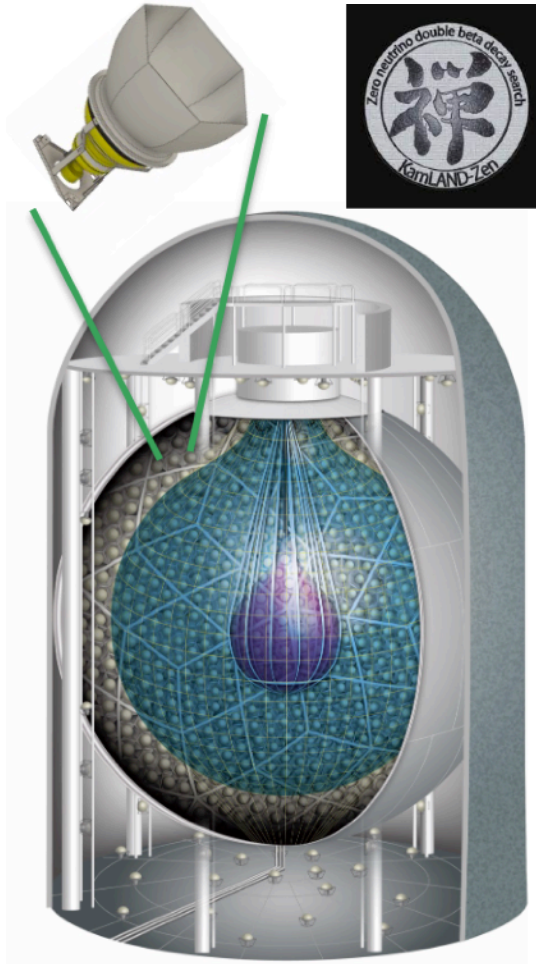




$0\nu\beta\beta$ - Status and R&D beyond next-generation



Neutrino - Majorana/Dirac particle?

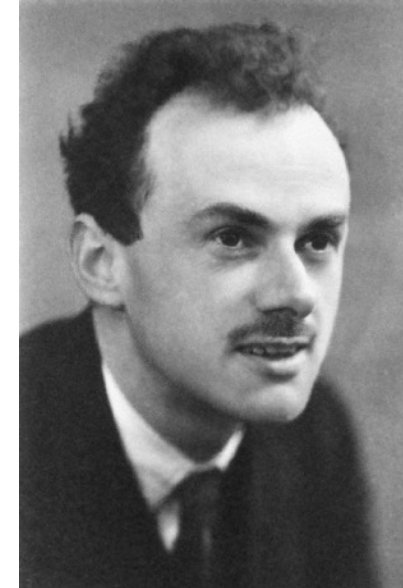
"Teoria simmetrica dell'elettrone e del positrone".
Il Nuovo Cimento. 14 (1937)

Neutrino mass scale

- Neutrinos are massive
- Mass scale is 6 orders below the mass of other leptons

Two theories - Majorana or Dirac ?

- Majorana - Allows Lepton Number Violation
Allows neutral leptons to be their own anti-particle
 - Potential to explain Baryogenesis through Leptogenesis matter generation
 - Potential to explain smallness of neutrino mass scale

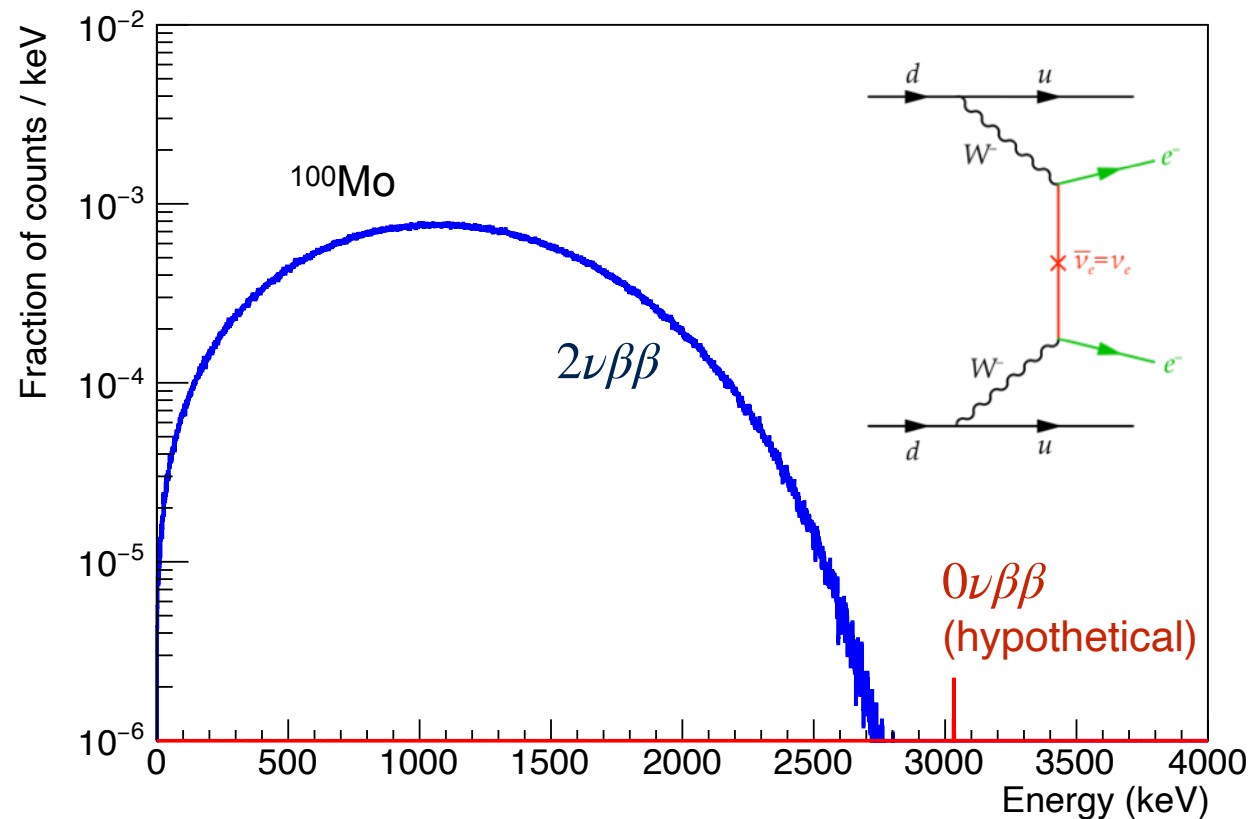
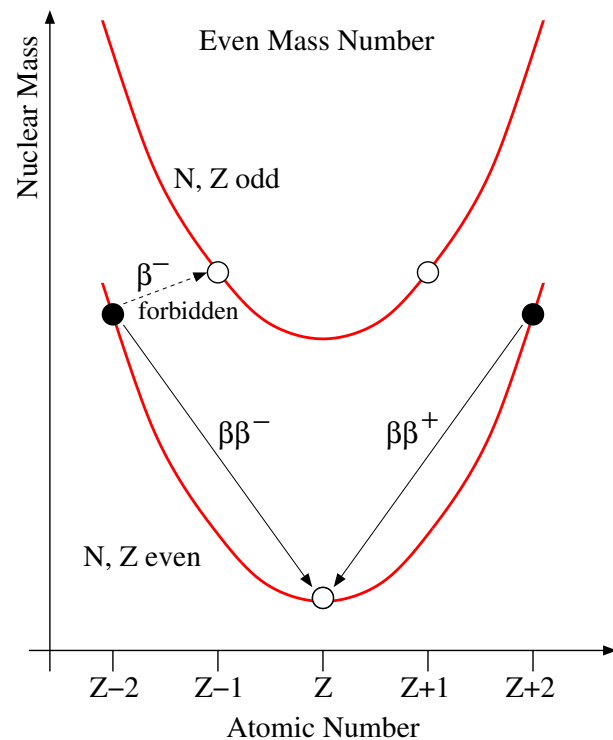
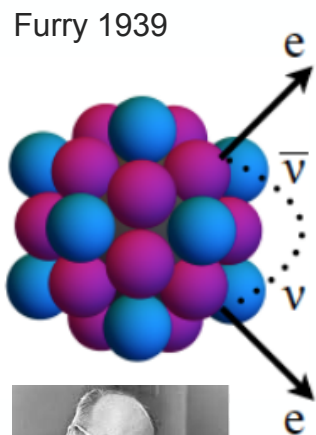


Majorana neutrino phenomenology - Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix: Majorana phases

Today
+ EW,
+ ν -Osc

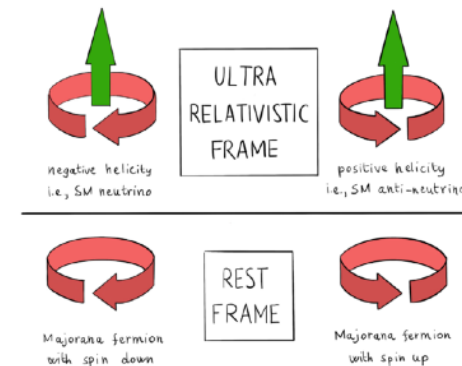
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinoless double beta decay



Observables / Implication

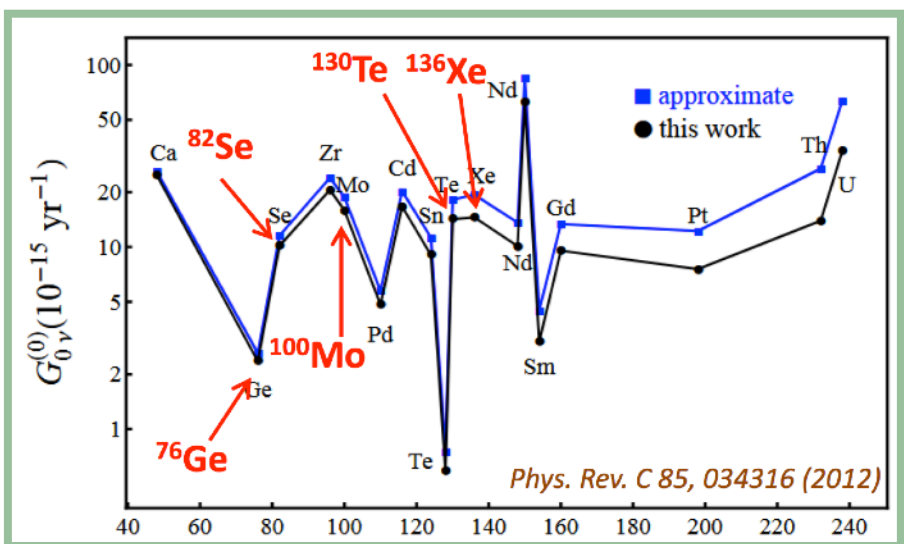
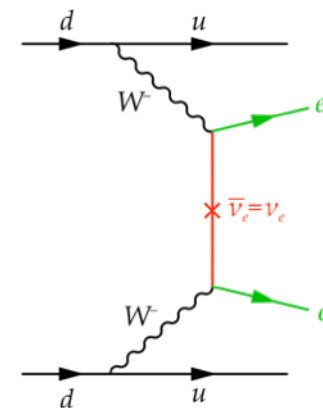
- $\Delta L = 2$, lepton number violation
- Creation of leptonic matter, without anti-matter



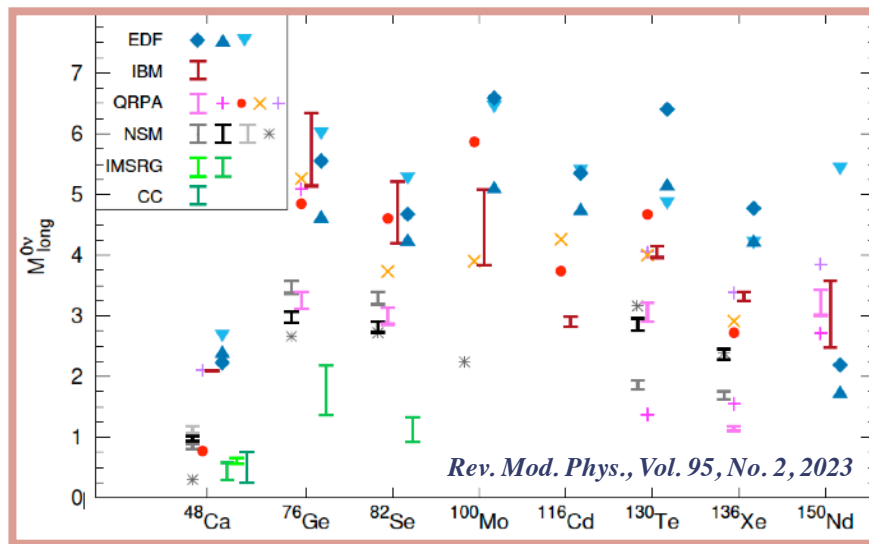
Neutrinoless double beta decay

Light Majorana neutrino exchange

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$



Phase space
Precisely calculable



Nuclear matrix element
Factor 3-4 uncertainty
Significant theory and exp. effort

Effective Majorana mass:

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} U_{e,i}^2 m_i \right|$$

Light Majorana neutrino exchange

Neutrino properties:
mixing angles,
CP and Majorana phases

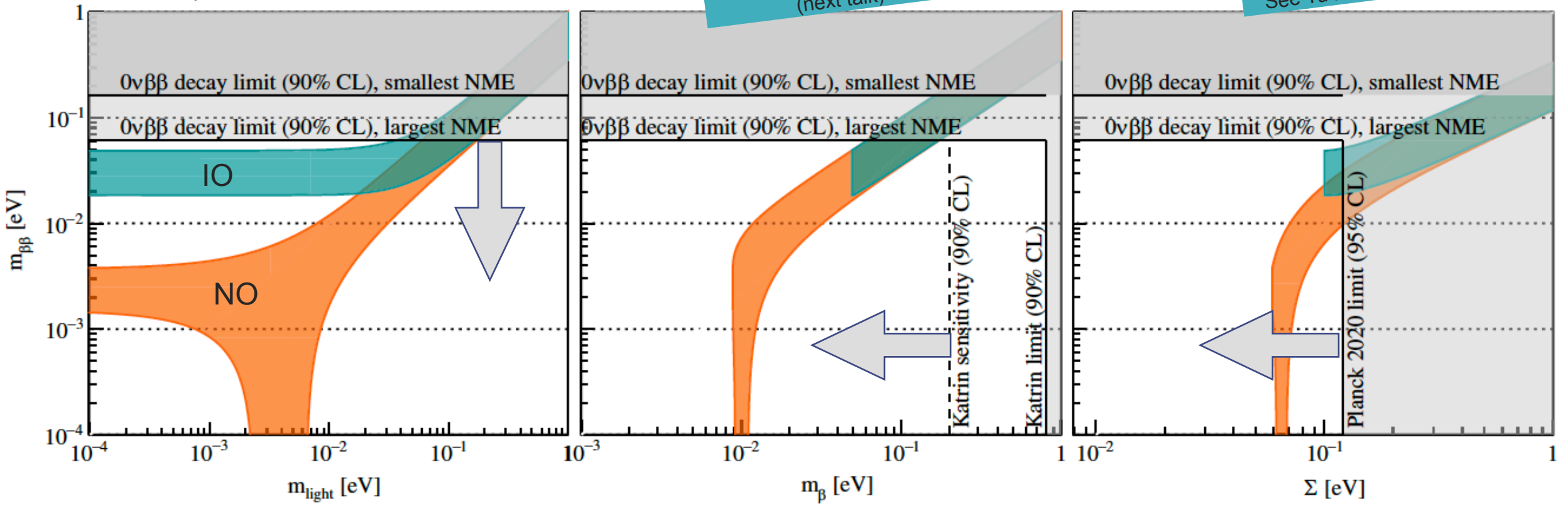
$0\nu\beta\beta$ parameter space



Rev. Mod. Phys., Vol. 95, No. 2, 2023

See Alessandro Schwemmer (next talk)

See Tu morning sessions



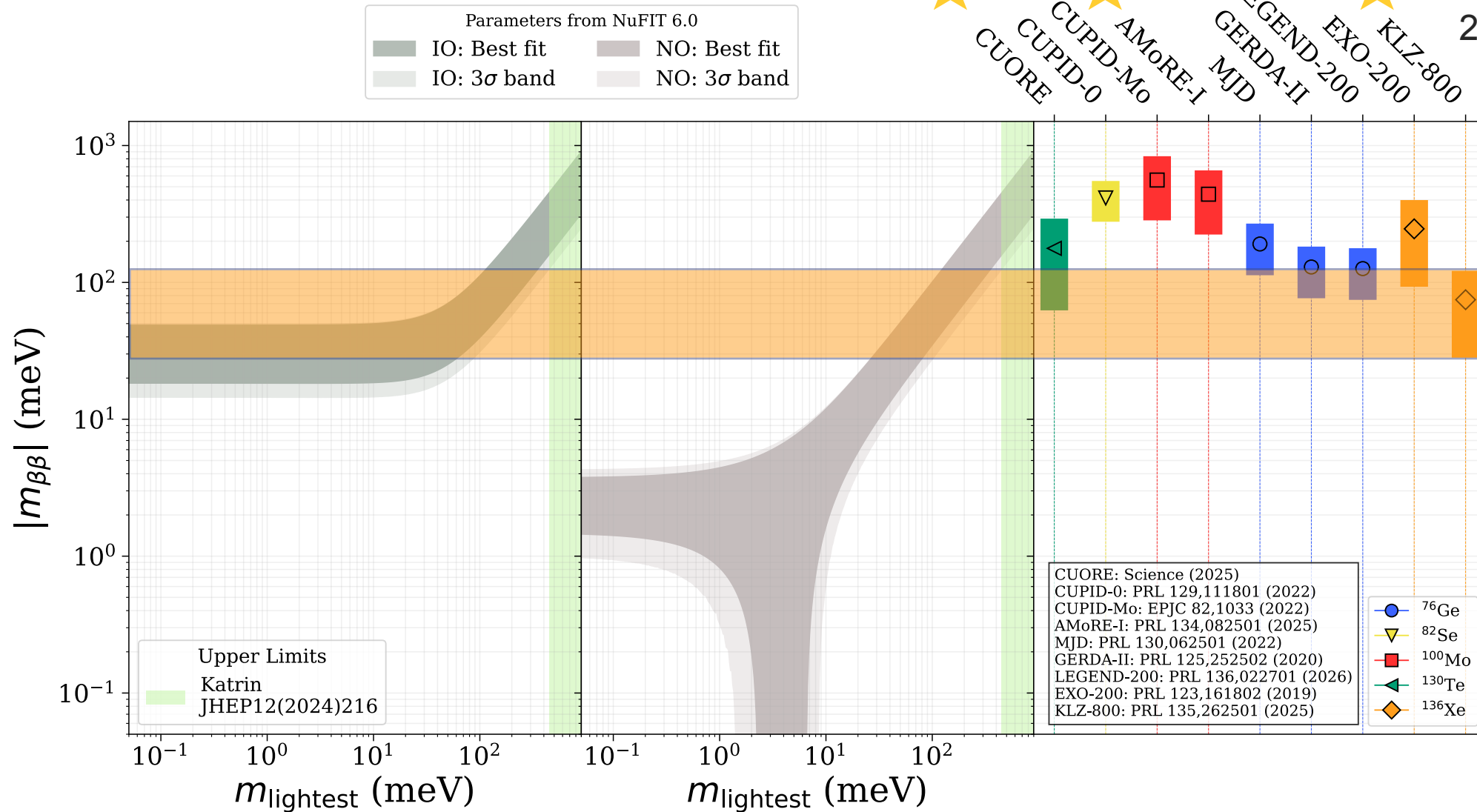
This talk $0\nu\beta\beta$

**β -decay endpoint/
mass measurements**

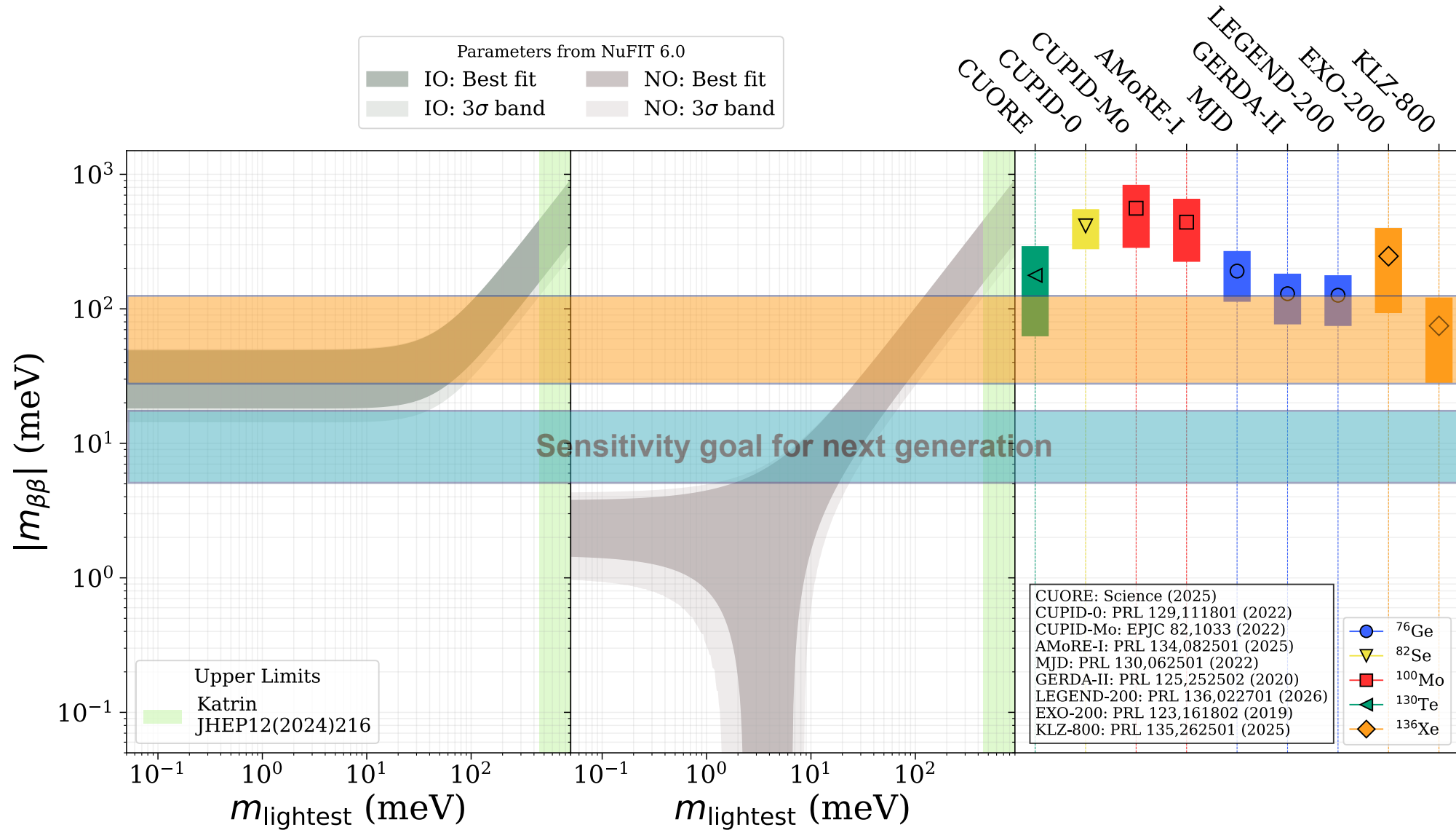
**Cosmological
bounds**

$0\nu\beta\beta$ Current status

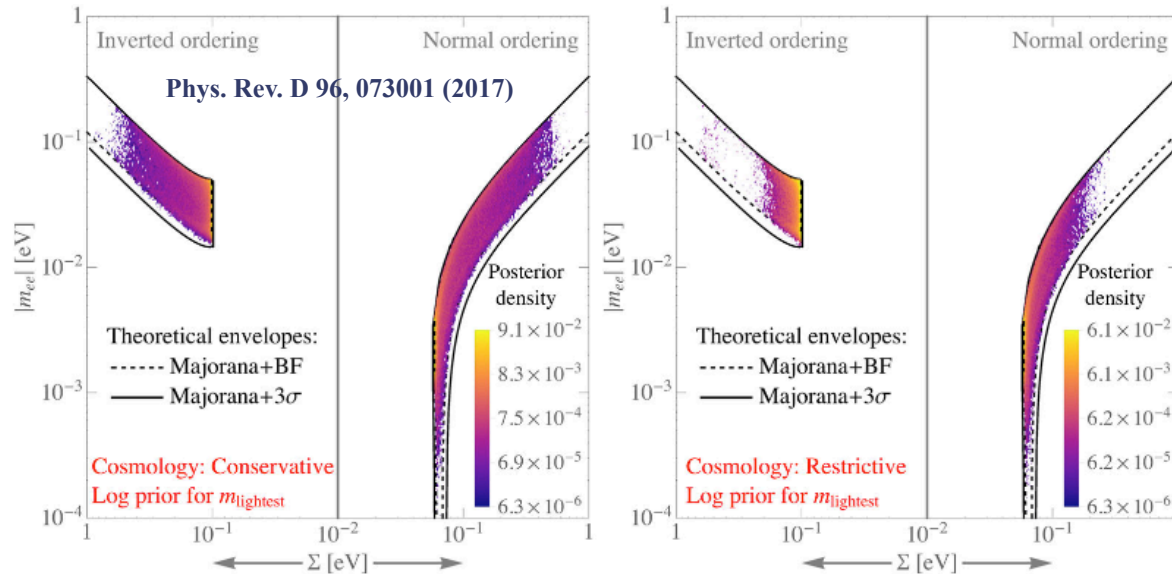
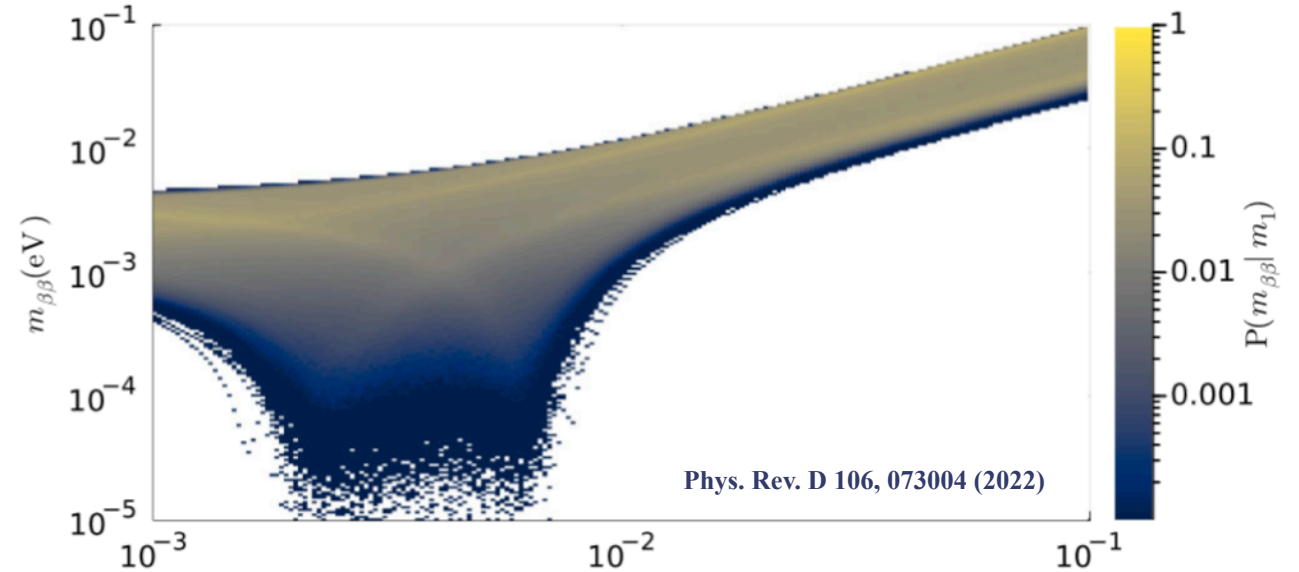
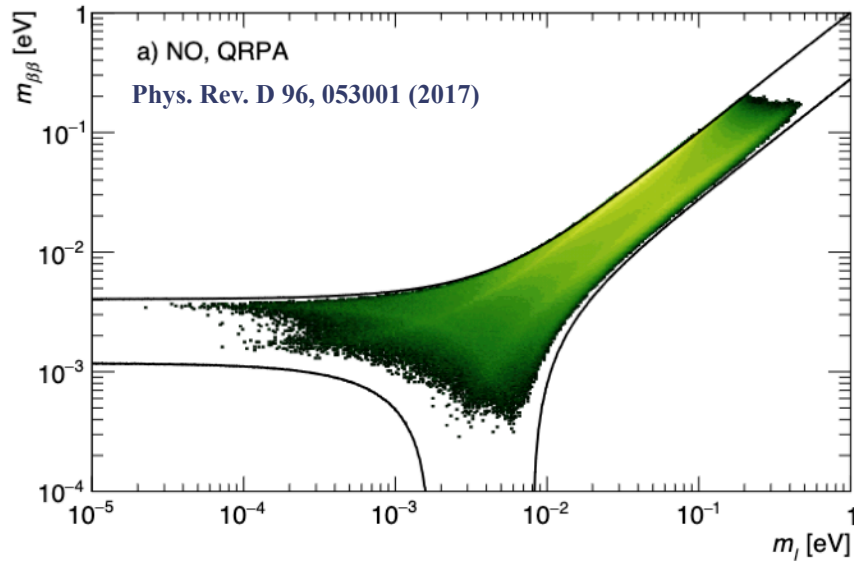
Published in
2025/2026



$0\nu\beta\beta$ Next generation



$0\nu\beta\beta$ - Next generation parameter space

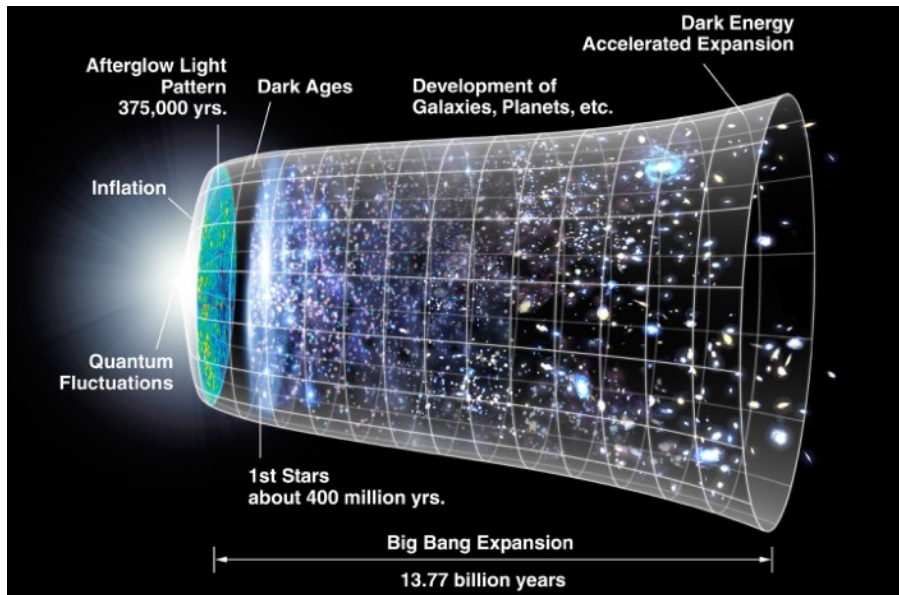


Bayesian analysis of discovery probabilities

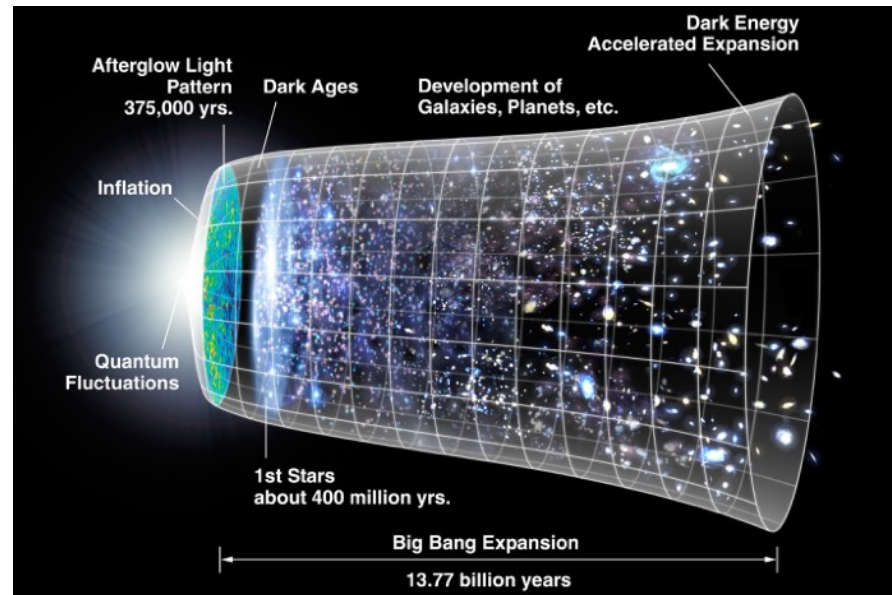
- Priors are important (log flat vs flat in m_1)
- Cosmological model/constraints are important
- Next generation experiments have discovery potential in NO
- Full cancellation Majorana mass is excessively fine-tuned

The experimental challenge

Probe a process with a half-life larger $> 10^{25}$ yr - 10^{26} yr



x



x 10^5 yr

Next generation experiments:

Need to find single events in a ton of isotope x year(s) of exposure!
Or search for an activity at the level of 3×10^{-14} Bq/g

We go to extreme length to limit ubiquitous radioactivity



15 Bq /
banana

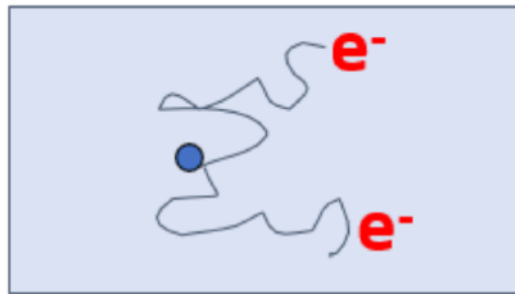
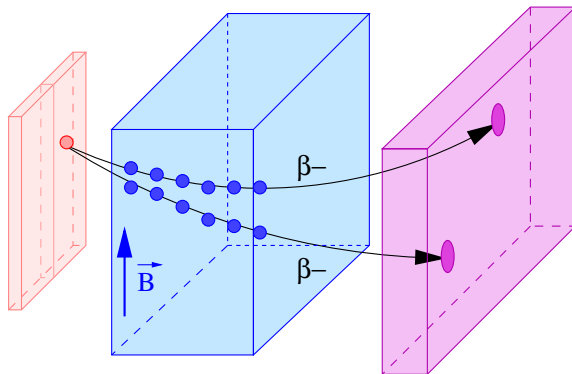
Common experimental challenges & techniques

Require isotope enrichment, large source mass O(1 t), good energy resolution, high signal efficiency and “zero” background

SuperNEMO Demonstrator @ LSM, taking data since 2025:

Source-Tracker-Calorimeter design for extra topology information -> Versatile & offers superb information for nuclear/particle physics, but difficult to scale/efficiency loss

Target: Leading Se results on exotic $0\nu\beta\beta$ modes with 17.5 kg/yr of exposure, (~3 yr, Rn free air required)

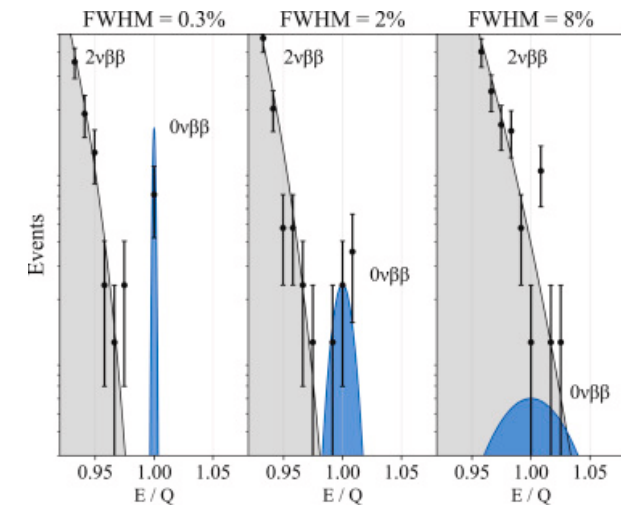


Source \subseteq Detector

Technology of choice for next generation experiments



Radiation Measurements 193 (2026) 107656



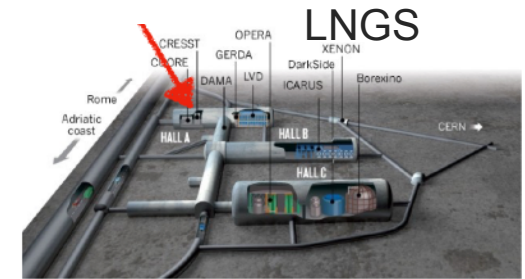
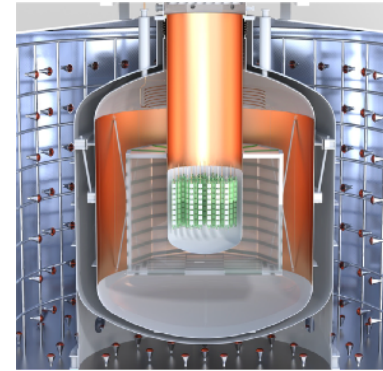
Experimental design features

Active & passive shielding

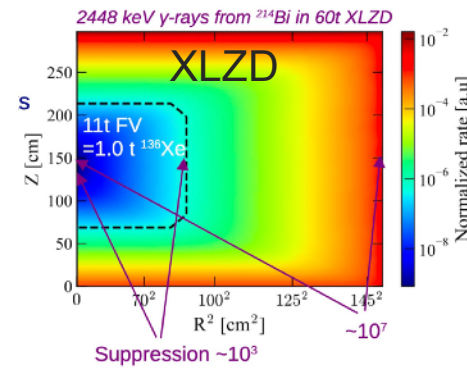
CUORE



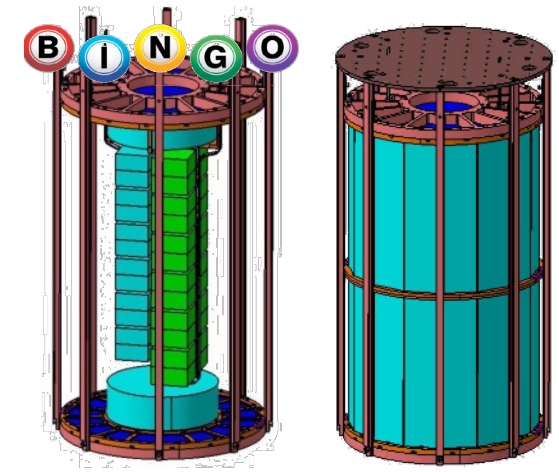
LEGEND



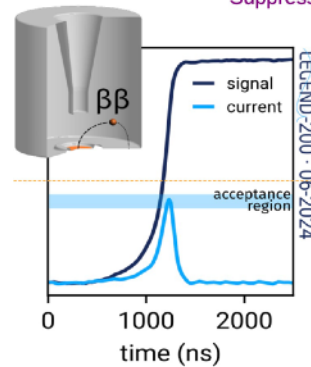
Implicit or dedicated inner active veto systems



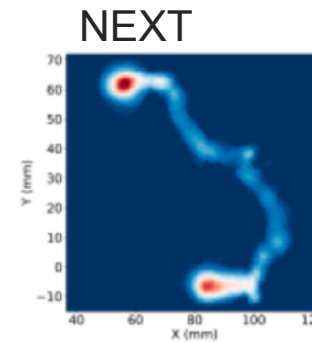
LEGEND



Leverage event topology information

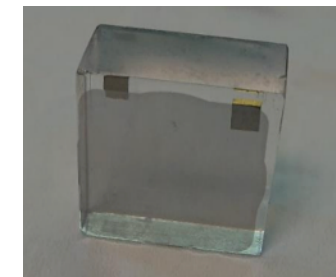


LEGEND



NEXT

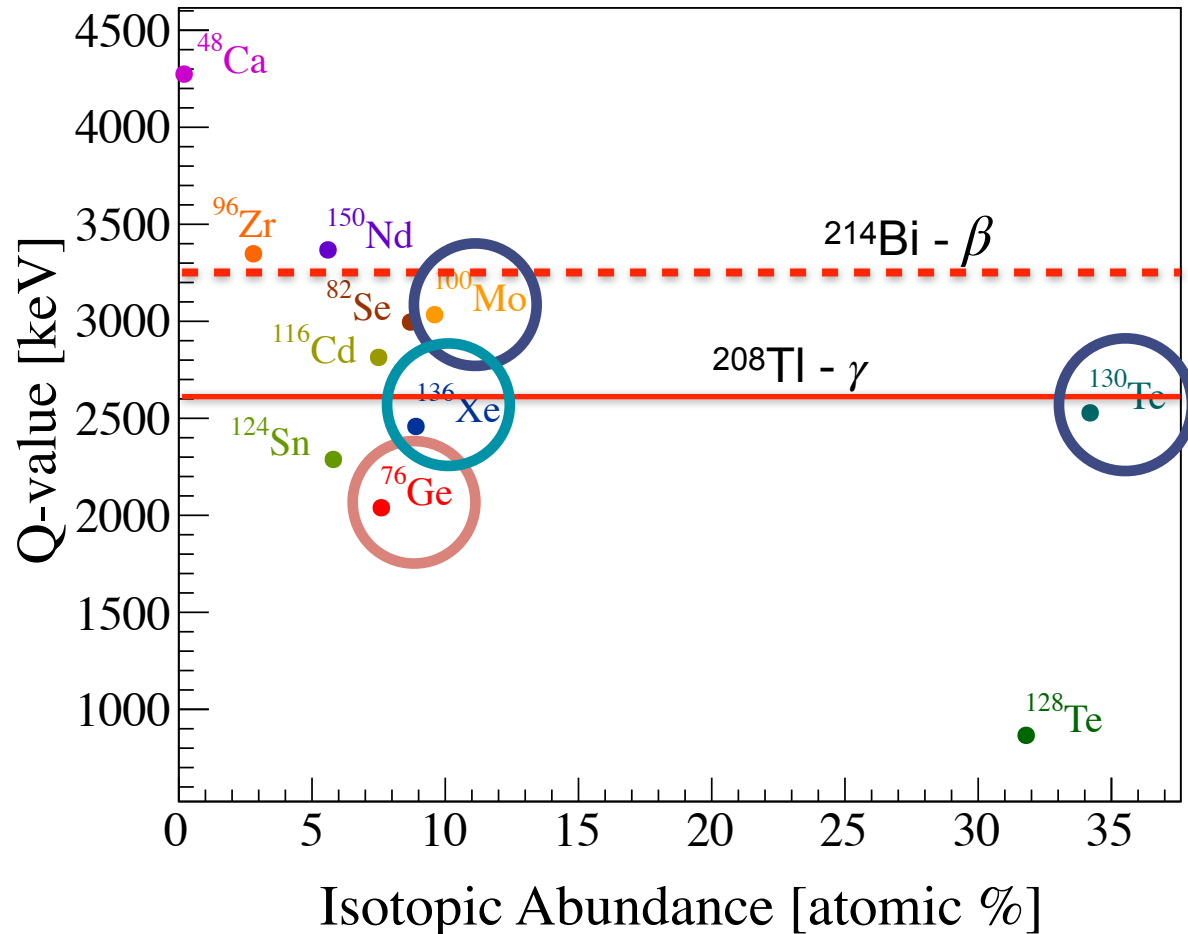
Benjamin Schmidt



CROSS R&D

Isotope choice

A set of “flagship” projects/isotopes



¹³⁶Xe: KamLAND-Zen, nEXO, NEXT, XLZD

- Liquid or gaseous target
- Ease of enrichment, Massively scalable
- Bg reduction through self-shielding
- Presently leading exclusion results

⁷⁶Ge: LEGEND, CDEX

- Advanced detector technology with superior energy resolution and background rejection
- Presently leading discovery sensitivity
- LEGEND-200 already taking data

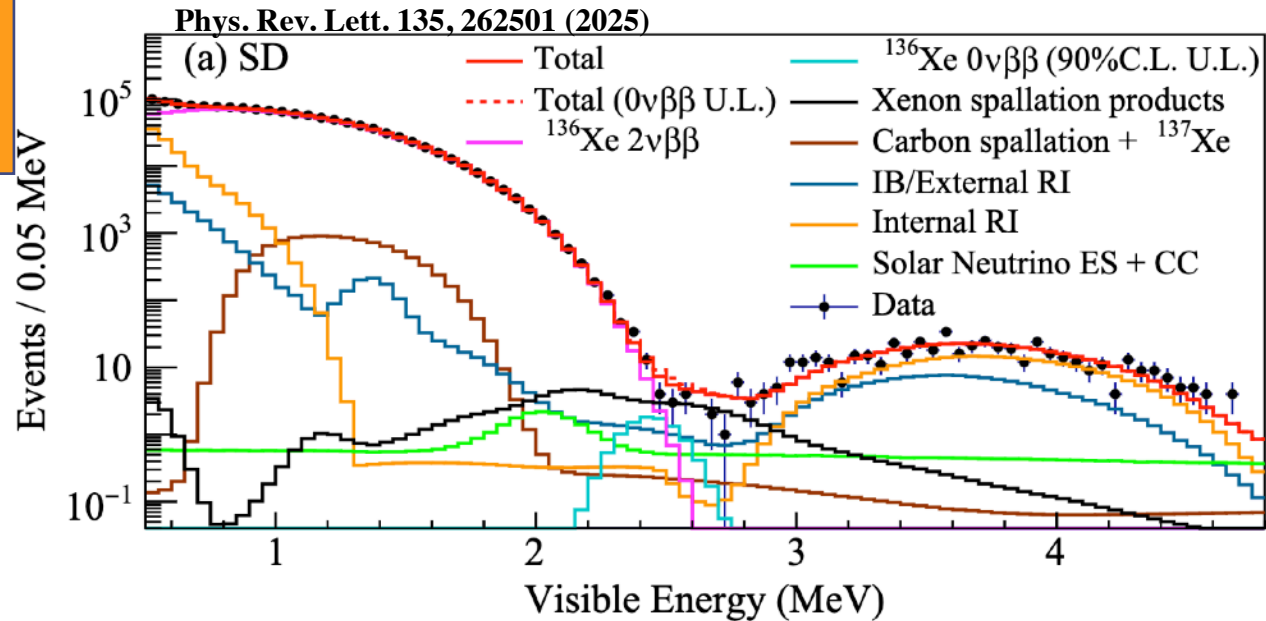
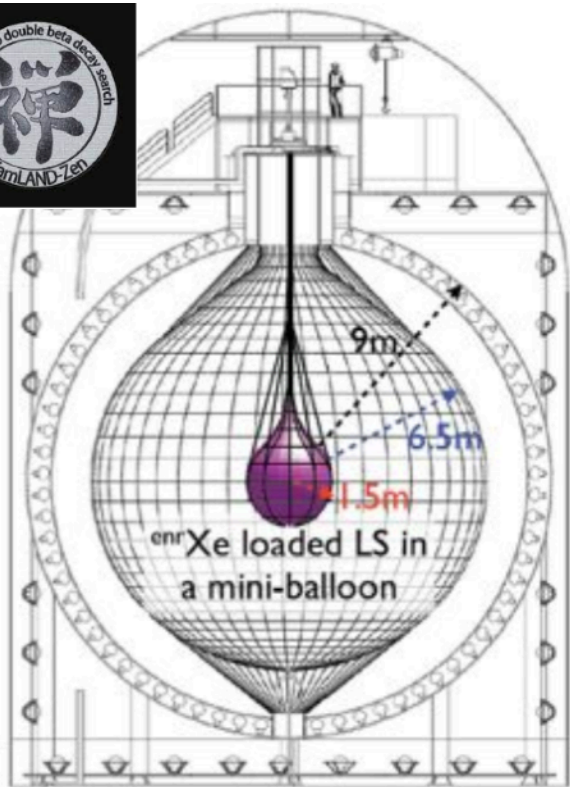
¹³⁰Te/¹⁰⁰Mo: CUORE, CUPID, AMoRE

- ¹³⁰Te unique in large natural isotopic abundance
- ¹⁰⁰Mo advantageous in transition phase space allowing the most cost-effective next generation effort
- Cryogenic calorimeters most versatile in isotope choice, plus large remaining optimisation potential for future

Experiment: ^{136}Xe

Adapted from K. Weerman
TAUP 2025

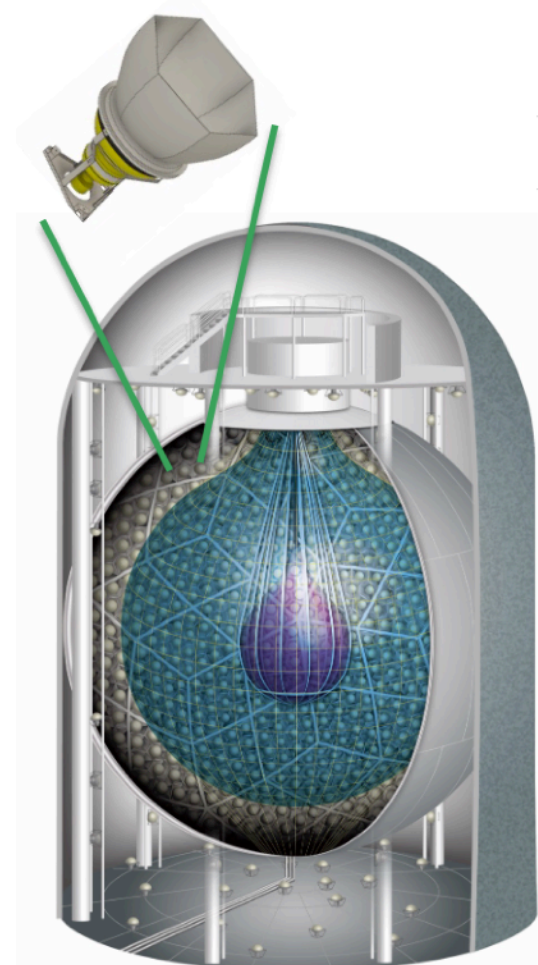
Leading exclusion results:
KamLAND-Zen 800



- Hosted at Kamioka, Japan
- KLZ-800: 745 kg of Xe (91% ^{136}Xe), 2.1 ton x yr exposure
- Data taking completed - World leading exclusion limit

$$|m_{\beta\beta}| < (28 - 122) \text{ meV (90 \% C . L.)}$$

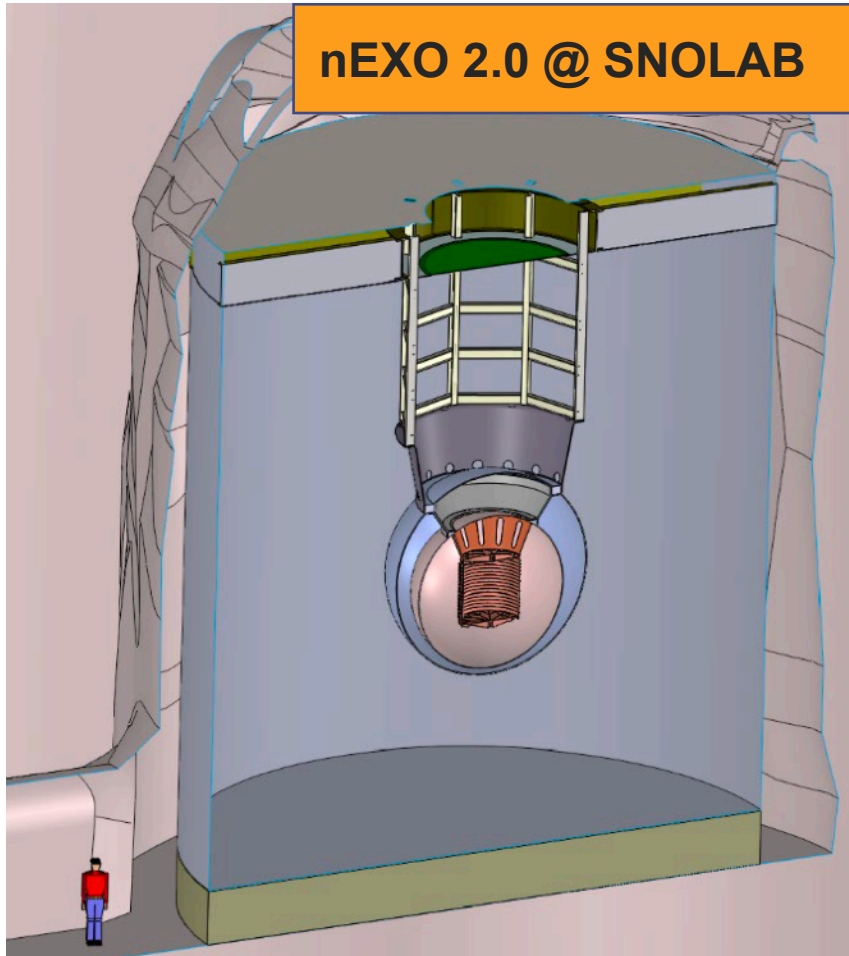
- $\sigma/E = 4 \% @ Q_{\beta\beta}$
- Upgrade to KamLAND2-Zen in progress



Upgrade to **KamLAND2-Zen (2028++)**: Target
 $|m_{\beta\beta}| < (17 - 71) \text{ meV (90 \% C . L.)}$

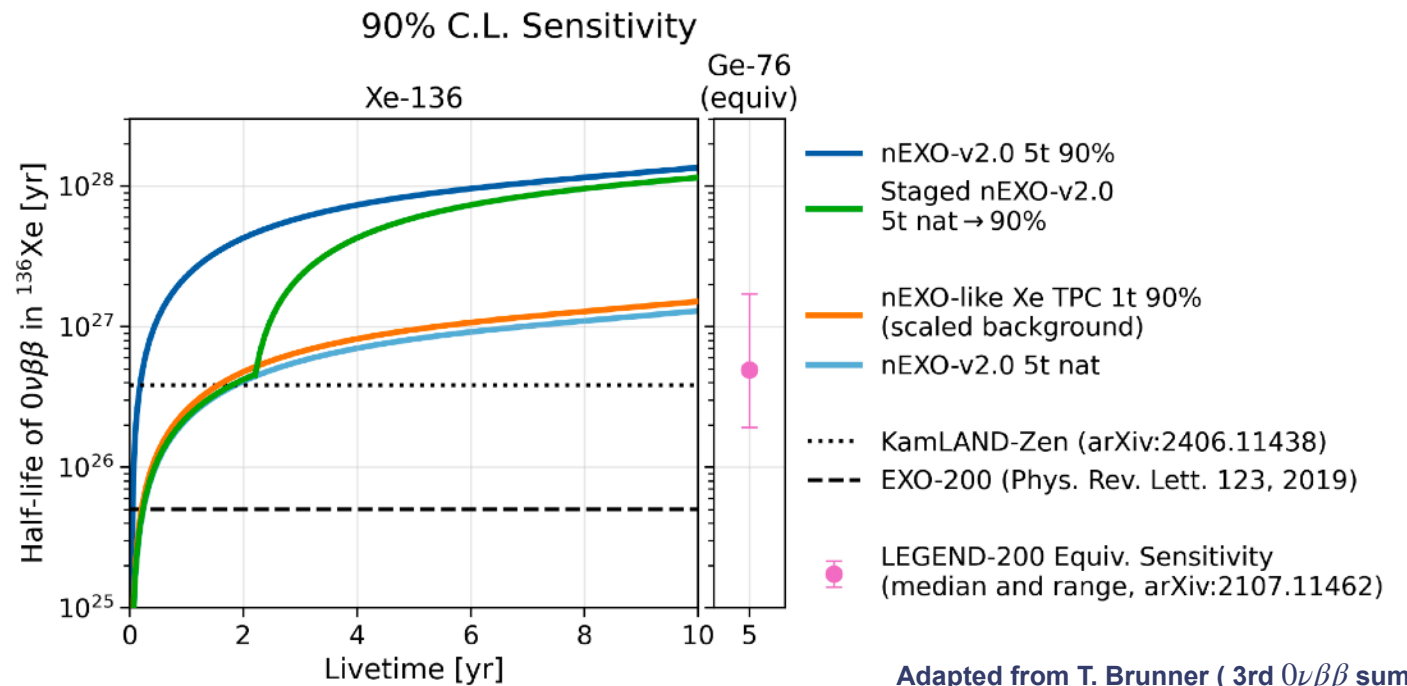
Experiment: ^{136}Xe

J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)



- 5 t enr. ^{136}Xe single phase TPC (demonstrated in EXO-200)
- Long history of successful Xe TPCs (Dark matter & $0\nu\beta\beta$)
- Charge and SiPM based light readout with $\sigma/E = < 1\% @ Q_{\beta\beta}$
- Exclusion sensitivity after 10 yrs: $|m_{\beta\beta}| < (6 - 18) \text{ meV}$
- Proposed phased approach (natural \rightarrow 90% enriched) to improve spending profile
- R&D for $^{136}\text{Ba}^{++}$ tagging for future background suppression

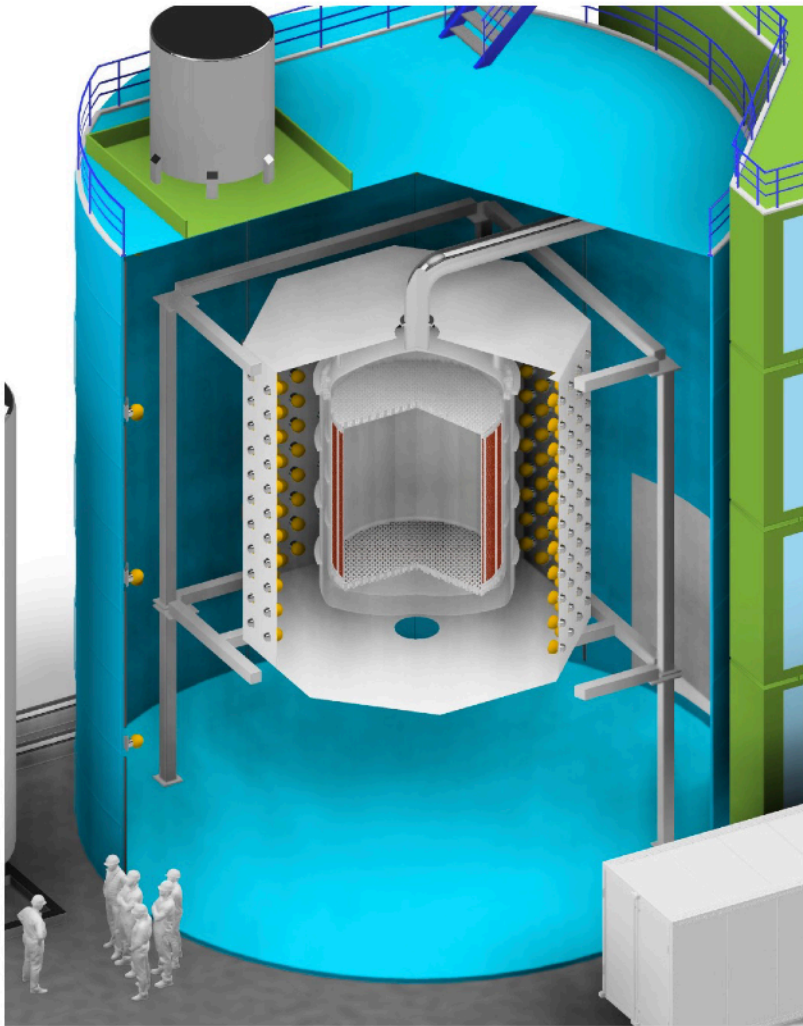
Phys. Rev. C 97, 065503 (2018)



Adapted from T. Brunner (3rd $0\nu\beta\beta$ summit)

Benjamin Schmidt

Experiment: ^{136}Xe



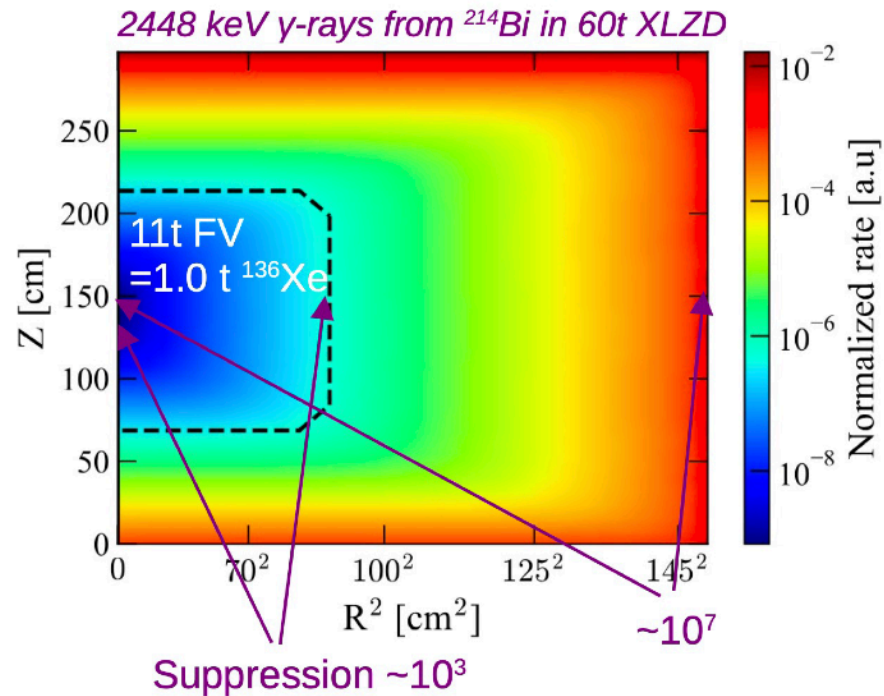
Adapted from M. Schumann (3rd Onbb summit 2025)

Next generation:
XLZD

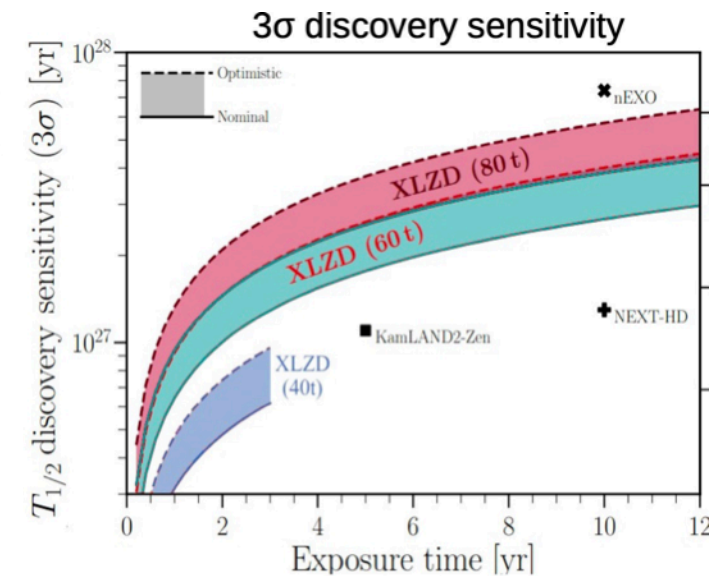
Note also
PandaX-xt (China)

XLZD: liquid $^{\text{nat}}\text{Xe}$ dual-phase TPC

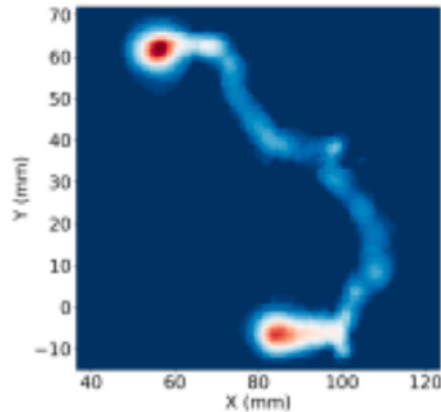
- 60 t active (78 t total) **natural Xe** target for DM search
 - Background suppression through self-shielding
 - Fiducial volume 11 t (1 t ^{136}Xe)
 - $\sigma/E = 0.65\% @ Q_{\beta\beta}$
 - LNGS, Boulby, SNOLAB and SURF as possible sites
- $|m_{\beta\beta}| < (4.8 - 20.5) \text{ meV (90\% C.L., 80t opt.)}$



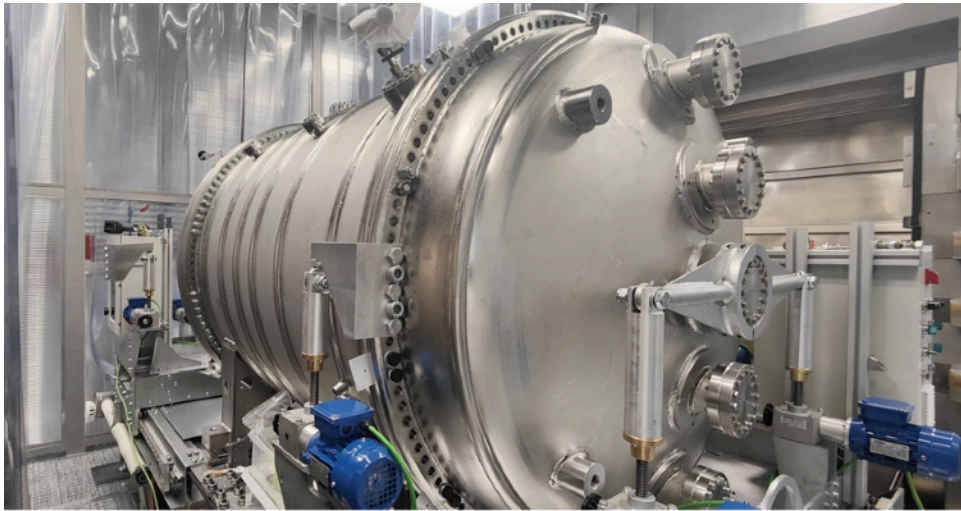
J. Phys. G 52, 045102 (2025)



Experiment: ^{136}Xe



The NEXT program



NEXT-100 @LSC 2023 — 2029

Adapted from S. Torelli (TAUP 2025)

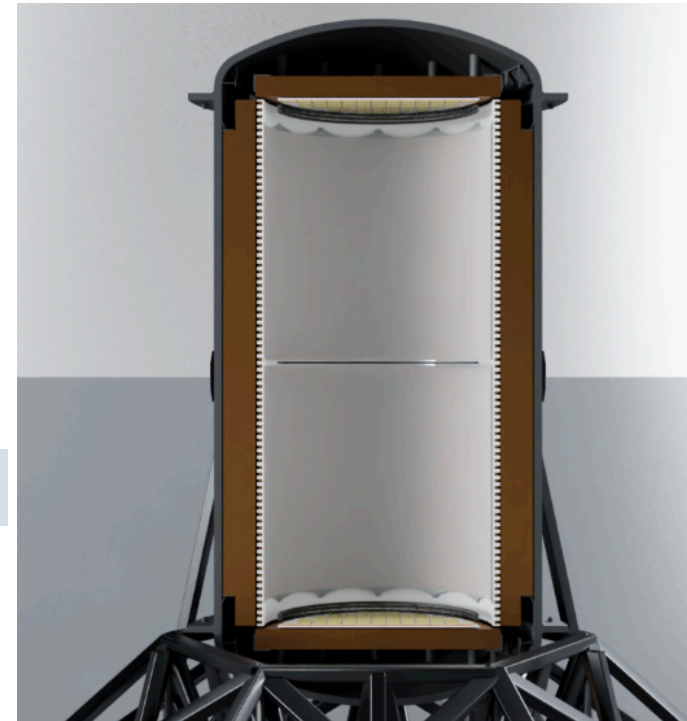
Real $2\nu\beta\beta$ event with topology reconstruction

JHEP 07, 146 (2021)

- High pressure (10-15 bar) gas ^{136}Xe TPC
- Background suppression through topology
- Energy resolution $< 1\%$
- **NEXT-100** ~100 kg
—> **NEXT-HD** (1 ton, 5 ton x yr)
 $|m_{\beta\beta}| < (11 - 46) \text{ meV (90\% C.L.)}$
—> **NEXT-BOLD**
(Ba^{2+} ion tagging for zero background, 10 ton x yr)
- $^{136}\text{Xe} \xrightarrow{0\nu\beta\beta} ^{136}\text{Ba}^{2+}$ ion can be tagged - Demonstrated by SMFI

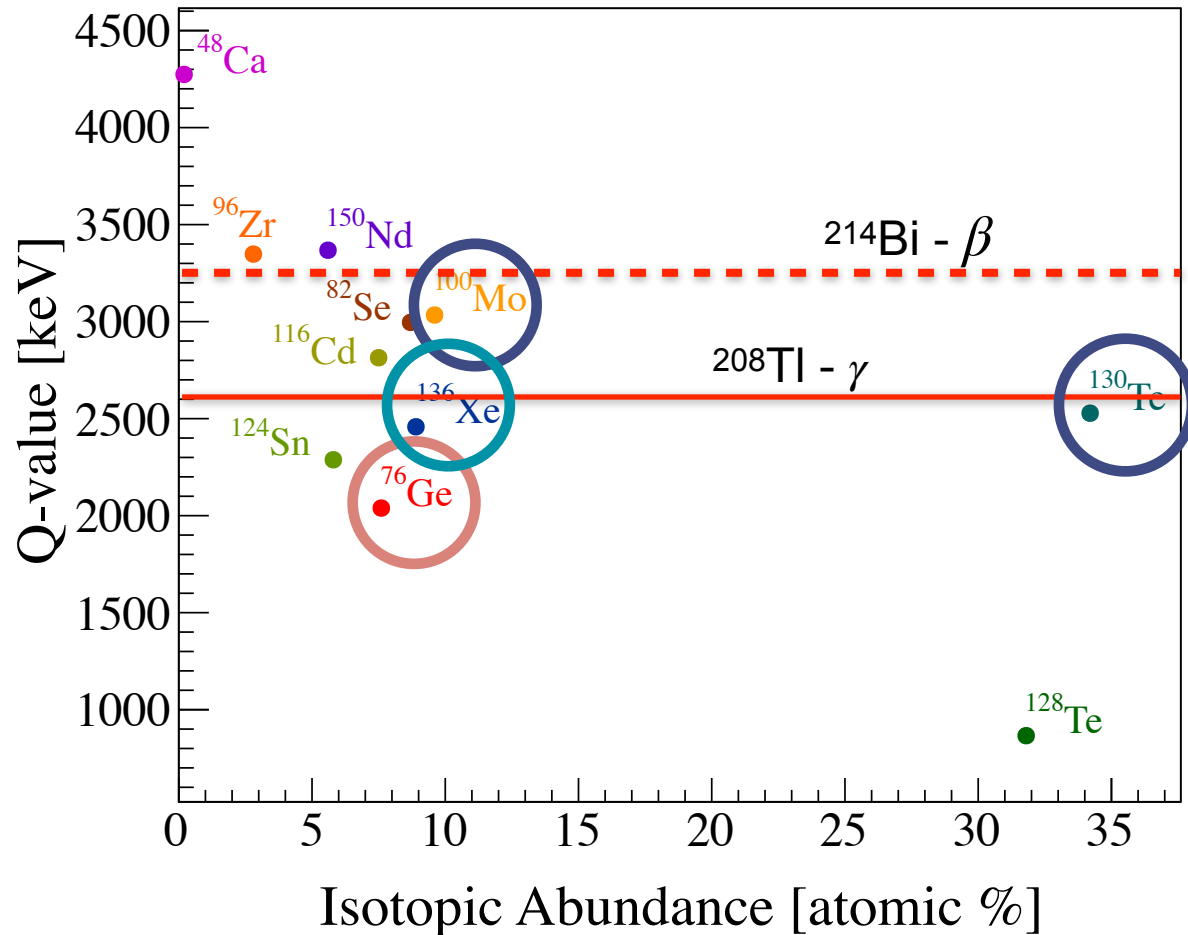
JINST 18 P08006 (2023)

**NEXT-HDFM 2029++
(first module)
—> multi modules
NEXT-HDMM 2035 ++**



Isotope choice

Ge diode based ionisation detectors

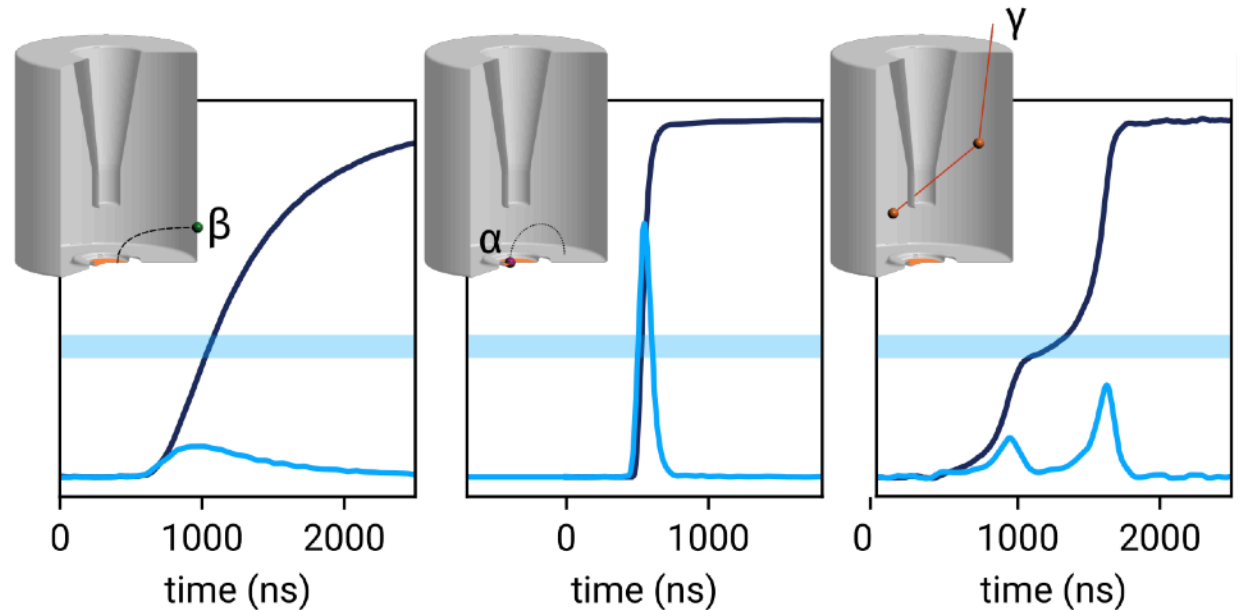
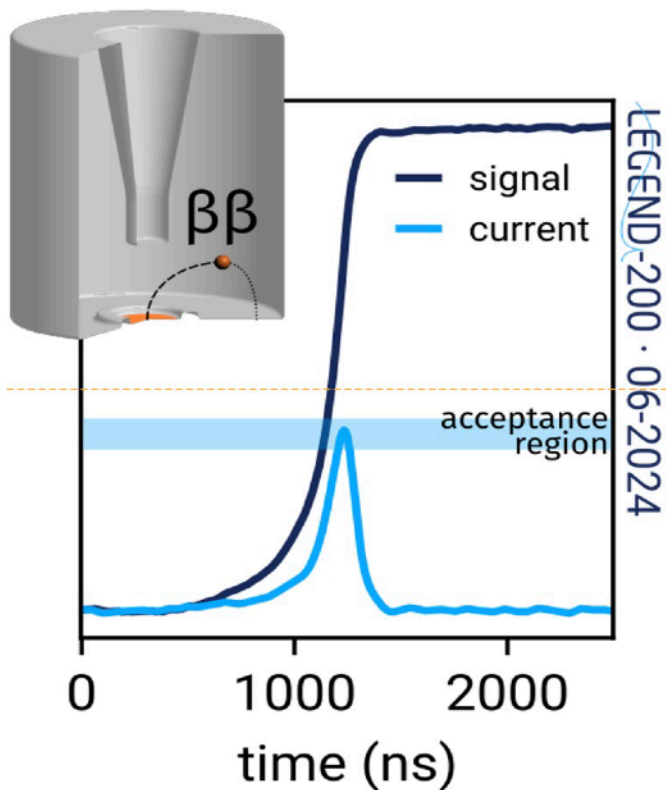


^{76}Ge : LEGEND, CDEX

- Advanced detector technology with superior energy resolution and background rejection
- Presently leading discovery sensitivity
- LEGEND-200 already taking data

Experiment: High purity Ge detectors

Technology



LEGEND

- Advanced detector technology with superior energy resolution: LEGEND-200 $\sigma/E = 0.05\% @ Q_{\beta\beta}$
- Pulse-shape based event topology discrimination
- Active liquid Ar veto

Note also **CDEXv** Ge program in Asia

Adapted from S. Schönert (MAYORANA Workshop 2025)

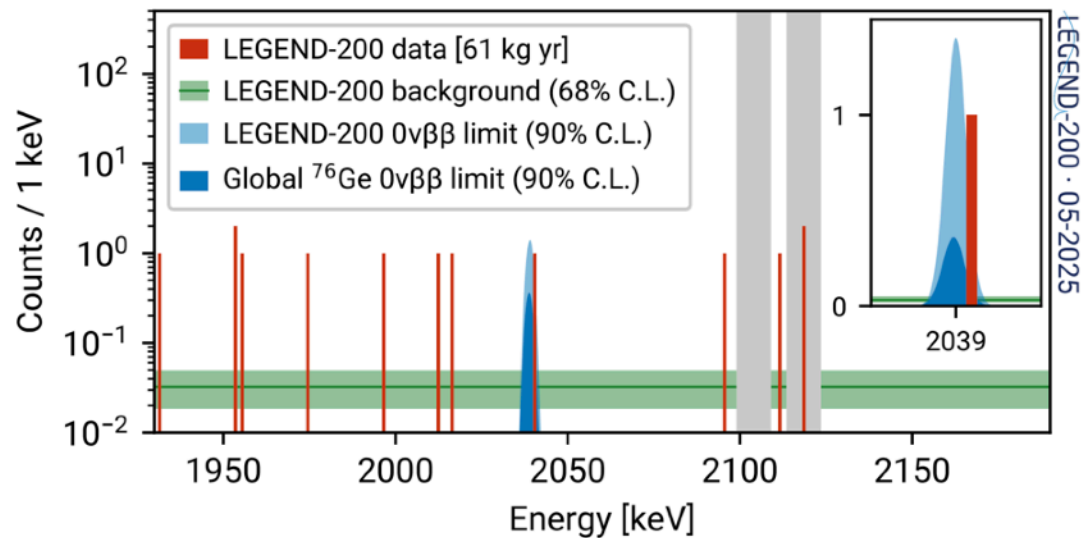
Experiment: ^{76}Ge

Leading Exclusion Sensitivity:
LEGEND-200 (incl. GERDA & Majorana)

- At LNGS, built upon **GERDA** and **Majorana** experience
- Target: 200 kg enr. HPGe detectors, 5 yrs
- First data in 2025, 61 kg x yr , $\sigma/E = 0.05\% @ Q_{\beta\beta}$
- BI: $\sim 5 \times 10^{-4}$ ckky

$$|m_{\beta\beta}| < (75 - 200) \text{ meV (90\% CI)}$$

Phys. Rev. Lett. 136, 022701



Adapted from S. Schönert (MAYORANA Workshop 2025)



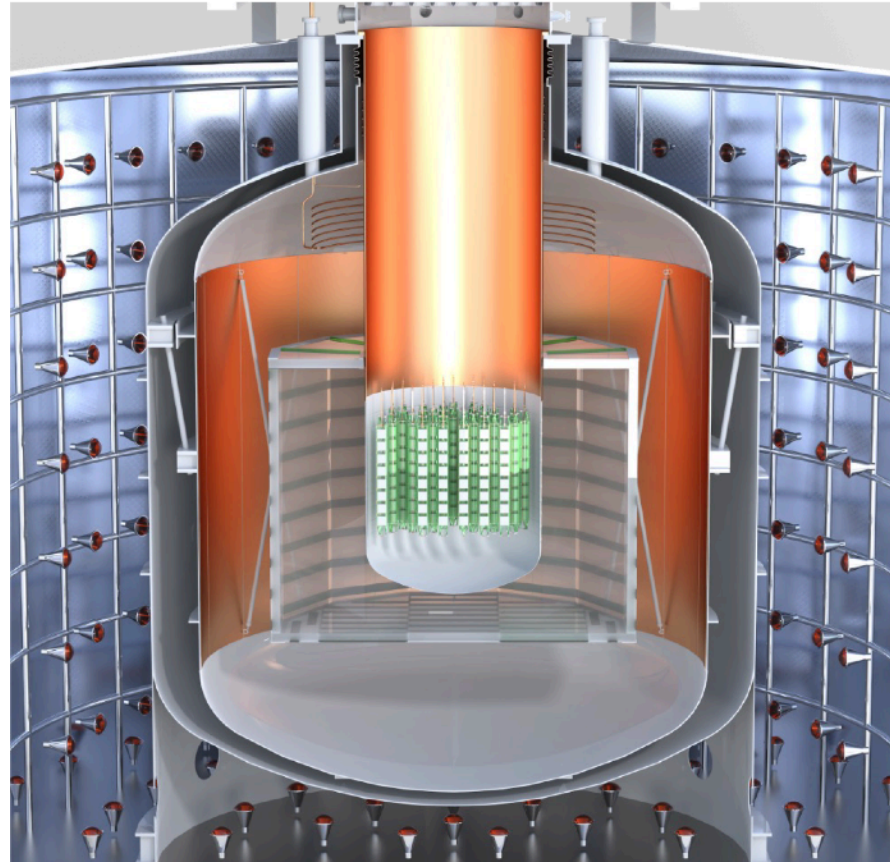
Experiment: ^{76}Ge

Next Generation: LEGEND-1000

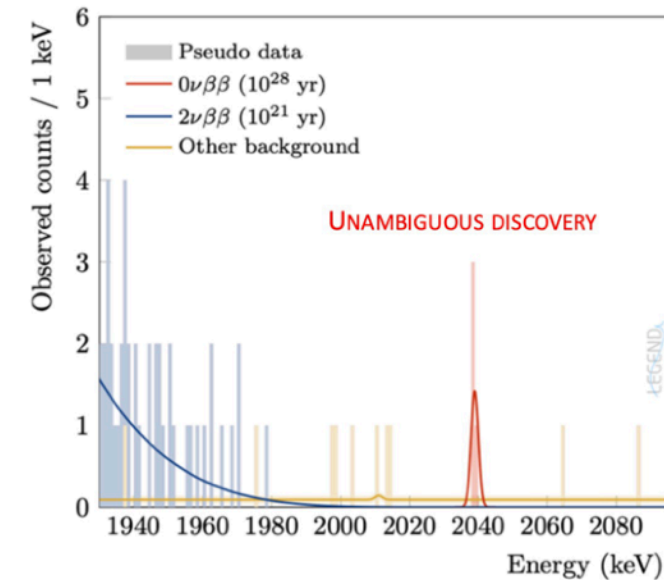
- New facility in preparation at LNGS
 - Target: 1 000 kg of enr. HPGe detectors, 10 yrs data taking
 - Background target: 1×10^{-5} c/kg/yr
- $|m_{\beta\beta}| < (8.5 - 19) \text{ meV (90 \% C.L.)}$

Novel techniques:

- Underground Ar (reduce ^{42}Ar)
- ASIC-based readout for improved signal quality
- Neutron moderator & tagger
- Cleaner materials

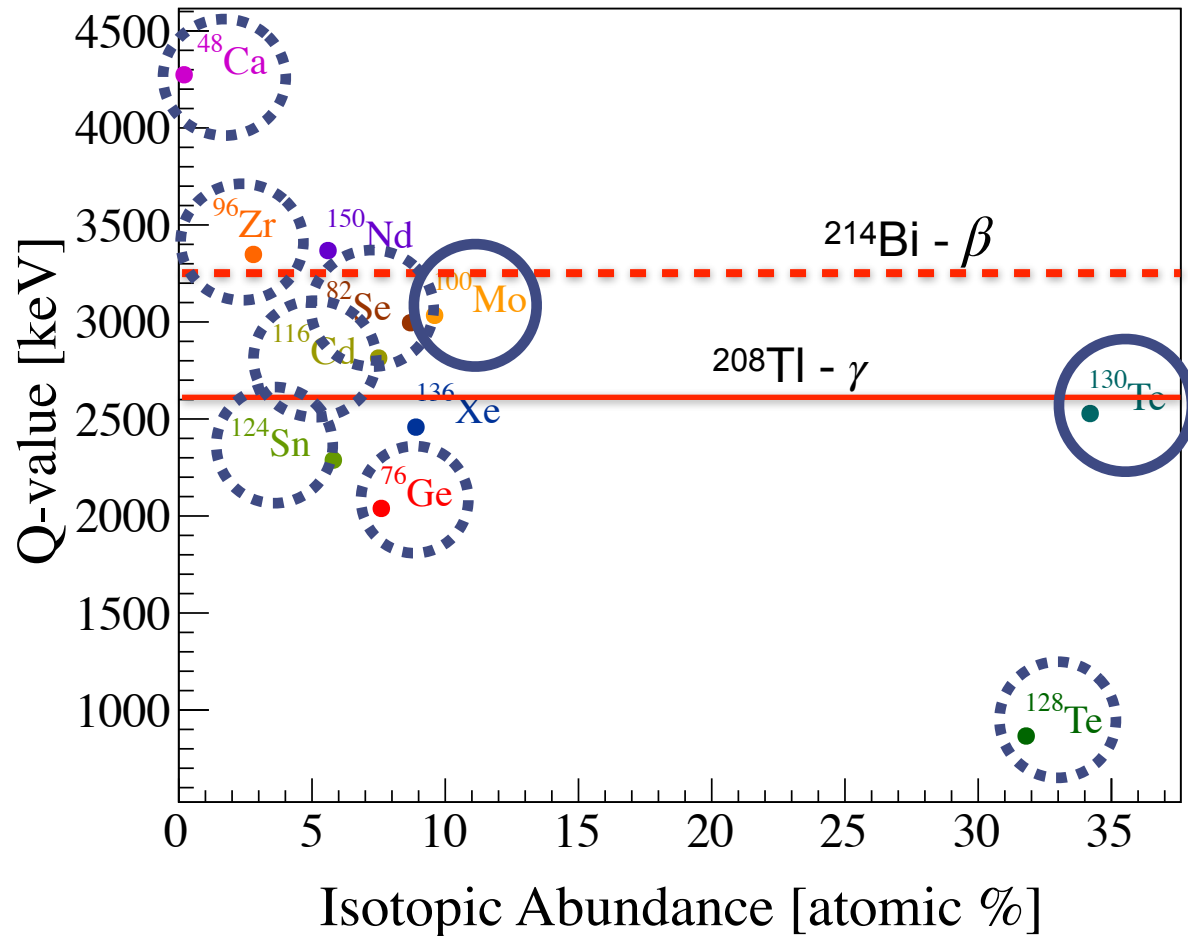


Adapted from S. Schönert (MAYORANA Workshop 2025)



Next Next generation:
“LEGEND 6000” and “CDEX 10T”

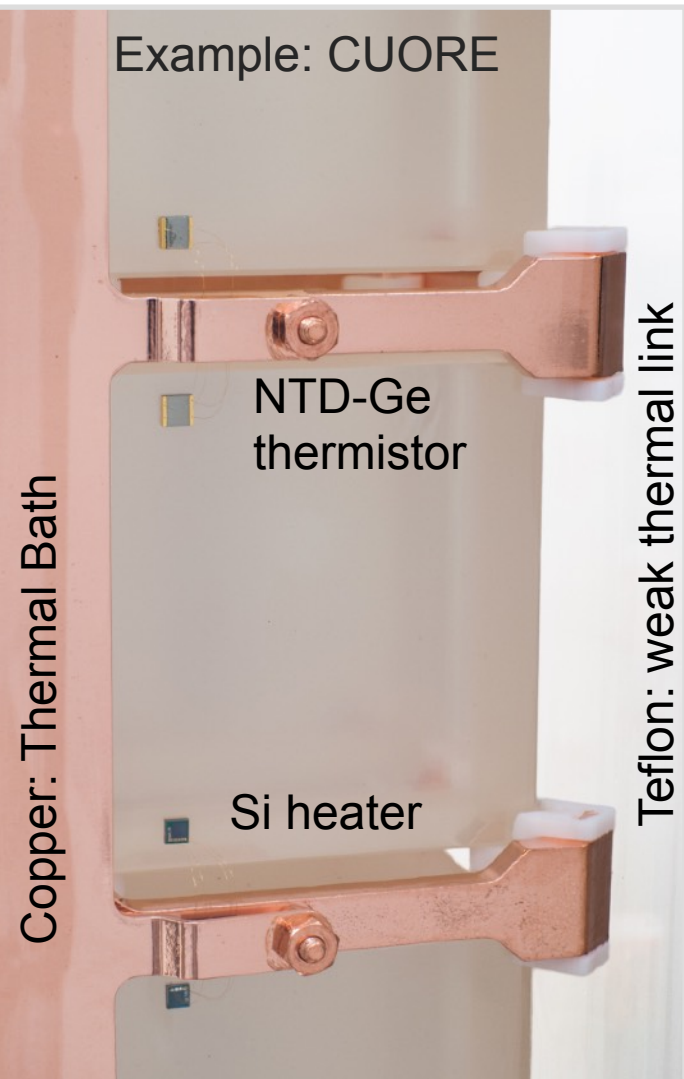
Isotope choice - Cryogenic calorimeters



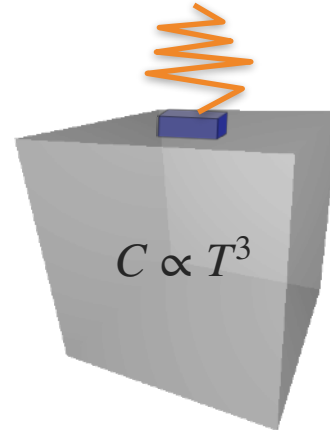
$^{130}\text{Te}/^{100}\text{Mo}$: CUORE, CUPID, AMoRE

- ^{130}Te unique in its large natural isotopic abundance
- ^{100}Mo advantageous in background and phase space, allowing the most cost-effective next generation effort
- Technology: Cryogenic calorimeters:
 - excellent energy resolution $\sim 0.1\%$ at $Q_{\beta\beta}$
 - versatile in isotope choice
 - scaling to ton-scale proven by CUORE
 - large remaining optimisation potential for cryogenic calorimeters

Experiment: Cryogenic calorimeters



Thermal bath @ 10-20 mK



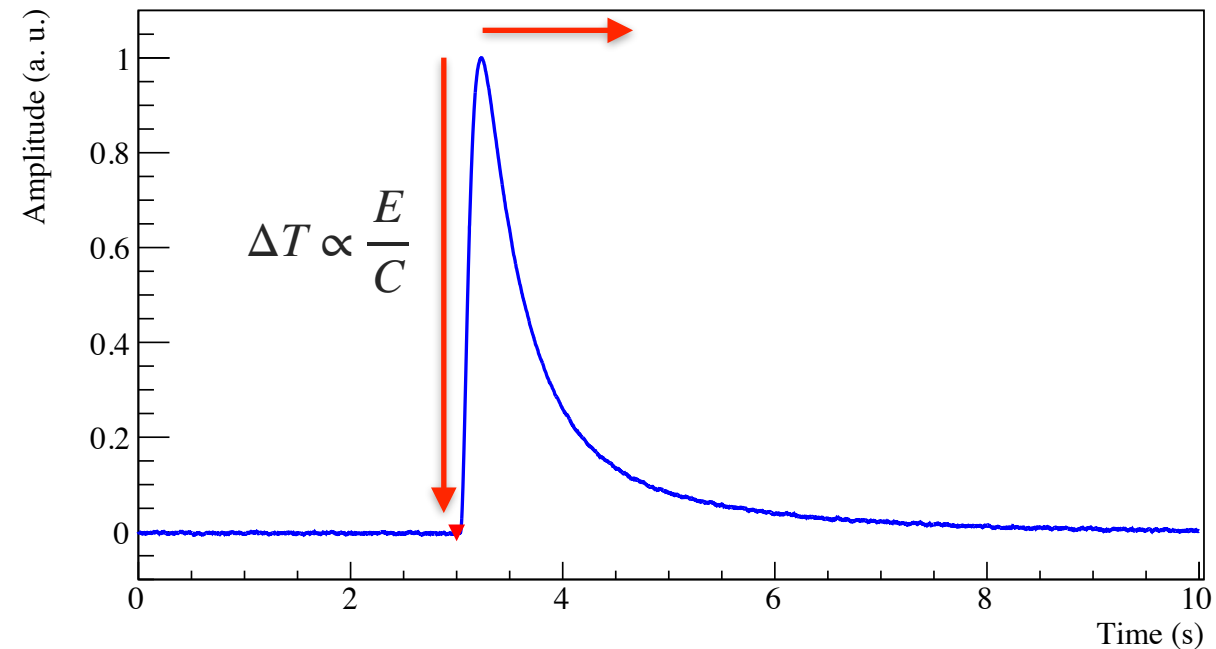
NTD-Ge thermistor as sensor

$$R(T) = R_0 \cdot e^{\sqrt{T_0/T}}$$

$$\Delta T \approx 100 \mu\text{K}/\text{MeV}$$

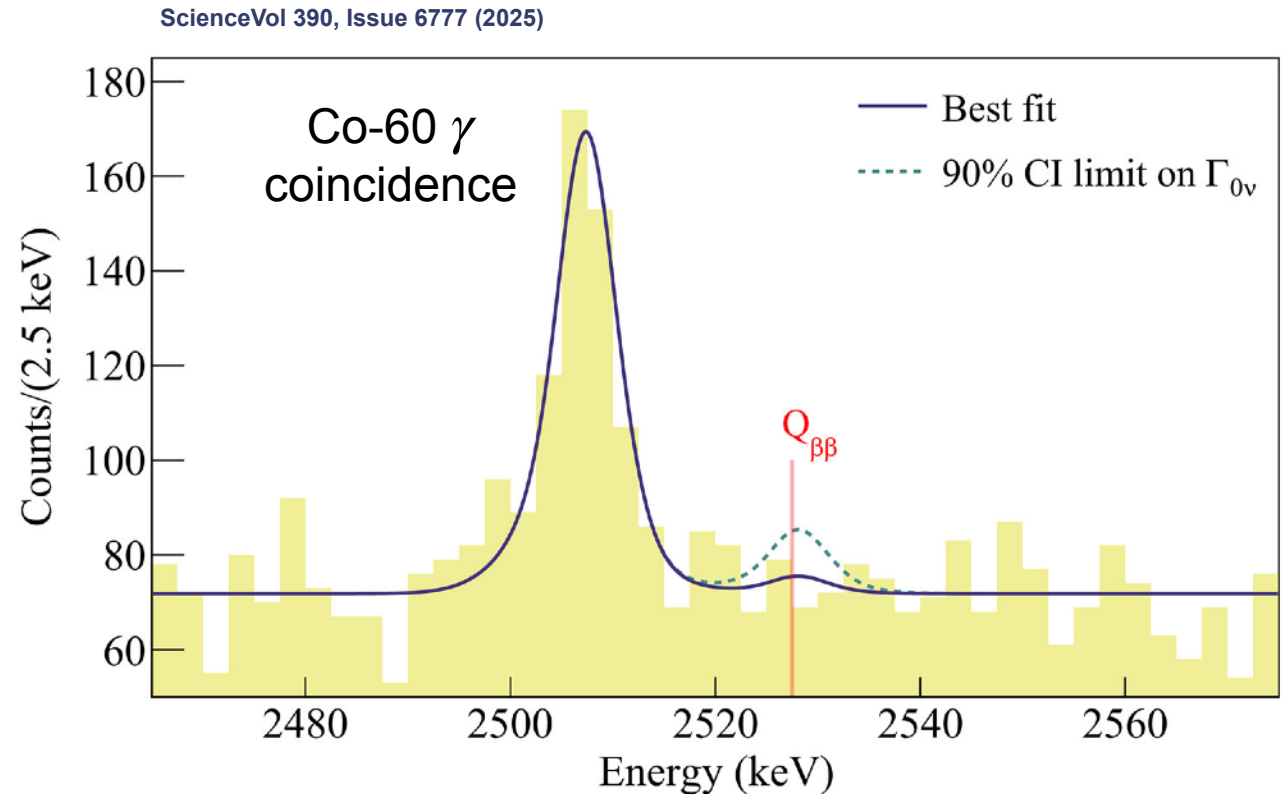
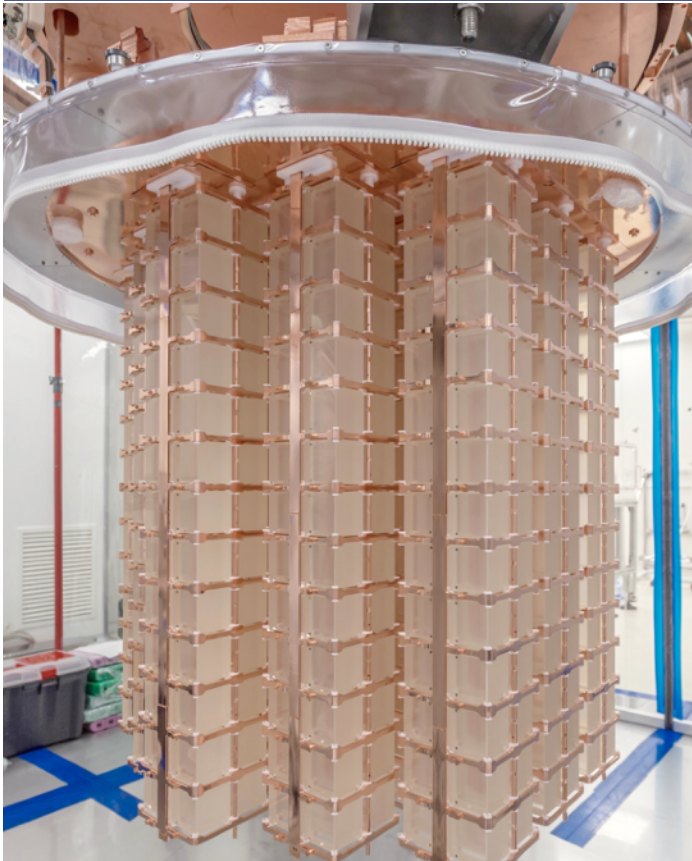
$$\tau \propto \frac{C}{G}$$

Many isotopes accessible in different crystals:
 TeO_2 , Li_2MoO_4 , CdWO_4 ,
 ZnSe , CaF , Cs_2ZrCl_6 ,



Experiment: ^{130}Te

Current: **CUORE @LNGS**



^{130}Te : CUORE

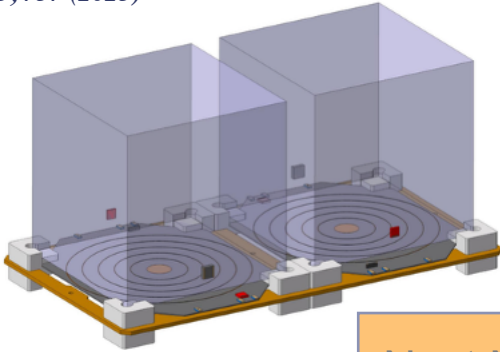
- 988 Detectors with 742 kg of natural TeO_2
- 3 t x yr TeO_2 of data acquired -> Stay tuned!
- 2 t x yr TeO_2 exposure analyzed & published
- Energy resolution $\sigma/E = 0.13\%$ @ $Q_{\beta\beta}$
- BI: $(1.42^{+0.03}_{-0.02}) \times 10^{-2}$ ckky

$$|m_{\beta\beta}| < (70 - 250) \text{ meV (90\% C.L.)}$$

ScienceVol 390, Issue 6777 (2025)

Experiment: ^{100}Mo

Eur. Phys. J. C 85, 737 (2025)

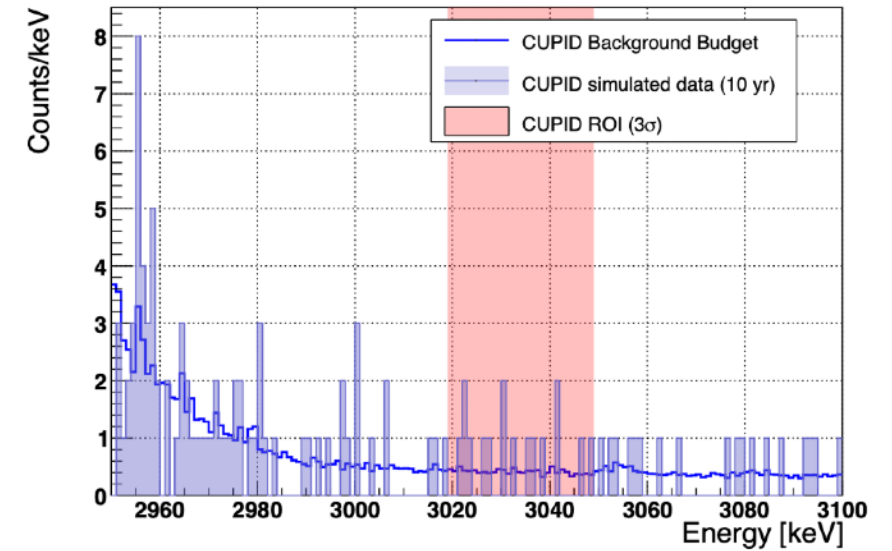
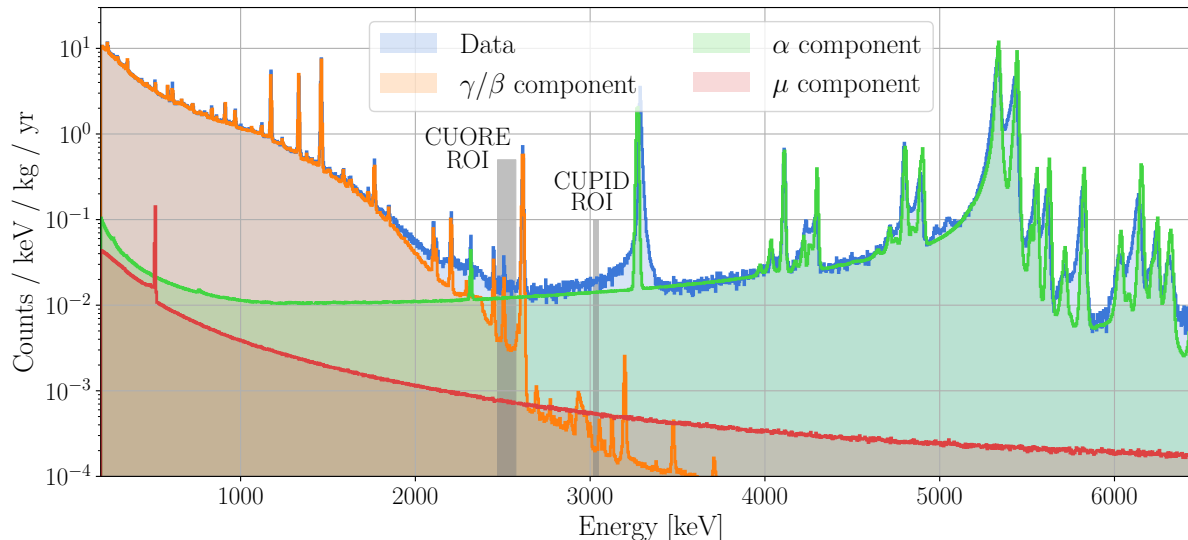


Next generation: **CUPID**

Note ^{100}Mo in AMoRE program in South Korea & CUPID-China

Next Next generation: “**CUPID 1 ton**”

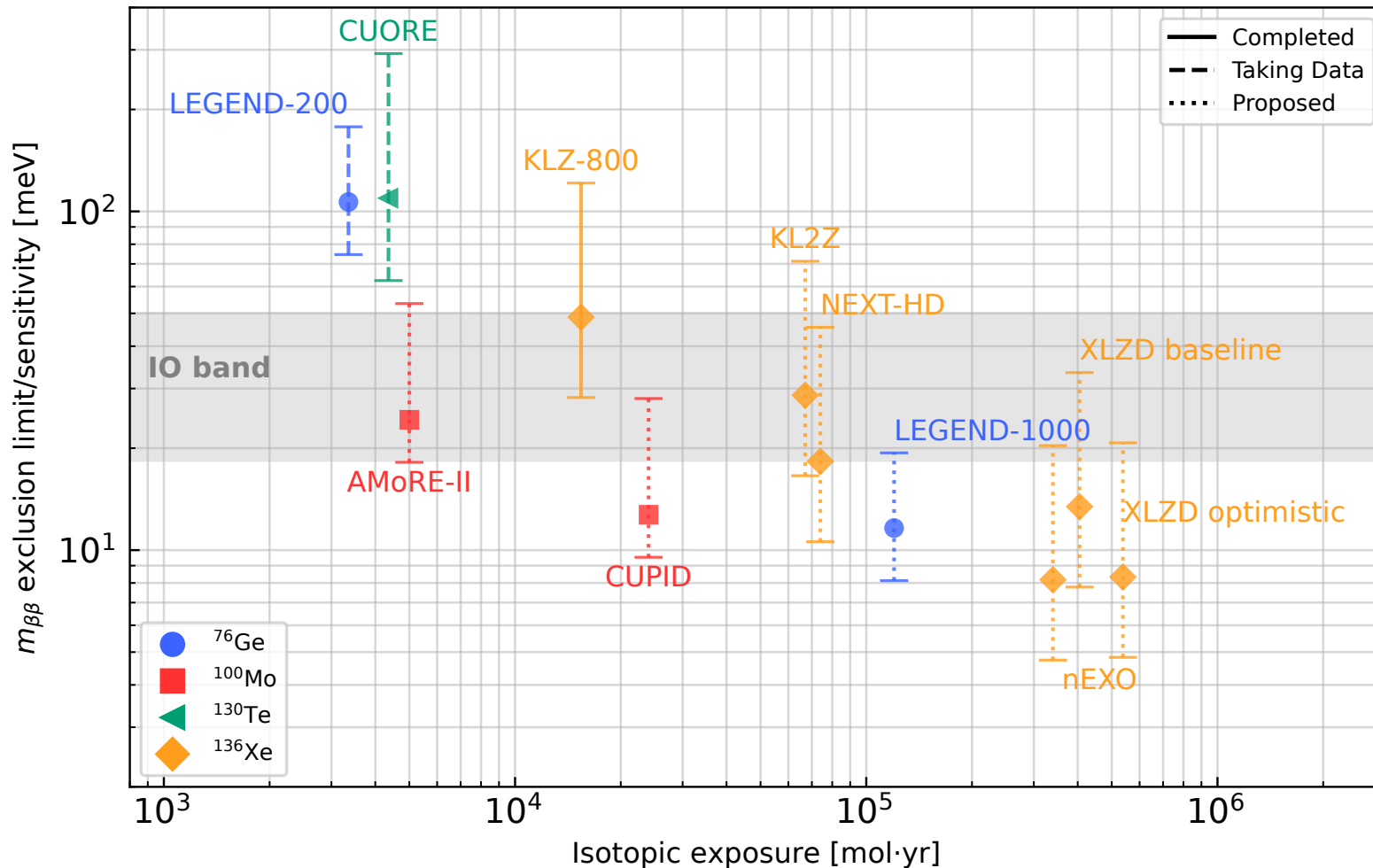
Phys. Rev. D 110, 052003 (2024) (Suppl material)



CUPID - CUORE Upgrade with Particle ID

- CUORE cryostat & infrastructure
- 1596 scintillating heat/light detector modules
- Advanced Neganov-Trofimov-Luke assisted light detectors - dev. in BINGO/CROSS (FR)
- Staged deployment 1/3 ~80 kg of ^{100}Mo in Stage1 -> Stage 2 (240 kg of ^{100}Mo)
- Complete α rejection
- Energy resolution: $\sigma/E = 0.07\% @ Q_{\beta\beta}$
- BI target: 1.0×10^{-4} ckky
- $|m_{\beta\beta}| < (9.6 - 28)$ meV (90% C.I.)

Summary - Selected experiments



Crucial science case for $0\nu\beta\beta$ lepton number violation & matter generation, origin of ν mass

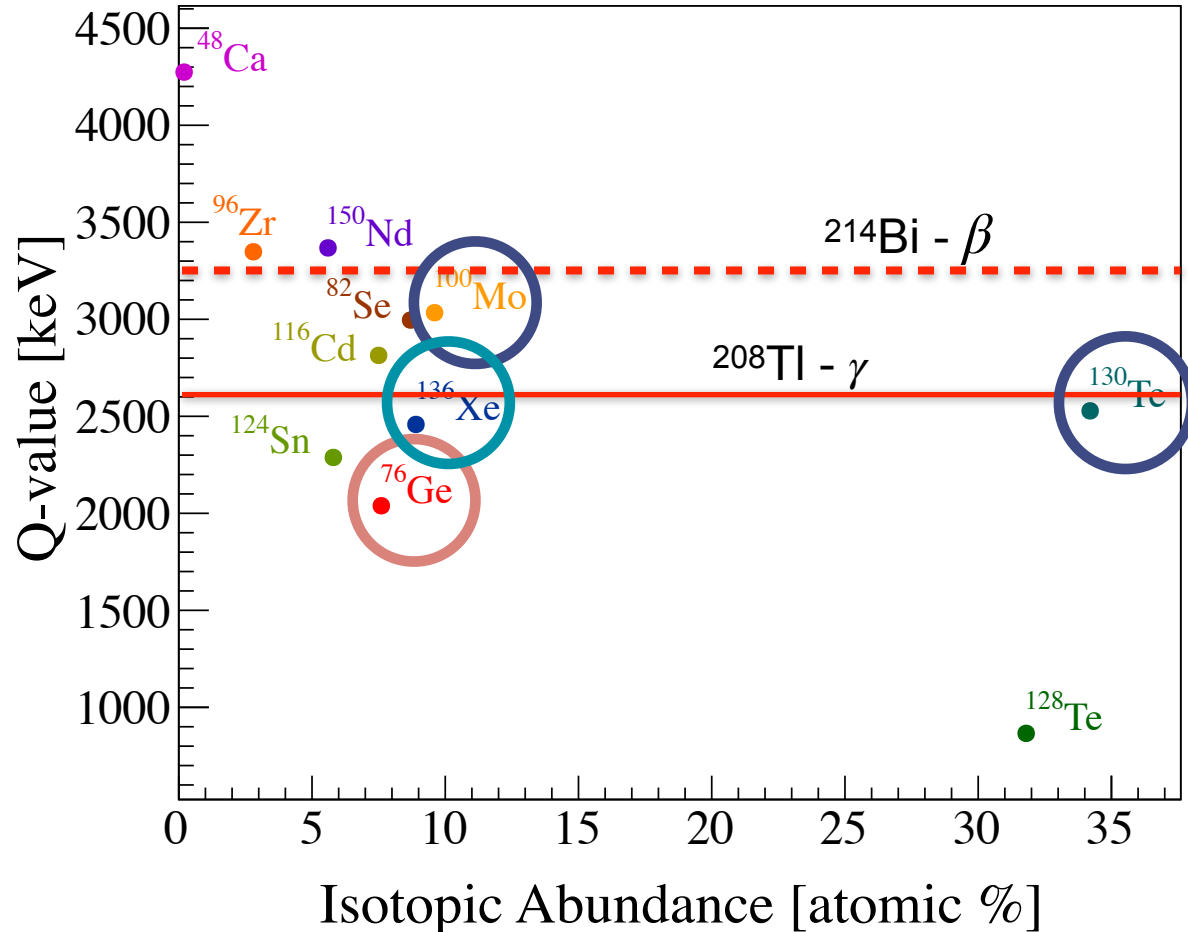
Major progress for ton-scale (next generation) experiments

Several DBD isotopes and techniques required ($0\nu\beta\beta$ mechanism, exploration of NO and confirmation)

Good discovery potential for all next generation experiments

Isotope choice

A set of “flagship” projects/isotopes

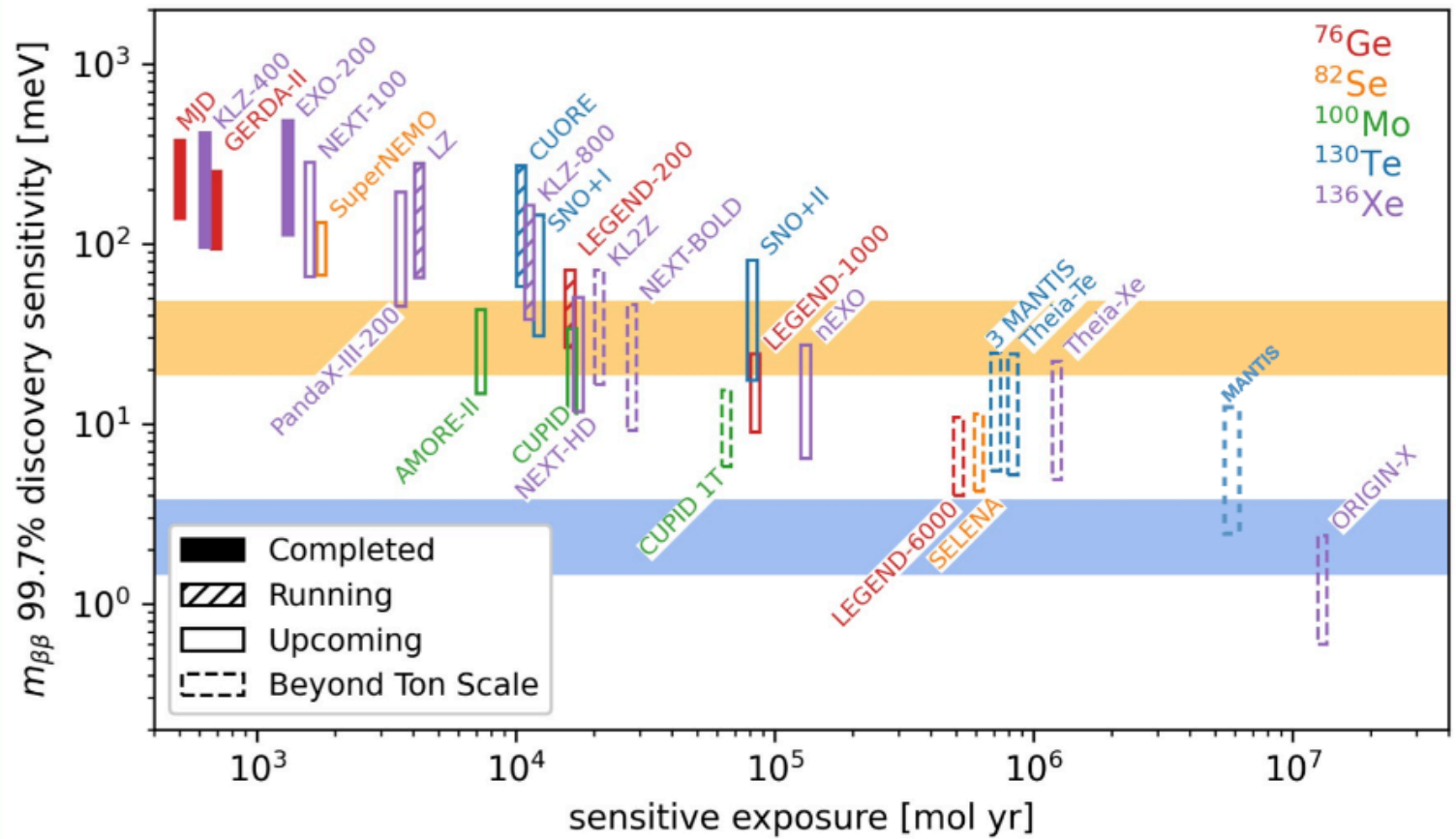


Take away:

- Both economic and technological considerations are important for next generation experiments
- Multiple isotopes/experiments reduce risks, can potentially provide information on the $0\nu\beta\beta$ mechanism and ensure the possibility of confirmation of a discovery
- Each isotope/detector technology provides unique advantages/challenges

Disclaimer:
Neutrino 2026 is coming - Expect several updates on experiments!

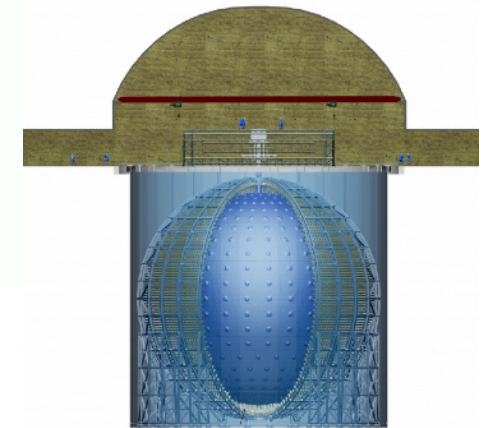
Outlook - Longer term



Adapted from R. Guénette (Neutrino 2024), NSAC long range plan arxiv:2304.03451

Many more ambitious and challenging projects and interesting technologies - but need to assess ton-scale performance and judge investments

Opportunities of note: modifications of existing infrastructures SNO+, JUNO, KamLAND

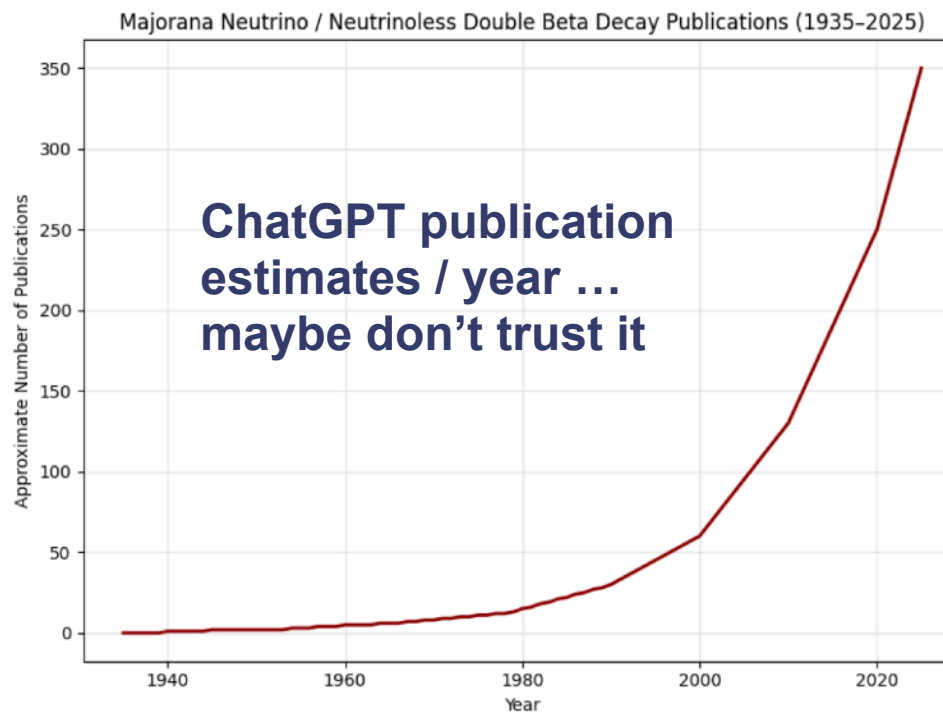


Omissions - there may be more



arXiv:2212.11099

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	$^{nat}\text{CaF}_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300 ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{72}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se , CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF_6 TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	$\text{Li}^{enr}\text{MoO}_4$, scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	$\text{Li}_2^{100}\text{MoO}_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		$\text{Li}^{enr}\text{MoO}_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	$\text{Li}^{enr}\text{MoO}_4$, scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		$^{enr}\text{CdWO}_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		$^{nat}\text{CdTe}$ det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe dissolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe dissolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	



I did not have time to discuss these ...

Benjamin Schmidt

Backup

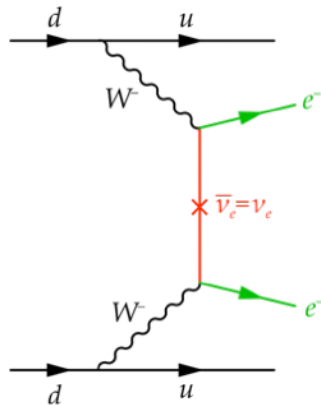


Neutrinoless double beta decay

The mechanism

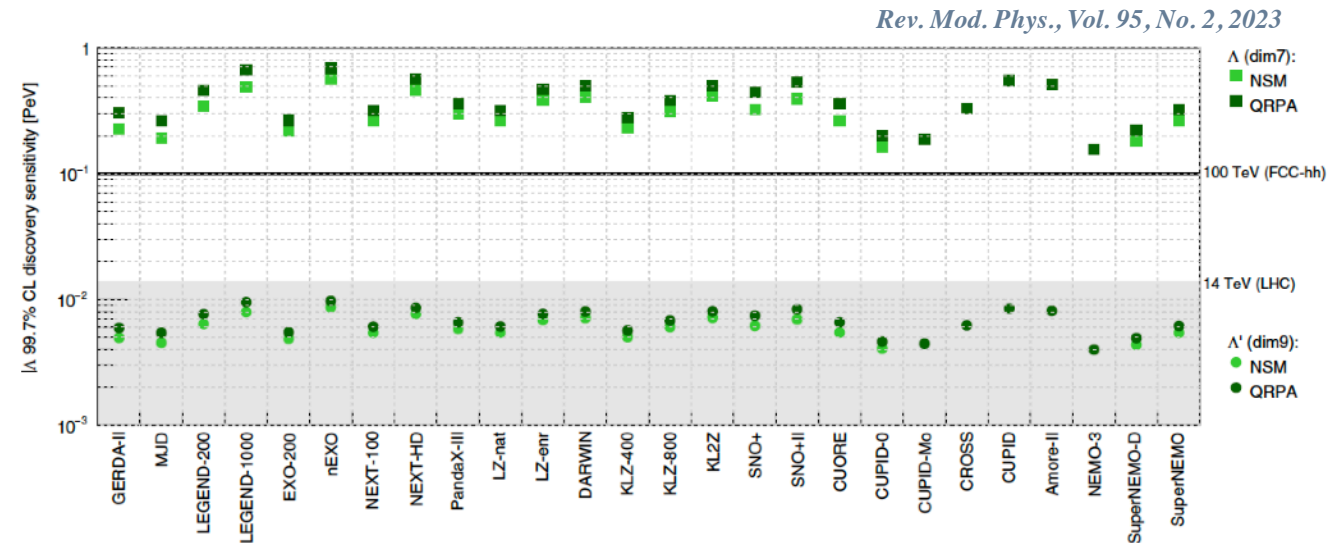
Standard (mass)-mechanism:

- Light massive Majorana neutrino (i.e. standard model neutrinos with known oscillation properties and Majorana phases)
- See-saw mechanism to explain neutrino masses

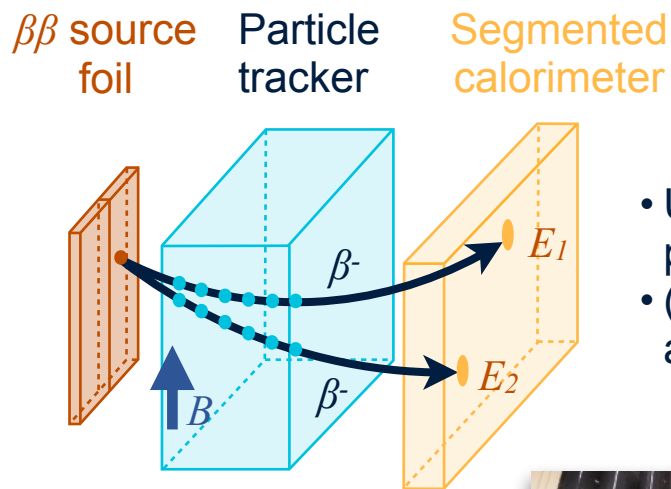


Other beyond SM physics

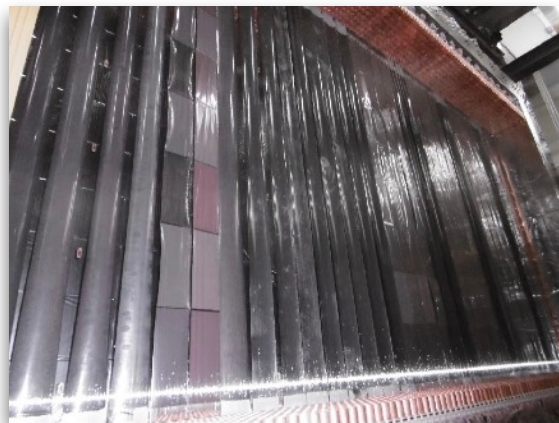
- Specific models: Massive right handed ν , Sterile ν , R-parity violating SUSY, Leptoquarks ...
- EFT analyses - Exceed collider constraints for several operators



SuperNEMO: a fully topological tracking detector for $0\nu\beta\beta$



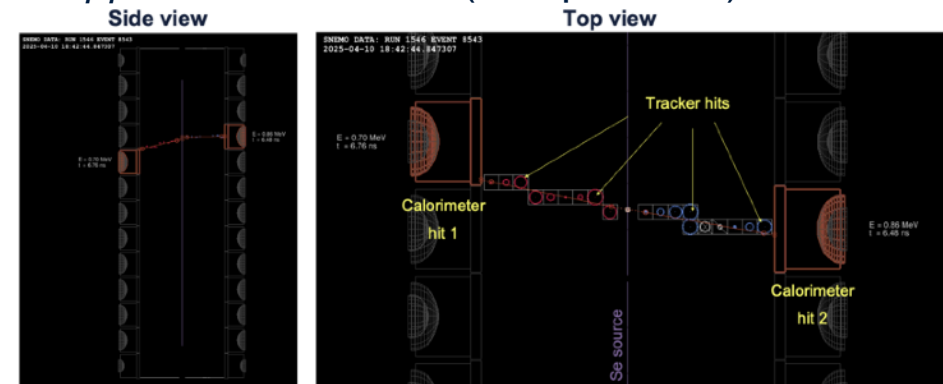
- Unique individual particle identification
- (Almost) isotope agnostic



- Excellent background rejection
- Background measurement (dedicated channels)
- Golden-event signature
- Individual energy
- Angular correlation

Key to probing and understanding $0\nu\beta\beta$ mechanism if it's discovered

Our first $\beta\beta$ -candidate event (10 April 2025)



98.4% of tracker,
97.4% of calorimeter
operational!



SuperNEMO Demonstrator has rich physics potential with ^{82}Se

- $0\nu\beta\beta$ V-A
- $0\nu\beta\beta$ V+A (λ and η)
- $0\nu\beta\beta$ with Majoron
- $2\nu\beta\beta$ and $0\nu\beta\beta$ to excited states
- Nuclear structure effects via $2\nu\beta\beta$ spectrum
- BSM decay searches: sterile neutrinos, Lorentz violation, bosonic neutrinos...

Currently taking physics data at
LSM, France

SuperNEMO challenges - runtime and radon-free air

- **SuperNEMO running steadily since April 2025**

- Total acquisition time 354 days (by mid-May 2026)
- 97.9% duty cycle (90.8 accounting for calibration)

- **Threat: reduced runtime**

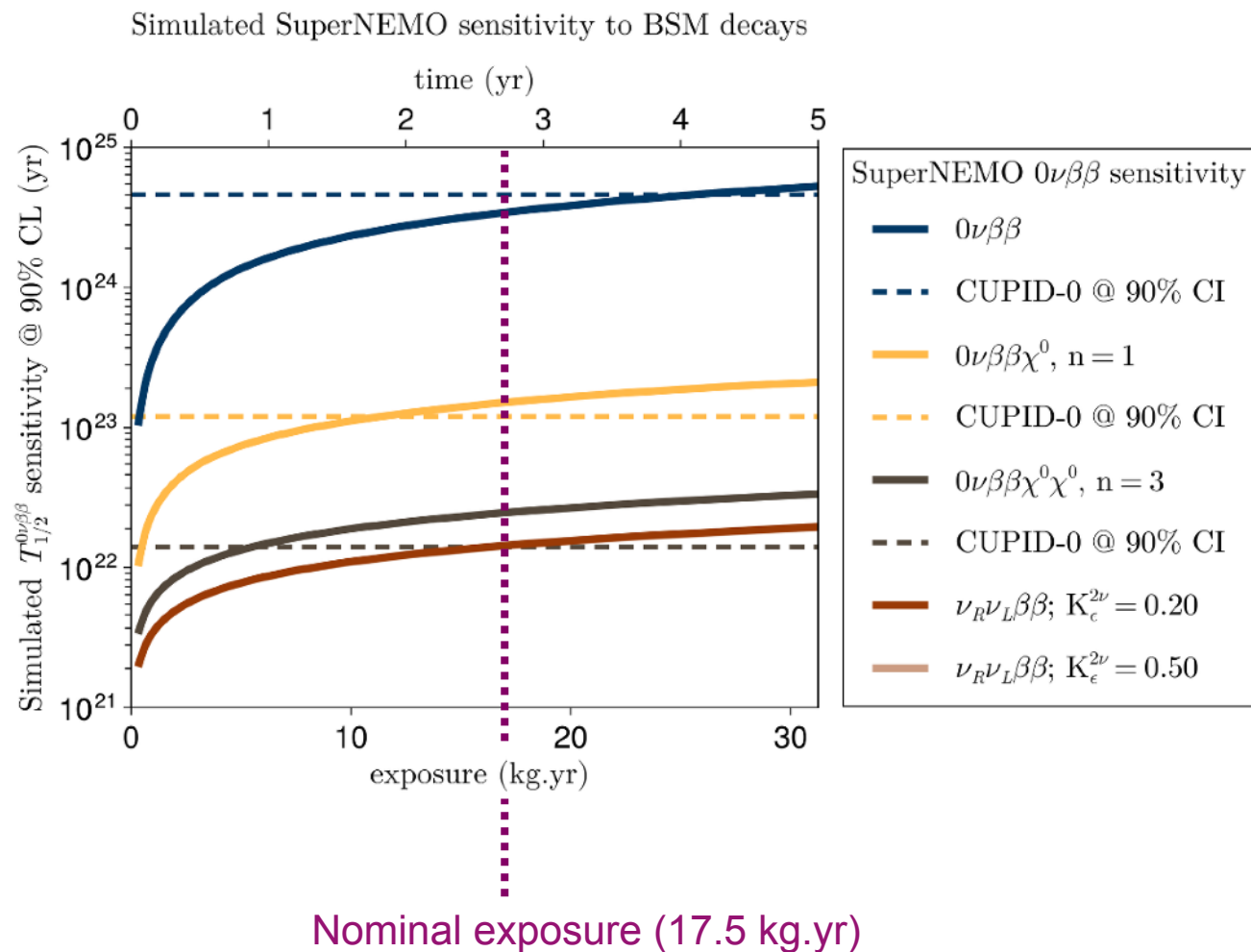
- Competition with other experiments for LSM space
- Nominal runtime needed to achieve physics potential

- **Threat - nominal background conditions not met**

- Goal: background free in $0\nu\beta\beta$ ROI
- Requires Rn-free (1mBq m^{-3}) surrounding air (supplied by LSM)
 - Anti-Rn facility activated Oct 2025 (6 months into run)
 - Facility malfunctioning: **still no Rn-free air**

SuperNEMO radon activity target: 0.15 mBq m^{-3}

Mean radon activity since first $\beta\beta$ run: 39 mBq m^{-3}



Rn-free air and nominal runtime critical to physics results!