Majorana Neutrinos and Matter Creation

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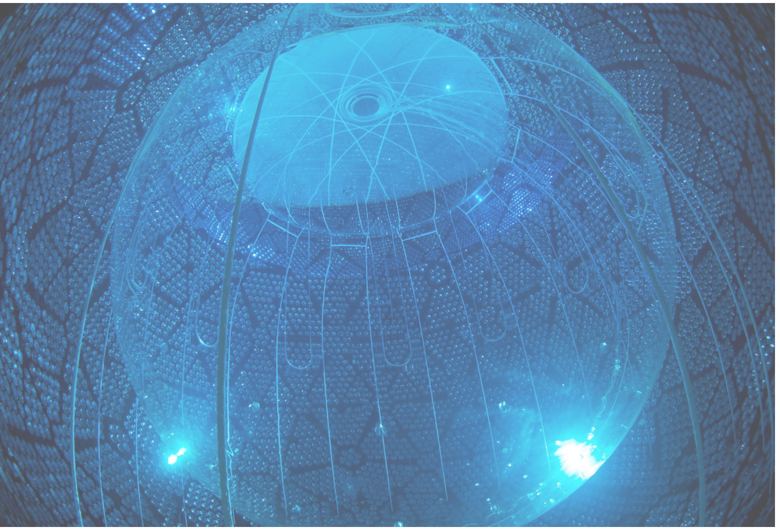
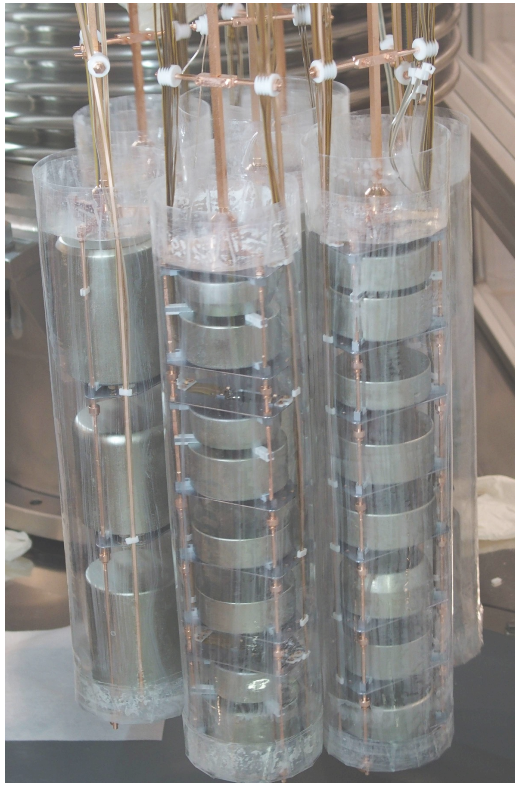


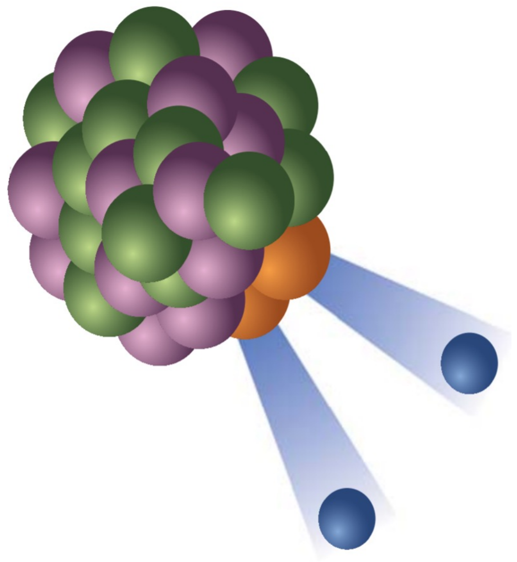
Windows on the Universe
30th Anniversary of Recontres du Vietnam
Quy Nhon
10-Aug-2023



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Outline

- Introduction and Motivation
- $0\nu\beta\beta$ and neutrino physics, physics reach
- Experimental approaches
- Outlook and international landscape



Disclaimer:

- Vibrant field: impossible to do justice to all projects
- Focus on giving an overview of most promising techniques and convey excitement about physics reach, with breakthroughs potentially around the corner

Much material from comprehensive recent review

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

Big Questions: Matter vs Antimatter

Standard Model

- particles/antiparticles symmetry
- energy ↔ particle + antiparticle
- But universe is dominated by matter (baryons)

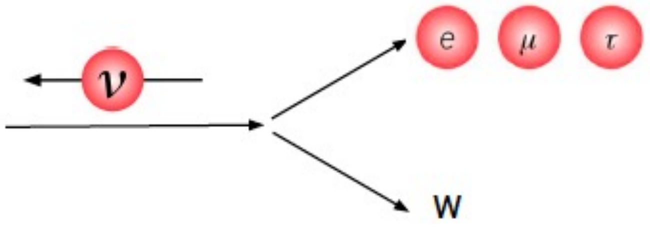
Matter			charge		Antimatter		
Quarks -> Baryons					Anti-Quarks -> Anti-Baryons		
u	c	t	+2/3	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
d	s	b	-1/3	+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons					Anti-Leptons		
e	μ	τ	-1	+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
ν_e	ν_μ	ν_τ	0	0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

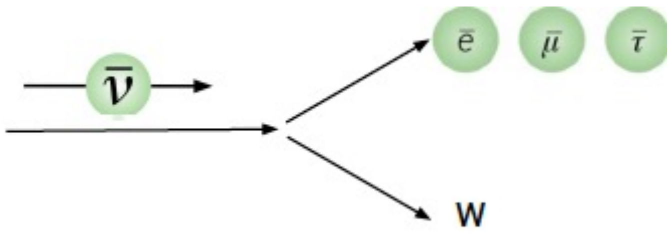
There could(should?/must?) be processes altering

- B = $N_{baryons}$ - $N_{anti\text{-}baryons}$ (proton decay)
- L = $N_{leptons}$ - $N_{anti\text{-}leptons}$ ($0\nu\beta\beta$)
- B-L → global symmetry of SM ($0\nu\beta\beta$)

What distinguishes neutrinos from antineutrinos?

Phenomenology:

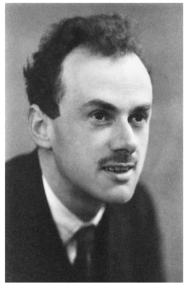




left-handed chirality -> creating **particles**

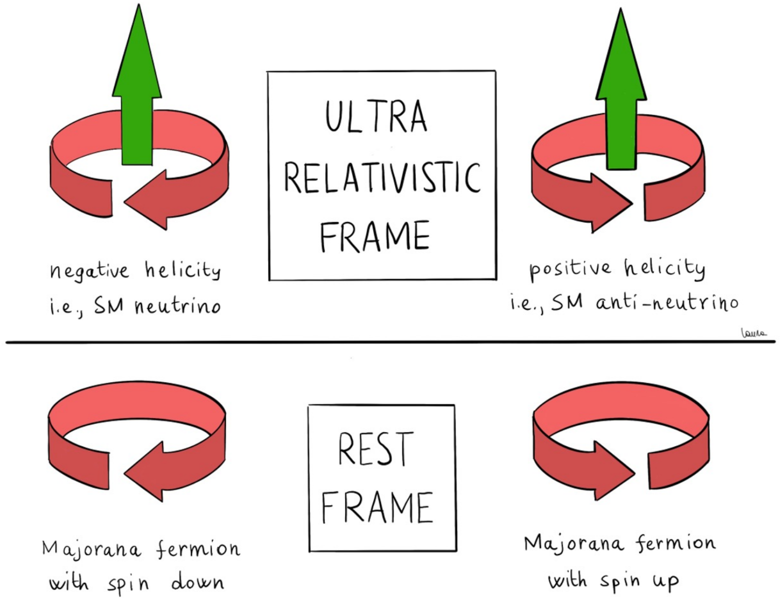
right-handed chirality -> creating **antiparticles**

BUT $m_\nu \neq 0$ (neutrino oscillations)



Dirac

Majorana

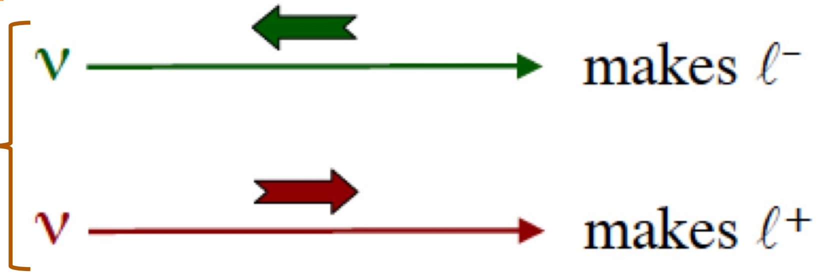


Accept there are two non-interacting "sterile" states

Or the same objects that has both chiral state

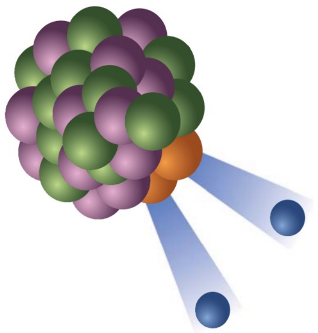
Neutrino ↔ "anti"-neutrino transformation and $0\nu\beta\beta$-decay

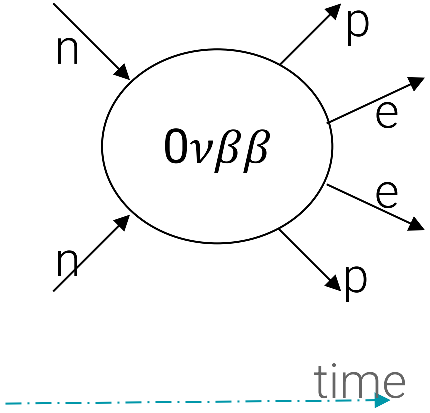
Majorana neutrinos can create both matter and antimatter



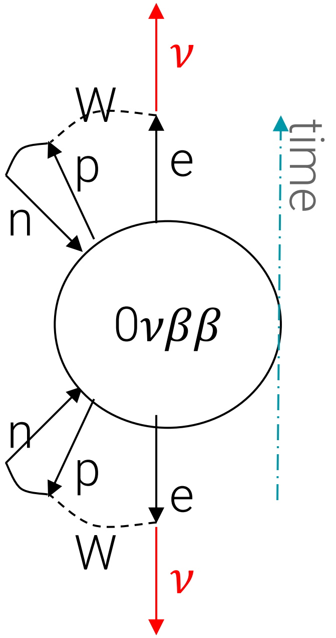
Most sensitive probe: $0\nu\beta\beta$ **(A,Z) → (A,Z+2) + 2e**

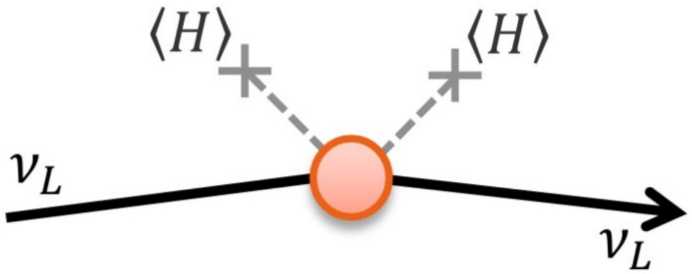
$$\Delta B = 0, \Delta L = 2$$





Schechter and Valle 1982





Direct violation of L and B-L
Direct (leptonic) matter creation

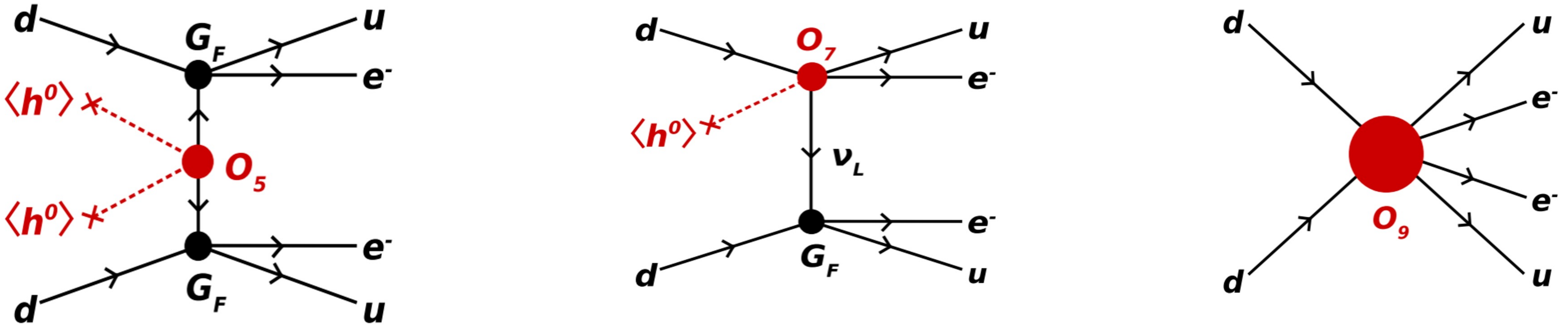
non-zero Majorana mass

Neutrino mass generation mechanism

$0\nu\beta\beta$: Generic test for UHE BSM 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 theorem: $0\nu\beta\beta$ observation provides unambiguous evidence for non-zero Majorana mass (even if it is not dominating mechanism)**

Double Beta Decay

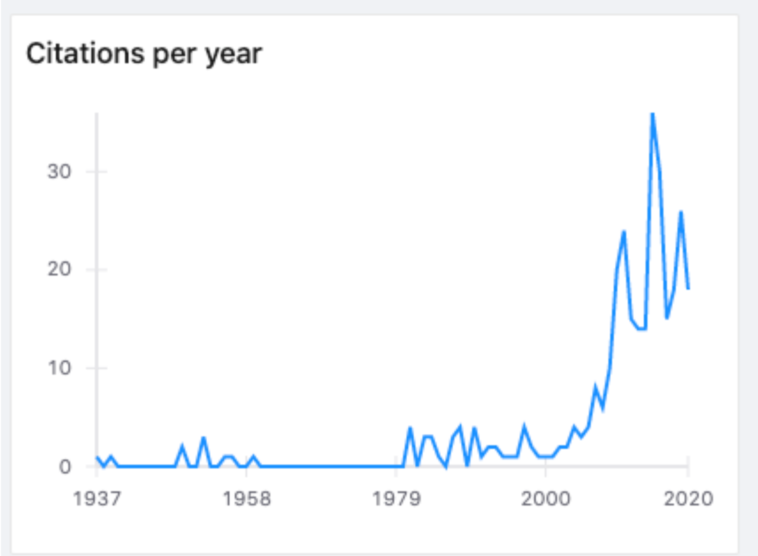
Abstract

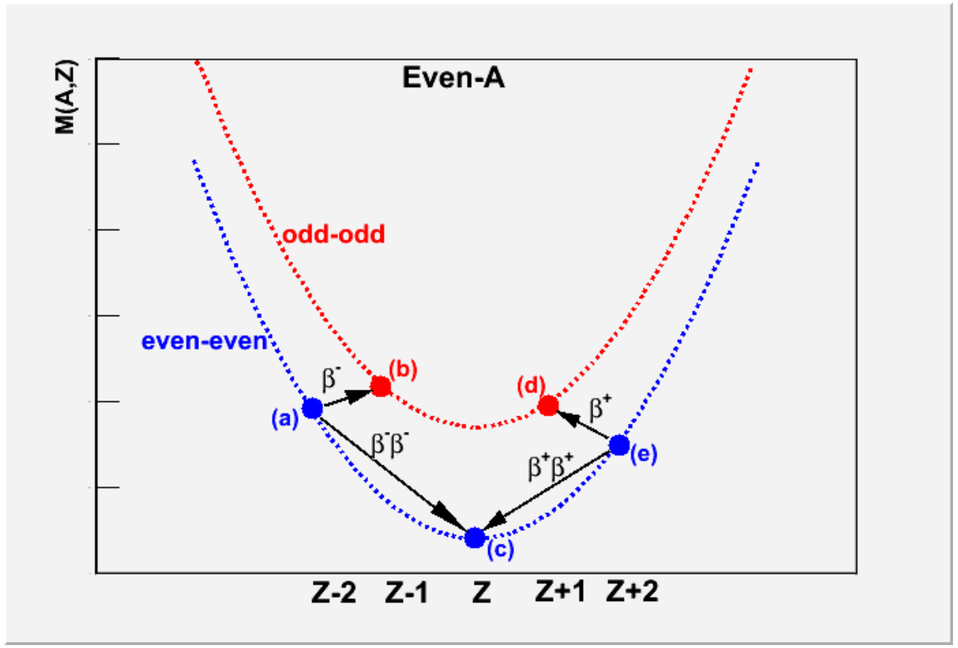
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

M. Goepert-Mayer

$2\nu\beta\beta$ ⟶ ***Double beta-Disintegration*, Phys.Rev. 48:512-16 (1935)**

1939: Furry ⟶ $0\nu\beta\beta$





Over **40 nuclei** can undergo **ββ**-decay (including **β⁺β⁺** and **2K-**capture)

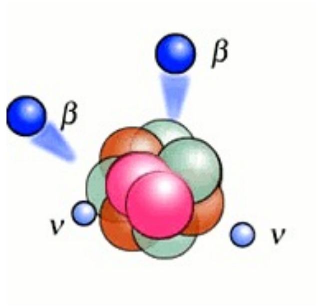
Only ~**9** experimentally **feasible for $0\nu\beta\beta$**

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

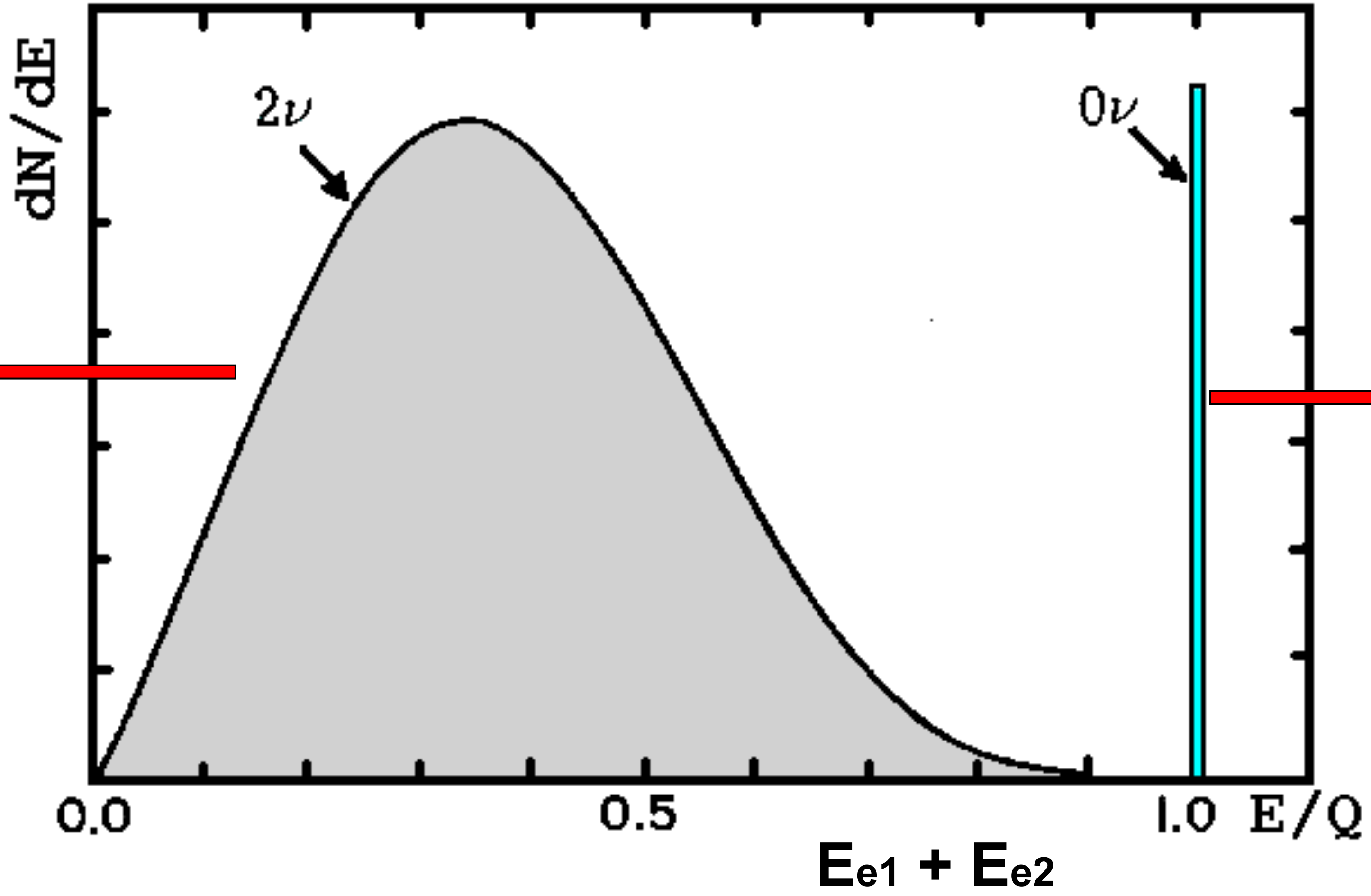
Experimental Observables

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

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

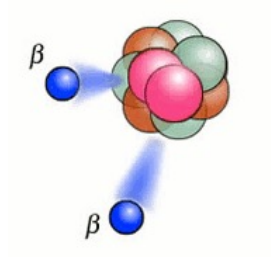


2νββ(EC/β⁺) has been detected in 13 nuclei!

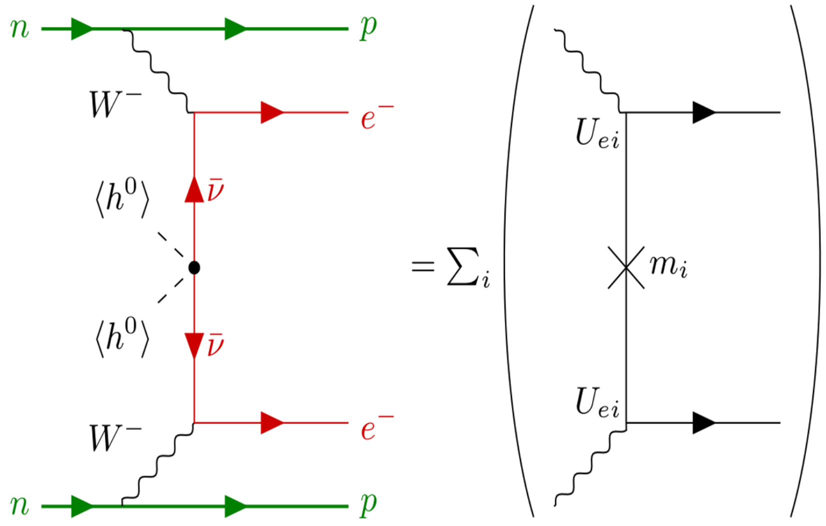


$\Gamma^{0\nu} \propto G_F^4 \cdot \eta_{LNV}^2$

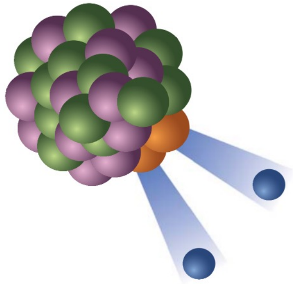
$T_{1/2} > 10^{26}$ yr!



If possible: individual electron energies, E_{e1}, E_{e2}, and angle θ between them



$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



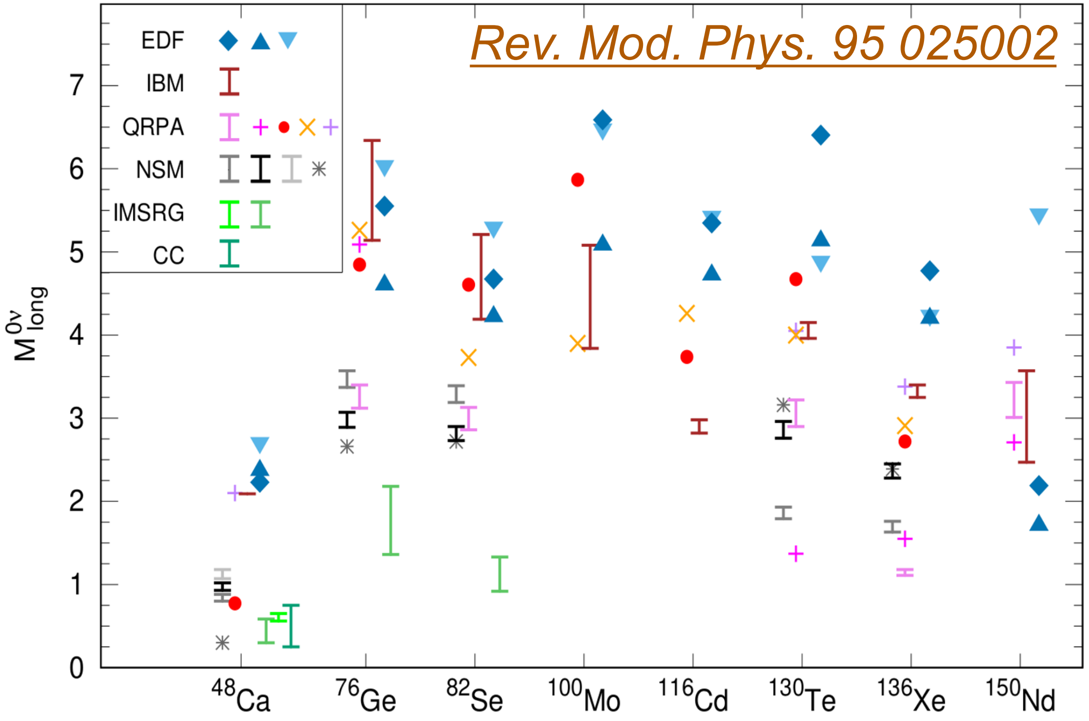
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

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

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

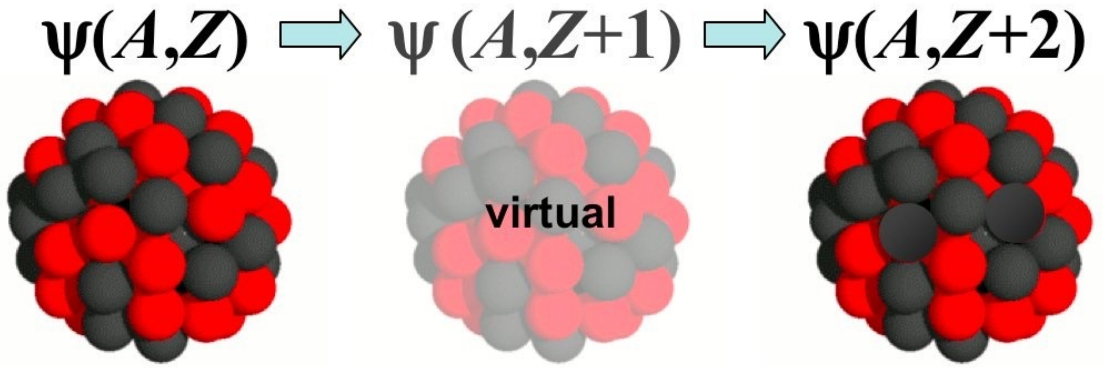
- Minimal extension of SM
- Access to absolute neutrino mass and Majorana CP-phases
- Reach interplay with neutrino oscillations, kinematic measurements (m_β), cosmology (Σ)

0νββ: Connection with Nuclear Physics



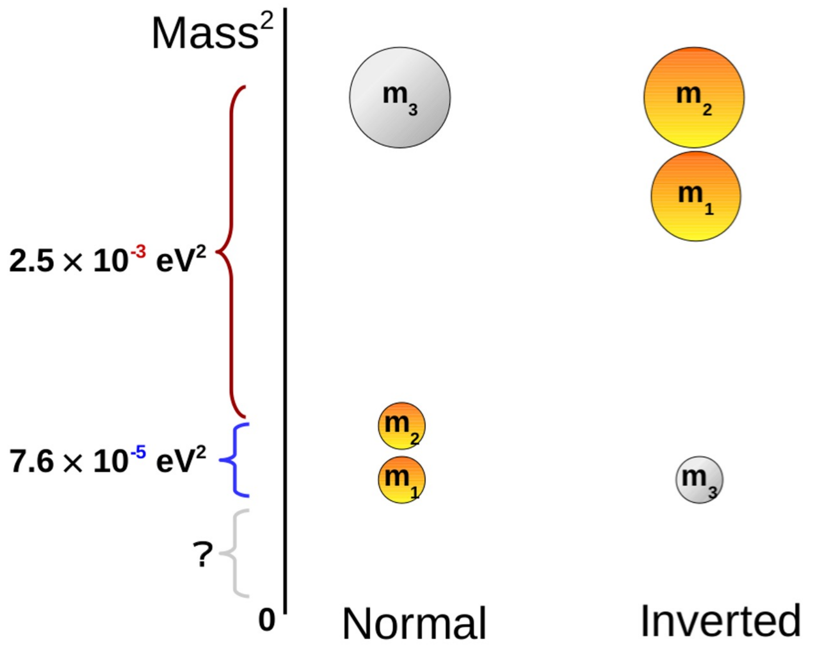
$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4 M^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

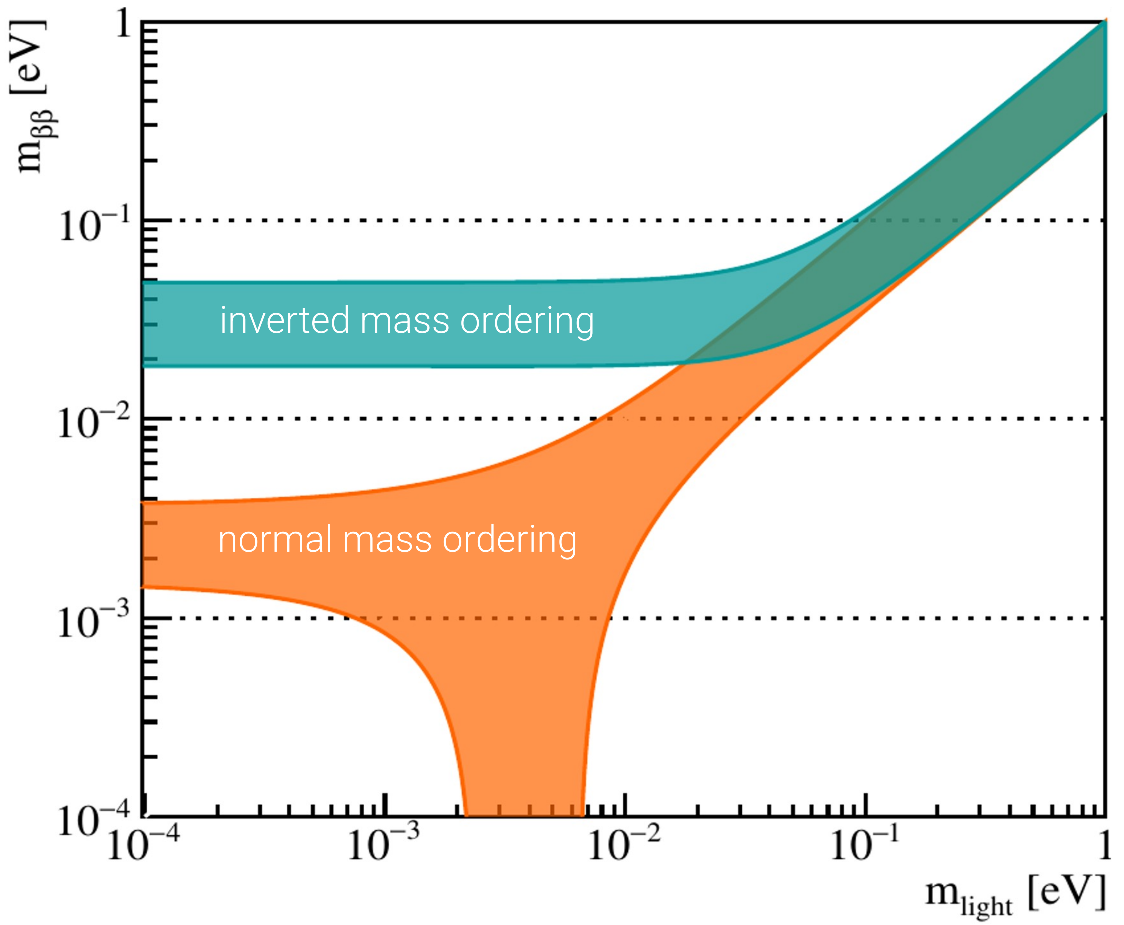
nuclear matrix element (NME)



- Significant effort from different groups and different nuclear models
- ***Question of g_A quenching under study***
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

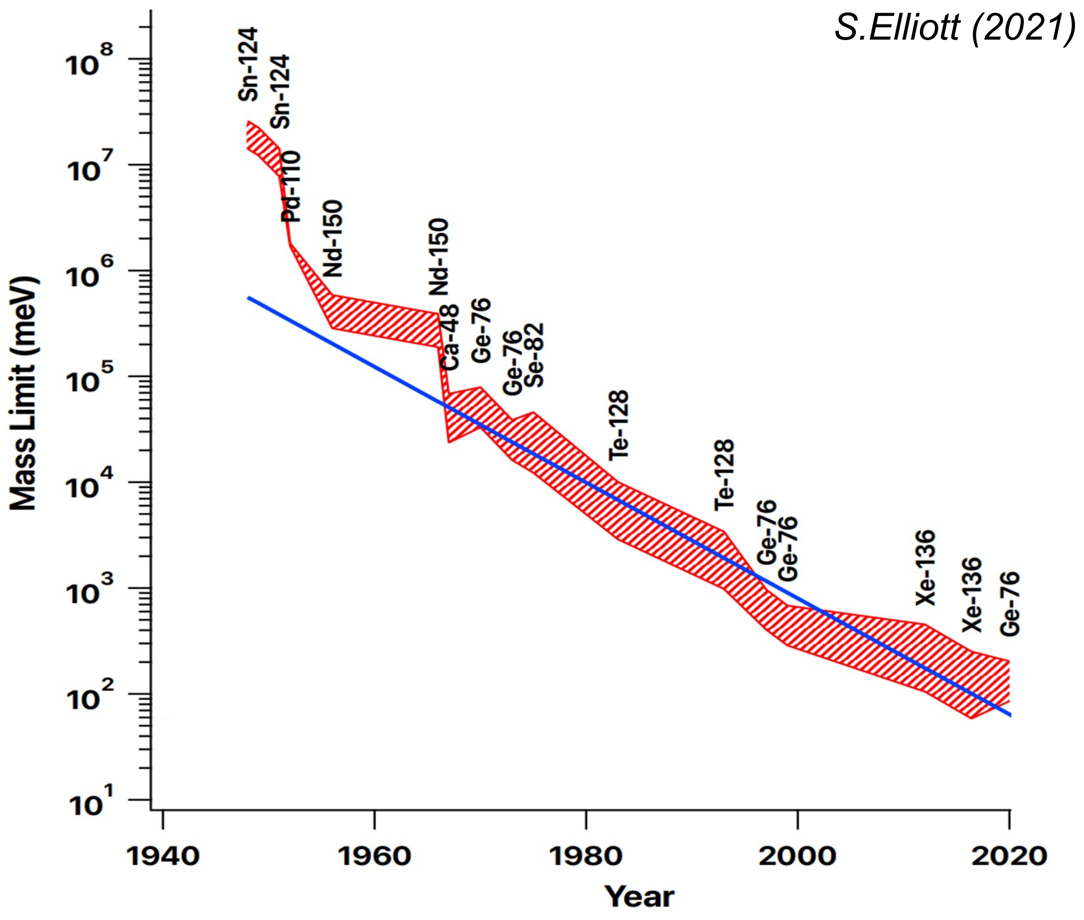
$0\nu\beta\beta$: Light Majorana neutrino mass, $m_{\beta\beta}$ and neutrino mass ordering



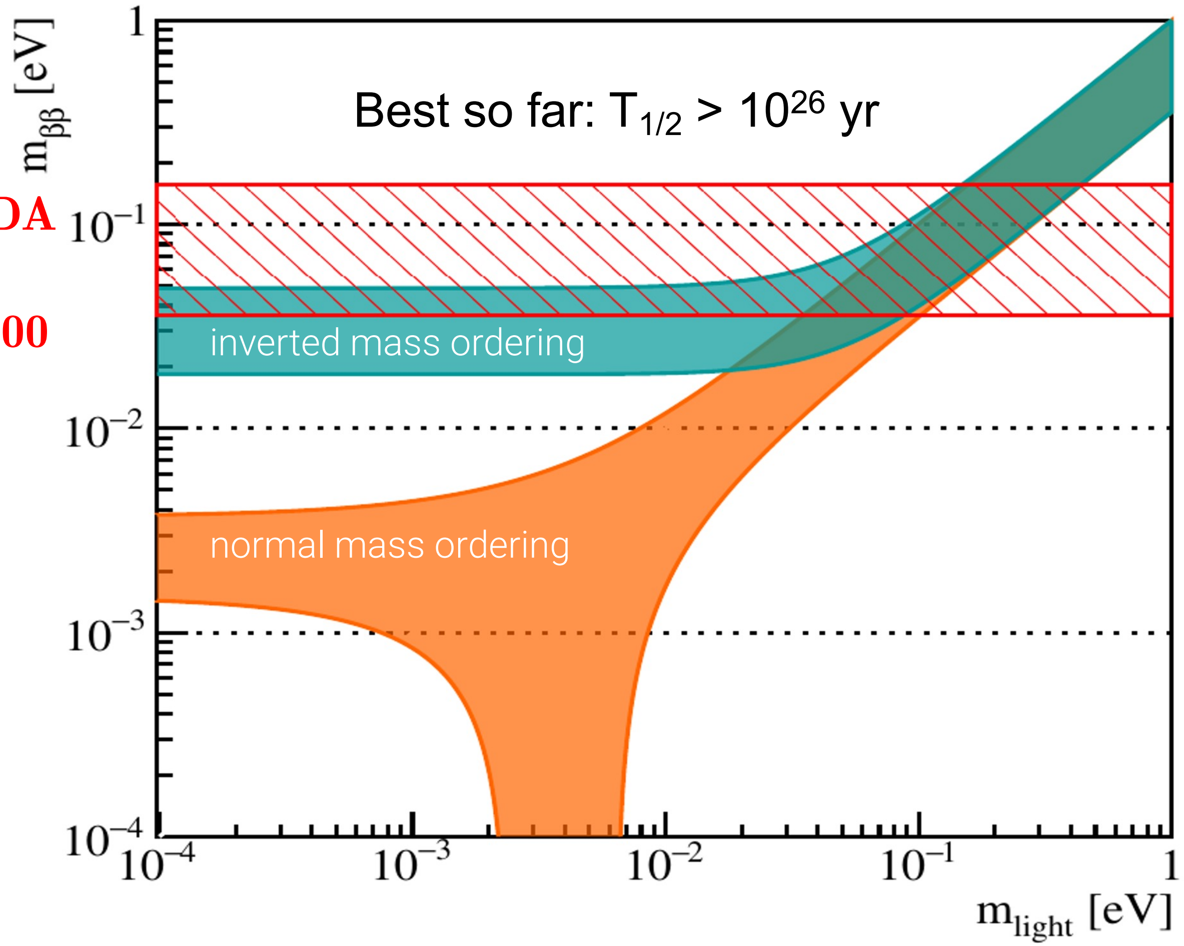


$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

$0\nu\beta\beta$ with $m_{\beta\beta}$ Where are we so far



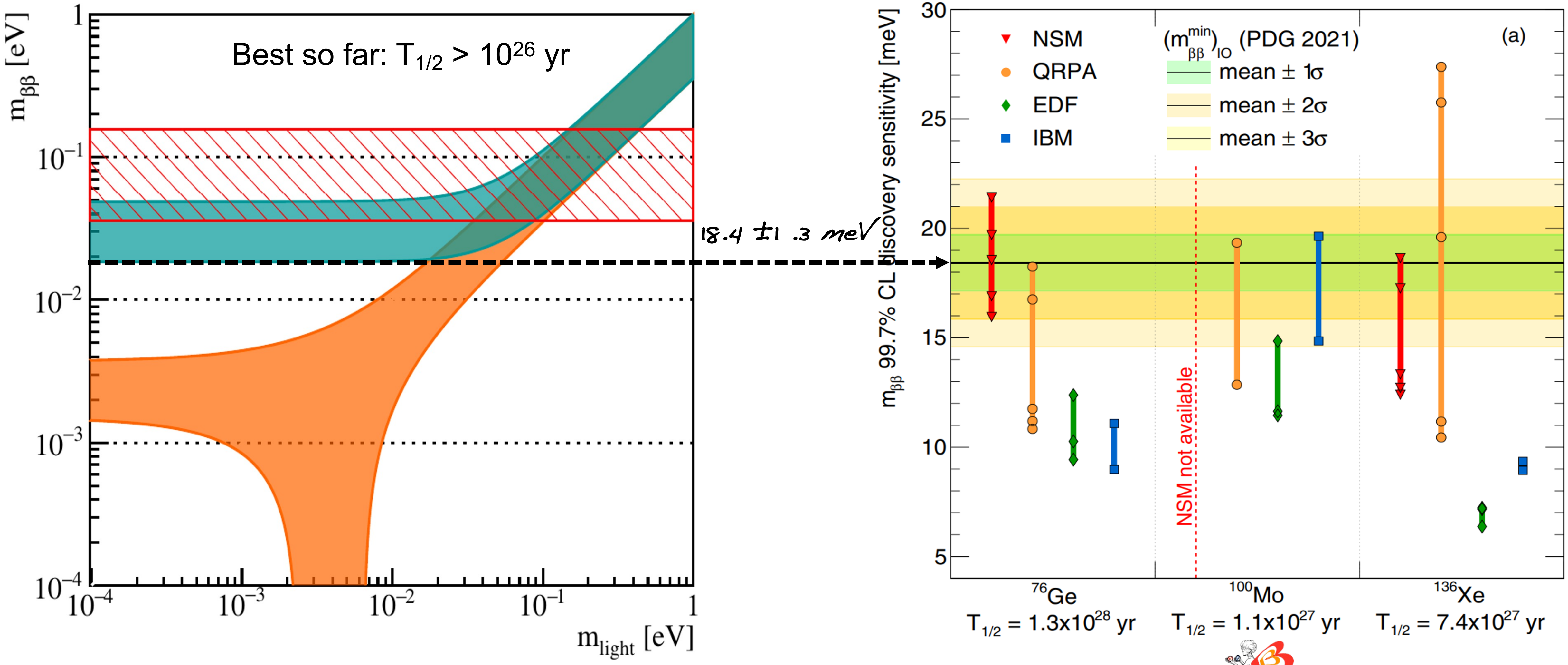
GERDA
KZ
Exo-200



$0\nu\beta\beta$ with $m_{\beta\beta}$ Where are we heading

UCL

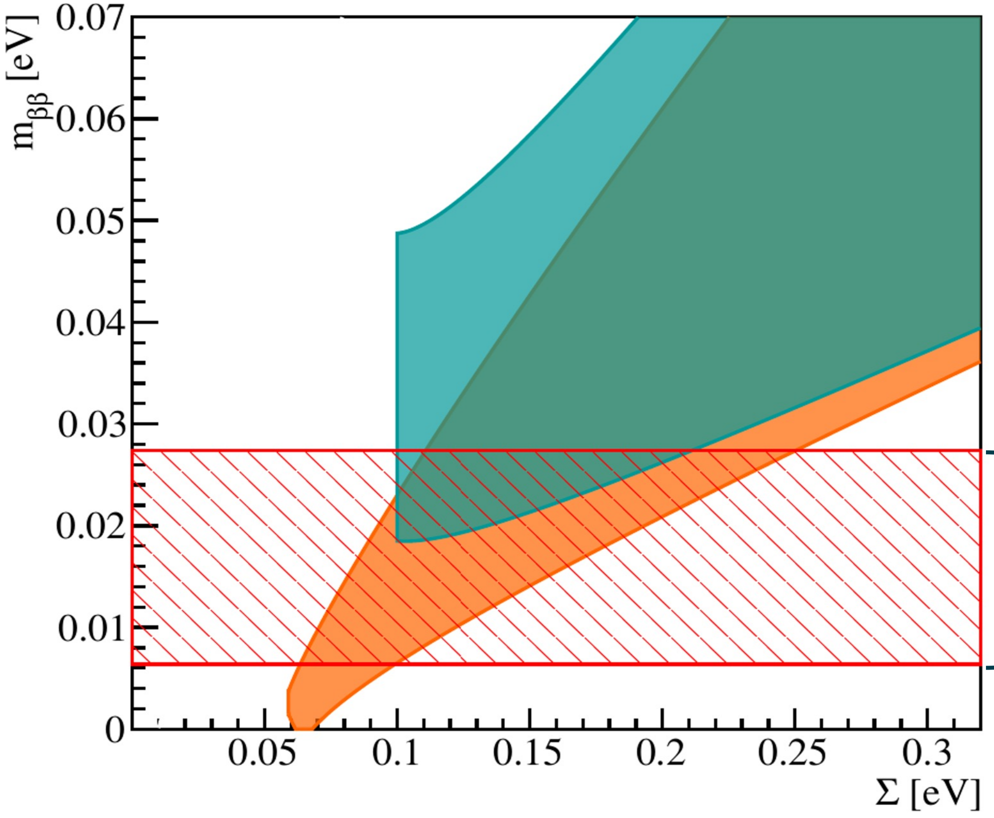
PRC 104, L042501 (2021)



LEGEND CUPID nEXO

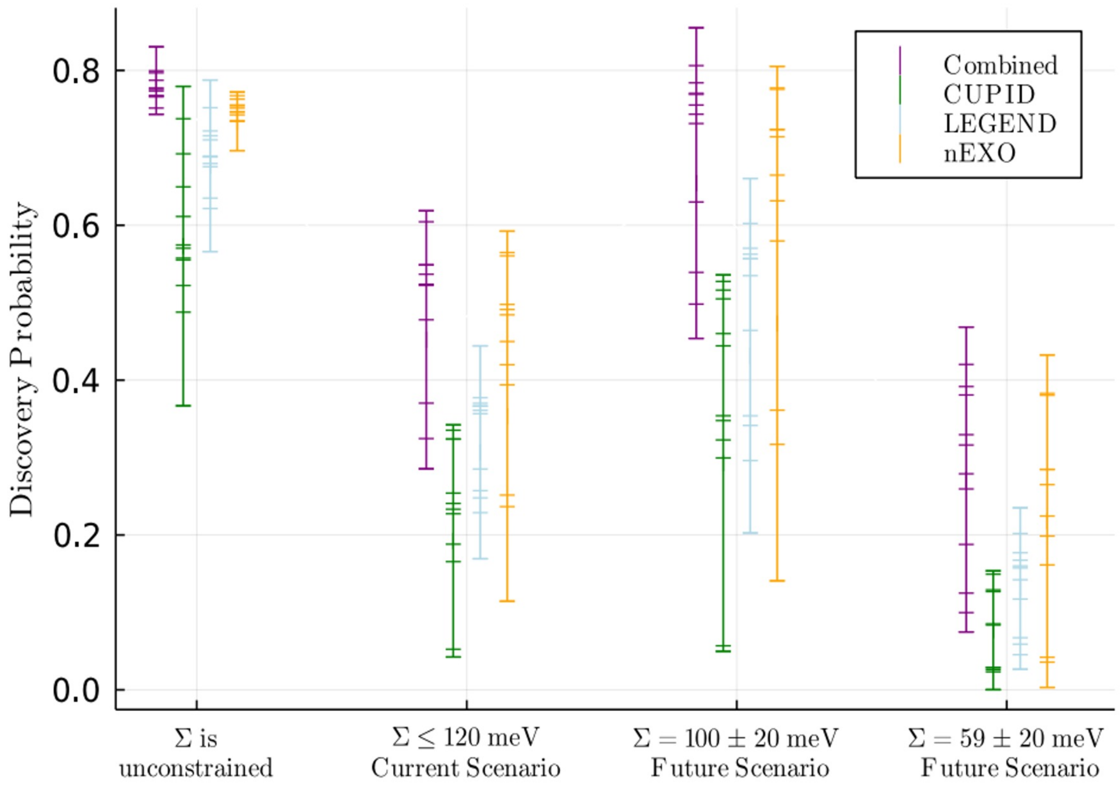
Cosmology surveys (DESI/EUCLID) closing in on positive measurement for Σ

$$\Sigma = \sum_i m_i$$



LEGEND
CUPID
nEXO

[Rev. Mod. Phys. 95 025002]



arXiv: 2208.09954

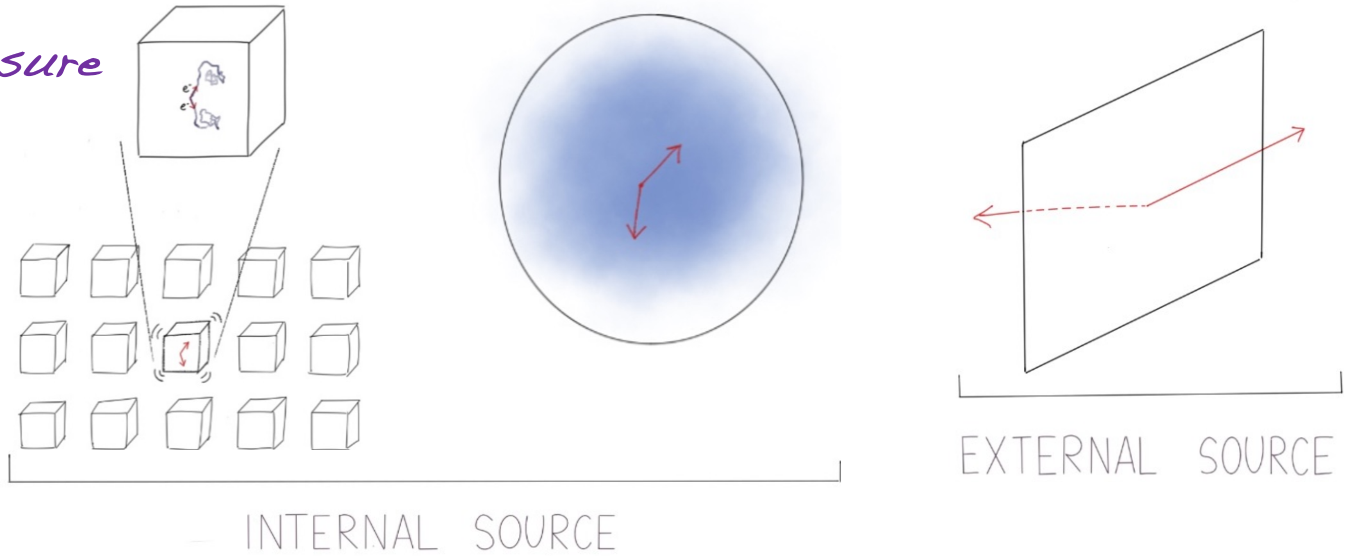
Experimental Approaches

maximise detection efficiency and ββ isotope abundance

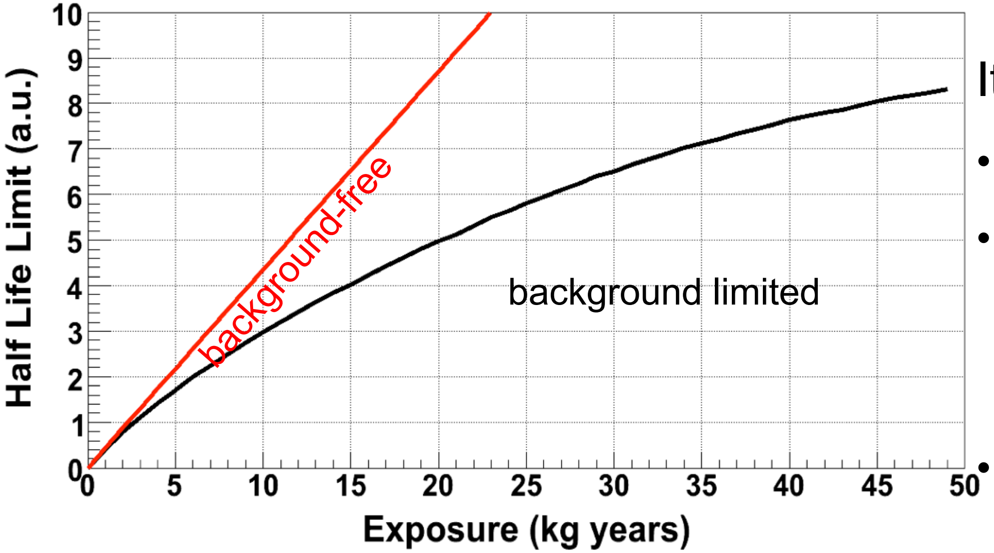
maximise exposure

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

minimise background

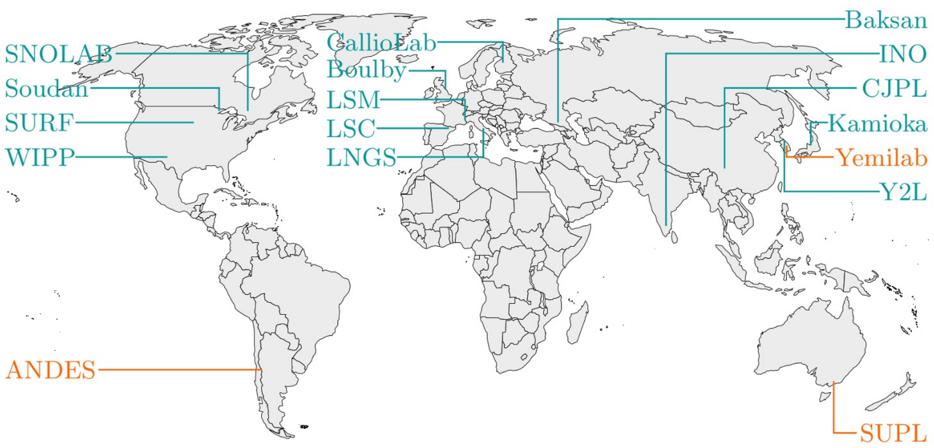


- Drawings courtesy of Laura Manenti

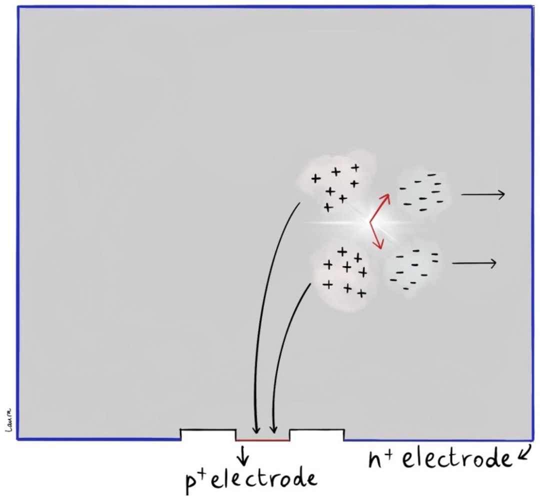


It's all about backgrounds

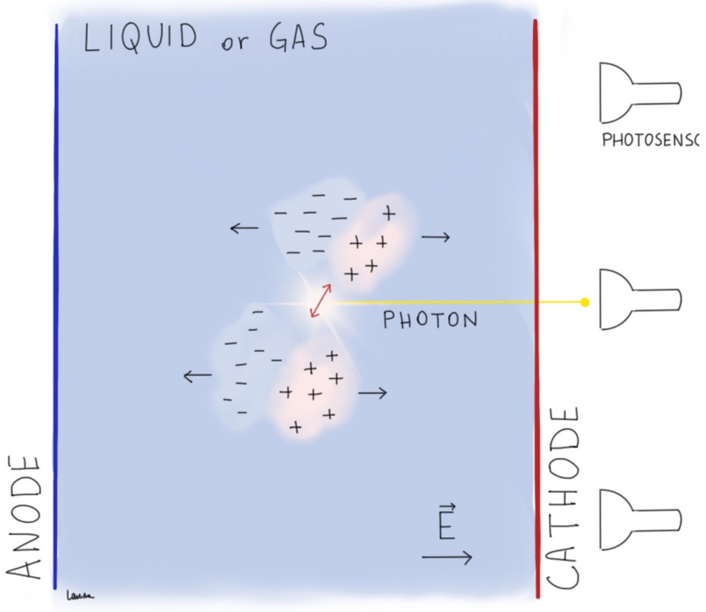
- Cosmic rays (underground)
- Natural radioactivity (clean materials, particle id and tagging)
- Standard Model $2\nu\beta\beta$ (energy resolution)



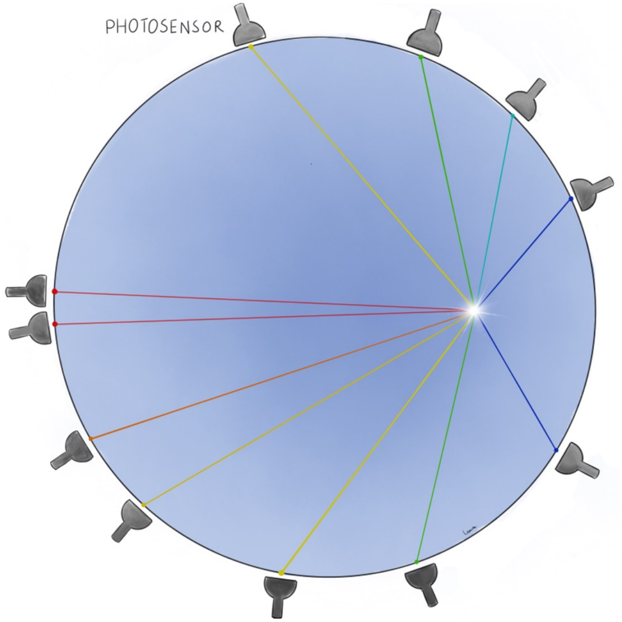
Leading Experimental Techniques



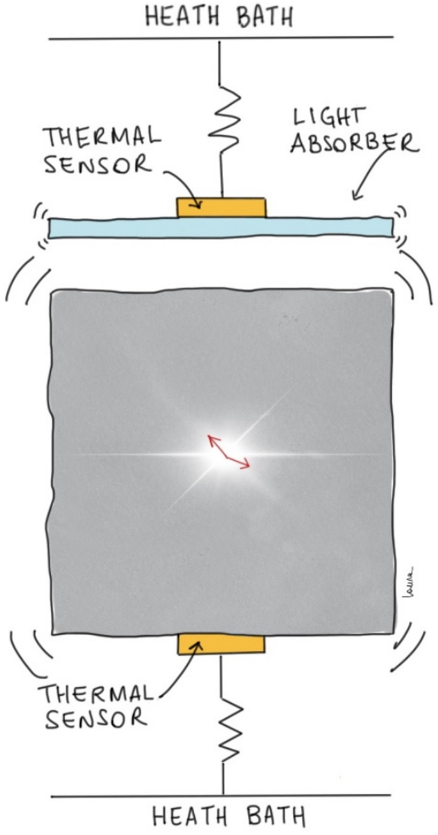
Ge Semiconductor detectors (^{76}Ge)



Xe Time Projection Chambers (^{136}Xe)



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



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

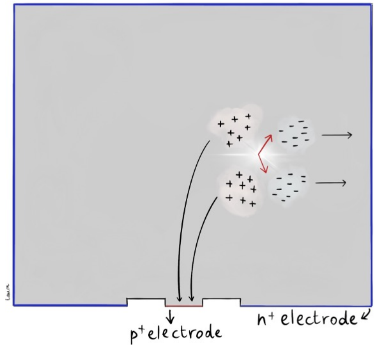
Drawings courtesy of Laura Manenti

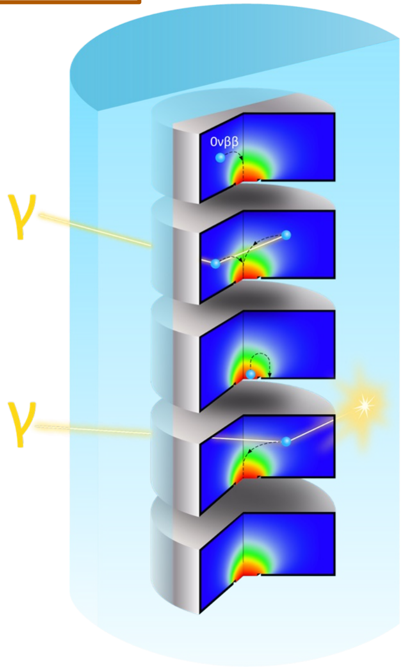
Enriched Ge semiconductor detectors

See talk by Valentina Biancacci on Tuesday, HEP T3

high-purity ^{76}Ge detectors

- ionization and charge drift
- < 0.1% energy resolution
- event topology





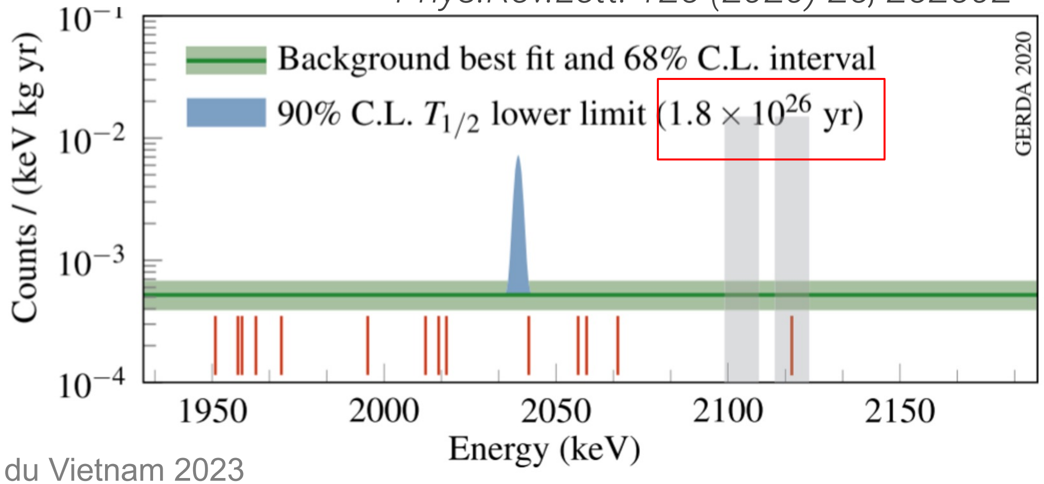
liquid Ar detector

- shield and scintillation light

Staged approach:

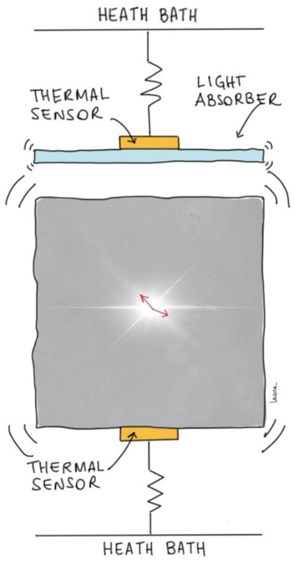
- **GERDA/MAJORANA** Demonstrator (40 kg)
- **LEGEND-200** (200 kg) taking data at LNGS
- **LEGEND-1000** conceptual design in preparation (1 t)

Phys.Rev.Lett. 125 (2020) 25, 252502



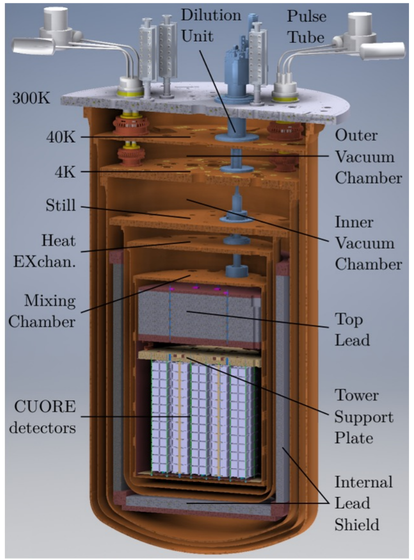
Cryogenic Calorimeters

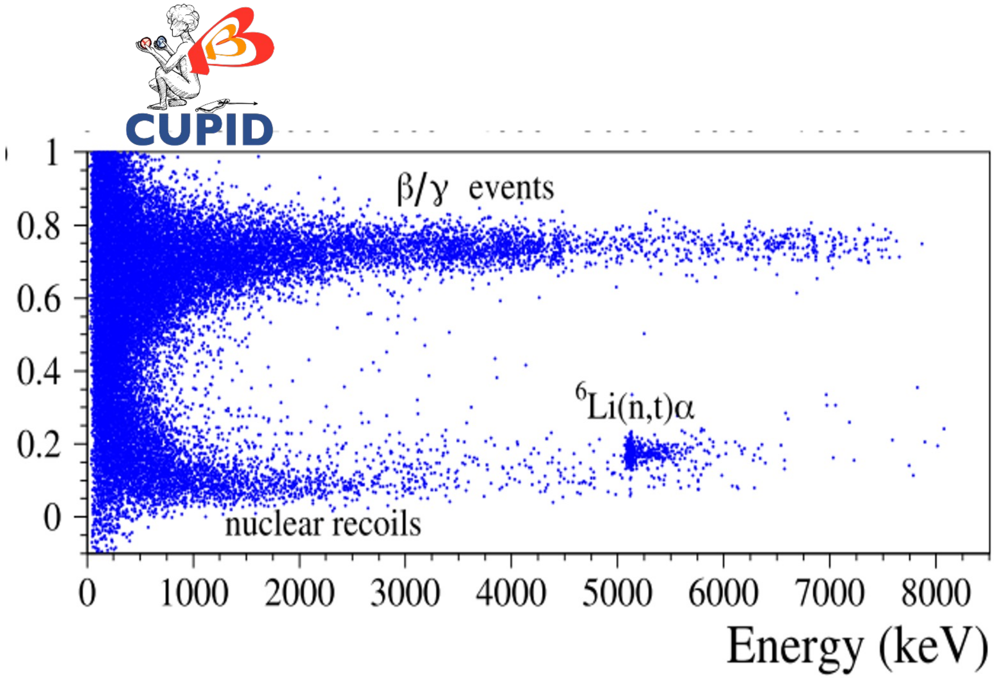
See talk by Stefano Ghislandi on Tuesday, HEP T3



- 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

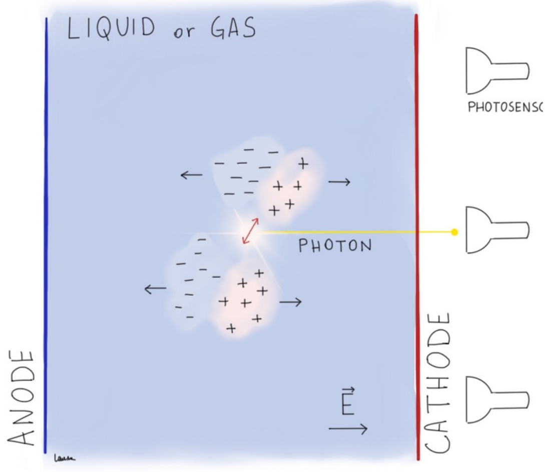
Experiment	Crystal	m_{tot} [kg]	f_{enr} [%]
CUORE	$^{nat}TeO_2$	742	34[a]
CUPID-0	$Zn^{enr}Se$	9.65	96
CUPID-Mo	$Li_2{}^{enr}MoO_4$	4.16	97
CROSS	$Li_2{}^{enr}MoO_4$	8.96	98
CUPID	$Li_2{}^{enr}MoO_4$	472	≥95
AMoRE	$Li_2{}^{enr}MoO_4$	200	96

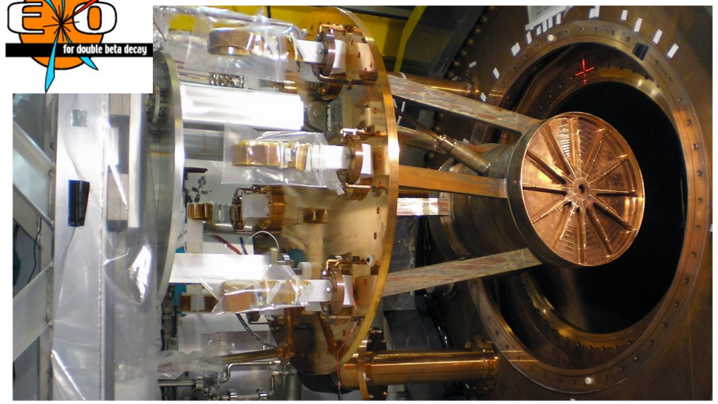




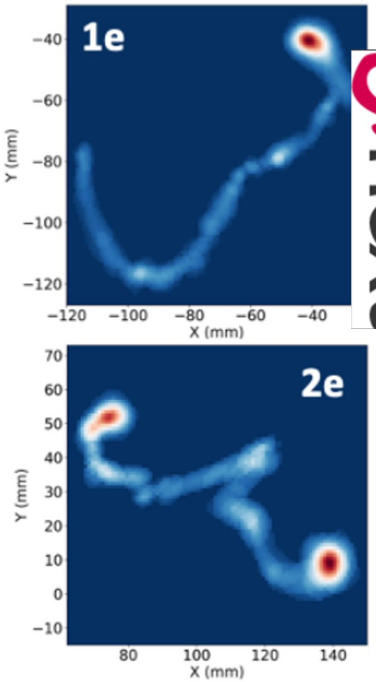
Enriched Xe TPCs

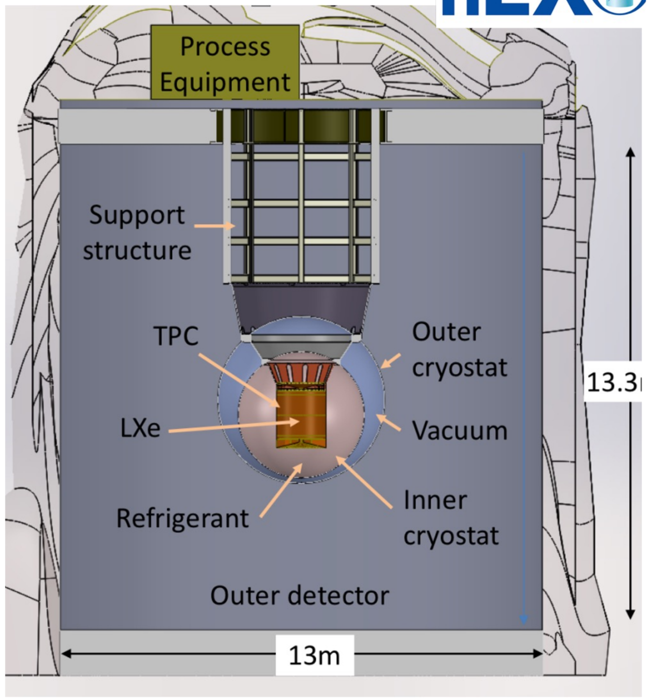
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope





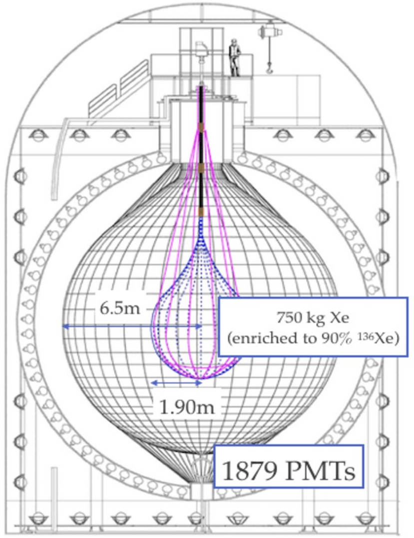
Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs
LZ-enr	7 000	90	dual-phase	PMTs
DARWIN	39 300	9	dual-phase	PMTs
XLZD	**70,000**			

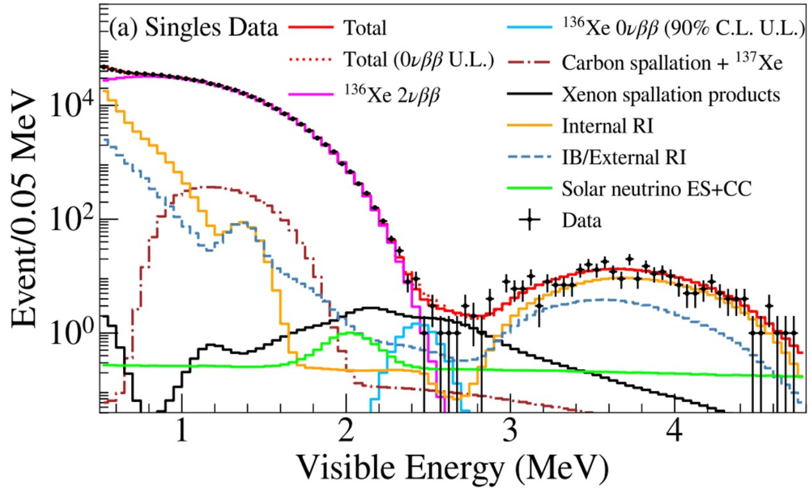




Large loaded liquid scintillators

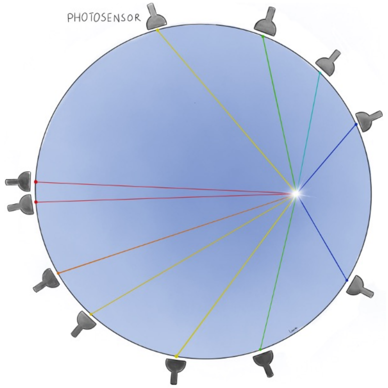
- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization
- Broad physics program (e.g. solar, reactor, geo-neutrinos)





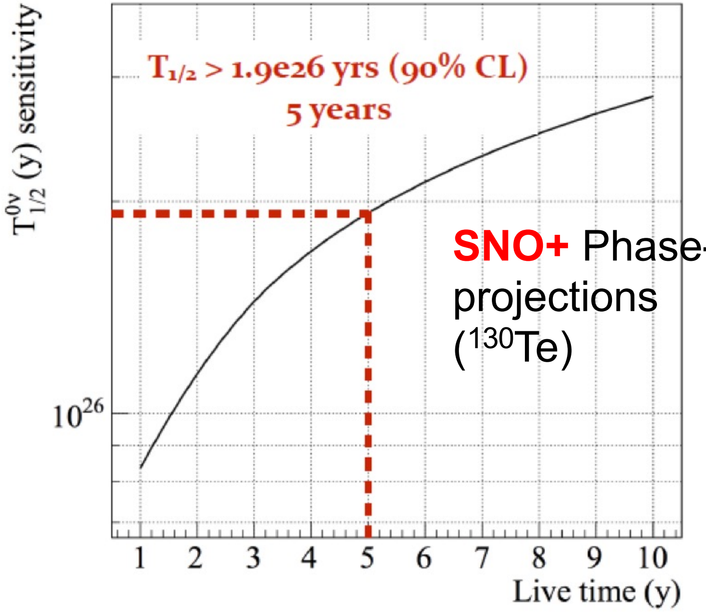
KZ collaboration, 2203.02139

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26} \text{ yr at } 90\% \text{ C.L.}$$



KamLAND-Zen-800 @Kamioka (^{136}Xe)

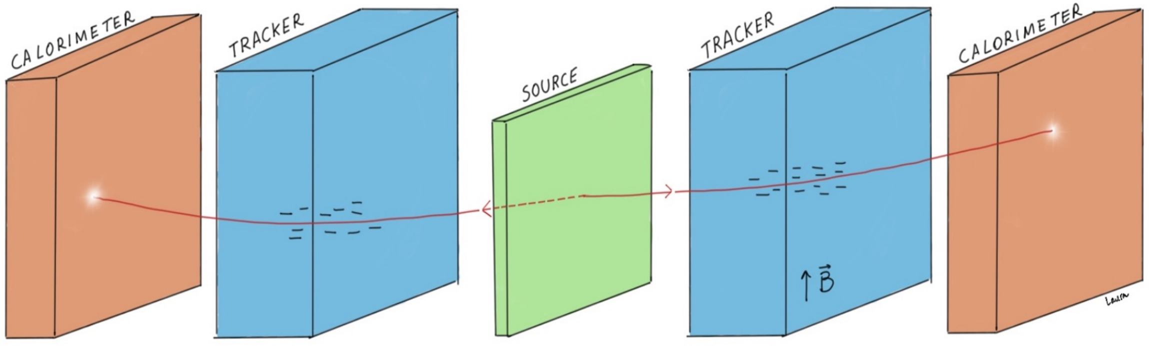
- 750 kg of enriched Xe in nylon balloon
- **Strongest constraints so far: $m_{\beta\beta} < 36$-156 meV**
- backgrounds:, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- next phase: improved resolution and purer scintillator



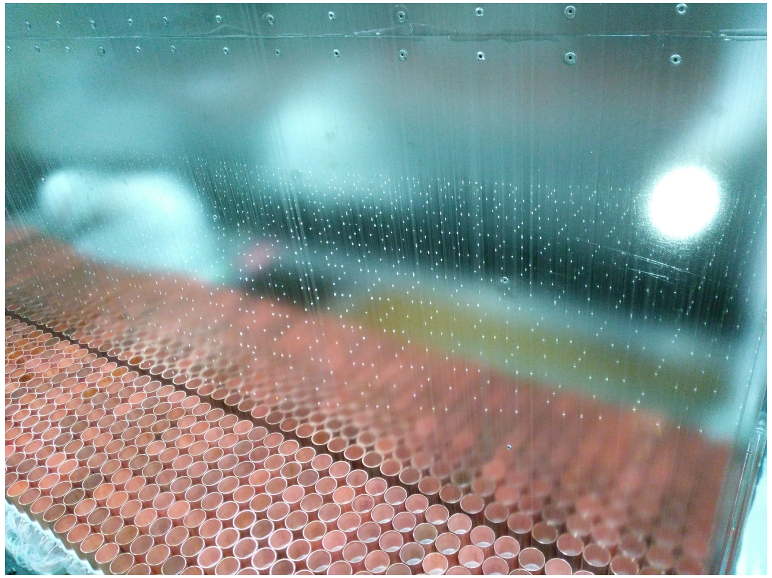
SNO+ Phase-I projections (^{130}Te)

Planning for success ($m_{\beta\beta} \gtrsim 50$ meV)

NEMO-technique: full topology reconstruction of final states

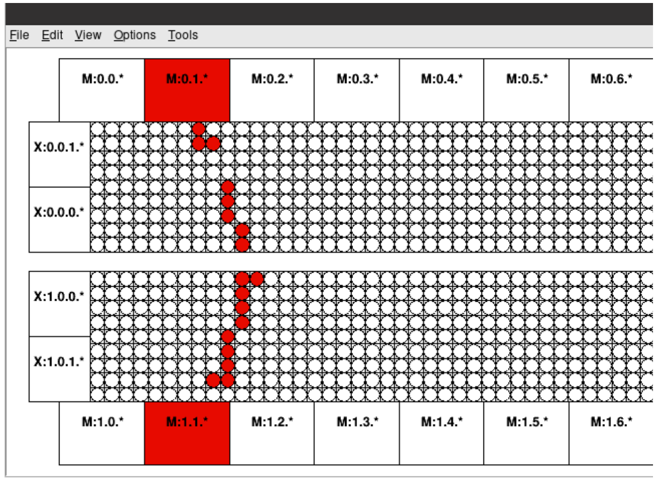


supernemo collaboration



SuperNEMO-Demonstrator *running* at LSM

- **Multi-isotope** confirmation
- Exploring underlying **physics mechanism**
  - Angular distributions
  - Single electron energies
- Constraining nuclear physics → **NME and g_A** through precision $2\nu\beta\beta$ studies
- **BSM** physics with **$2\nu\beta\beta$** (*Phys.Rev.Lett.125 (2020) 17, 171801*)

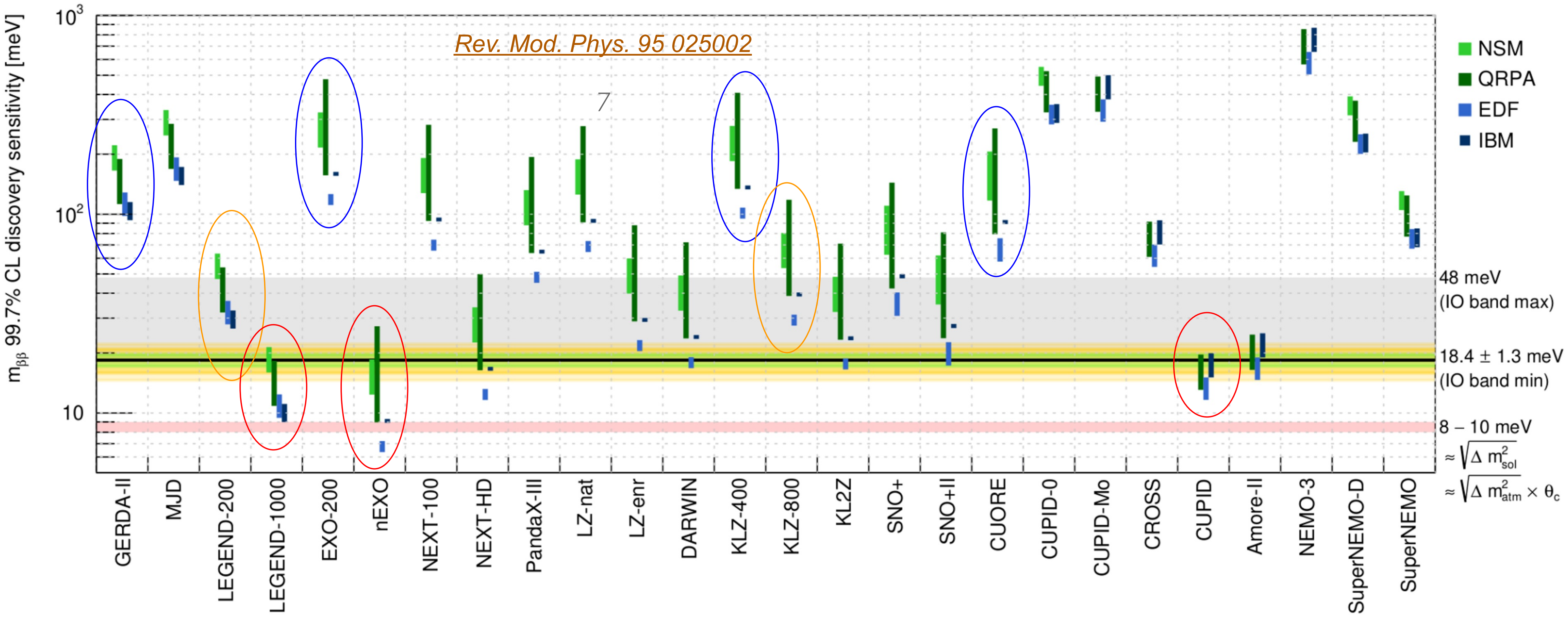


Outlook

The Big 4 of last decade: **GERDA, EXO-200, KamLAND-Zen-400, CUORE**

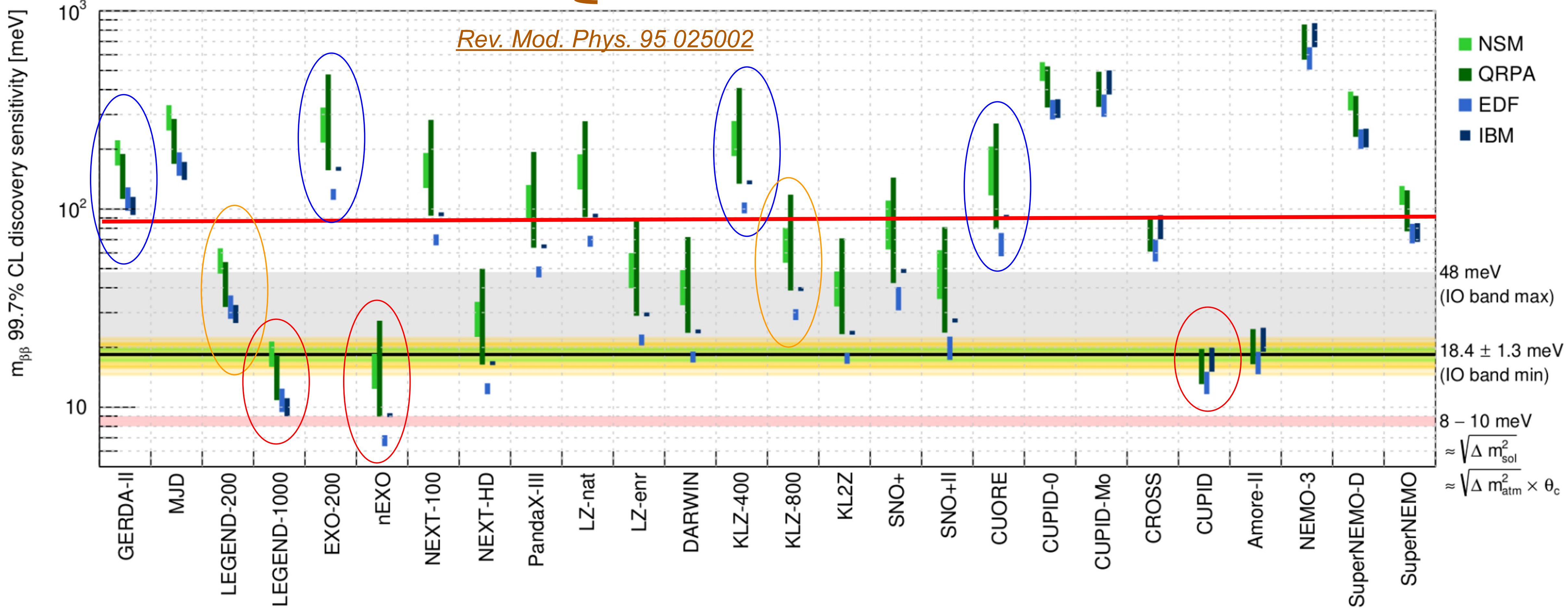
The two to watch: **LEGEND-200, KamLAND-Zen-800**

The ultimate I.O. experiments: **LEGEND-1000, CUPID, nEXO**



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

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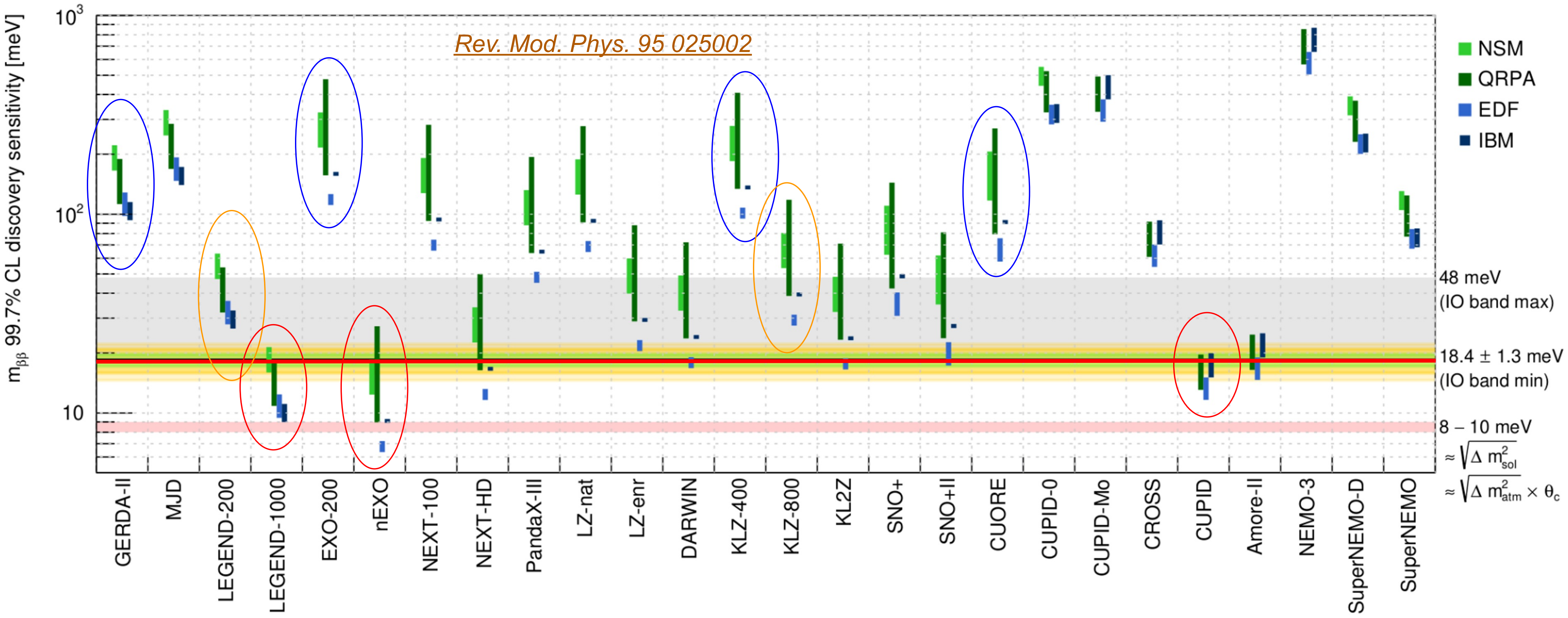
Scenario 2:
signal at bottom of I.O.

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



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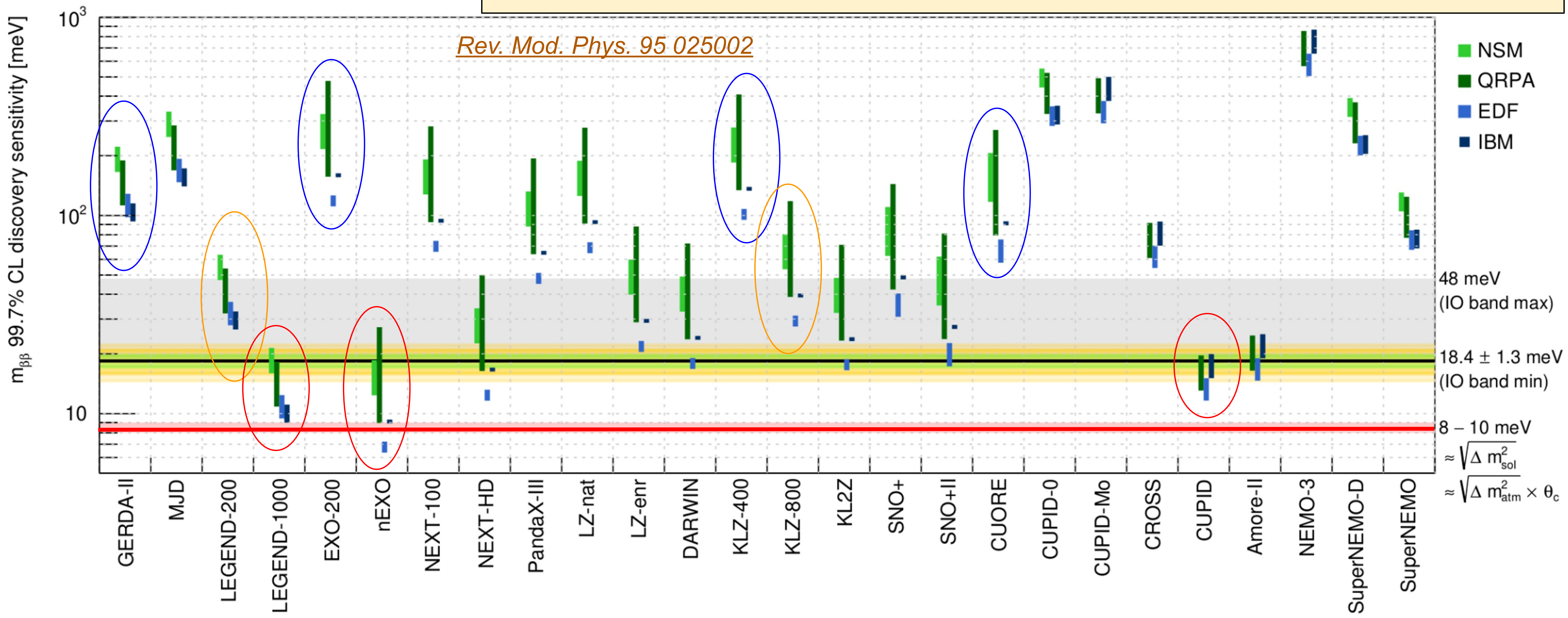
Scenario 3:
signal < 10meV

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

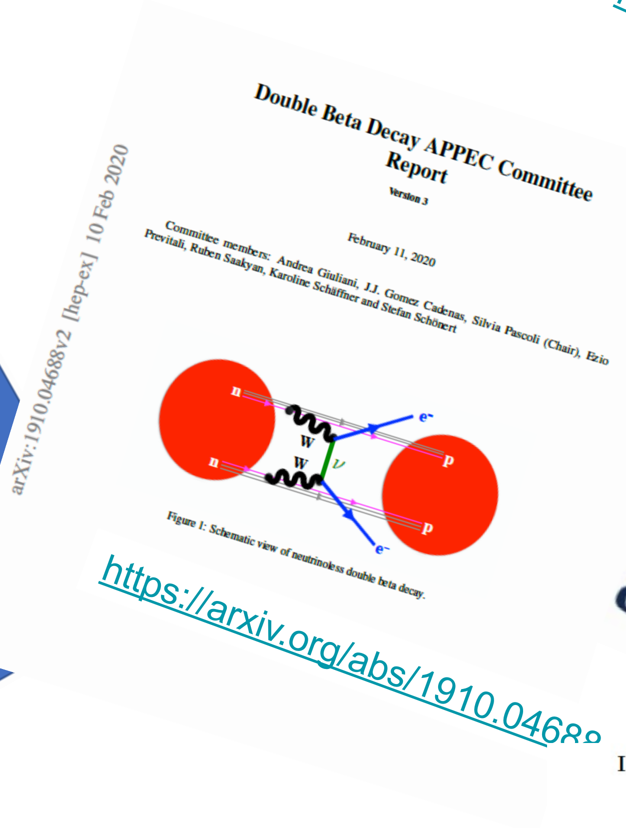


International Landscape

UCL

https://science.osti.gov/np/nsac

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO



https://arxiv.org/abs/1910.04688

https://agenda.infn.it/event/27143/

IUPAP Neutrino Panel White Paper

New LRP process started (2023-2032)

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**!
- $0\nu\beta\beta$ could be driven by a different LNV mechanism – open minded, **discovery oriented** search