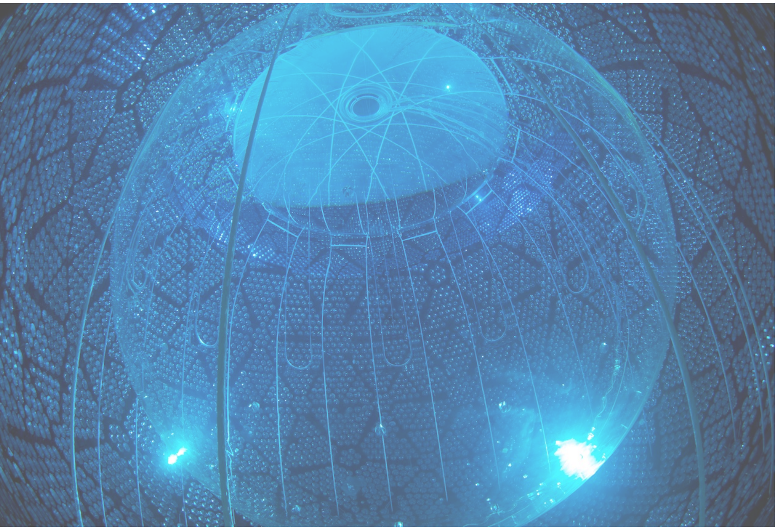
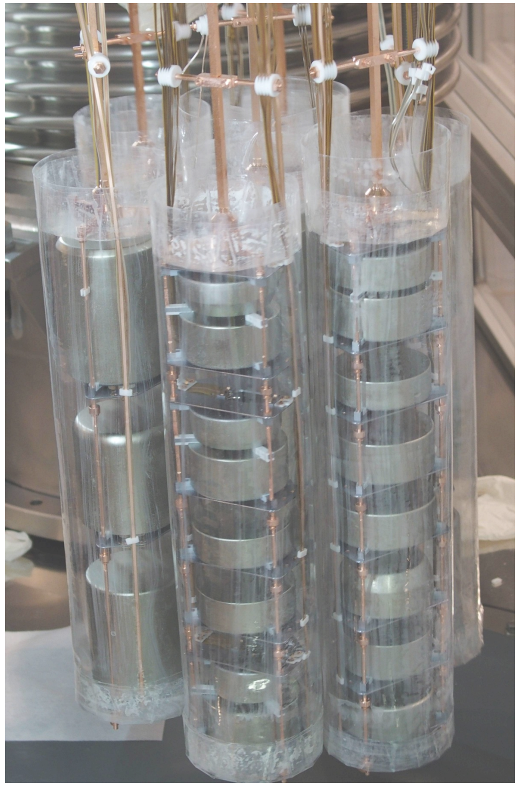
Majorana Neutrinos and Matter Creation

Ruben Saakyan
University College London

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

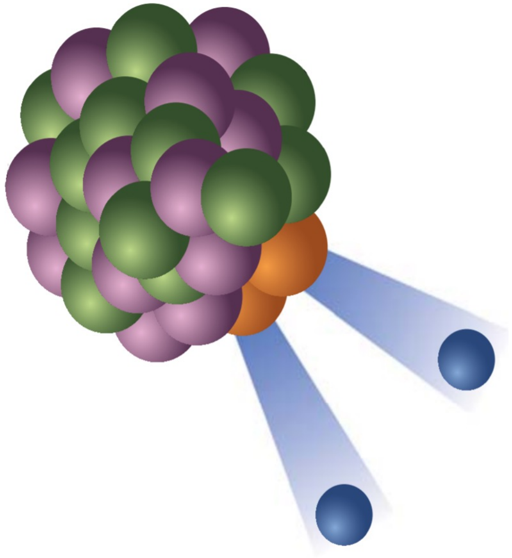




Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

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

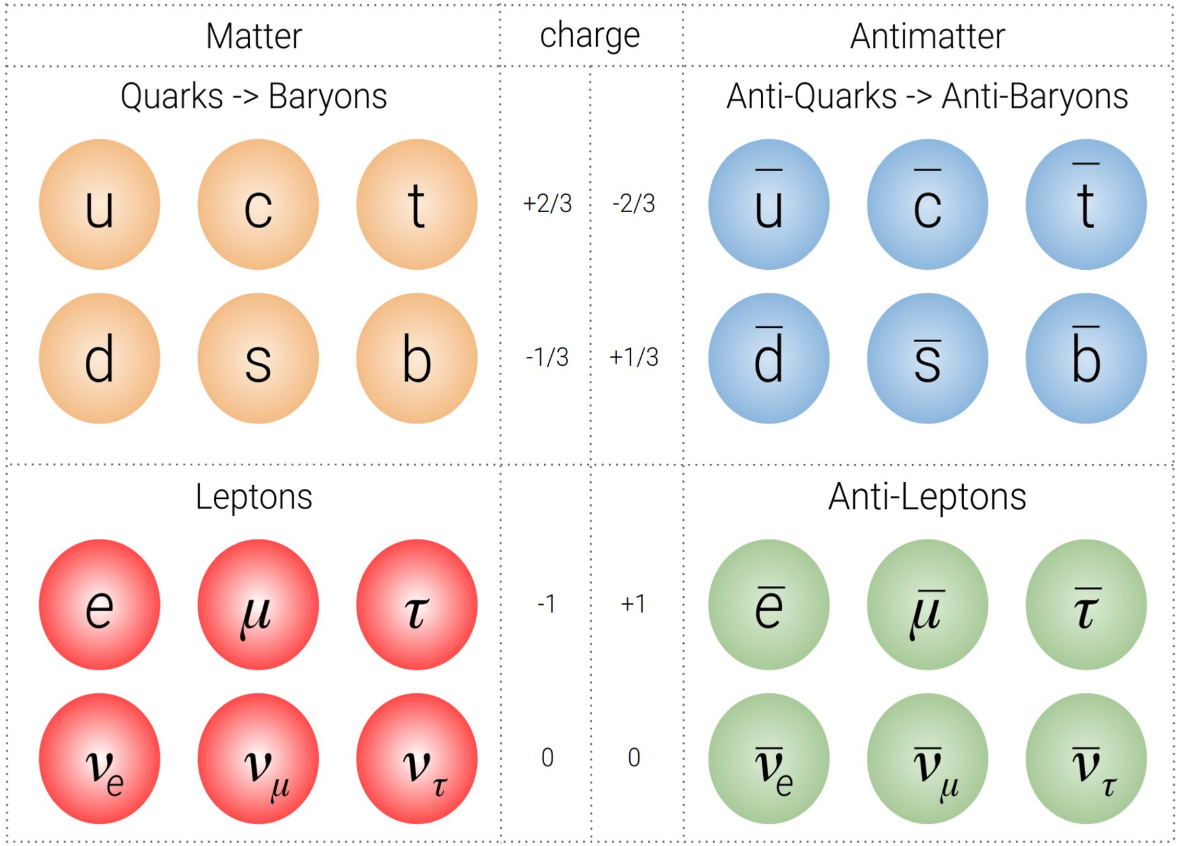
Big Questions: Matter vs Antimatter

Standard Model

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

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

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

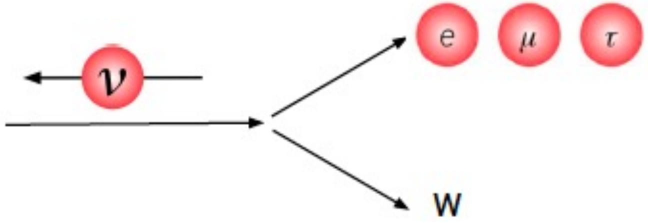


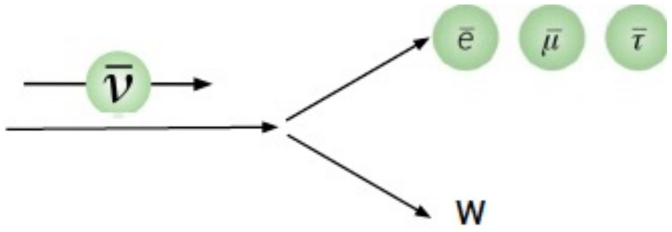
Matter			charge		Antimatter		
Quarks -> Baryons					Anti-Quarks -> Anti-Baryons		
u	c	t	+2/3	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
d	s	b	-1/3	+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons					Anti-Leptons		
e	μ	τ	-1	+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
ν_e	ν_μ	ν_τ	0	0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Big Questions: Matter vs Antimatter and neutrino mass

What distinguishes neutrinos from antineutrinos?

Phenomenology:

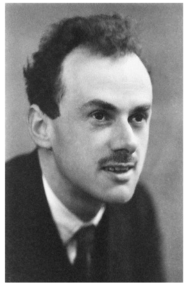




left-handed chirality -> creating **particles**

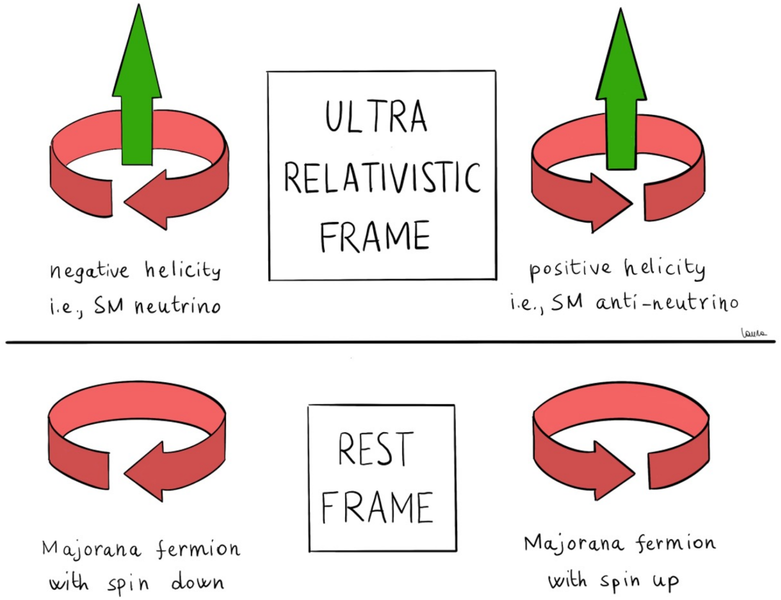
right-handed chirality -> creating **antiparticles**

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



Dirac

Majorana

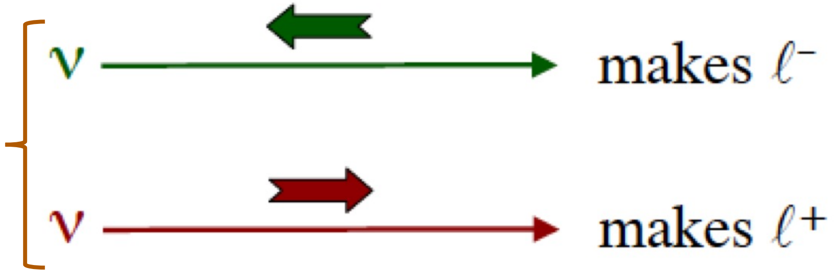


Accept there are two non-interacting "sterile" states

Or the same objects that has both chiral state

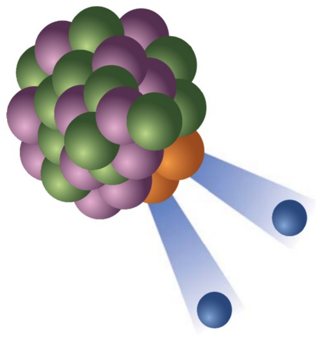
Neutrino ↔ “anti”-neutrino transformation and $0\nu\beta\beta$-decay

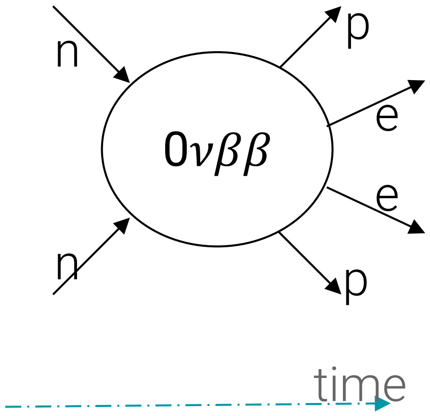
Majorana neutrinos can create both matter and antimatter



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

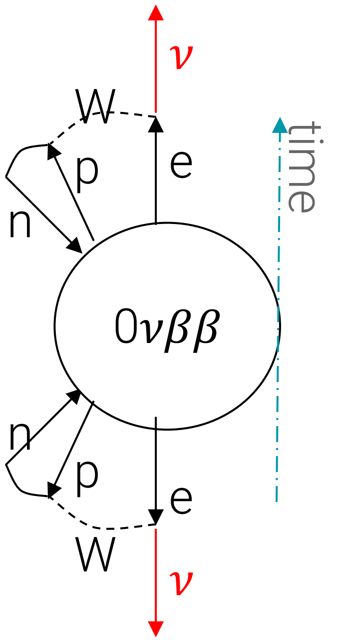
$$\boxed{\Delta B = 0, \Delta L = 2}$$

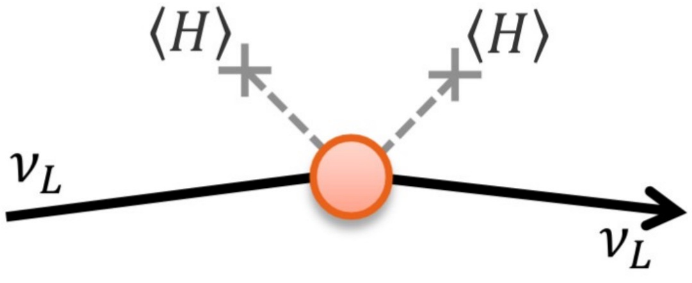




Schechter and Valle

1982





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

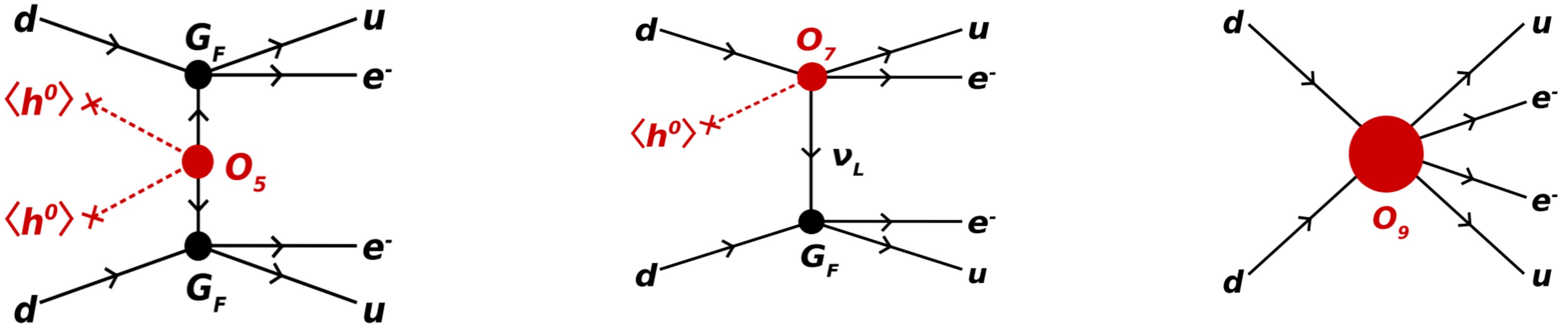
non-zero Majorana mass

Neutrino mass generation mechanism

$0\nu\beta\beta$: Generic test for UHE BSM physics

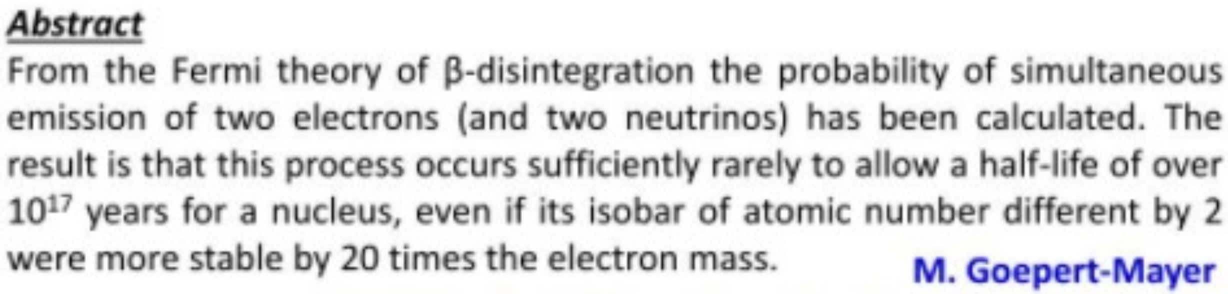
Cirigliano et al., JHEP 12, 097 (2018)

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



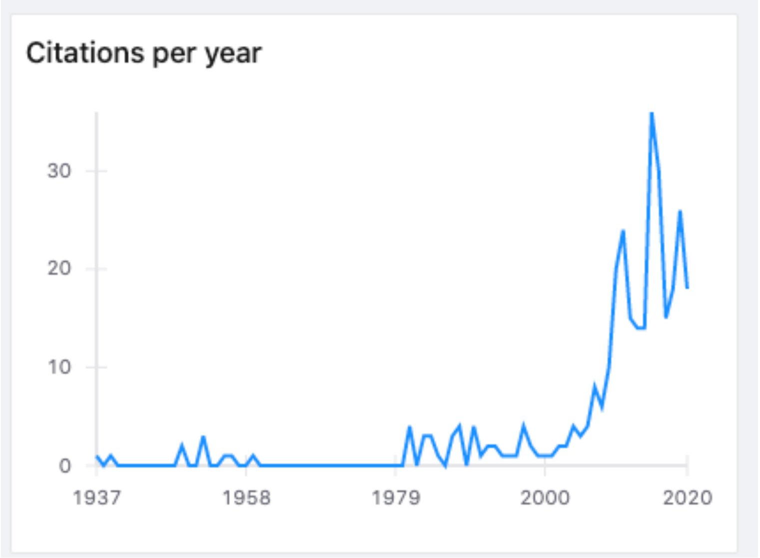
Abstract

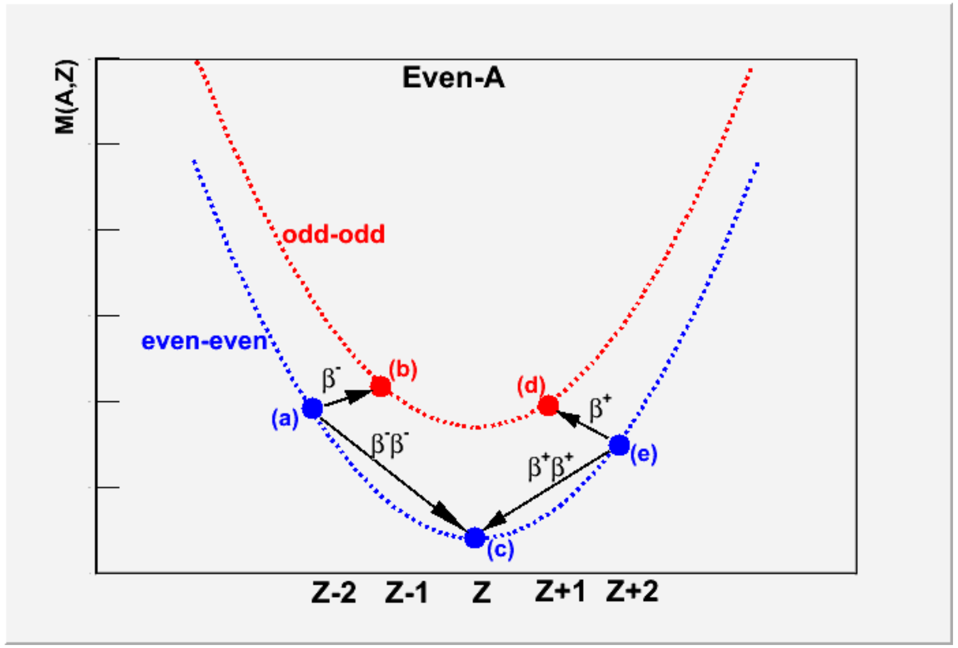
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different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

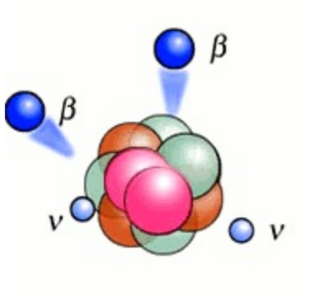
Only ~**9** experimentally **feasible for $0\nu\beta\beta$**

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

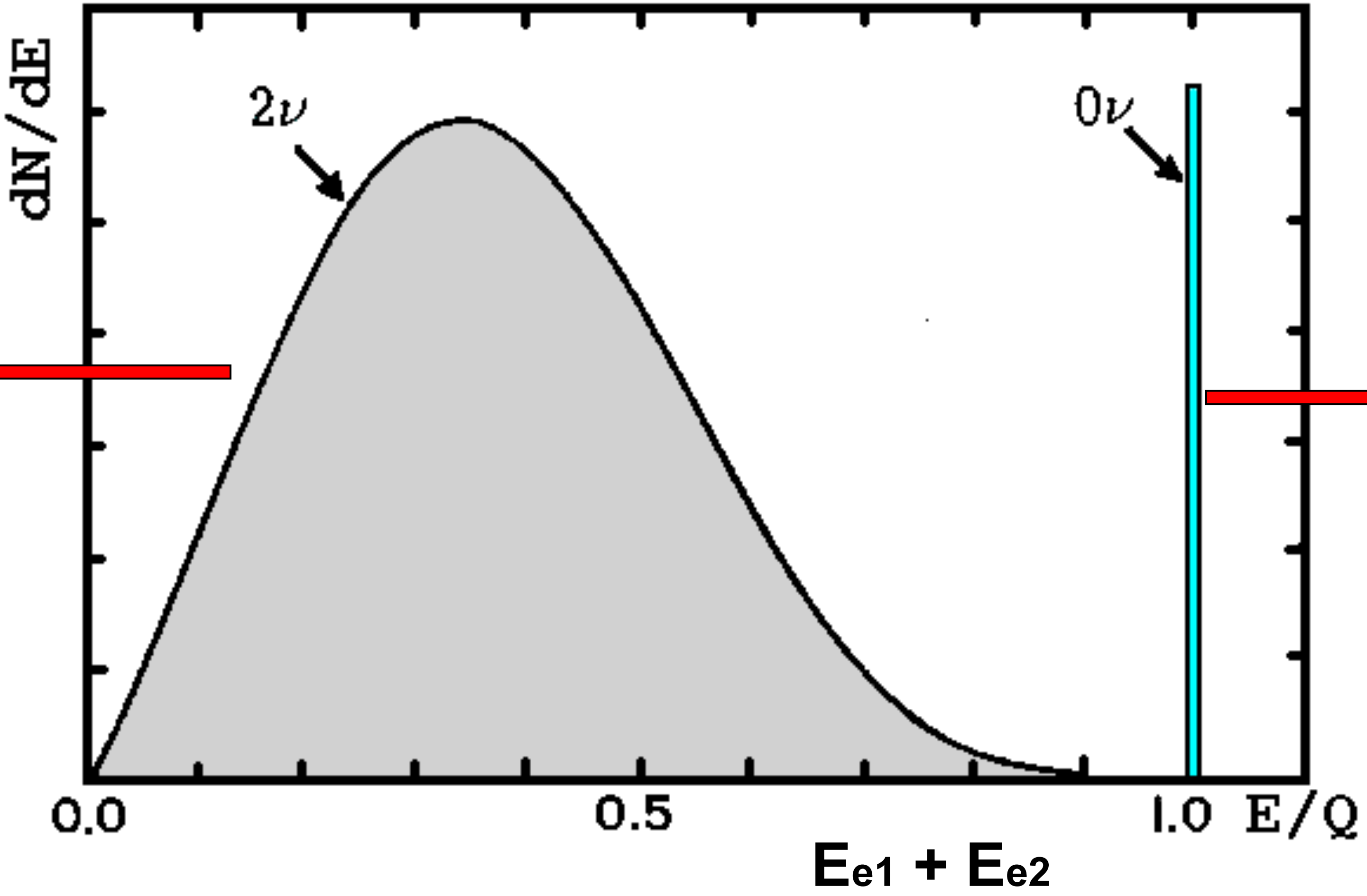
Experimental Observables

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

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

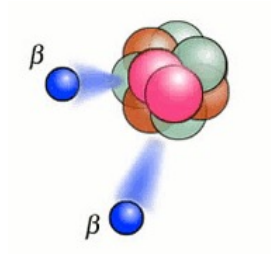


$2\nu\beta\beta(EC/\beta^+)$ has been detected in 13 nuclei!



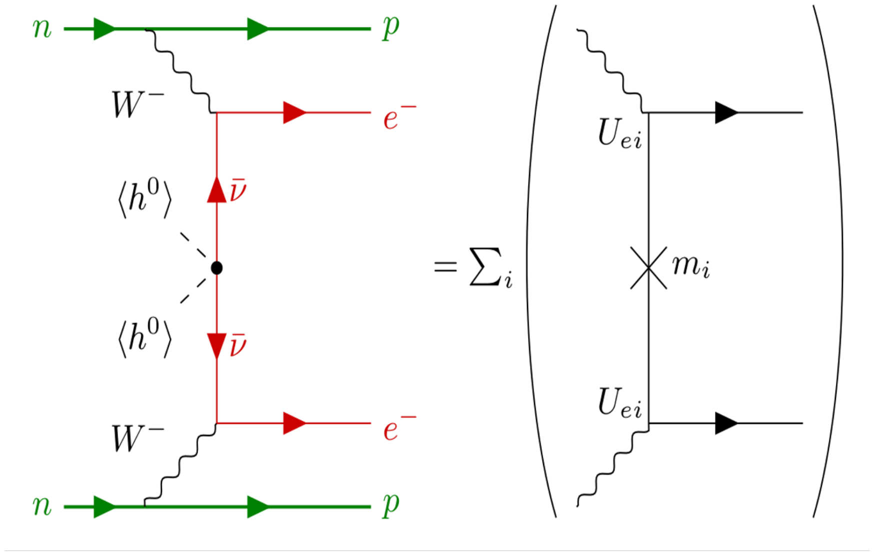
$\Gamma^{0\nu} \propto G_F^4 \cdot \eta_{LNV}^2$

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

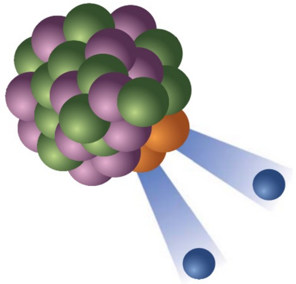


If possible: individual electron energies, E_{e1}, E_{e2}, and angle θ between them

0νββ: Light Majorana neutrino mass, $m_{\beta\beta}$



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



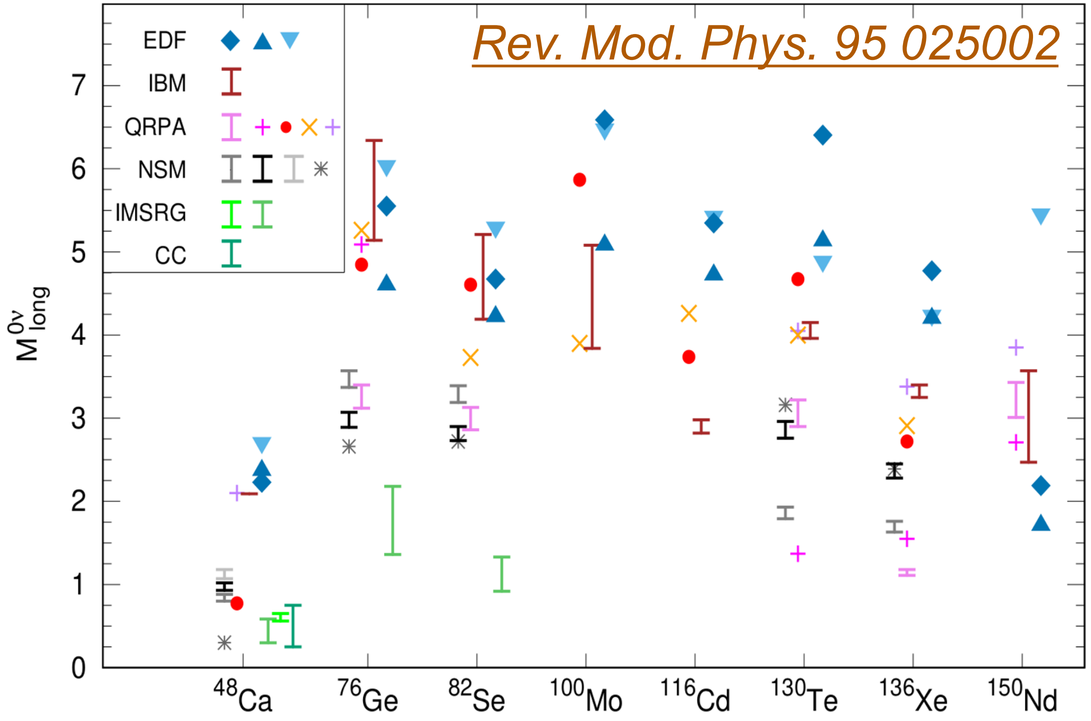
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

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

$m_{1,2,3}$ → 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

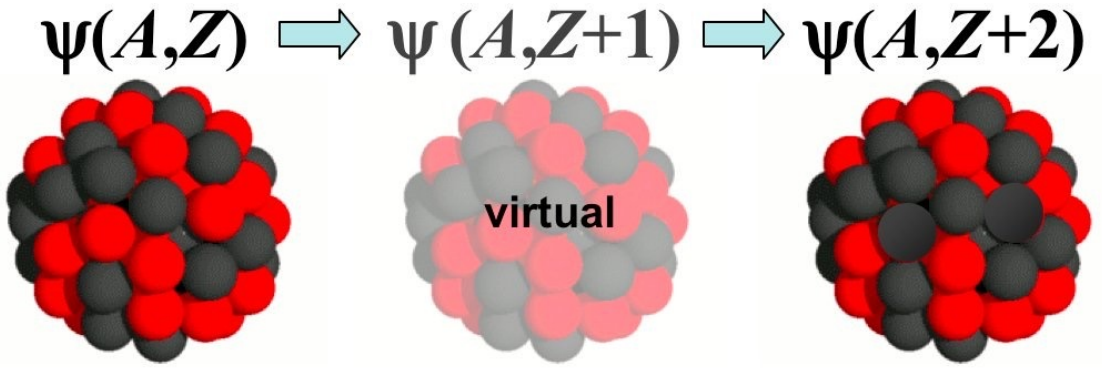


Rev. Mod. Phys. 95 025002

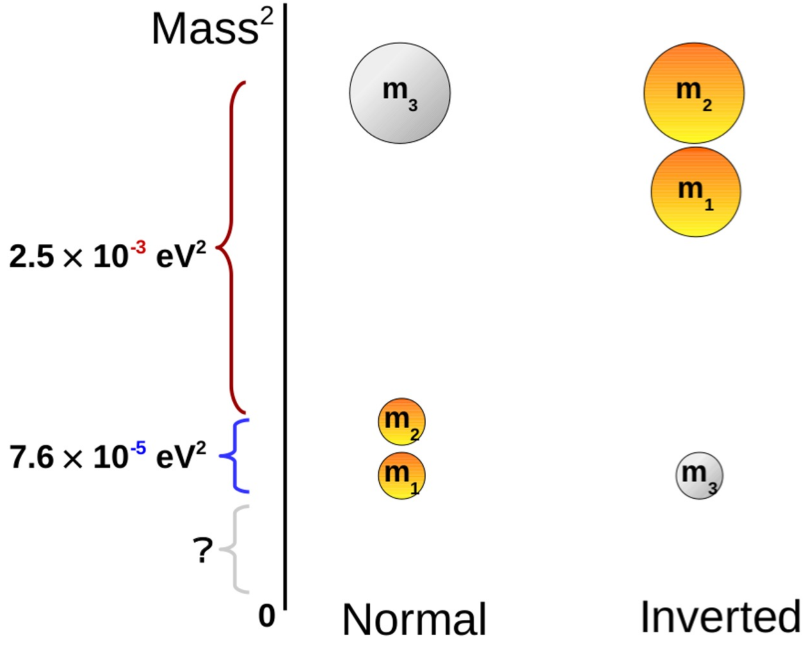
$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4 M^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

nuclear matrix element (NME)

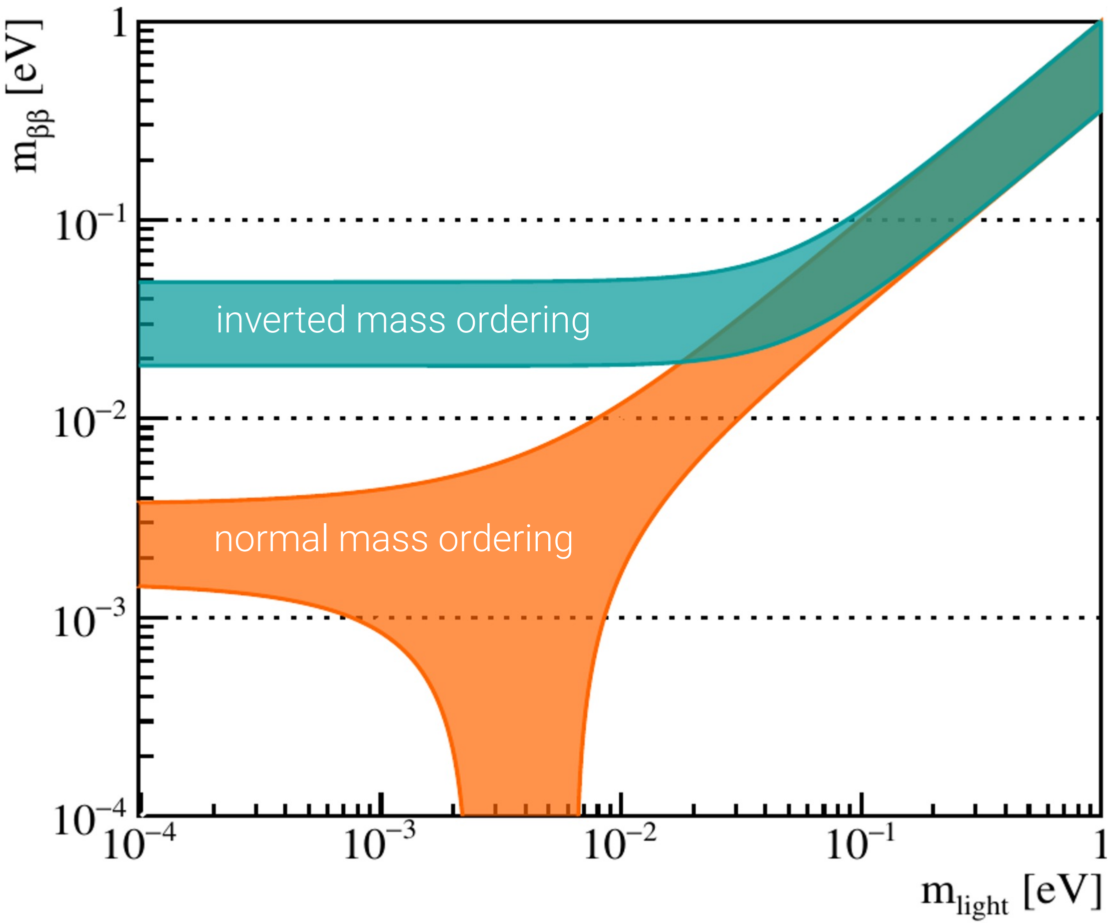
- Significant effort from different groups and different nuclear models
- *Question of g_A quenching under study*
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - »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



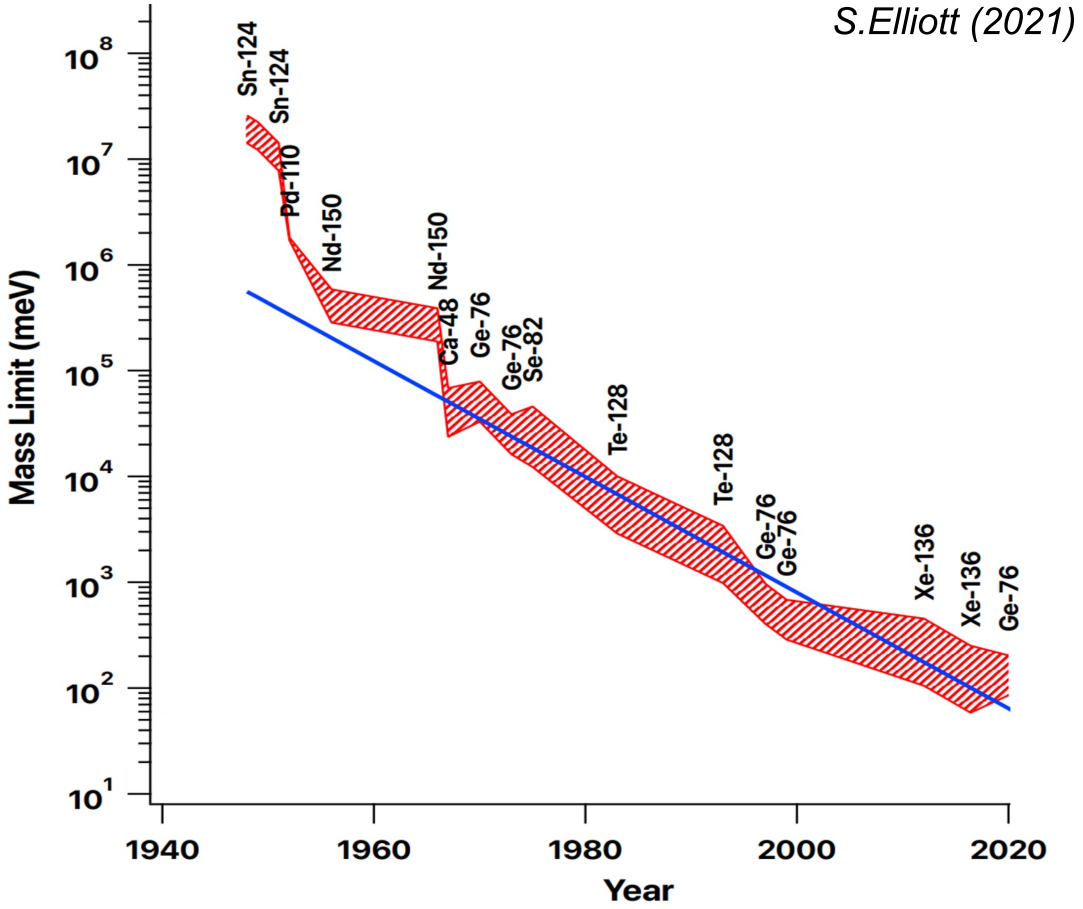
$0\nu\beta\beta$: Light Majorana neutrino mass, $m_{\beta\beta}$ and neutrino mass ordering

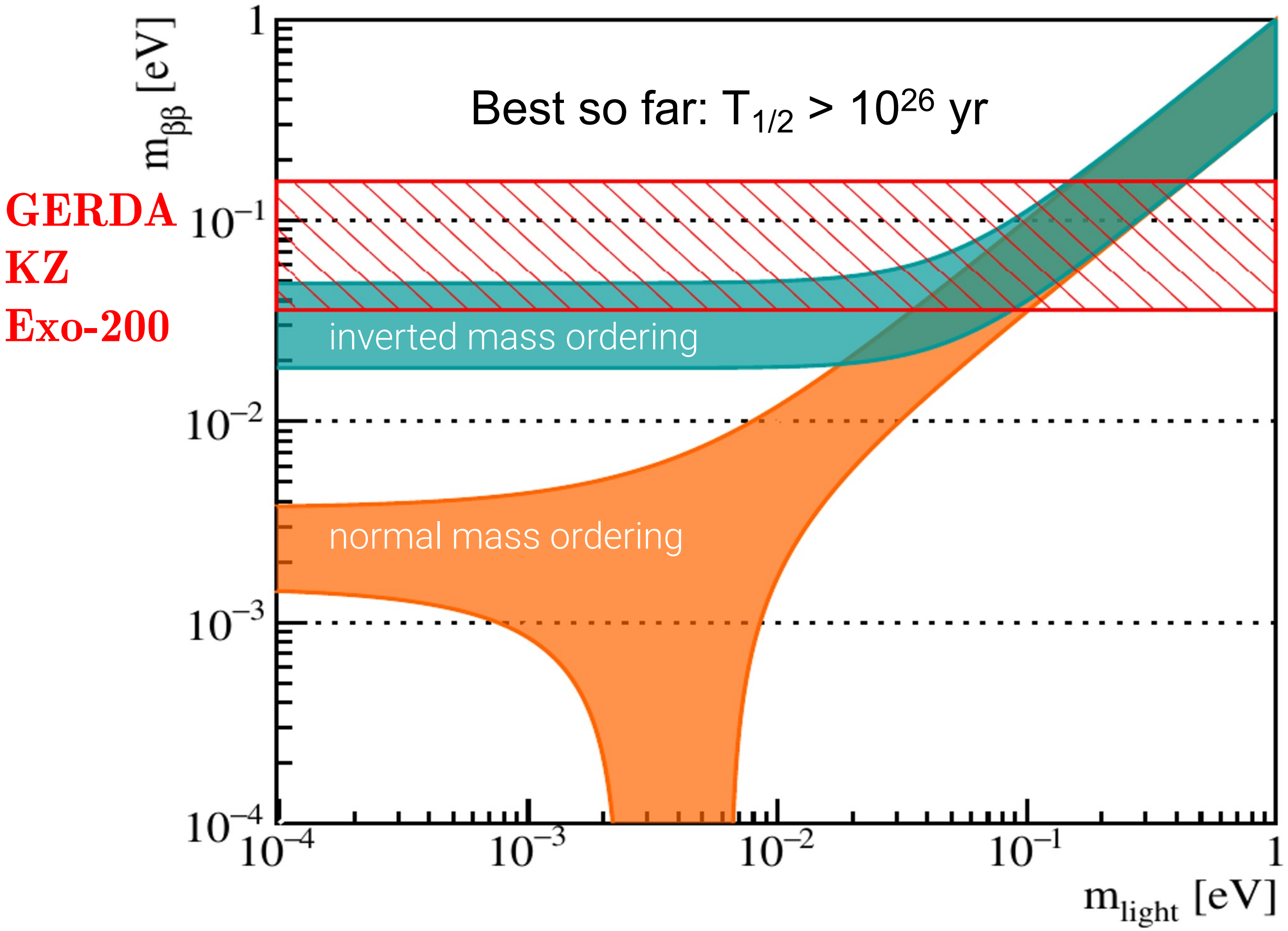


$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$



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

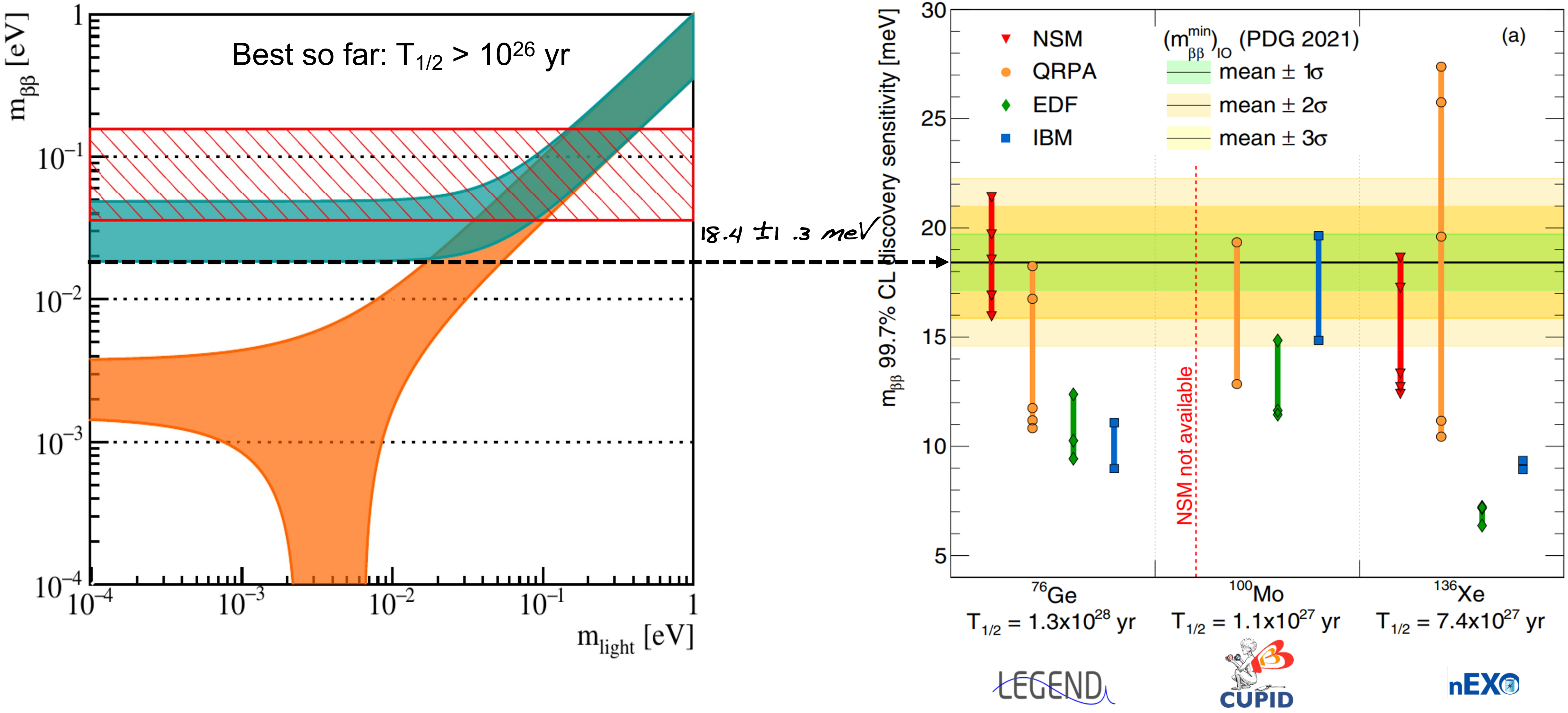

S.Elliott (2021)


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

GERDA
KZ
Exo-200

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

PRC 104, L042501 (2021)

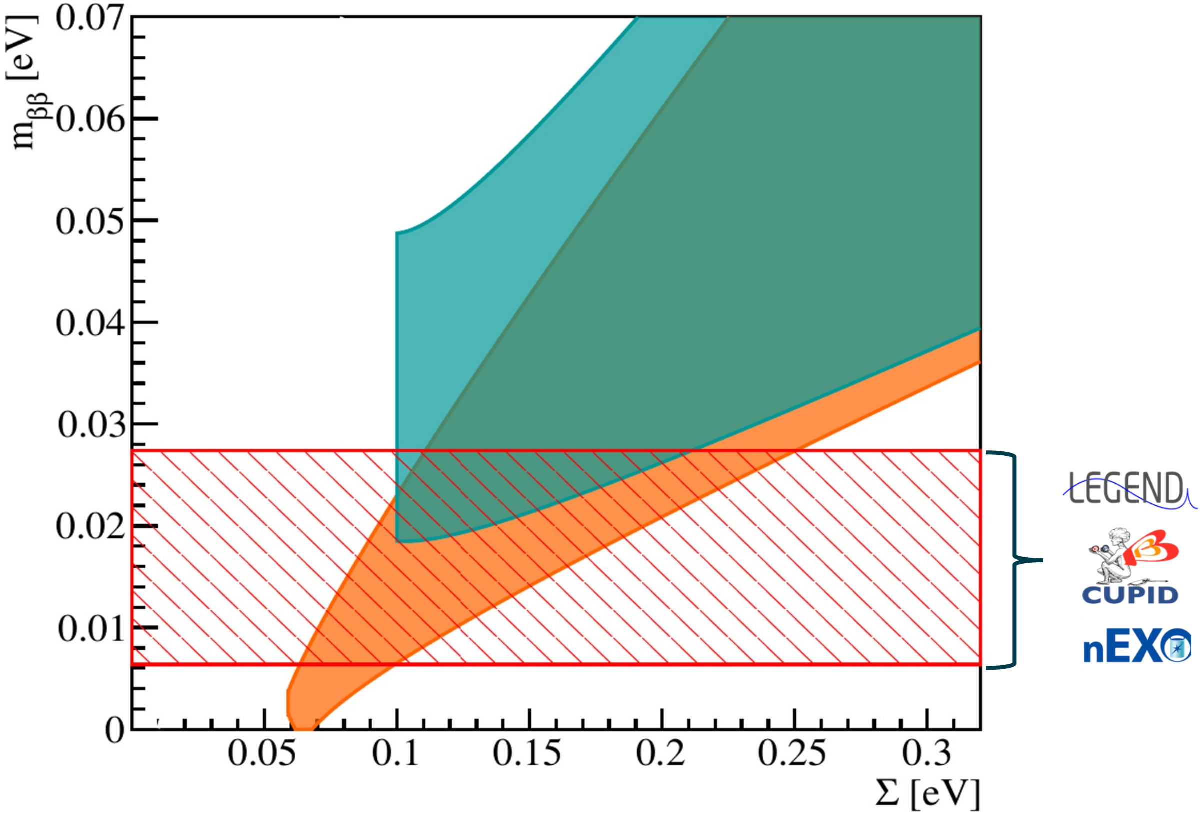

Best so far: $T_{1/2} > 10^{26}$ yr

18.4 ±1.3 meV

$0\nu\beta\beta$ with $m_{\beta\beta}$. Interplay with Cosmology.

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

$$\Sigma = \sum_i m_i$$



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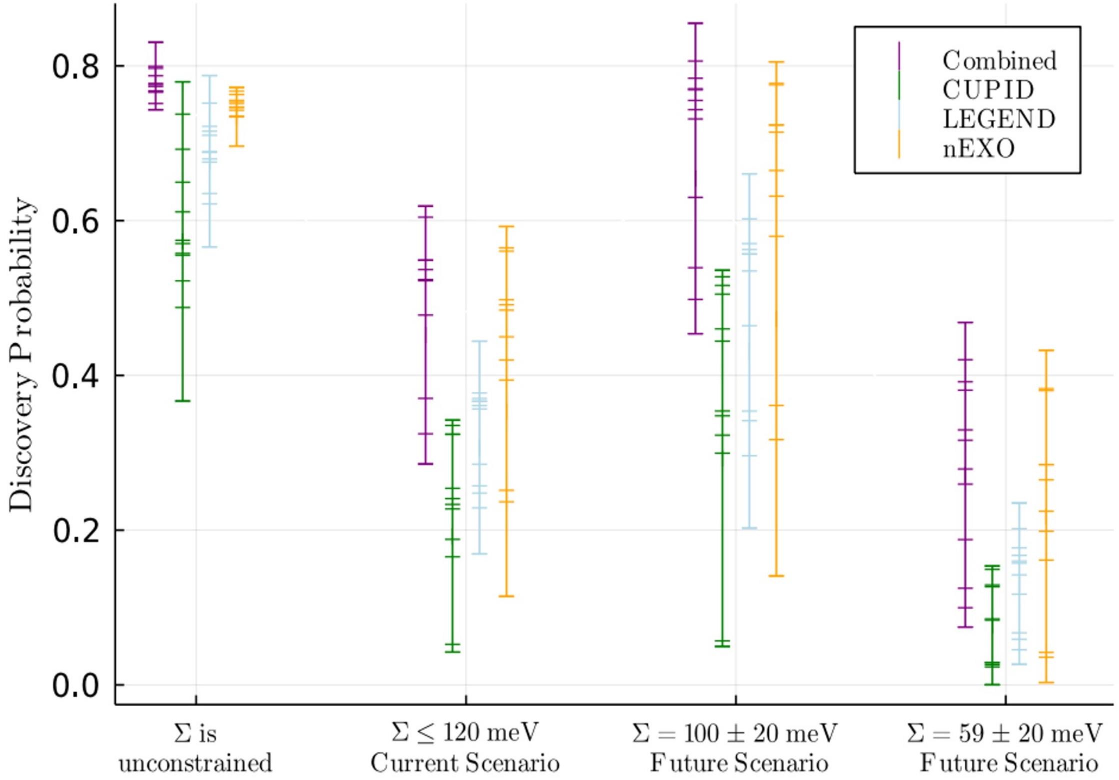
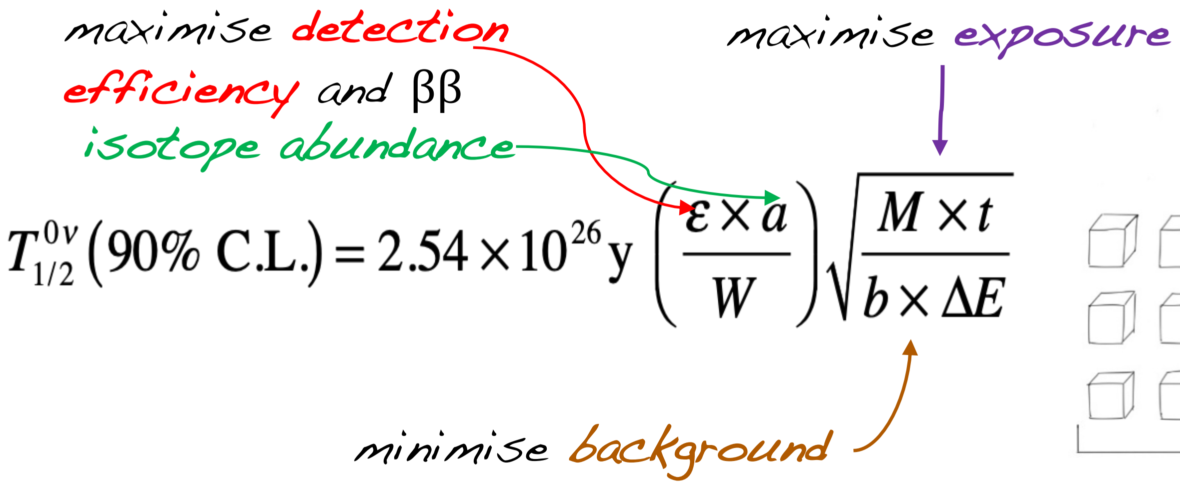


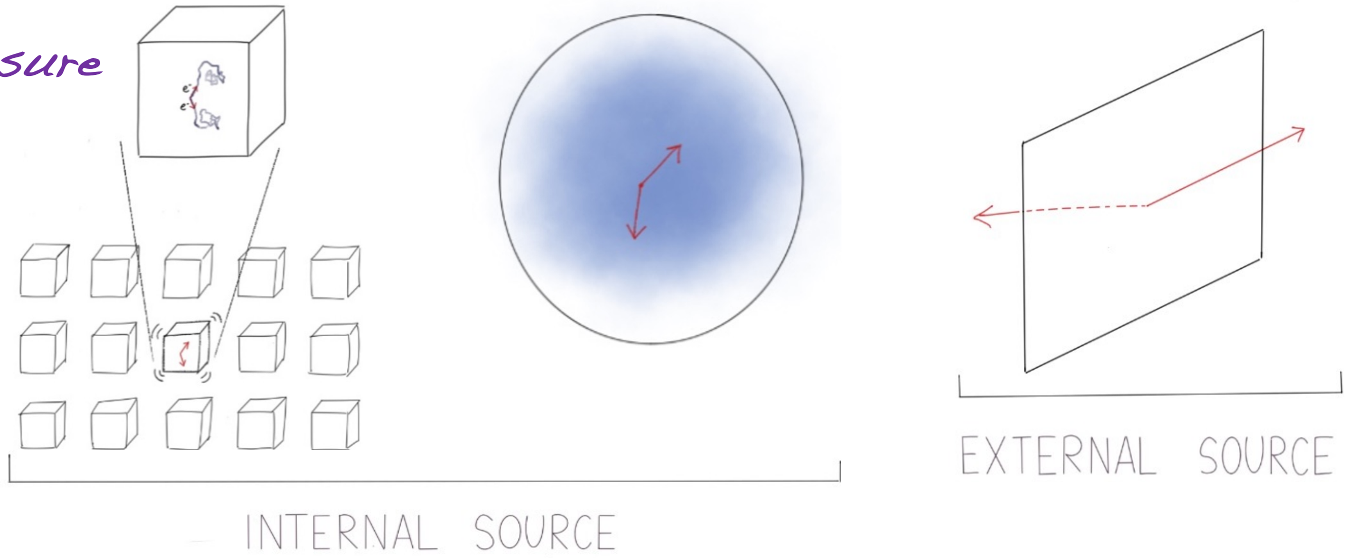
arXiv: 2208.09954

Experimental Approaches

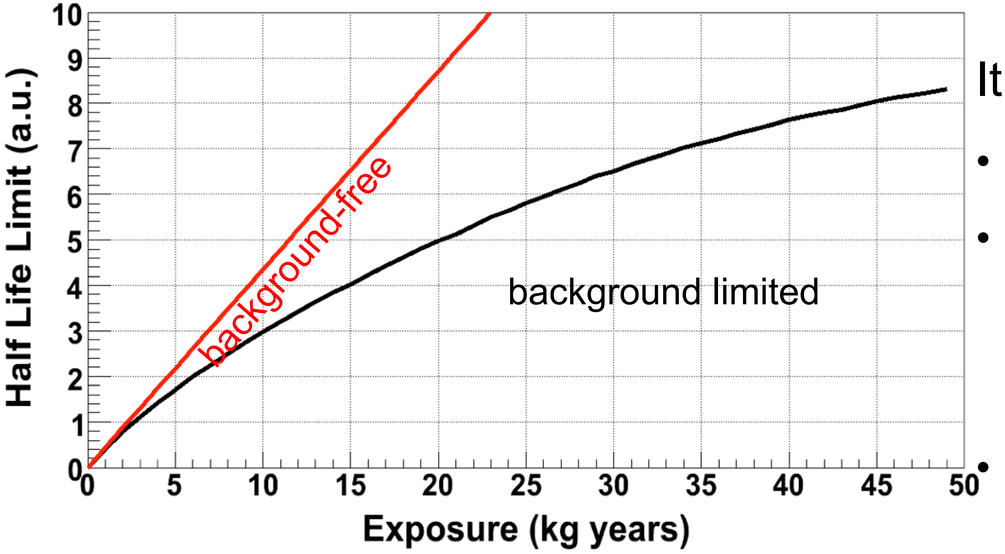
Detection Principles



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

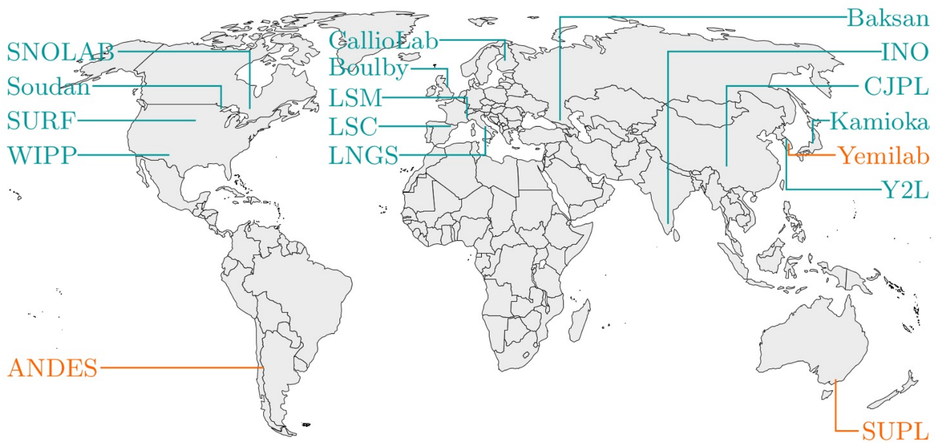


- Drawings courtesy of Laura Manenti

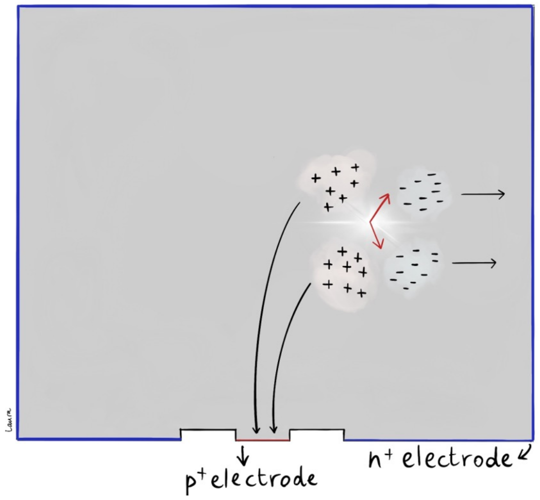


It's all about backgrounds

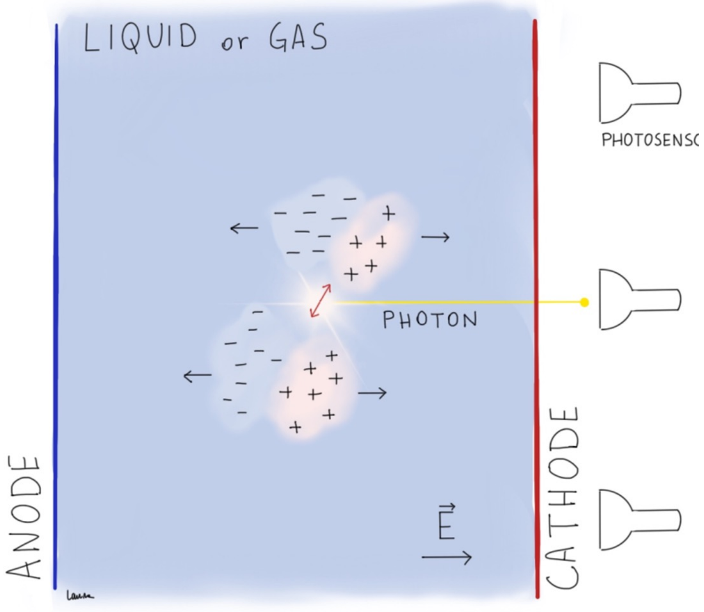
- Cosmic rays (underground)
- Natural radioactivity (clean materials, particle id and tagging)
- Standard Model $2\nu\beta\beta$ (energy resolution)



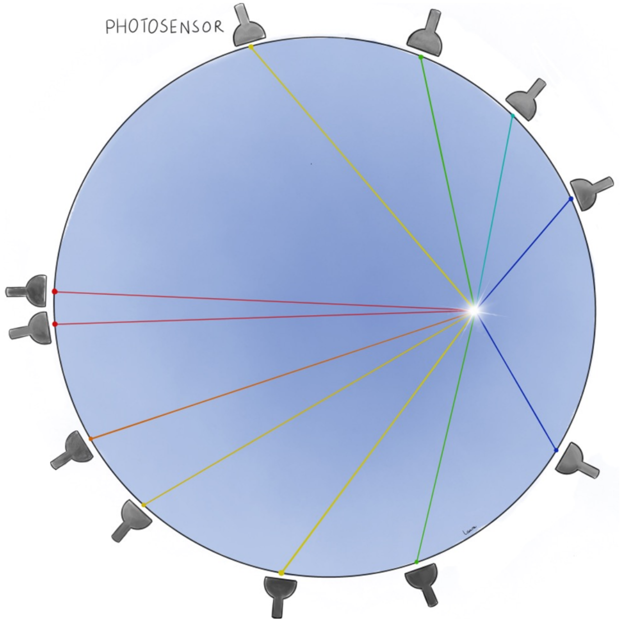
Leading Experimental Techniques



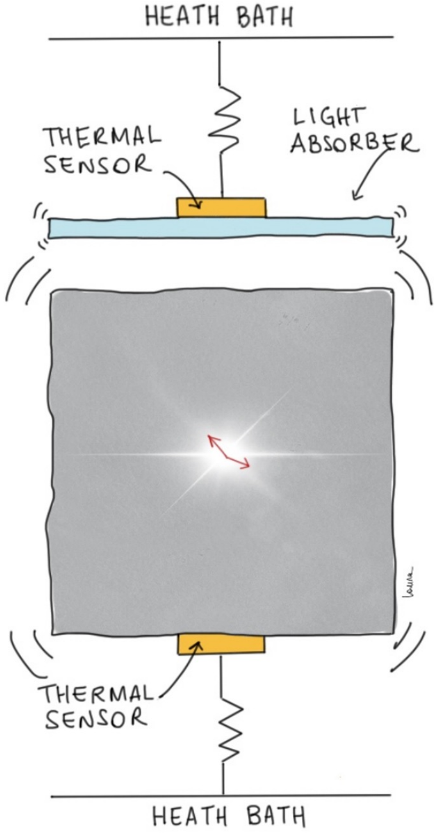
Ge Semiconductor detectors (^{76}Ge)



Xe Time Projection Chambers (^{136}Xe)



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



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

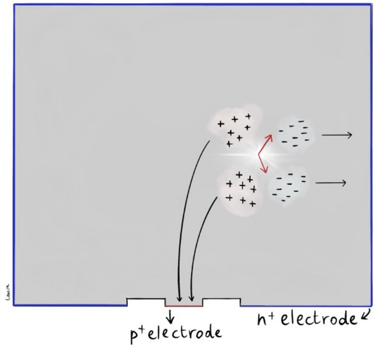
Drawings courtesy of Laura Manenti

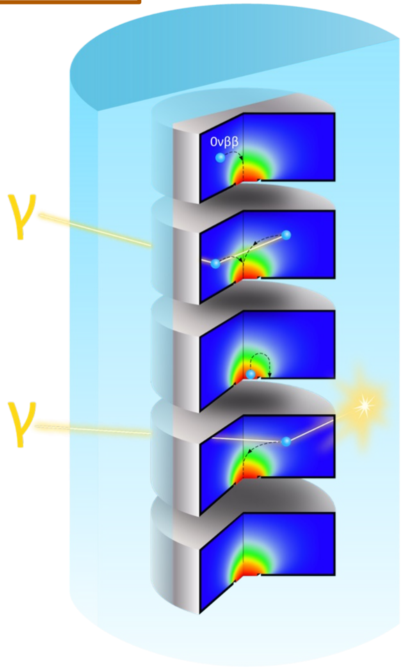
Enriched Ge semiconductor detectors

See talk by Valentina Biancacci on Tuesday, HEP T3

high-purity ^{76}Ge detectors

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





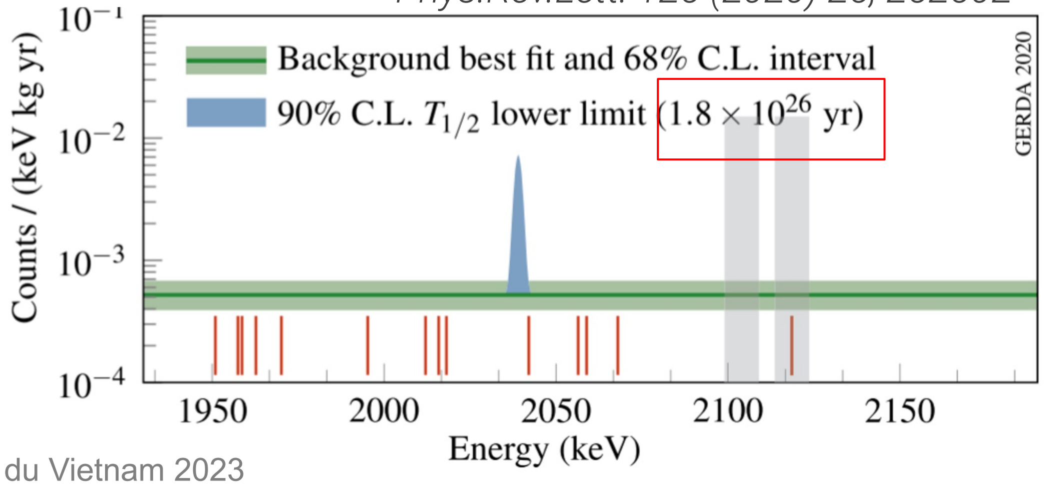
liquid Ar detector

- shield and scintillation light

Staged approach:

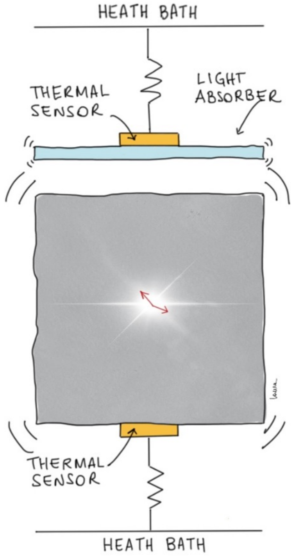
- **GERDA/MAJORANA** Demonstrator (40 kg)
- **LEGEND-200** (200 kg) taking data at LNGS
- **LEGEND-1000** conceptual design in preparation (1 t)

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



Cryogenic Calorimeters

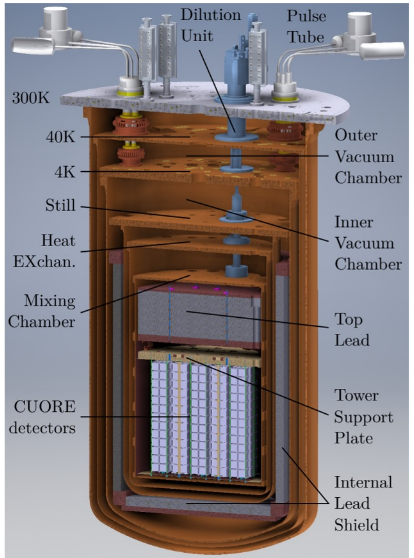
See talk by Stefano Ghislandi on Tuesday, HEP T3



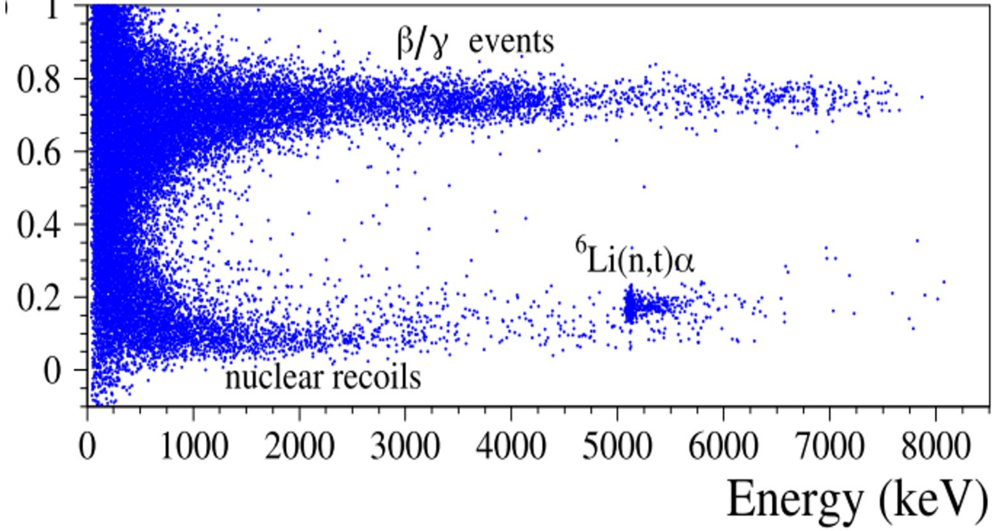
- array of isotopically enriched crystals operated at ~10 mK
- thermal and scintillation signal
- particle ID and good energy resolution
- Leading results for ^{130}Te and ^{82}Se, future focus on ^{100}Mo

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


CUORE @ LNGS

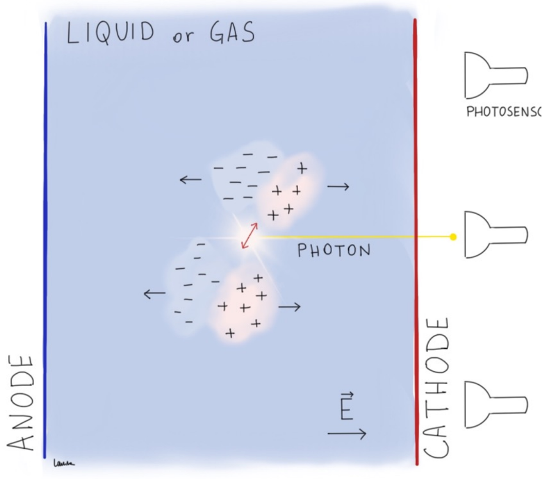


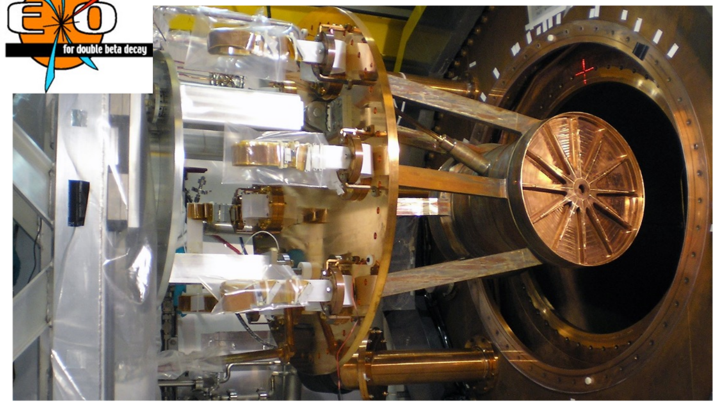
CUPID



Enriched Xe TPCs

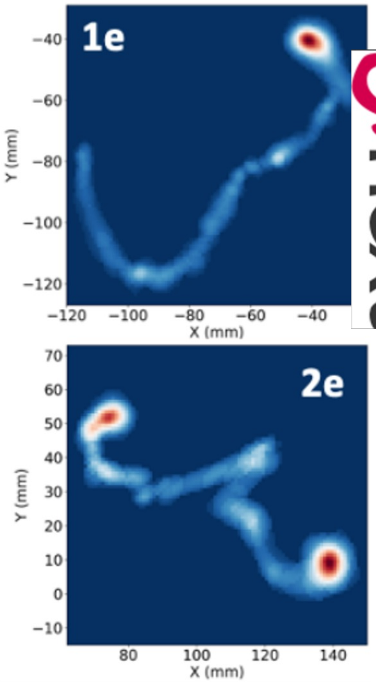
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope

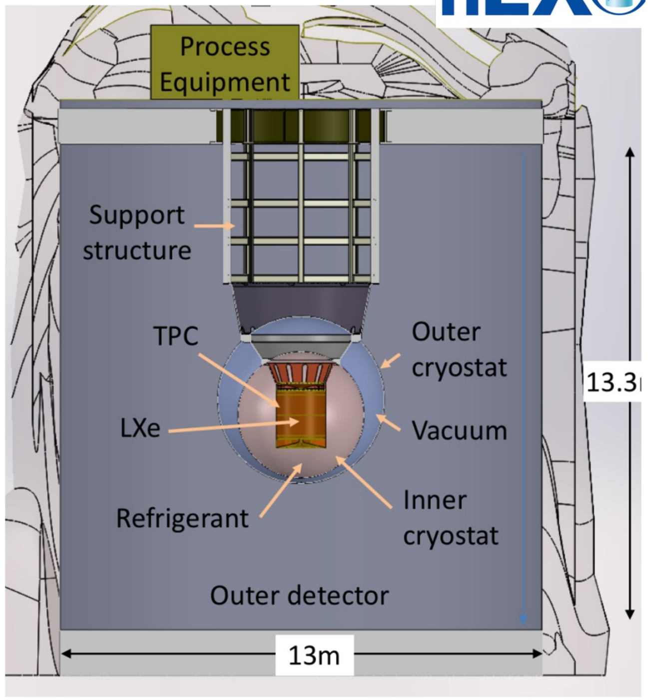




Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPMs
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs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

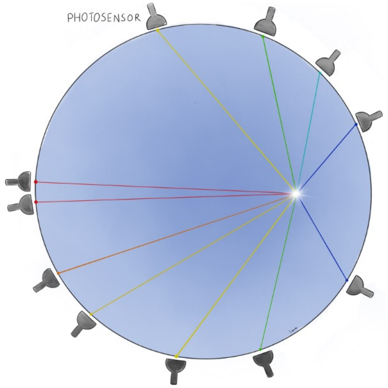
XLZD **70,000**

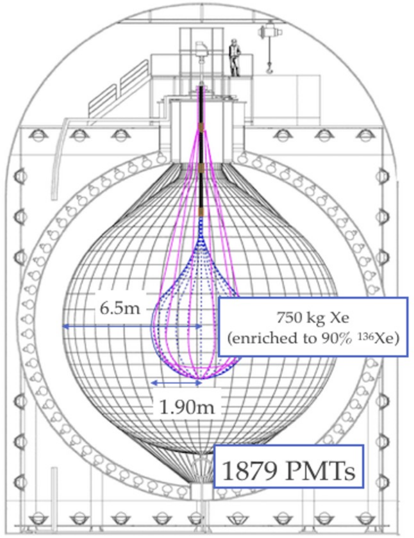


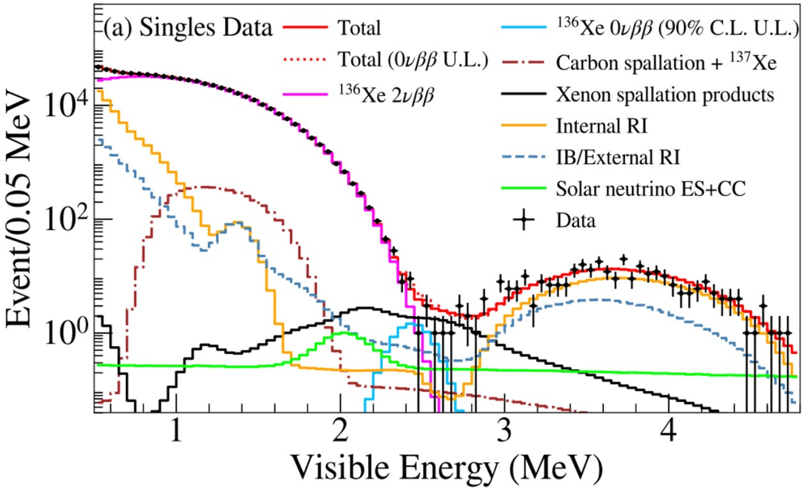


Large loaded liquid scintillators

- 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)





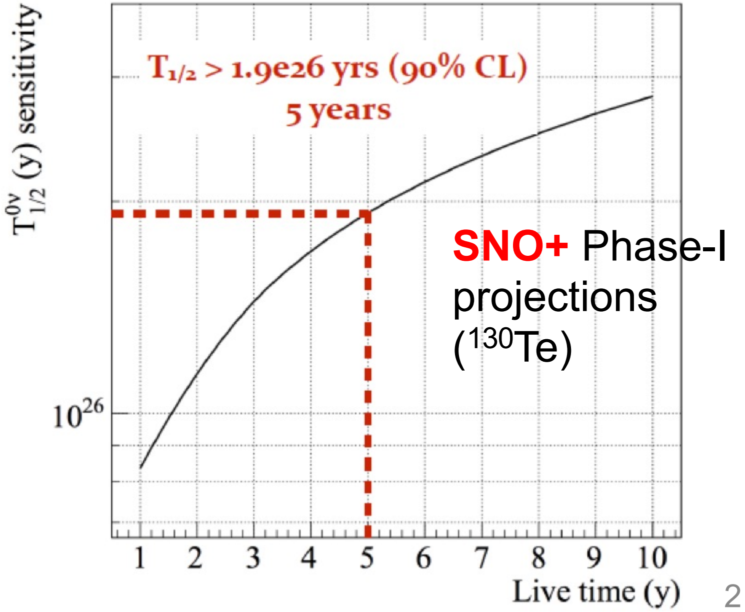


KZ collaboration, 2203.02139

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

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

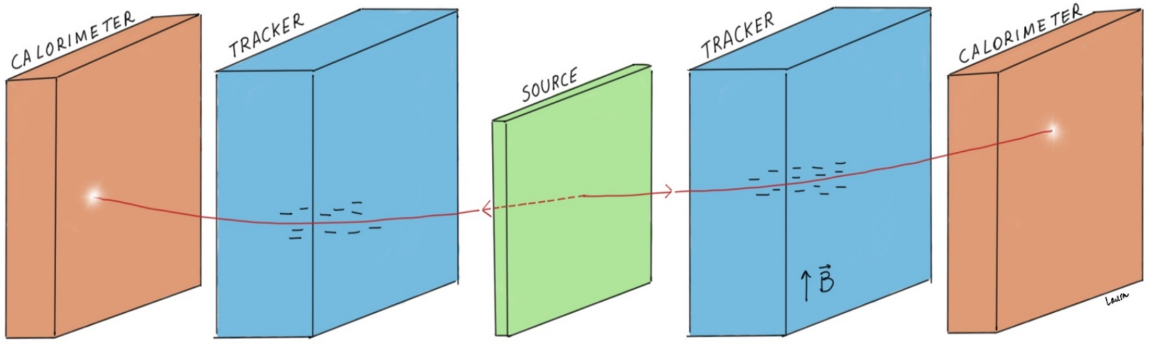
- 750 kg of enriched Xe in nylon balloon
- **Strongest constraints so far: $m_{\beta\beta} < 36$-156 meV**
- backgrounds:, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- next phase: improved resolution and purer scintillator

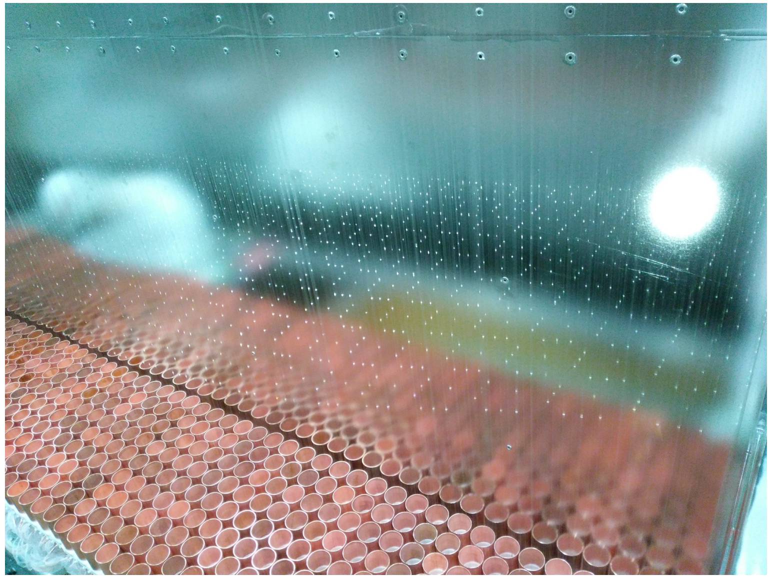


SNO+ Phase-I projections (^{130}Te)

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

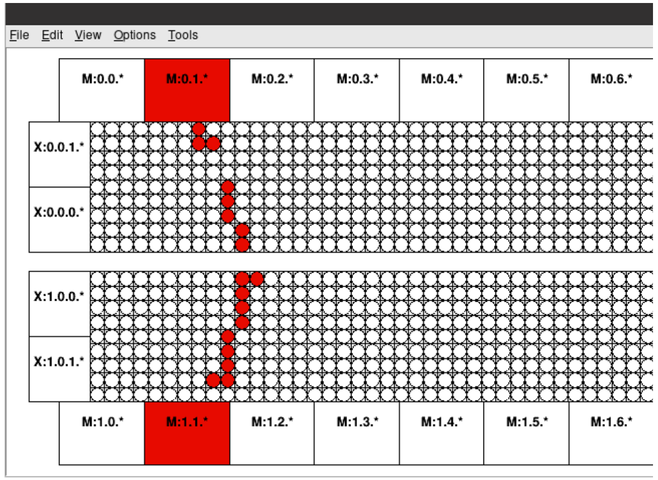
NEMO-technique: full topology reconstruction of final states





SuperNEMO-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*)

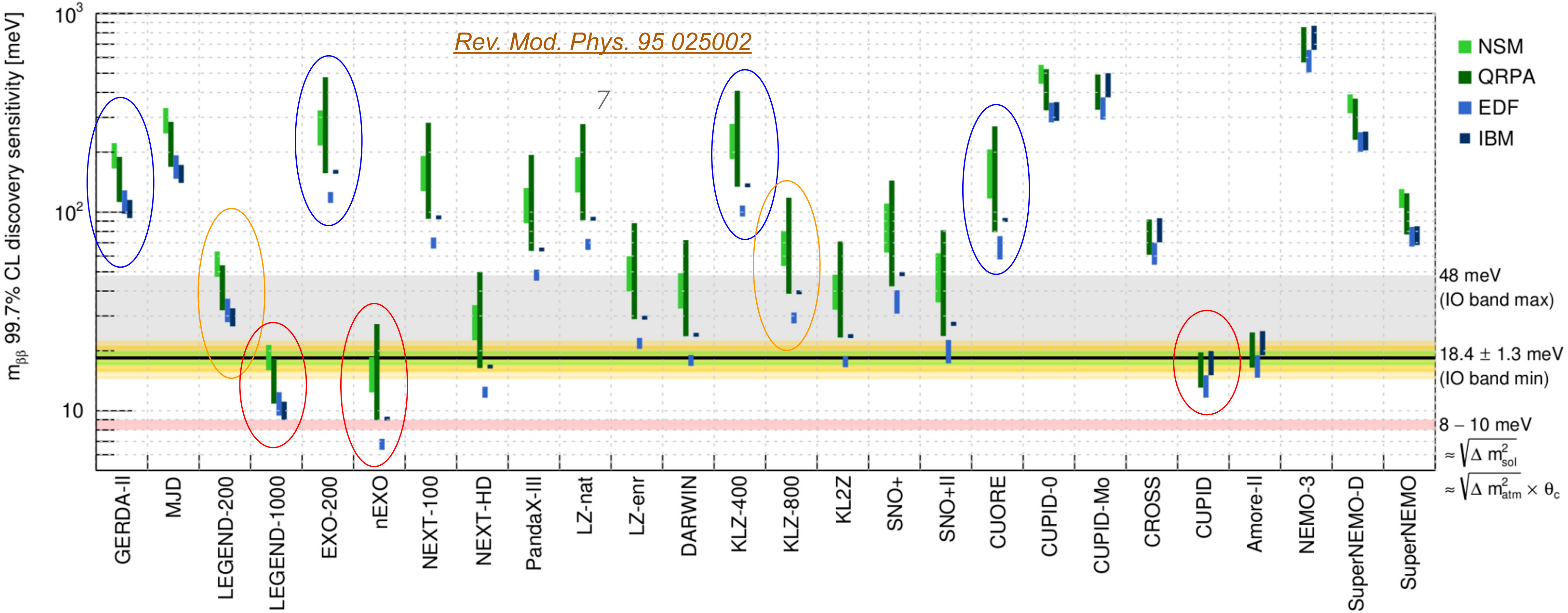


Outlook

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

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

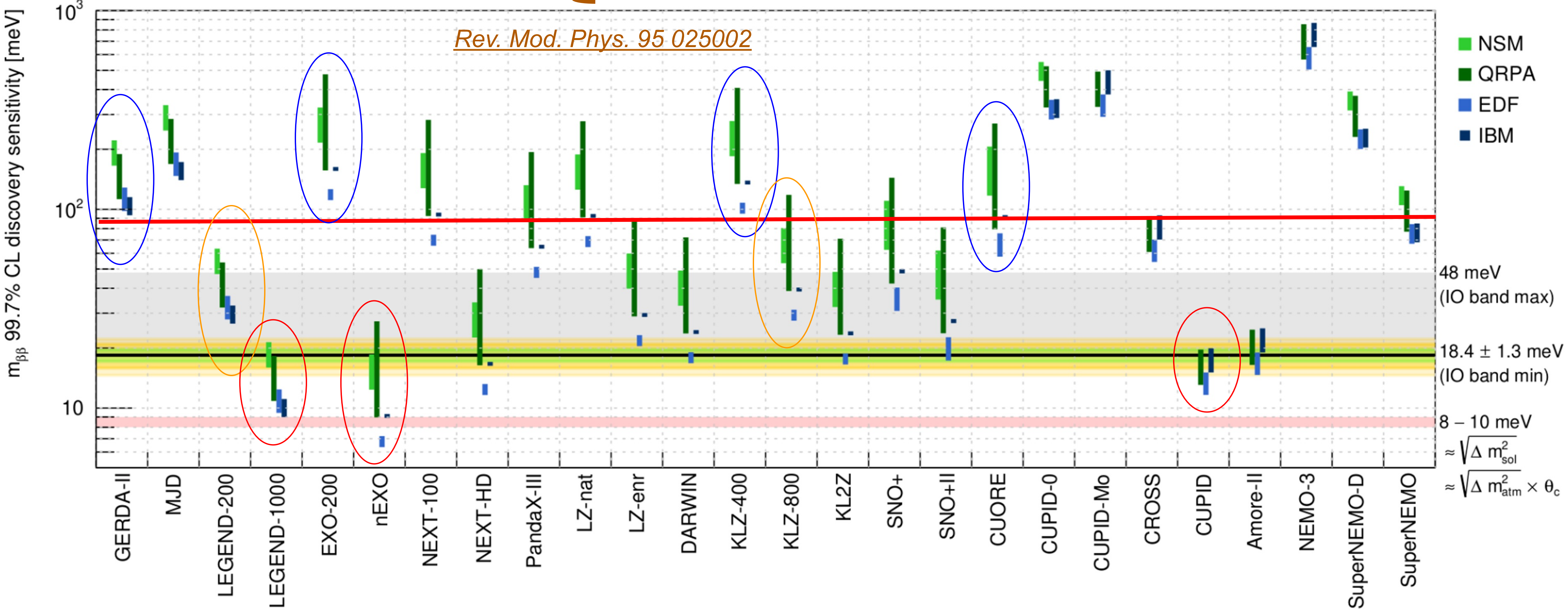
The ultimate I.O. experiments: **LEGEND-1000, CUPID, nEXO**



Outlook

Scenario 1:
signal just beyond current limits

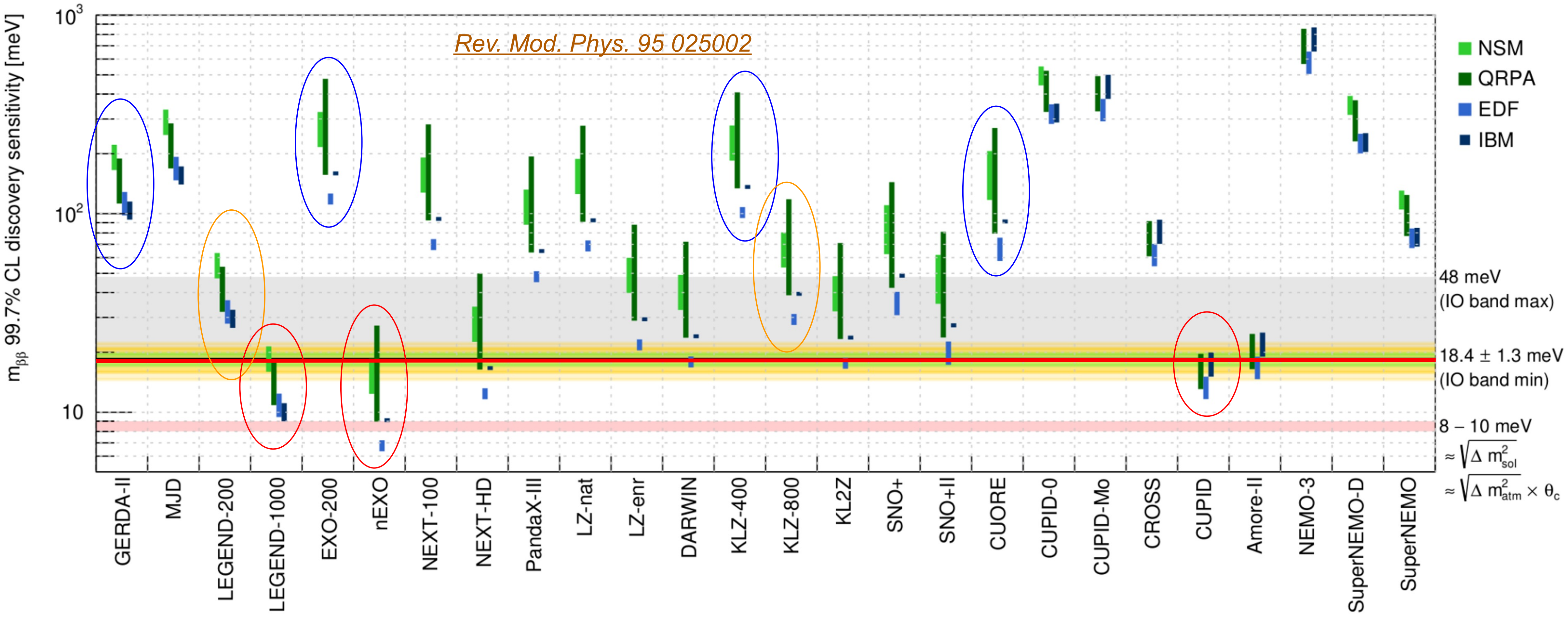
- discovery within few years
- precise rate measurement with next-gen experiments
- Access to underlying mechanism with SNEMO-like technique



Outlook

Scenario 2: signal at bottom of I.O.

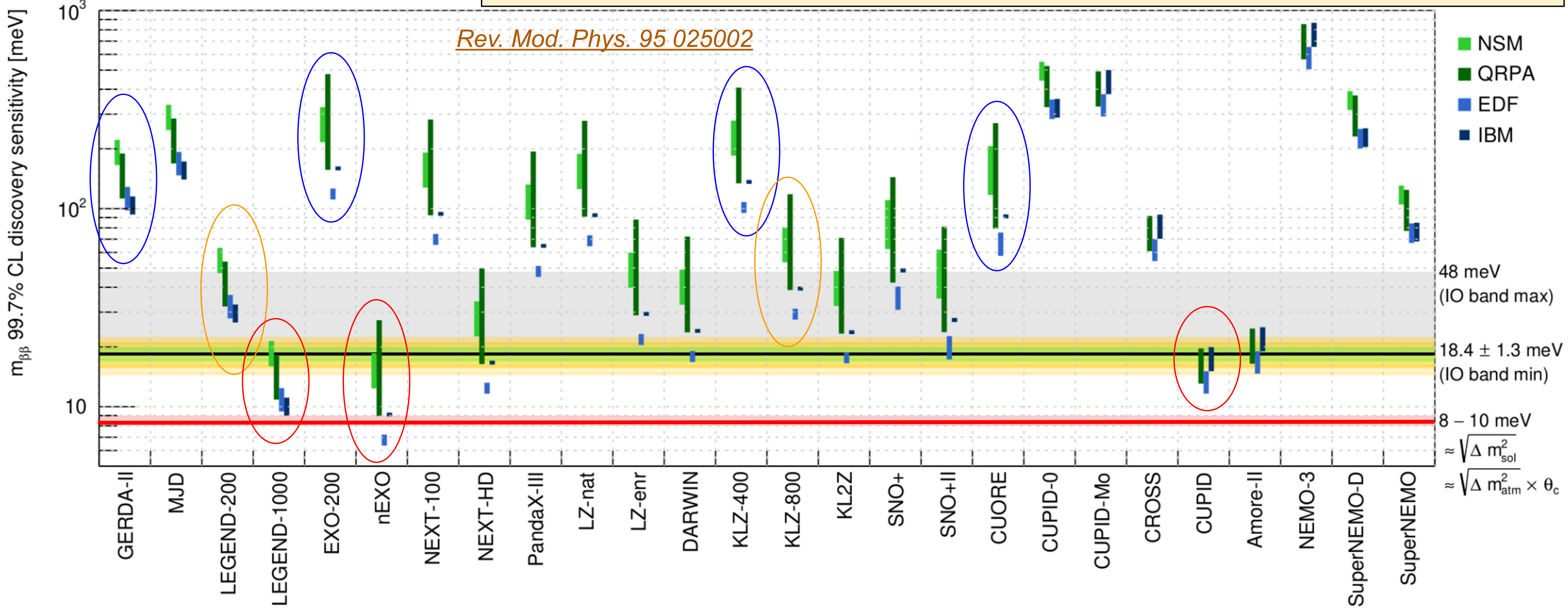
- need to wait next-gen experiments for a discovery
- need R&D to measure decay features



Outlook

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

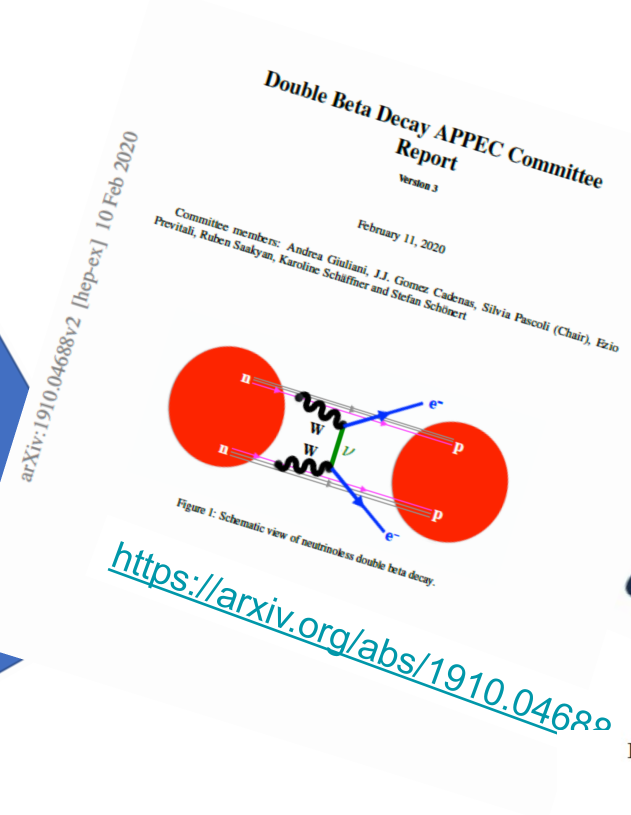
https://science.osti.gov/np/nsac


REACHING FOR THE HORIZON

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

New LRP process started (2023-2032)

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO


arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

https://arxiv.org/abs/1910.0468

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


North America - Europe Workshop on Future of Double Beta Decay

29 September 2021 to 1 October 2021
Gran Sasso National Laboratory (LNGS)

The Majorana nature of neutrino and the possible contribution of neutrinos to explain the matter-antimatter asymmetry in the universe are among the most challenging physics goals in the next decade. The purpose of the North America-Europe workshop on Double Beta Decay is to stimulate the discussion between the North American and European double beta decay community and the corresponding funding agencies to consolidate a strategy and define a path to the discovery of Majorana neutrinos. The discussion will focus on the upcoming generation of high sensitivity projects, their discovery potentials and the underground infrastructures.

The Workshop is jointly organized by INFN, APPEC and DOE.


Community Summer Study

SNOWMASS

July 17-26 2022, Seattle

IUPAP Neutrino Panel White Paper

Concluding Remarks

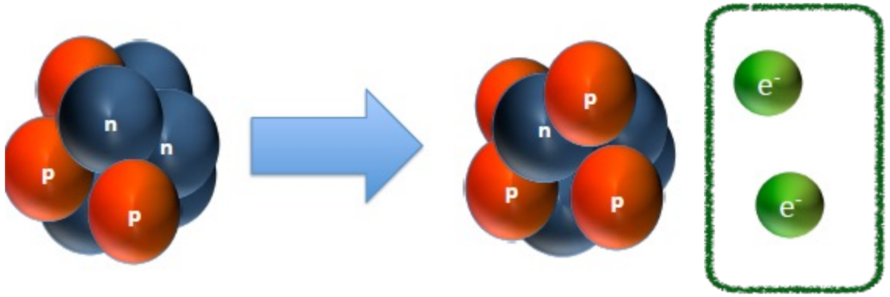
- 0νββ is the best way to probe **Lepton Number Violation** and its connection to preponderance of **matter** and **neutrino mass** generation mechanism
- Huge progress over past decade has led to a **coordinated international effort**
  - Phased approach, convergence on experiments fully covering I.O. 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**!
- 0νββ could be driven by a different LNV mechanism – open minded, **discovery oriented** search

Additional Material

The Big Questions

Proton Decay:
“Disappearance” of nucleons

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

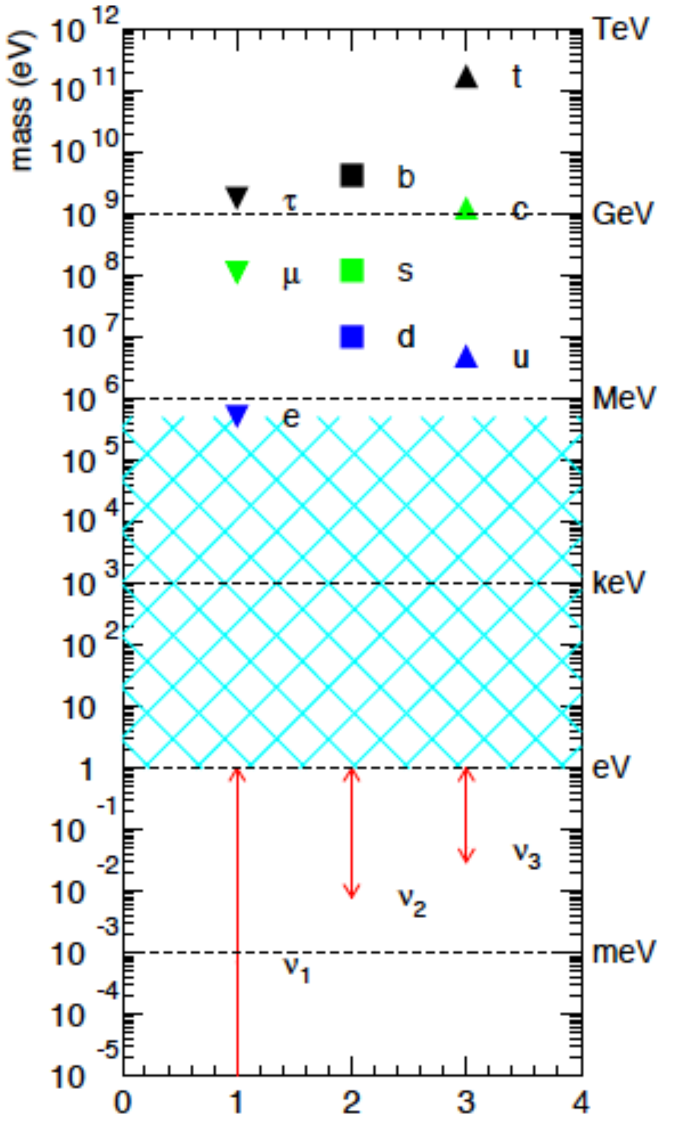


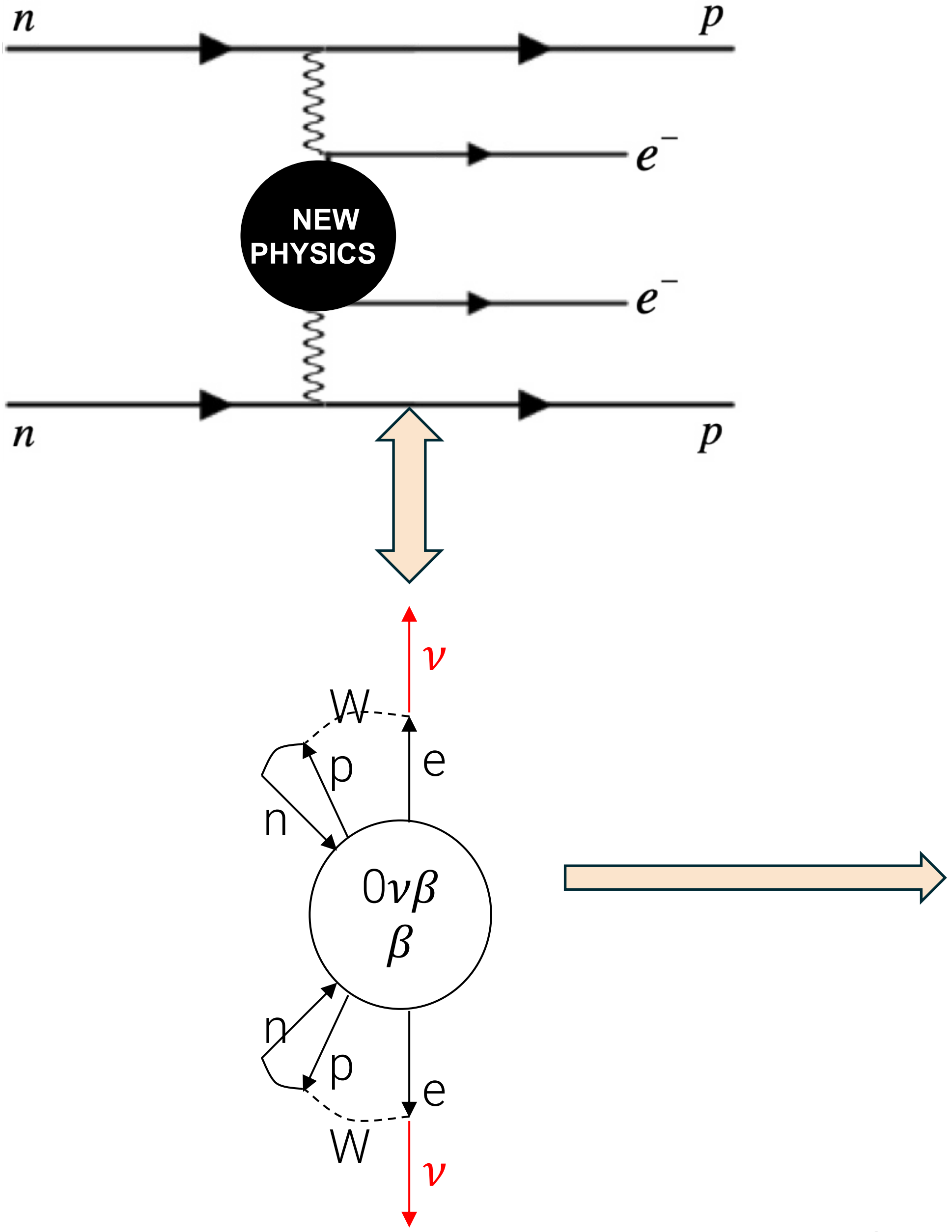
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
“Creation” of electrons

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

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





NME:
~~Nasty~~ Nuclear
Matrix
Element

phase space

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2\eta^2$$

LNV parameter

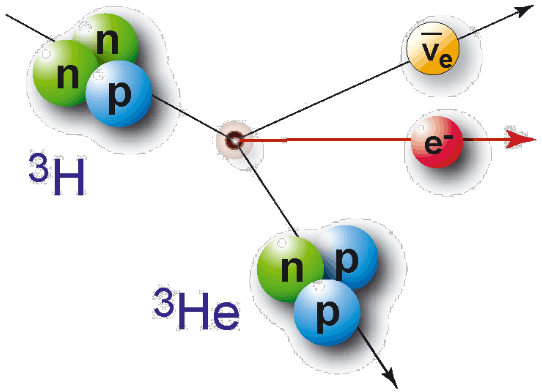
η can be due to $< m_{\beta\beta} >$, $V + A$, Majoron, SUSY, *H*--, leptoquarks *<u>or a combination of them</u>*

Schechter and Valle, 1982:

Observation is <u>unambiguous evidence</u> for <u>non-zero Majorana mass</u> (even if it is not dominating mechanism)

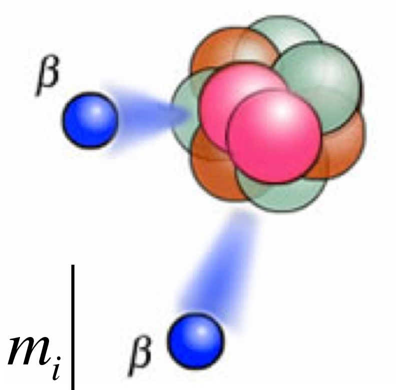
Different ways of measuring absolute neutrino mass

β-decay

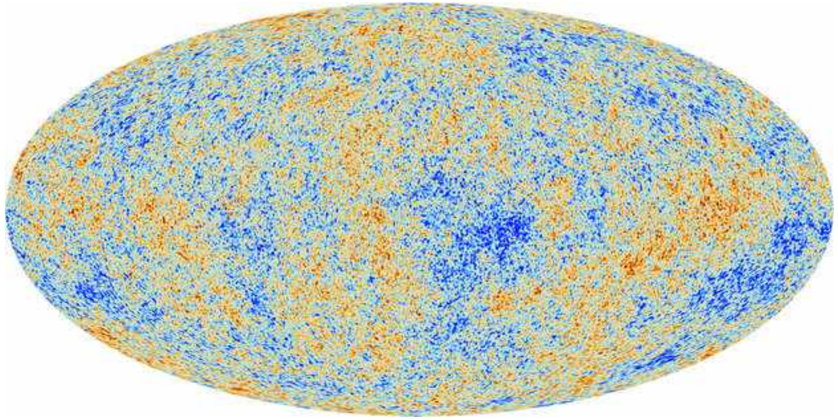


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

0νββ-decay



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



Cosmology

$$\sum_i m_i$$

Experimental Parameters

$$N_{0\nu\beta\beta} = \text{atoms} \cdot \text{time} / T_{1/2}$$

$$N_{0\nu\beta\beta} \gtrsim N_{\text{background}} = B \cdot \text{atoms} \cdot \text{time}$$

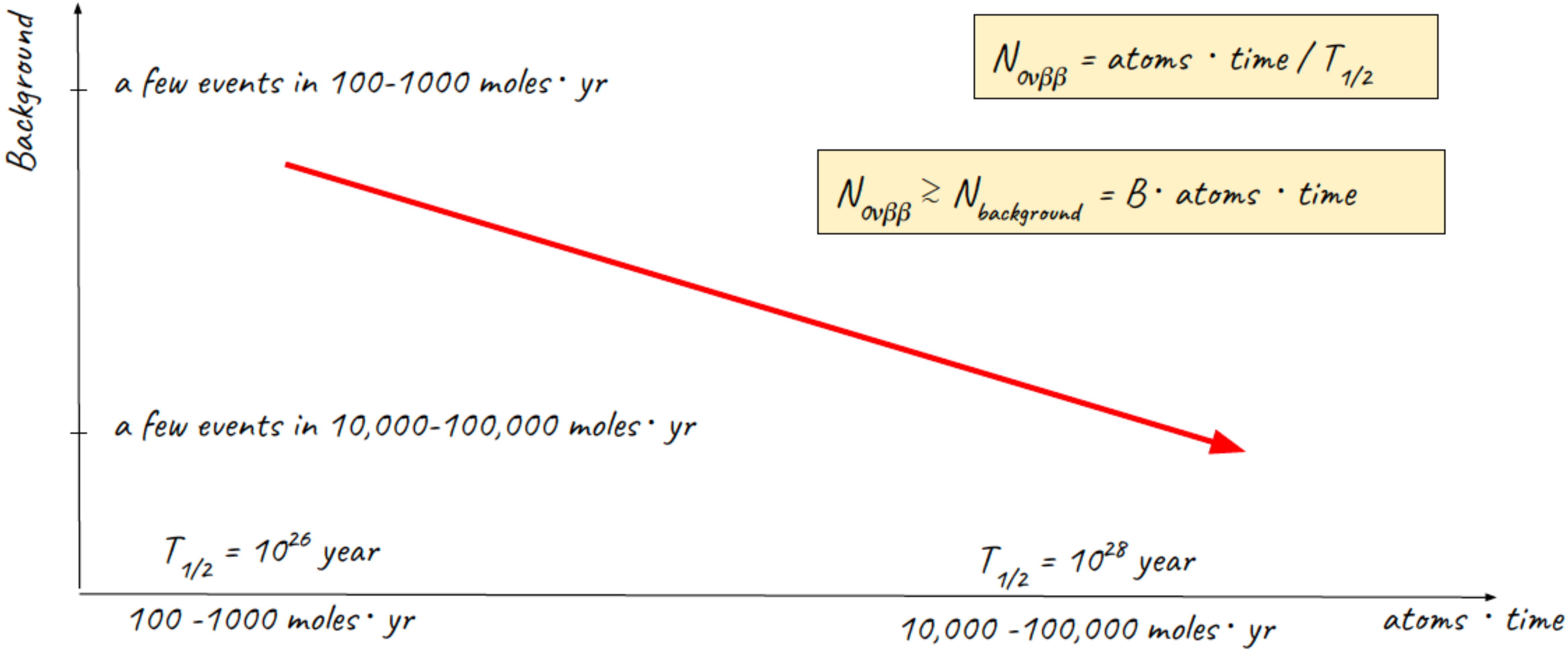
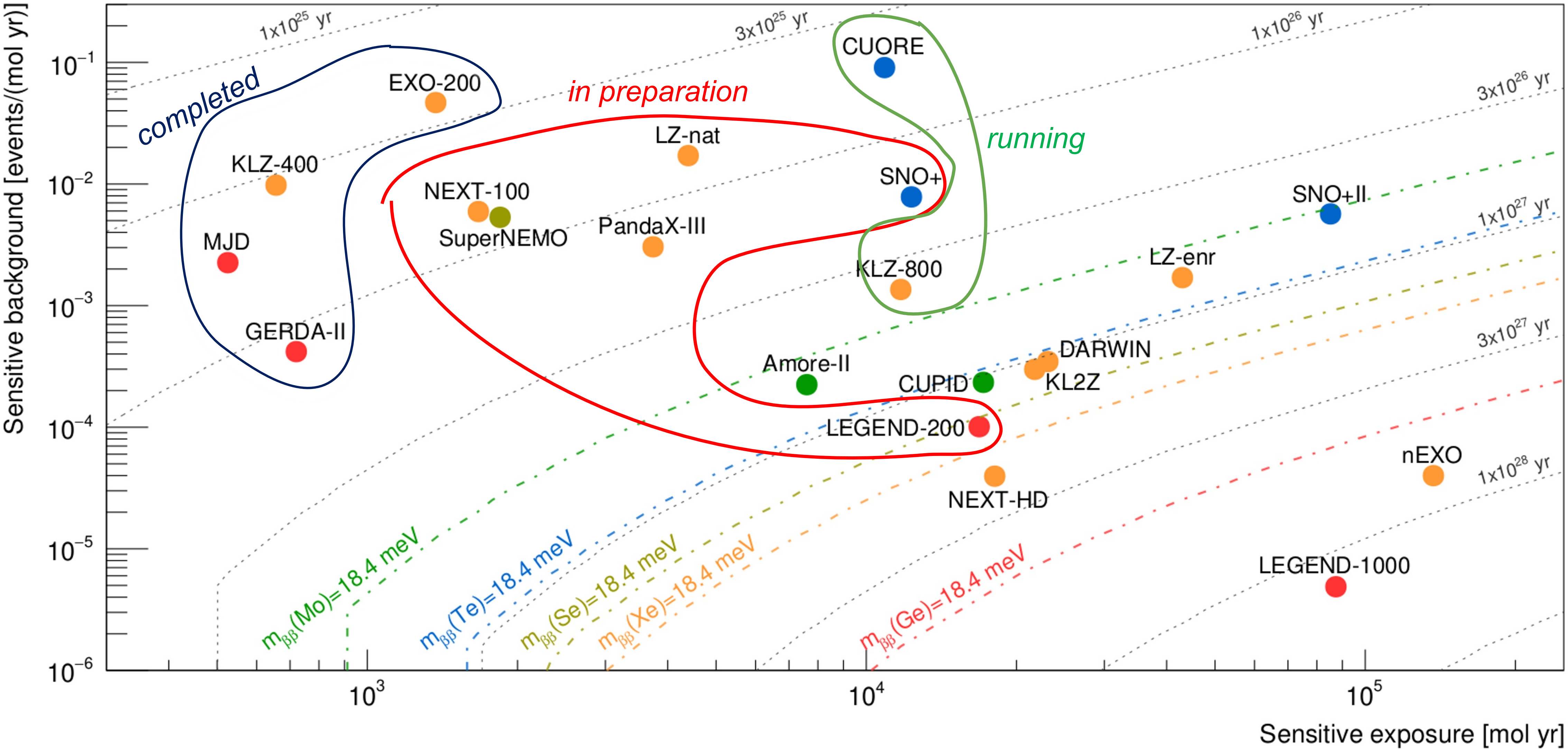


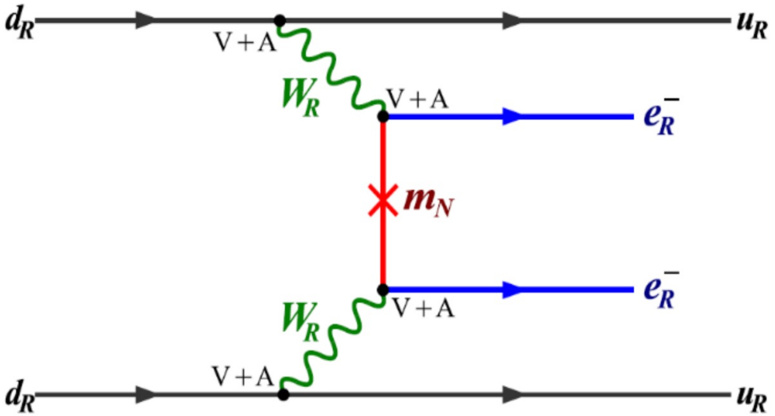
Image courtesy M. Agostini

Rev. Mod. Phys. 95 025002

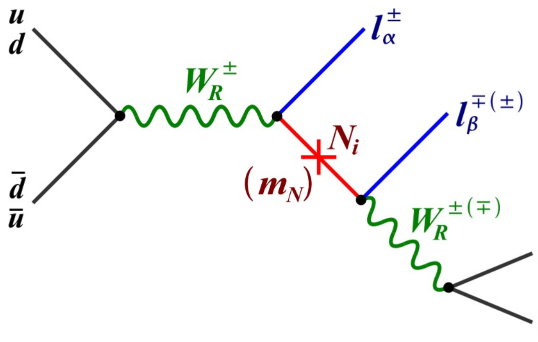


$0\nu\beta\beta$: Generic test for L-violating BSM physics

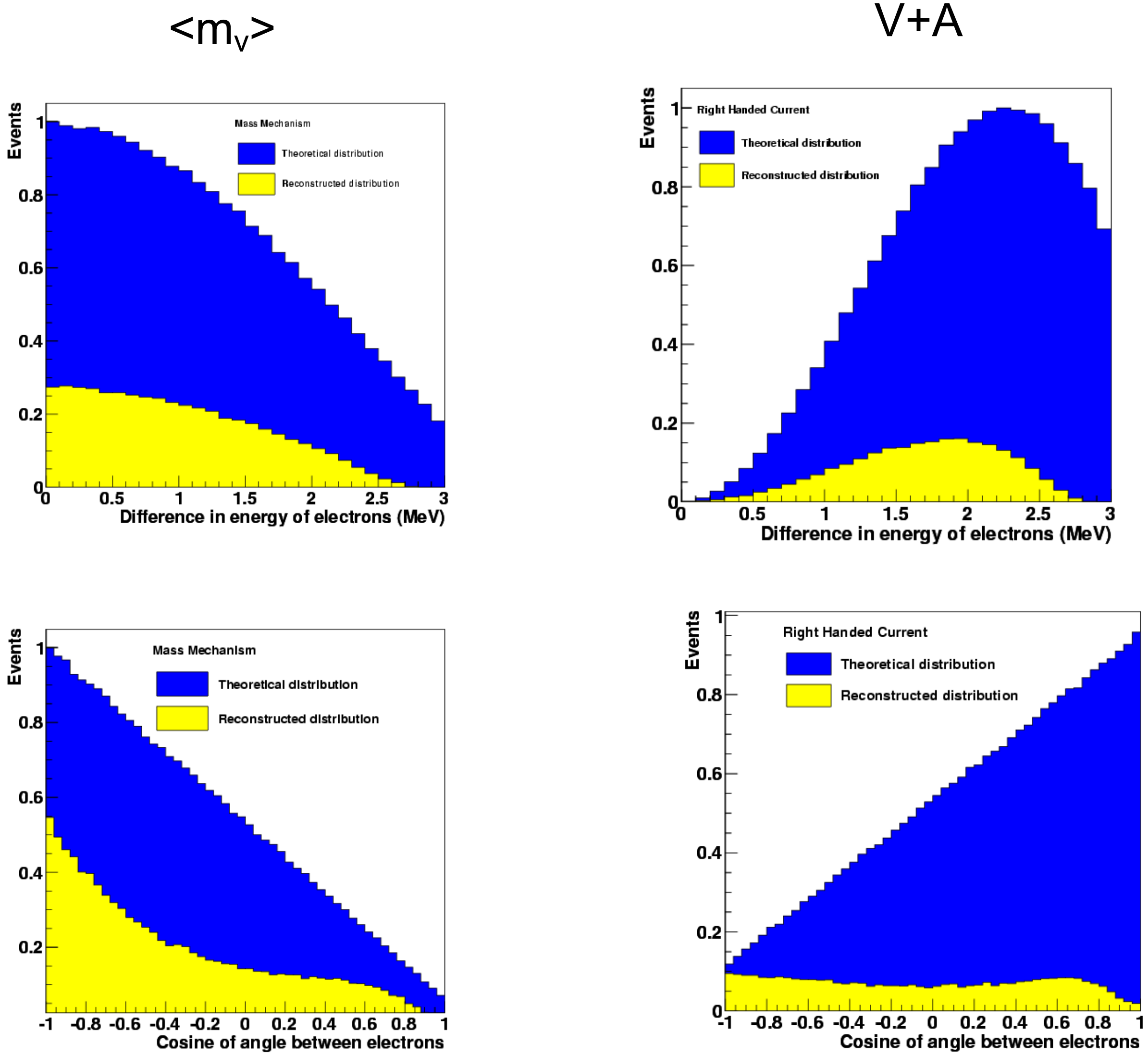
Example: Left-Right Symmetric models



Synergies with LHC searches



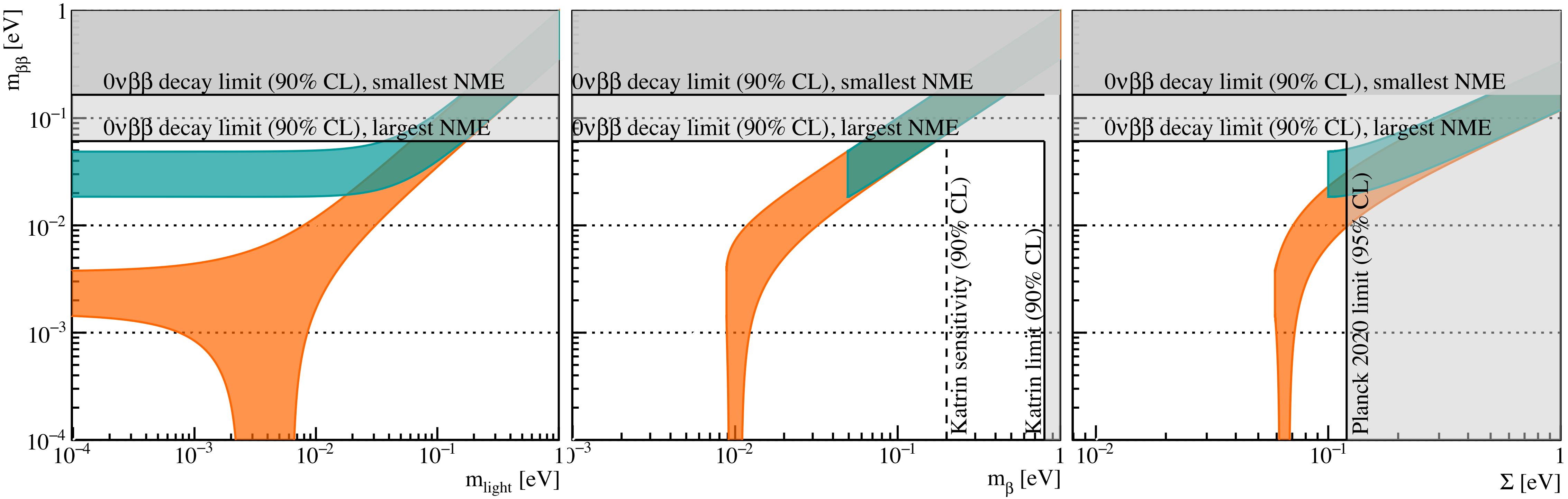
Deppisch, Graf, Iachello and Kotila Phys.Rev.D 102 (2020) 9, 095016



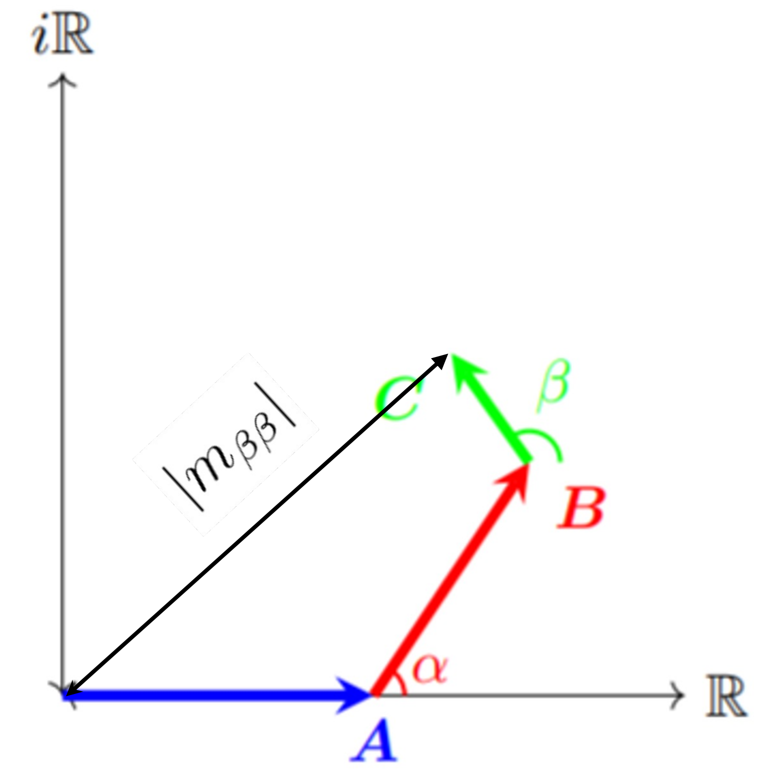
SuperNEMO Collaboration EPJ C (2010) 70, pp. 972-943.

Interplay between different neutrino mass measurements

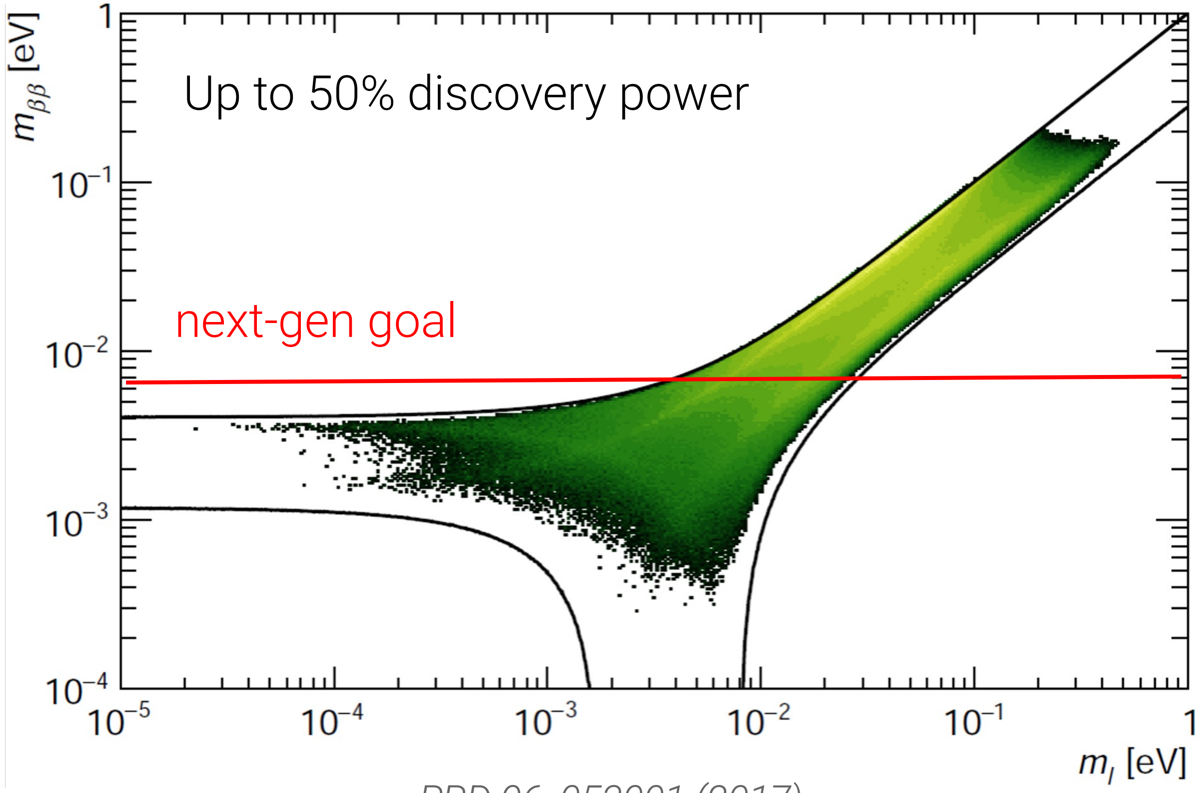
<u>*Rev. Mod. Phys. 95 025002*</u>



$$|m_{\beta\beta}| = \left|\overset{A}{c_{12}^2\, c_{13}^2\, m_1} + \overset{B}{s_{12}^2\, c_{13}^2\, m_2}\, e^{i2\alpha} + \overset{C}{s_{13}^2\, m_3}\, e^{i2\beta}\right|$$

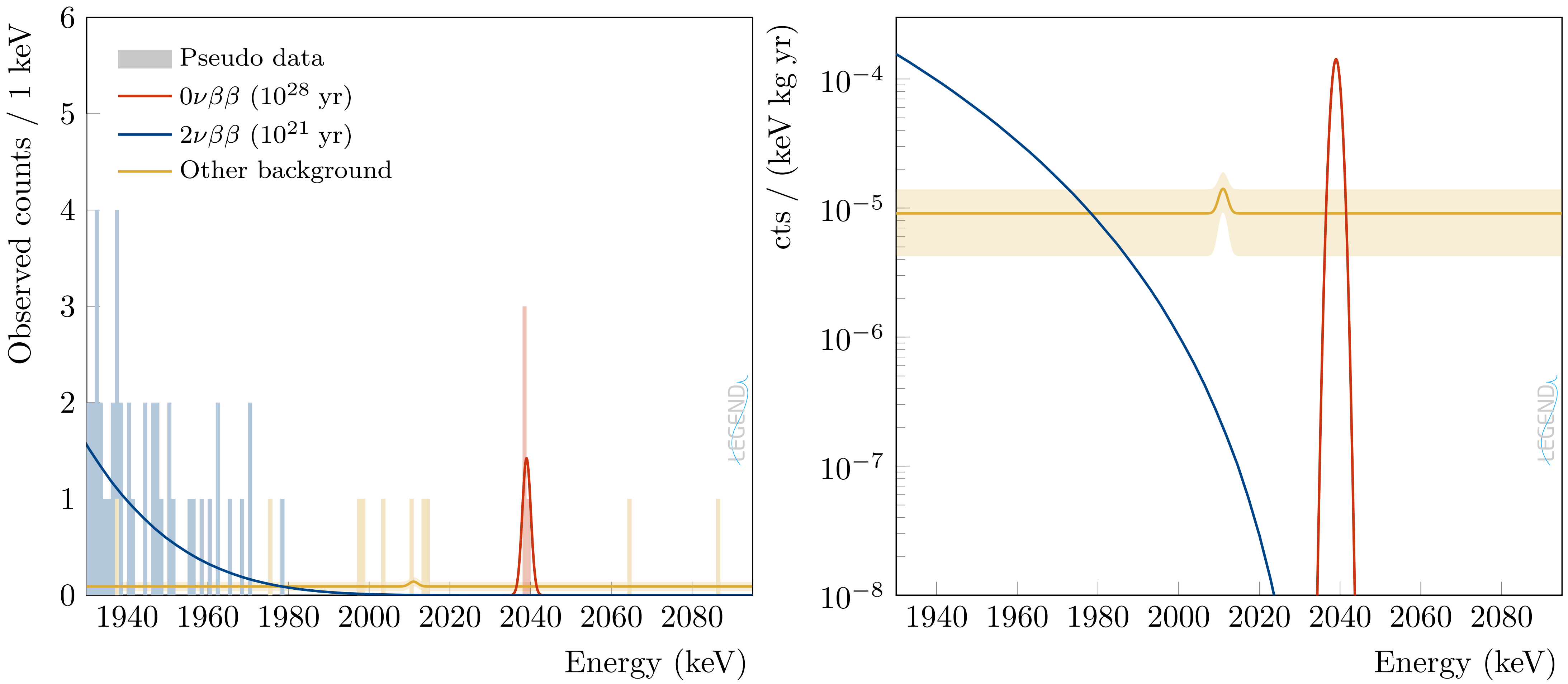


Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.

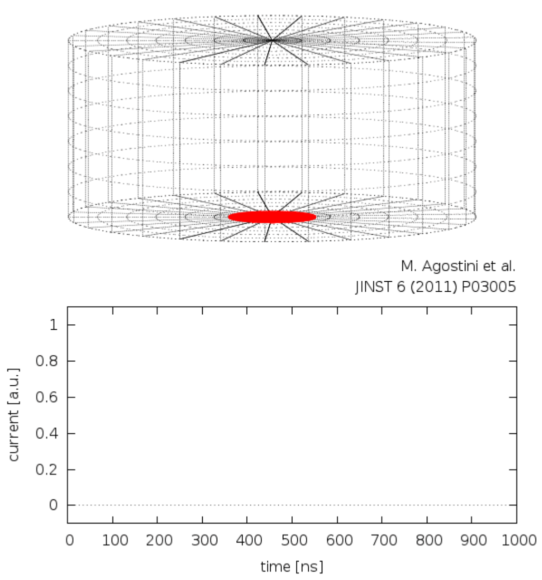


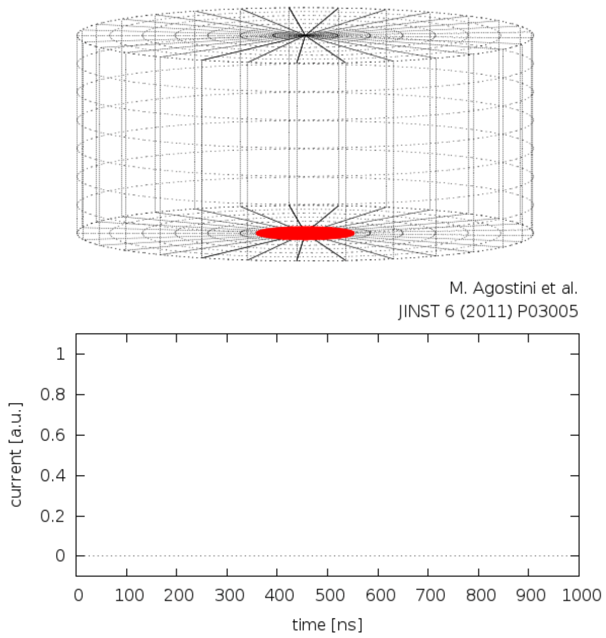
PRD 96, 053001 (2017)

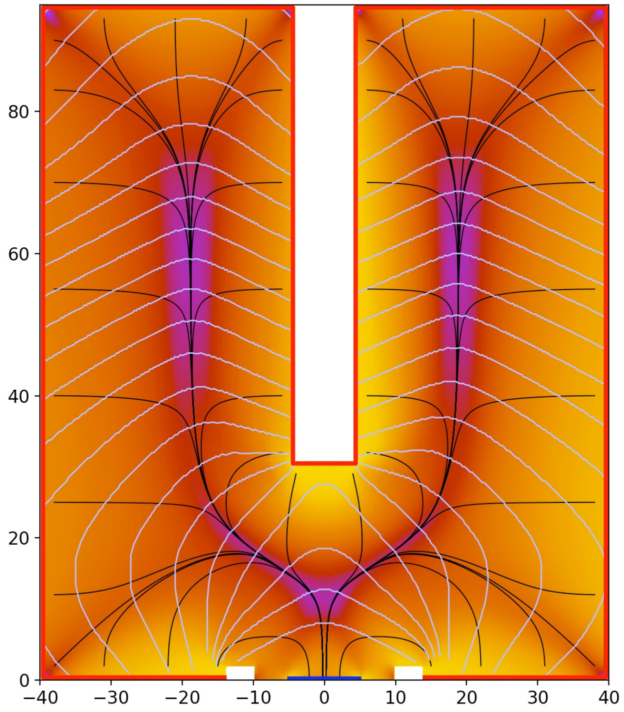
LEGEND 10 t.yr exposure



HPGe point-like detectors


M. Agostini et al.
JINST 6 (2011) P03005


M. Agostini et al.
JINST 6 (2011) P03005



Inverted **C**oaxial **P**oint **C**ontact

- Source = Detector: HP^{76}Ge
- Superb energy resolution ~0.1% at Q_{bb} = 2039 keV
- "Solid state TPC" capabilities: particle ID and background rejection
- Feasibility to reach zero BG regime

{ GERDA, Majorana } → LEGEND-200 → LEGEND-1000