XXI Workshop on Neutrino Telescopes
Padova September 29 - October 3 2025

Review of Neutrinoless Double Beta Decay

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Disclaimer

In a 30-minute review you have to make choices, so here are mine.

Some background + a selection (my personal one) of experiments. I apologize for not being able to properly report all the activities that are in progress in this field!

Where possible, I'll add **timelines** to show past progress and future goals, based on publicly available material – with **future projections always linked to technical readiness**.

Do not miss the talks we have at the conference

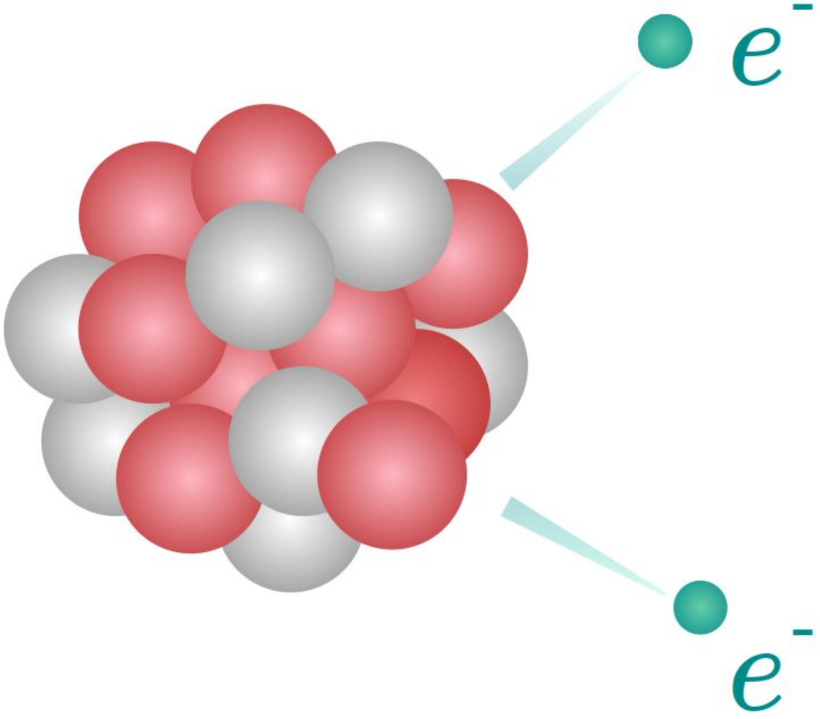
- The **CUPID** $0\nu\beta\beta$ experiment - S. Fu
- Latest results from the **CUORE** experiment P. Gorla
- **LEGEND:** $0\nu\beta\beta$ decay search with germanium detectors K. Gusev
- Status of the **SuperNEMO** Experiment and physics objectives M. Petro
- The **NEXT** program and status of the NEXT-100 detector Brais P. Pazos

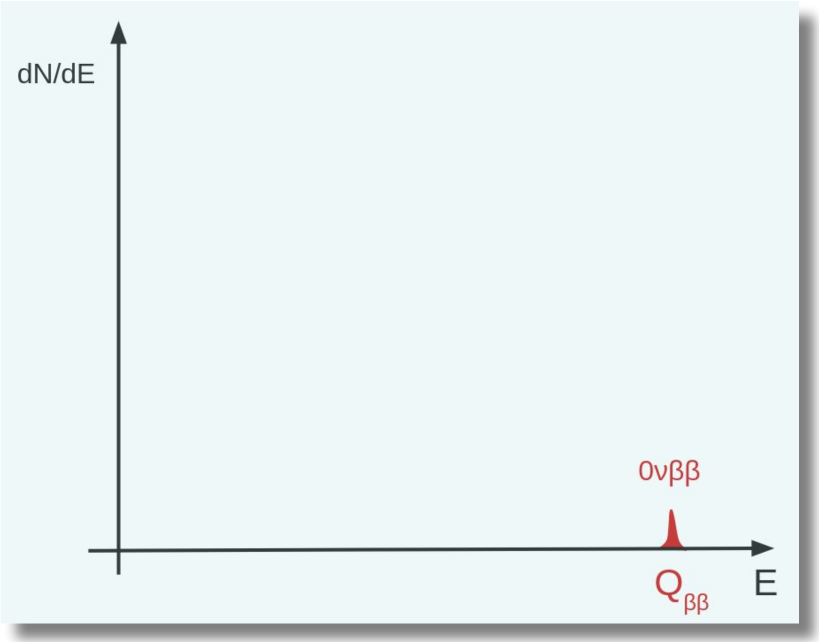
Any mistakes, inaccuracies, or omissions are entirely my responsibility and I apologize in advance for them.

Neutrinoless Double Beta Decay 0νββ

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

- violates Lepton Number $\Delta L=2$
- signature used for its identification is the sum E of electrons = $Q_{\beta\beta}$

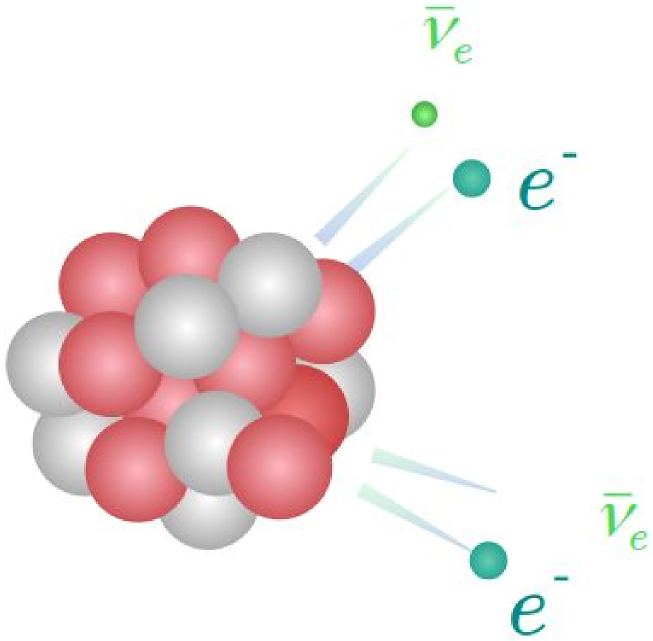


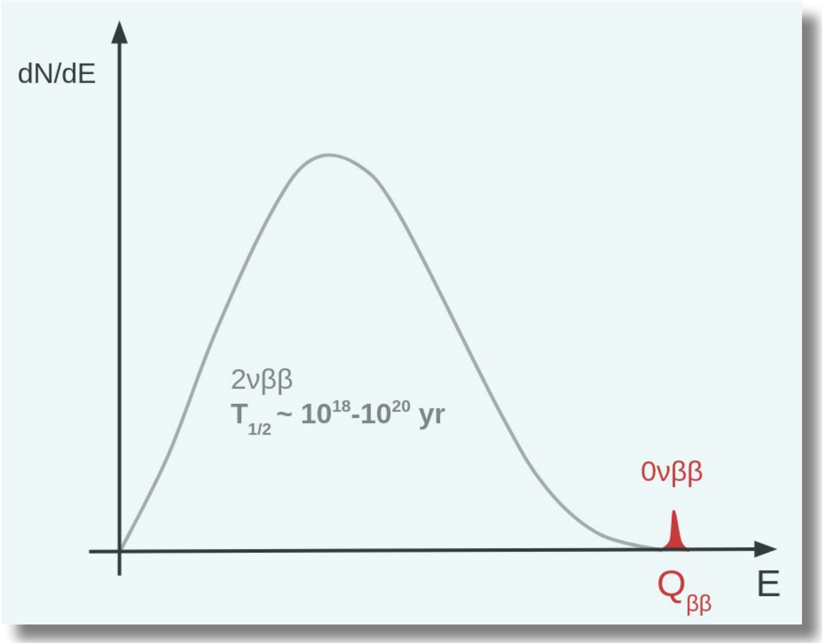


Neutrinoless Double Beta Decay 0νββ

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

- SM allowed
- rare but oserved





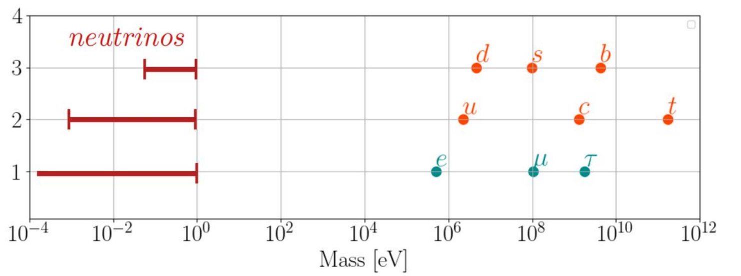
Why ? a window on BSM Physics

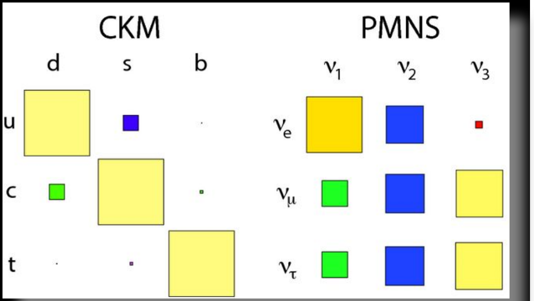
oscillations → L_{flavor} violated → neutrinos have mass → two options:

- Dirac massive neutrino (need to postulate L conservation)
- Majorana massive neutrino → $\Delta(B-L)=2$

  "natural" solution that may lead to a theory able to explain

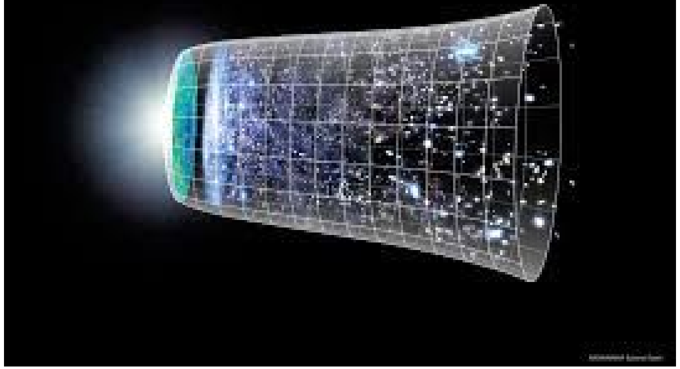
Problem of flavour





explain the observed fermionic mass spectrum and mixing

Matter vs anti-Matter

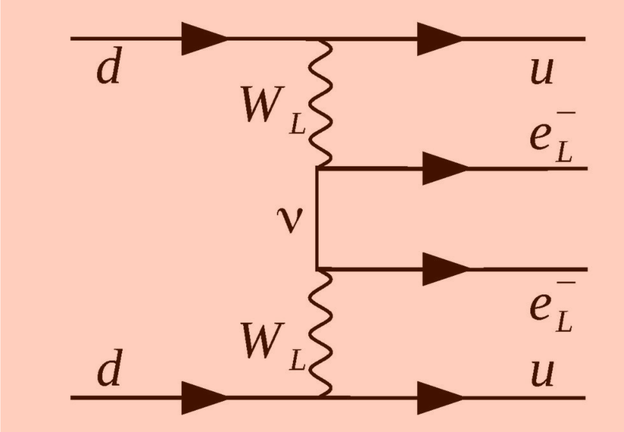


What do we measure with 0νββ?

Neutrino Majorana mass

$$m_{\beta\beta} = \sum U_{ek}^2 m_i$$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{m_{\beta\beta}^2}{m_e^2}$$



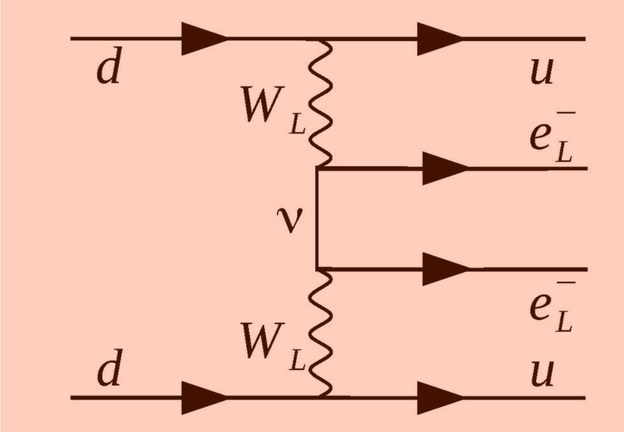
exchange of a light Majorana neutrino is the "reference" diagram (most "natural") → Majorana mass $m_{\beta\beta}$

What do we measure with 0νββ?

Neutrino Majorana mass

$$m_{\beta\beta} = \sum U_{ek}^2 m_i$$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{m_{\beta\beta}^2}{m_e^2} + \dots$$



\+ ....

exchange of a light Majorana neutrino is the "reference" diagram (most "natural") → Majorana mass $m_{\beta\beta}$

other diagrams are possible depending on how the SM is extended → **the decay rate is a sum over different contributions**

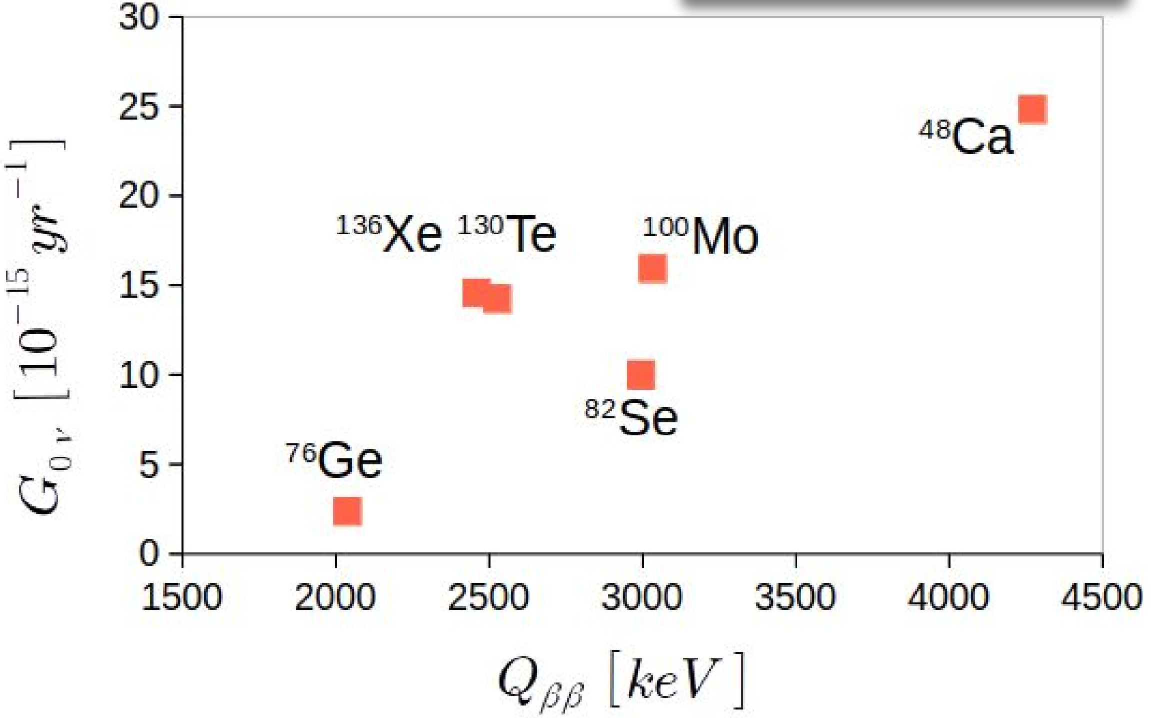
Nuclear Physics

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{m_{\beta\beta}^2}{m_e^2}$$

Phase Space

- calculated
- increases with $Q_{\beta\beta}$ (motivation for the study of isotopes with large $Q_{\beta\beta}$)

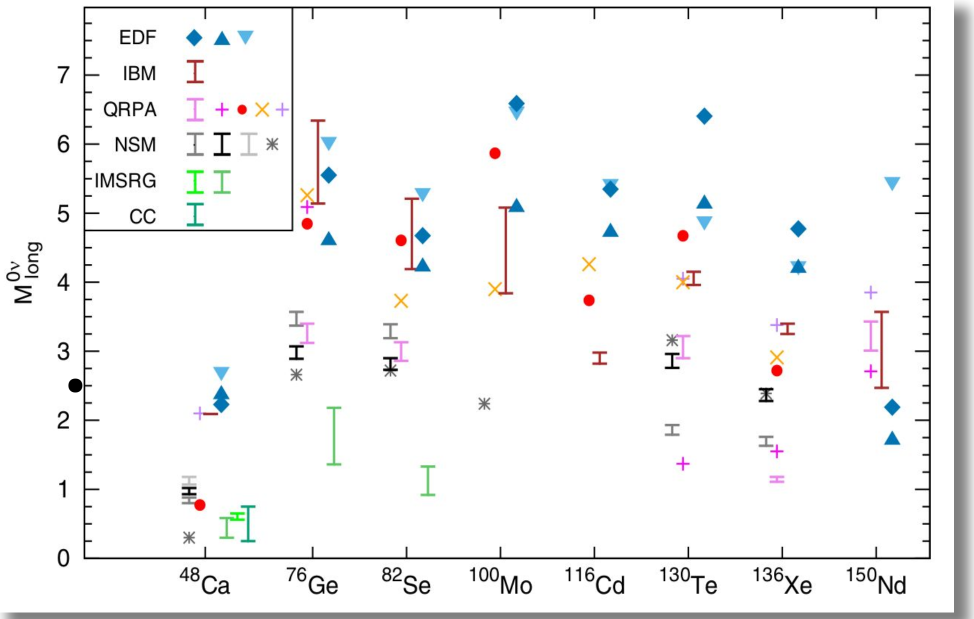
PRC 85, 034316 (2012)



Nuclear Physics

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{m_{\beta\beta}^2}{m_e^2}$$

RevModPhys 95, 025002 (2023)



Nuclear Matrix Element

- calculation based on approximate solutions of the many-body nuclear problem

Nuclear Physics: prediced half-lives

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{18.5\, meV^2}{m_e^2}$$

- converted into half-life with $m_{\beta\beta}$=18.5 meV
- group results obtained with the same model (the spread is not a rigorous measure of the uncertainty but it's all we have):
  - SHELL
  - QRPA (Quasi Random Particle Approximation=
  - EDF (Energy Density Functional model)
  - IBM (Interacting Boson Model)
- add recent **Ab Initio results** (still work in progress)

Nuclear Physics: prediced half-lives

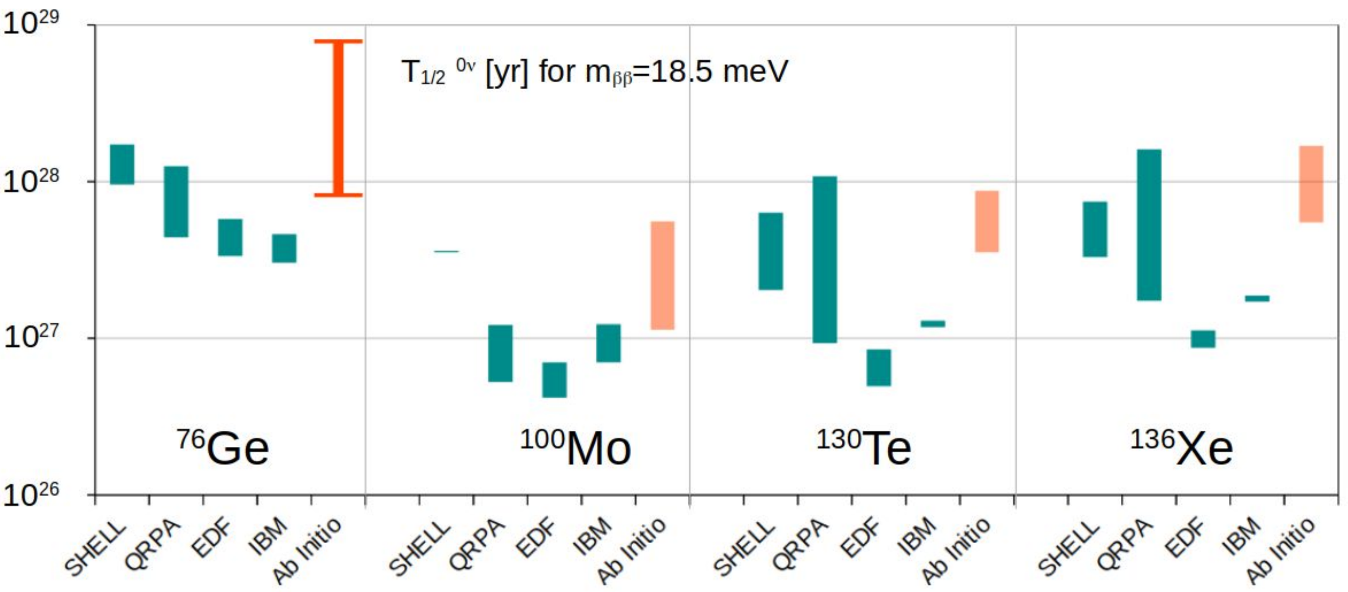
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} \cdot g_A^4 \cdot M_{0\nu}^2 \cdot \frac{18.5\, meV^2}{m_e^2}$$

Phase Space from PRC 85, 034316 (2012)

RevModPhys 95, 025002 (2023)

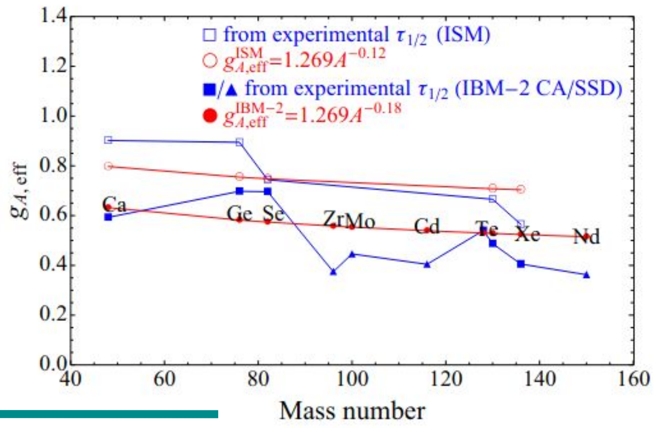
Ab Initio, PRELIMINARY, 14th International Spring Seminar on Nuclear Physics 2025

1 σ NME interval
PRL 8132, 182502 (2024)



NME puzzle

PRC 91, 034304 (2015)Value of gA,eff extracted from experiment for IBM-2 and the ISM.



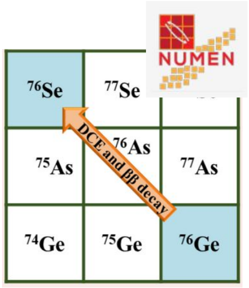
Many nuclear models look to over predict beta decay rate → g_A **quenching**

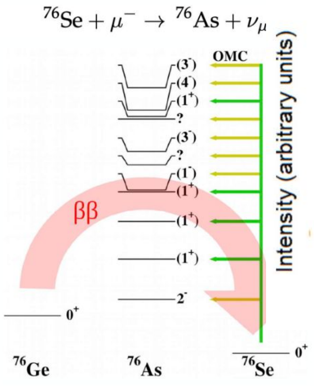
- is it needed by all models ? (no, see e.g. PRC 100, 014316 (2019)
- does it apply also to 0νββ NME ?

Experimental input are spectroscopic data, β and 2νββ half-lives, additional inputs may come from:

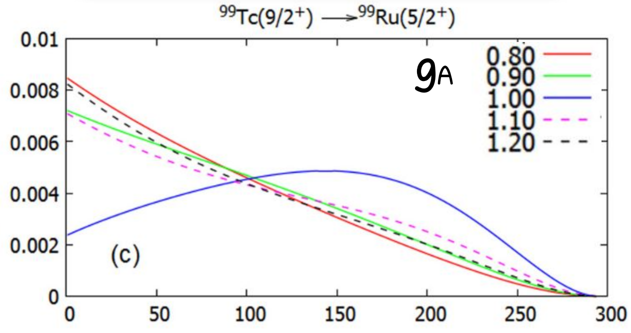
- **Double Exchange Reactions**
- **Forbidden Beta Decay Spectra**
- **Muon Capture**

See 14th International Spring Seminar on Nuclear Physics 2025





PRC 91, 034304 (2015)



Spectra predicted my MQpM for different gA

$m_{\beta\beta}$ bounds from other observables

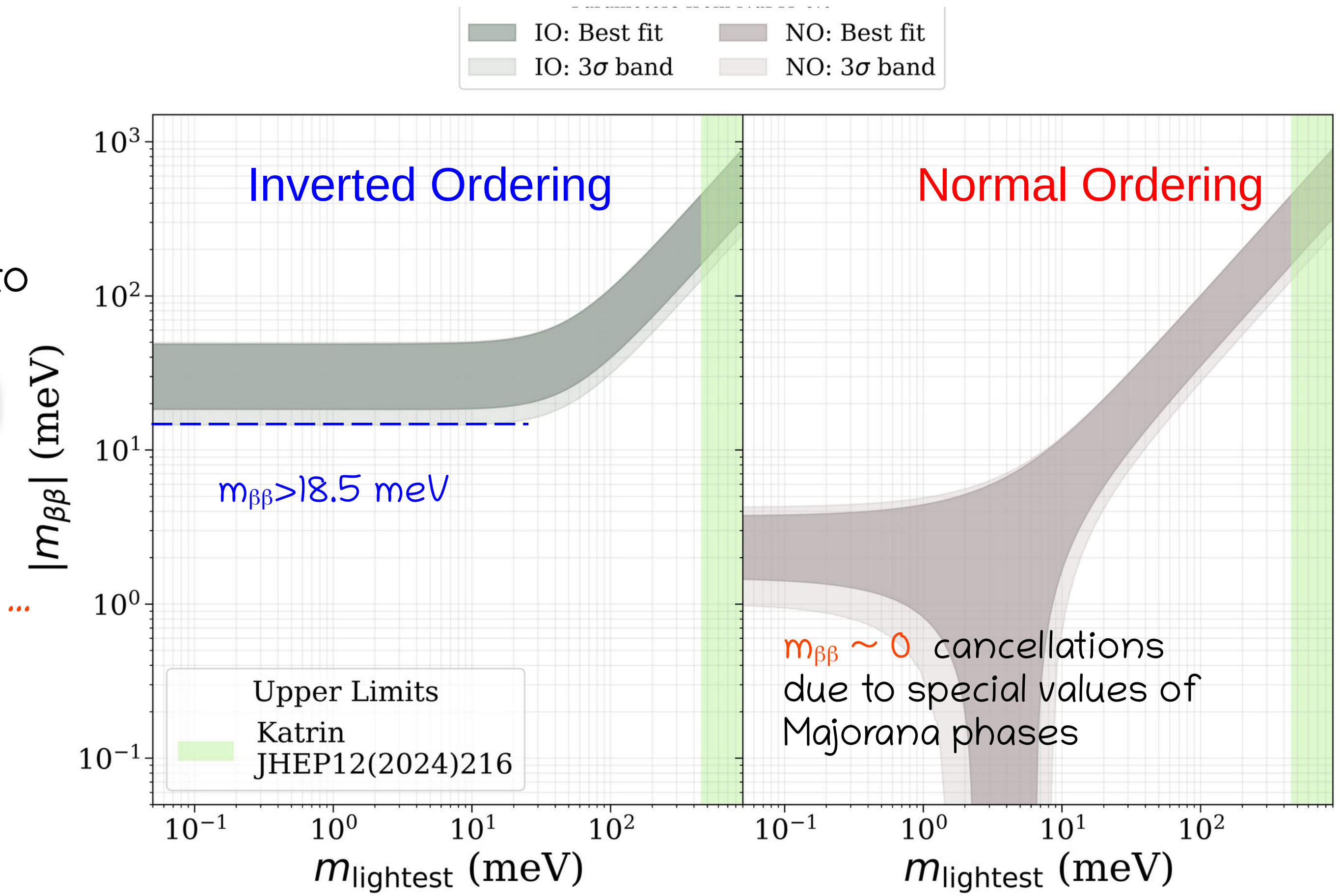
(1) Oscillation data only -

JHEP 12 (2024) 216

(2) **KATRIN limit** can be used to bound $m_{lightest}$

Science 388 (2025) 180

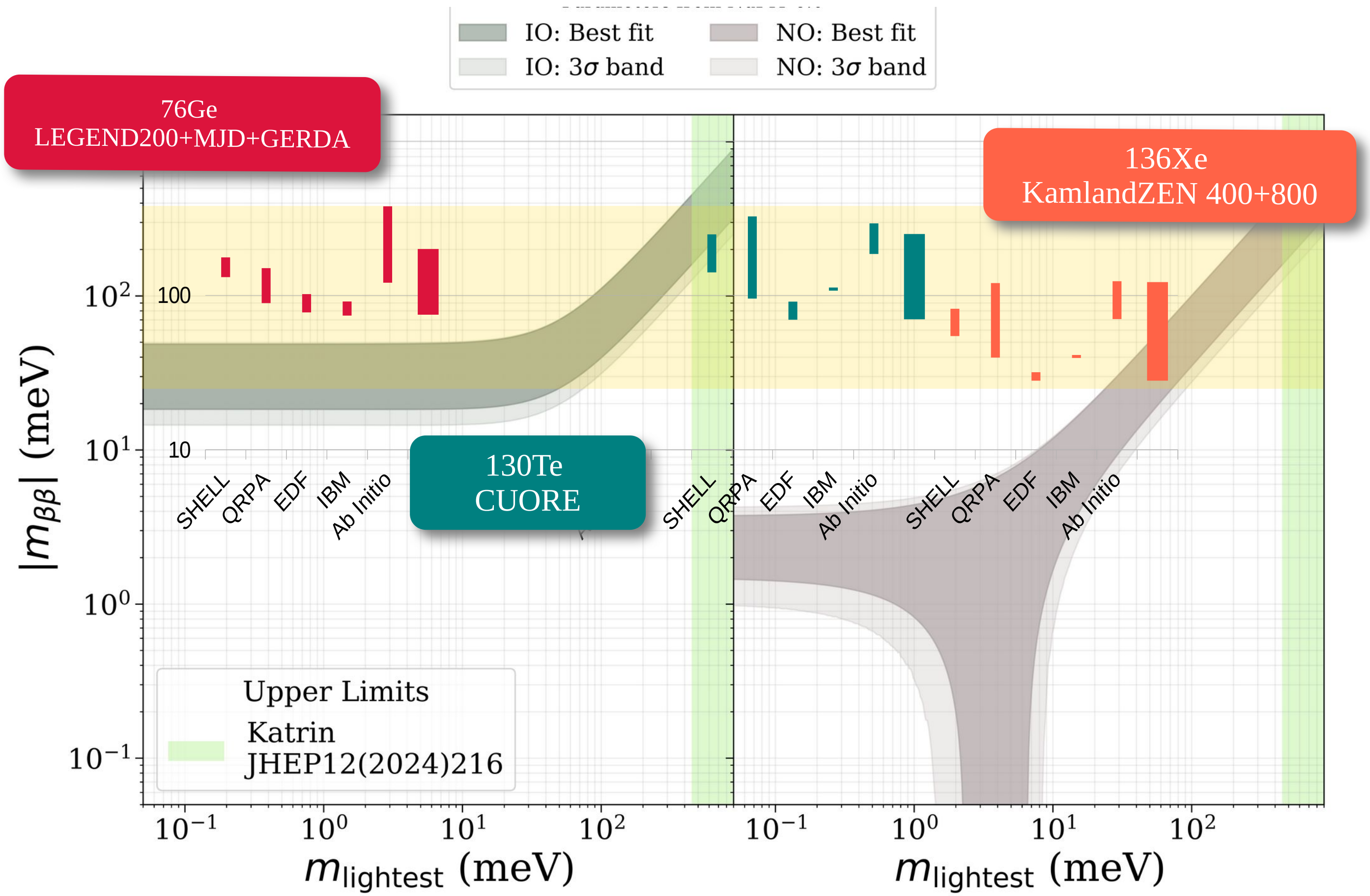
N. B. Cosmology could be added too ...



$m_{\beta\beta}$ bounds from other observables

(3) $0\nu\beta\beta$ results

TAUP 2025
$0\nu\beta\beta$ results



Experiments

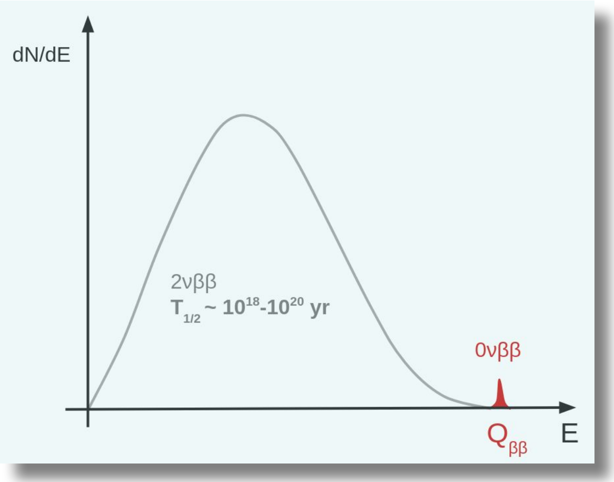
Isotope

- Feasibility of enrichement
- $Q_{\beta\beta}$ (high $Q_{\beta\beta}$ → large phase space + low background)

Tecnology

- Energy resolution
- Active Background Rejection
- Scalability

Signature



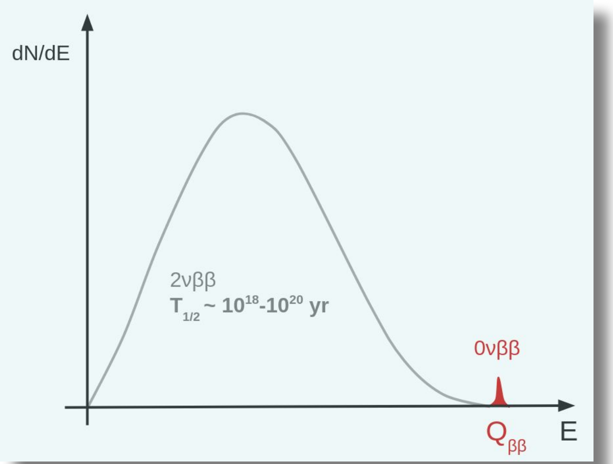
Experiments

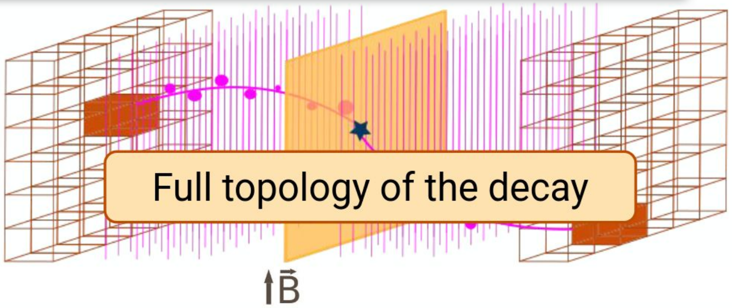
SUPRENEMO ^{82}Se $Q_{\beta\beta}$ = 3 MeV

Isotope
- Feasibility of enrichement
- $Q_{\beta\beta}$ (high $Q_{\beta\beta}$ → large phase space + low background)

Tecnology
- Energy resolution
- Active Background Rejection
- Scalability

Signature

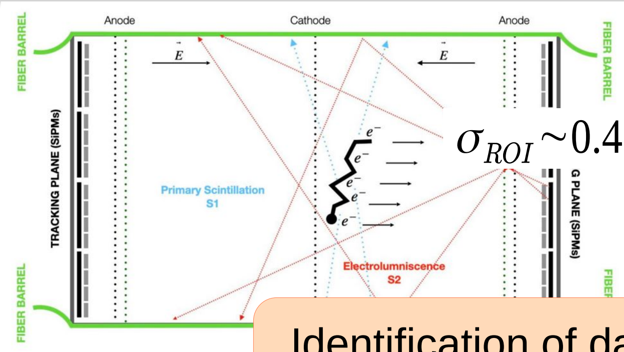




Full topology of the decay

1. ββ source foil: free choice of solid isotopes
2. Tracker: charged particles' trajectory and angular distribution
3. Calorimeter : particle's individual energy and time of flight

NEXT ^{136}Xe $Q_{\beta\beta}$ = 2.4 MeV



$\sigma_{ROI} \sim 0.4\% \rightarrow 10\ keV$

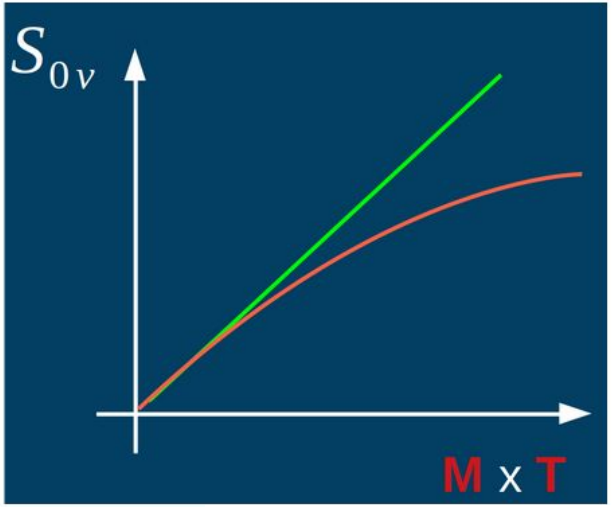
Identification of daughter – Ba tagging (luminescence)

Sensitivity requirements for future experiments

- **Exclusion sensitivity** = assume there is no signal, the 90% C.L. upper limit on halflife
- **Discovery sensitivity** = assume there is a signal, the 3σ value for halflife

Ingredients are:

- Mass (i.e. number of candidates)
- Time
- ΔE=ROI width → FWHM energy resolution
- Background counting rate → counts/ΔE/M/T



N.B. I will use ckky for B
i.e. counts /(keV kg yr)

$$S_{0\nu\beta\beta} \propto \sqrt{\frac{M \times T}{B \times \Delta E}}$$

"zero bkg" → M x T x B x ΔE < 1

$$S_{0\nu\beta\beta} \propto M \times T$$

^{136}Xe based 0νββ experiments:

$Q_{\beta\beta}$ = 2.4 MeV

i.a. 8.87%

gas, scintillator

Two tecnologies adopted so-far:

→ diluted in liquid scintillator (**KamLAND-ZEN**)

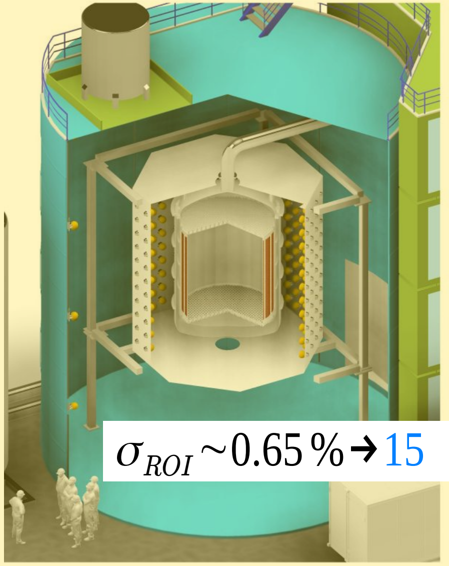
→ single phase TPC liquid (**EXO**) or gas (**NEXT**)

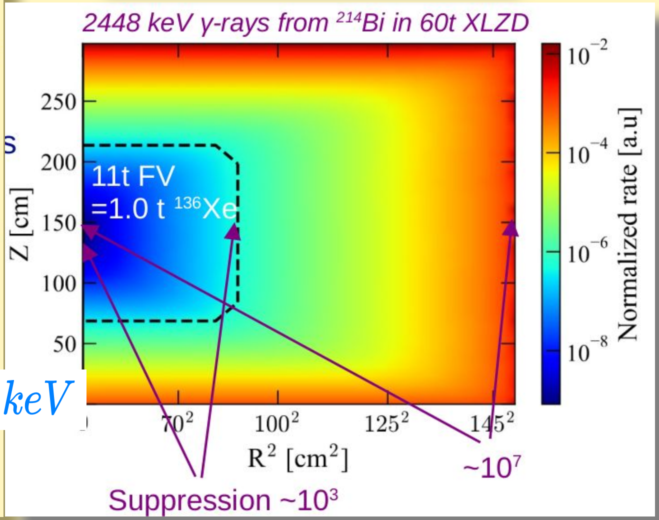
future:

→ dual-phase Xe TPC for DM searches will have large volumes PandaX-xT (43 ton) XLZ (60 ton) use **huge amount of natural Xe → sizable ^{136}Xe fraction**

→ ^{136}Xe diluted in LAr TCP (DUNE far detectors = 17 kton/module)

M. Schumann – XLZD
DBD Summit May 2025

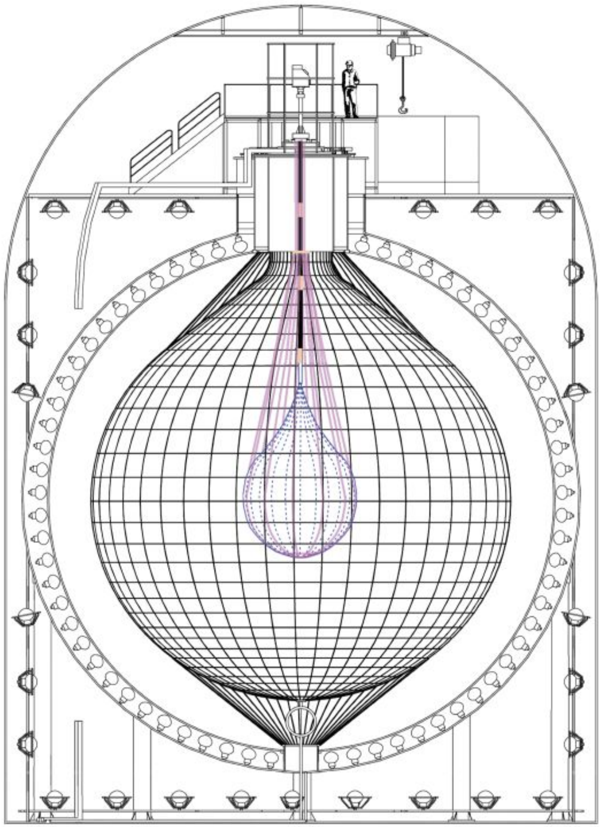




$\sigma_{ROI} \sim 0.65\% \rightarrow 15\ keV$

KamLAND-ZEN

Phased Experiment KZ-400 → KZ-800 → KZ-2



@ KAMIOKA ~2700 m.w.e

VETO = Water Cherenkov

DETECTOR = LS + PMT

Energy Resolution $\frac{6.7\%}{\sqrt{E(MeV)}}$ → $\sigma_{ROI} \sim 100\ keV$

Vertex Resolution $\frac{13.7\ cm}{\sqrt{E(MeV)}}$

KZ-800 arXiv 2406.11438

SOURCE = Inner Baloon = LS + enriched Xe (90% ^{136}Xe)

Fiducial Volume and time-position cuts used to remove background
- relevant cosmogenic contribution due to shallow depth.

KamLAND-ZEN

2010	2012	2014	2016	2018	2020	2022	2024	2028	2030	2032	2034

ZEN-400 320 kg → ZEN-400 381 kg → ZEN-800 745 kg

LXe purification
- ^{100m}Ag removed

New Inner Balloon
- more Xe
- better radioactivity

- **Limited energy resolution** → full background reconstruction needed to extract 0νββ

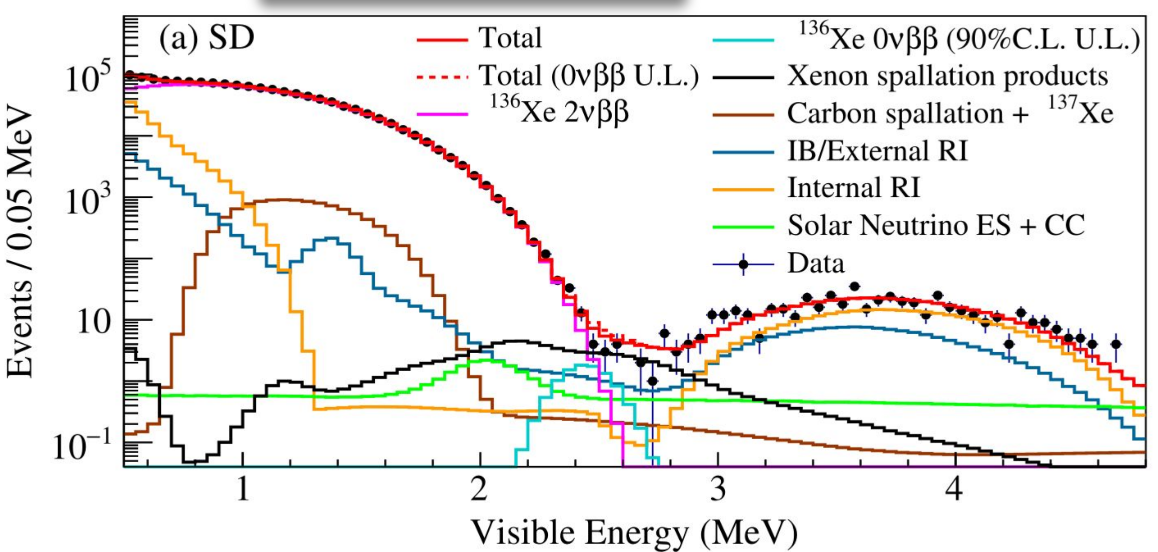
KamLAND-ZEN 400+800

$T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ yr

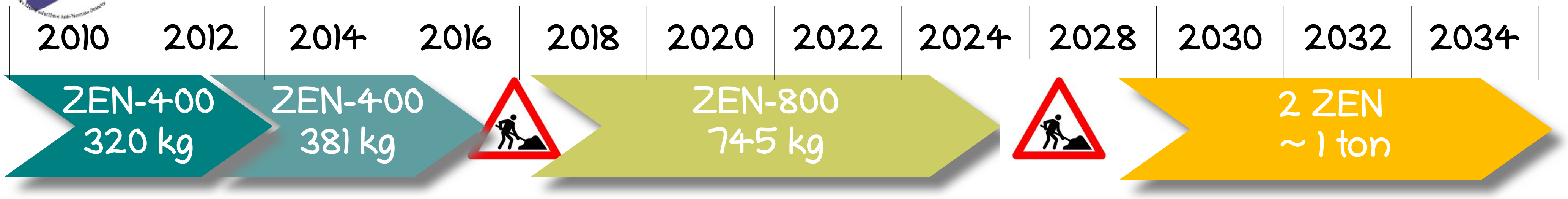
$S_{1/2}^{0\nu} = 2.6 \times 10^{26}$ yr

→ $m_{ee} < 28\text{-}122$ meV

KZ-800 arXiv 2406.11438



KamLAND-ZEN



KamLAND 2 ZEN - Major Upgrade

Major Upgrade that aims at 5 times better sensitivity with similar isotope mass

Main Factors Driving the new phase are

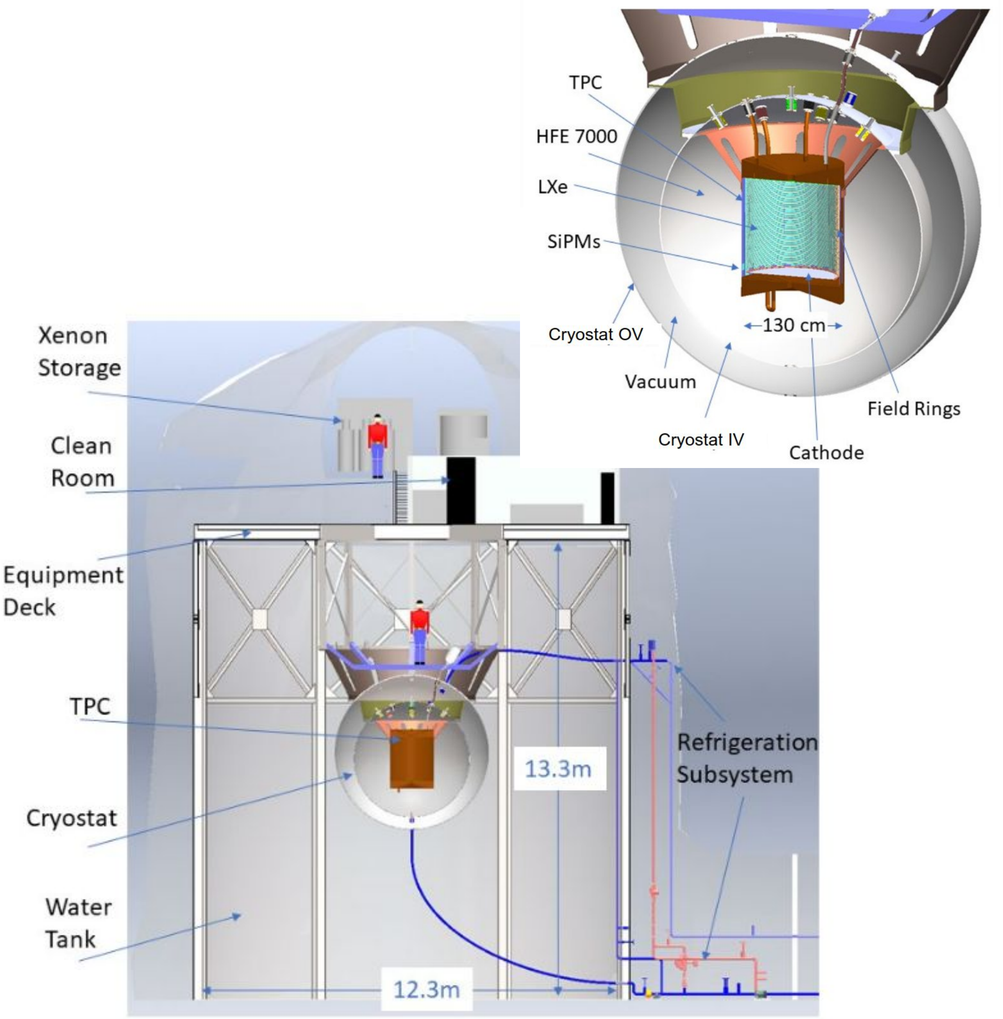
- improve energy resolution (new PMT+mirrors) σ_{ROI} 4% to 2%
- reduce radioactivity (new OuterBalloon)
- improve background rejection (change LS in IB+ dead-time free electronics)

KamLAND2-Zen Goal

$S_{1/2}^{0\nu} \sim 2 \times 10^{27}$ yr in 5 yrs

$\rightarrow m_{ee} < 12\text{-}53$ meV

n-EXO



@ SNOLab ~5890 m.w.e

VETO = 1.5 kton Water Cherenkov - μ tagging and shielding

DETECTOR Liquid Xe single phase TPC

- **Ligth** (175 nm) → 4.5 m2 SiPM
- **Charge** = segmented anode

$\sigma_{ROI} \sim 1.2\% \rightarrow 30\ keV$

- Bkg rejection using topology

SOURCE 5 tonne LXe enriched 90% ^{136}Xe

nEXO

2010	2018				2034		2037				2045

EXO-200
200 kg enrXe

EXO-200 @ WIPP

- BI ~ 2 x 10^{-3} ckky → $S_{1/2}^{0\nu}$ = 5 x 10^{25} yr
- $T_{1/2}^{0\nu}$ > 3.5 x 10^{25} yr → m_{ee} < 93-286 meV

nEXO

2010 | 2018 | T. Brunner DBD Summit Heilderberg 2025 | 2034 | 2037 | 2045

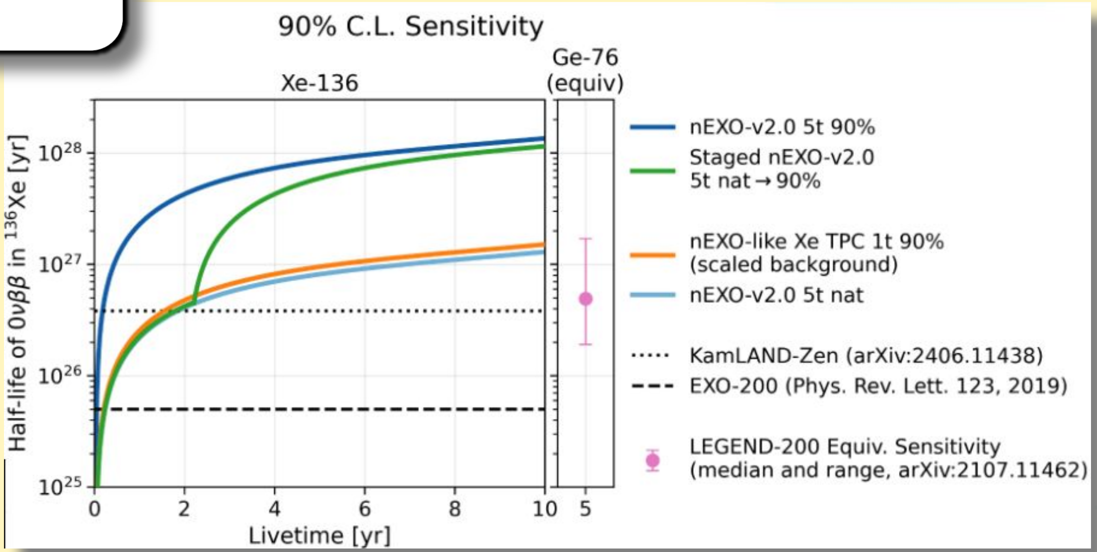
EXO-200
200 kg enrXe

nEXO
5 ton natXe

nEXO
5 ton enrXe

NEXOv2.0 5 ton Goal

$S_{1/2}^{0\nu} \sim 1 \times 10^{28}$ yr - 10 yrs → $m_{ee} < 5\text{-}23$ meV



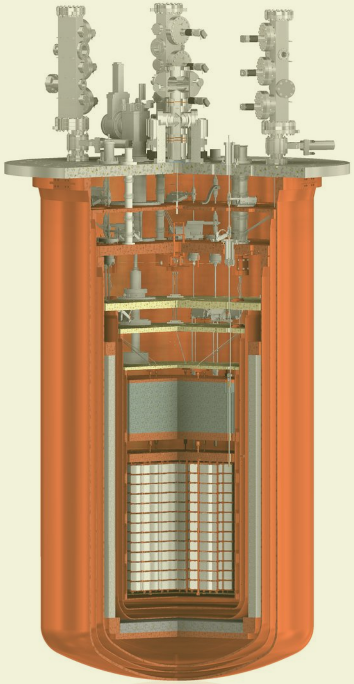
^{130}Te based $0\nu\beta\beta$ experiments:

$Q_{\beta\beta}$ = 2.5 MeV

i.a. 34%

High isotopic abundance, natural Te is already a good source

→ Te use pioneered with Low Temperature Calorimeters (Bolometers)

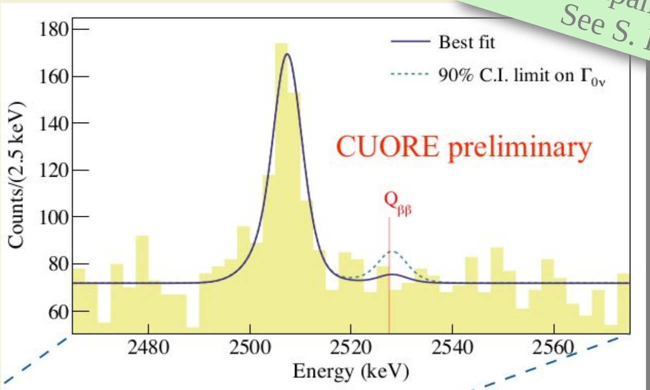


CUORE @ LNGS (~3800 m.w.e) :

- 988 TeO_2 bolometers in operation since 2017
- 742 (206) kg TeO_2 (^{130}Te)
- High Energy Resolution

$$\sigma_{ROI} \sim 0.1\% \rightarrow 2\ keV$$

- No active bkg rejection



A. Campani TAUP 2025
See S. Fu's talk

CUORE - 2 ton yr

BI ~ 1.4 x 10^{-2} ckky → $S_{1/2}^{0\nu}$ = 4.4 x 10^{25} y

$T_{1/2}^{0\nu}$ > 3.5 x 10^{25} yr → m_{ee} < 70-250 meV

^{130}Te based 0νββ experiments:

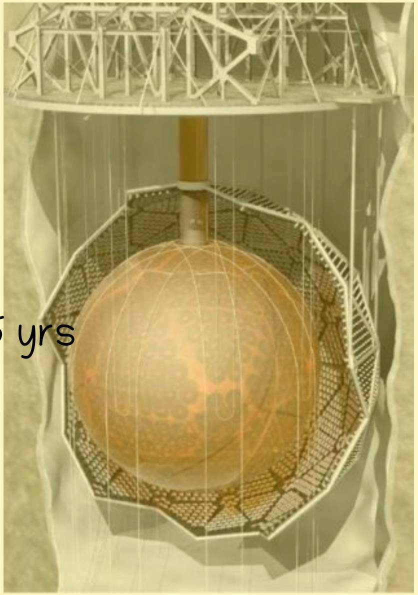
$Q_{\beta\beta}$ = 2.5 MeV

i.a. 34%

- High isotopic abundance, natural Te is already a good source → load a Liquid Scintillator

G. Li TAUP 2025

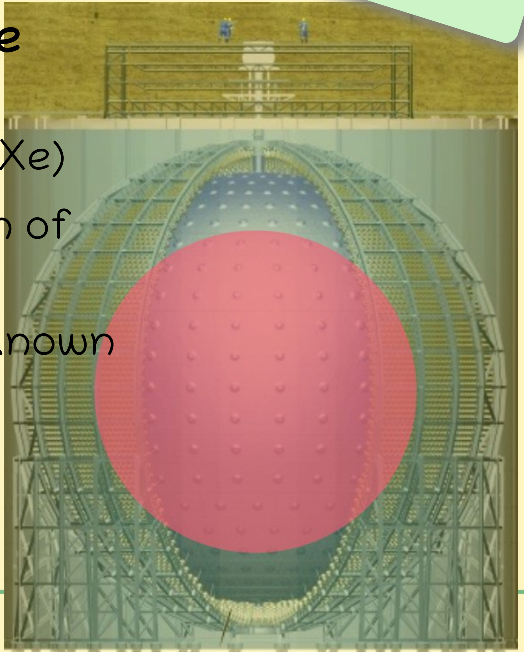
SNO+ @ SNOLab ~5890 m.w.e



- ~4 tonnes of natTe
- $\sigma_{ROI} \sim 3\% \rightarrow 75\ keV$
- $S_{1/2}^{0\nu} \sim 1 \times 10^{27}$ yr in 5 yrs

JUNO @ Jangmen ~1800 m.w.e

- 20 kton LS - upt to 100 ton Te(Xe)
- 0νββ searches after completion of oscillation studies (2030)
- radioactive background still unknown



^{76}Ge based 0νββ experiments:

$Q_{\beta\beta}$ = 2.0 MeV

i.a. 7.75%

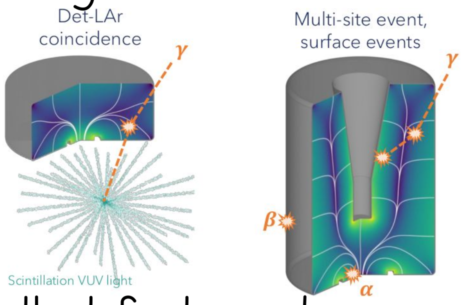
semiconductor

Exploit a long-standing industrial technnology HPGe diodes

- Excellent Radiopurity
- High Energy Resolution $\sigma_{ROI} \sim 0.05\,\% \rightarrow 1\ keV$
- Pulse Shape Discrimination

(fully compensate the disadvantage of a Low $Q_{\beta\beta}$)

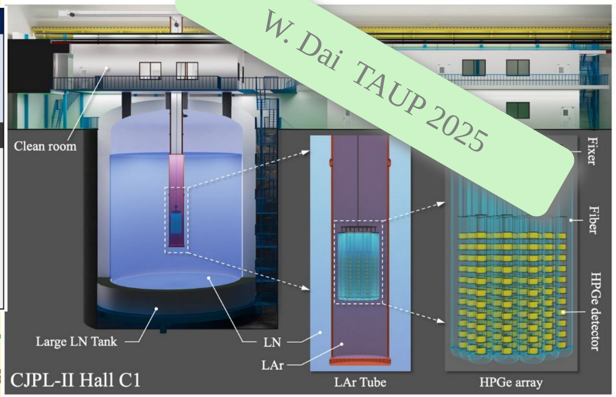
→ **LEGEND** = Majorana + GERDA merged using the most succesful technologies



- Operation in LAr
- Inverted Coaxial Diodes that features large mass and excellent discrimination

→ **CEDEX-300** = evolution of a DM program @ CJPL (China), experiment desing and goal similar to LEGEND-200

Physics Goal	
0νββ half-life	3.06×10^{27} yr (exc) 1.91×10^{27} yr (dis)
Effective mass	18.5 ~ 44.2 meV (exc) 23.4 ~ 55.8 meV (dis)
Detector Parameter	
Detector mass	225 kg
Operation time	10 yr
Ge-76 enrichment	≥ 86%
Signal efficiency	76%
Background level	1E-4 cpkky
Energy resolution	2.5 keV FWHM



W. Dai TAUP 2025

From LEGEND 200 to LEGEND 1000

LEGEND-200

GERDA infrastructure

up to 200 kg enrGe

@ **LNGS** (~3800 m.w.e)

VETO

- Water Cherenkov
- Cryostat filled with LAr + underground LAr (no ^{42}Ar) in detector proximity

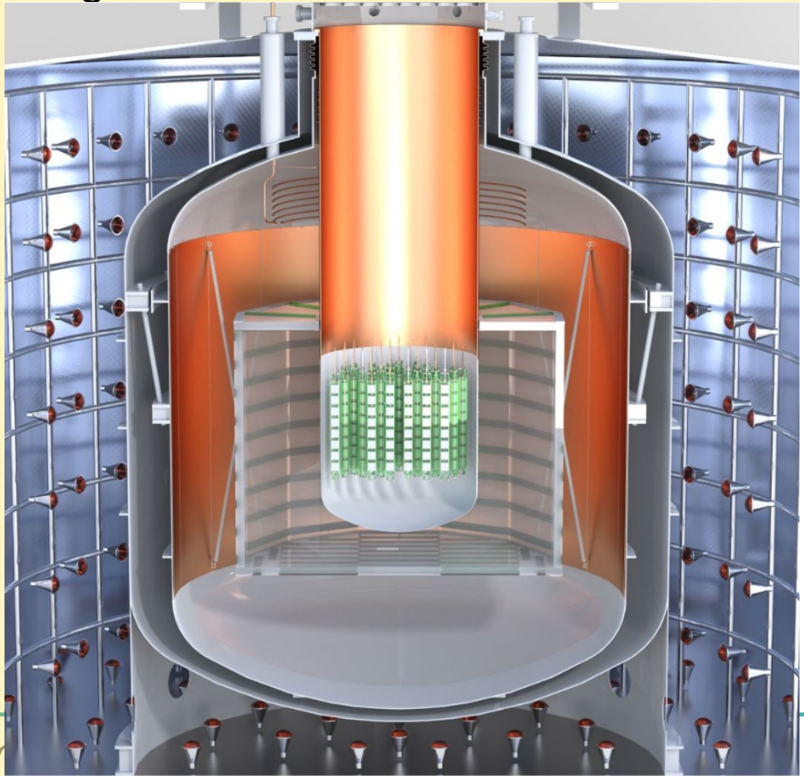
DETECTOR

- IC Ge diodes ^{76}**Ge >90%**
- enable easy and safe phased deployment

LEGEND-1000

new infrastructure @ LNGS Hall C

1000 kg enrGe

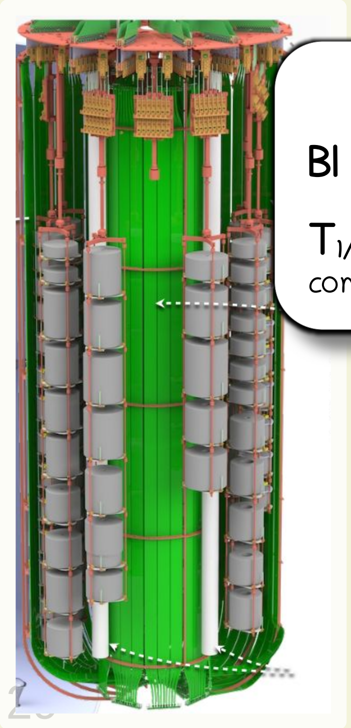


arXiv:2505.10440v3 – A. Garfagnini TAUP 2025

LEGEND-200 @LNGS Hall A
GERDA infrastructure

2023	2024	2025							2032		2034		2036	

Run #1



LEGEND-200 Run #1

BI = $5^{+3}_{-2} \times 10^{-4}$ ckky ("golden data" - BI ~ GERDA)

$T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr ($S_{1/2}^{0\nu} = 2.8 \times 10^{26}$ yr)
combined with GERDA & MJD

Garfagnini TAUP 2025

LEGEND-200 @LNGS Hall A
GERDA infrastructure

2023	2024	2025		2032	2034	2036

Run #1

Future Phase
~160 kg IC + few BEGe

campaing to identify excess contamination

LEGEND-200 Goal - 1 ton x yr

BI ~ 2 x 10^{-4} ckky

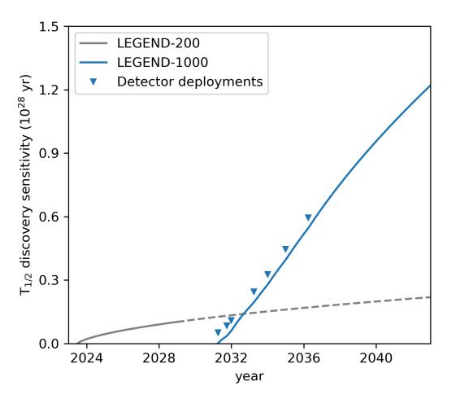
$S_{1/2}^{0\nu}$ ~ 1 x 10^{27} → m_{ee} < 30-70 meV

LEGEND-200 @LNGS Hall A
GERDA infrastructure

2023 2024 2025 2032 2034 2036

new infrastructure
isotope/detectors

LEGEND-1000 @ LNGS Hall C
detector phased deployment



LEGEND-200 Goal - 1 ton x yr

BI =2 x 10^{-4} ckky

$S_{1/2}^{0\nu} > 2 \times 10^{27}$ → m_{ee} < 30-70 meV

LEGEND-1000 goal - 10 ton x yr

BI ~ 1 x 10^{-5} ckky

$S_{1/2}^{0\nu} \sim 1 \times 10^{28}$ → m_{ee} < 10-23 meV

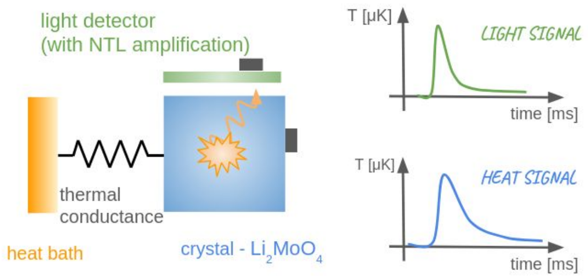
^{100}Mo based 0νββ experiments:

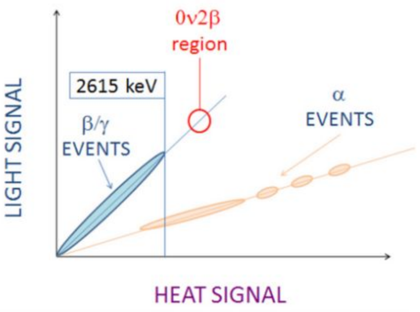
$Q_{\beta\beta}$ = 3.0 MeV

i.a. 9.82%

$T_{1/2}^{2\nu}$ ~ 7.1 x 10^{18} yr

- High $Q_{\beta\beta}$ → large phase space, lower background
- Scintillating bolometer technnology e.g. using Li_2MoO_4 crystals
  - Excellent Radiopurity
  - High Energy resolution
- Alpha Background Rejection with Light/Heat





CUPID and AMORE different solution for the signal read-out

CUPID = Ge thermistor as in CUORE

AMORE = MMC (better performances reproducibility and read-out more challenging)

CUPID CUORE Upgrade with Particle IDentificaiton

@ LNGS (~3800 m.w.e)

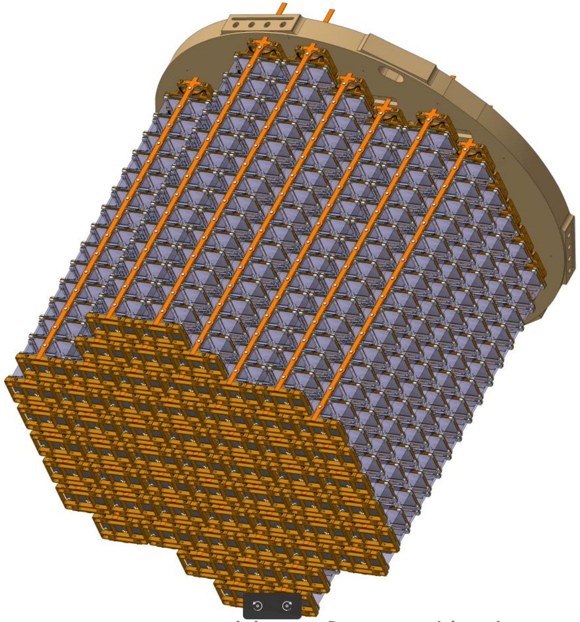
Reuse CUORE infrastructure (cryostat & shields)

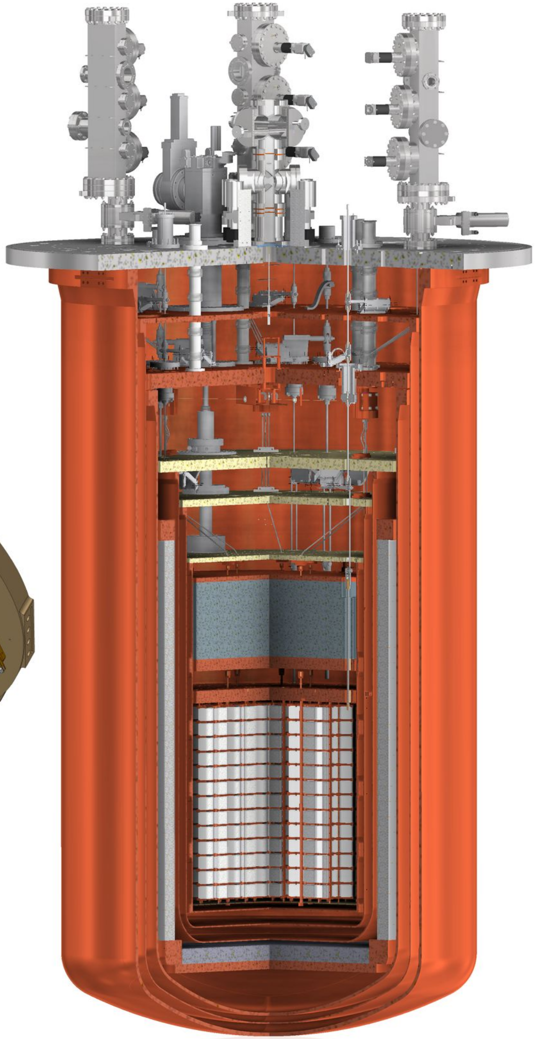
- upgrade of cryogenic system
- add μ veto (plastic scintillators)

DETECTOR

1596 Li_2MoO_4 scintillating bolometers
→ **240 kg ^{100}Mo >95%**

- Heat signal $\sigma_{ROI} \sim 0.07\,\% \rightarrow 2\ keV$
- Light signal alpha rejection





CUPID

2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036

CUORE

CUPID stage I

CUPID stage I:
80 kg 100Mo

CUPID stage II:

CUPID full experiment
240 kg 100Mo

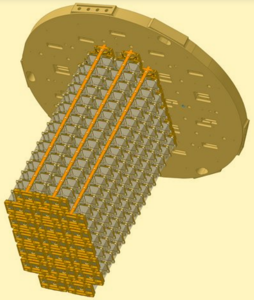
Precursors:

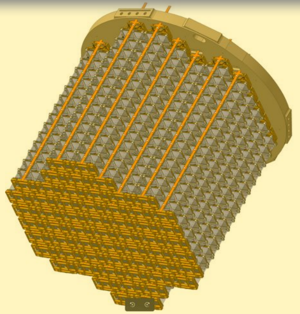
CUPID-0 & CUPID-Mo

- scintillating bolometer technology

CUORE

- operation of large bolometric arrays
- infrastructure BI in ^{100}Mo ROI ~ 10^{-4} ckky (removing μ & α)





CUPID goal - 450 kg x yr

BI ~ 1 x 10^{-4} ckky

$S_{1/2}^{0\nu}$ ~ 1 x 10^{27} → m_{ee} < 12-21 meV

AMORE

2020		2023	2028	2026	2030	2031	2032	2033	2034	2035	2036

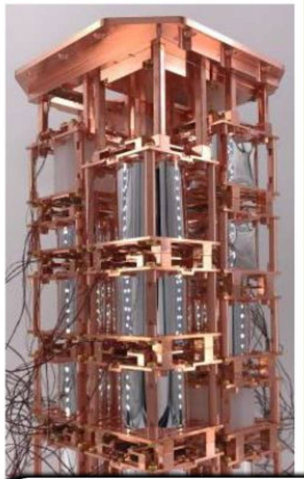
AMORE-I

AMORE-II stage I
~15 kg ^{100}Mo

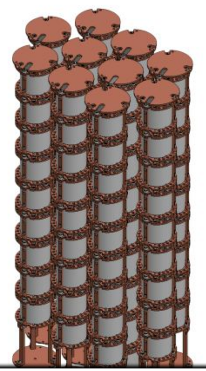
AMORE-II stage I
~85 kg ^{100}Mo

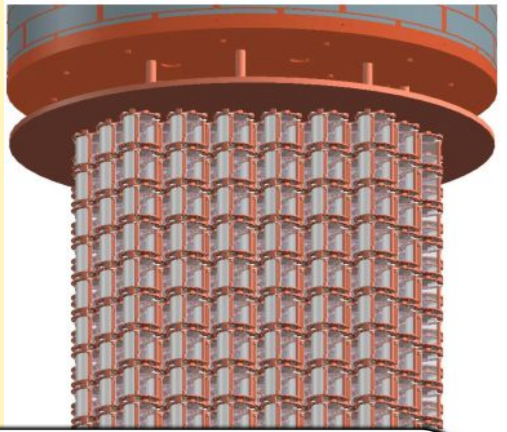
@Yemilab (700 m)

@Yemilab (~2500 m.w.e)



- ^{100}Mo > 95% scintillating bolometers
- MMC read-out





AMORE II - 4 kg (^{00}Mo) yr

BI = 2.5 x 10^{-2} ckky

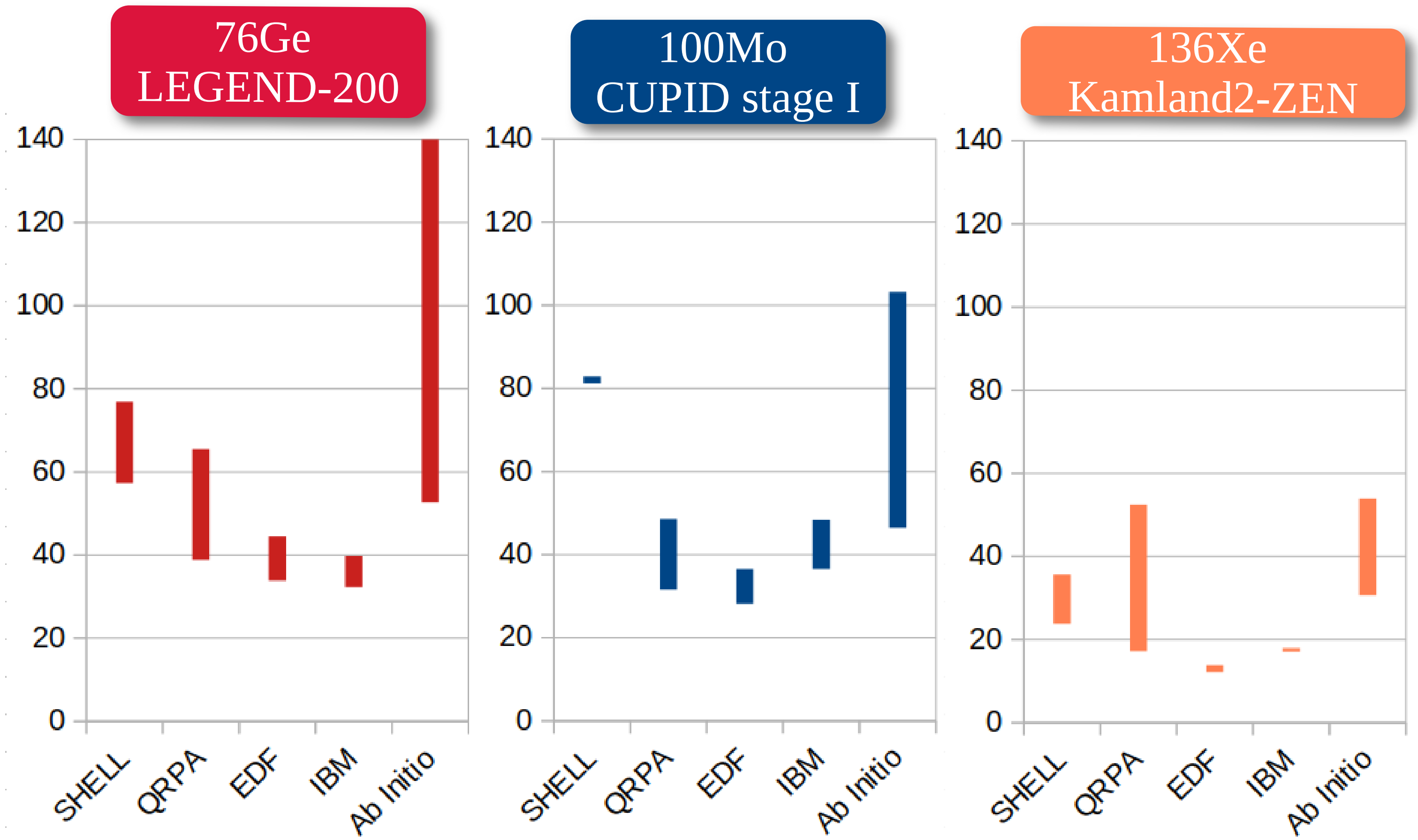
$T_{1/2}{}^{0n}$ > 2.9 x 10^{24} → m_{ee} <210-610 meV

AMORE II - 85 kg (^{00}Mo) yr

BI ~ 10^{-4} ckky

$T_{1/2}{}^{0n}$ > 4 x 10^{26} → m_{ee} <210-610 meV

CONCLUSIONS: $m_{\beta\beta}$ [meV] results in 2030-2033



CONCLUSIONS: $m_{\beta\beta}$ [meV] results in ~2040