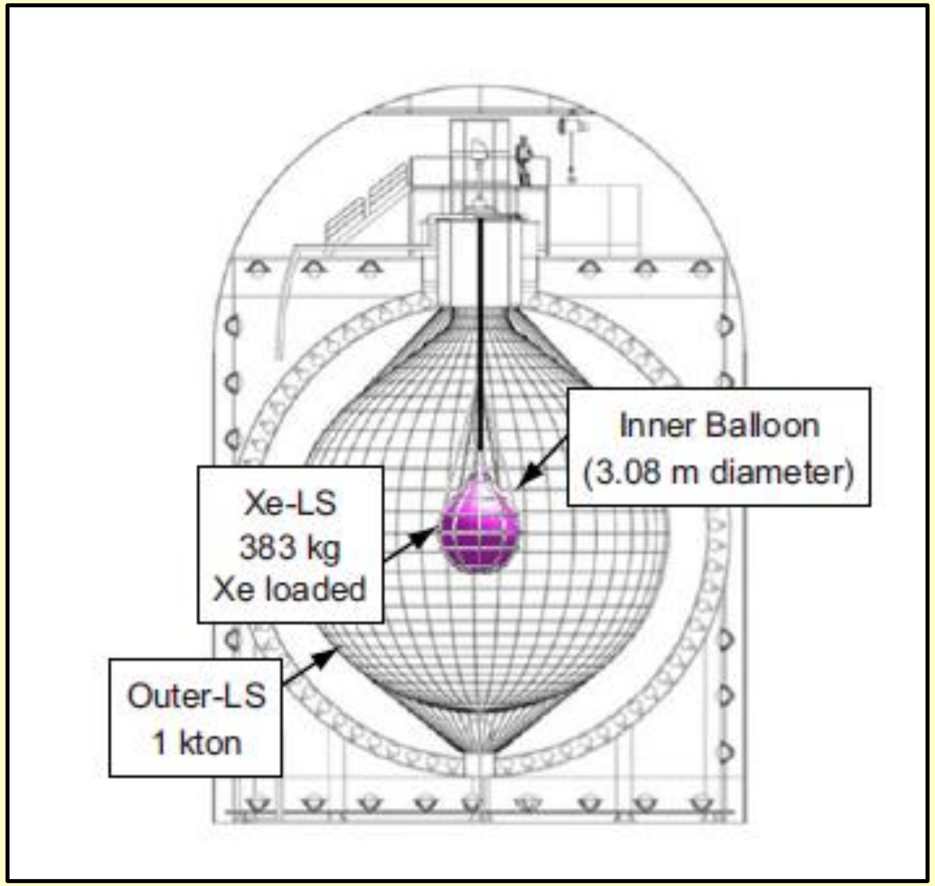
A glance at global effort for NDBD search



Matteo Agostini et al, DOI: 10.1103/RevModPhys.95.025002

Kamland-Zen (^{136}Xe)

Located in Japan (2700 mwe)



arXiv:2203.02139

Liquid Xenon loaded scintillator

~91% enriched

Water Cerenkov for muon veto

Resolution ~ 4%

Phase I : Background in the ROI limited by ^{110m}Ag

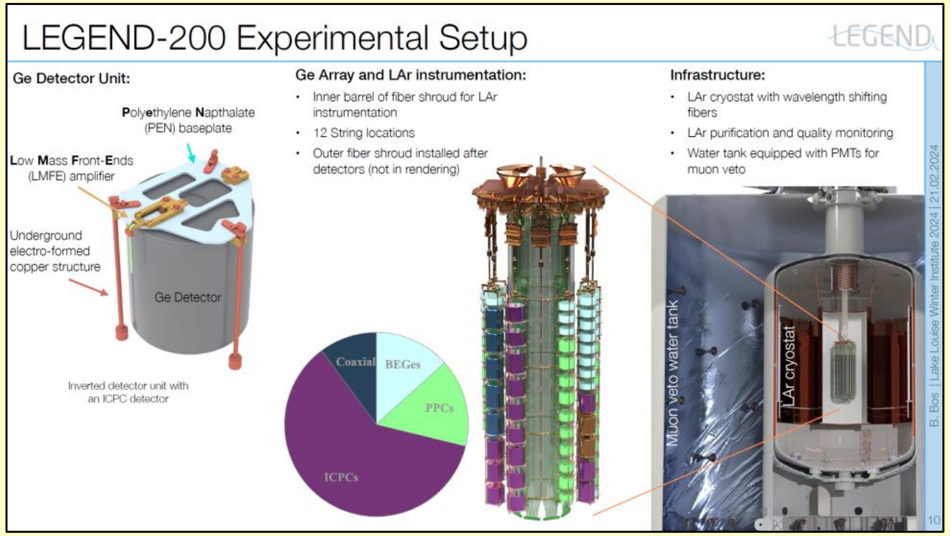
Phase II: after purification with improved background

Kamland Zen 800: $T_{1/2} > 2.3 \times 10^{26}$ yr (90% C.L.), effective neutrino mass 36-156 meV

LEGEND (^{76}Ge)

The Large Enriched Germanium Experiment for Neutrinoless double-beta Decay

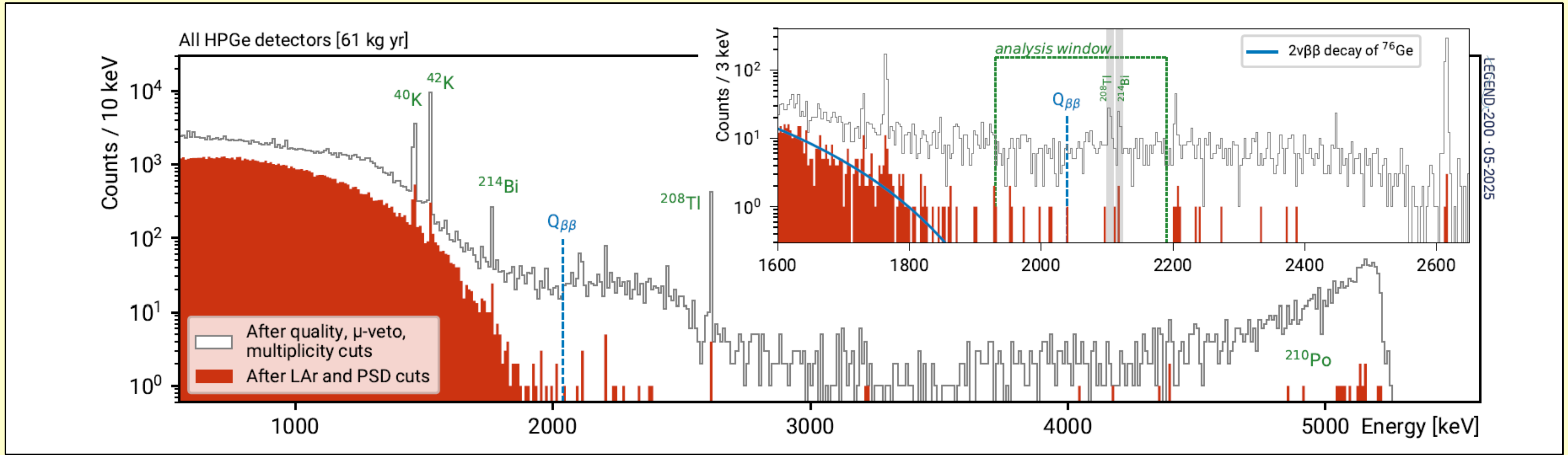
^{76}Ge based double-beta decay experimental program (ton scale enriched Ge) discovery potential : half-life > 10^{28} years



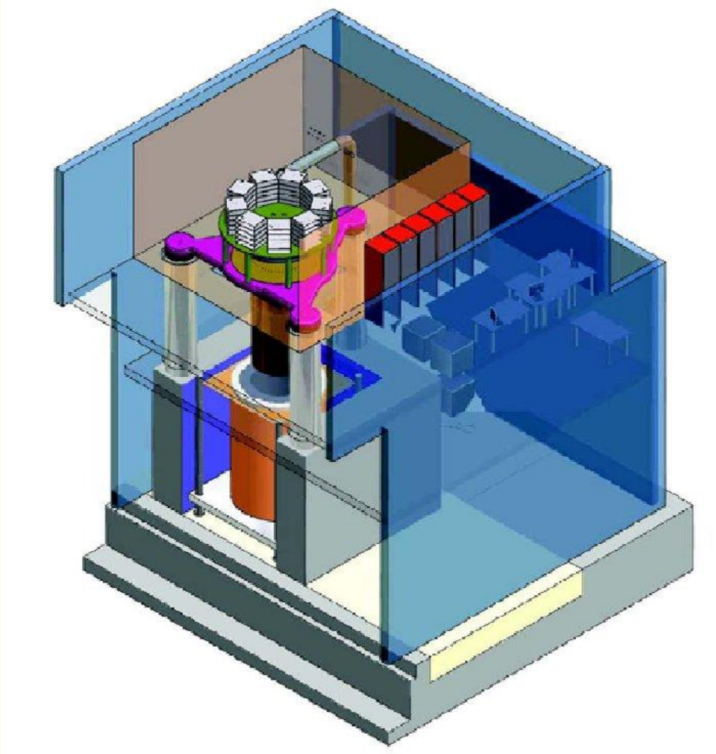
Background : $0.5^{+0.3}_{-0.2}$ cts / (keV ton yr)

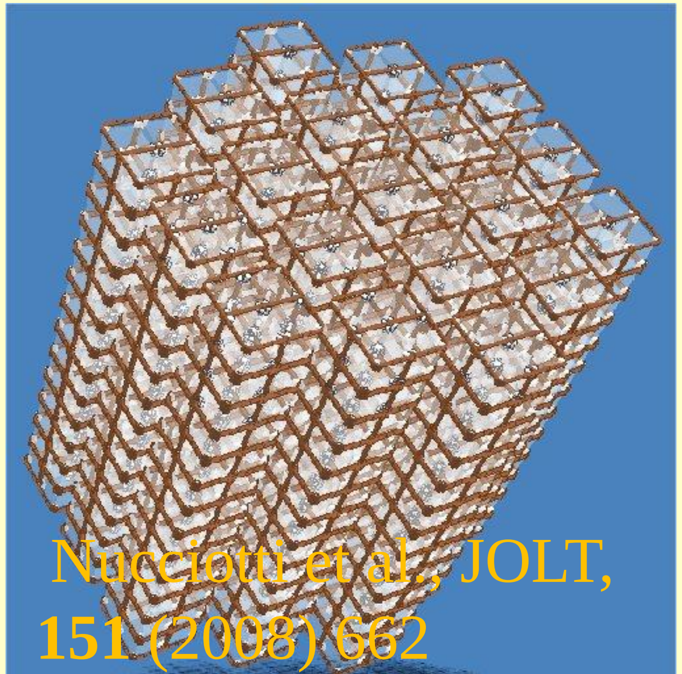
$m_{\beta\beta} < 70–200$ meV

arXiv:2505.10440v1 [hep-ex]



Cryogenic Underground Observatory (for) Rare Events



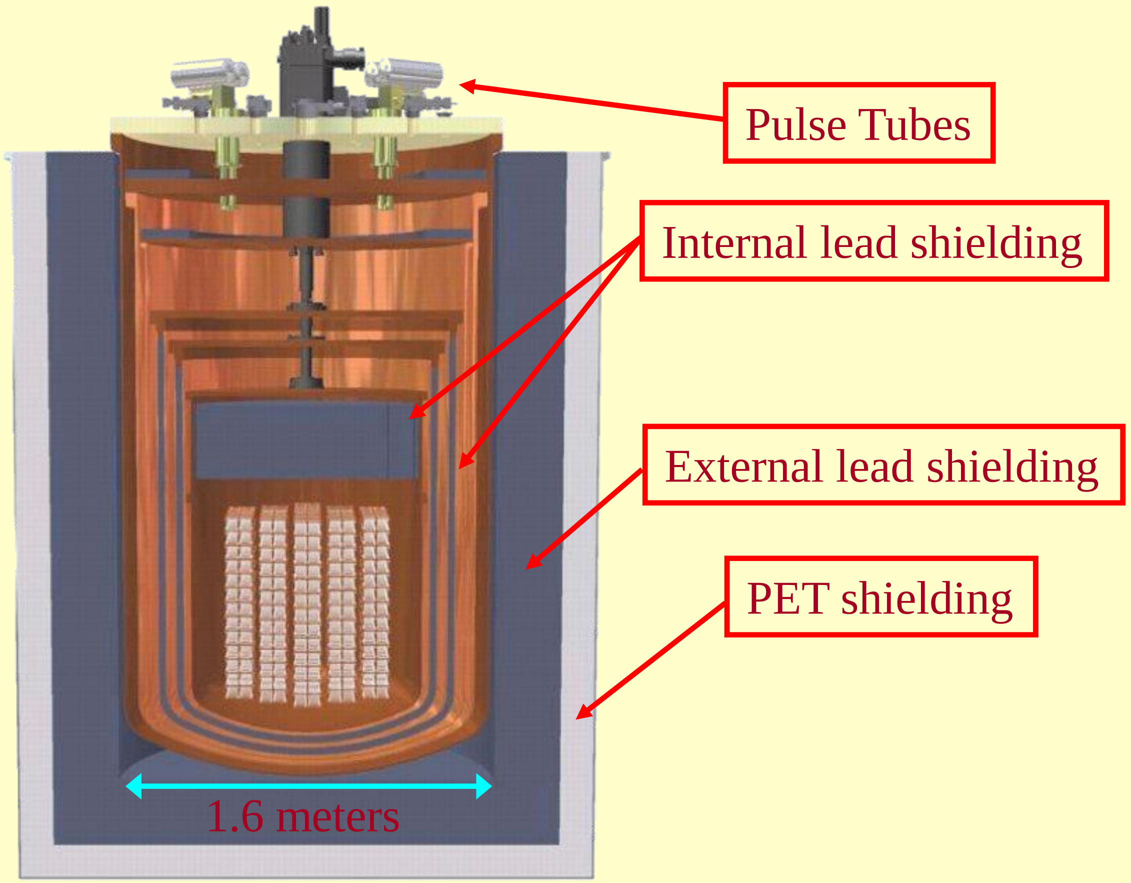


$T_{1/2}^{0\nu\beta\beta} > 2.2 \times 10^{25}\, y$ (90% C.L.),

$\langle m \rangle < 0.090\text{-}0.305$ eV

Nature ***604***, *53–58 (2022)*

M = 0.75 ton

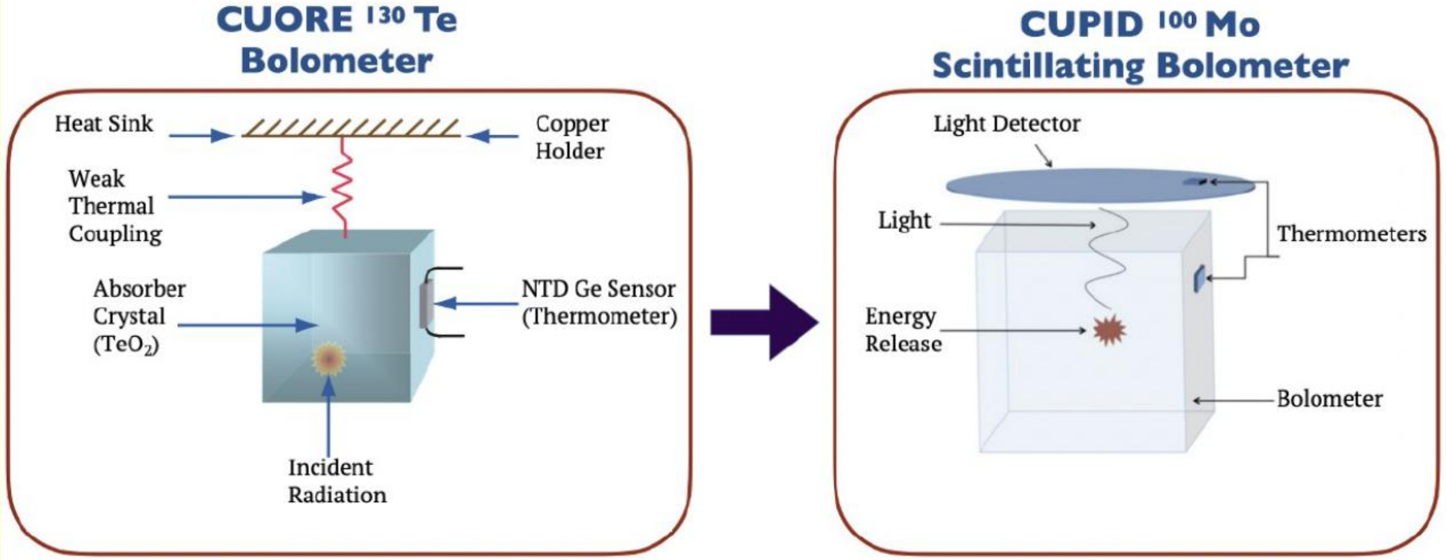


Array of 988 detectors:

19 towers , 13 modules/tower, 4 detectors/module

CUPID

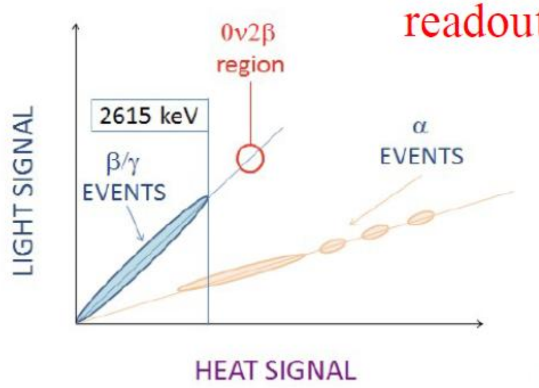
^{100}Mo

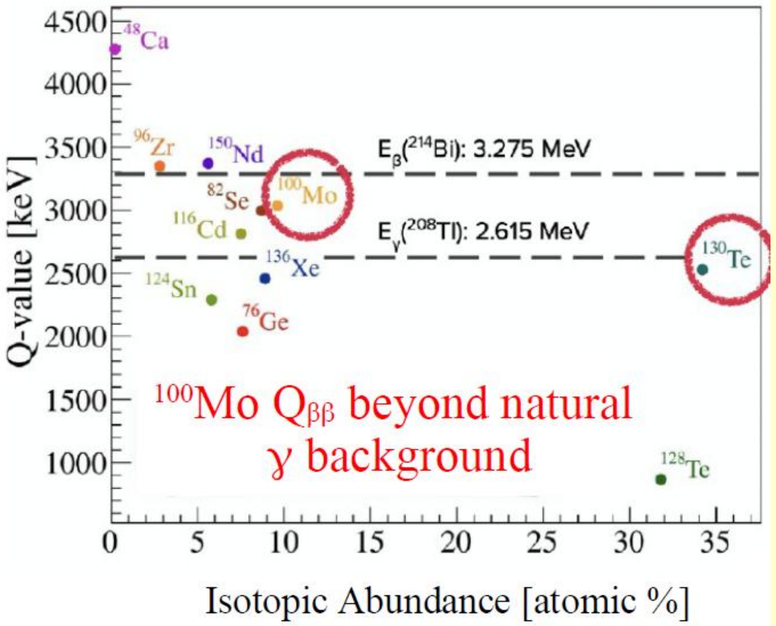


CUORE: no PID

CUPID: PID allows to separate β/γ from α events

Light +heat readout





^{100}Mo $Q_{\beta\beta}$ beyond natural γ background

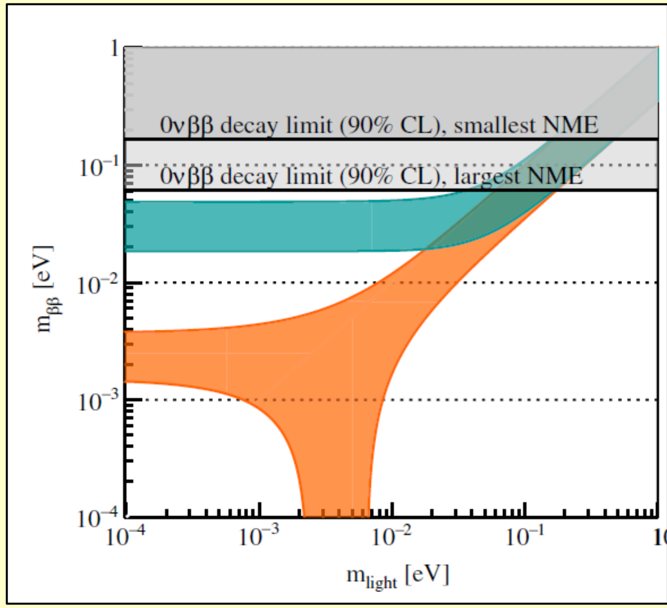
A Li_2MoO_4 (LMO) scintillating cryogenic detector to search for the 0νββ decay of ^{100}Mo

Best Limits so far…

Isotope	$T^{0\nu}_{1/2}$ (years)	Experiment
^{48}Ca	$> 5.8 \times 10^{22}$	ELEGANT VI [197]
^{76}Ge	$> 1.8 \times 10^{26}$	GERDA [2]
^{82}Se	$> 4.6 \times 10^{24}$	CUPID-0 [8]
^{96}Zr	$> 9.2 \times 10^{21}$	NEMO-3 [54]
^{100}Mo	$> 1.8 \times 10^{24}$	CUPID-Mo [7]
^{116}Cd	$> 2.2 \times 10^{23}$	Aurora [61]
^{128}Te	$> 3.6 \times 10^{24}$	CUORE [198]
^{130}Te	$> 2.2 \times 10^{25}$	CUORE [4]
^{136}Xe	$> 2.3 \times 10^{26}$	KamLAND-Zen [6]
^{150}Nd	$> 2.0 \times 10^{22}$	NEMO-3 [71]

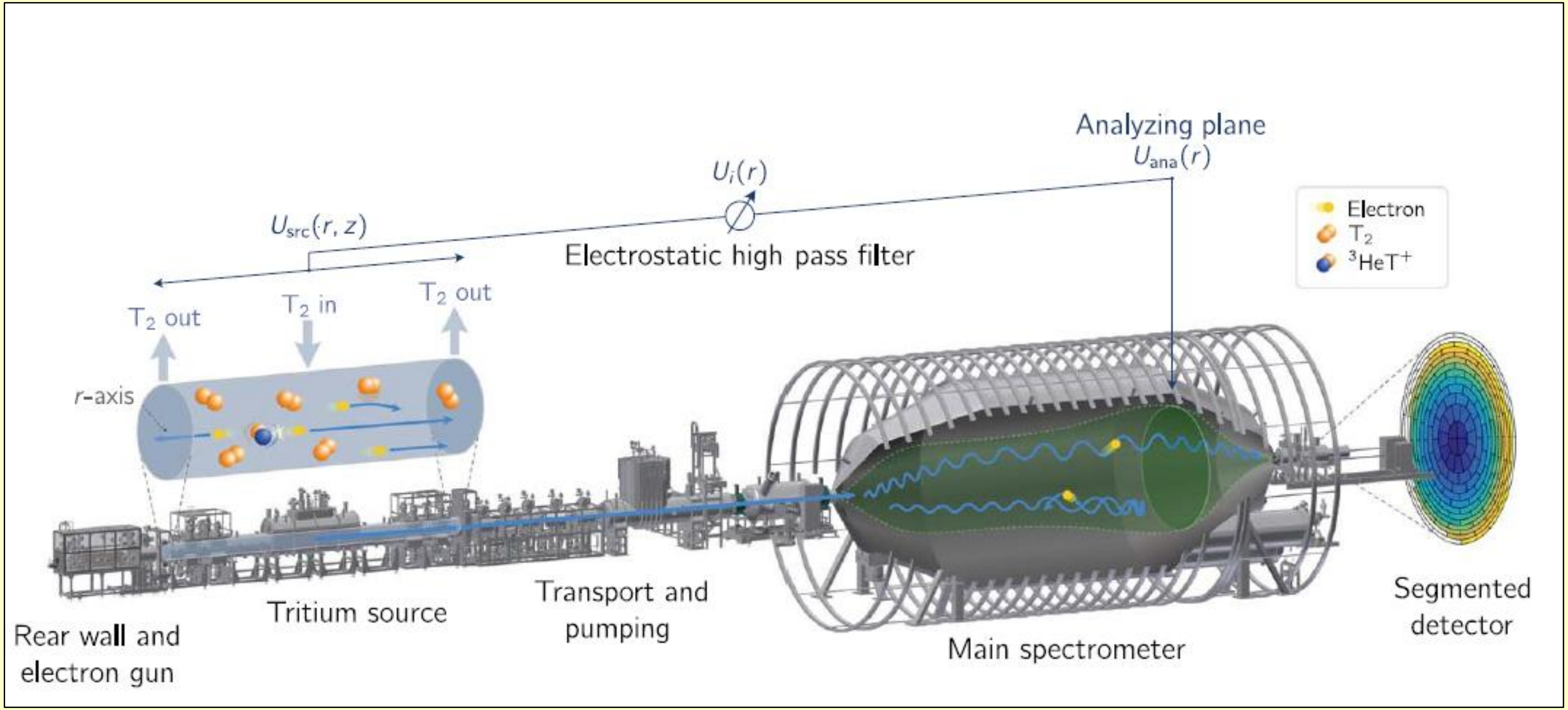
J. J. Gómez-Cadenas et al.

https://doi.org/10.1007/s40766-023-00049-2



Direct neutrino mass measurement

KATRIN (^3H, Q~18 keV, proposed sensitivity ~ 0.2 eV),



m_ν < 0.45 eV at 90% CL.

KATRIN Collaboration et al., Science 388, 180–185 (2025)

Initiative for DBD experiment in India

A multi-institutional effort

Proposal for an experiment at underground laboratory

^{124}Sn (Q = 2292.64 ± 0.39 keV)

- Sn has T_C ~ 3.7 K
- Electronic specific heat falls off exponentially below T_C
- Only lattice specific heat (~T^3) present below ~ 500 mK
- Z=50 shell is closed
- Simple metallurgy (enrichment?)

^{124}Sn: $T_{1/2} > (0.8\text{-}1.2) \times 10^{21}$ yrs Nucl. Phys. A **807,** 269(2008)

Strongly Multi-disciplinary project

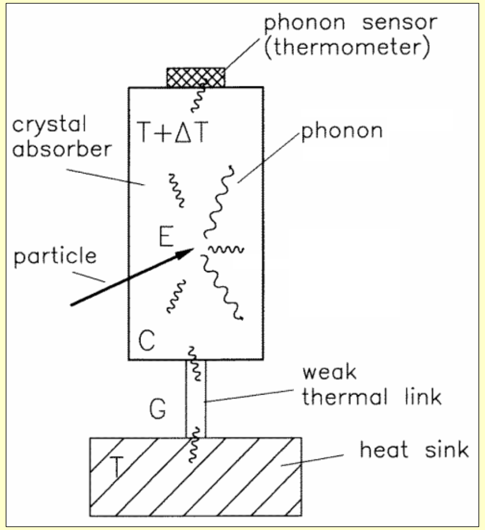
Nuclear Physics, Neutrino Physics, Low Temperature Physics, Material Science, Physical Chemistry

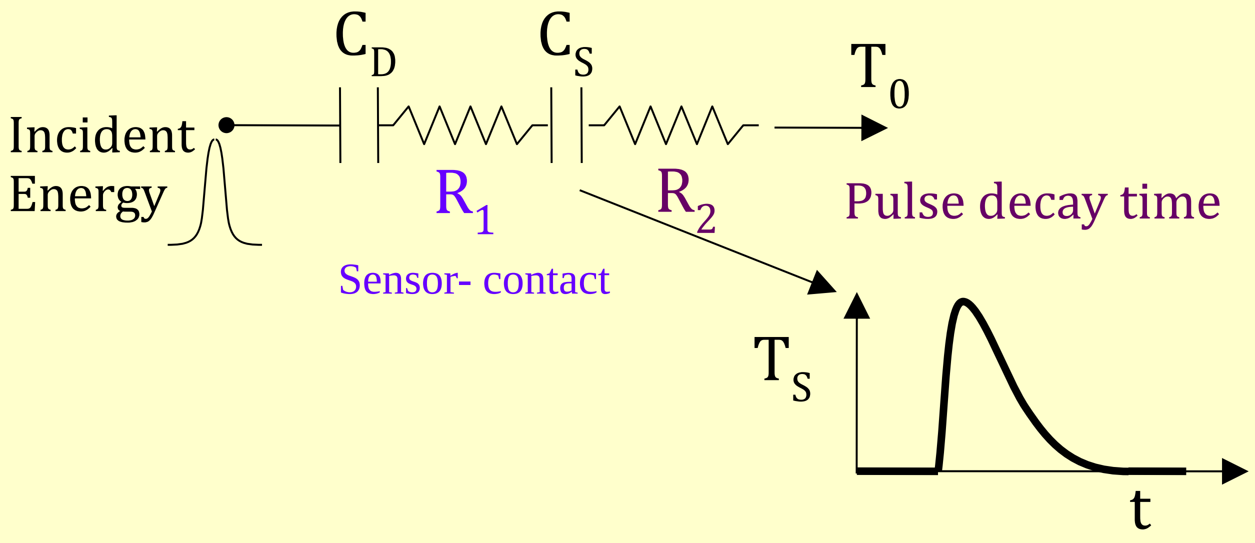
Low Temperature Bolometry

A bolometer is a calorimetric detector.

Energy of particle → Thermal energy in detector → *measurable temperature rise if net heat capacity is very low*

Bolometer Schematic





Resolution of Bolometer

- Limited by Thermodynamical fluctuation noise $\{\delta E=(kT^2C(T))^{1/2}\}$
- Depends only on operating temperature and specific heat
- Independent of incident Energy

Cryo-free dilution refrigerator installed @ TIFR

Base Temp. ~7 mK

cooling power
1.4 mW@120mK

V. Singh et. al. Pramana ***81*** *(2013) 719*

NTD Ge Sensors for mK Thermometry

Thermal Neutron irradiation of Ge at Dhurva Reactor (BARC, Mumbai)

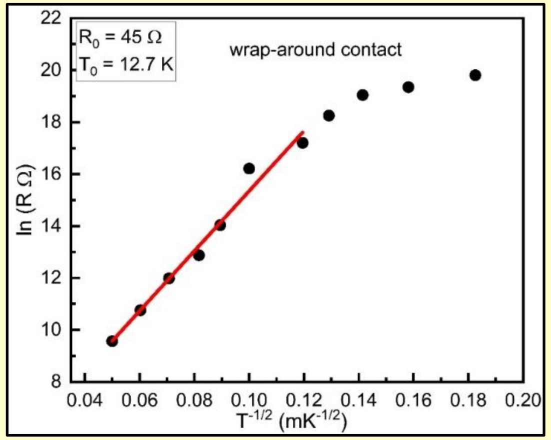
^{71}Ge, ^{75}Ge $\rightarrow$ decay As, Se, Ga

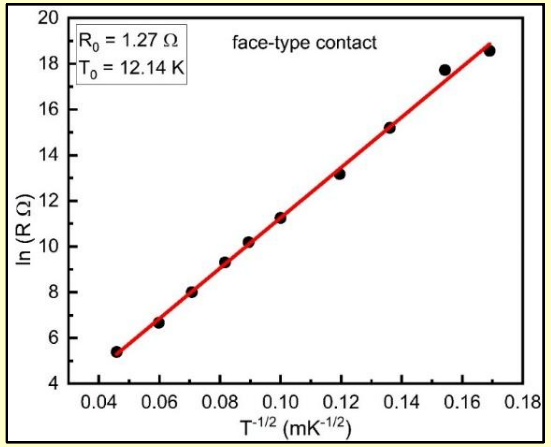
- Change in physical property – e.g. resistance with T

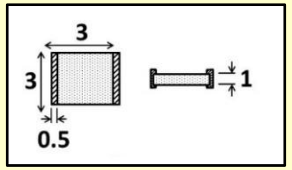
$$R\ (T) = R_0\ \exp(T_0/T)^{0.5}$$

- Radioactive impurity studies (~2 year cooldown period)
- Fast neutron induced defect studies (PALS, Channeling) & mitigation
- Sensor Fabrication

S. Mathimalar *et. al.*, NIM A **774** (2015) 68,
S. Mathimalar *et. al.* NIM B **345** (2015) 33.

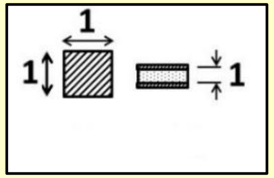






3x3 wrap-around contacts

1x1 face-type contacts

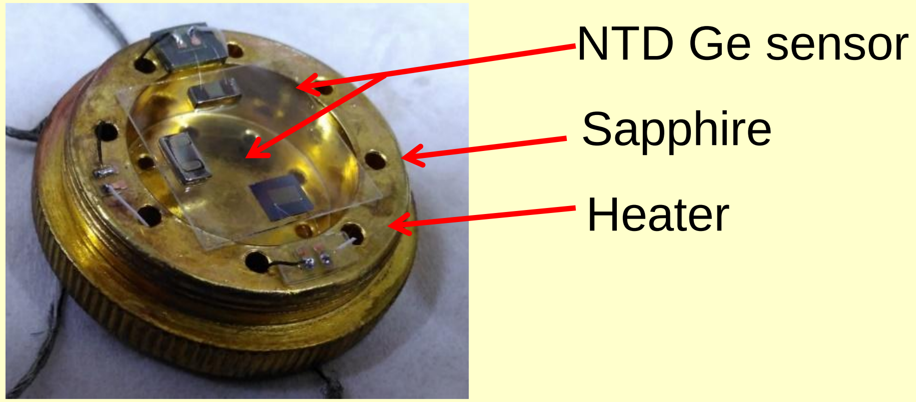


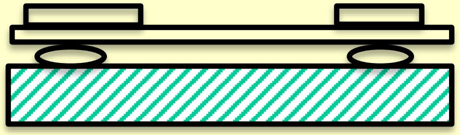
- Samples from wrap-around geometries show deviation below T = 50-70 mK
- Overall performance of the face-type contact is found to be better.

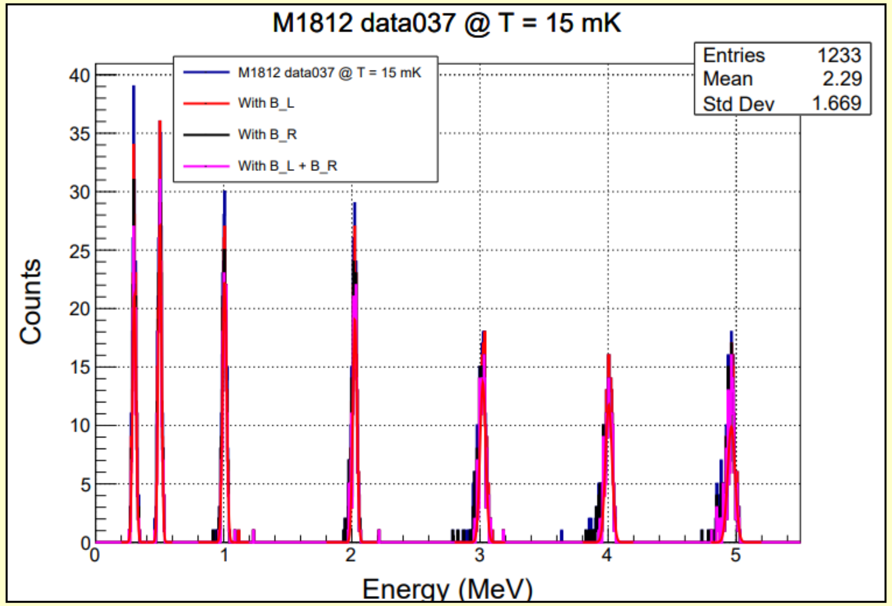
A. Garai,et al, J Low Temp Phys 199, 95 (2020)

V. Vatsa et al. WOLTE-14, (2021)

Test with sapphire-Sn bolometer





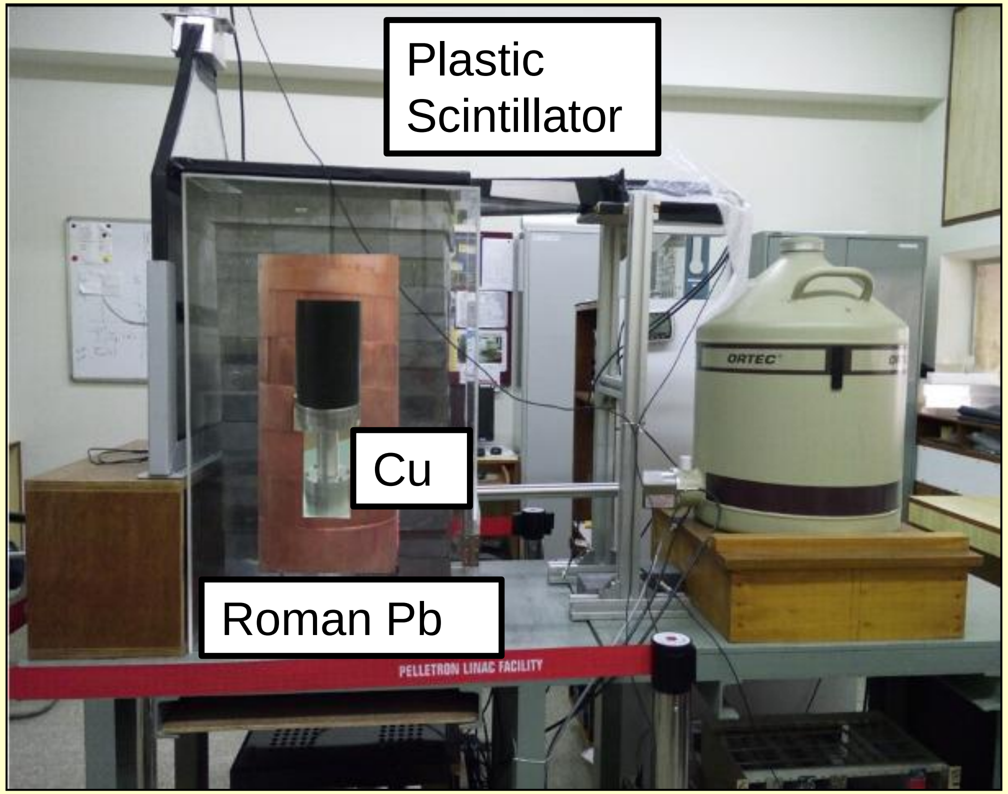


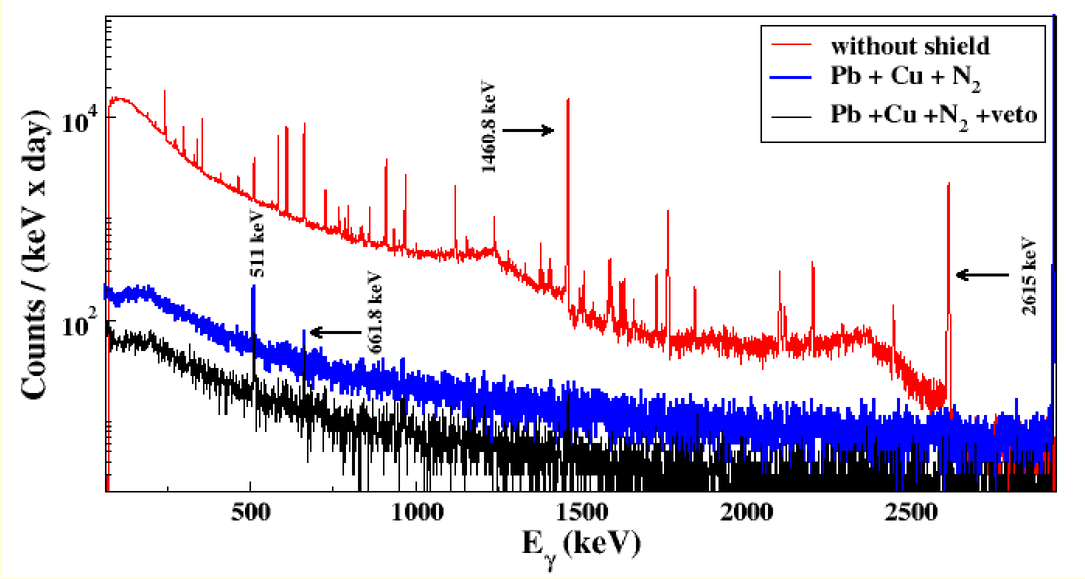
A. Garai,et al, J Low Temp Phys **199**, 95 (2020)

Detailed noise characterization, investigation of various noise sources, and its mitigation to improve the performance of a cryogenic bolometer detector have been studied

V. Vatsa et al., *JINST* 17 T11013 (2022)

Tifr Low background Experimental Setup (TiLES)



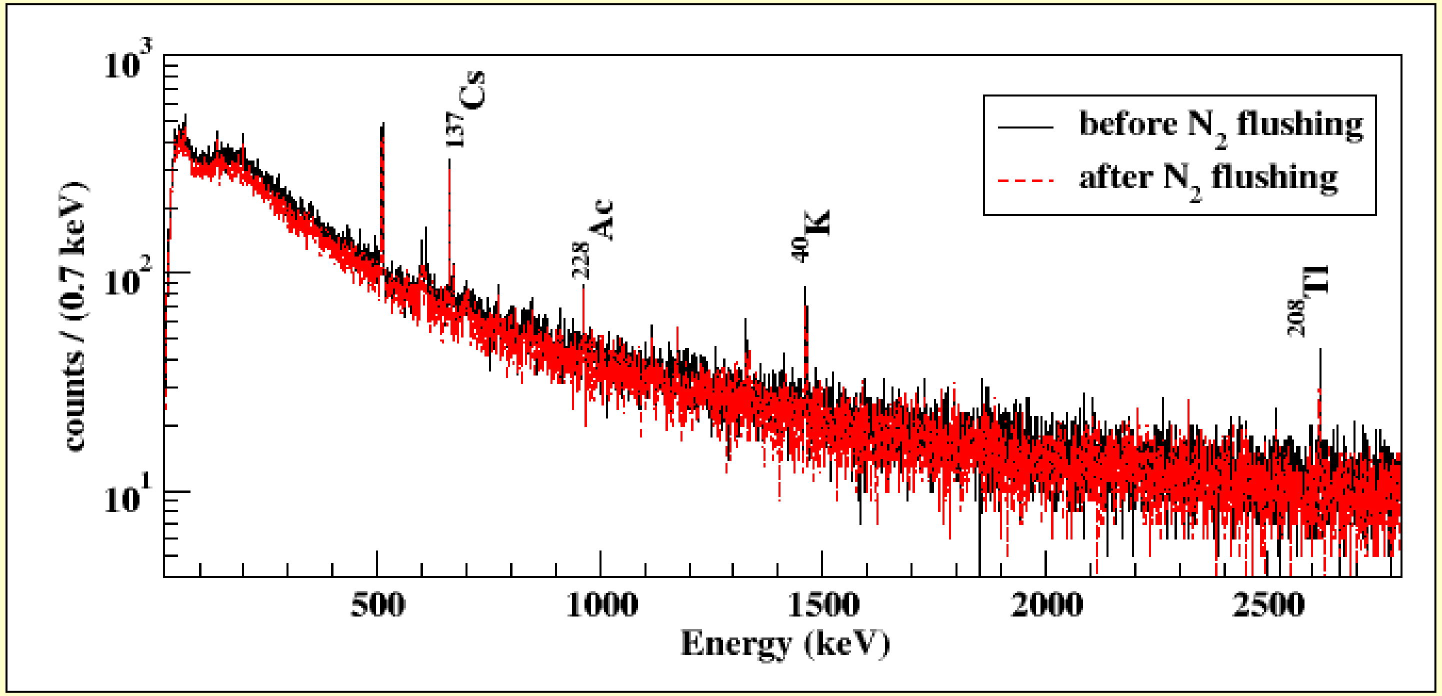


Sensitivity of the setup:***~1 mBq/g (~10 ppb)***

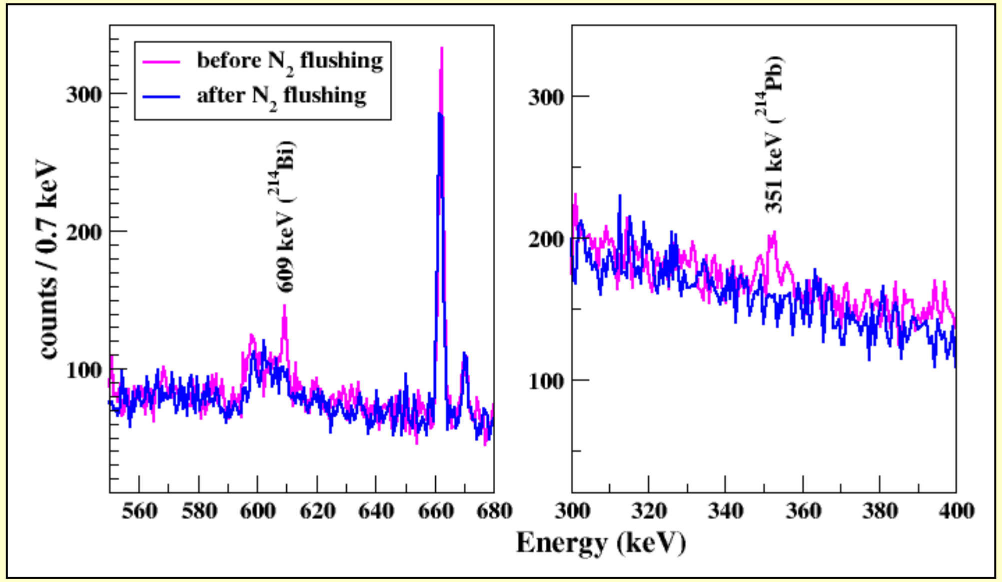
- Detector surrounded by **OFHC Cu (5 cm), Pb (10 cm) (^{210}Pb < 0.3 Bq/kg)**.
- N_2 purging system and active muon veto (plastic scintillators)
- TiLES is used for material screening such as ETP Cu, INO site rock, CsI crystals for DINO, etc.

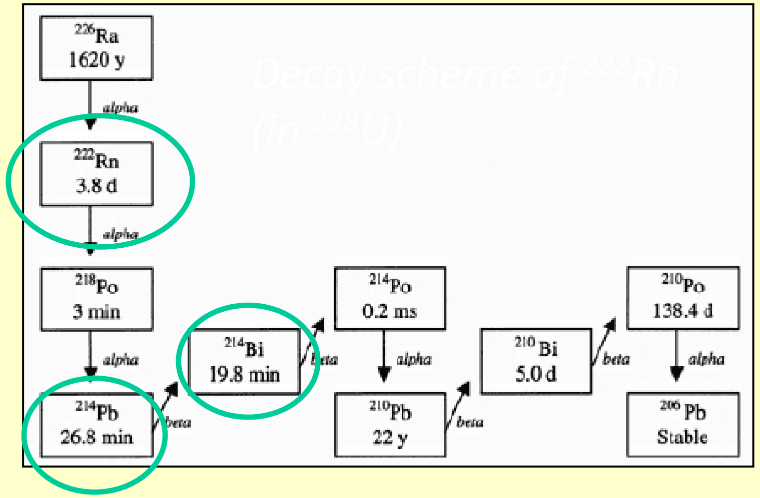
N_2 flushing in the TiLES

Radon produced in the natural decay chains of U and Th gets trapped in the volume of the detector.



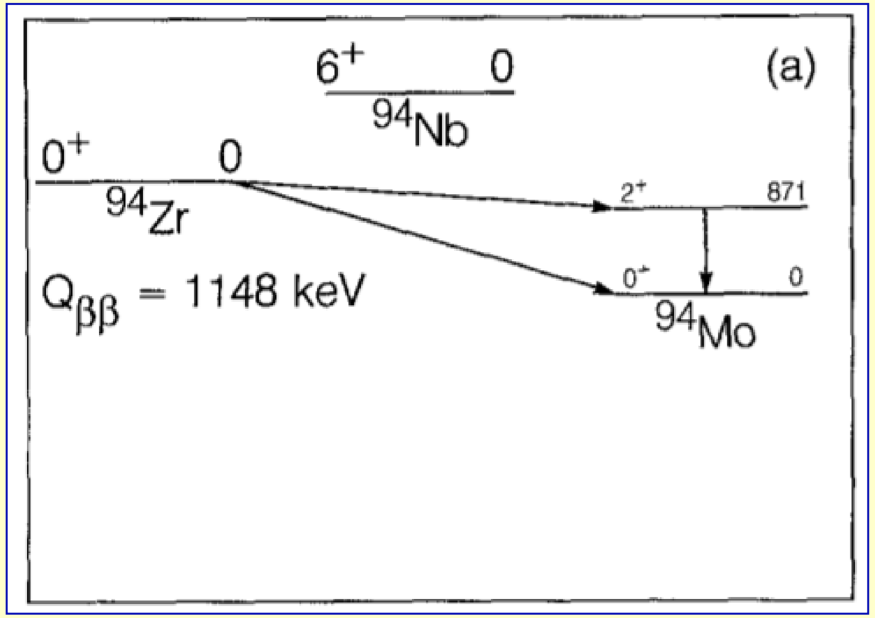
Gamma ray spectra of room background in TiLES (t = 7d)

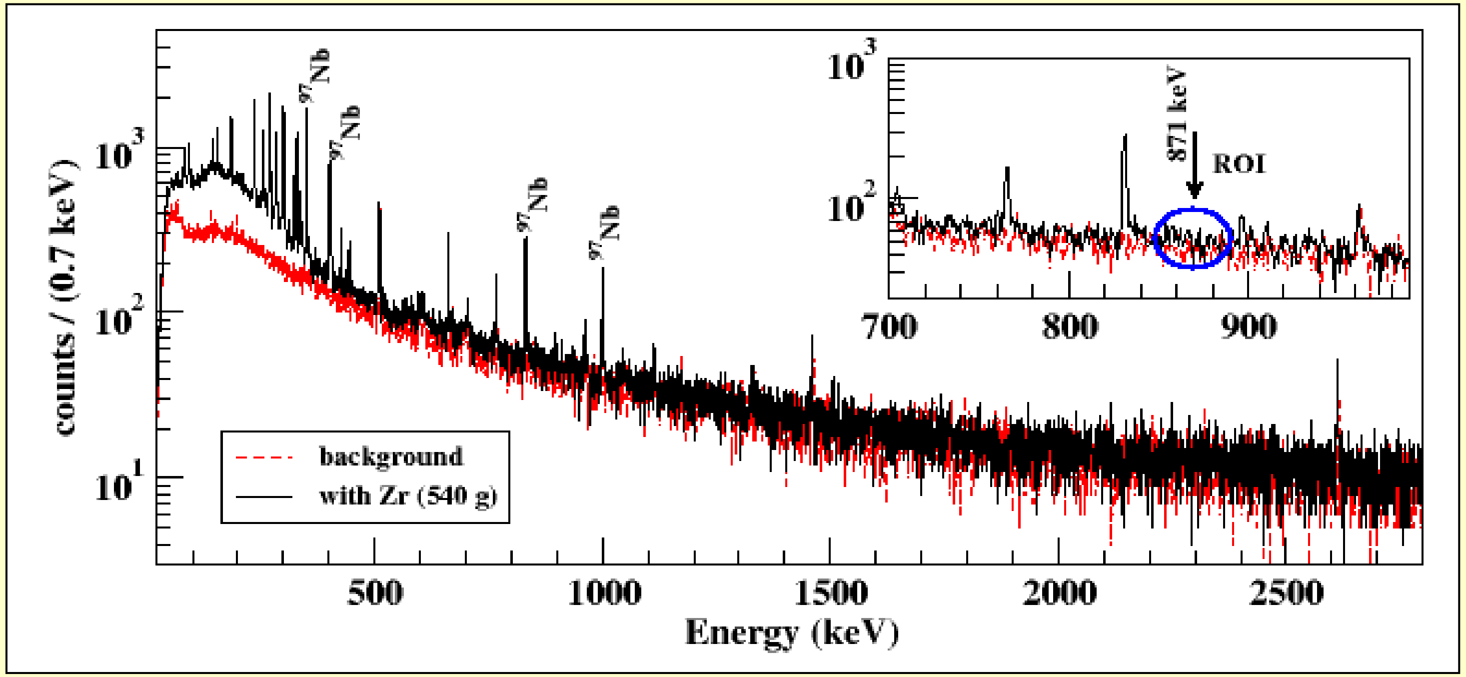




DBD to excited state in ^{94}Zr

Decay Scheme of ^{94}Zr





Gamma ray spectra of ^{nat}Zr in TiLES for t = 7d

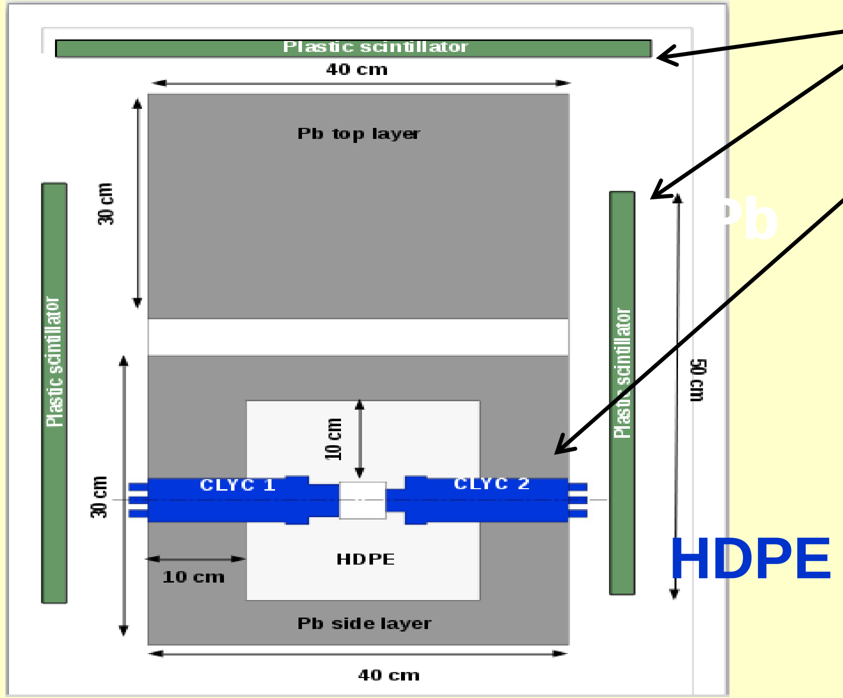
- The current best experimental limits are **$T_{1/2}$ > 1.3 x 10^{19} y** (68% C.L.) (***Norman et al., Phys. Lett. B 195*, 126 (1987)).**
- 540 g of ^{nat}Zr (99.5% purity) counted in the TiLES

Double beta decay of ^{94}Zr to the 1st excited state in ^{94}Mo

$T_{1/2}$ > 2.0 x 10^{20} y* 68% C.L, 6.12 *x* 10^{19} *y at 90% C.L.

N. Dokania et al EPJ A **53** (2017) 74

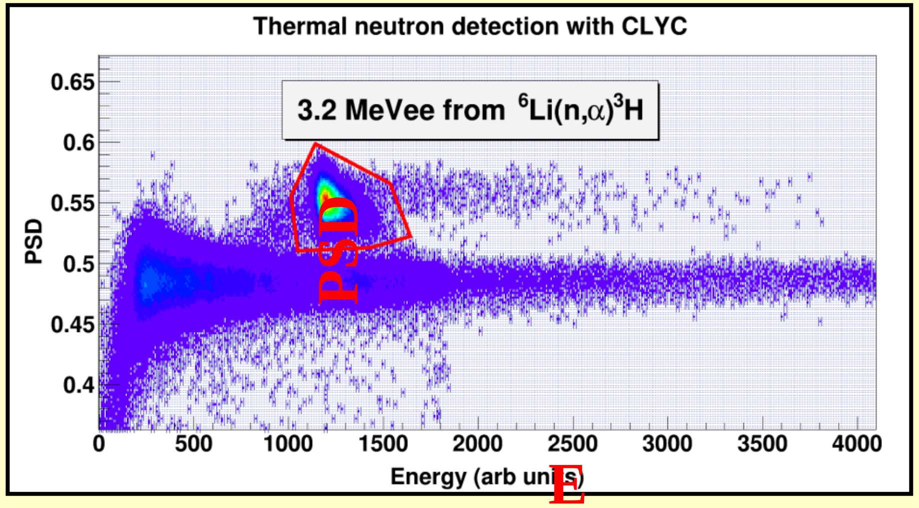
Muon Induced Neutron detector setup at Tifr



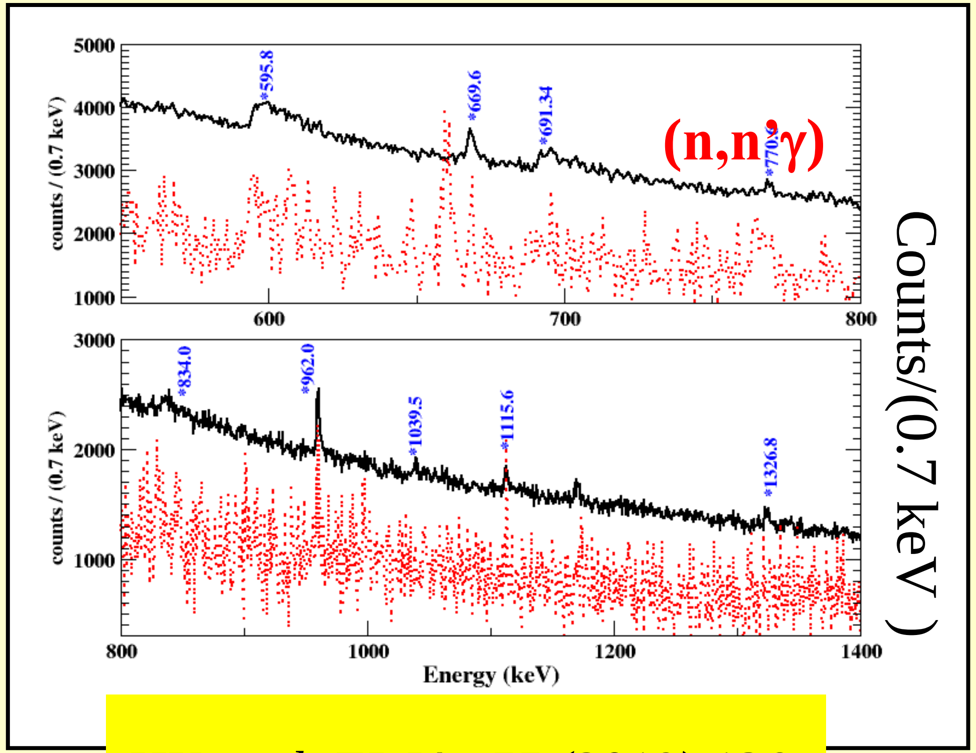
Muon detectors (plastic Scintillators)

Neutron detectors (CLYC)

provided crucial input for validation of GEANT4.10.05 simulation of both muon induced neutron production and neutron inelastic scattering.



Gamma spectrum gated by muons in TiLES



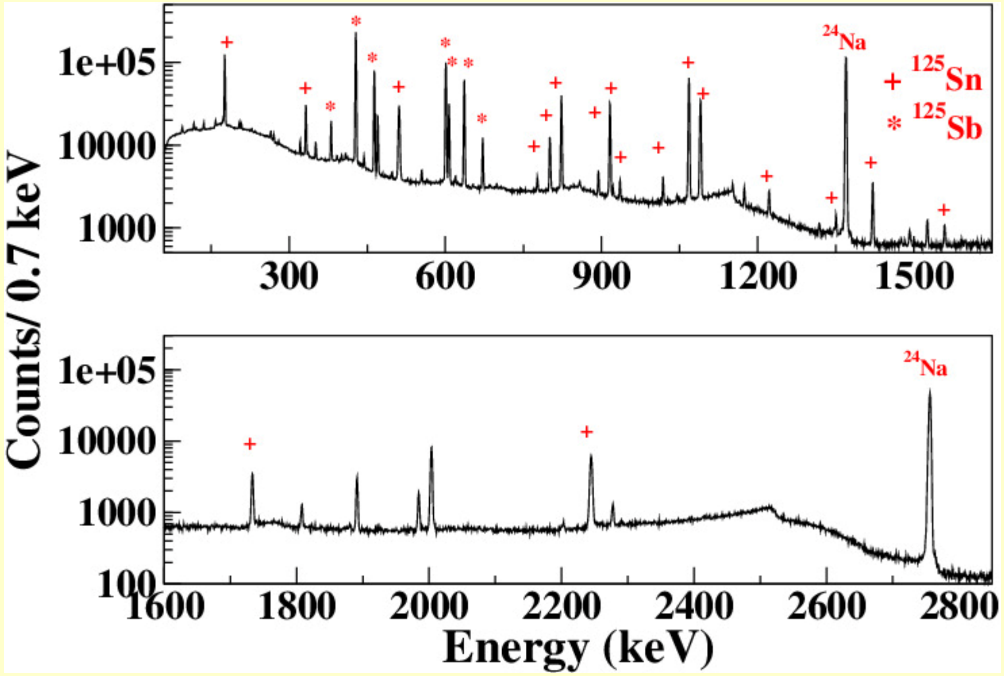
Harisree Krishnamoorthy, NUPHYS2018

HK et al, EPJA ***55*** *(2019) 136*

n-induced background in ^{124}Sn

- ❖ $^{124}Sn\ (n, \gamma)\ ^{125}Sn$
- ❖ ^{125}Sn : β decay → ^{125}Sb,
  $Q_\beta = 2357$ keV
- ❖ $T_{1/2} =$ 9.52m, 9.64 days
- ❖ ^{125}Sb β-decay → ^{125}Te
  ($T_{1/2}$ =2.75 y, Q_β=766 keV)

- ❖ $^{124}Sn\ (n, \gamma)\ ^{125}Sn\ (n, \gamma)\ ^{126}Sn$
- ❖ ^{126}Sn β- decay → ^{126}Sb
  ($T_{1/2} = 2.3 \times 10^5$ years, $Q_\beta = 378$ keV)
- ❖ ^{126}Sb β-decay → ^{126}Te
  ($T_{1/2}$ =12.35 days, Q_β = 3673 keV)



($Q_{\beta\beta}$ of ^{124}Sn = 2293 keV)

- Simulation studies to estimate neutron flux based on rock composition carried out.

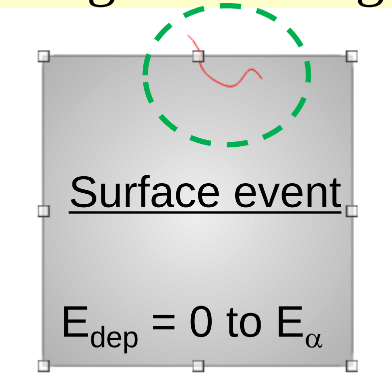
*N. **Dokania** et al., JINST, **10** (2015) T12005*

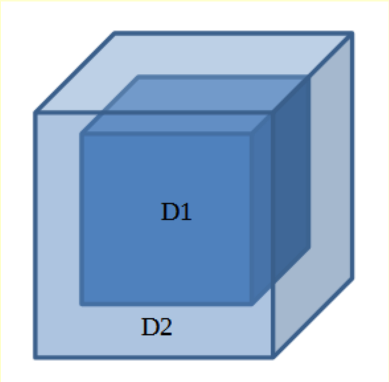
- n-induced reactions in Sn, Pb, Cu are being studied at PLF and Dhruva

*G. Gupta et al. ARI **158** (2020), 108923*

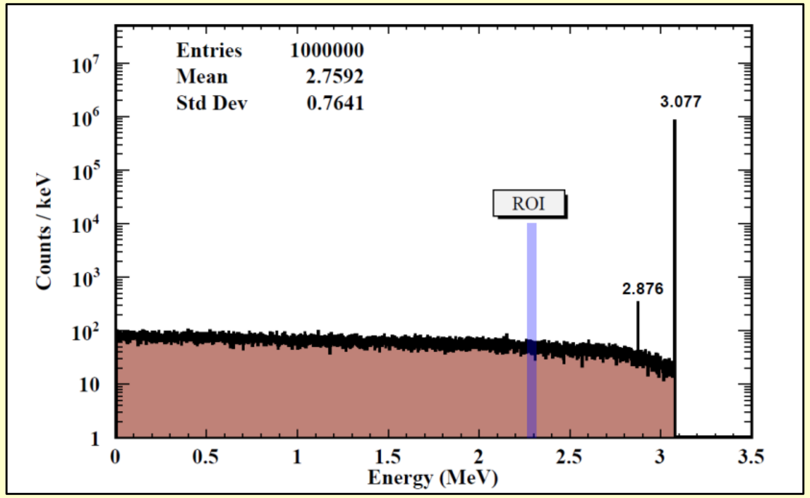
Estimation of radiation background for Sn-Bi bolometers

Usually limited by backgrounds originating from sources internal to the bolometer





Range of 3 MeV α in Sn: 8 mm;
Hence, width D2: 10 mm



- Surface events can increase the background in ROI (2291 $\pm$ 25 keV) since they can lead to partially contained events.

- The size of the bolometer was varied – 27 cc, 64 cc and 125 cc.

0.25 % Bi

Volume	Bkg (cts/(keV.kg.y)
27 cc	2.6×10^{-5}
64 cc	2.0×10^{-5}
125 cc	1.6×10^{-5}

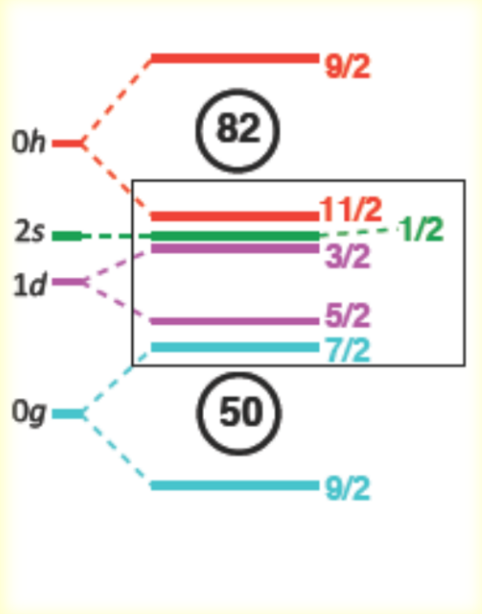
A. Mazumdar, thesis

125 cc

Impurity level	Source	Bkg (cts/(keV.kg.y)
0.2 ppt	Th chain	3.1×10^{-5}
0.2 ppt	U chain	5.8×10^{-3}
0.25%	^{209}Bi	1.6×10^{-5}
Total		5.8×10^{-3}

Occupation probabilities of valence orbitals relevant to NDBD of ^{124}Sn

Occupation and vacancy of valance neutrons in ^{124}Sn and ^{124}Te
in a consistent expt.al manner, using consistent prescription of potential parameters in DWBA analysis



Choice of reactions (expt @ IPNO, France)

Transfer x-sec for relevant active orbitals : 1d, 2$s_{1/2}$, 0$h_{11/2}$, (0$g_{7/2}$ weak)

Vacancy: ^{124}Sn,^{124}Te(d,p) : for 1$d_{5/2}$, 1$d_{3/2}$, 2$s_{1/2}$

^{124}Sn,^{124}Te(^{4}He,^{3}He): for $h_{11/2}$, 0$g_{7/2}$

Occupancy: ^{124}Sn,^{124}Te(p,d) : for 1$d_{5/2}$, 1$d_{3/2}$, 2$s_{1/2}$

^{124}Sn,^{124}Te(^{3}He,^{4}He): for $h_{11/2}$, 0$g_{7/2}$

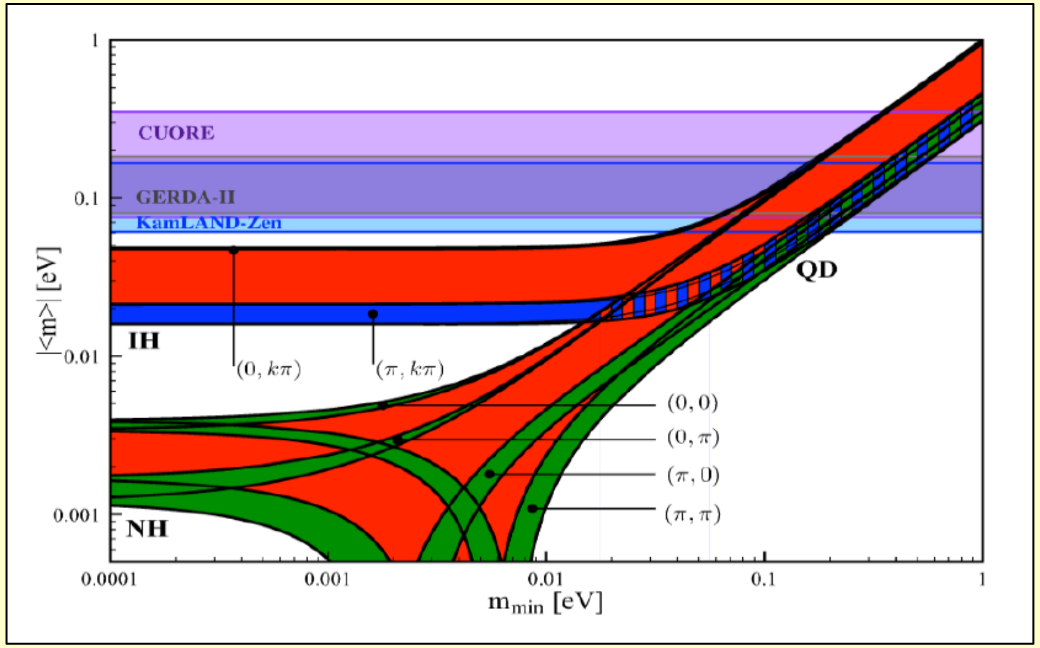
- **A. Shrivastava et al., Phys. Rev. C 105, 014605 (2022)**

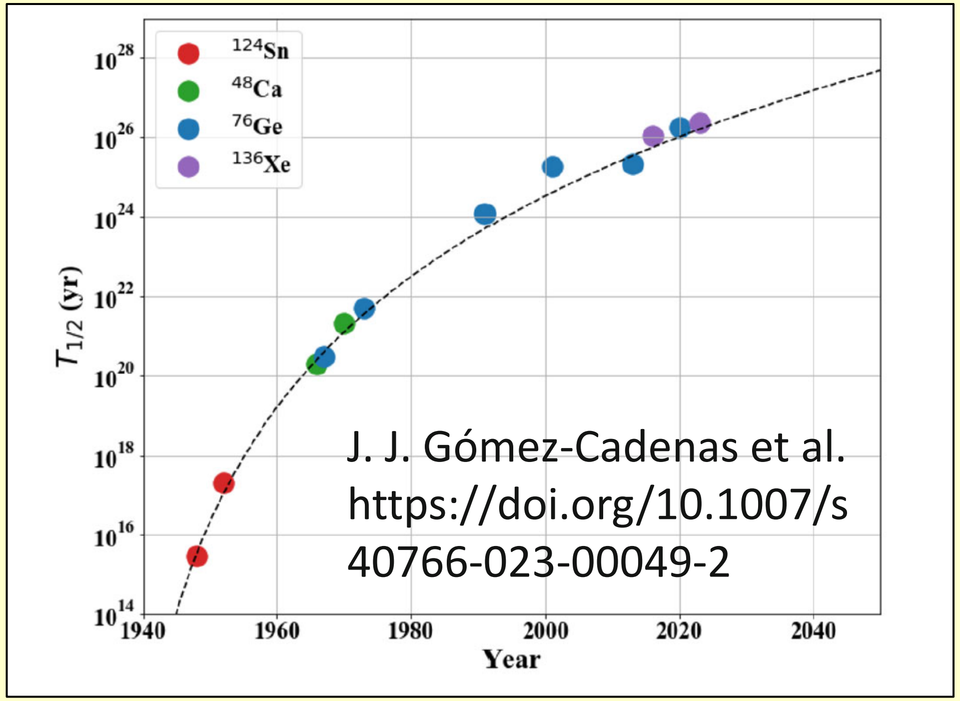
Experimental values differs with shell model calculations (PRC93, 024308 (2016))
Change in vacancy of orbitals between ^{124}Sn and ^{124}Te : 0h and 1d are under predicted and 0g7/2 is over predicted

- Nuclear matrix elements calculation for 0νββ decay of ^{124}Sn using non-closure approach in nuclear shell model, Shahariar Sarkar et al. Phys Rev C **109**, 024301 (2024)

Summary

- *Neutrinoless Double Beta Decay to test nature of neutrino – Majorana or Dirac?*
- *Several large scale experiments with increased sensitivity are proposed and some are underway*
- *Efforts aimed : to achieve near-zero background and to obtain reliable NTME*





Sergei Petcov, doi: 10.5281/zenodo.4134015

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Tin.Tin Collaboration

TIFR, Mumbai

Vivek Singh, Neha Dokania, S. Mathimalar,

A. Garai , Harisree krishnamoorthy,

Aparajita Mazumdar, Ghnashyam Gupta,

Ashif Reza Vishal Vatsa, Nishant Jangid,

Upasana Gupta

M.S. Pose, Mallikarjun

V. Nanal, R. Palit,

V.M. Datar*, S. Ramakrishnan*, R.G. Pillay*

BARC, Mumbai

A. Shrivastava, K.C. Jagadeesan*, S.V. Thakare*

IIT Ropar

P.K. Raina*, Pushpendra P Singh, Swati Thakur

Univ. of Lucknow P.K. Rath*

http://www.tifr.res.in/~tin.tin/

Pictures from Wikipedia