Search for Lepton Creation in Nuclear $\beta\beta$ Decays

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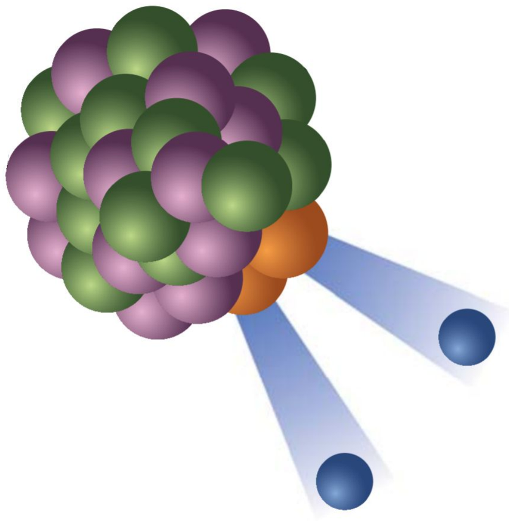
STFC Ernest Rutherford Fellow at UCL

Baryon and Lepton Number Violation (BLV2022)
Université Libre de Bruxelles (ULB), Sep 5-8 2022



Most of the material taken from
M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

UCL

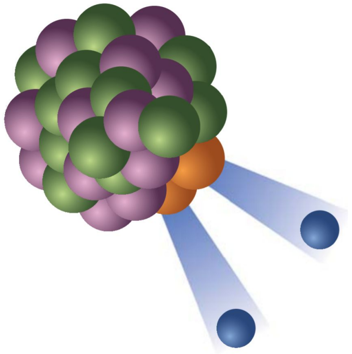
UKRI Science and Technology Facilities Council

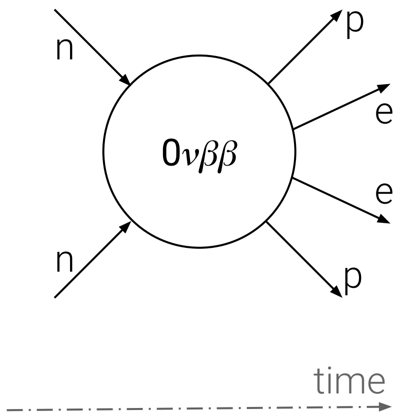
Introduction

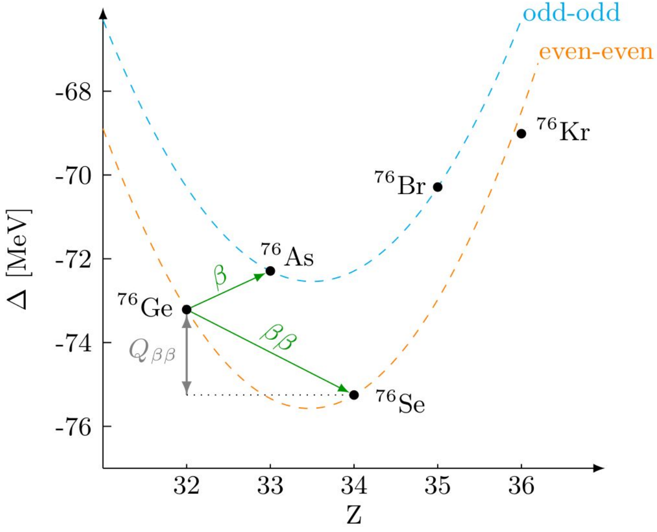
What are we searching for?

Nuclear decay: (A,Z) -> (A,Z+2) + 2

- 2 neutrons -> 2 protons ($\Delta B = 0$)
- 2 electrons are emitted ($\Delta L = 2$)







Direct violation of L and B-L

Possible only for a few isotopes

A bit of history

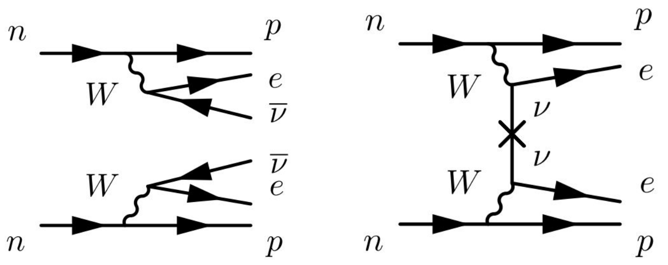
1935: Goeppert-Mayer → $\beta\beta$ decay

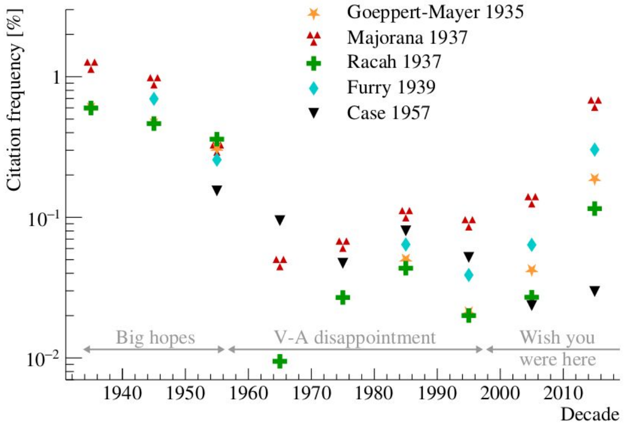
1937: Majorana and Racah → the neutrino is its own antiparticle

1939: Furry → “neutrinoless $\beta\beta$ decay” ($0\nu\beta\beta$)

1987: Moe’s → first observation of a $\beta\beta$ decay with neutrinos ($2\nu\beta\beta$)

2000: SNO/SK → discovery that neutrinos oscillate → are massive



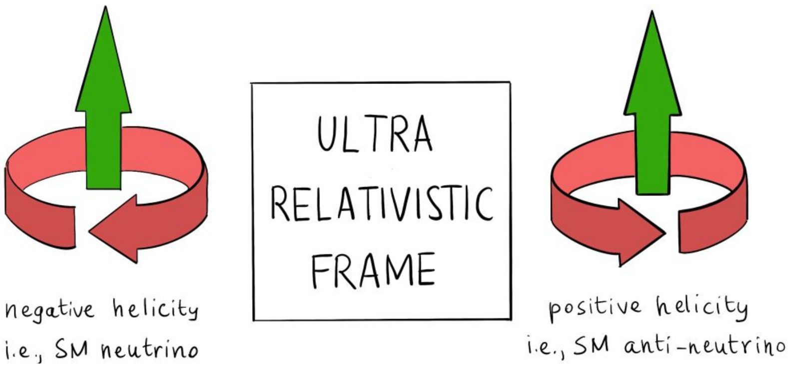


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

What distinguishes neutrinos from antineutrinos?

Phenomenological differences:

- they have opposite heilicity
- one interacts with particles, the other one with antiparticles (helicity=chirality)



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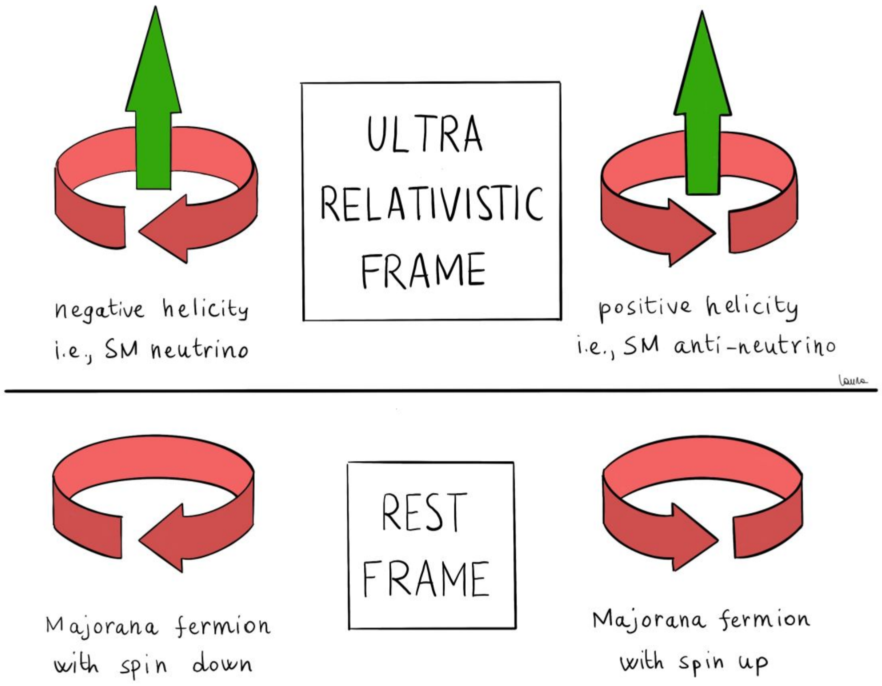
But if they are massive how do we distinguish them in their rest frame?

- need to introduce ad-hoc quantum number (for instance L)
- accept they are not different



helicity-flip probability prop to neutrino mass

arXiv:2202.01787 - Image courtesy of Laura Manenti

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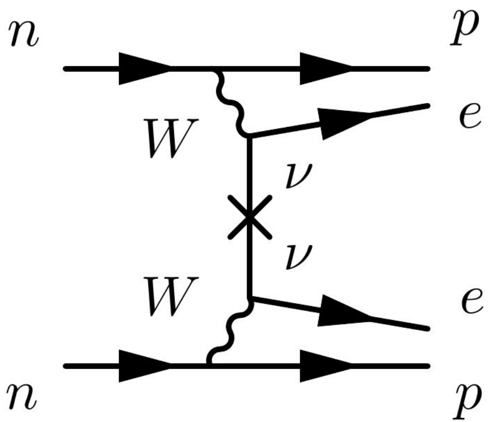
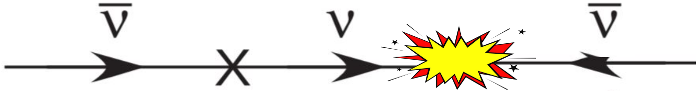


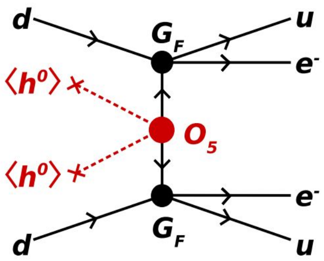


helicity-flip probability prop to neutrino mass

A portal to new physics beyond the SM

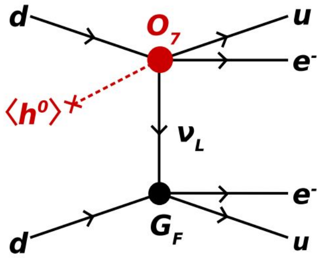
Dim 5: Weinberg Operator

$$P \propto \left(\frac{\nu}{\Lambda}\right)^2 \quad \text{with } \frac{\nu}{\Lambda} \propto m_{\beta\beta}$$



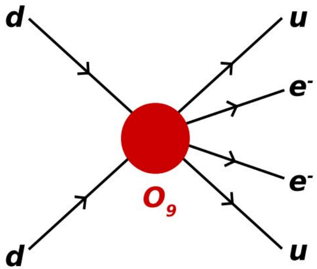
Dim 7

$$P \propto \left(\frac{\nu}{\Lambda}\right)^6$$



Dim 9

$$P \propto \left(\frac{\nu}{\Lambda}\right)^{10}$$



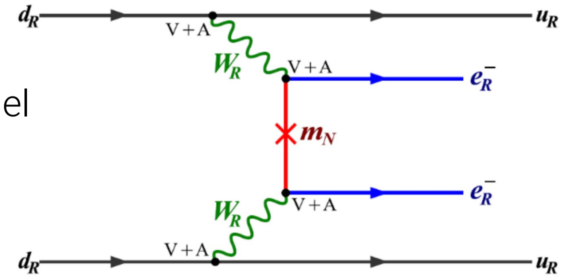
Cirigliano et al., JHEP 12, 097 (2018)

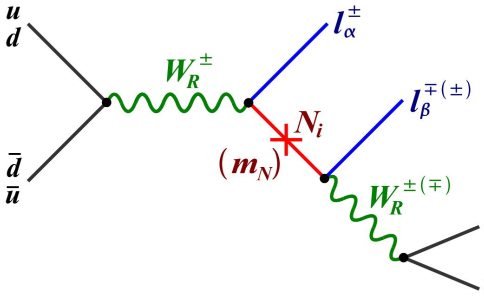
Deppisch, Graf, Iachello and Kotila Phys.Rev.D 102 (2020) 9, 095016

A generic search for ultrahigh-energy BSM physics

Example: left-right symmetry

$0\nu\beta\beta$ decay channel
(dim 9 operator)

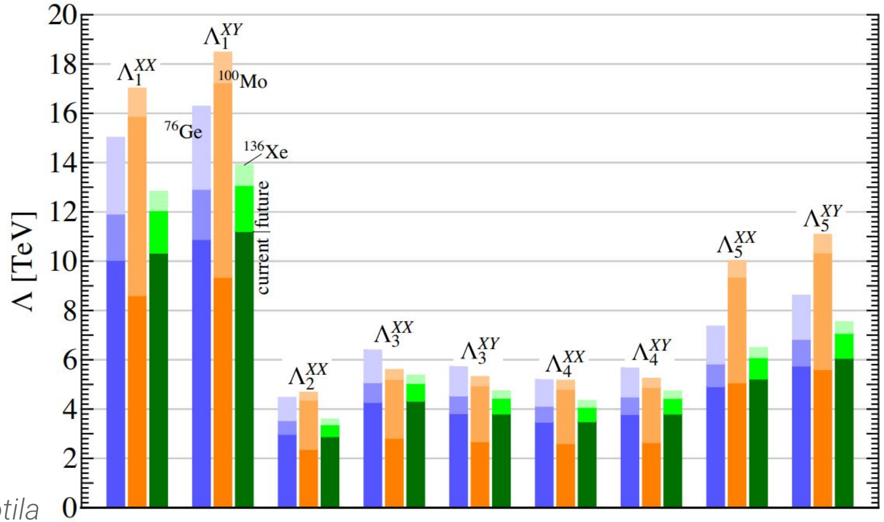




Same as dilepton signature at LHC

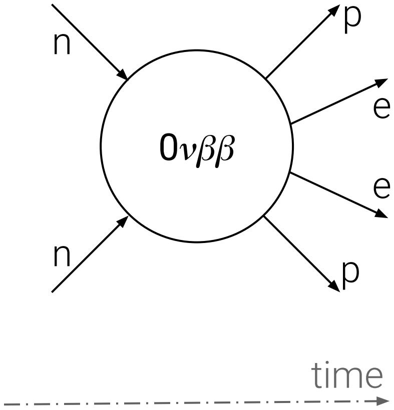
$0\nu\beta\beta$ and collider searches are complementary

Rate proportional to the energy scale, and a signal can manifest at any time!



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

What would we learn from a discovery?

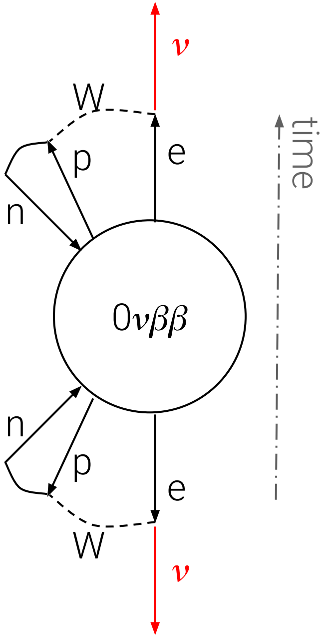


Same diagram

creates $\mathbf{\nu}\leftrightarrow\bar{\mathbf{\nu}}$

Schechter and Valle

1982



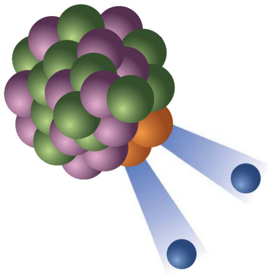
Direct violation of L and B-L

A tiny, but non-zero, neutrino-antineutrino conversion probability

Interplay with Neutrino Physics

How to connect the rate with particle physics?

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



phase space factor

hadronic matrix element

nuclear matrix element (NME)

Can be computed accurately

(even if sometime ***g*** is used to incorporate biases in NME calculations)

Requires calculations of :

- wavefunction overlap between initial and final states
- lepton-nucleus interaction

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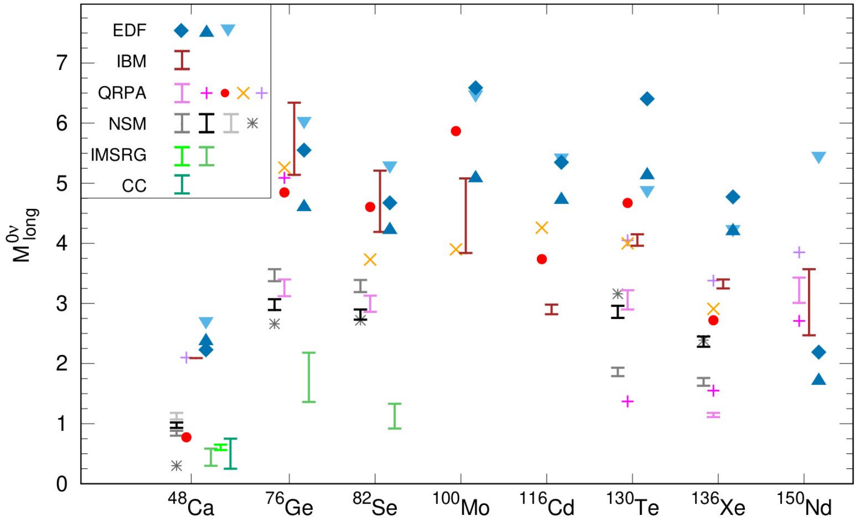

M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

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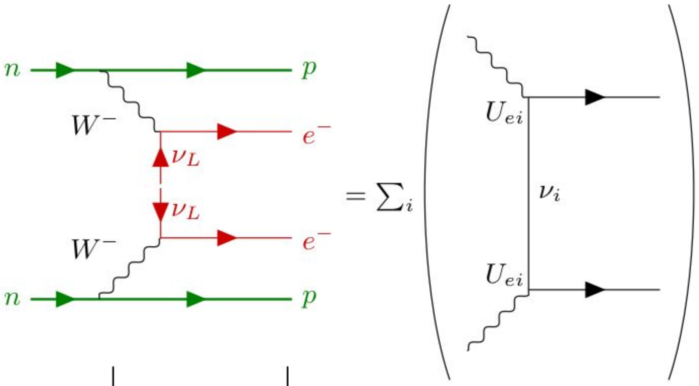
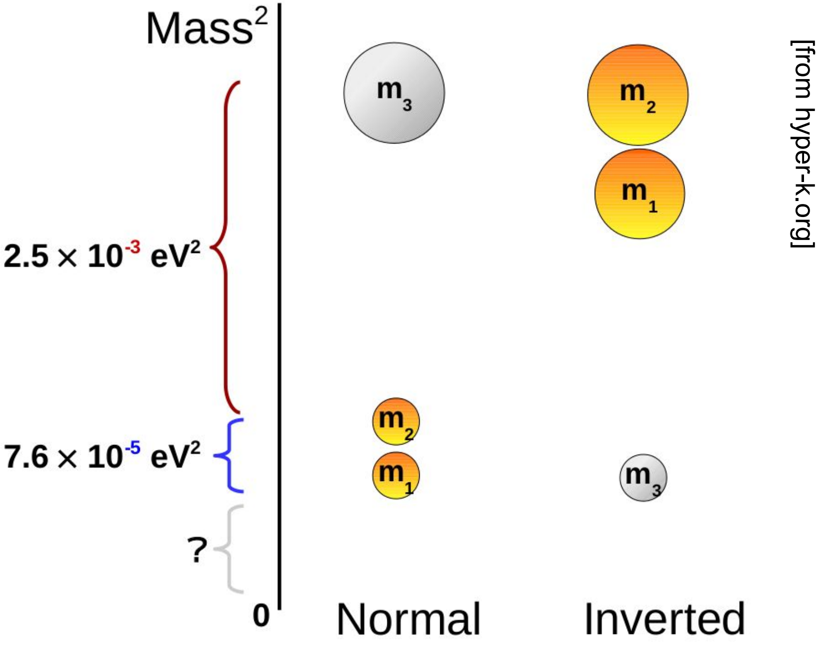
Light Majorana neutrino exchange

Parameter connected to neutrino mixing probabilities, masses and complex phases



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

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



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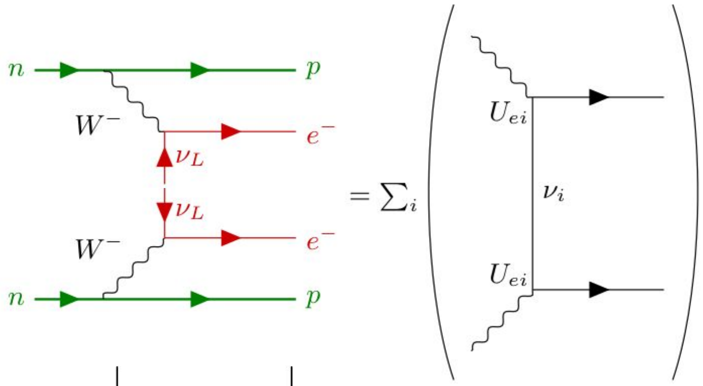

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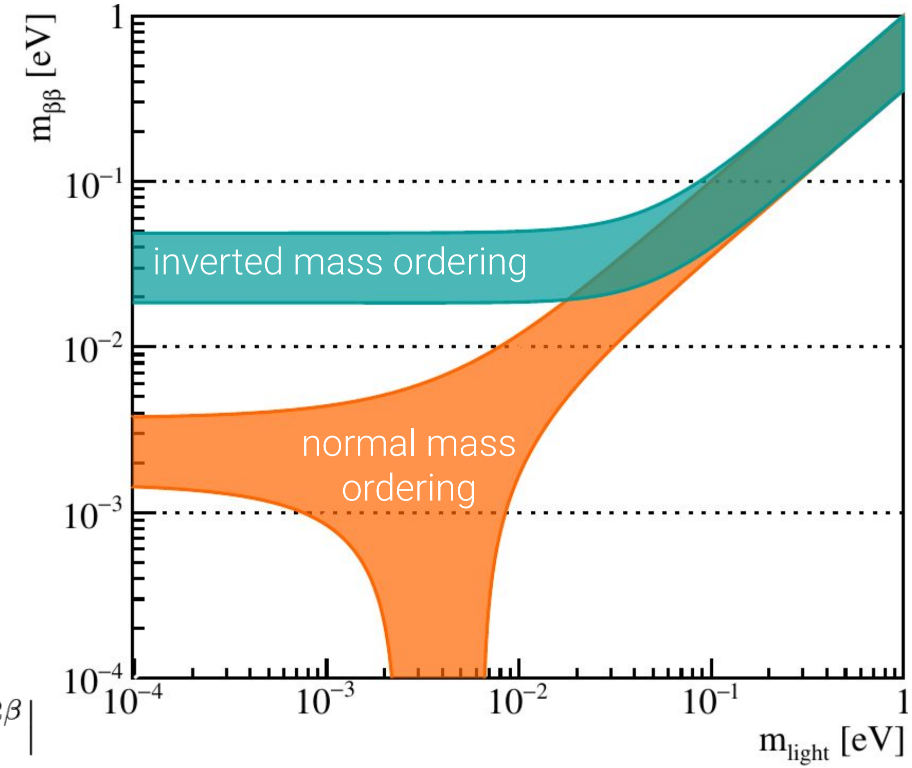
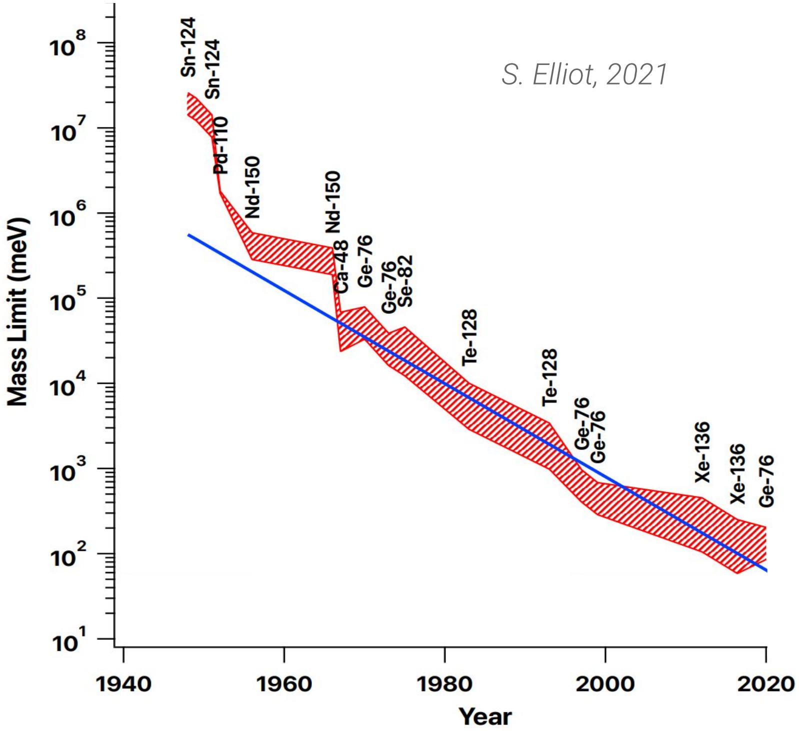
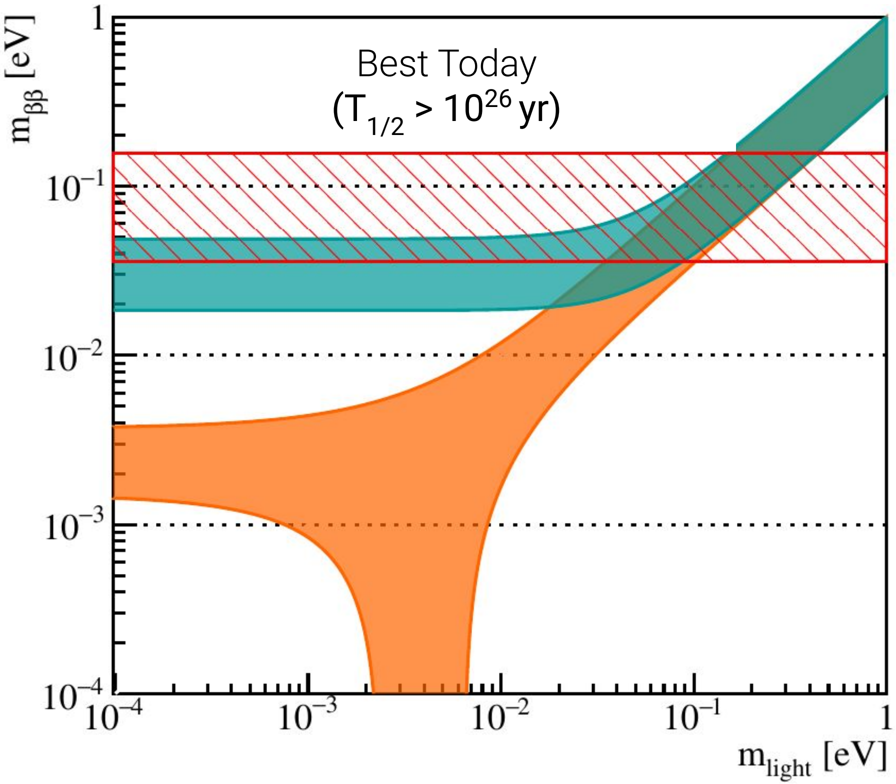
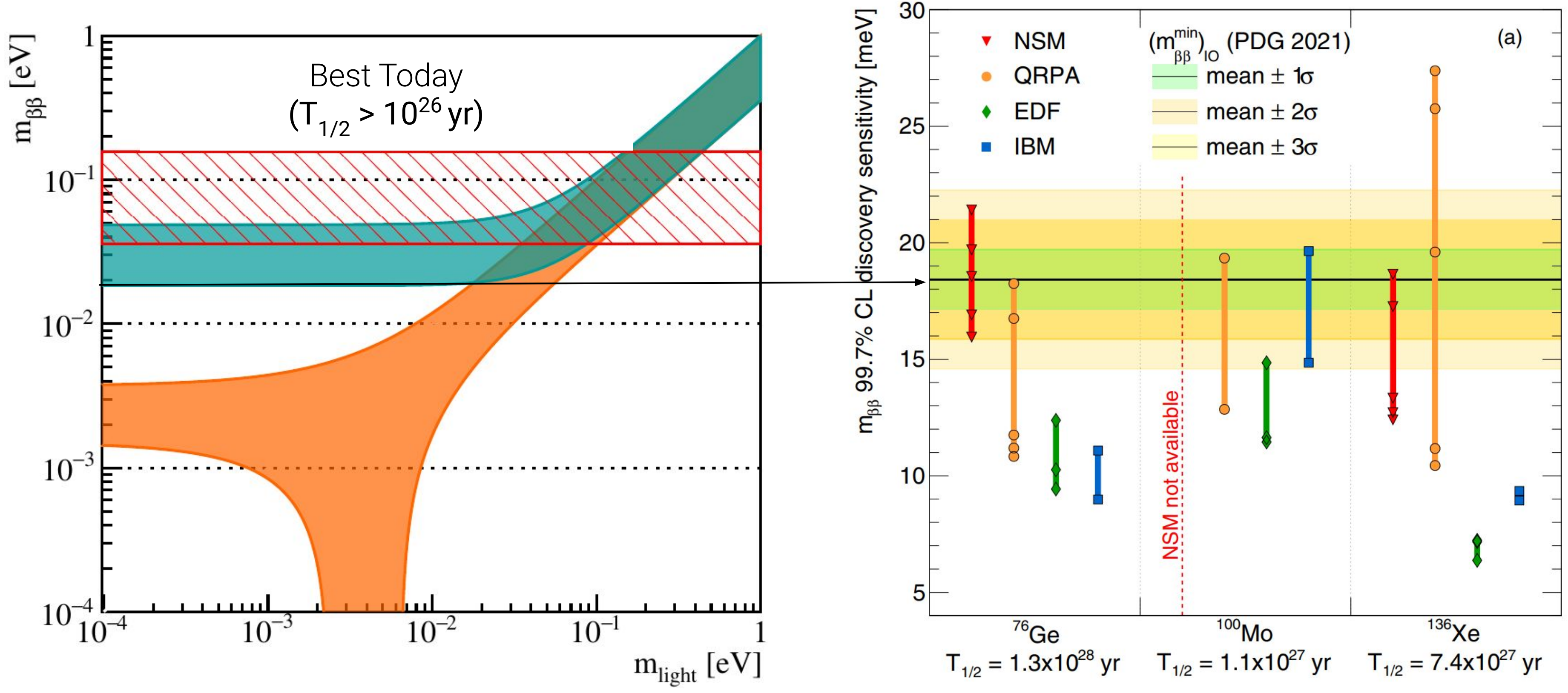


The experimental effort to date





Future discovery odds for **inverted** ordered neutrinos

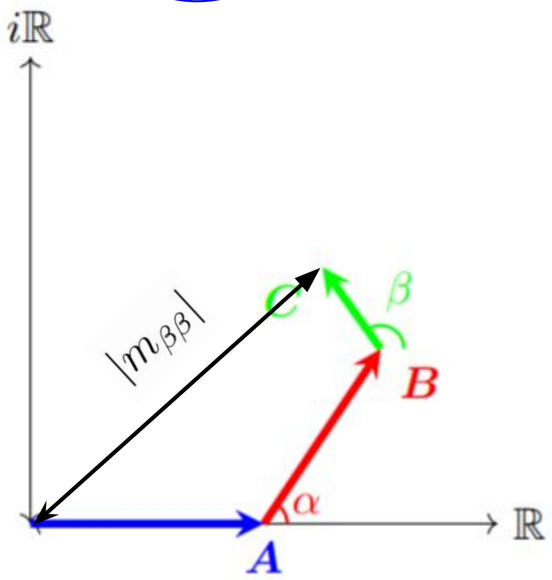


M.A., Benato, Detwiler, Menéndez and Vissani
PRC 104, L042501 (2021)

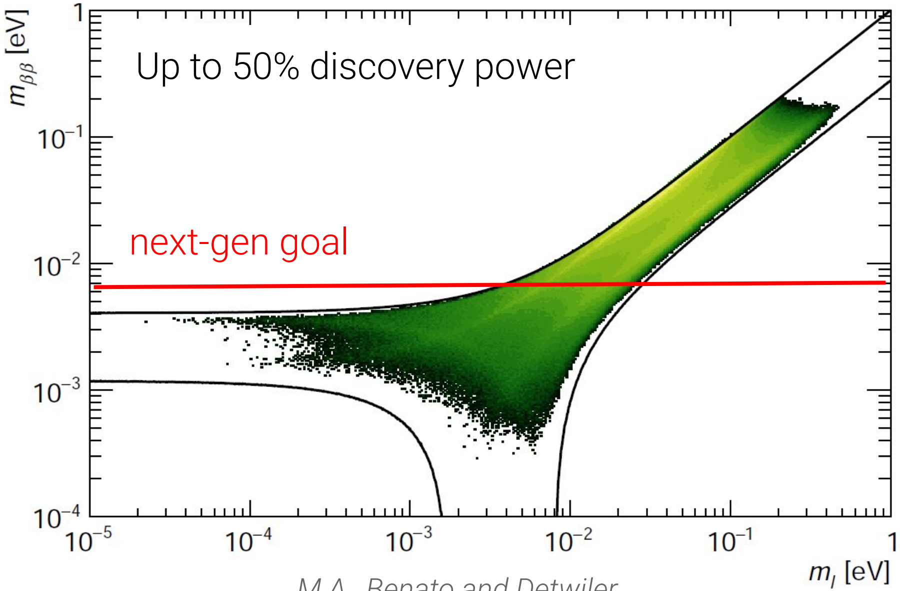
Future discovery odds for **normal** ordered neutrinos

A B C

$$|m_{\beta\beta}| = |c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}|$$



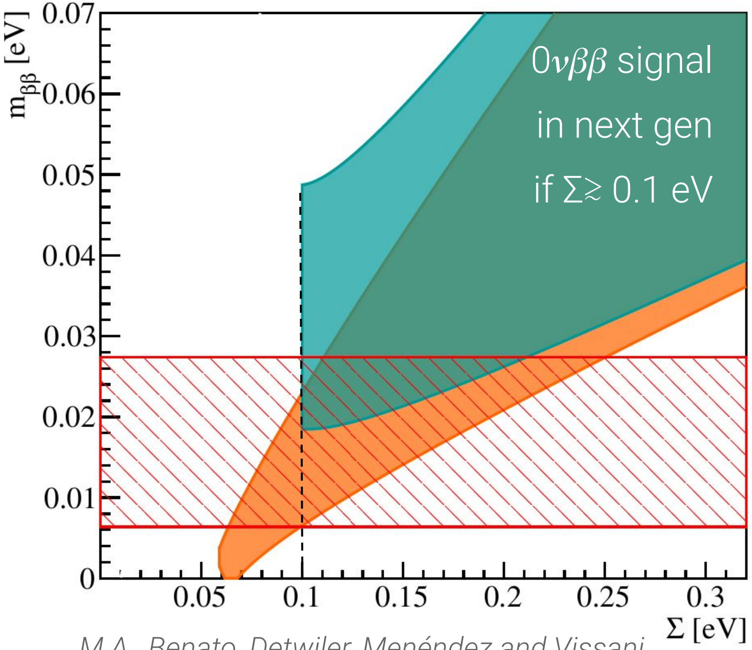
Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.



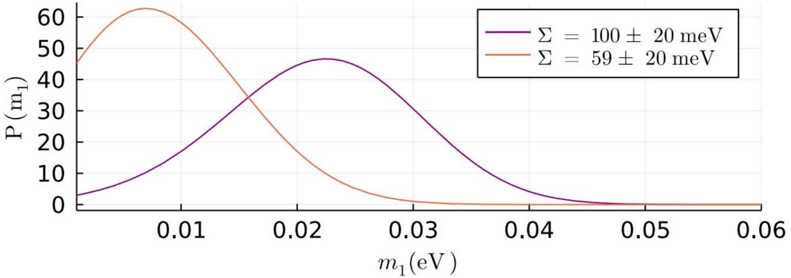
M.A., Benato and Detwiler PRD 96, 053001 (2017)

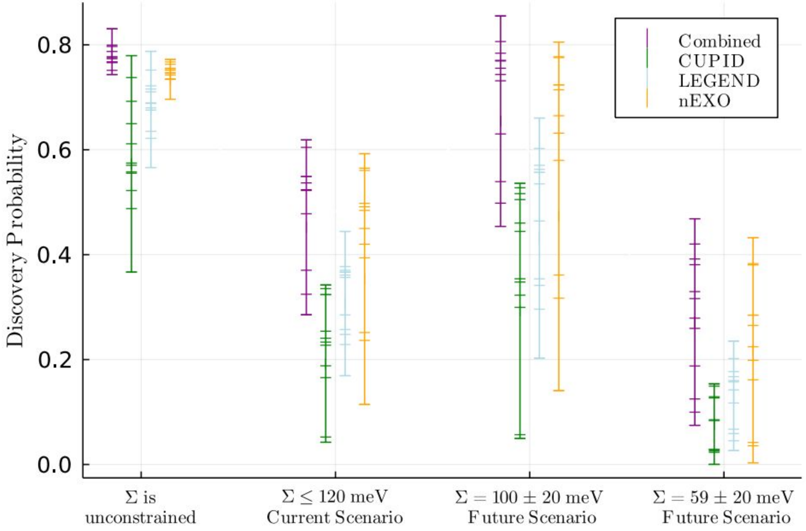
Interplay with Cosmology

Cosmology surveys (DESI/EUCLID) close to measure $\Sigma = \sum_i m_i$



M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787



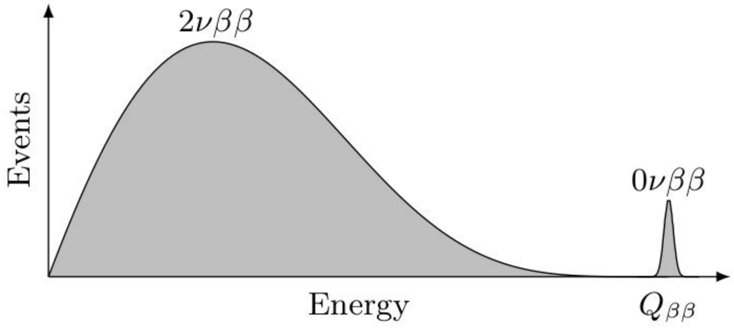


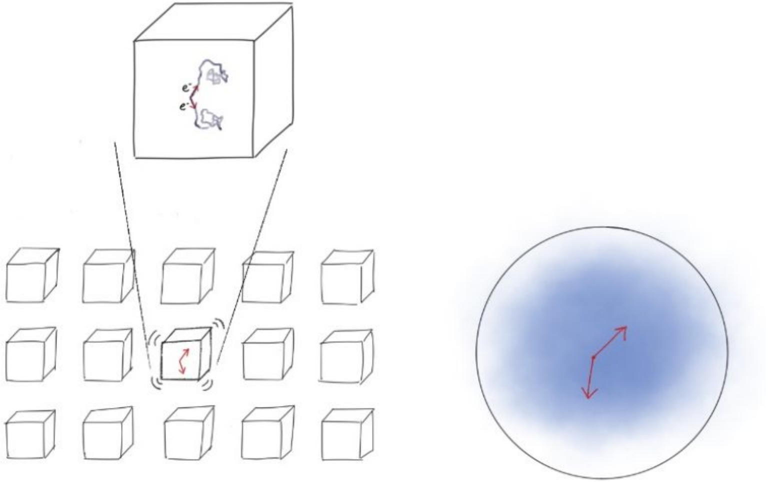
Ettengruber, M.A., Caldwell, Eller and Schulz 2208.09954

Experiments

Detection concepts

- calorimetric approach: source = detector
- solid state: pixelated detector
- liquid: monolithic self-shielding volume
- energy: primary and sufficient observable





arXiv:2202.01787 - Image courtesy of Laura Manenti

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 parameters

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

$T_{1/2} = 10^{26}$ year

100 - 1000 moles · yr

$T_{1/2} = 10^{28}$ year

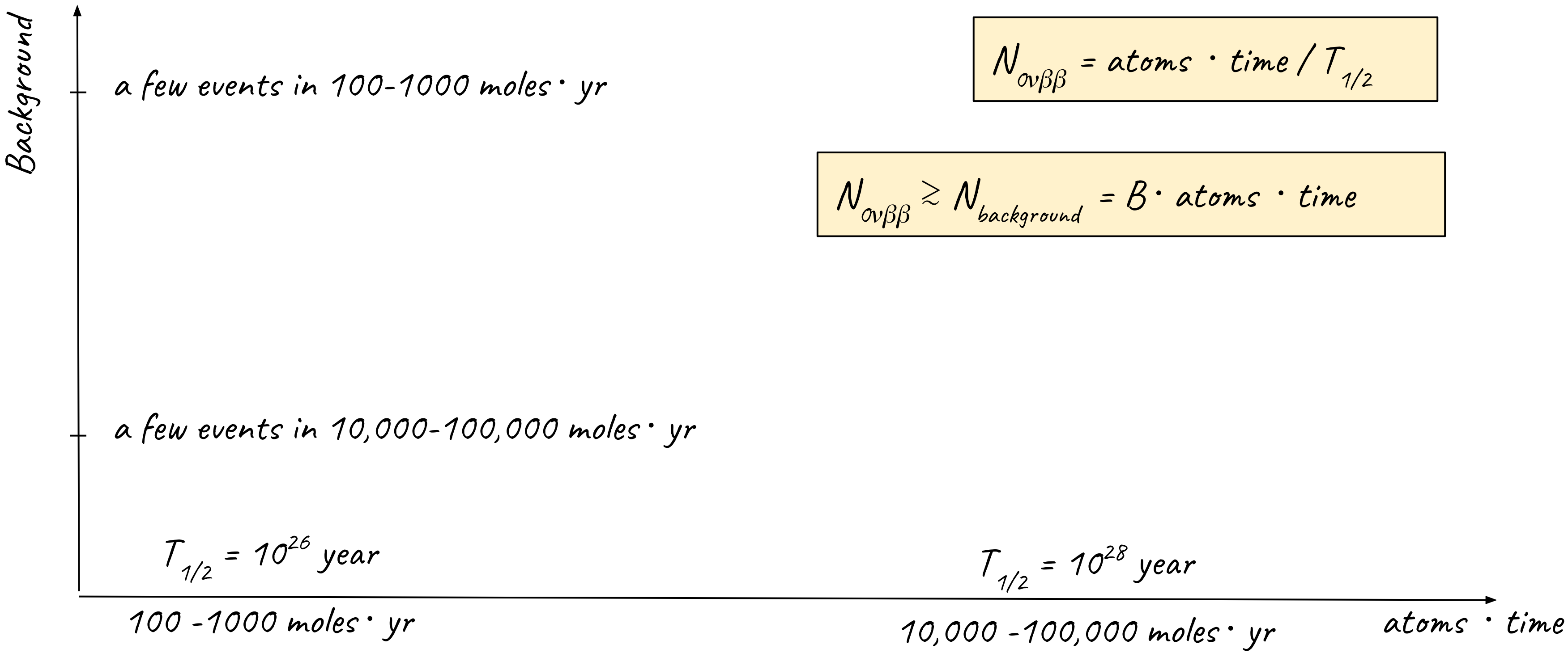
10,000 - 100,000 moles · yr

atoms · time

Experimental parameters

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

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



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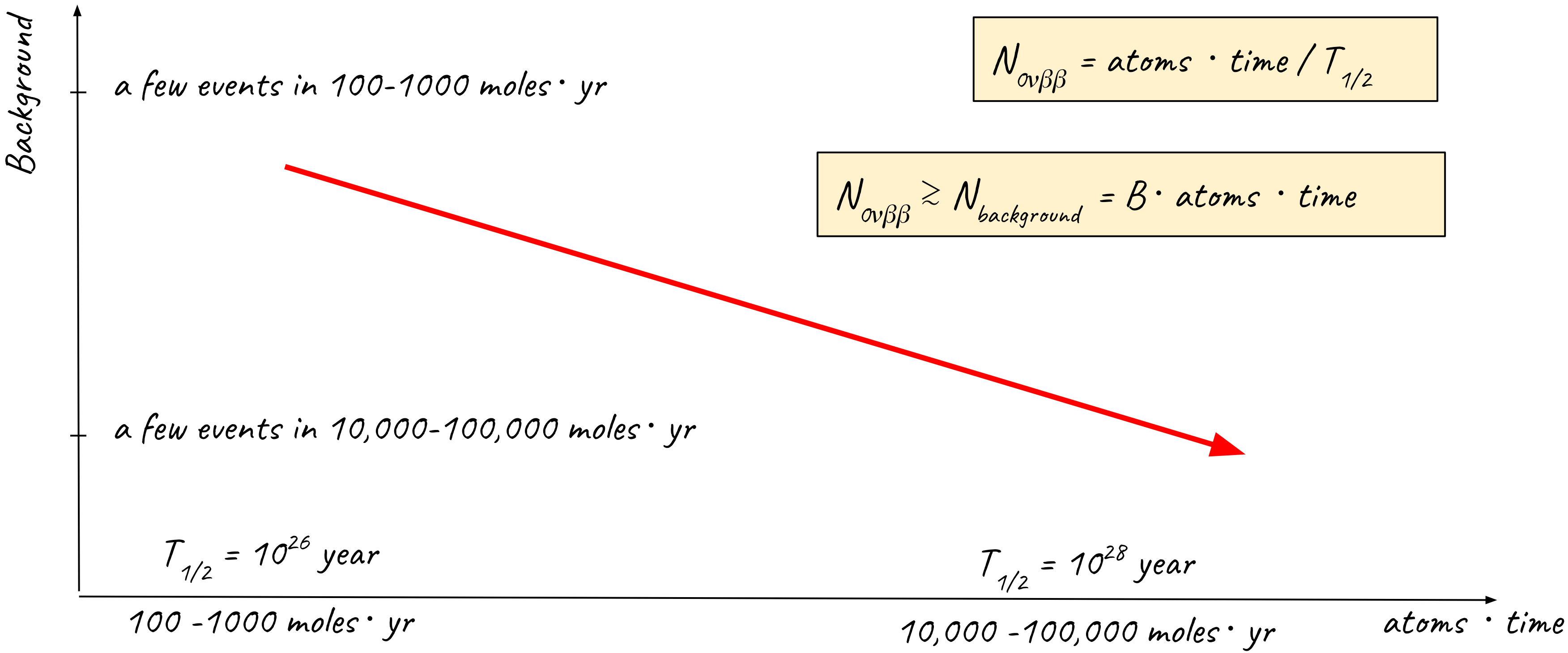
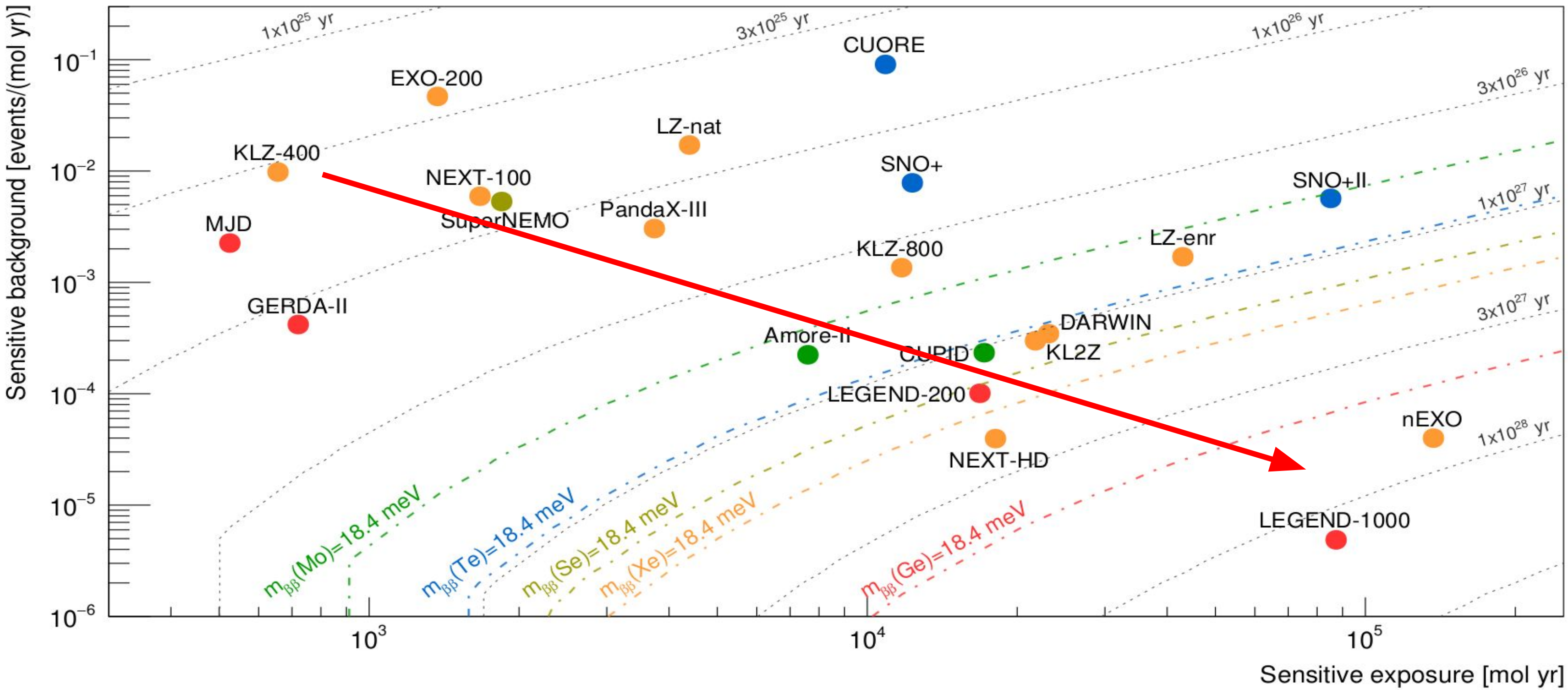


Recent and future experiments



M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

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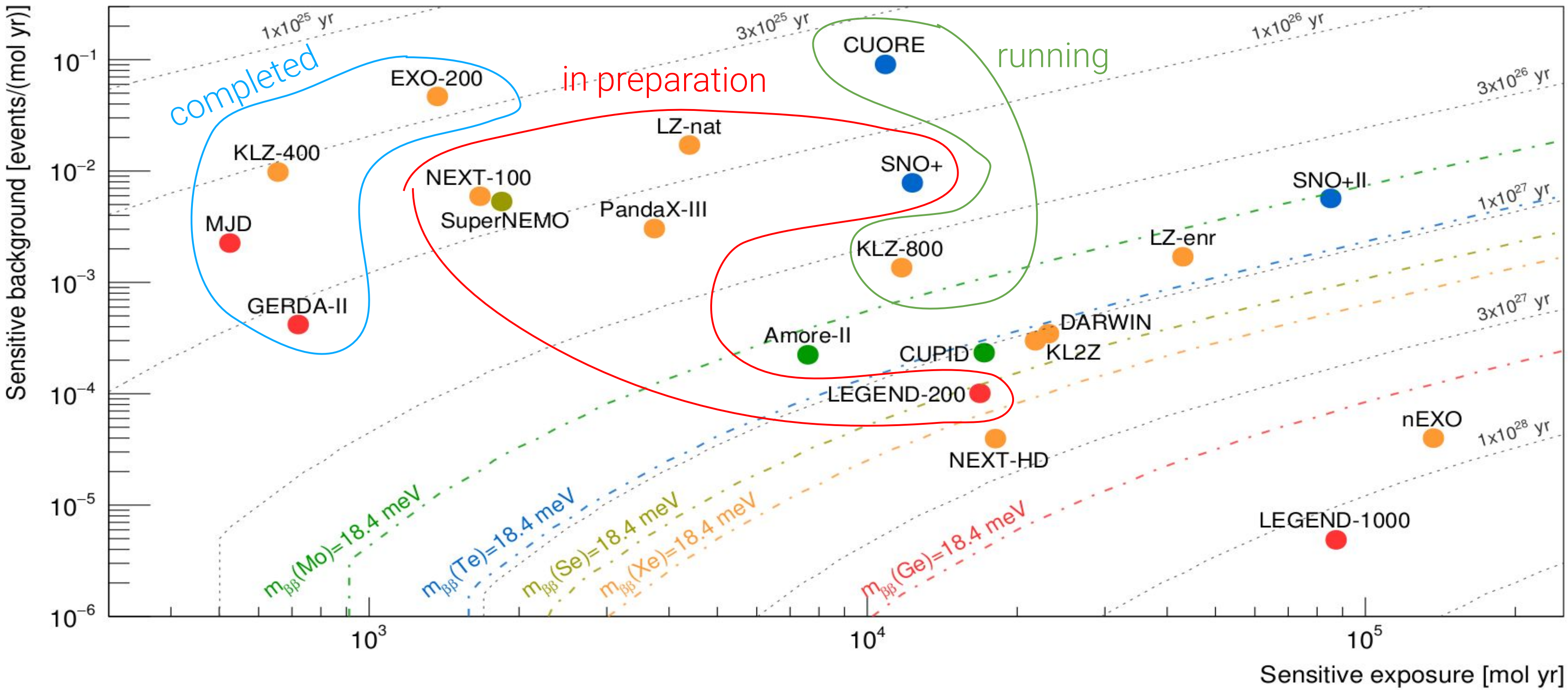
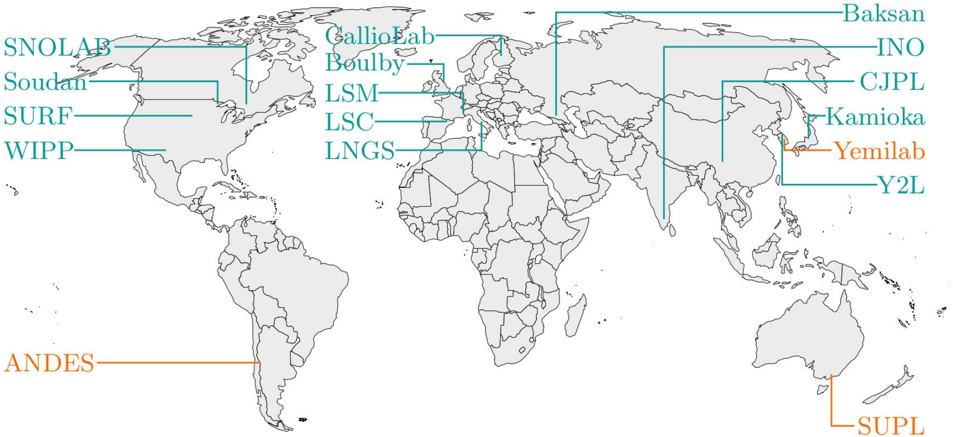


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Signal & Background



Tagging $0\nu\beta\beta$ decay events:

- two-electron summed energy = Q-value
- two-electron event topology
- (excited states/daughter isotope)

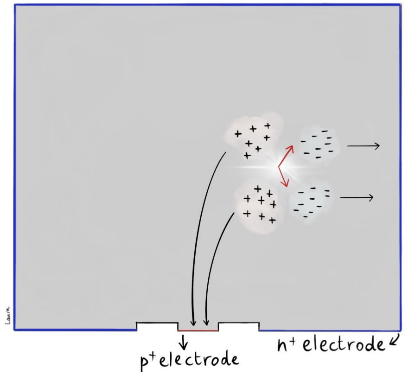
Backgrounds:

- cosmic-ray induced
- ^{238}U/^{228}Th decay chains
- neutrons
- solar neutrinos
- $2\nu\beta\beta$ decay (only irreducible background)

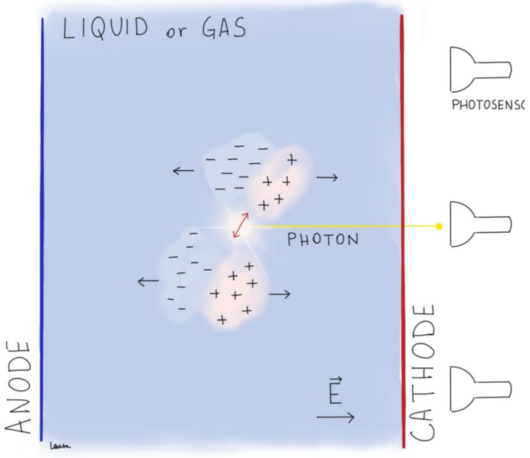
Mitigation

- underground laboratory
- material selection
- shielding strategy
- multivariate analysis
- energy tagging (only way to mitigate 2vbb)

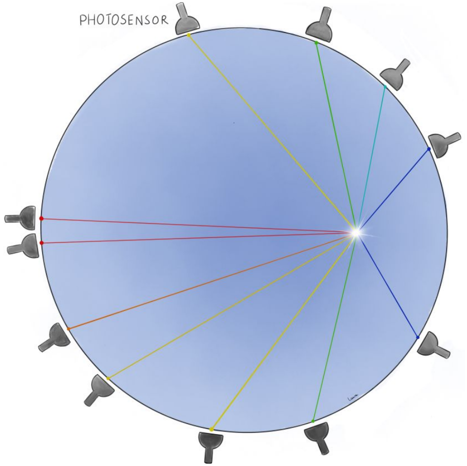
The most sensitive technologies



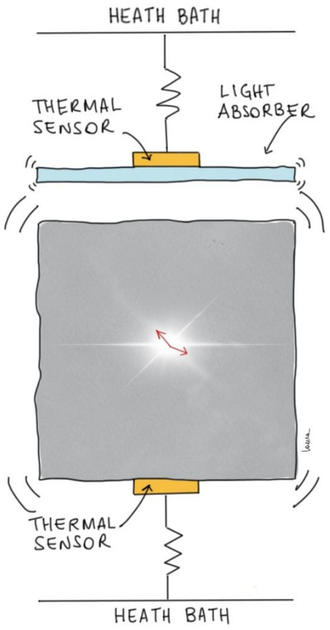
Ge Semiconductor detectors (^{76}Ge)



Xe Time Projection Chambers (^{136}Xe)



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



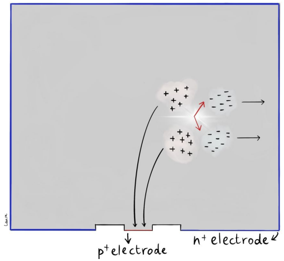
Cryogenic Calorimeters (^{100}Mo, ^{30}Te)

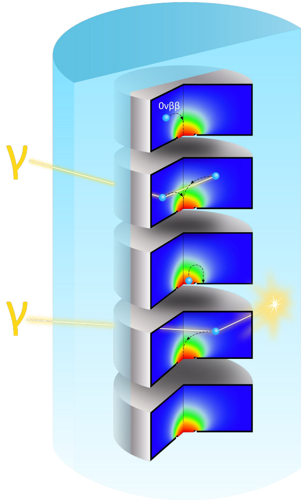
arXiv:2202.01787 - Image courtesy of Laura Manenti

Ge semiconductor detectors

high-purity ^{76}Ge detectors

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





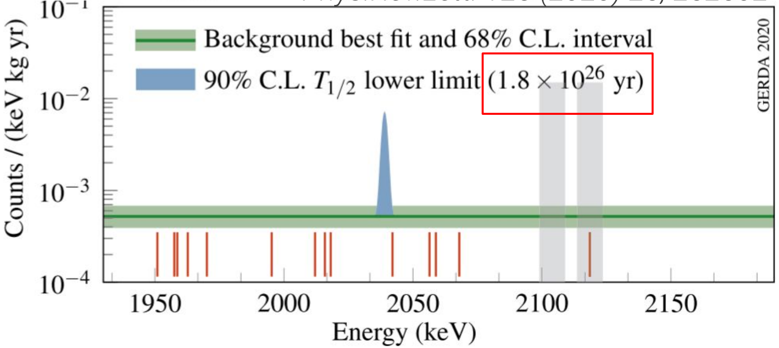
liquid Ar detector

- shield and scintillation light

Staged approach:

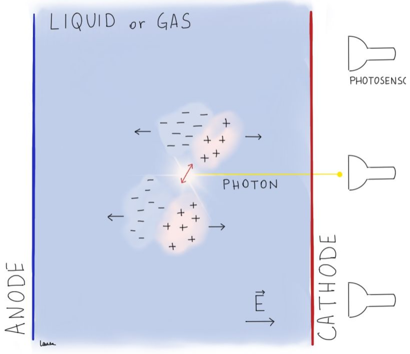
- **GERDA/MAJORANA** Demonstrator (40 kg)
- **LEGEND-200** under commissioning (200 kg)
- **LEGEND-1000** conceptual design in preparation (1 t)

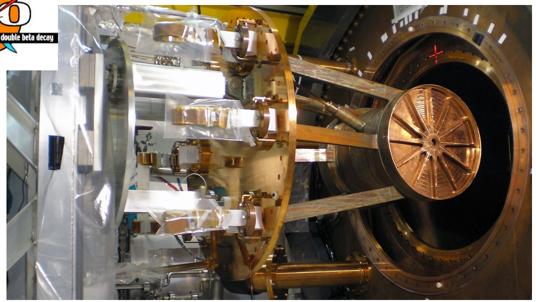
Phys.Rev.Lett. 125 (2020) 25, 252502



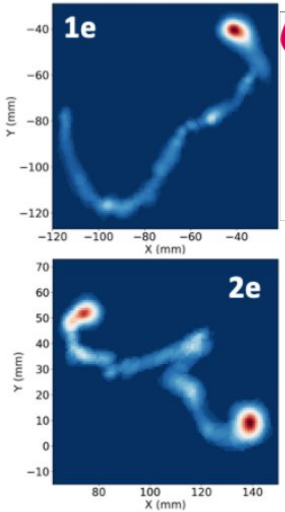
Xe time projection chambers

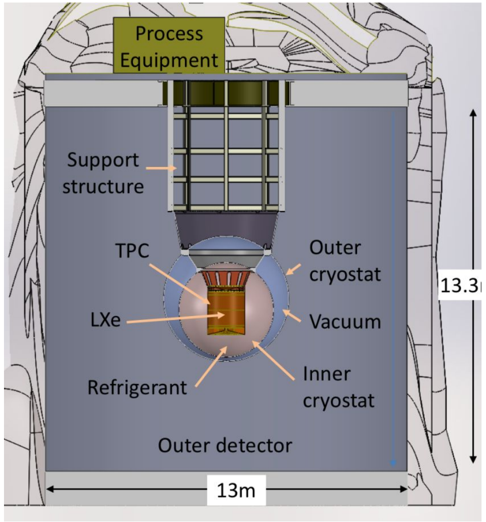
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope





Experiment	m_{tot} [kg]	$f_{\text{enr.}}$ [%]	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

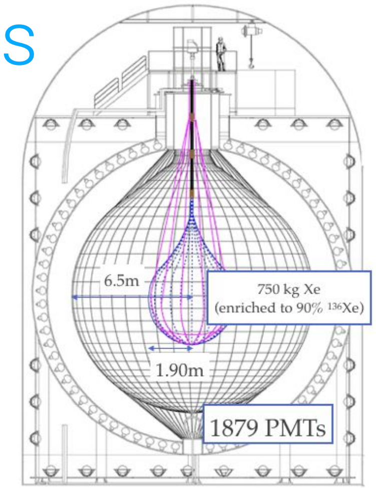


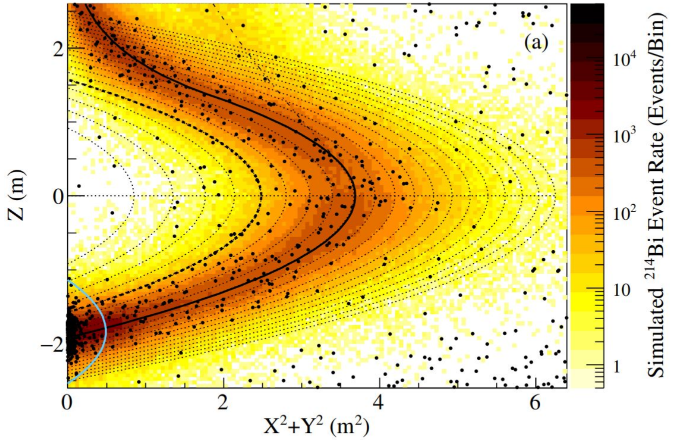


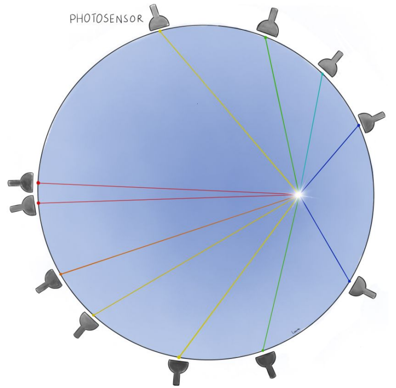
Large liquid scintillators

KZ collaboration, 2203.02139

- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization



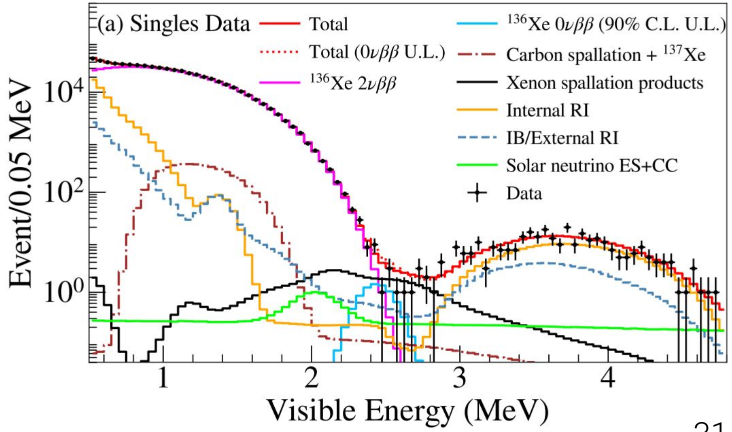




KamLAND-Zen-800 @Kamioka

- 750 kg of enriched Xe in nylon balloon
- backgrounds: $2\nu\beta\beta$, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- next phase: improved resolution and purer scintillator

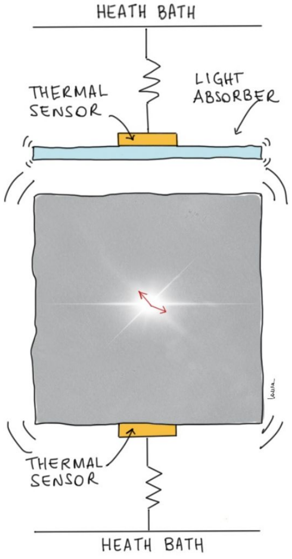
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at 90\% C.L.}$$



Cryogenic calorimeters

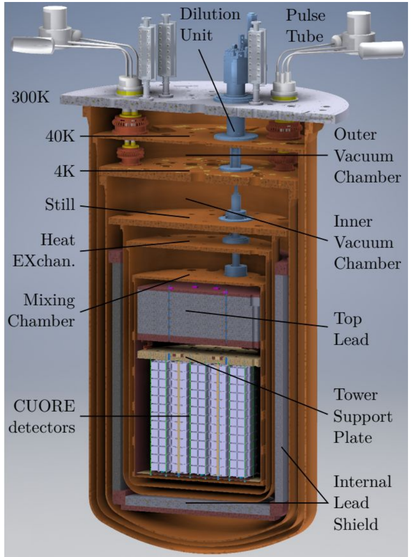
- temperature variation and scintillation light
- particle identification and good resolution
- array of isotopically enriched crystals operated at ~10 mK

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

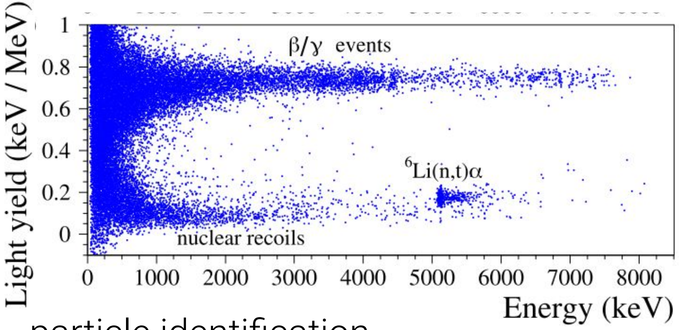


Nature 604 (2022) 7904, 53-58

$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr



CUPID

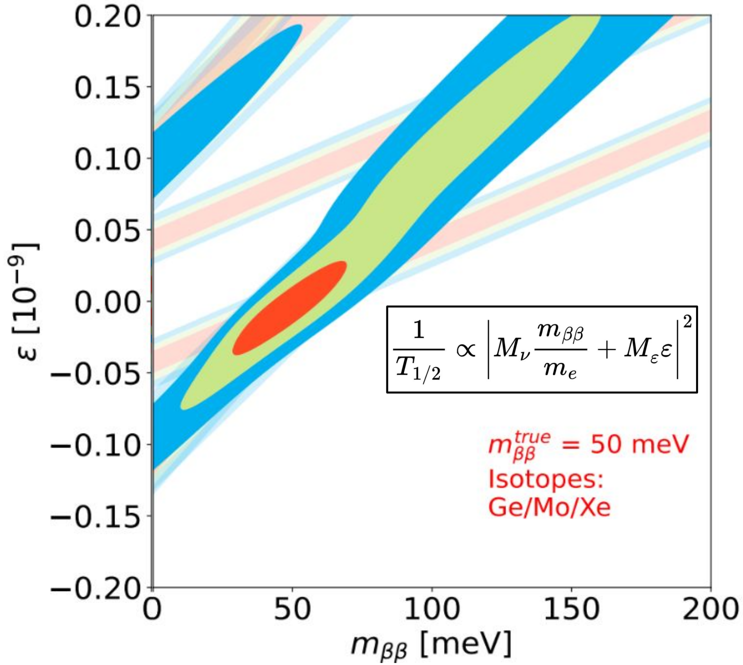


particle identification

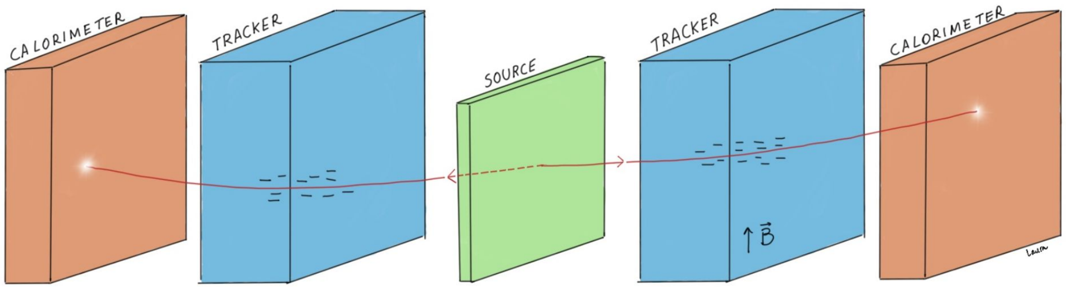
Beyond a simple rate measurement

How to gain insight on the decay channel?

- measure the electron momenta → angular distribution
- compare decay rate in different isotopes
- combined analysis of neutrino physics, including cosmology



M.A., Deppisch and Van Goffrier
In preparation



supernemo
collaboration

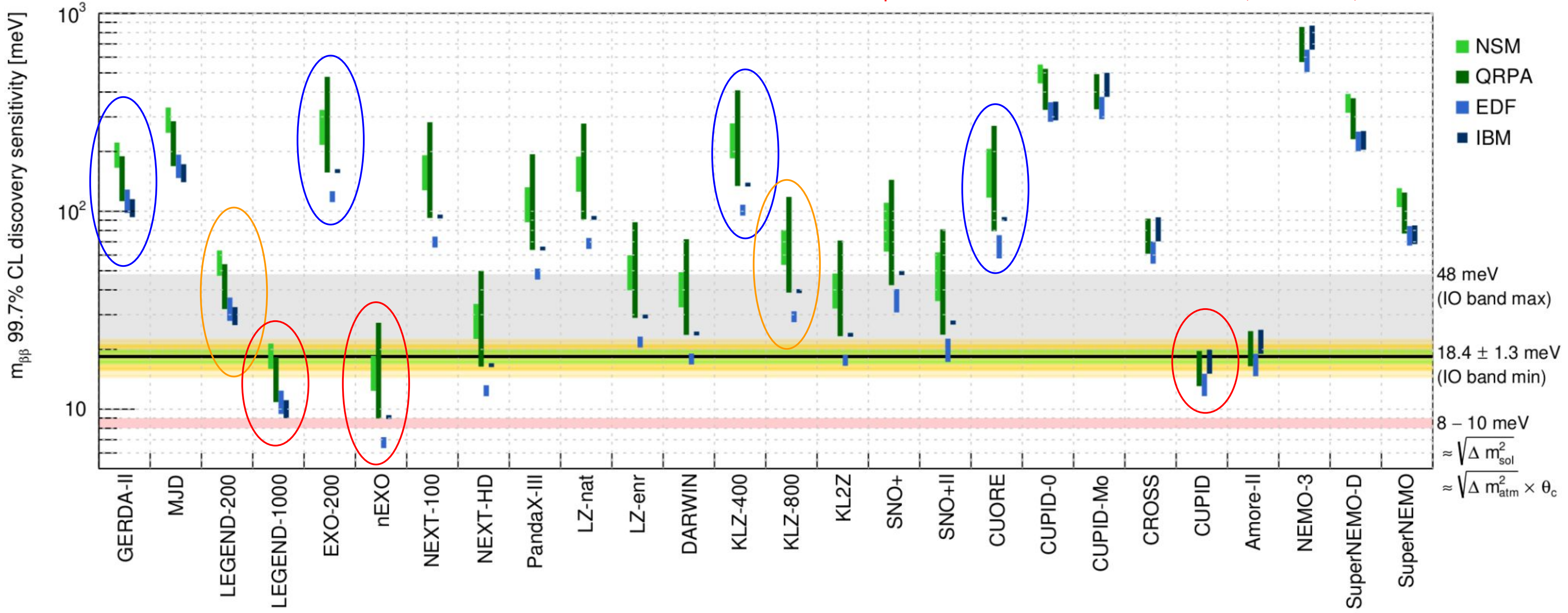
arXiv:2202.01787 - Image courtesy of Laura Manenti

Where are we heading?

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

The two that will dominate the next few years: **LEGEND-200, KamLAND-Zen-800**

The ultimate 1-ton experiments: **LEGEND-1000, CUPID, nEXO**

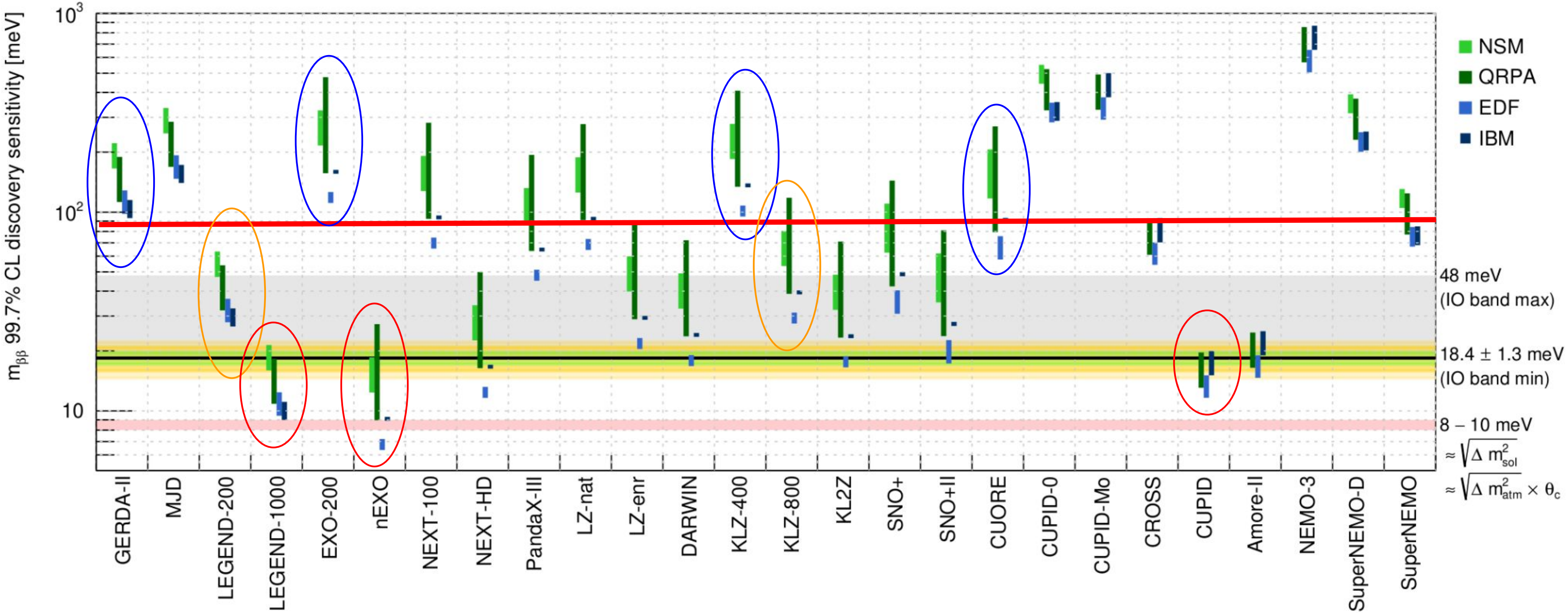


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 1: signal just beyond current limits

- experiments will discover it within a few years
- next-gen experiments will measures rate
- follow-up measurements of decay features

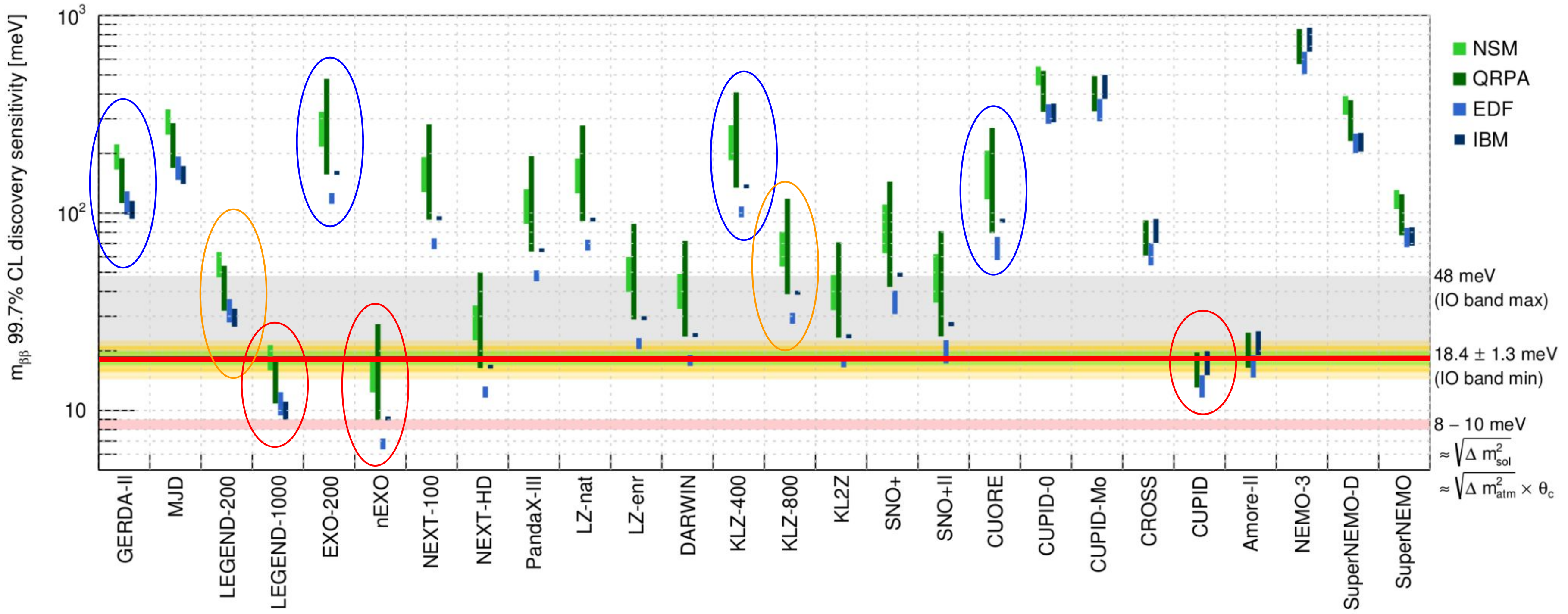


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 2: weakest signal for inverted ordered neutrinos

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

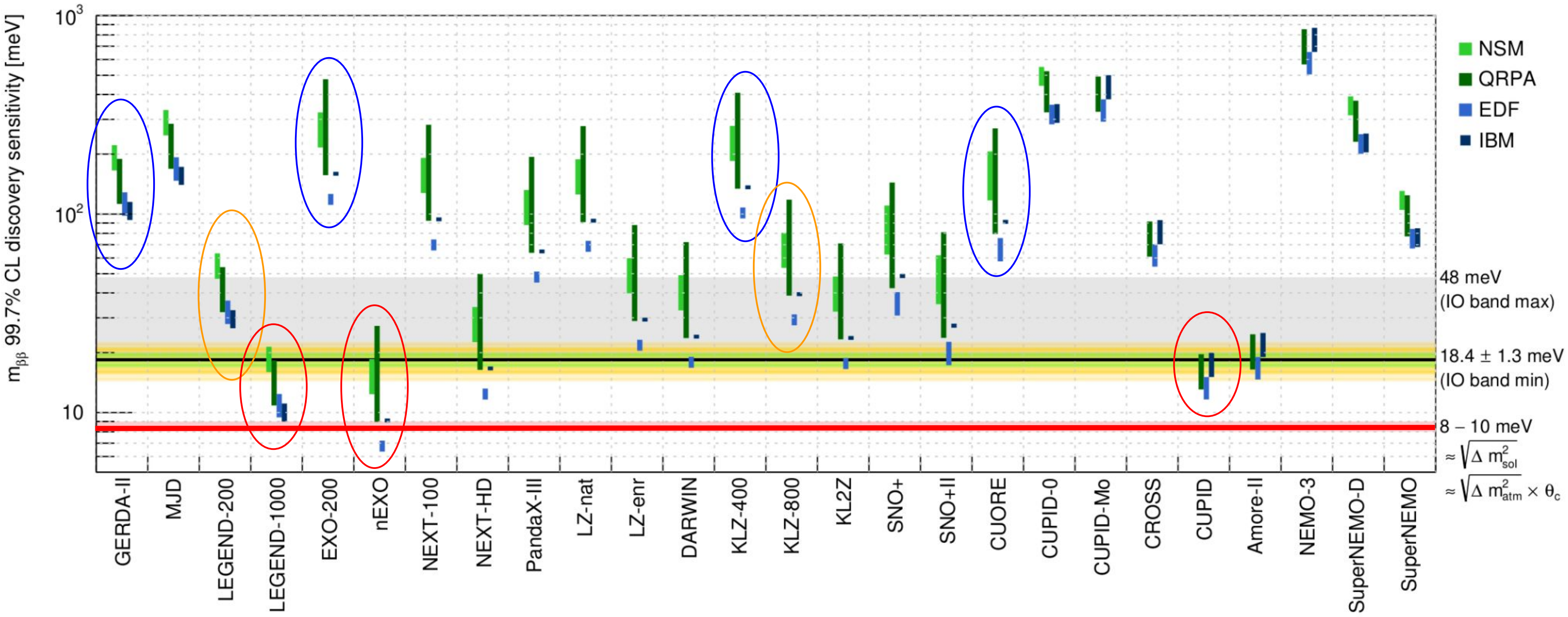


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 3: signal even weaker or absent

- need R&D for a convincing discovery
- interplay with oscillation experiments and cosmology can still lead to theory breakthroughs



M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Conclusions

$0\nu\beta\beta$ decay can lead to the **direct observation of B-L violation** at low-energy in a controlled **laboratory** environment

$0\nu\beta\beta$ decay is strongly linked to **L-violating Majorana** neutrinos

The discovery of $0\nu\beta\beta$ decay would lead to a **new "standard model"**, with a new interpretation of the fundamental symmetries and the matter-antimatter concept

A worldwide, **multi-isotope** experimental program is exploring an exciting parameter space, where a signal can be around the corner