Neutrinoless $\beta\beta$ Decay

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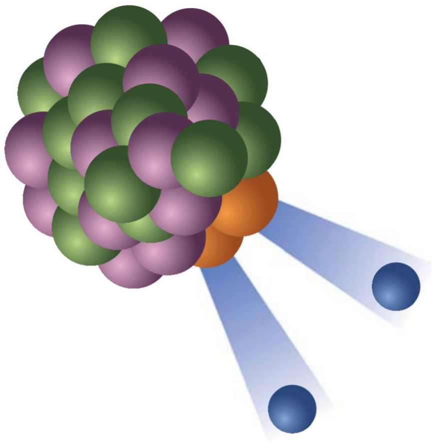
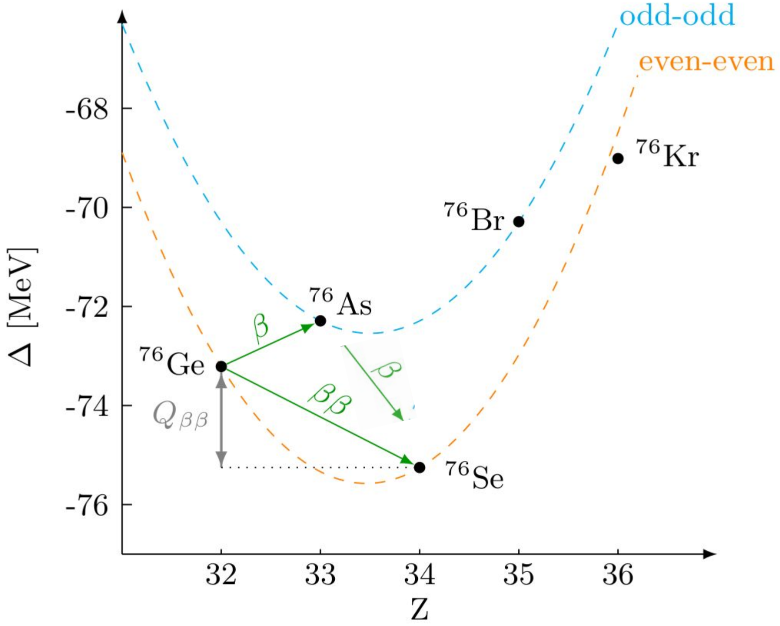
What is neutrinoless $\beta\beta$ Decay?

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

- 2 neutrons -> 2 protons
- 2 electrons are emitted



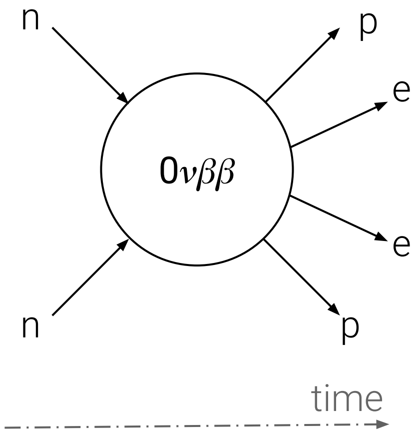
Possible to detect only if single-β decay is strongly suppressed



Why are we looking for it?

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

- 2 neutrons -> 2 protons (ΔB = 0)
- 2 electrons are emitted (ΔL = 2)



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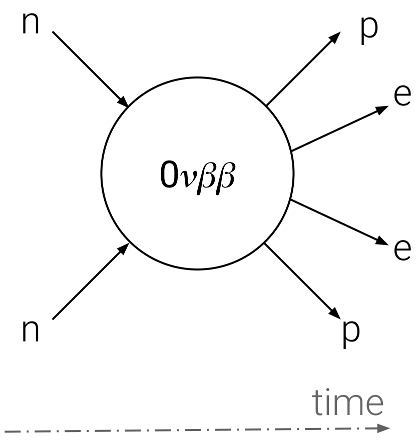

Matter-creation in the laboratory!
Direct violation of **L** and **B-L**

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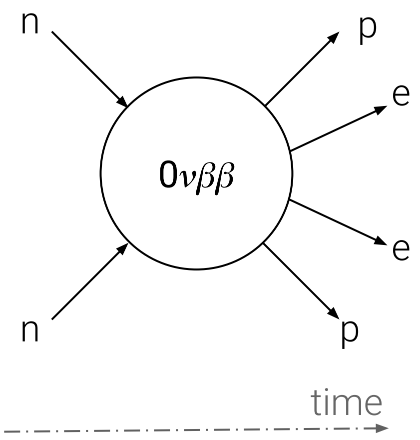

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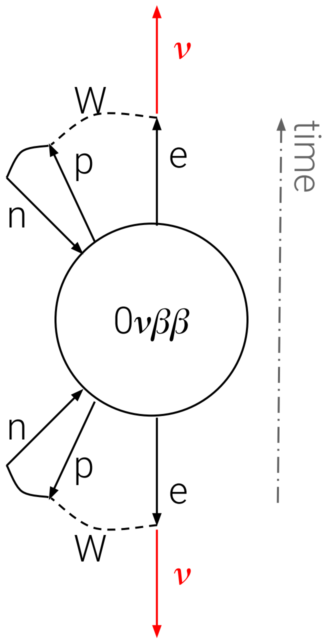
Direct violation of **L** and **B-L**

Same diagram

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

Schechter and Valle

1982



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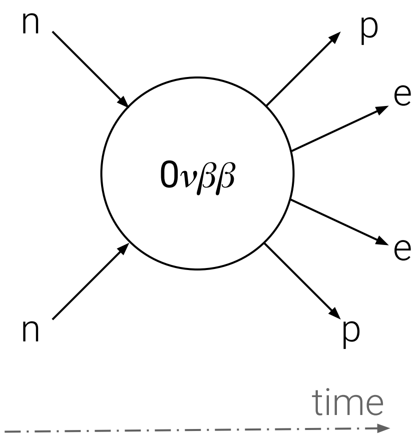

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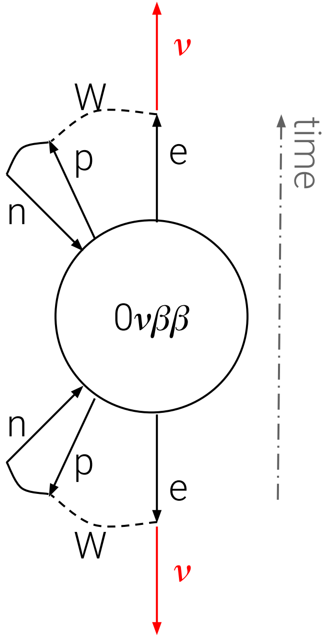


Prove that **neutrinos and antineutrinos** are the **same object**

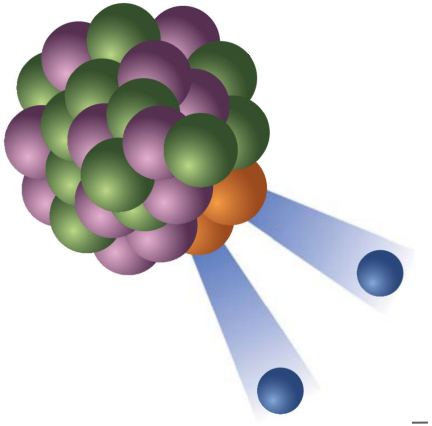
A portal to new physics beyond the SM

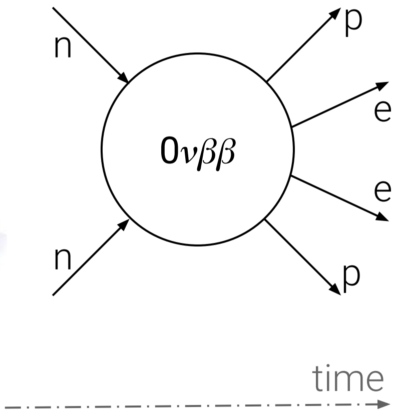
$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Experiments

Nuclear theory

Particle theory





A portal to new physics beyond the SM

$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Particle Physics

phase space factor

hadronic matrix element

nuclear matrix element (NME)

Can be computed accurately

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

Requires calculations of :

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

A portal to new physics beyond the SM

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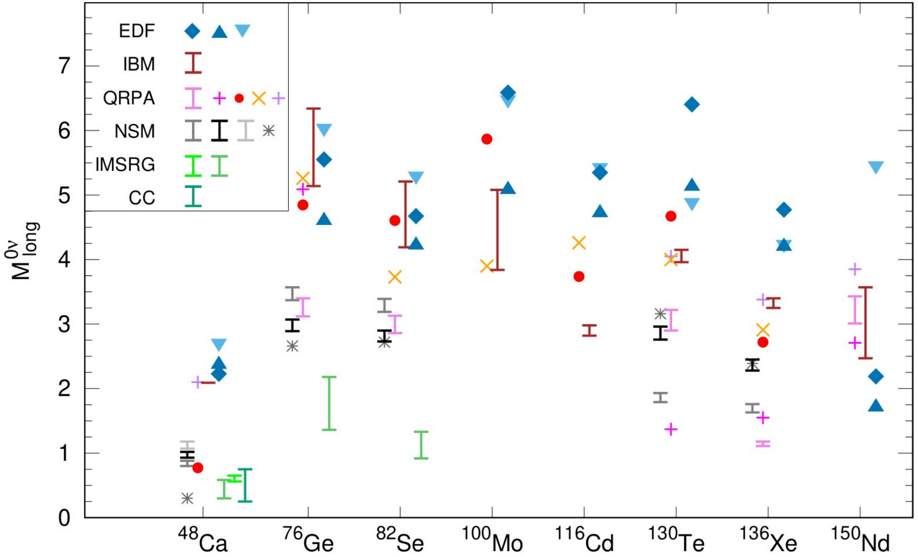
Particle Physics

nuclear matrix element (NME)



Uncertainties

- approximations in many-body methods
- overall scaling due to missing contributions (e.g. “g_a quenching physics” or contact term)

MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

A portal to new physics beyond the SM

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

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

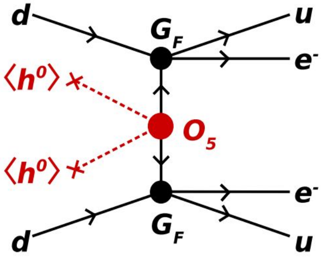
$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

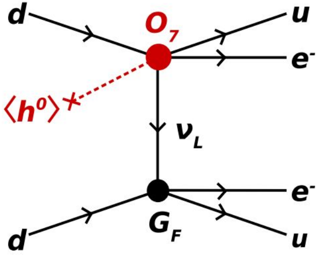
Dim 5: Weinberg Operator

$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\lambda}\right)^2 \quad \text{with } \frac{\nu}{\Lambda} \propto \frac{m_{\beta\beta}}{m_e}$$



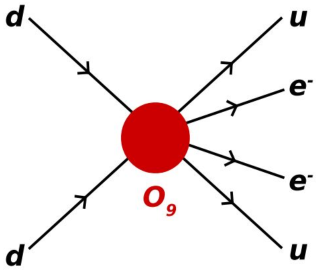
Dim 7

$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^6$$



Dim 9

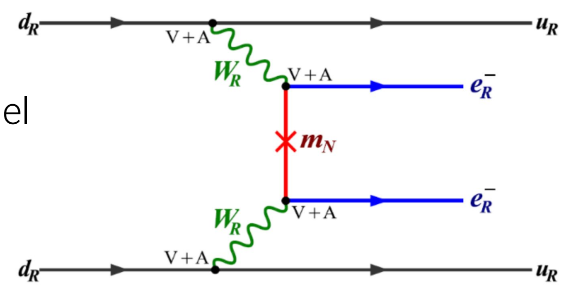
$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^{10}$$

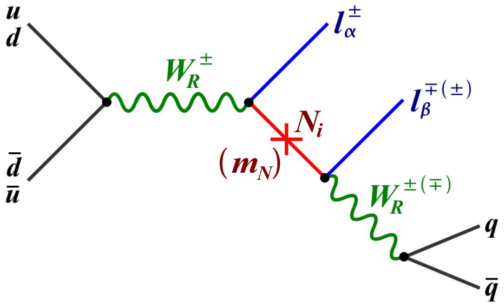


A generic search for ultrahigh-energy BSM physics

Example: left-right symmetry

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

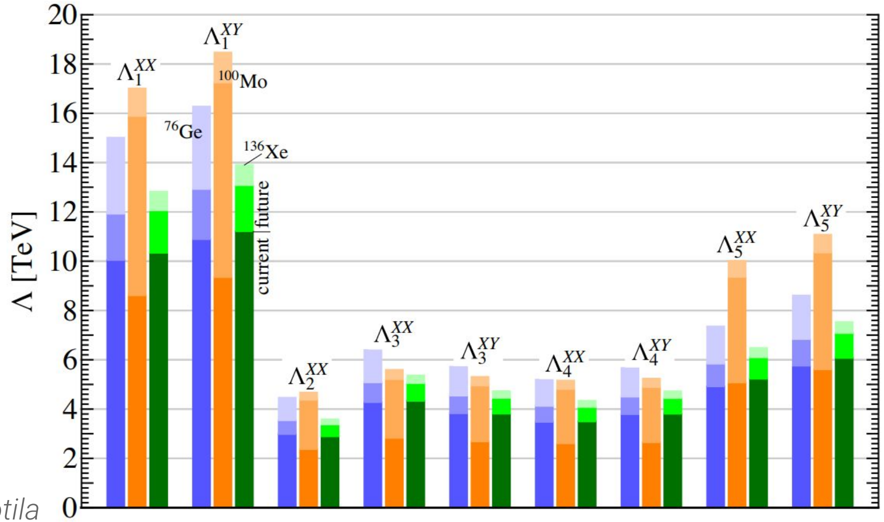




Same as dilepton signature at LHC

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

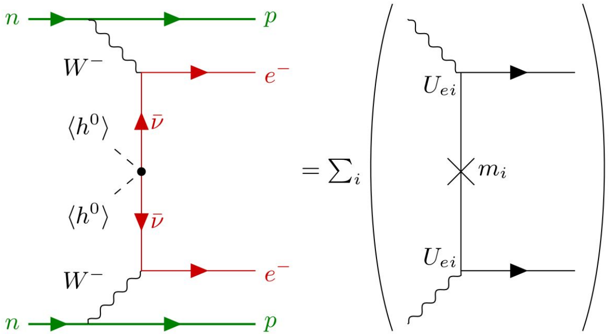
$0\nu\beta\beta$-decay experiments are open searches for new physics, and a discovery could come at any time



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

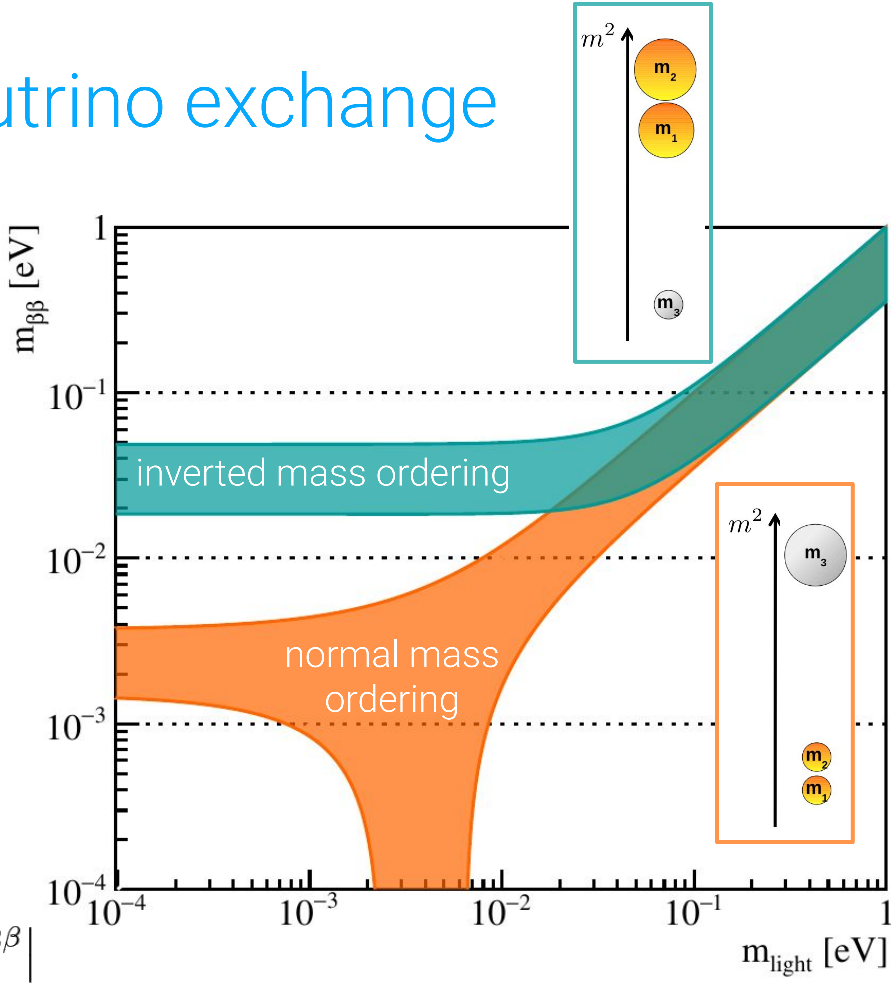
Weinberg operator: light neutrino exchange

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

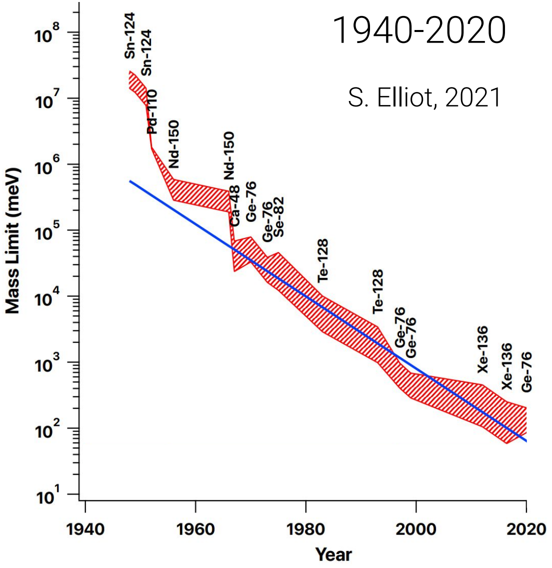


$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

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



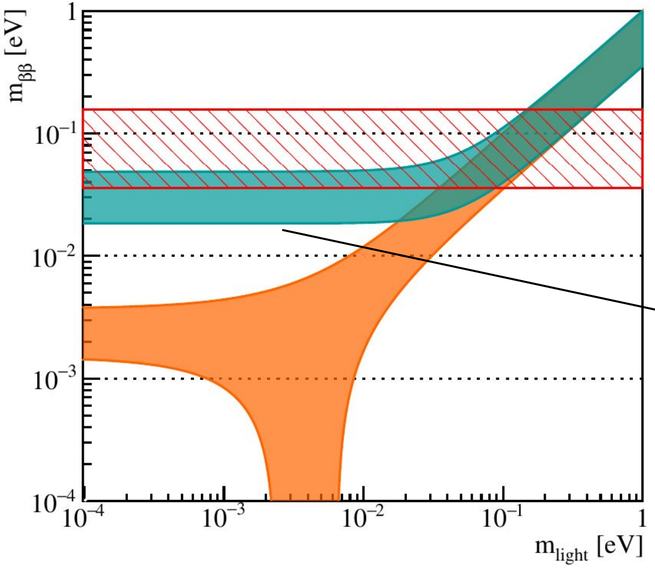
Closing up on the inverted ordering



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

Best Today

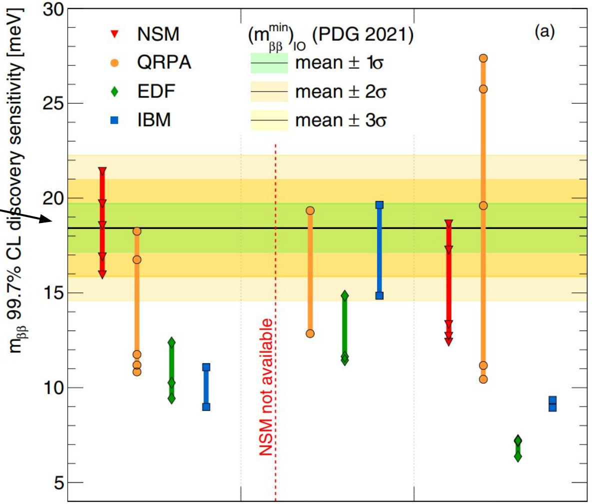
($T_{1/2}$ > 10^{26} yr)



MA, Benato, Detwiler, Menéndez and Vissani
PRC 104, L042501

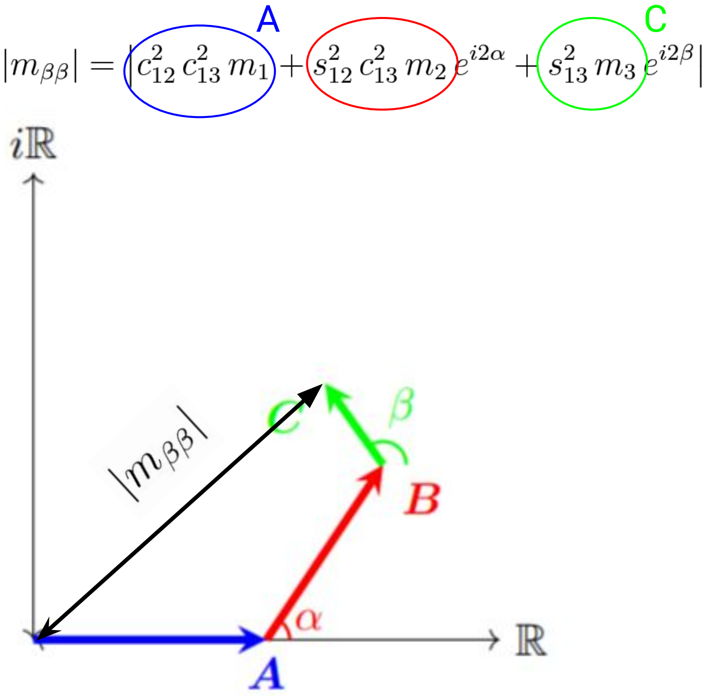
Best Nex Gen

($T_{1/2}$ > 10^{27} - 10^{28} yr)

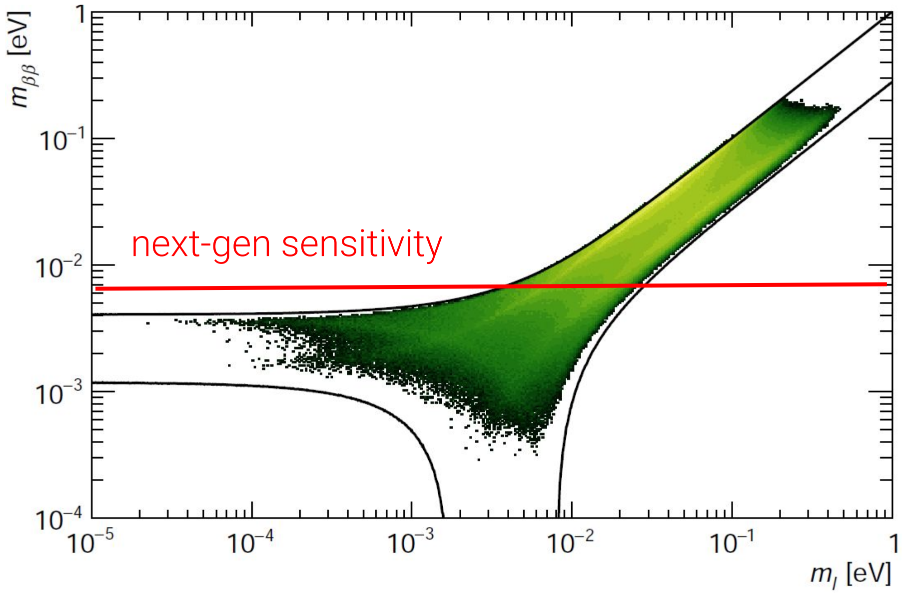


What about normal ordering?

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



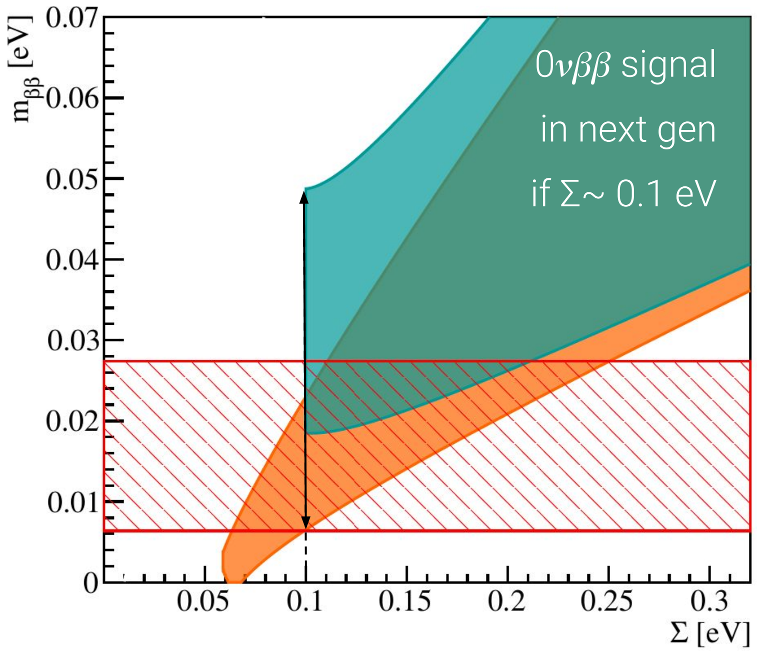
Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.



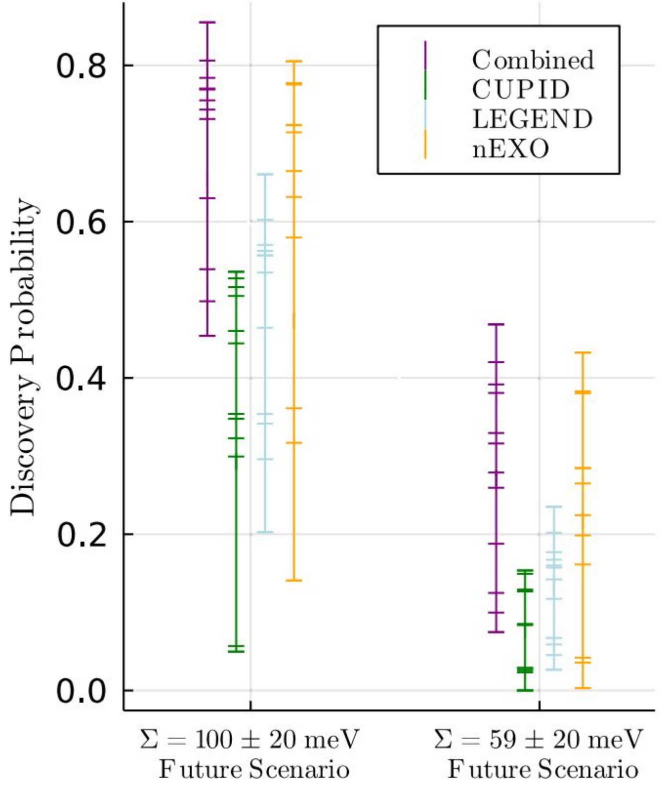
***MA**, Benato and Detwiler, PRD 96, 053001 (2017)*

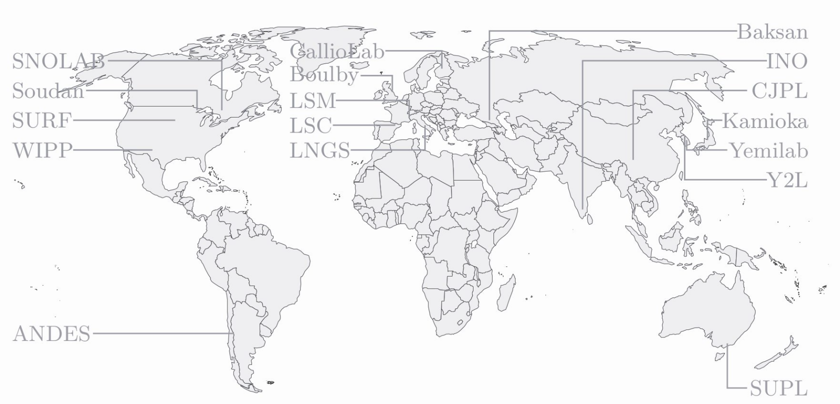
The interplay with cosmology

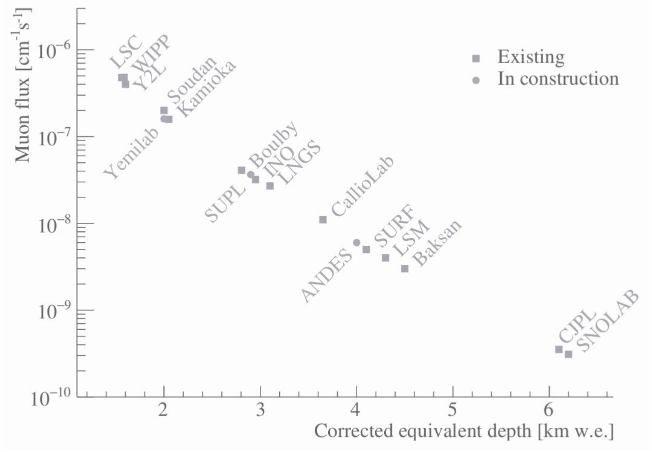
Cosmology surveys (DESI/EUCLID) close to measure $\Sigma = \sum_i m_i$



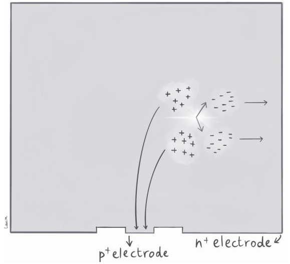
*Ettengruber, **MA**, Caldwell, Eller and Schulz*
PRD 106, 073004 (2022)

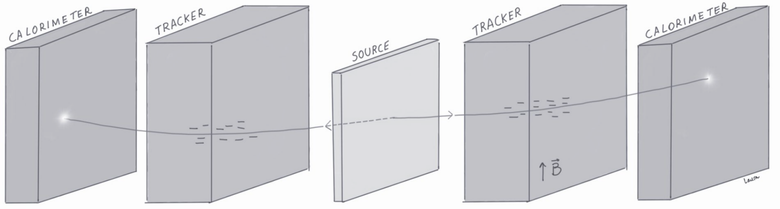


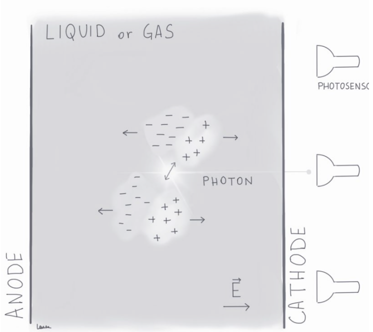


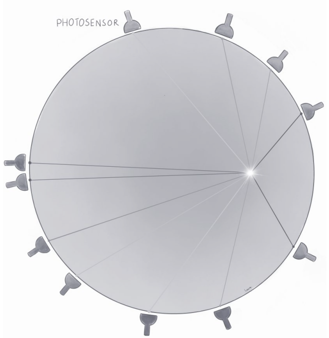


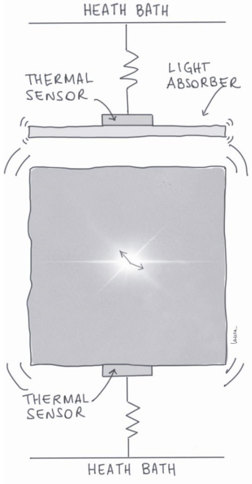
The experimental landscape







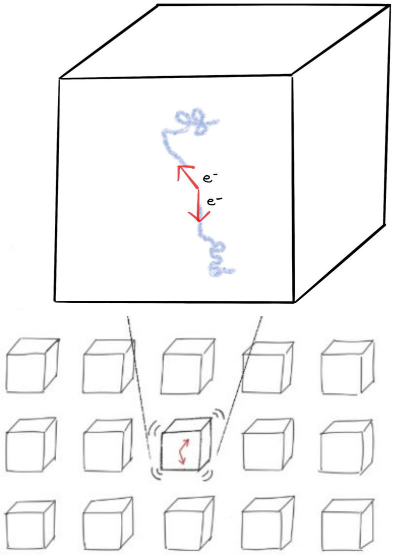


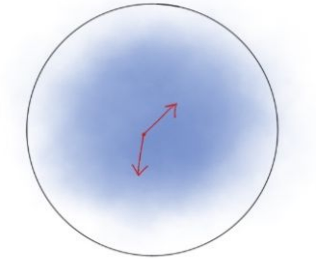


Detection concepts

Calorimetric approach: source = detector

- solid state: pixelated detector
- liquid: monolithic self-shielding volume





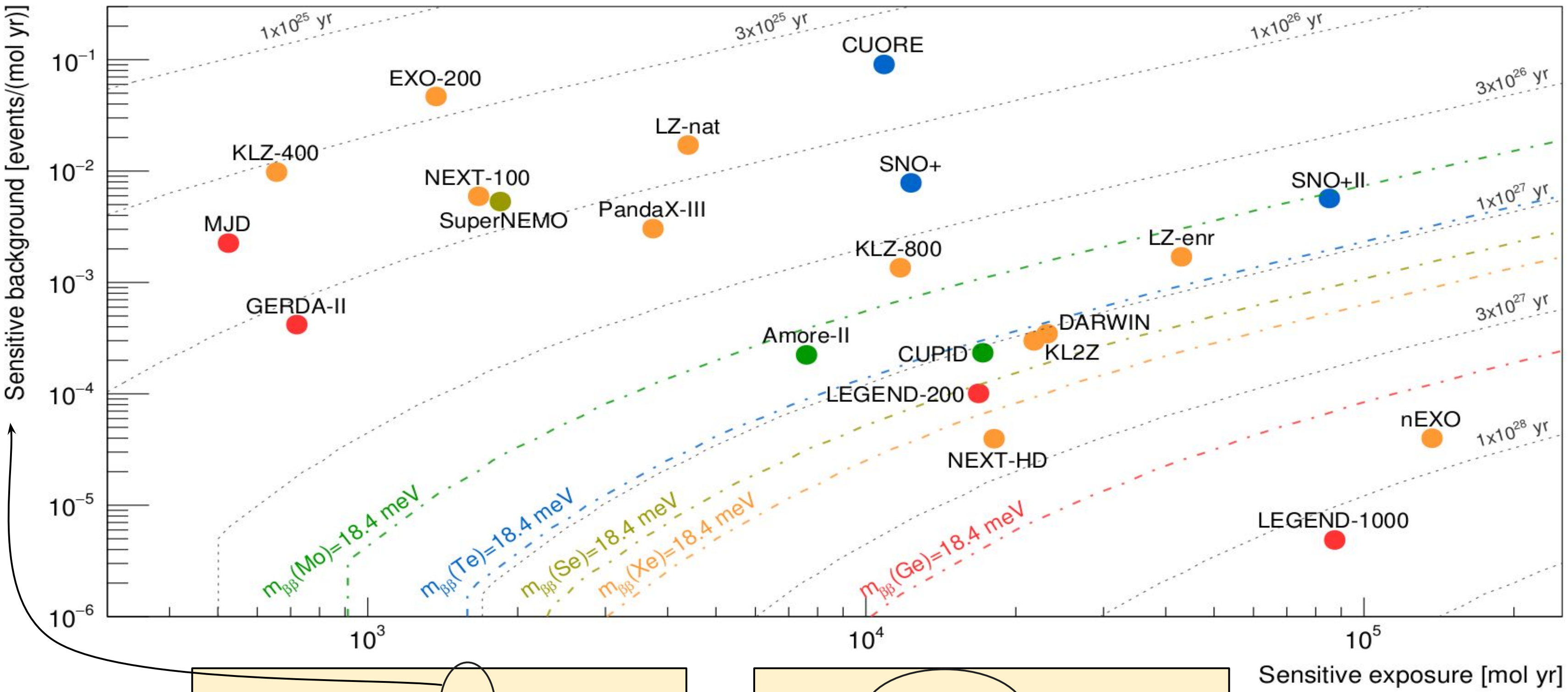
Experimental signature

- 2 electron final state
- **electron summed energy = Q-value**
- (daughter isotope)

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

Recent and future experiments

***MA**, Benato, Detwiler, Menéndez, Vissani,*
Rev. Mod. Phys. 95, 025002 (2023)

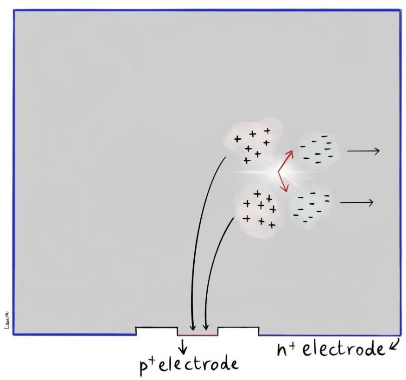


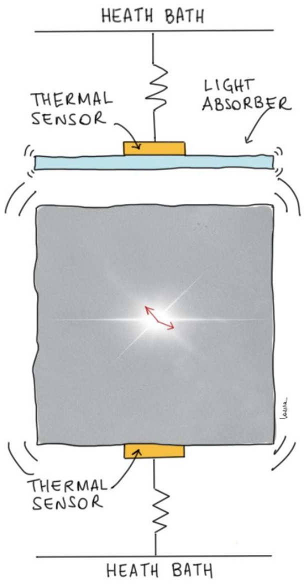
$N_{0\nu\beta\beta} \gtrsim N_{background} = B \cdot atoms \cdot time$

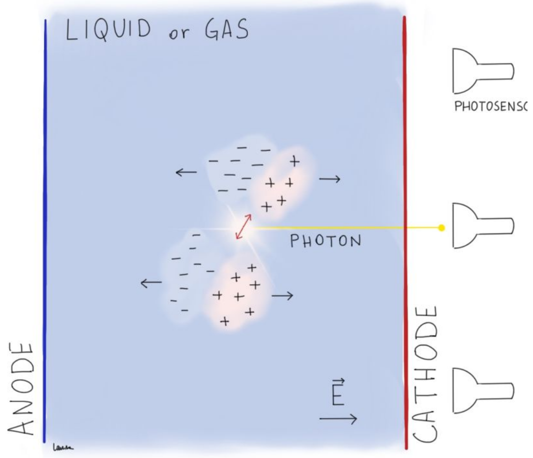
$N_{0\nu\beta\beta} = atoms \cdot time / T_{1/2}$

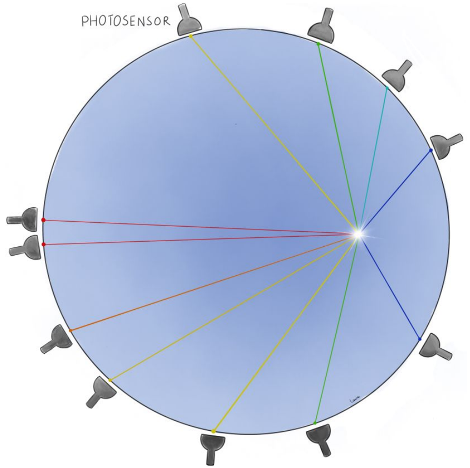
The most sensitive technologies

***MA**, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023) (Image courtesy of Laura Manenti)*









Ge Semiconductor detectors (^{76}Ge)

Cryogenic Calorimeters (^{100}Mo, ^{130}Te)

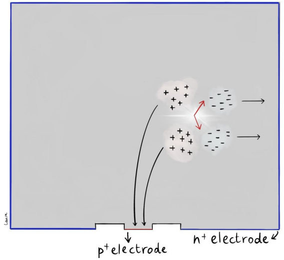
Xe Time Projection Chambers (^{136}Xe)

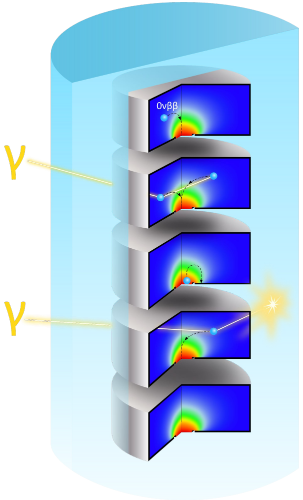
Large Liquid scintillator detectors (^{130}Te, ^{136}Xe)

Ge semiconductor detectors

high-purity ^{76}Ge detectors

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





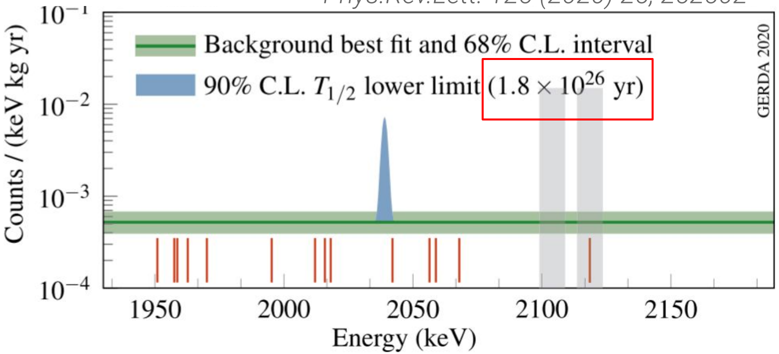
liquid Ar detector

- shield and scintillation light

Staged approach:

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

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

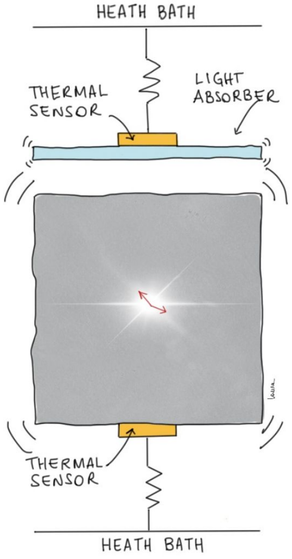


Cryogenic calorimeters

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

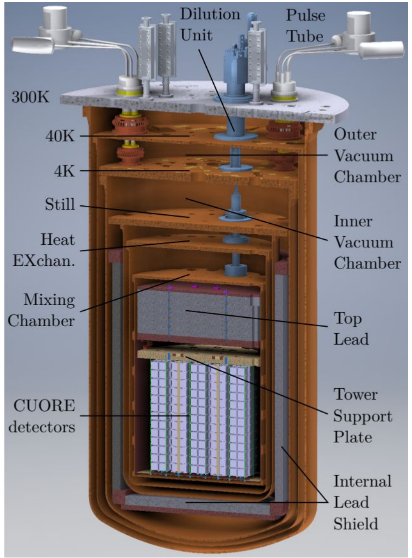
Experiment	Crystal	m_{tot} [kg]	f_{enr} [%]
CUORE	$^{nat}TeO_2$	742	34[a]
CUPID-0	$Zn^{enr}Se$	9.65	96
CUPID-Mo	$Li_2{}^{enr}MoO_4$	4.16	97
CROSS	$Li_2{}^{enr}MoO_4$	8.96	98
CUPID	$Li_2{}^{enr}MoO_4$	472	≥95
AMoRE	$Li_2{}^{enr}MoO_4$	200	96

in Korea (Prof. Kim, discussed yesterday)



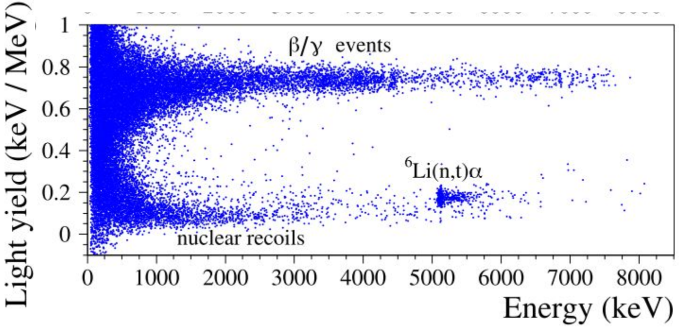
Nature 604 (2022) 7904, 53-58

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



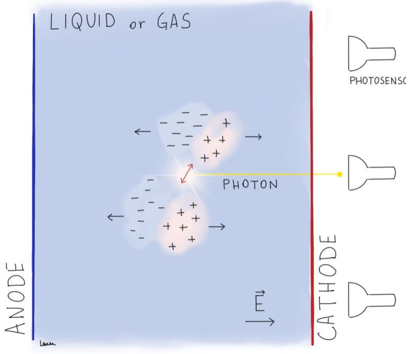
CUPID

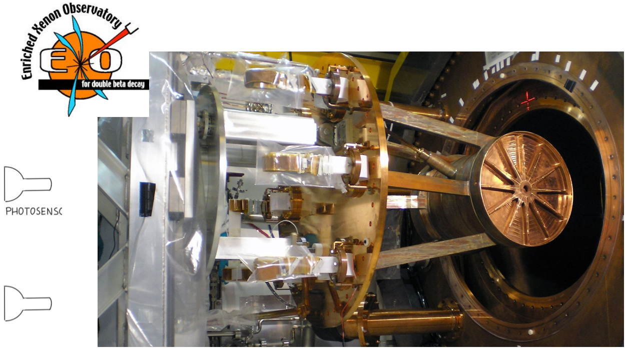
See B. Oregui's talk this afternoon



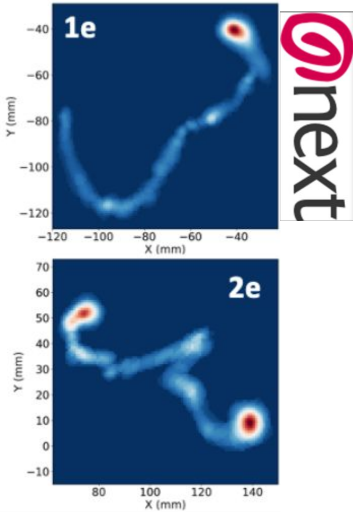
Xe time projection chambers

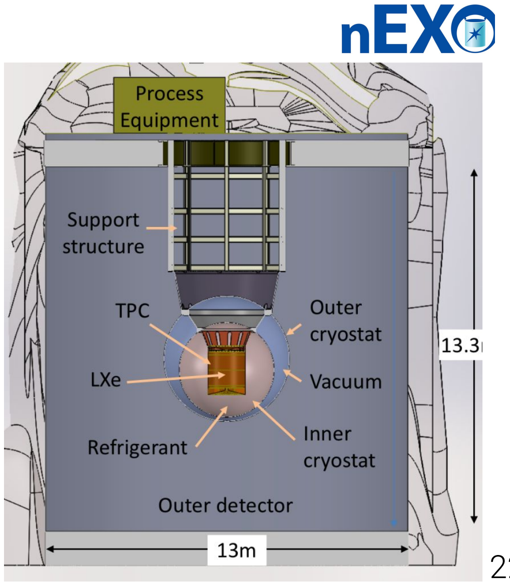
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope





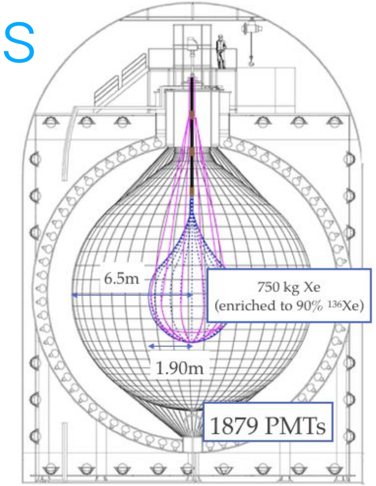
Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs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



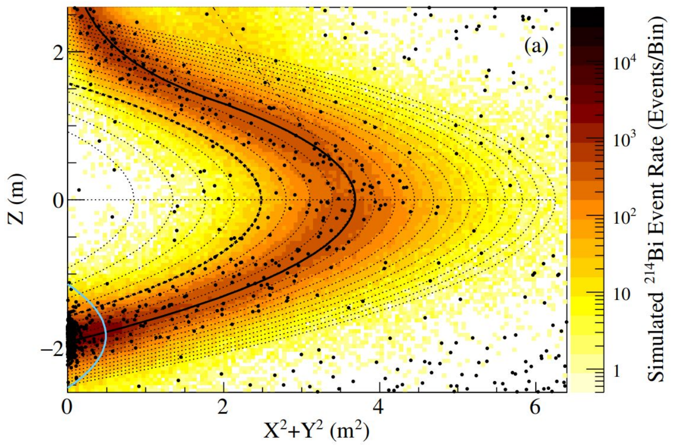


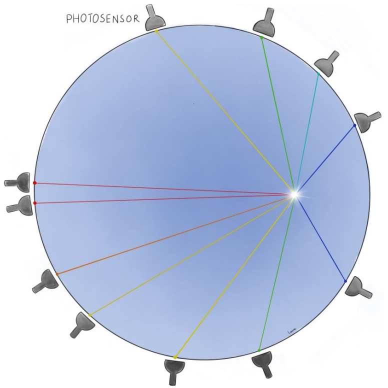
Large liquid scintillators

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



KZ collaboration, PRL 130 (2023)

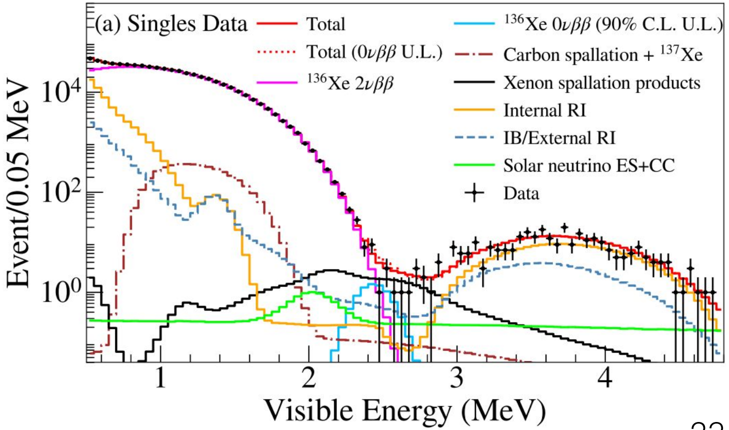




KamLAND-Zen-800 @Kamioka

- 750 kg of enriched Xe in nylon balloon
- backgrounds: $2\nu\beta\beta$, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- in data taking

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



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

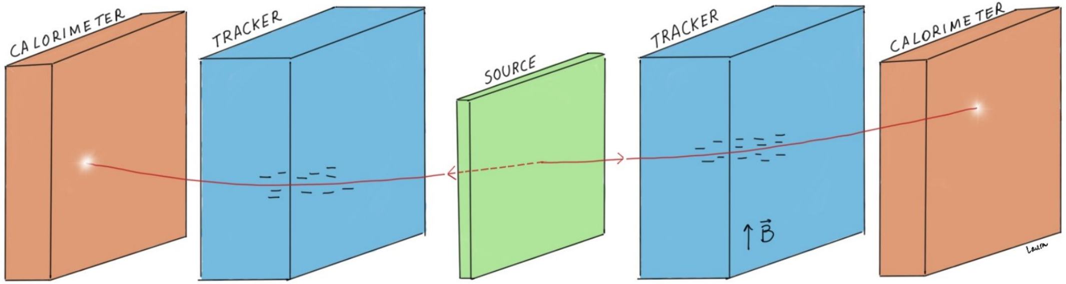
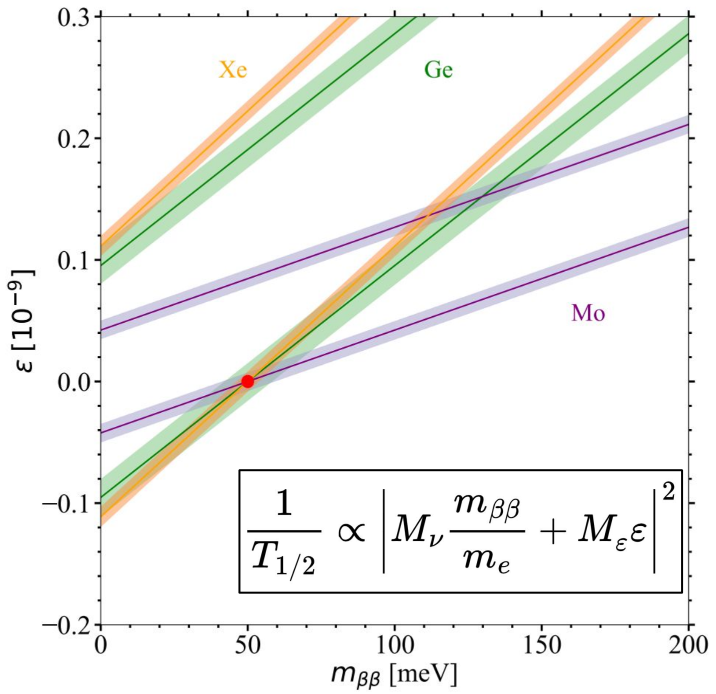


Image courtesy of Laura Manenti



***MA**, Deppisch, Van Goffrier, JHEP 02 (2023)*

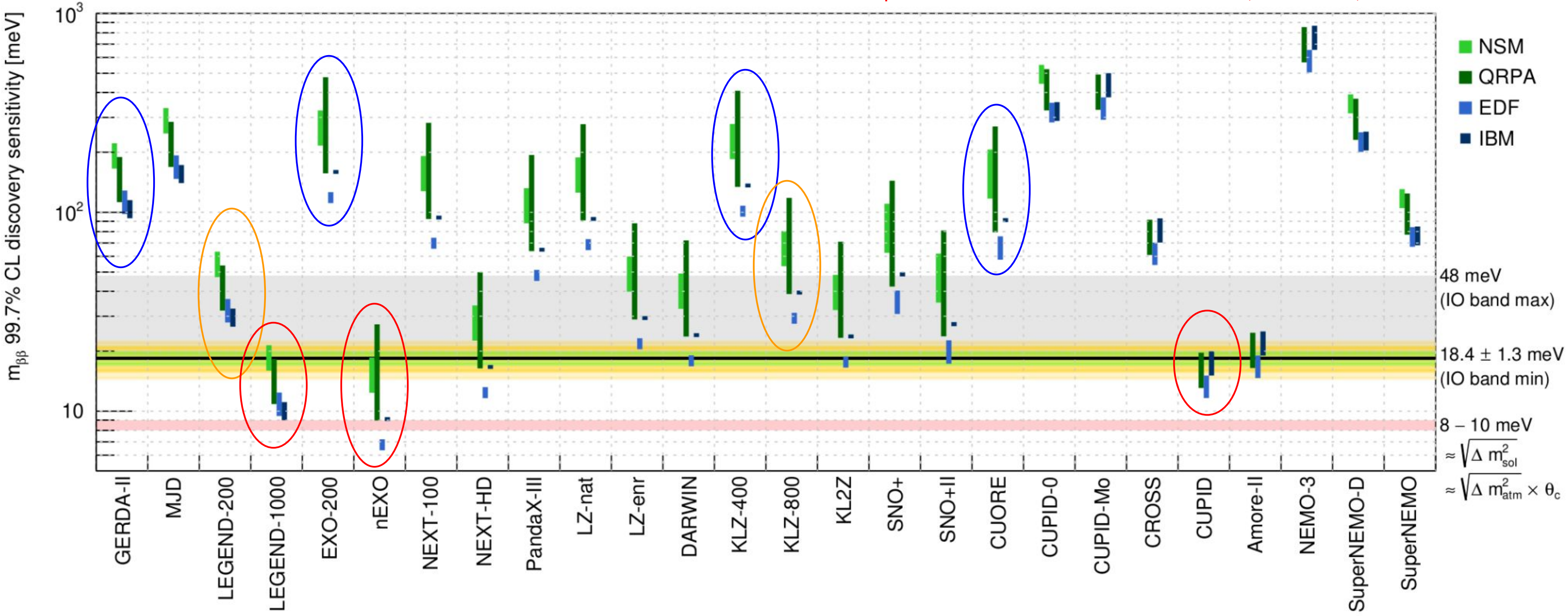
supernemo collaboration

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**

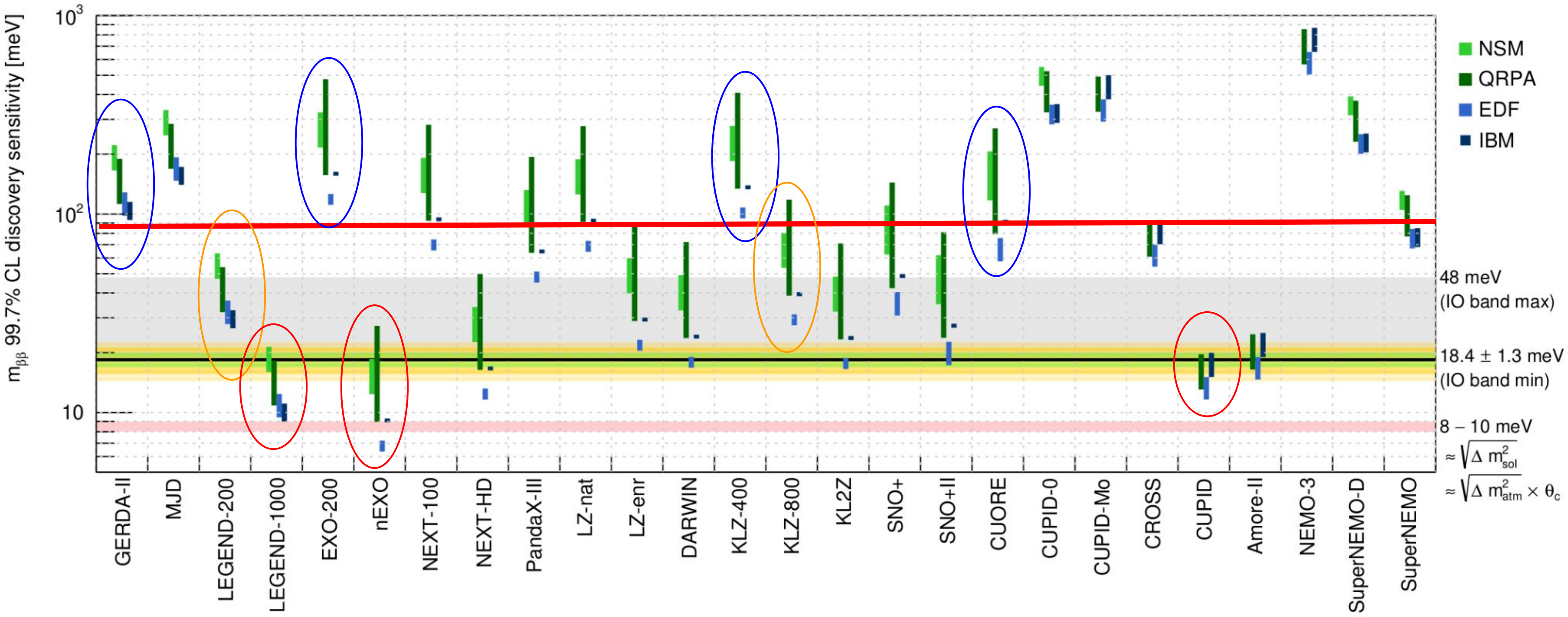
The ultimate 1-ton experiments: **LEGEND-1000, CUPID, nEXO**



Where are we heading?

Scenario 1: signal just beyond current limits

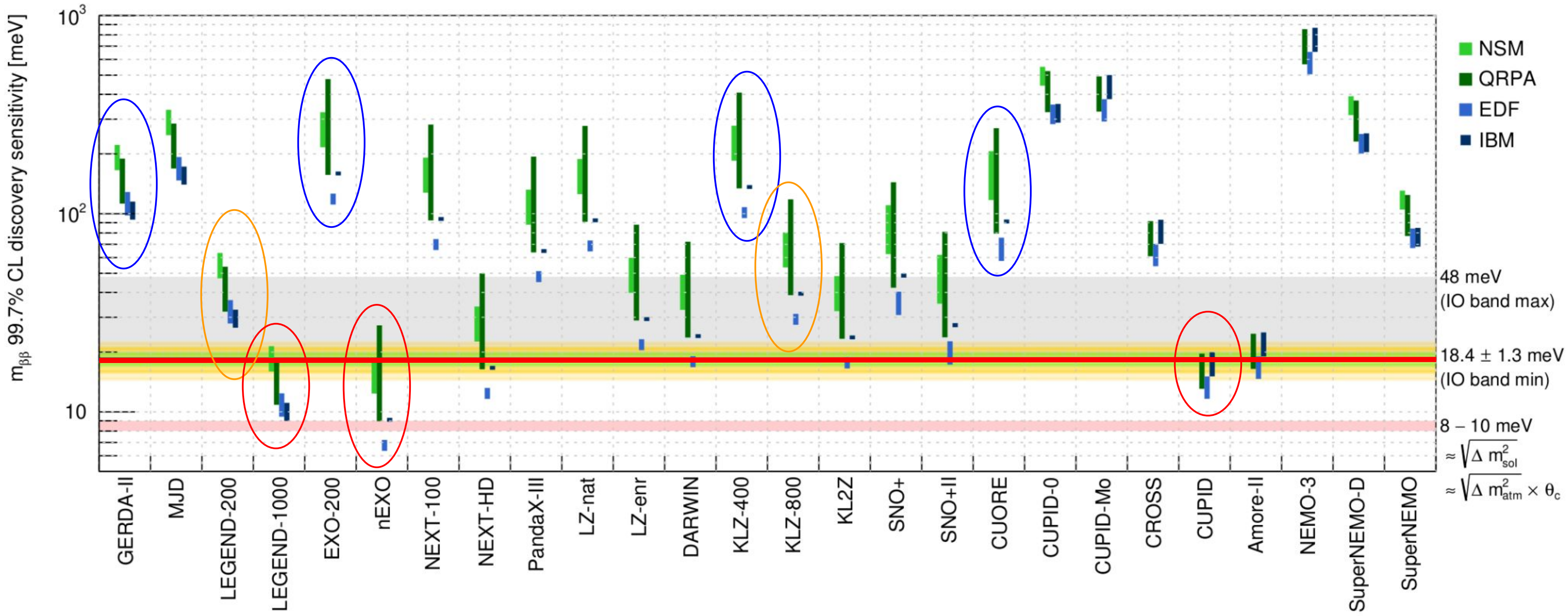
- experiments will discover it within a few years
- next-gen experiments will measures rate
- follow-up measurements of decay features



Where are we heading?

Scenario 2: weakest signal for inverted ordered neutrinos

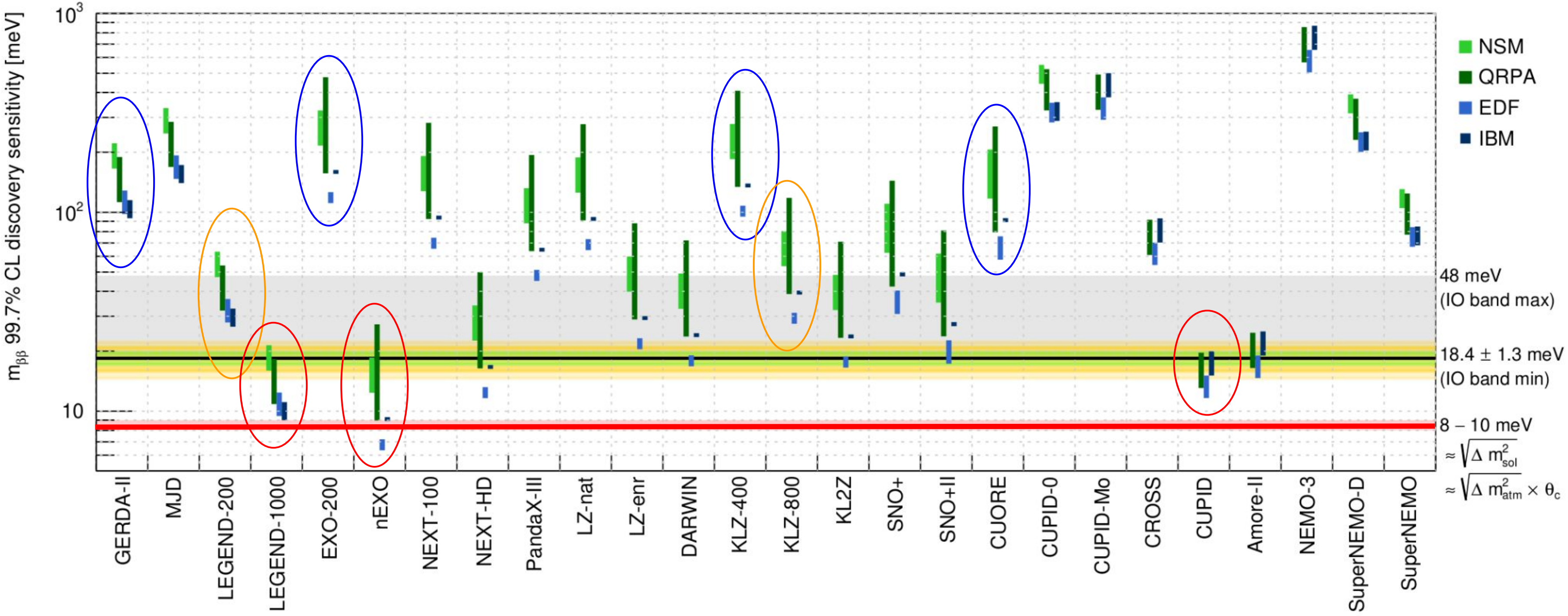
- need to wait next-gen experiments for a discovery
- need R&D to measure decay features



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



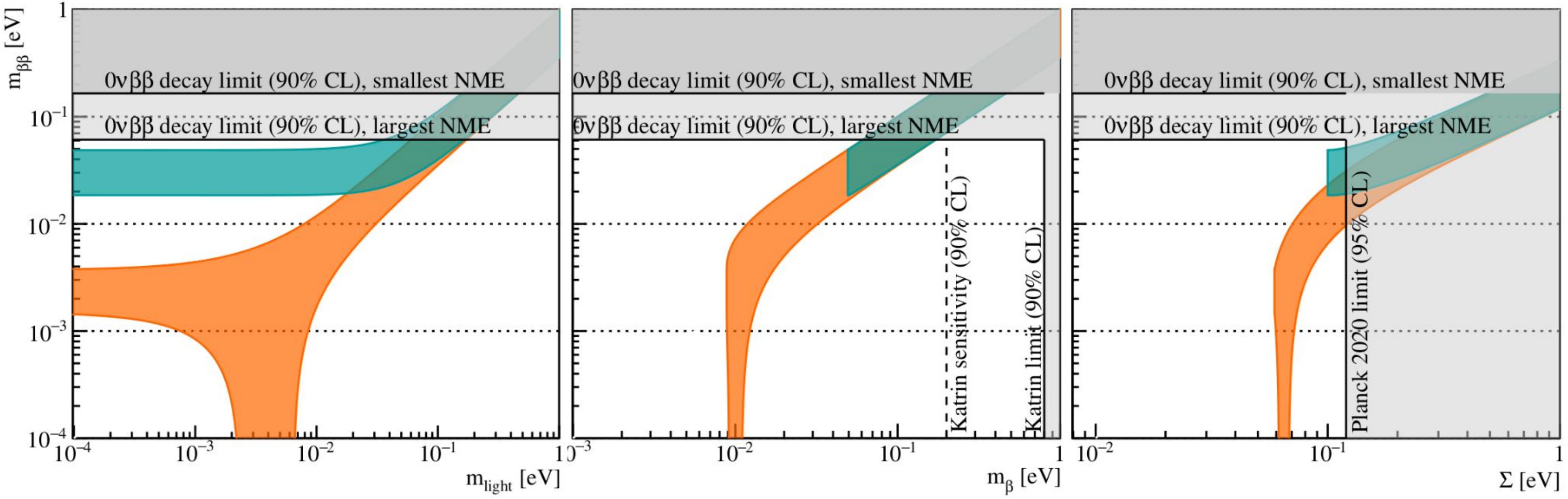
Conclusions

- The discovery of $0\nu\beta\beta$ decay would be the first observation of **matter creation** (without antimatter), essential to explain the matter-antimatter asymmetry

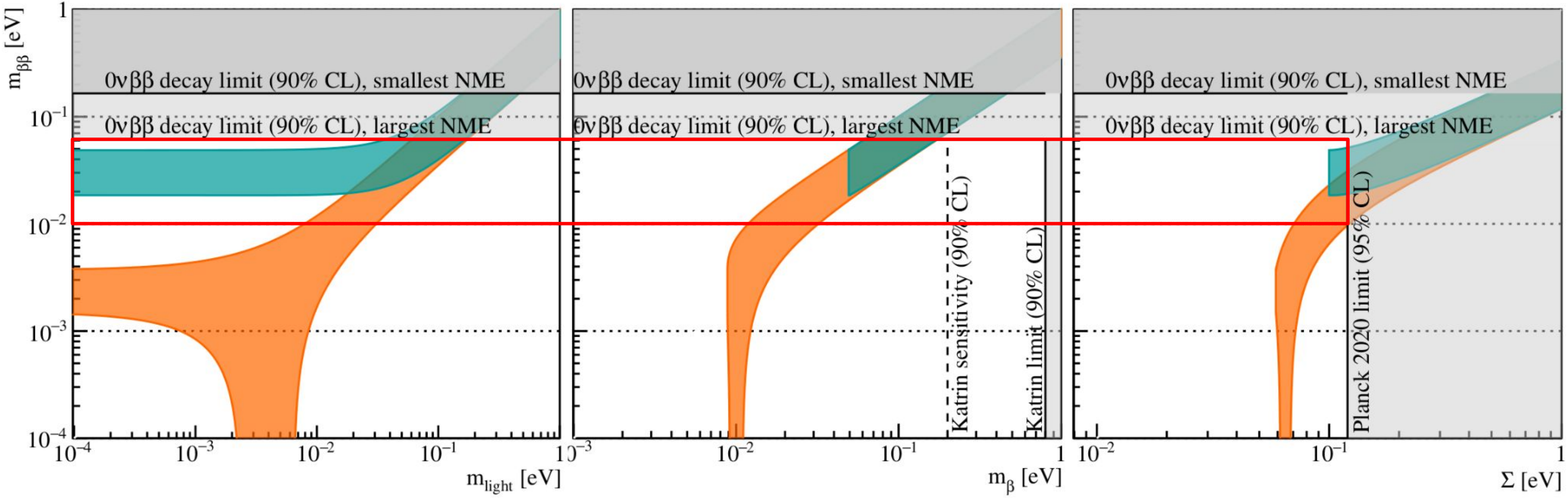
- The discovery of $0\nu\beta\beta$ decay would prove that neutrinos are **Majorana particles** and **B-L** (i.e., the last global symmetry of the SM) is violated

- A worldwide, **multi-isotope** experimental program is exploring an exciting parameter space, where a **discovery** could come at any time

Interplay between mass experiments

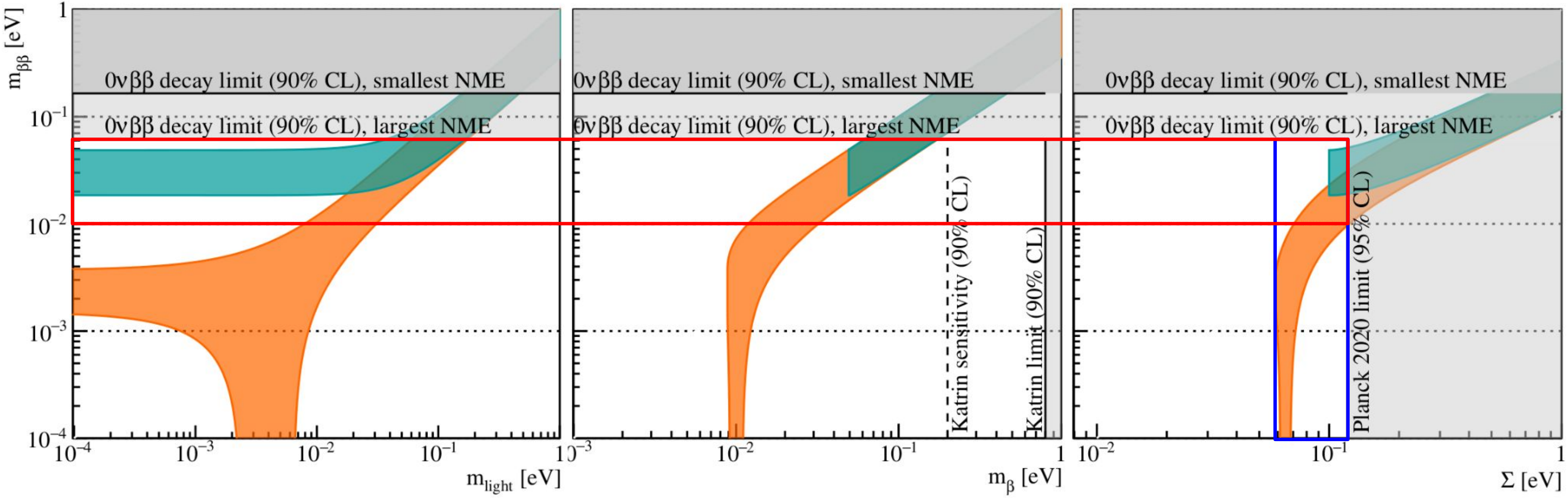


Interplay between mass experiments



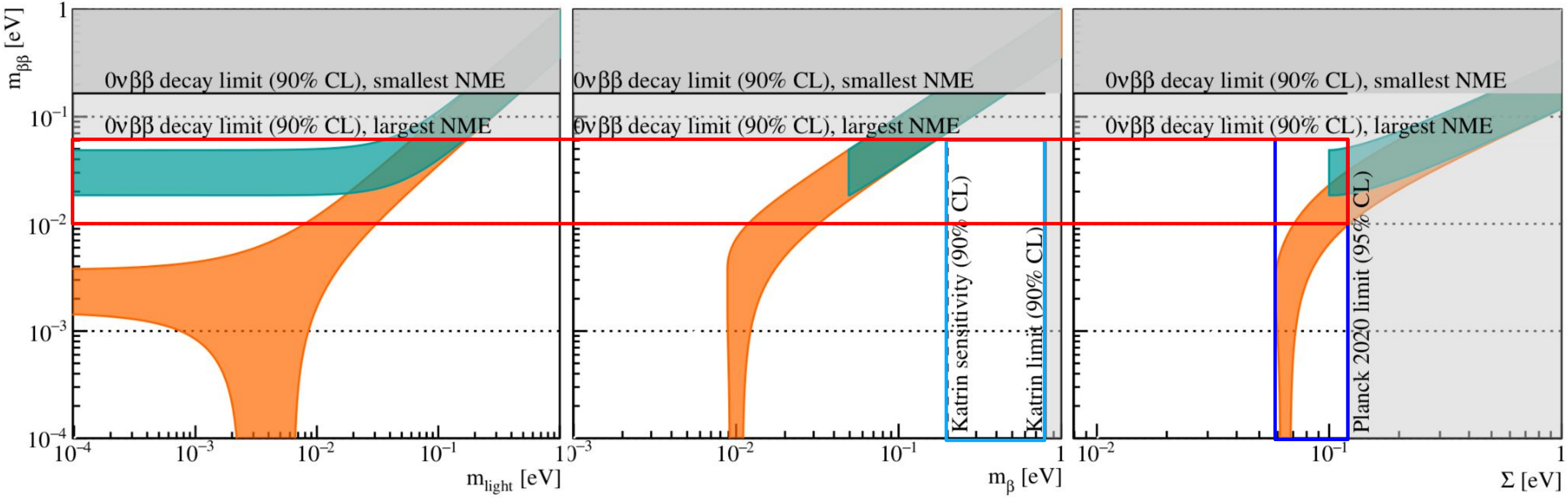
CUPID, LEGEND, nEXO will explore $m_{\beta\beta}$ values till the bottom of the inverted ordering and beyond, with a good chance to discover matter-creation

Interplay between mass experiments



DESI and EUCLID promise to measure Σ. This will define a target for $0\nu\beta\beta$ experiments, with a no observation potentially hinting at Dirac masses or non-standard cosmology

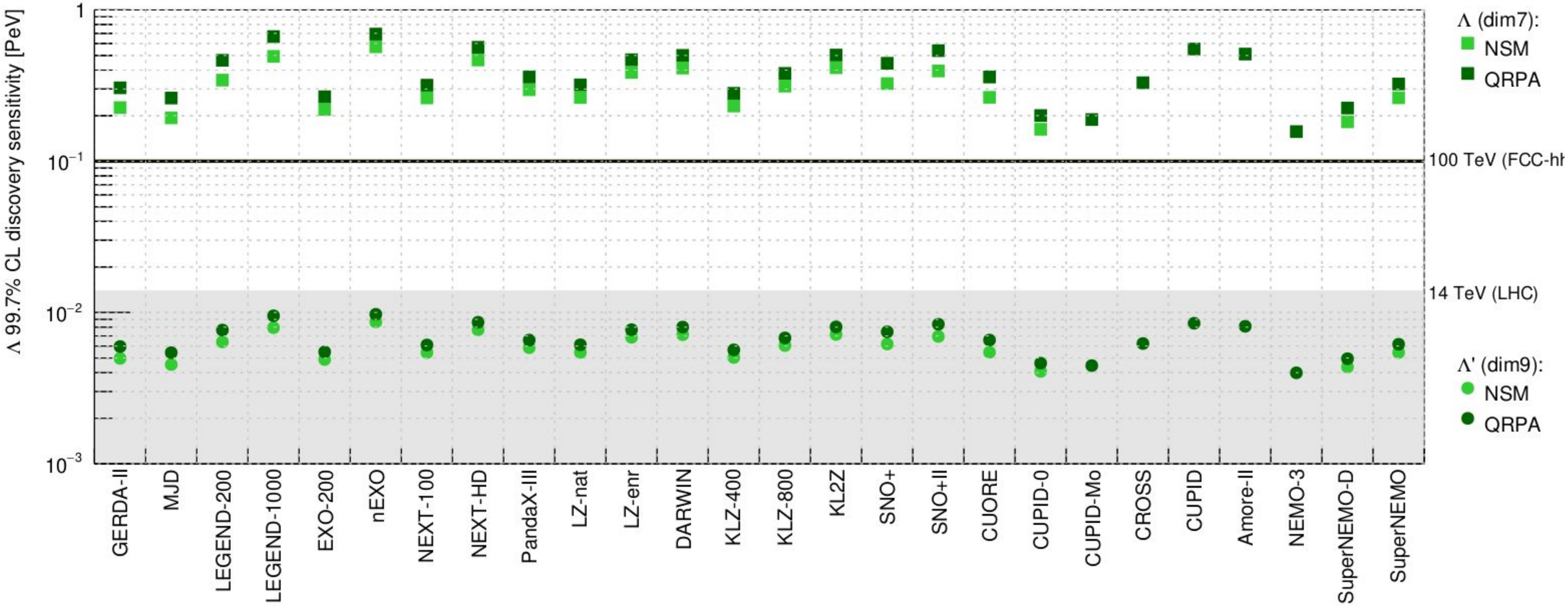
Interplay between mass experiments

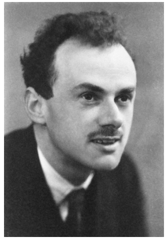


KATRIN's parameter space is already excluded by both $0\nu\beta\beta$ decay and cosmology.

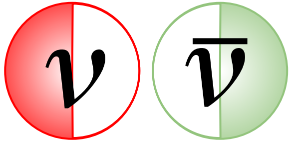
A signal would force to drastically rethink our phenomenology theory framework

Where are we heading?



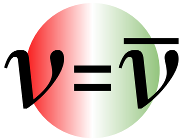


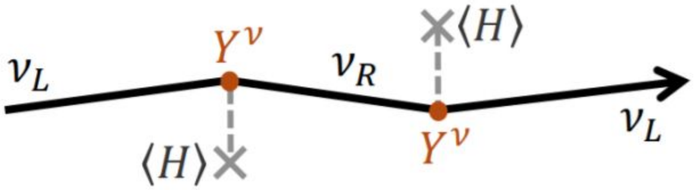
Dirac



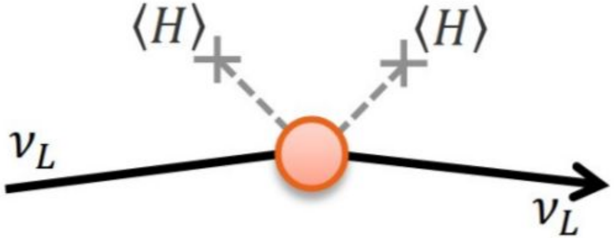
Neutrino masses

Majorana





- new right-handed neutrinos
- standard Higgs mechanism
- “unnaturally” small neutrino masses



- alternative Higgs mass mechanism
- neutrino mass violates L (and thus B-L)
- “naturally” small mass (see-saw mechanism)