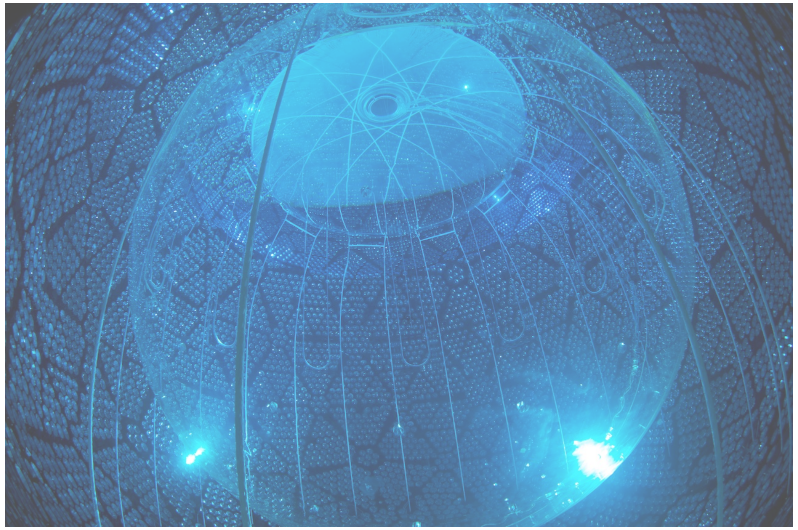
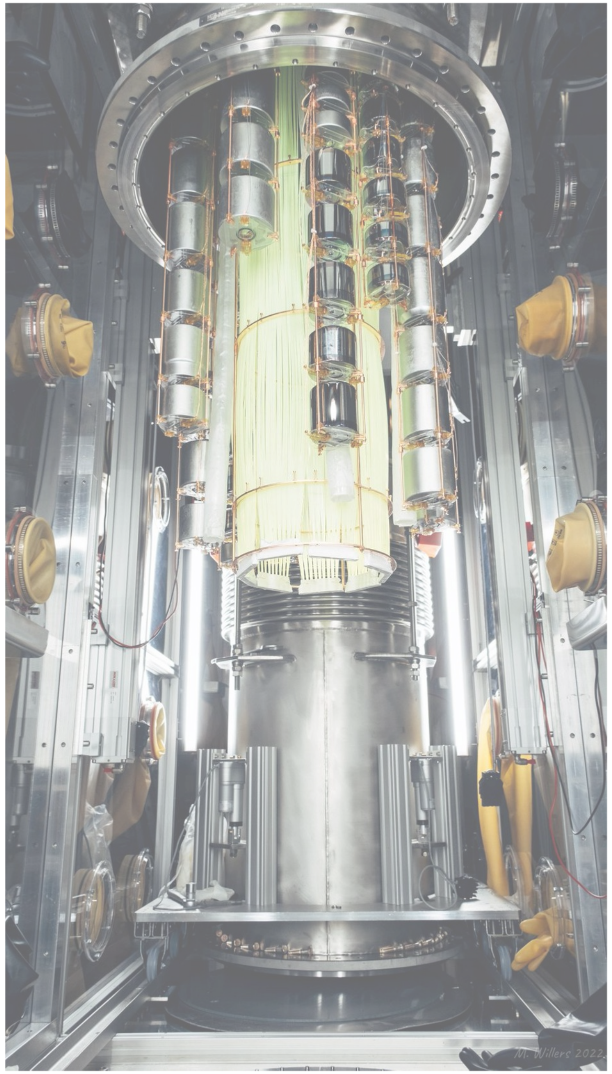
Neutrinoless Double-Beta Decay and neutrino mass



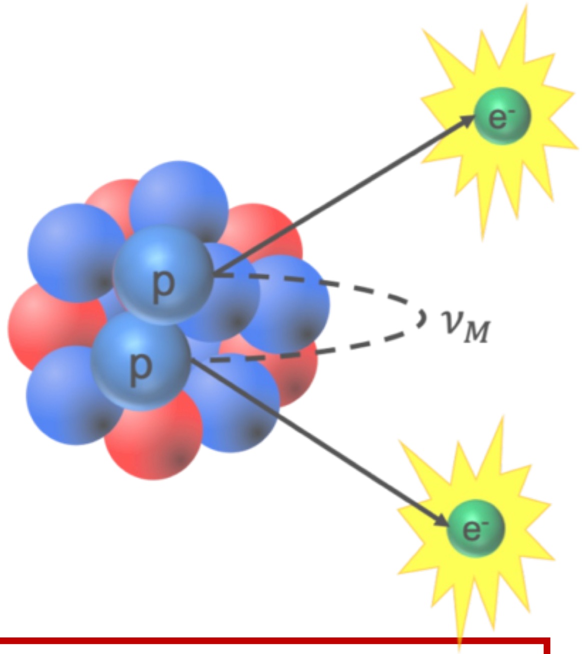
Ruben Saakyan
University College London

Joint IoP Annual HEPP, NP, APP Conference
Liverpool
8-11 April 2024



Outline

- $0\nu\beta\beta$ Physics and Experimental Approaches
- Current results and (near)-future programme (UK flavour)
- International Landscape and UK strategy



Disclaimer:

- Vibrant field: impossible to do justice in 17 min
- Focus on giving an overview of most promising developments, convey excitement about physics reach*, and present UK strategy

* Potentially around the corner!

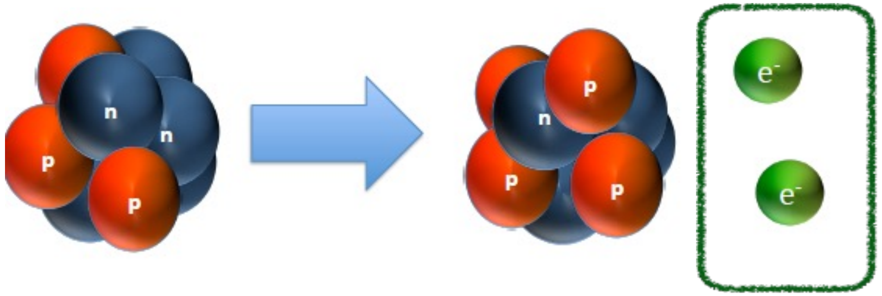
Much of material from comprehensive recent review

Agostini, Benato, Detwiler, Menendez, Vissani
Rev. Mod. Phys. 95 025002

Big Questions requiring BSM Physics

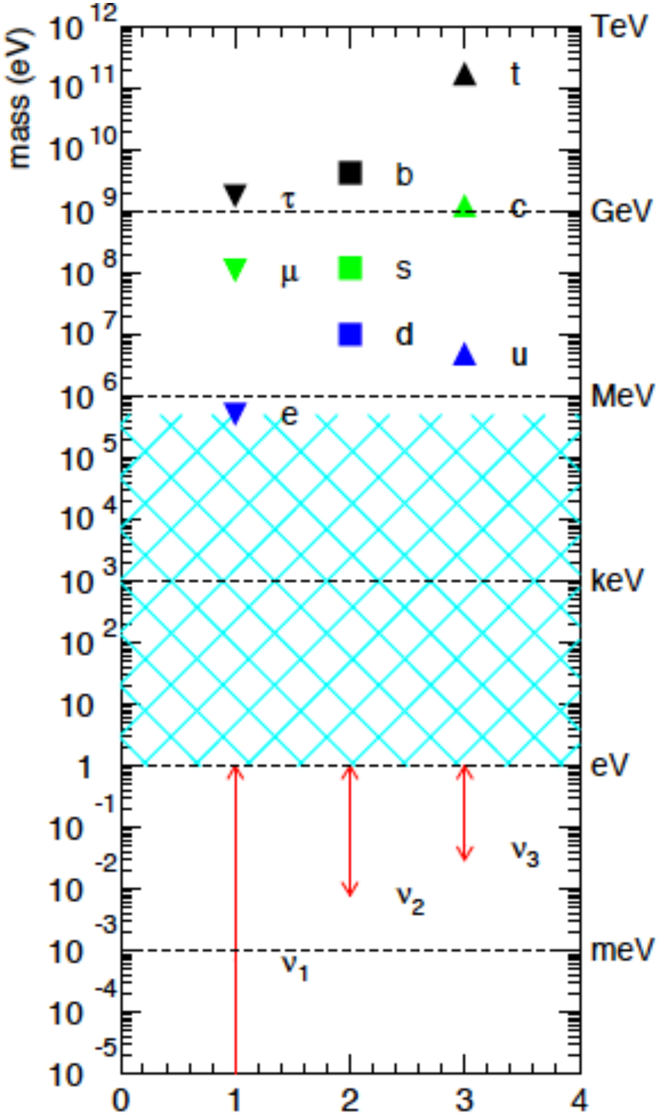
Proton Decay:
"Disappearance" of nucleons

$B = N_{baryons} - N_{anti\text{-}baryons}$



Neutrinoless Double Beta Decay
($0\nu\beta\beta$) "Creation" of leptonic matter

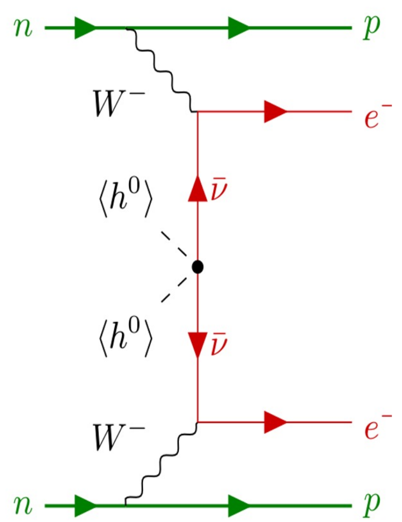
$L = N_{leptons} - N_{anti\text{-}leptons}$



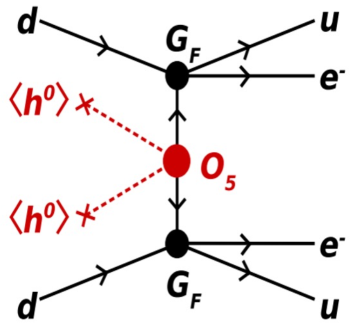
L and B-L non-conservation

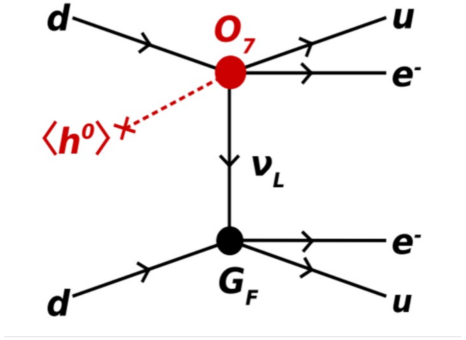
- Crucial for understanding ***dominance of matter*** over anti-matter
- Crucial for understanding mechanism behind ***ν-mass*** (***Majorana*** vs **Dirac**)
- 0νββ is the most sensitive way to address **L**epton **N**umber **V**iolation ***regardless*** of underlying mechanism

$0\nu\beta\beta$: Generic test for (B-L)-violating new physics

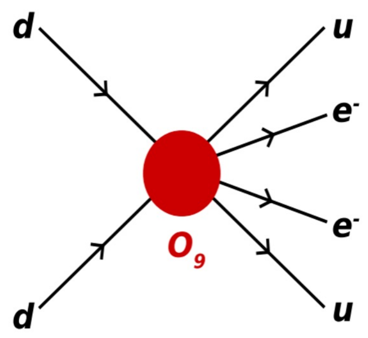


Cirigliano et al., JHEP 12, 097 (2018)





Deppisch, Graf, Iachello and Kotila
Phys.Rev.D 102 (2020) 9, 095016



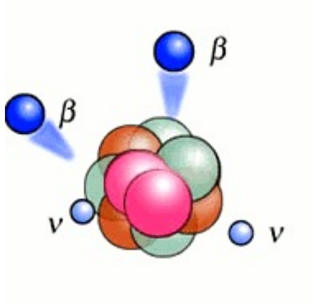
- **Any new L-violating physics can result in $0\nu\beta\beta$ (access to ultra-high energy BSM)**
- **Schechter-Valle: $0\nu\beta\beta$ observation provides unambiguous evidence for non-zero Majorana mass (even if it is not dominating mechanism)**

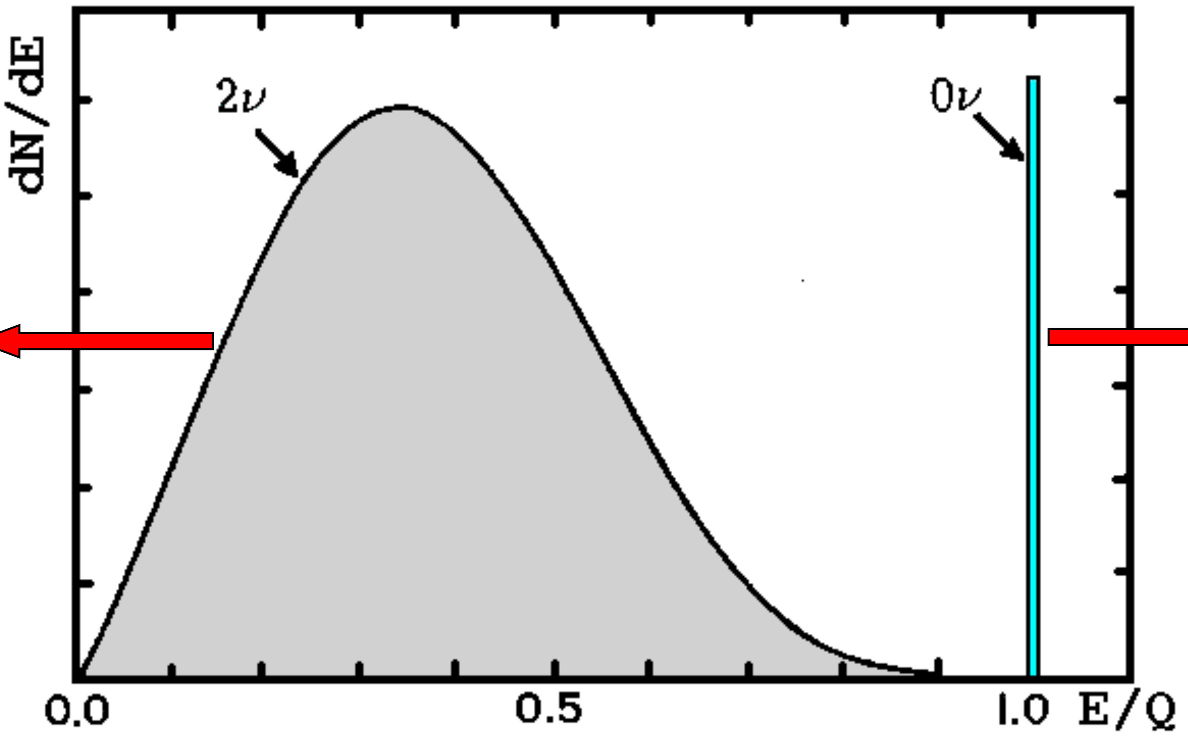
J. Schechter and J. W. F. Valle Phys. Rev. D **25**, 2951 (1982)

0νββ Experimental Observables

$\Gamma^{2\nu} \propto G_F^4$

$T_{1/2} \sim 10^{19} - 10^{24}$ yr!

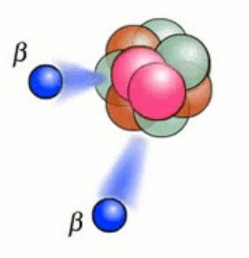




$E_{e1} + E_{e2}$

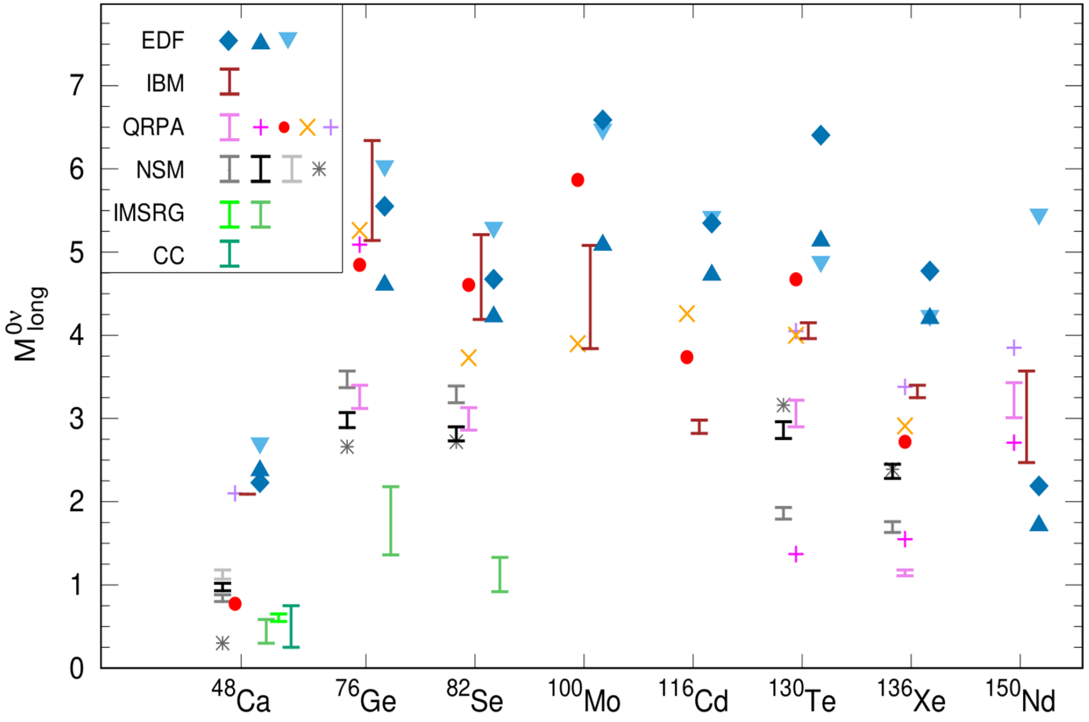
$\Gamma^{0\nu} \propto G_F^4 \cdot \eta_{LNV}^2$

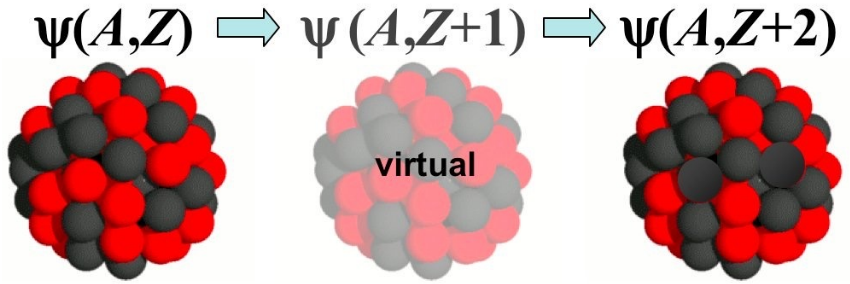
$T_{1/2} > 10^{26}$ yr!



$2\nu\beta\beta(EC/\beta^+)$ has been detected in 13 nuclei!

Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91





phase space

$$\Gamma^{0\nu} \propto \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

nuclear matrix element (NME)

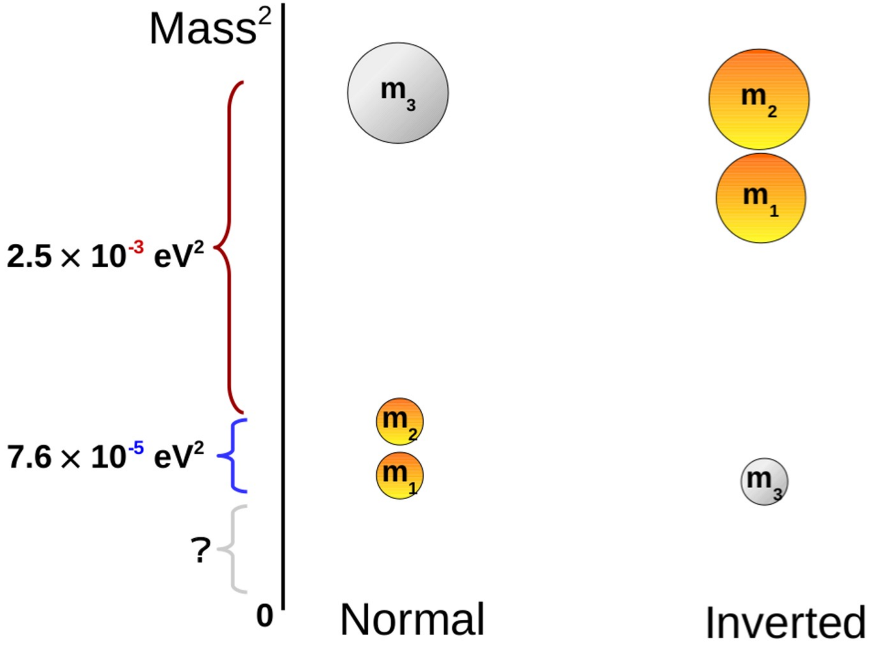
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta}\right|$$

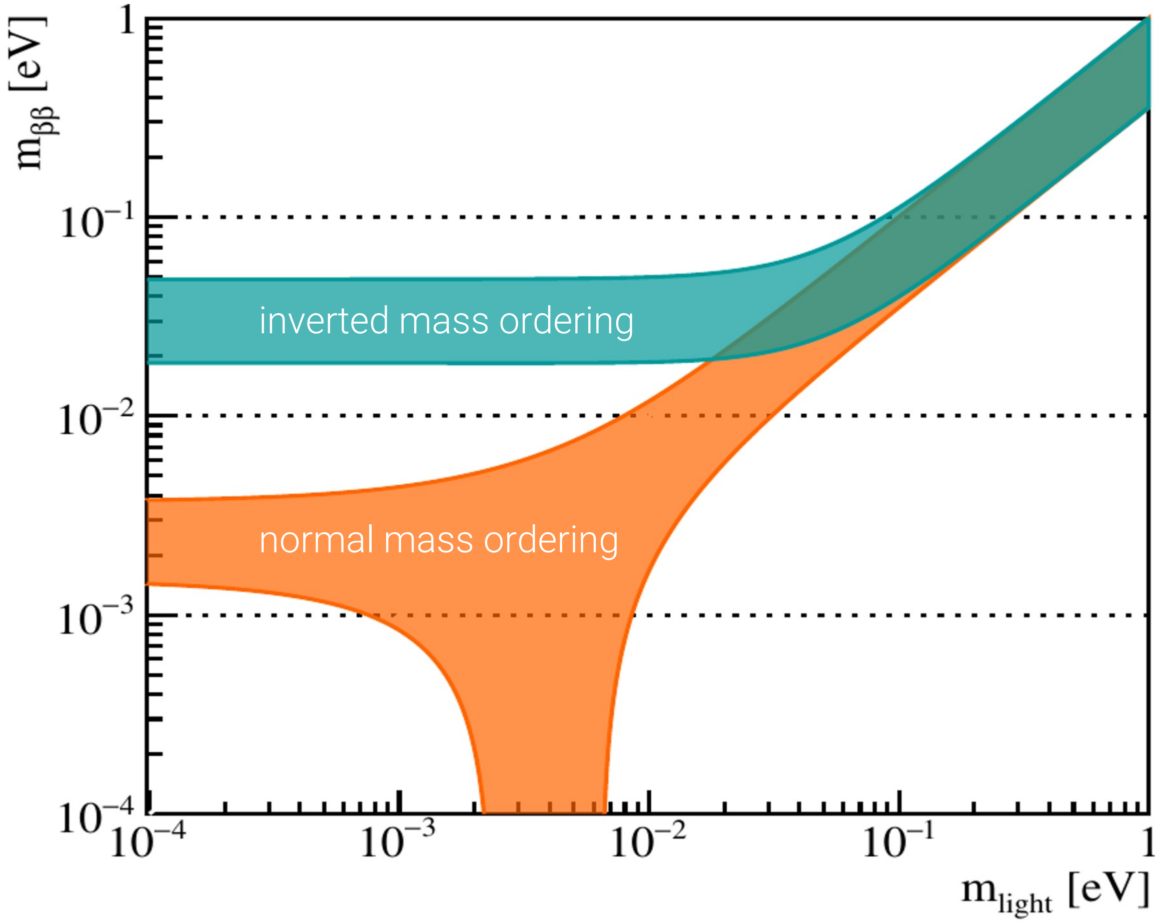
$c_{12} = cos\theta_{12}, c_{13} = cos\theta_{13}, s_{12} = sin\theta_{12}, s_{13} = sin\theta_{13}$

$m_{1,2,3}$ → mass eigenstates α, β → Majorana CP-phases

Reach interplay with neutrino oscillations, kinematic measurements (m_β), cosmology (Σ)

$0\nu\beta\beta$: Majorana neutrino mass, $m_{\beta\beta}$ and neutrino mass ordering

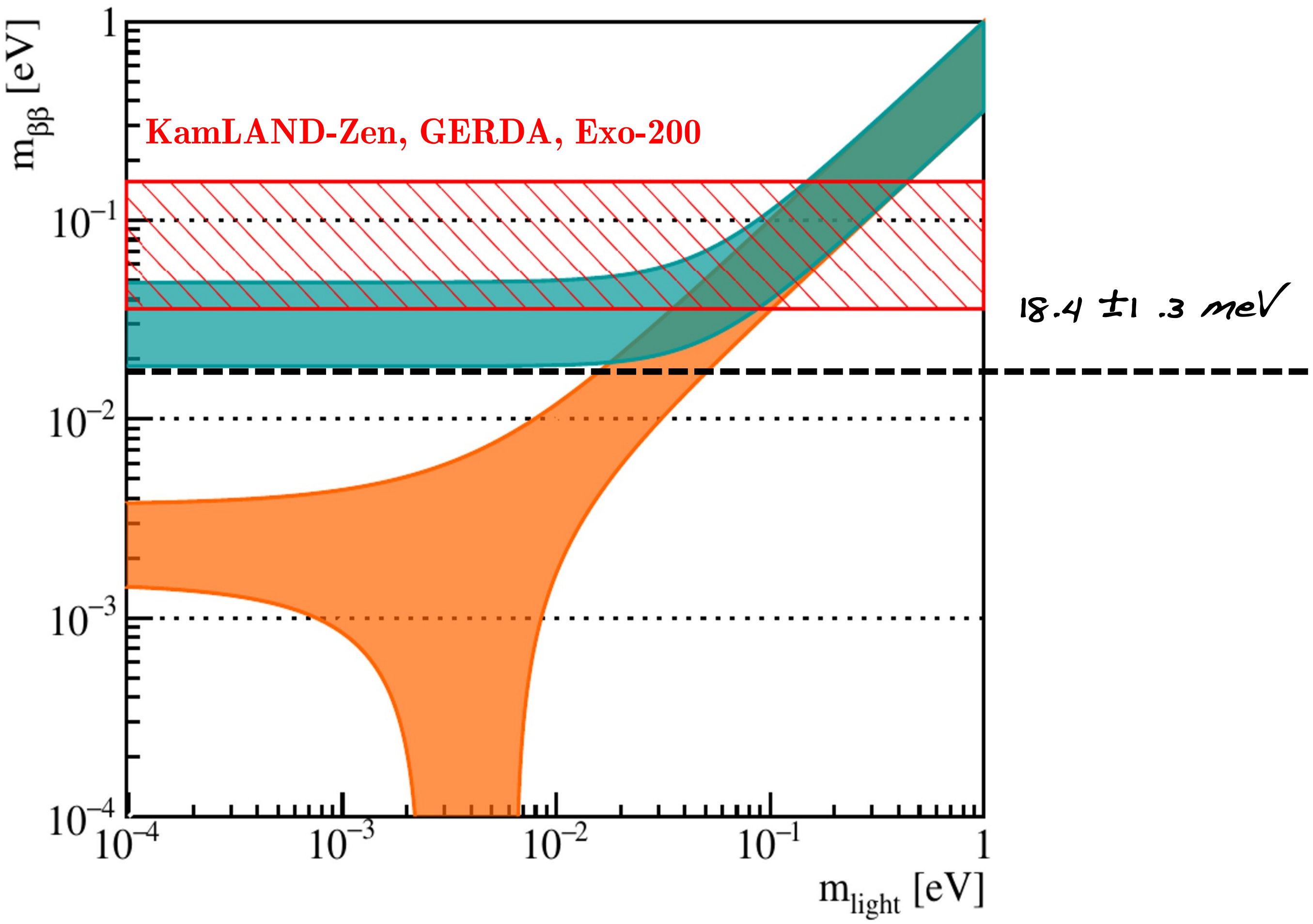


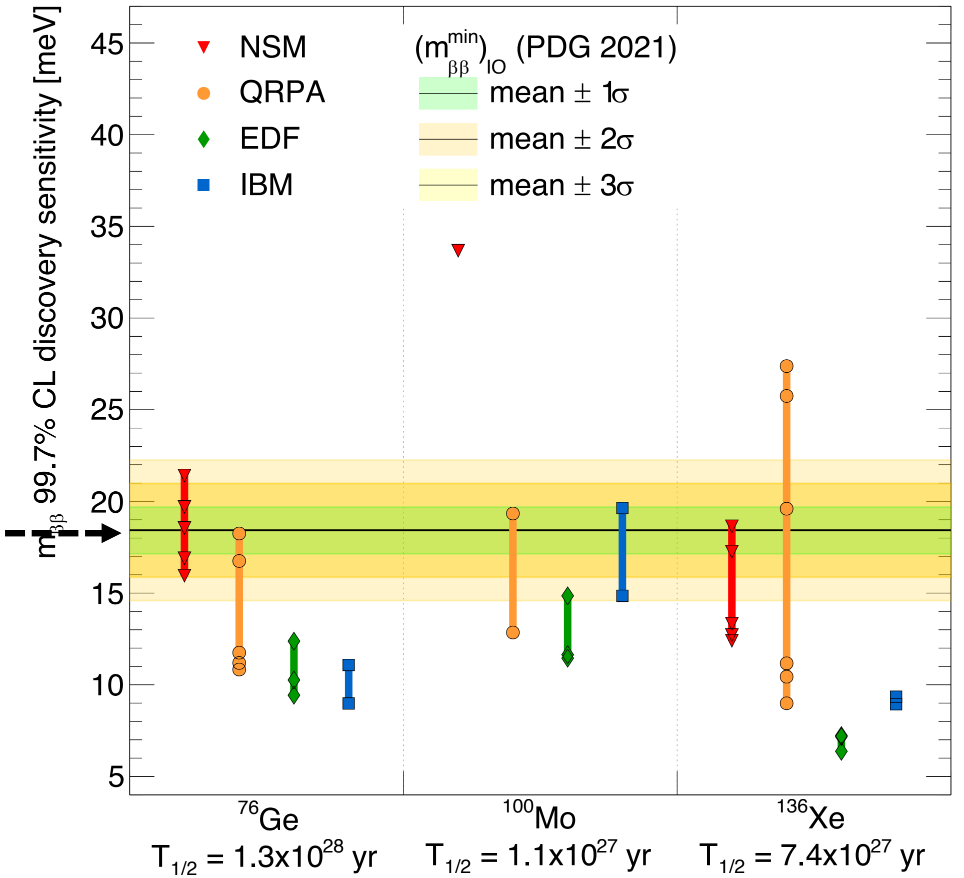


$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

$0\nu\beta\beta$ with $m_{\beta\beta}$ Status and Future Goals

Best so far: $T_{1/2} > 10^{26}$ yr





LEGEND CUPID nEXO

Experimental Approaches

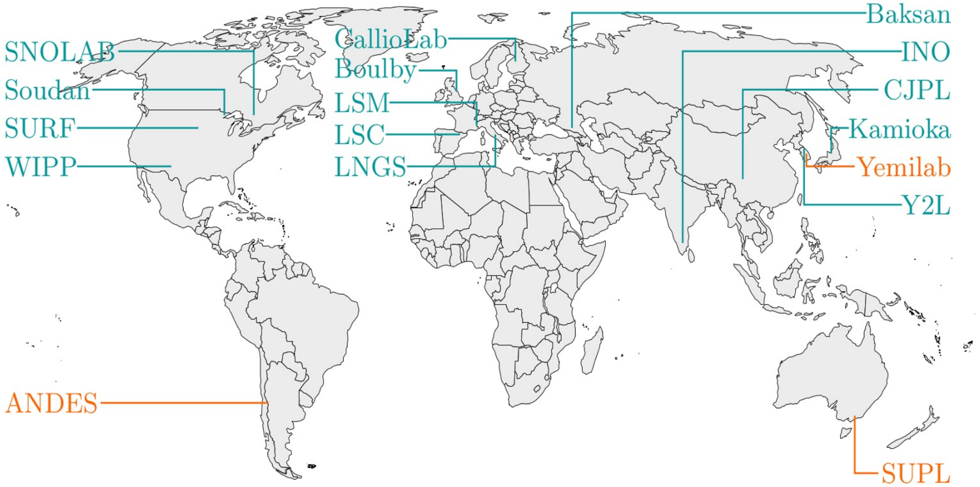
Detection Principles

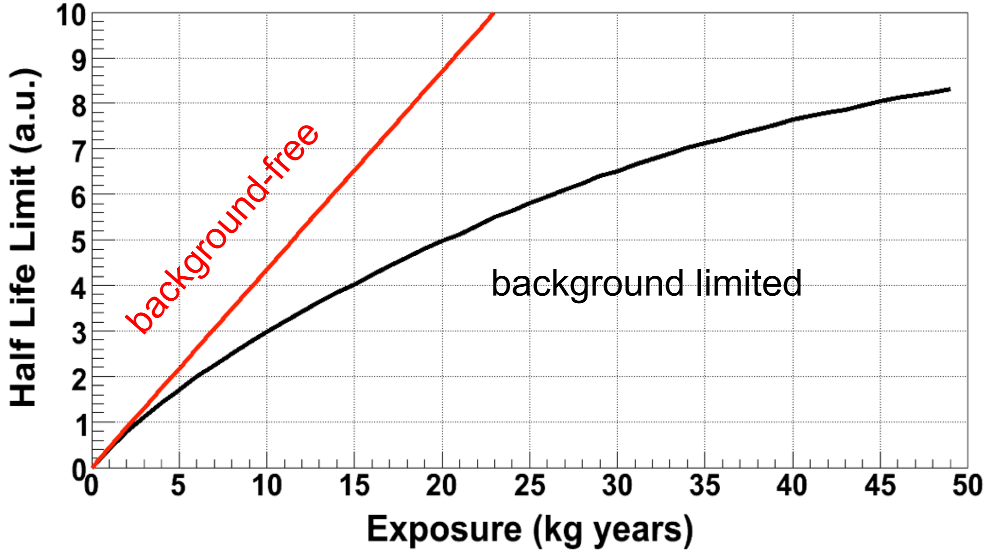
maximise **detection efficiency** and ββ **isotope abundance**

maximise **exposure**

$$T_{1/2}^{0\nu}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

minimise **background**

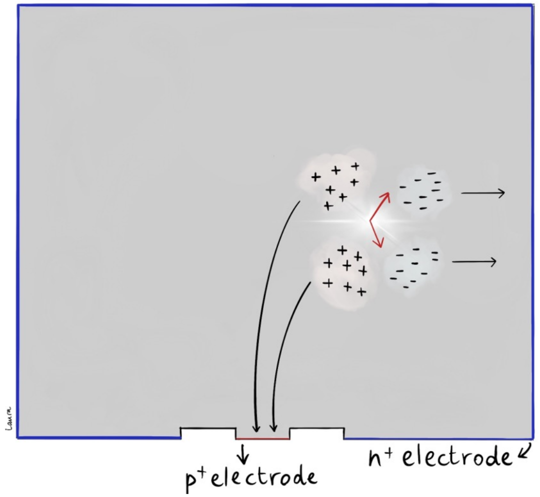




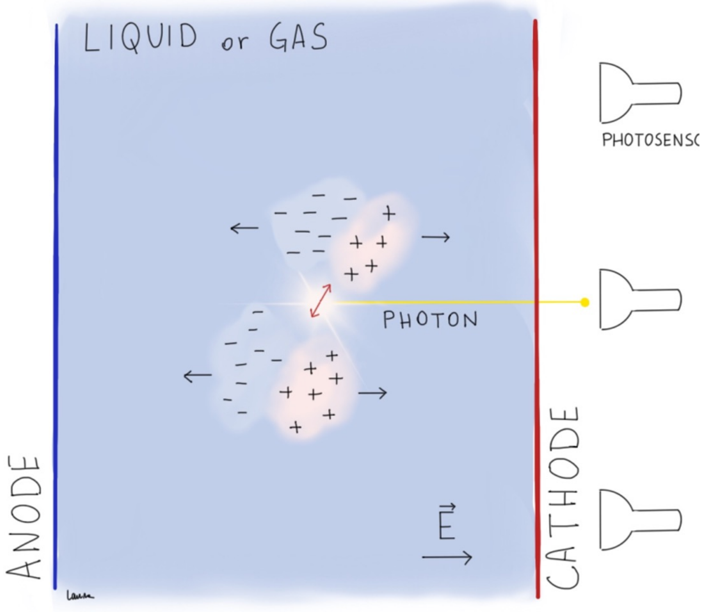
It's all about *backgrounds*

- Cosmic rays (underground)
- Natural radioactivity (clean materials, particle id and tagging)
- Standard Model 2νββ (energy resolution)

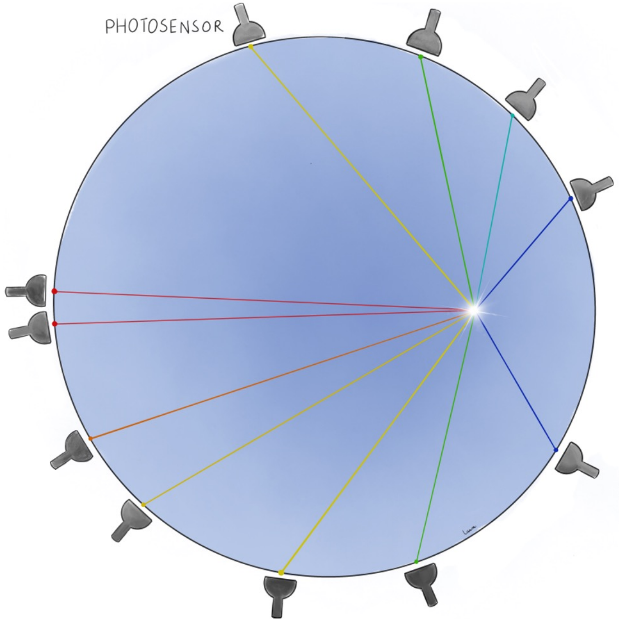
Leading Experimental Techniques



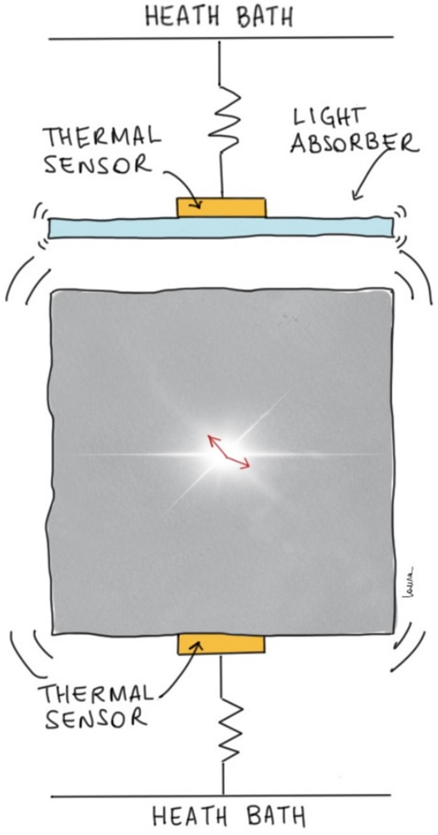
Ge Semiconductor detectors (^{76}Ge)



Xe Time Projection Chambers (^{136}Xe)



Large Liquid scintillator detectors (^{130}Te,^{136}Xe)



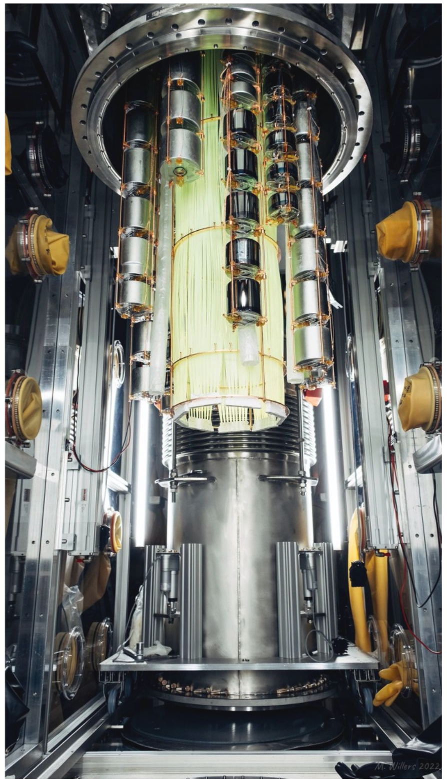
Cryogenic Calorimeters (^{100}Mo, ^{30}Te)

Drawings courtesy of Laura Manenti

LEGEND-200

Wednesday III, C: G. Marshall

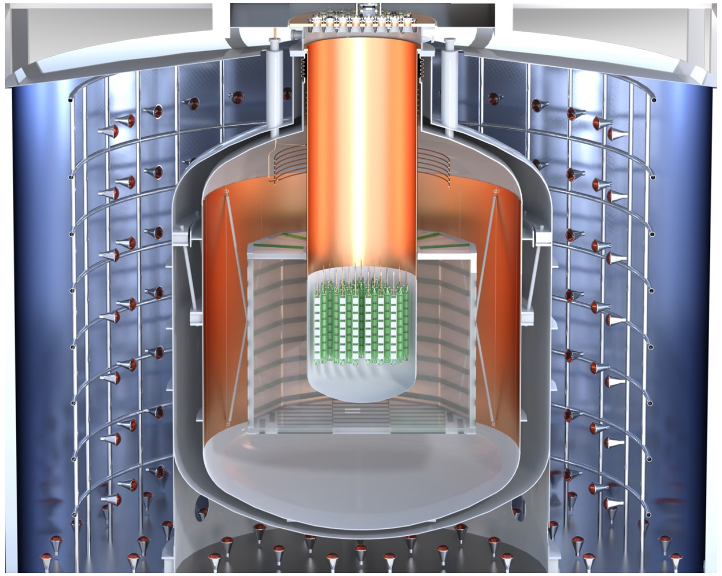
- 200kg ^{76}Ge enriched > 88%
- BG goal: < 0.5 cts/FWHM t yr)
- Physics run with 10 strings (142kg) since Mar-2023 at LNGS

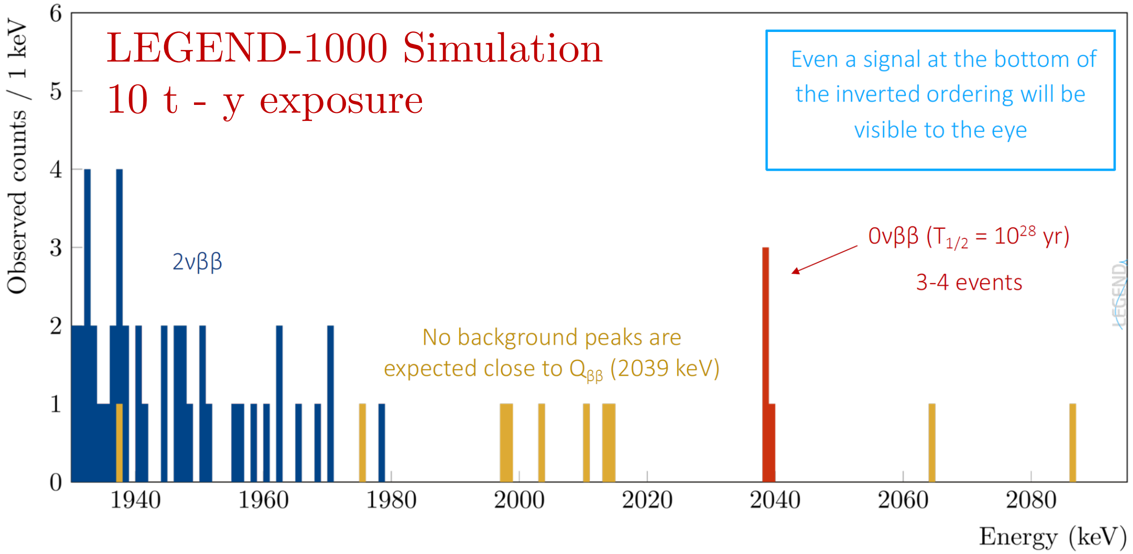


LEGEND-1000

Wednesday III, C: D. Waters

- 1000kg ^{76}Ge enriched > 90%
- BG goal: < 0.025 cts/FWHM t yr)
- Location LNGS

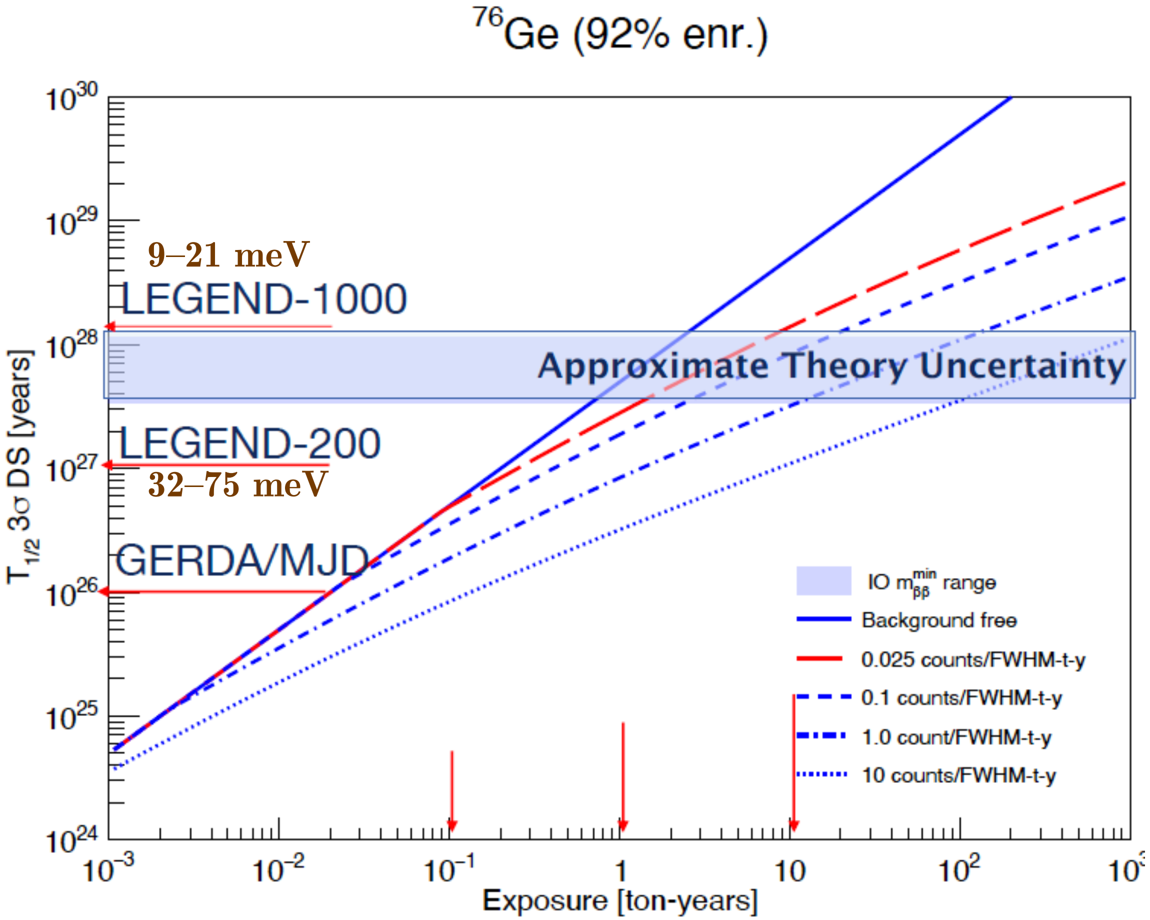




LEGEND-200

Wednesday III, C: G. Marshall

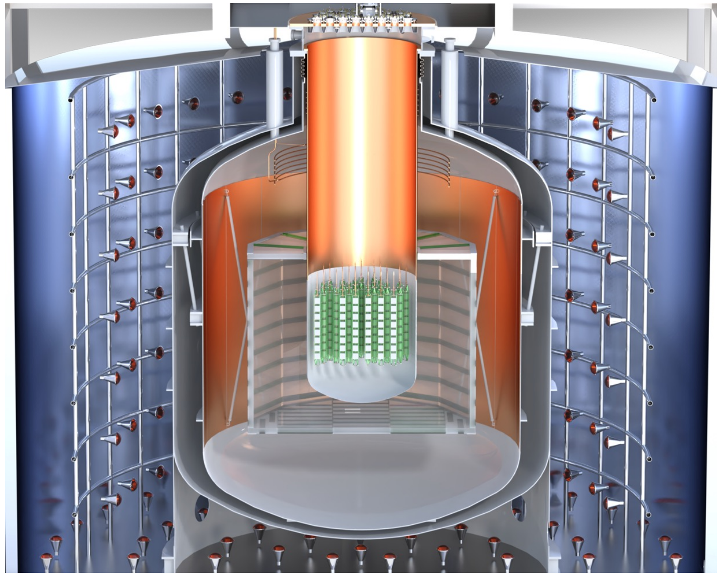
- 200kg ^{76}Ge enriched > 88%
- BG goal: < 0.5 cts/FWHM t yr)

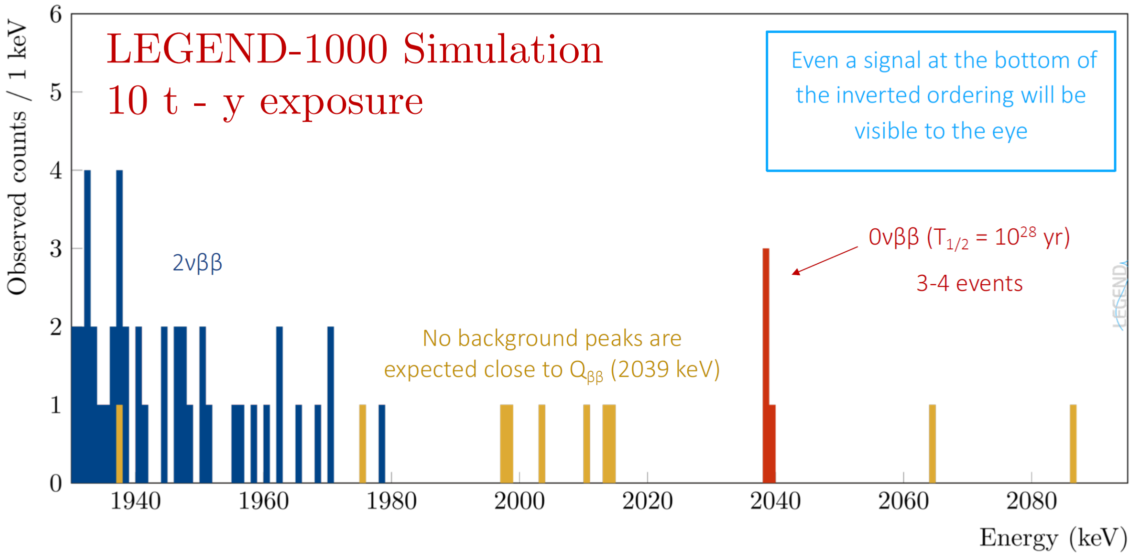


LEGEND-1000

Wednesday III, C: D. Waters

- 1000kg ^{76}Ge enriched > 90%
- BG goal: < 0.025 cts/FWHM t yr)
- Location LNGS



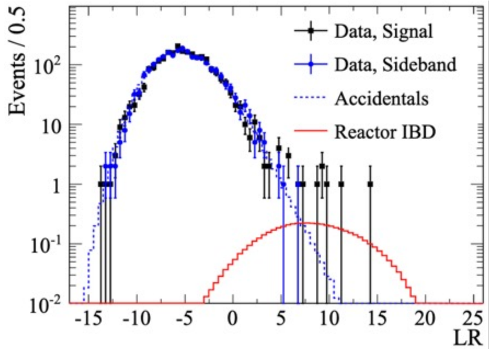


Loaded (Te) liquid scintillators

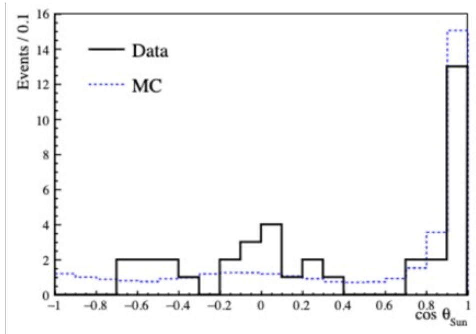
KCL, Lancaster, Liverpool, Oxford, Sussex

Highly scalable, no need for enrichment, rich physics programme

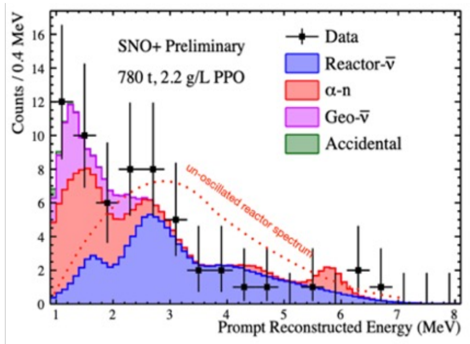
Courtesy of S. Biller



First ever observation of reactor anti-ν's in a water detector (PRL 130, 2023)

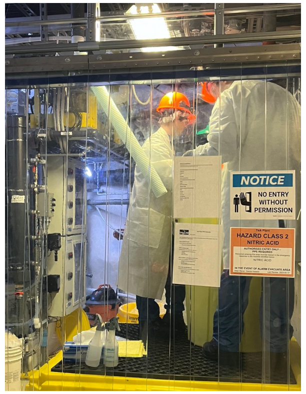


First ever directional reconstruction of solar ν's in high light-yield scintillator (to appear in PRD)

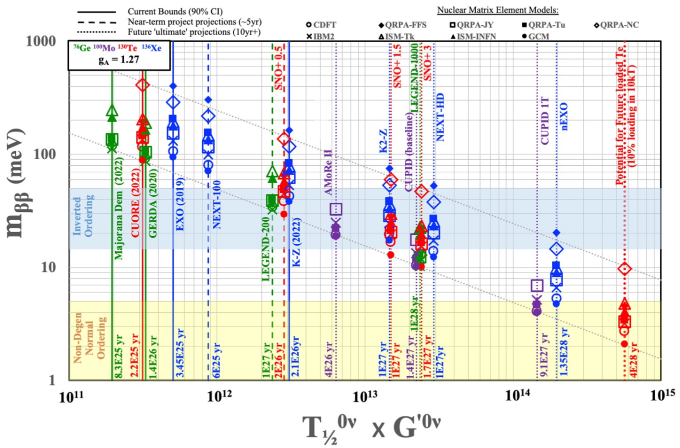


Prelim. reactor & geo anti-ν measurement (< 150d scint. data)

Wednesday I C: J.Page and K. Dixon
Wednesday II E: B. Tam



Test batch operation of Te systems, preparation for loading next year



Canadian proposal to be submitted this year to treble loading to 1.5% Te

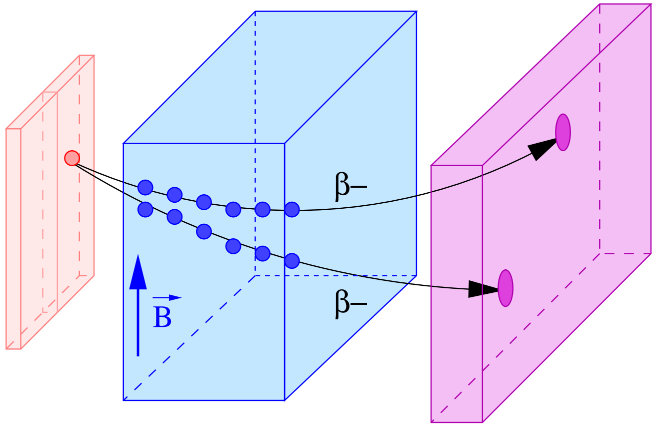
2025	2026	2027	2028	2029
final commissioning	Te deployment	Phase I data taking	increase Te loading	Phase II higher loading data taking

supernemo collaboration

Edinburgh, UCL, Warwick, Manchester

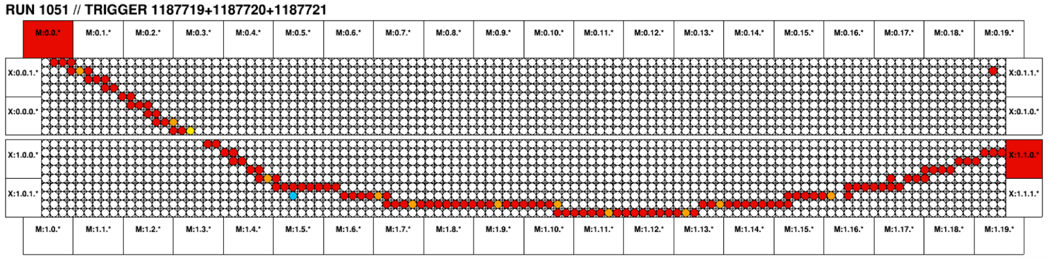
Courtesy of C. Patrick

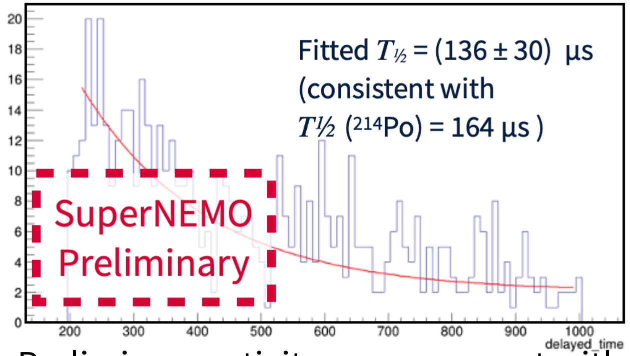
$\beta\beta$ source + High-granularity tracker + Segmented calorimeter



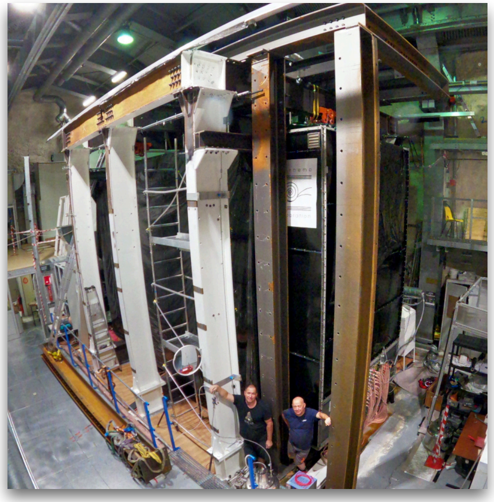
= Individual electron energies and trajectories

Taking background and calibration data at LSM; 99% of tracker channels live!

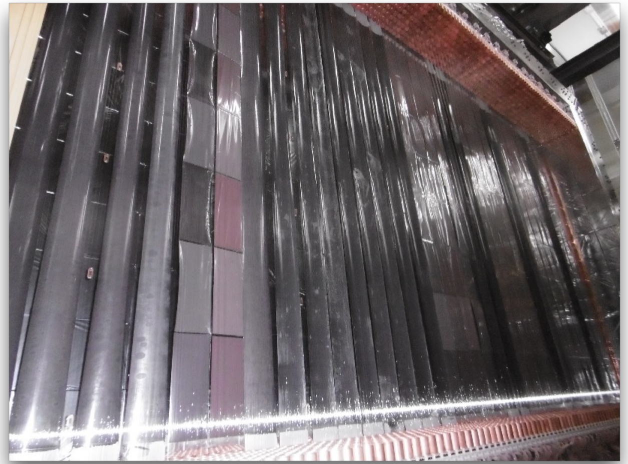




Preliminary activity measurement with BiPo's yields radon level comparable to predecessor NEMO-3 (before shielding/radon-free air)



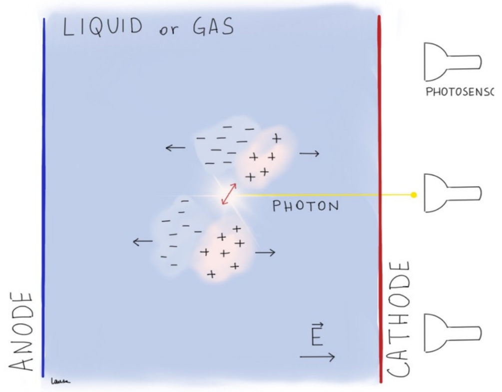
Shielding installation underway!



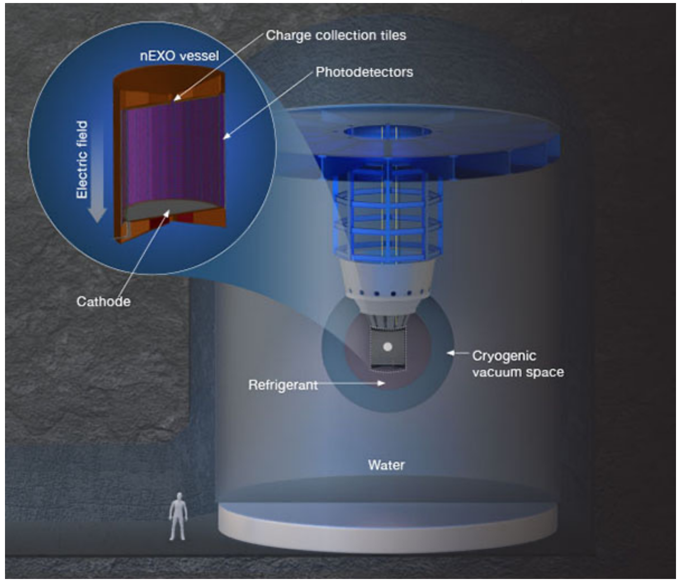
- (Almost) isotope agnostic
- Excellent background rejection
- Nuclear structure effects
- Decays to excited states
- Exotic decay searches

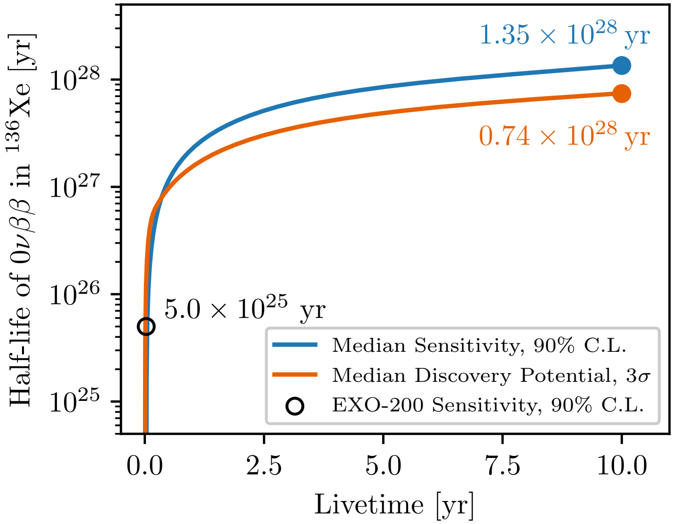
Enriched Xe TPCs

- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface
- R&D to tag $0\nu\beta\beta$ decay daughter isotope



nEXO





Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs
LZ-enr	7 000	90	dual-phase	PMTs
DARWIN	39 300	9	dual-phase	PMTs
XLZD	**80,000**			

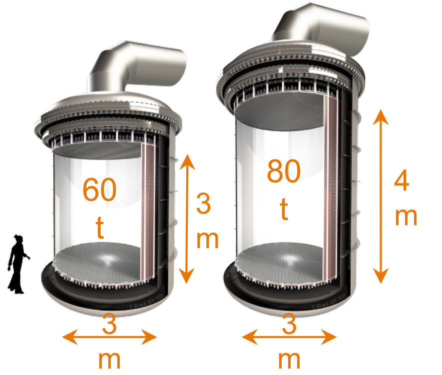
Enriched Xe TPCs

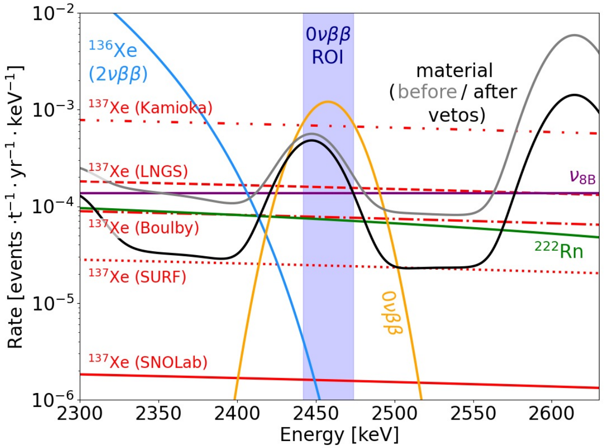
^{136}Xe $0\nu\beta\beta$ in **XLZD**

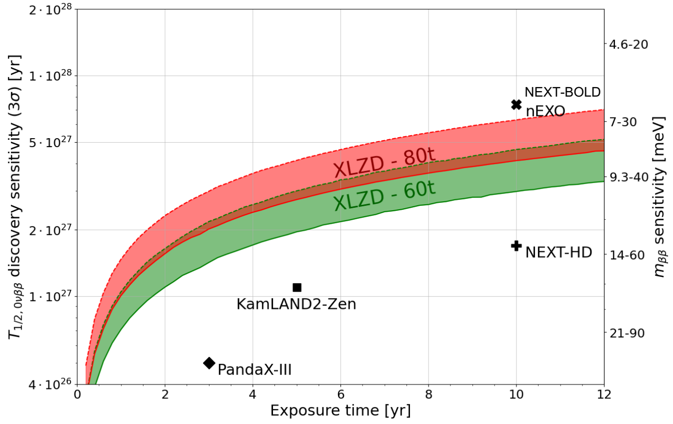
Liquid ^{136}Xe TPC

Courtesy of A. Lindote
see also A. Cottle talk

Nominal **Opportunity**







- 60 - 80 t of natural abundance xenon
  - 5.3 - 7.1 t of ^{136}Xe
- Xenon self-shielding + MS rejection + vetoes
  - 11.1 - 18.3 t fiducial volume
- $E_{Res} = 0.67\%$ (σ, demonstrated in LZ)

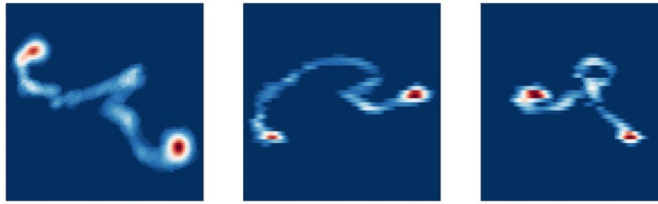
NEXT

Manchester

Courtesy of R. Guenette

High-Pressure Gas ^{136}Xe TPC

- Phased approach
- NEXT-White demonstrated technology
  - sub% FWHM



$T_{1/2}^{2\nu} = (2.34\ ^{+0.85}_{-0.49})\times10^{21}$ yr

NEXT Collaboration, *PRC* 105 (2022) 5

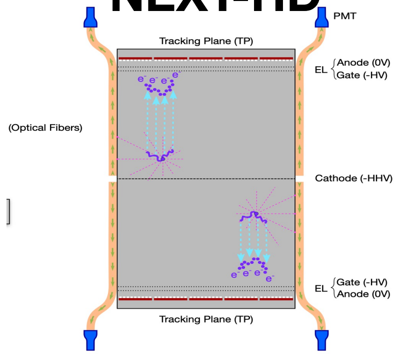
$T_{1/2}^{0\nu} > 0.6\text{-}1.3\times10^{24}$ yr at 90% CL

NEXT Collaboration, *JHEP* 09 (2023) 190

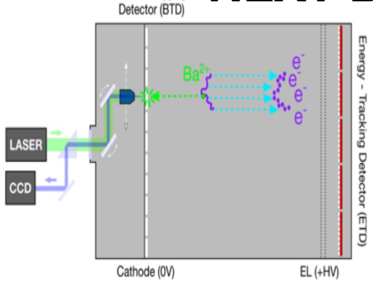
NEXT-100 under commissioning (data taking in summer 2024)

Towards 1t scale

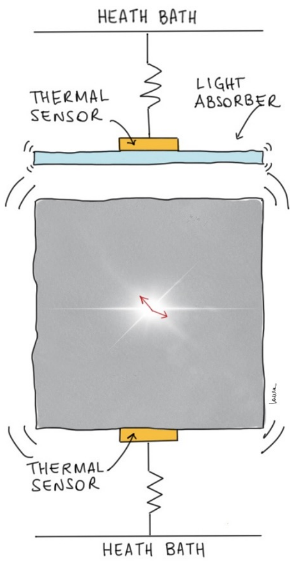
NEXT-HD



NEXT-BOLD

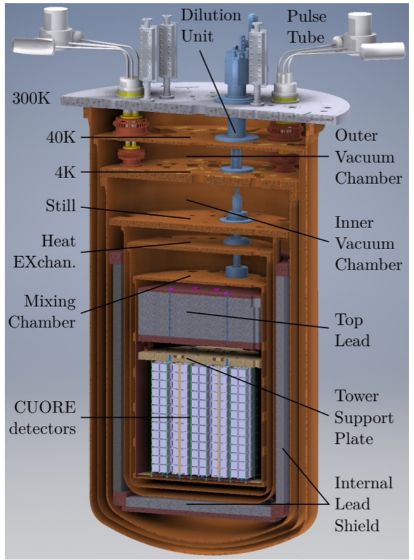


Cryogenic Calorimeters

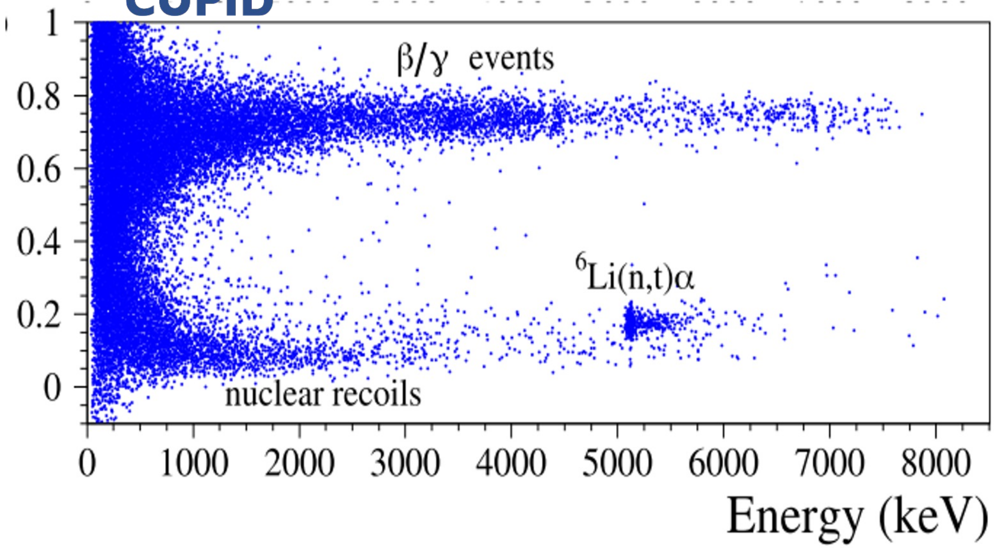


- array of isotopically enriched crystals operated at ~10 mK
- thermal and scintillation signal
- particle ID and good energy resolution
- Leading results for ^{130}Te and ^{82}Se, future focus on ^{100}Mo

Experiment	Crystal	m_{tot} [kg]	f_{enr} [%]
CUORE	$^{nat}TeO_2$	742	34[a]
CUPID-0	$Zn^{enr}Se$	9.65	96
CUPID-Mo	$Li_2{}^{enr}MoO_4$	4.16	97
CROSS	$Li_2{}^{enr}MoO_4$	8.96	98
CUPID	$Li_2{}^{enr}MoO_4$	472	≥95
AMoRE	$Li_2{}^{enr}MoO_4$	200	96



CUPID

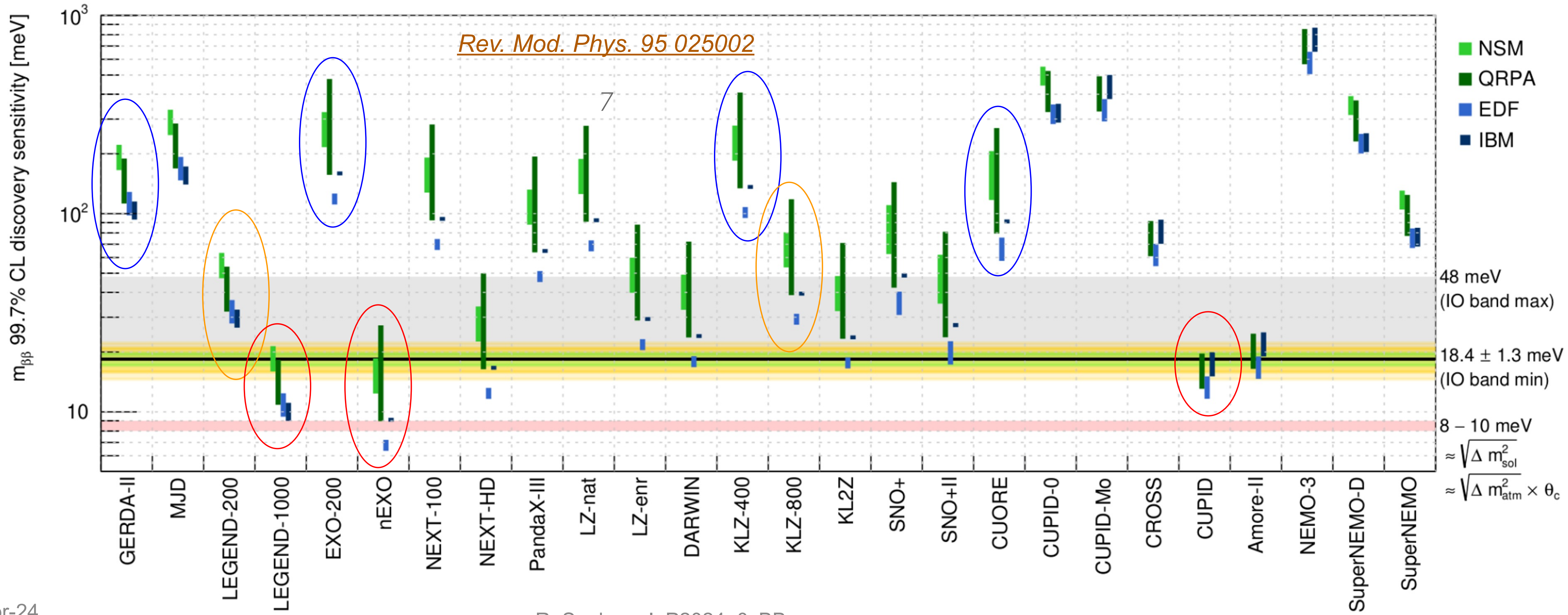


Outlook

Last decade: **GERDA, EXO-200, KamLAND-Zen-400, CUORE**

The two to watch: **LEGEND-200, KamLAND-Zen-800**

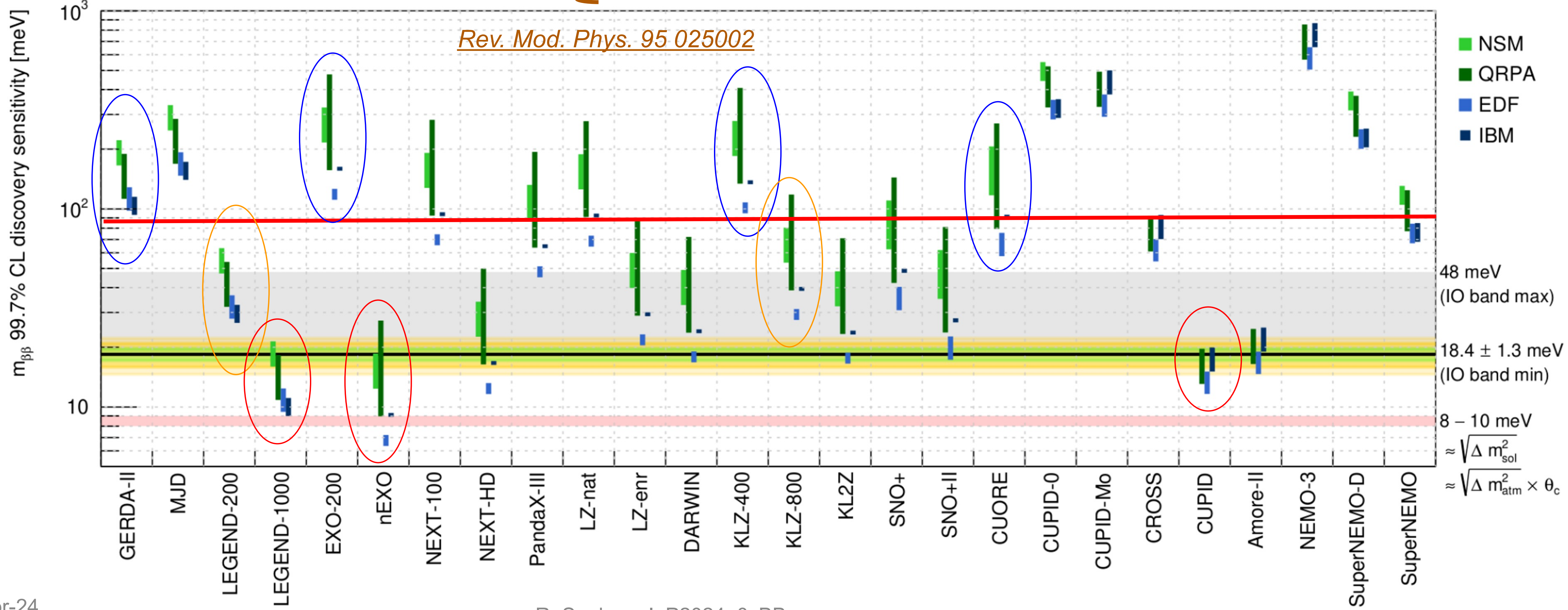
Coming up (10-15 yrs): **LEGEND-1000, CUPID, nEXO, +…**



Outlook

Scenario 1: signal just beyond current limits

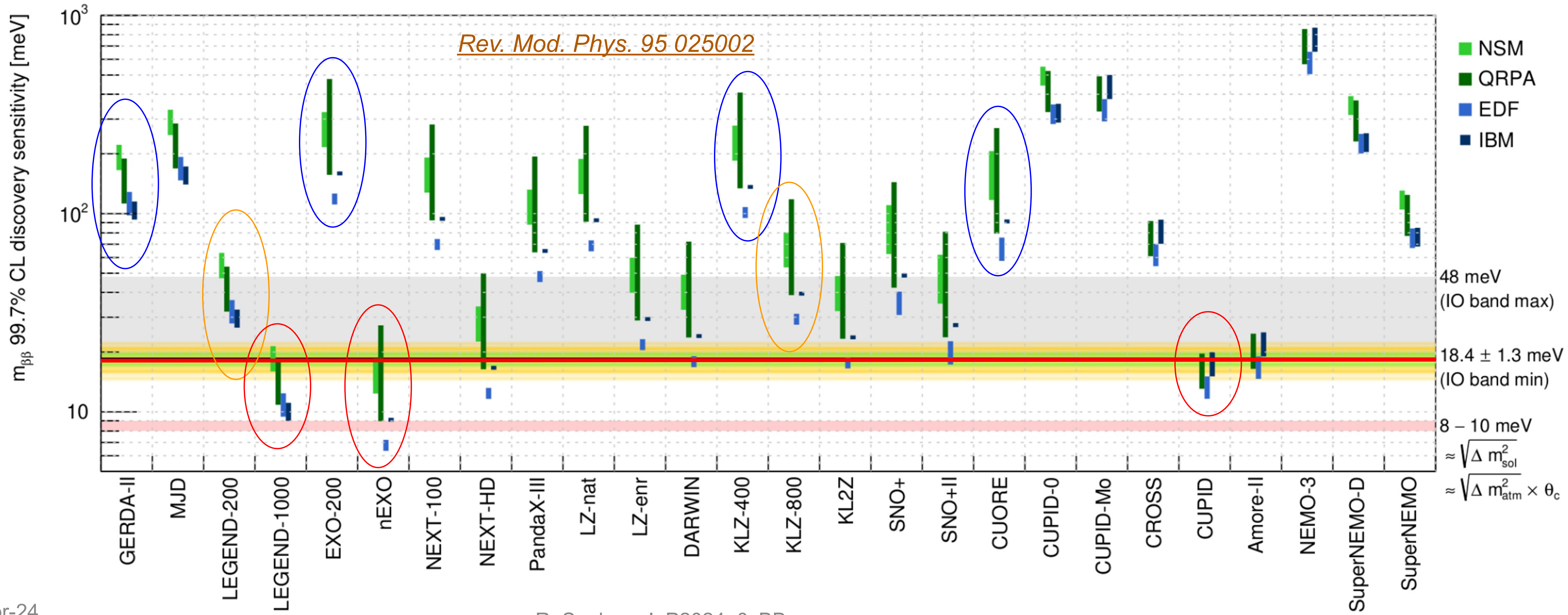
- discovery within few years
- precise rate measurement with next-gen experiments
- Access to underlying mechanism with SNEMO-like technique



Outlook

Scenario 2:
signal at bottom of I.O.

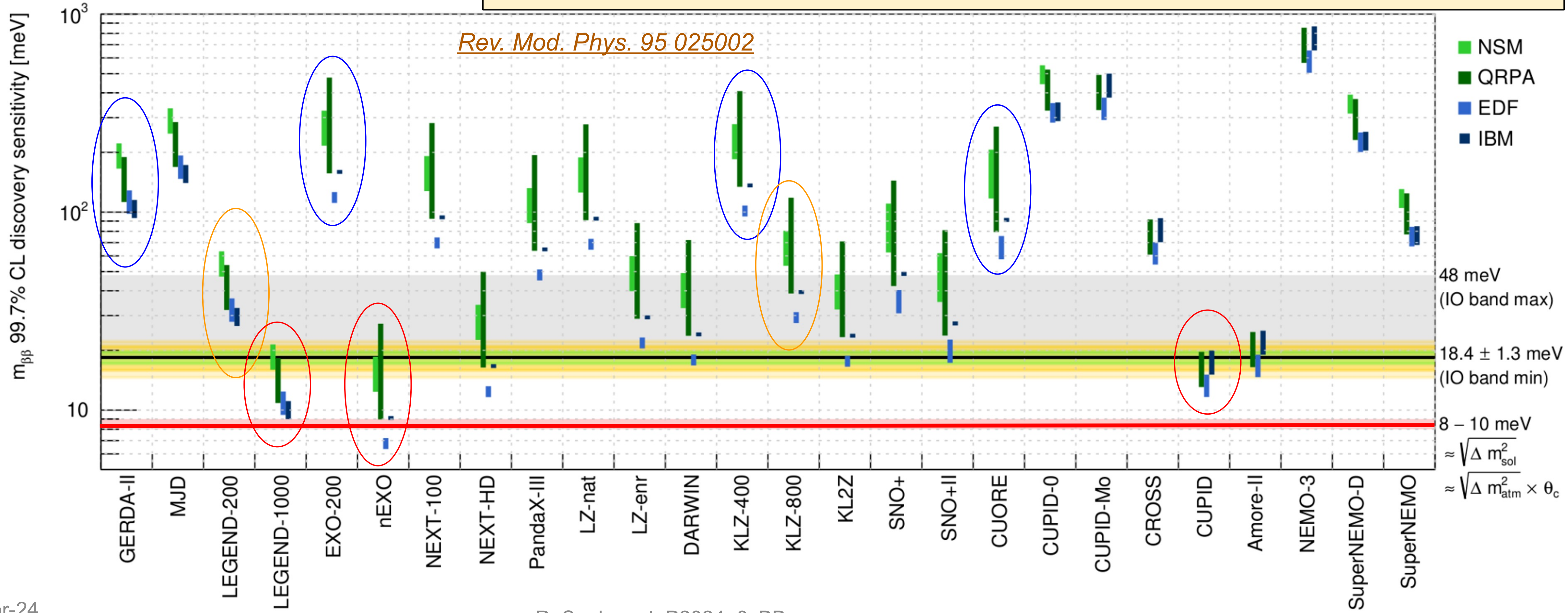
- need to wait next-gen experiments for a discovery
- need R&D to measure decay features



UCL

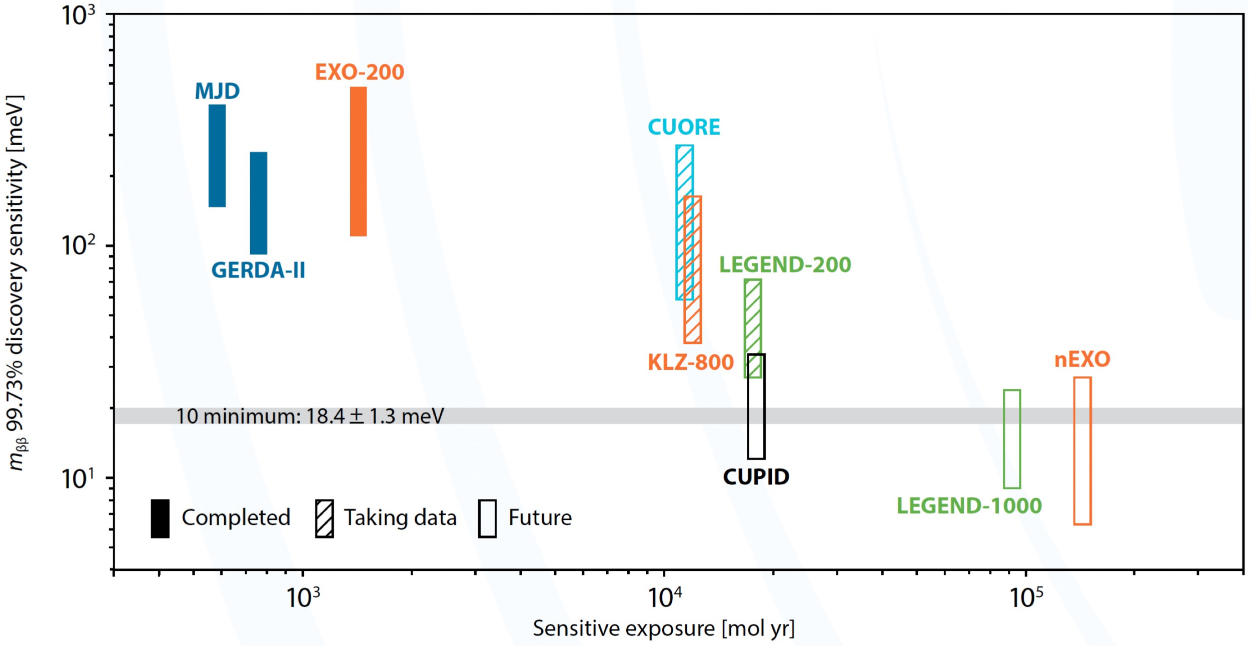
Scenario 3:
signal < 10meV

- R&D and new ideas for convincing discovery
- interplay with oscillation experiments, cosmology and β-decay can lead to breakthroughs even in absence of signal



International Landscape

Figure 6.5, A New Era of Discovery, the 2023 Long Range Plan for Nuclear Science



Strong support and programme to realise > 1 "ton-scale" experiment from both sides of the pond

UK Community Strategy

https://zenodo.org/records/10620723


zenodo | Search records... | Communities | My dashboard

Published November 28, 2023 | Version 1 | Publication | Open

Neutrinoless double-beta decay: UK community strategy

UK Neutrinoless Double-Beta Decay Community

Files

UK_NDBD_strategy.pdf

Page: 1 of 3 | Automatic Zoom

Neutrinoless double-beta decay: UK community strategy

M. Agostini*[1], H. Araujo[2], S. Biller[3], M. Borri[4], A. Boston[5], H. Boston[5], S. Burdin[5], A. Cottle[1], F. Deppisch[1], P. Di Bari[6], J. Dobaczewski[7], J. Dobson[8], J. Evans[9], L. Falk[10], H. Flaecher[11], H. Fox[12], C. Ghag[1], R. Guenette[9], L. Harkness-Brennan[5], J. Hartnell[10], R.-D. Herzberg[5], R. Jones[12], S. Jones[13], D. Judson[5], A. Khan[14], S. King[6], M. Kogimtzis[4], L. Kormos[12], H. Kraus[3], P. Kyberd[14], M. Labiche[4], I. Lazarus[4], J. March-Russell[3], I. Martinez Soler[15], C. McCabe[8], N. McCauley[5], A. Mehta[5], D. Muenstermann[12], S. Paling[16], K. Palladino[3], S. Paschalis[7], C. Patrick[17], S.J.M. Peeters[10], M. Petri[7], Y. Ramachers[18], T. Rawlings[4], A. Reichold[3], J. Rose[5], R. Saakyan[1], P. Scovell[16], S. Shaw[17], R. Smith[4], S. Soldner-Rembold[9], T. Sumner[2], D. Tovey[13], J. Tseng[3], J. Turner[15], Y. Uchida[2], C. Unsworth[4], D. Waters[1], S. West[19], J. Wilson[8], and I. Zavala[20]

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near-term: 5 yr
mid-term: 5 – 15 yr
long-term > 15 yr

1) Continued support for running experiments* exploitation
2) Support for construction of LEGEND-1000 in the *near-term* aiming at 3σ I.O. discovery sensitivity in *mid-term*
3) Support the development and implementation of higher-loading phased of SNO+ to address *long-term* goals
4) Support complementary opportunities of XLZD and future blue-skies R&D in *long-term*

Support from particle, astro-particle and nuclear physics communities

* LEGEND-200, SNO+, SuperNEMO

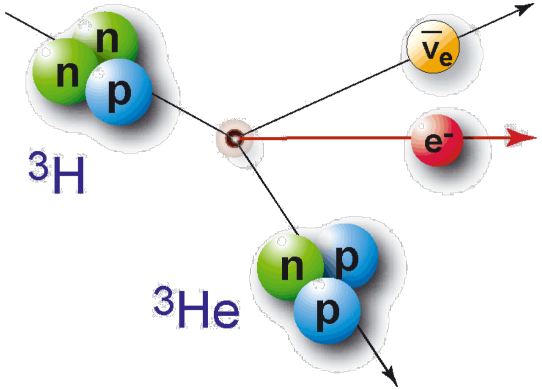
Concluding Remarks

- $0\nu\beta\beta$ is the best way to probe **Lepton Number Violation** and its connection to preponderance of **matter** and **neutrino mass** generation mechanism
- Huge progress over past decade has led to a **coordinated international effort**
  - Phased approach, convergence on experiments fully covering I.O. sensitivity
  - Continuing R&D to tackle N.O. and detailed exploration of signal
  - Strong effort in NME modelling, ab initio calculations, experimental input
- Interplay with oscillations, cosmology and β-decay results yields a significant likelihood of **discovery in next 2-15 years**!
- **UK** is in enviable leadership position but needs to "stick to the plan".

Additional Material

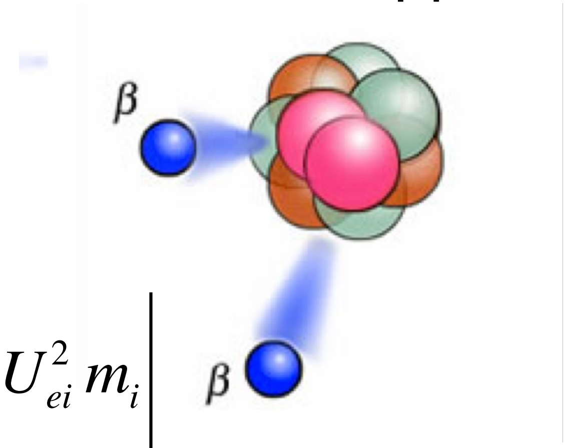
Different ways of measuring absolute neutrino mass

β-decay

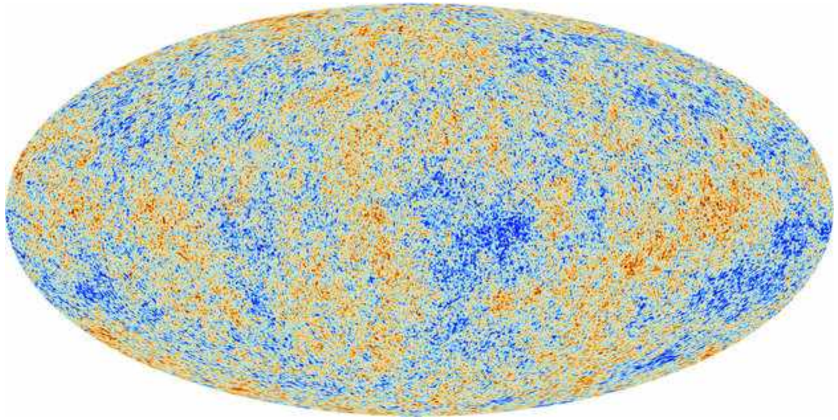


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

0νββ-decay



$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

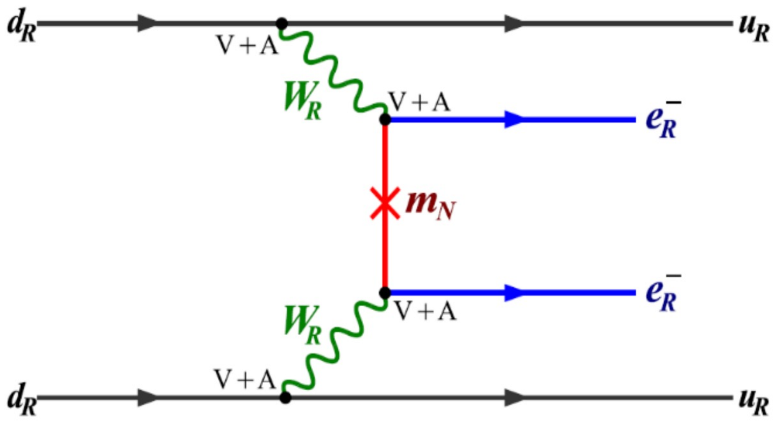


Cosmology

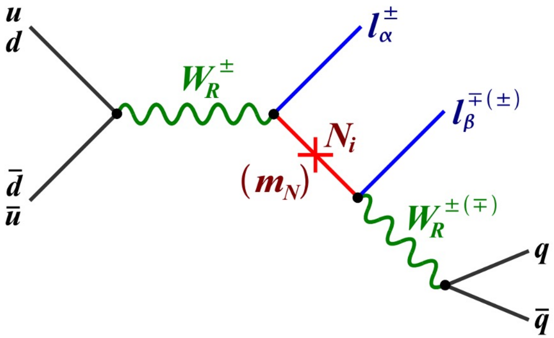
$$\sum_i m_i$$

$0\nu\beta\beta$: Generic test for L-violating BSM physics

Example: Left-Right Symmetric models

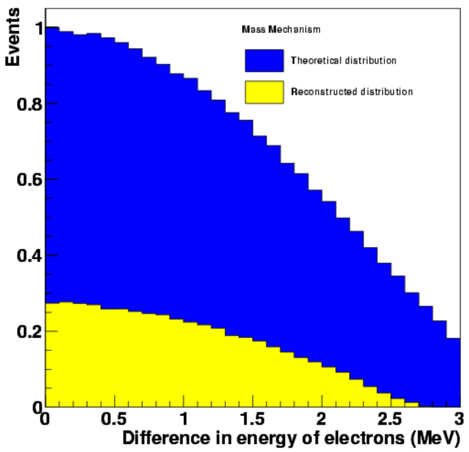


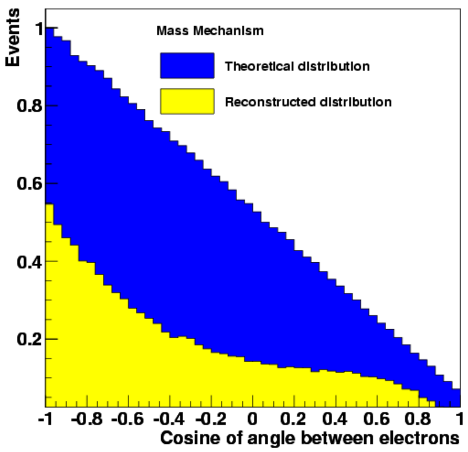
Synergies with LHC searches



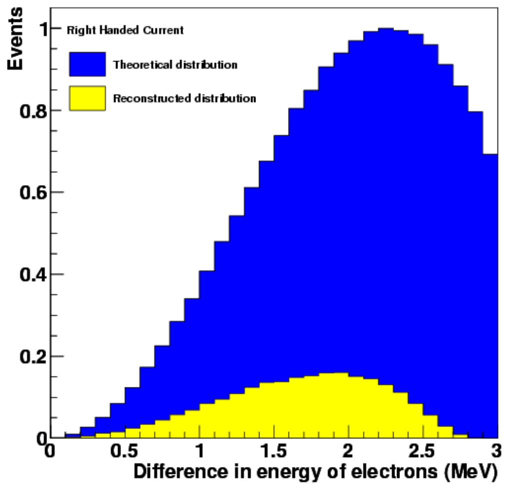
Deppisch, Graf, Iachello and Kotila
Phys.Rev.D 102 (2020) 9, 095016

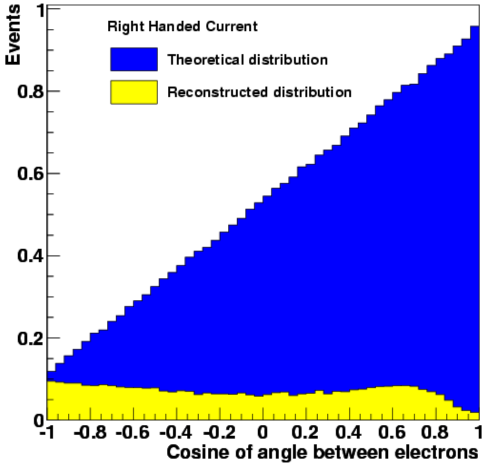
$<m_\nu>$





V+A

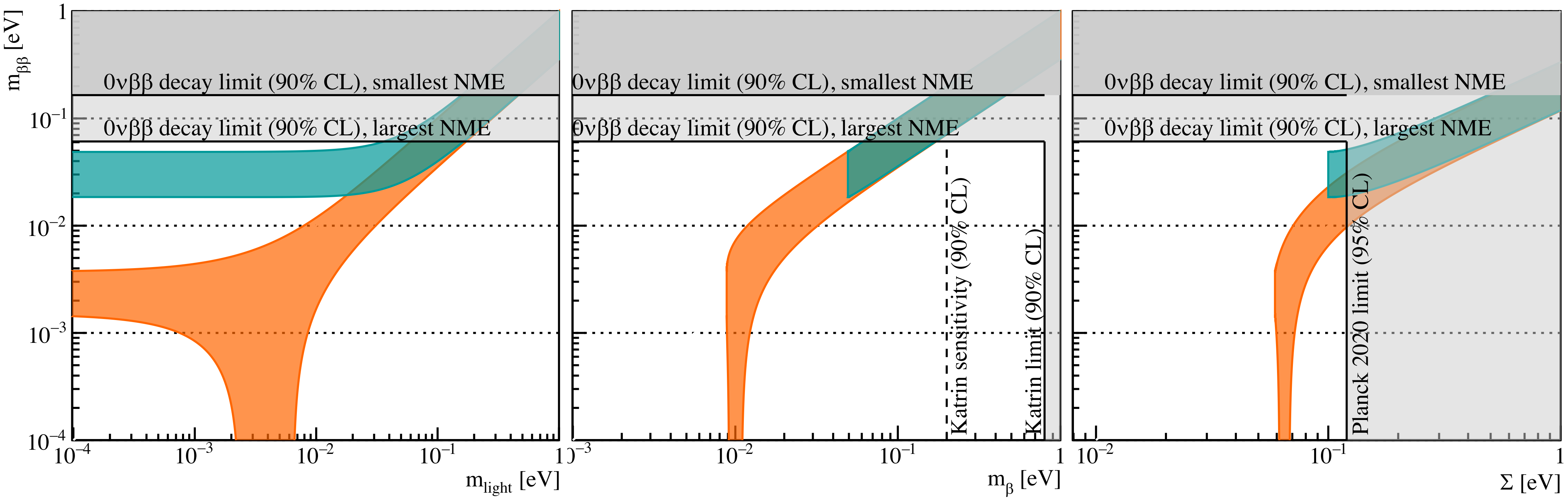


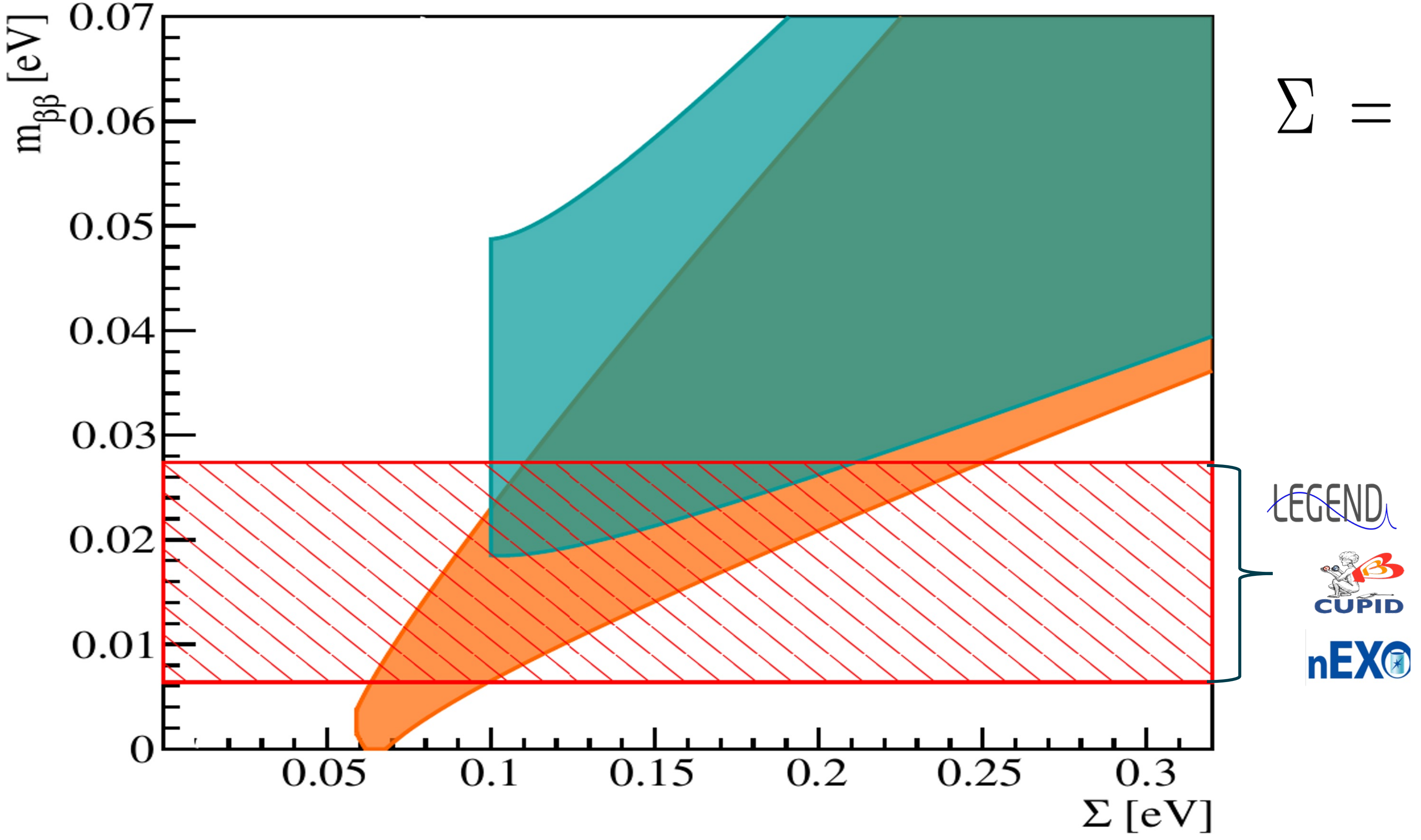


SuperNEMO Collaboration
EPJ C (2010) 70, pp. 972-943.

Interplay between different neutrino mass measurements

Rev. Mod. Phys. 95 025002





$$\Sigma = \sum_i m_i$$