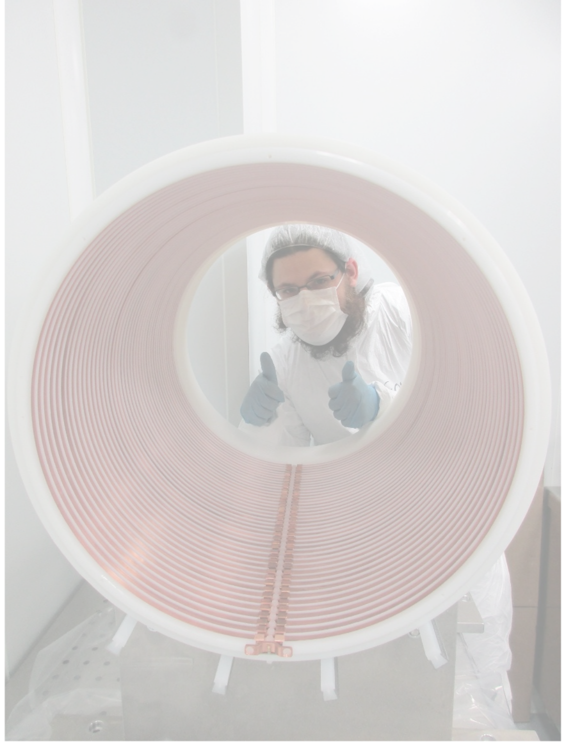
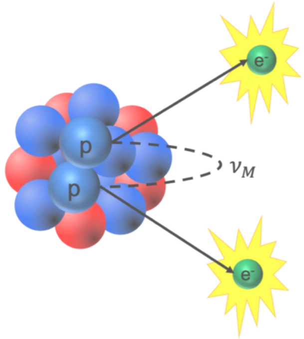
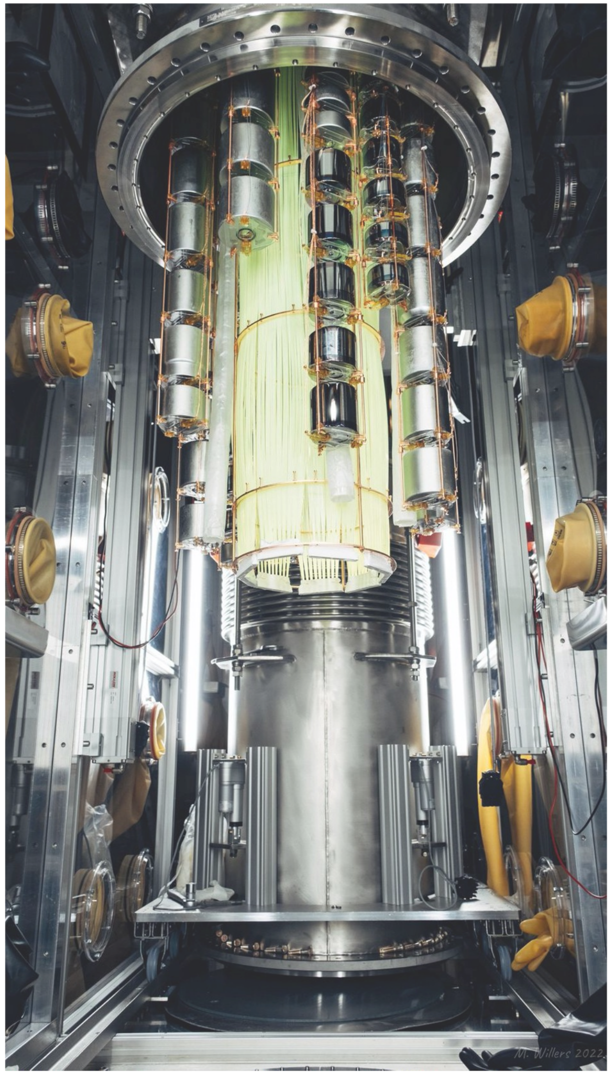






Neutrinoless Double-Beta Decay and Lepton Number Violation

Ruben Saakyan
University College London

International Neutrino Summer School
Bologna
12 June 2024

UCL

First thing I saw walking through Bologna’s “portici”

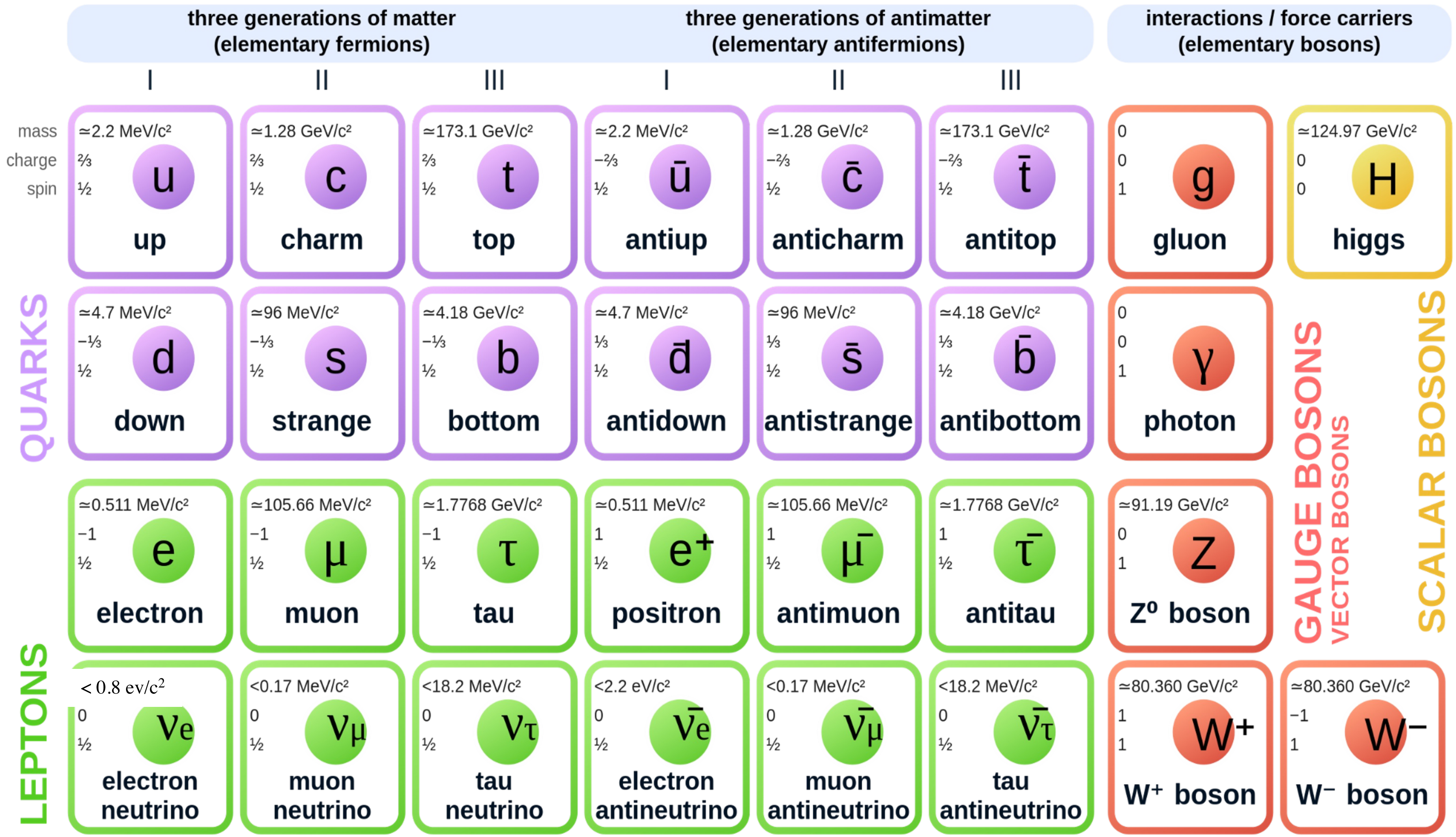
Outline

- Matter, Anti-matter, neutrinos and Lepton Number (and B-L !)
- The Standard Model and neutrino mass
- Majorana neutrino masses as bridge between matter and anti-matter
- Neutrinoless double beta decay: a matter creating process
- Experimental approaches
- Where we are and where we are heading
  - and why it is special time for $0\nu\beta\beta$!

Recent comprehensive review

Rev. Mod. Phys. 95 025002

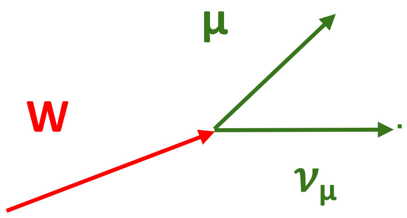
Standard Model of Elementary Particles

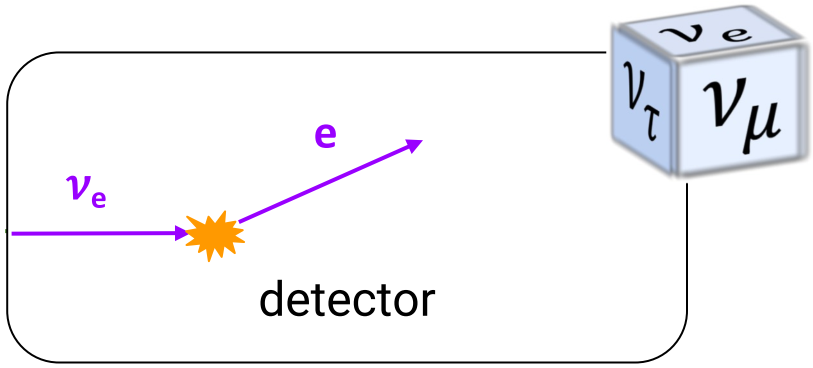


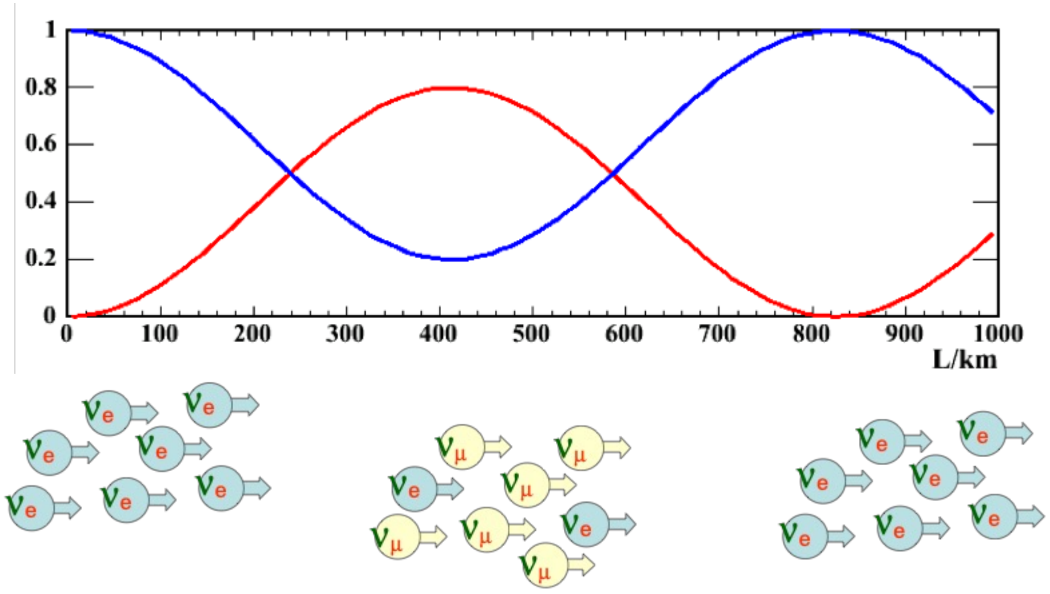
Neutrino Oscillations

"Two-flavour" case

$$|\nu_\mu > = U_{\mu 1}|\nu_1 > + U_{\mu 2}|\nu_2 >$$
$$|\nu_e > = U_{e1}|\nu_1 > + U_{e2}|\nu_2 >$$







$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{21}) \sin^2\left(k\, \Delta m^2_{21} \frac{L}{E}\right)$$

25 years of Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$
θ_{ij} : the mixing angles

δ : CP-violating phase
α, β : Majorana phases

Neutrinos have mass

Atmospheric	"Reactor/LBL"?	Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

Oscillations show **violation** of **global symmetries**

- $L_e - L_\mu$
- $L_\mu - L_\tau$
- and linear combinations (e.g. $L_e - L_\tau$)

The only **global symmetry** remaining is

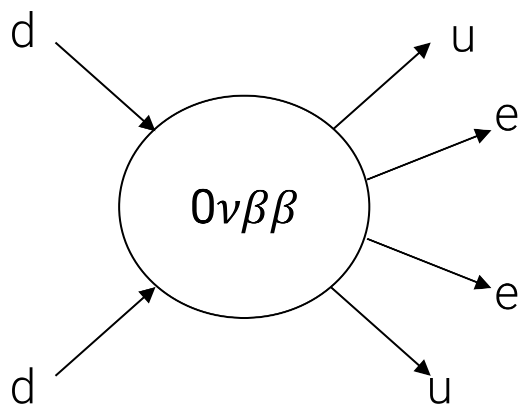
B – L

But oscillations cannot measure its absolute value

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

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

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



Would constitute a discovery of first matter-creating process

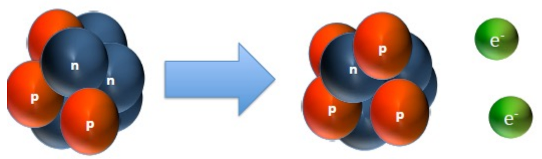
- production of leptons w/o antileptons in the lab
- direct violation of **L** and **B-L**

- Essential for matter-antimatter asymmetry generation
- Arguably, more fundamental than proton decay (violates only B)

Proton Decay: "Disappearance" of nucleons

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

L and B-L non-conservation



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

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

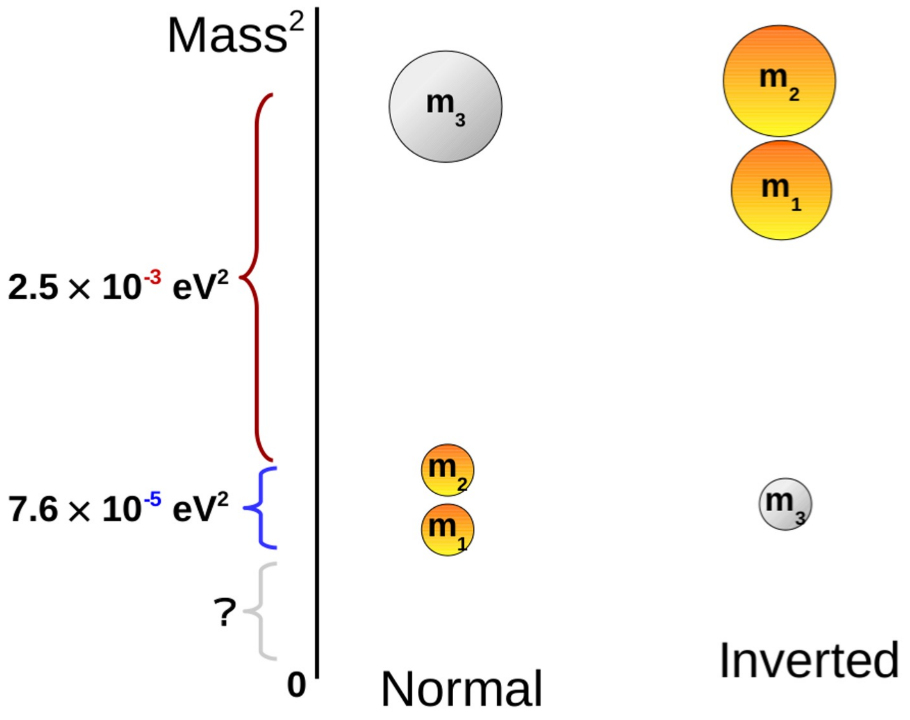
Known knowns and Known Unknowns

Knowns

- At least 2 of 3 neutrinos have non-zero mass
- neutrinos mixing probabilities
- some hints on CP-violating phase

Unknowns

- what's the absolute mass scale?
- what's the mass ordering?
- is delta CP violated?
- **what's the origin of neutrino masses?**
- **what are the fundamental symmetries?**
- **what's the origin of the matter-antimatter asymmetry in our Universe?**



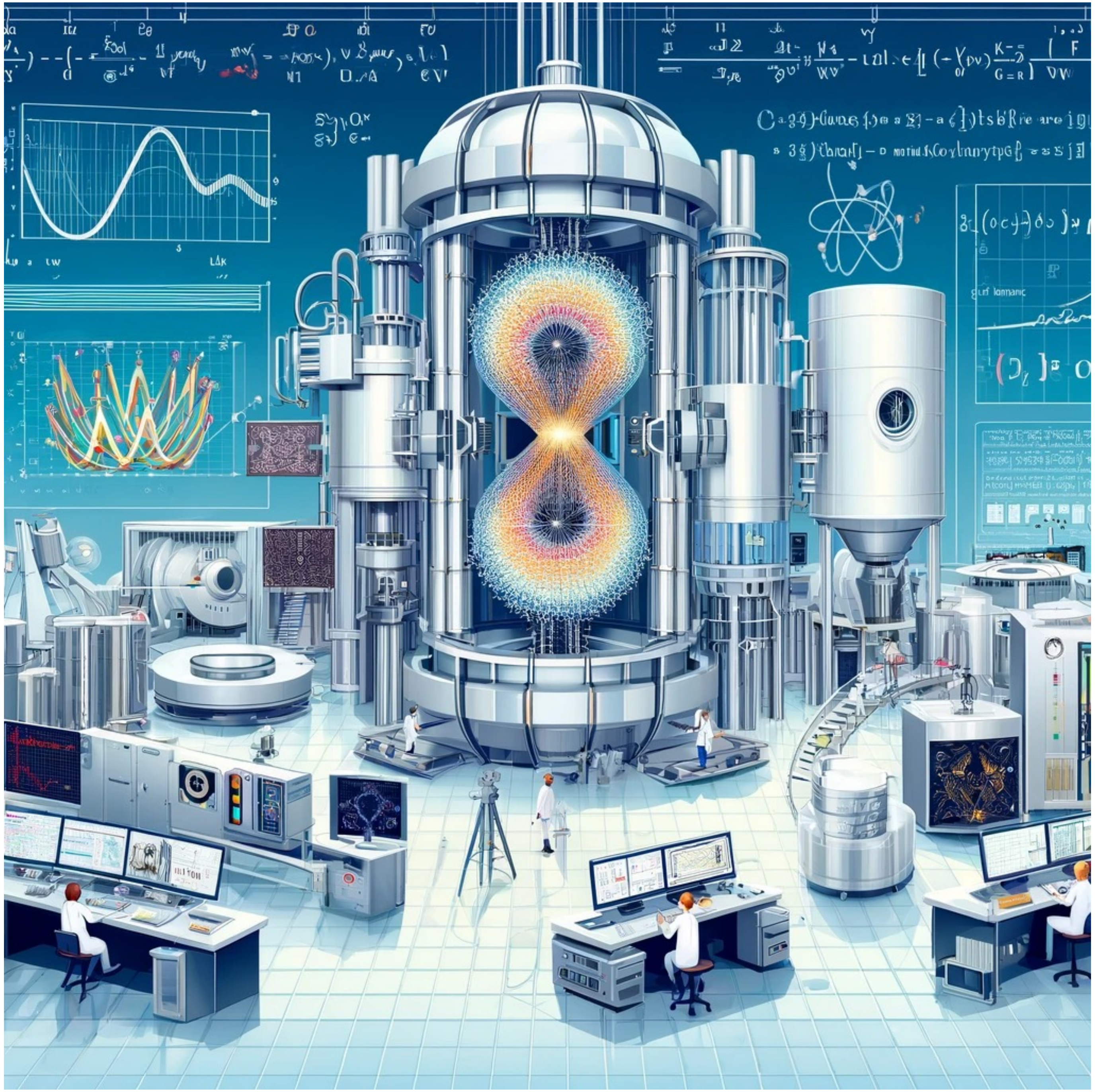
Absolute mass (eigenstates)

$$\geq \sqrt{2.5\times10^{-3}} = 0.05\ eV$$

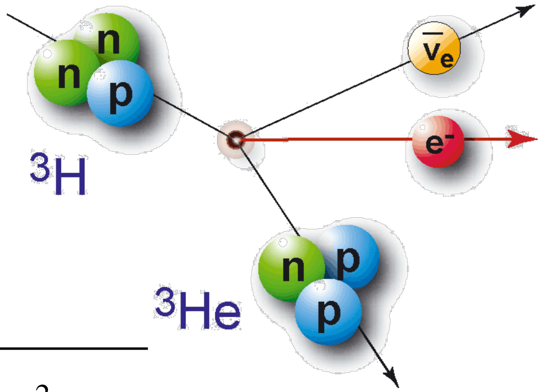
And, most likely, there are unknown unknowns

How to measure absolute neutrino mass?

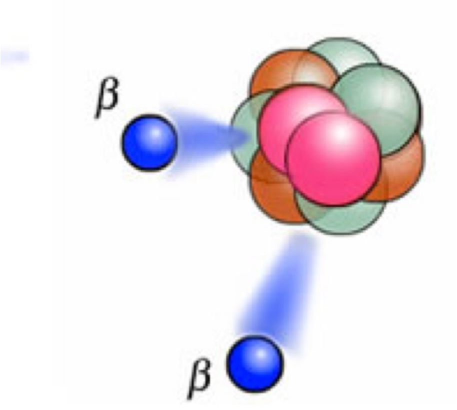
ChatGPT version



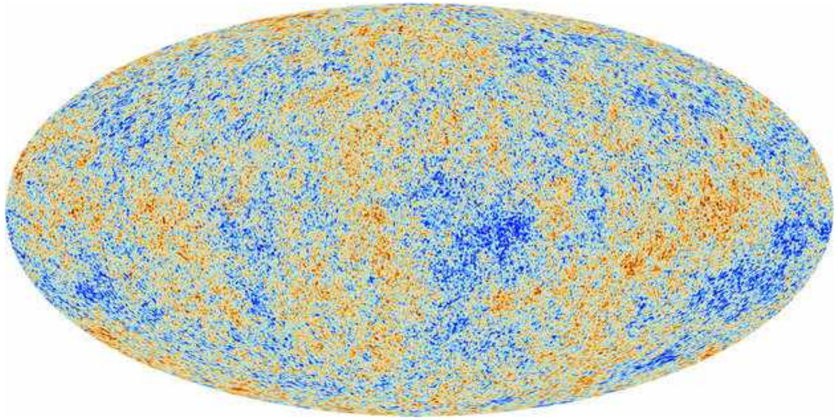
How to measure neutrino absolute mass



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



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

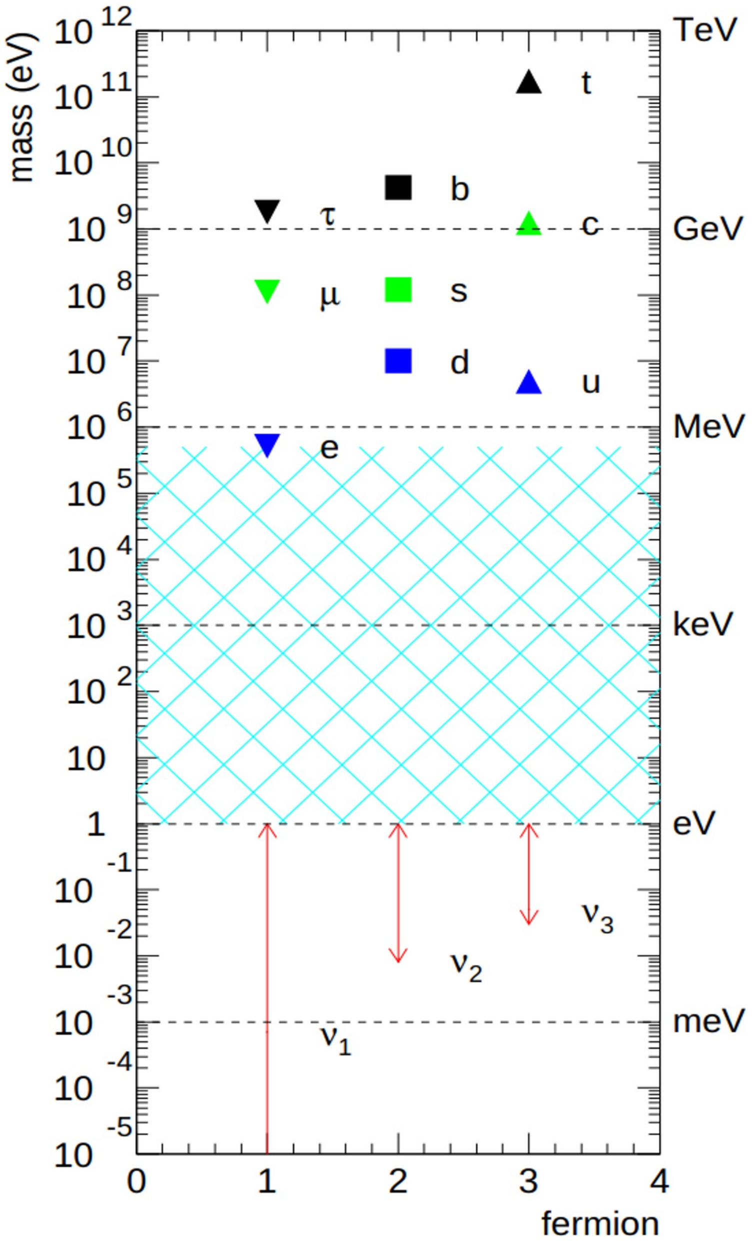


$$\sum_i m_i$$

Existing constraints

Method	ν mass parameter	Constraint	Comment
Tritium(and other) β-decay	$m_{\nu_e} = \sqrt{U_{e1}^2 m_1^2 + U_{e2}^2 m_2^2 + U_{e3}^2 m_3^2}$	< 0.8 eV 90% CL	expected soon: < 0.2 eV, Challenges to go further but there are ideas, **Low bound > 9meV!**
0νββ	$\langle m_{\beta\beta}(\nu_e)\rangle = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}$	<0.04-0.1 eV 90%CL	aim to reach 0.01 eV with next phase Only for Majorana particles
Cosmology	$\Sigma = m_1 + m_2 + m_3$	<0.3 eV (i.e. <0.1 eV “per mass”) 90%CL	Should start “seeing” neutrinos soon Strong model dependence

The smallness of neutrino masses points at new physics at high energy scale



Neutrino Mass in Standard Model

Dirac Lagrangian for neutrinos: $L = \bar{\nu}(i\gamma^{\mu}\partial_{\mu} - m_D)\nu \quad \Rightarrow \quad m_D\bar{\nu}\nu$ Dirac mass term

In terms of left and right chiral fields:

$$L_{mass} = m_D\bar{\nu}\nu = m_D(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L)$$

mass couples left and right chiral fields

In SM $m_\nu = 0$ because we do not see right-handed neutrino (or left-handed anti-neutrino)

However, if $m_\nu \neq 0$ (as we know now) the Dirac fermion interpretation is:

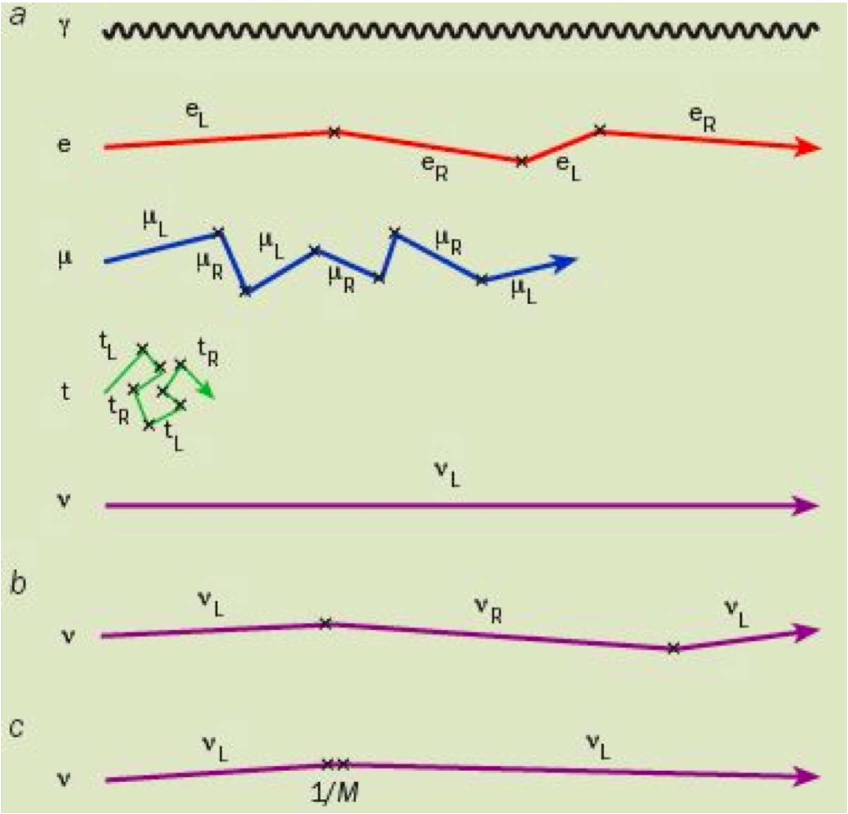
There 4 neutrinos:

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_L \\ \bar{\nu}_R \end{pmatrix}$$

two of them are "sterile"

- Gauge invariance requires introduction of Higgs field
- Dirac mass terms conserves lepton number

Neutrino Mass in Standard Model



Higgs Mechanism

$$m_D = g_\nu \frac{\langle \varphi \rangle}{\sqrt{2}}$$

$\langle \varphi \rangle$ ~ 246 GeV — V.E.V.

g_ν ~ Yukawa coupling

m_D ~ Dirac fermion mass

From current constraints on m_ν (~0.1eV scale):

- $g_\nu < 10^{-13}$
- Sterile ν_R needs to be added to SM

Requires fine tuning of neutrino Yukawa coupling down to unnaturally tiny values

- In 1937 Ettore Majorana suggested an alternative with only two active neutrinos
- Massive neutrino could be described using a single left-handed field.

Recall Charge Conjugation operator $C = i\gamma^2\gamma^0$ The right-handed field can be constructed with $\nu_L^C = C\overline{\nu}_L^T$

You can check it is right-handed by applying $P_L(C\overline{\nu}_L^T) = \frac{1}{2}(1-\gamma^5)(C\overline{\nu}_L^T) = 0$

The Majorana field becomes $\nu = \nu_L + \nu_R = \nu_L + \nu_L^C$

and $\nu^C = (\nu_L + \nu_L^C)^C = \nu_L^C + \nu_L = \nu$ **i.e. particle=antiparticle**

- **The only fundamental fermion for which this is possible is the neutrino**

  Other particles have non-zero electric charge

Majorana Mass Term

$$L_M = \frac{1}{2} m_L (\overline{\nu}_L^C \nu_L + \overline{\nu}_L \nu_L^C)$$

The Majorana mass term couples neutrino and anti-neutrinos.

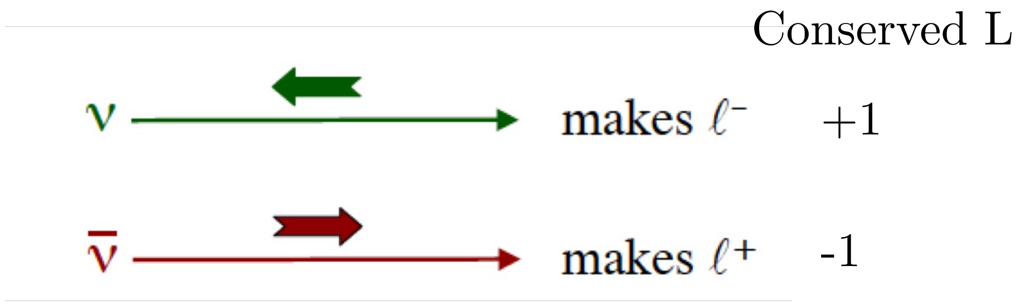
$\Delta L \neq 0\ (=2)$ ⇒ $0\nu\beta\beta$

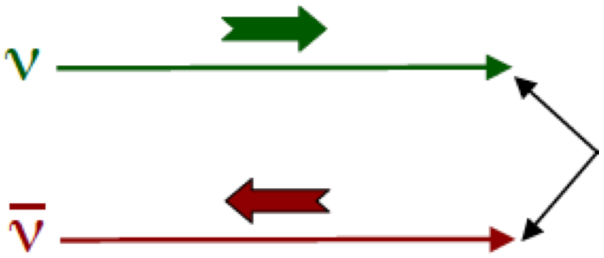
- "Price" to pay: Lepton Number Violation
- Turns out to be a good thing:
  - Accidental symmetry
  - Requires by (almost all) Grand Unification Theories)

What distinguishes neutrino and “anti”-neutrino?

Standard Model Interactions of
Dirac Neutrinos

4 mass-degenerate states

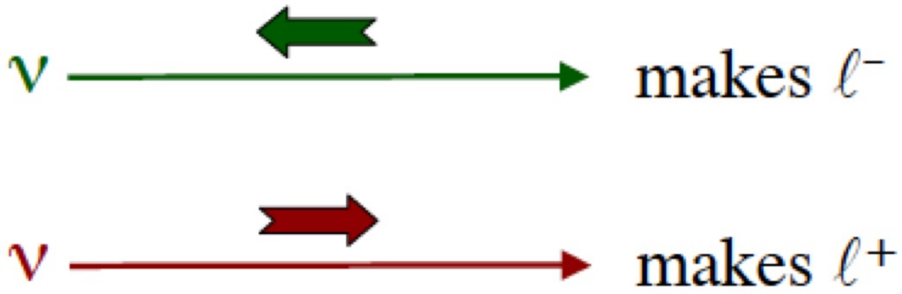




These states do not interact, “sterile”.

Standard Model Interactions of
Majorana Neutrinos

There is only one neutrino, 2 mass-degenerate states



Left-handed Majorana neutrino makes l^-

Right-handed Majorana neutrino makes l^+

- The problem is that $m_L \bar{\nu}_L^C \nu_L$ is not gauge invariant

  - One could make it gauge invariant by introducing a Higgs triplet

  - An alternative is to introduce heavy right-handed neutrino that only interacts with Higgs field and gravity – the **SEESAW Mechanism**

- Either way the non-zero neutrino mass implies **BSM Physics**.

  (I) Right-handed state exists with a standard mass mechanism

  (II) Higgs triplet

  (III) **Different mass mechanism, e.g. SEESAW**

The See-Saw Mechanism

(there are more than one type shown below)

Assume two Majorana neutrinos, one very light and one very heavy

$$L_{mass} \sim L_L^D + L_R^D + L_L^M + L_R^M + h.c. = m_D \bar{N}_R \nu_L + m_D \bar{\nu}_L^C N_R^C + m_L \bar{\nu}_L^C \nu_L + m_R \bar{N}_R^C N_R + h.c.$$

which can be written in a matrix form

$$L_{mass} \sim \begin{pmatrix} \bar{\nu}_L^C & \bar{N}_R \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix} + h.c.$$

Right-handed fields

Non-diagonal

Left-handed fields

Due to non-zero off-diagonal m_D the fields ν_L, N_R do not have definite masses

ν_L, N_R are superposition of state with definite mass ν, N

$$\begin{pmatrix} \nu_L \\ N_R \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

ν is mostly ν_L, N is mostly N_R

The See-Saw Mechanism

Diagonalise matrix to rewrite Lagrangian in terms of mass eigenstates

$$M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \quad \longrightarrow \quad M' = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

$$m_{1,2} = \frac{1}{2}\left[\left(m_L + m_R\right) \pm \sqrt{\left(m_L - m_R\right)^2 + 4m_D^2} \right]$$

From gauge invariance $m_L = 0$ and we choose $m_R >> m_D$ Therefore

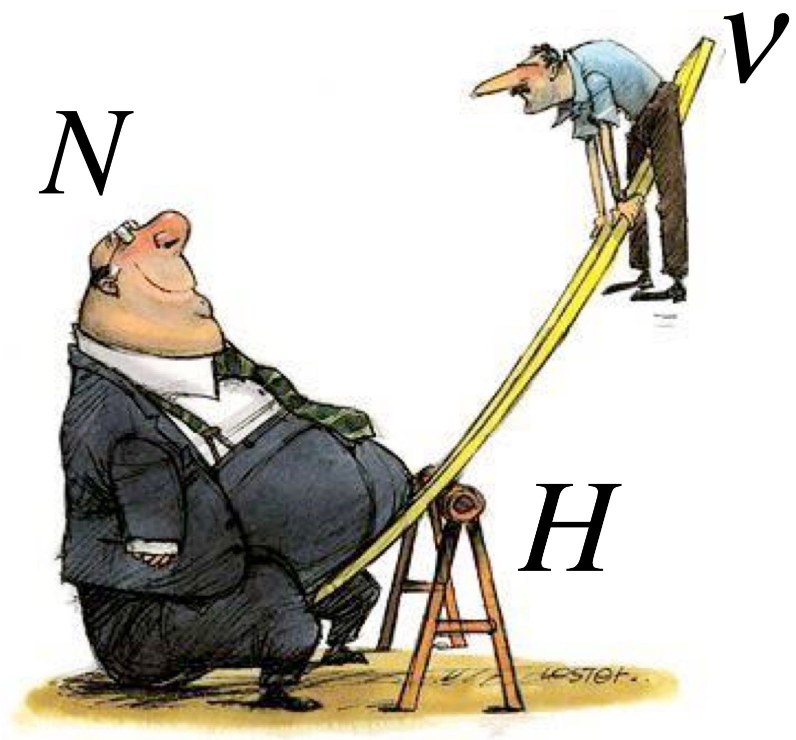
$$m_1 = \frac{m_D^2}{m_R} \qquad m_2 = m_R\left(1 + \frac{m_D^2}{m_R^2}\right) \approx m_R$$

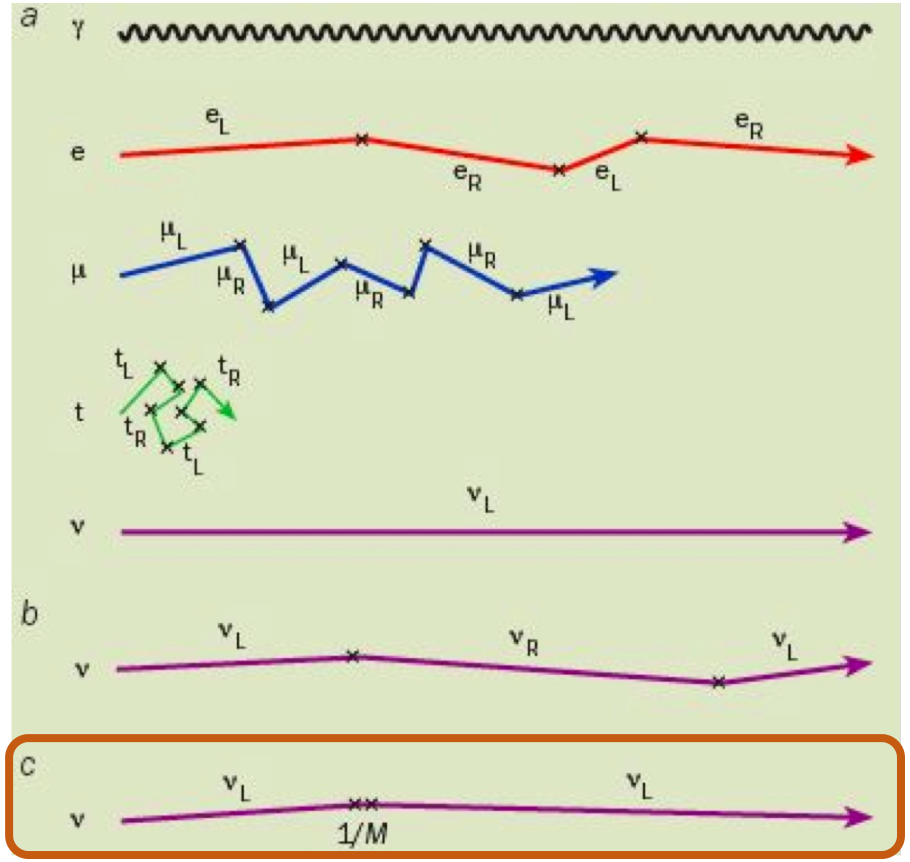
light neutrino mass we see in experiments

Heavy sterile neutrino

Recall: $\nu(m_1)$ is mostly ν_L, $N(m_2)$ is mostly N_R

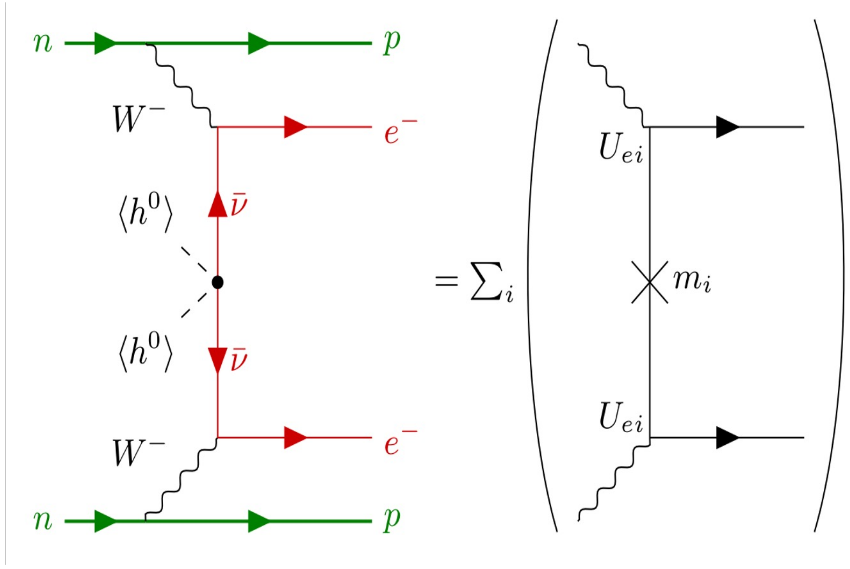
The See-Saw Mechanism





If $m_D \sim 1$ GeV and $m_\nu \sim 0.1$ eV, $m_R \equiv M = \dfrac{m_D^2}{m_\nu} \sim 10^{19}$ eV ⇒ **Link to GUT, natural smallness of neutrino mass**

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



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

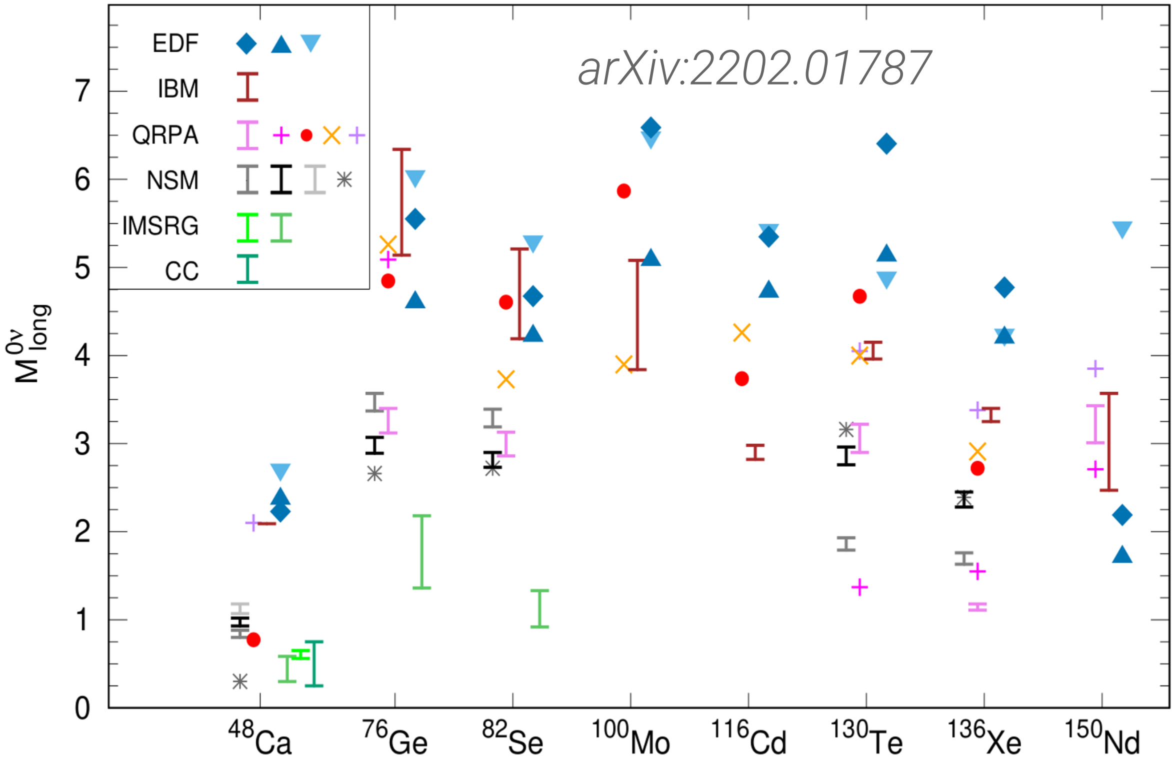
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

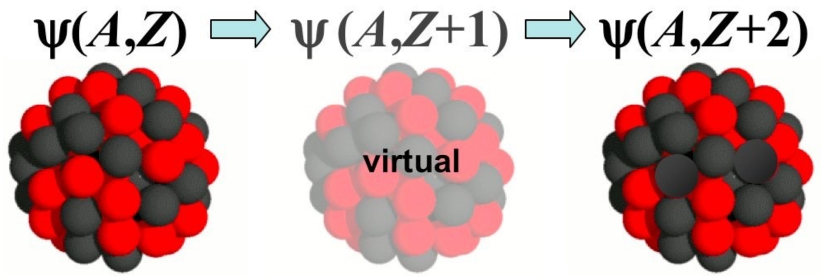
$c_{12} = cos\theta_{12}, c_{13} = cos\theta_{13}, s_{12} = sin\theta_{12}, s_{13} = sin\theta_{13}$

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

- Minimal extension of SM
- Access to absolute neutrino mass
- 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
- *Ab-initio* methods look promising
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

$0\nu\beta\beta$. A portal to new physics beyond SM

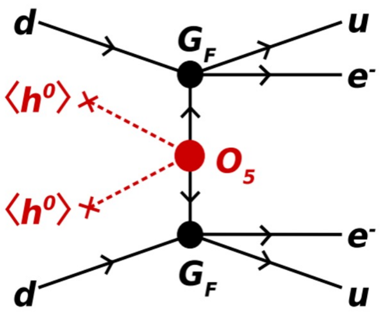
$$\frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

Dim 5: Weinberg Operator

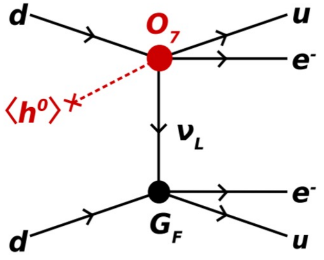
$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\lambda}\right)^2 \quad \text{with } \frac{\nu}{\Lambda} \propto \frac{m_{\beta\beta}}{m_e}$$



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

Dim 7

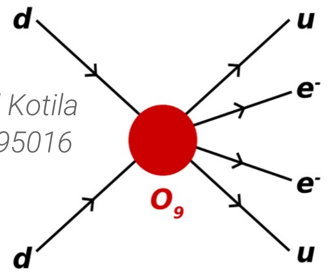
$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^6$$



Dim 9

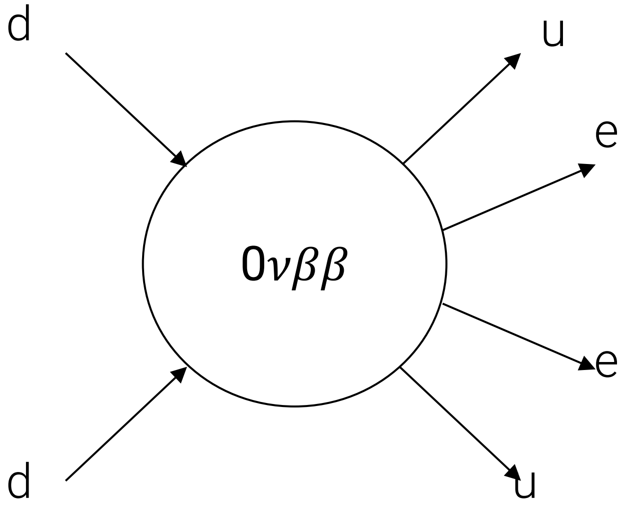
$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^{10}$$

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)
- That includes Heavy Neutral Leptons and many other

Schechter and Valle, PRD 25, 2951 (1982)



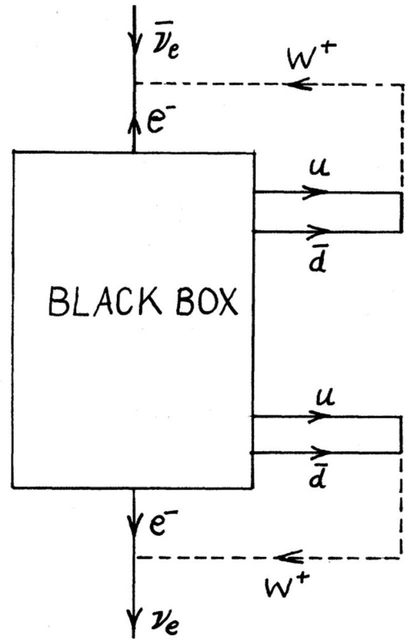
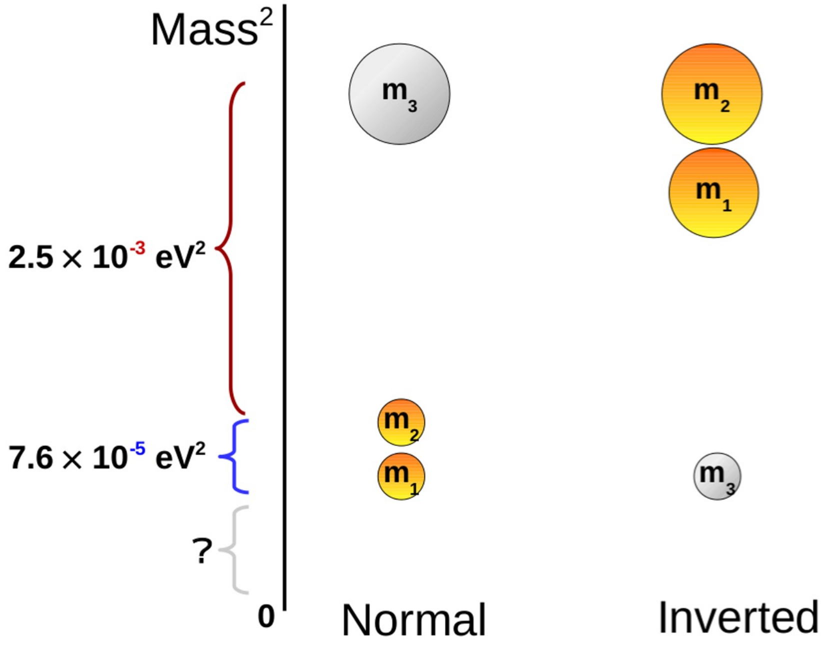


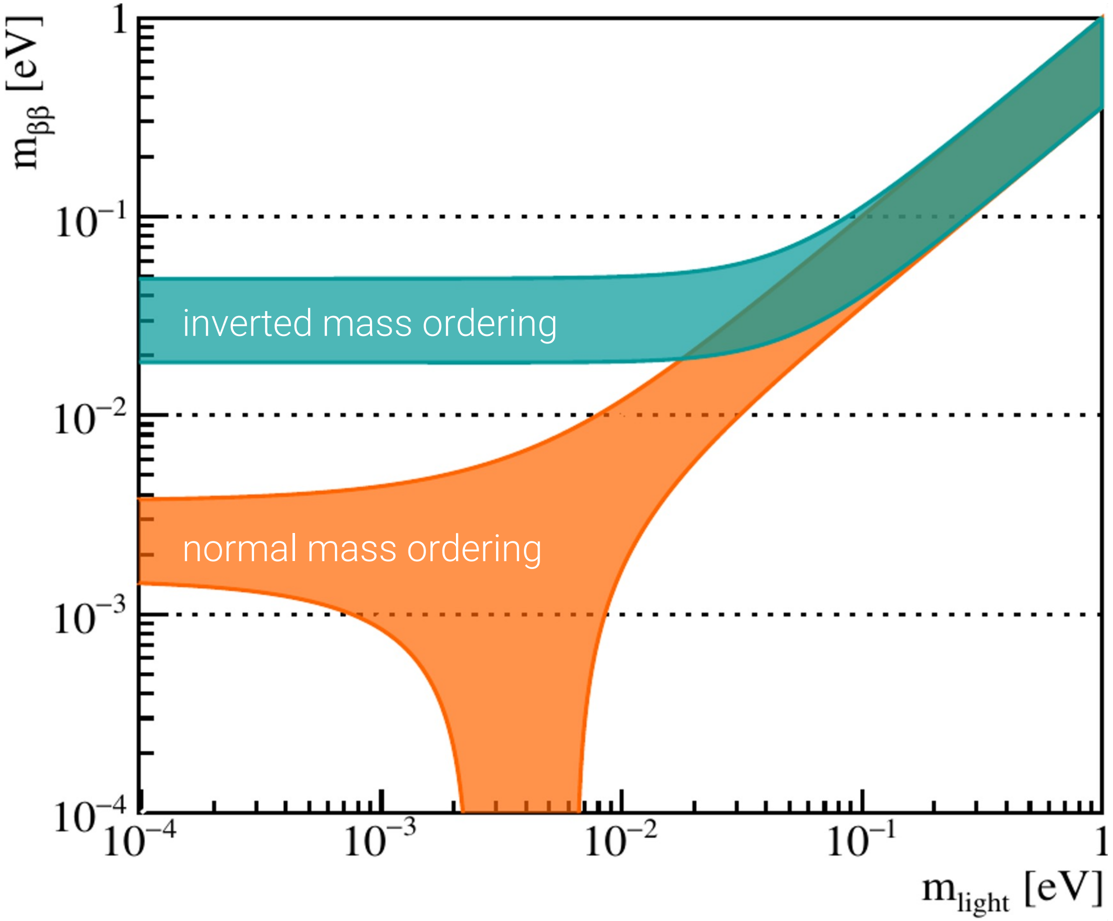
FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

Observation is <u>unambiguous evidence</u> for

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

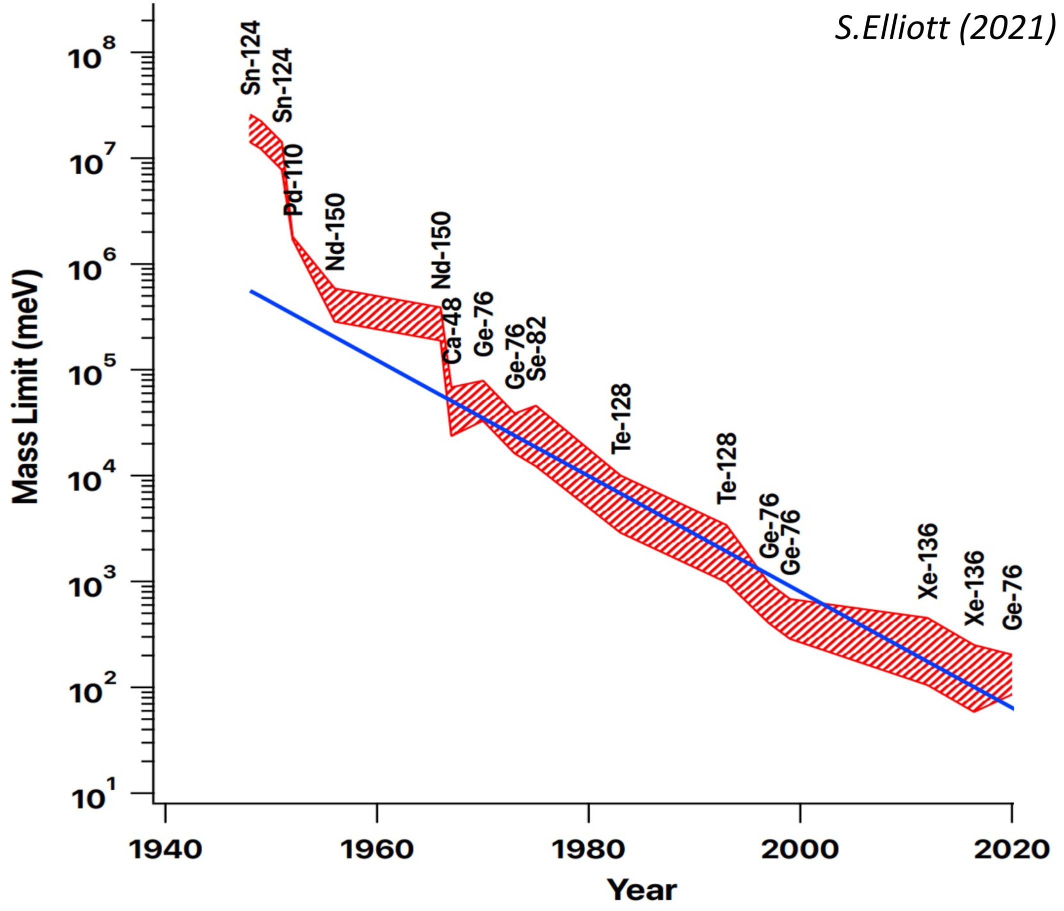
$m_{\beta\beta}$, neutrino oscillations and mass ordering

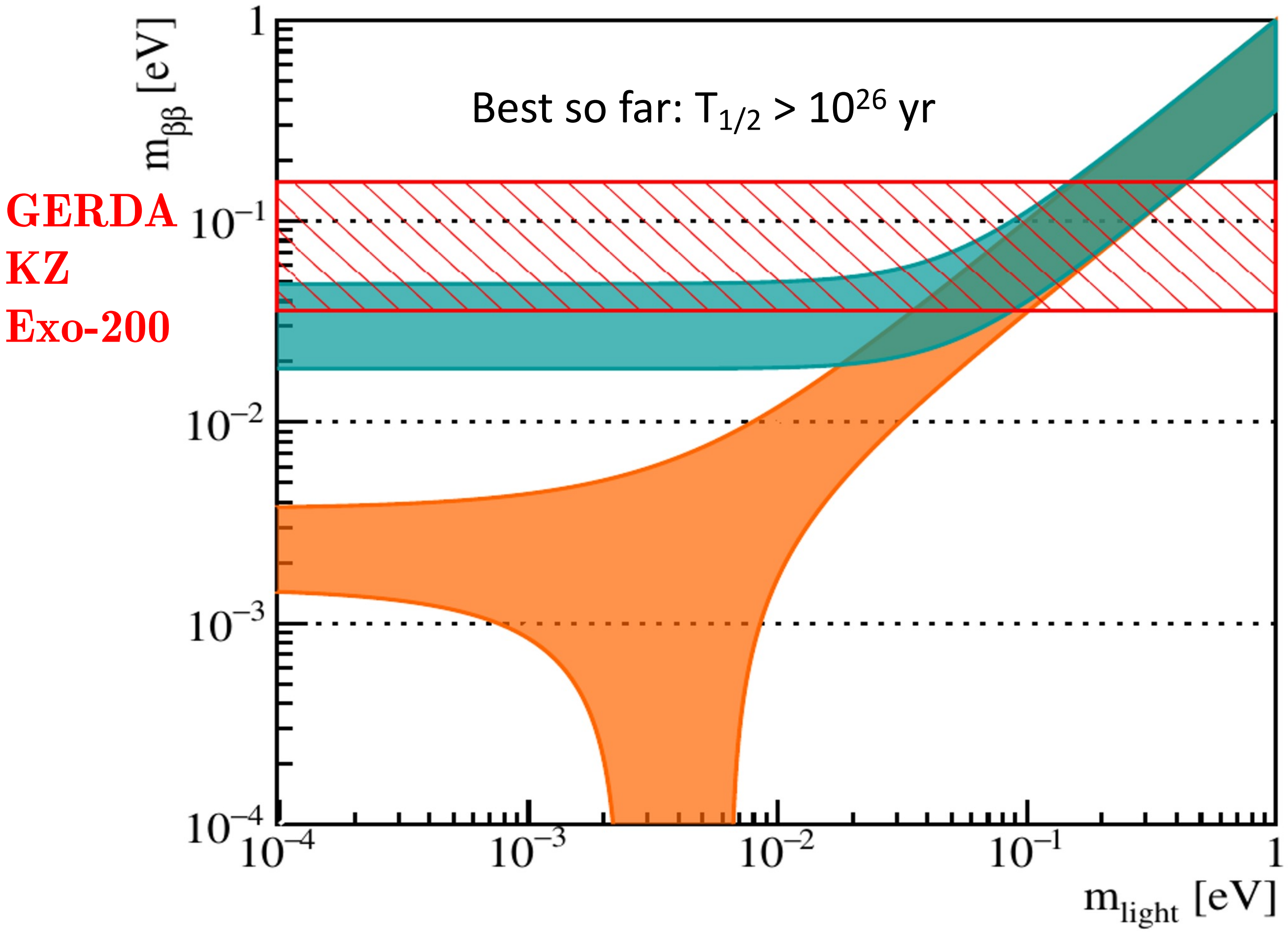




$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

0νββ with $m_{\beta\beta}$. Where are we so far?





Experimental Approaches

Abstract

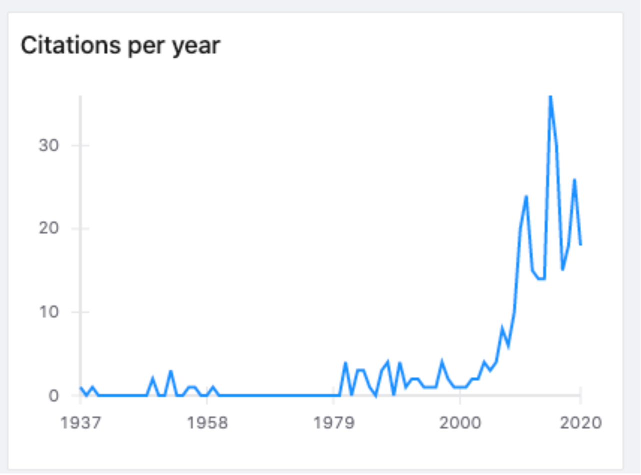
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different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

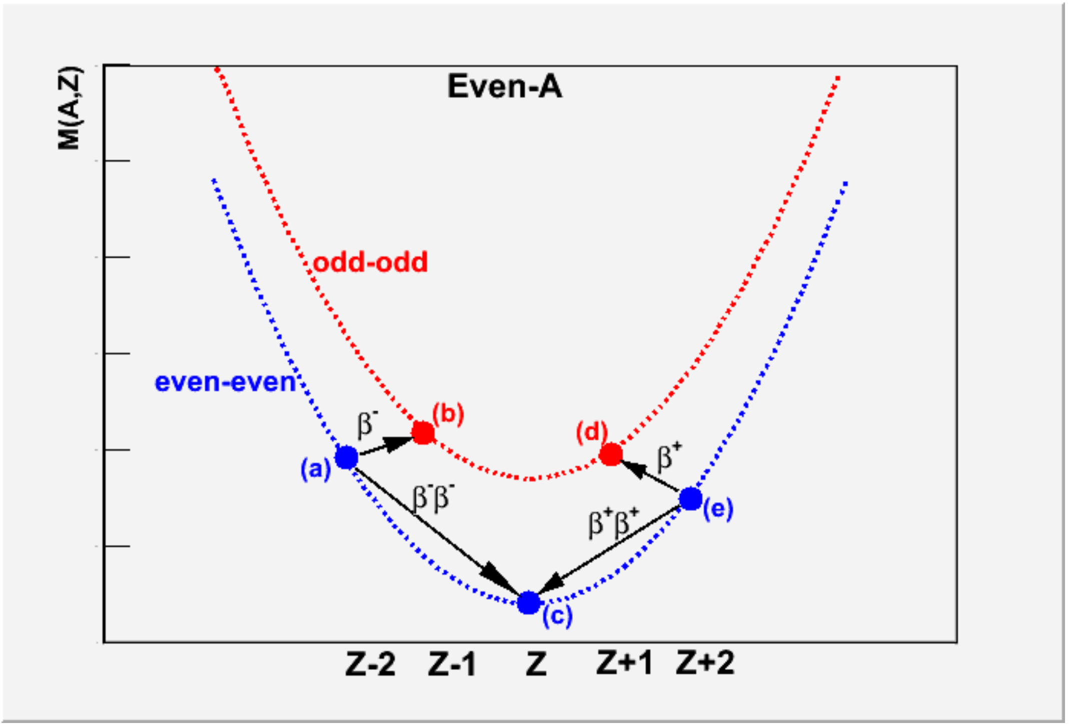
M. Goepert-Mayer

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

Nobel Prize (1963) for Nuclear Shell Model

1939: Furry $0\nu\beta\beta$





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

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

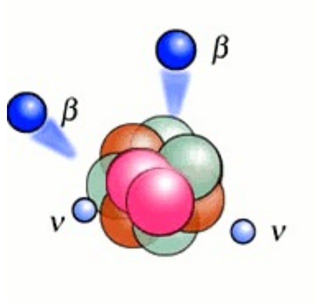
Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	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

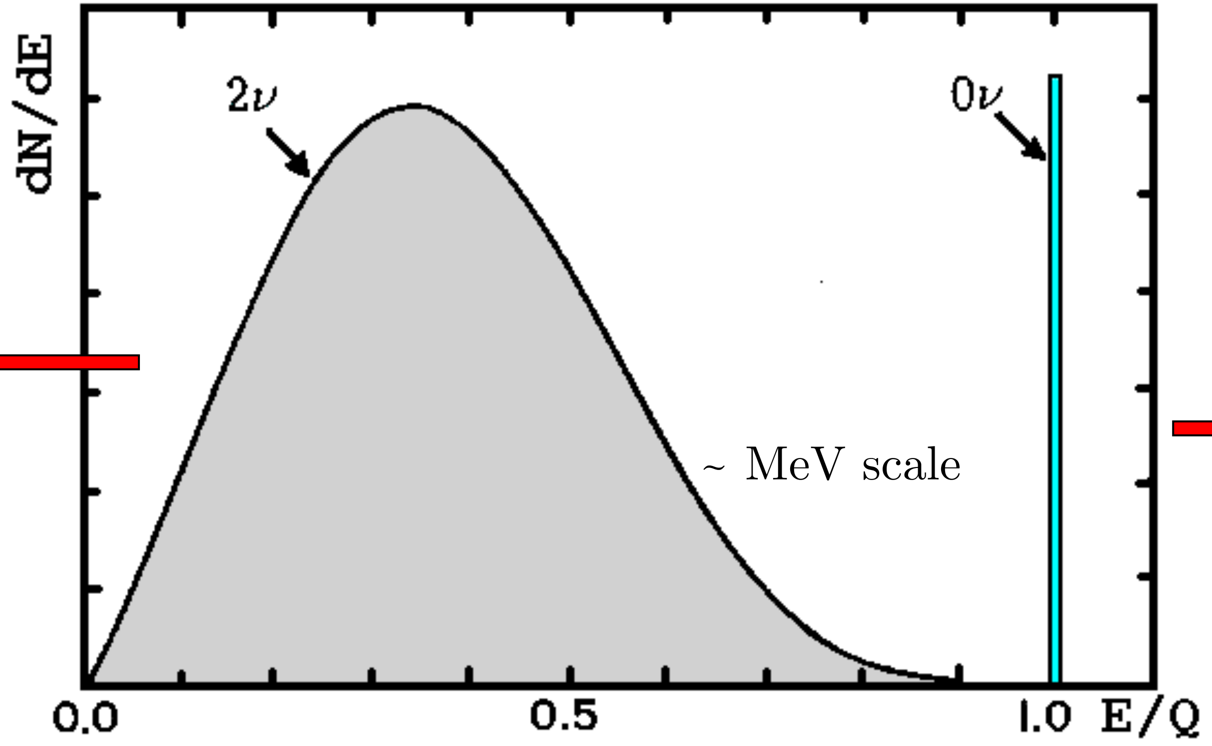
Experimental Observables

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

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

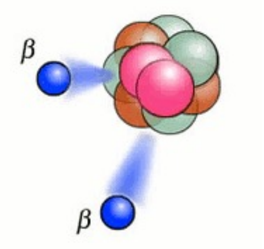
$T_{1/2} \sim 10^{19} - 10^{24}$ yr!





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

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



$$\Gamma^{2\nu} = \frac{1}{T_{1/2}^{2\nu}} = G^{2\nu} g_A^4 \left|M^{2\nu}\right|^2$$

Want to maximise Q_{bb} to boost phase space, and minimise backgrounds from natural radioactivity

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

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

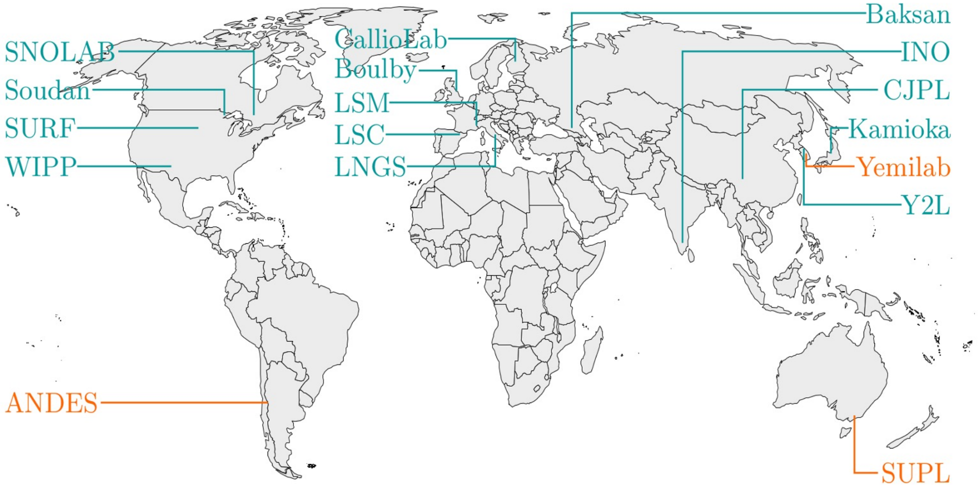
Sensitivity and requirements

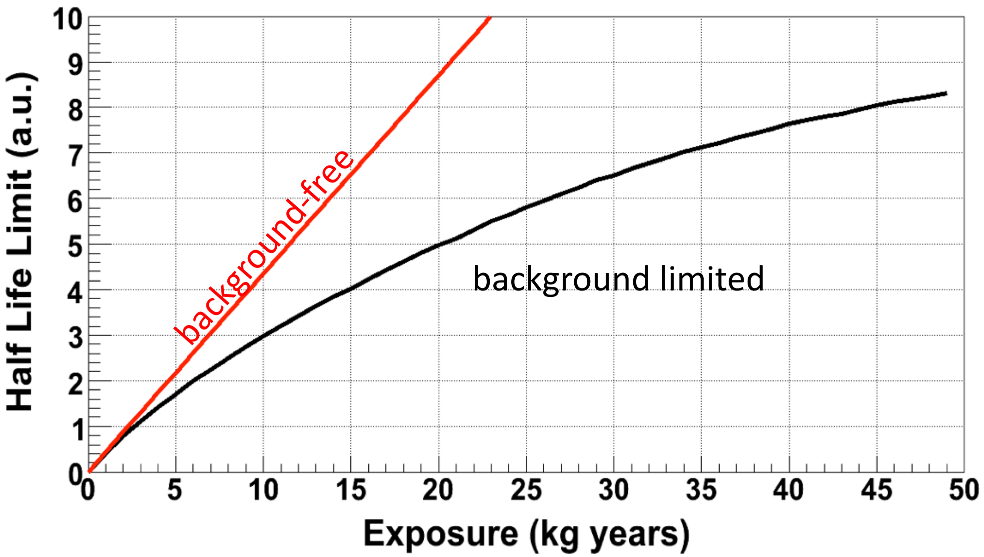
maximise **detection efficiency** and ββ **isotope abundance**

maximise **exposure**

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

minimise **background**

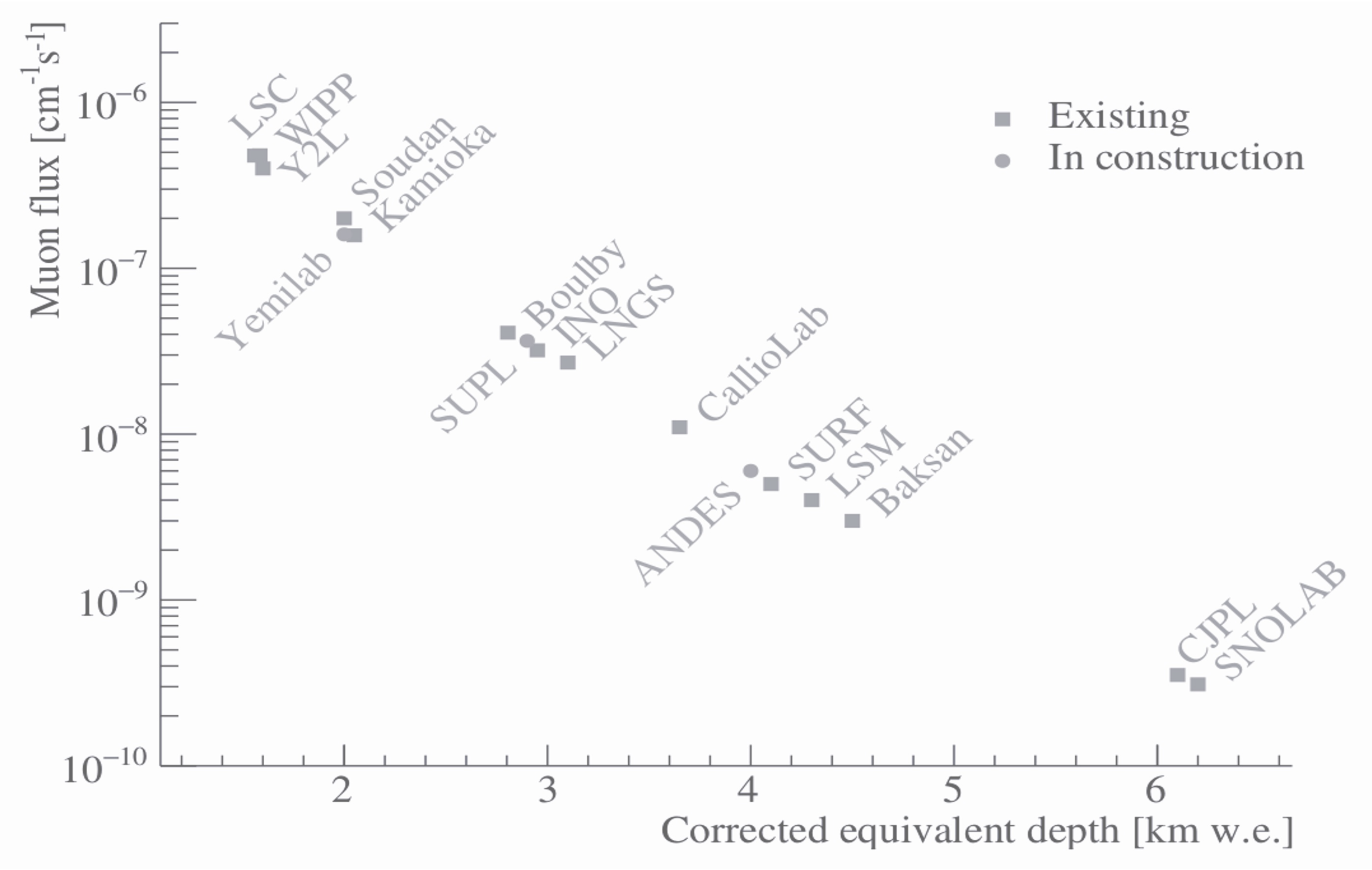


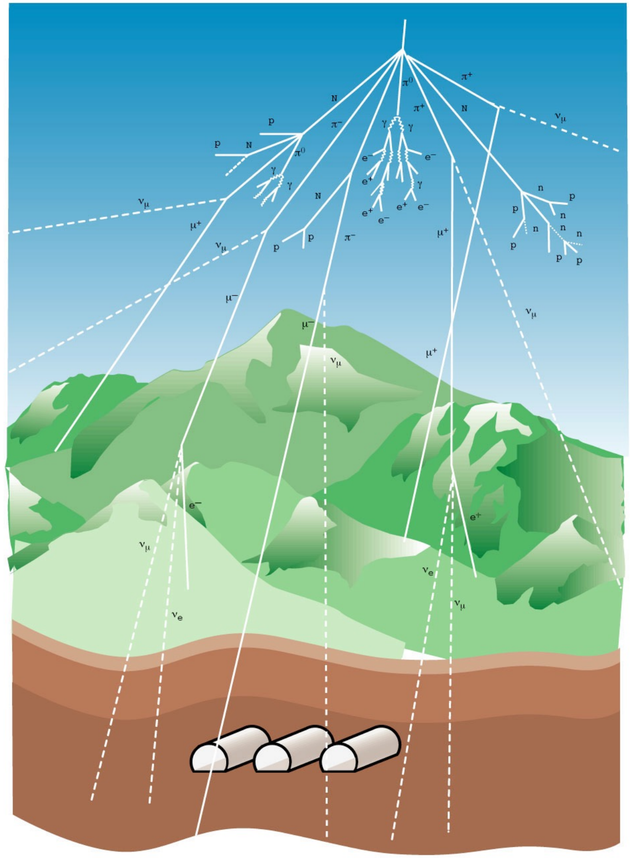


It's all about *backgrounds*

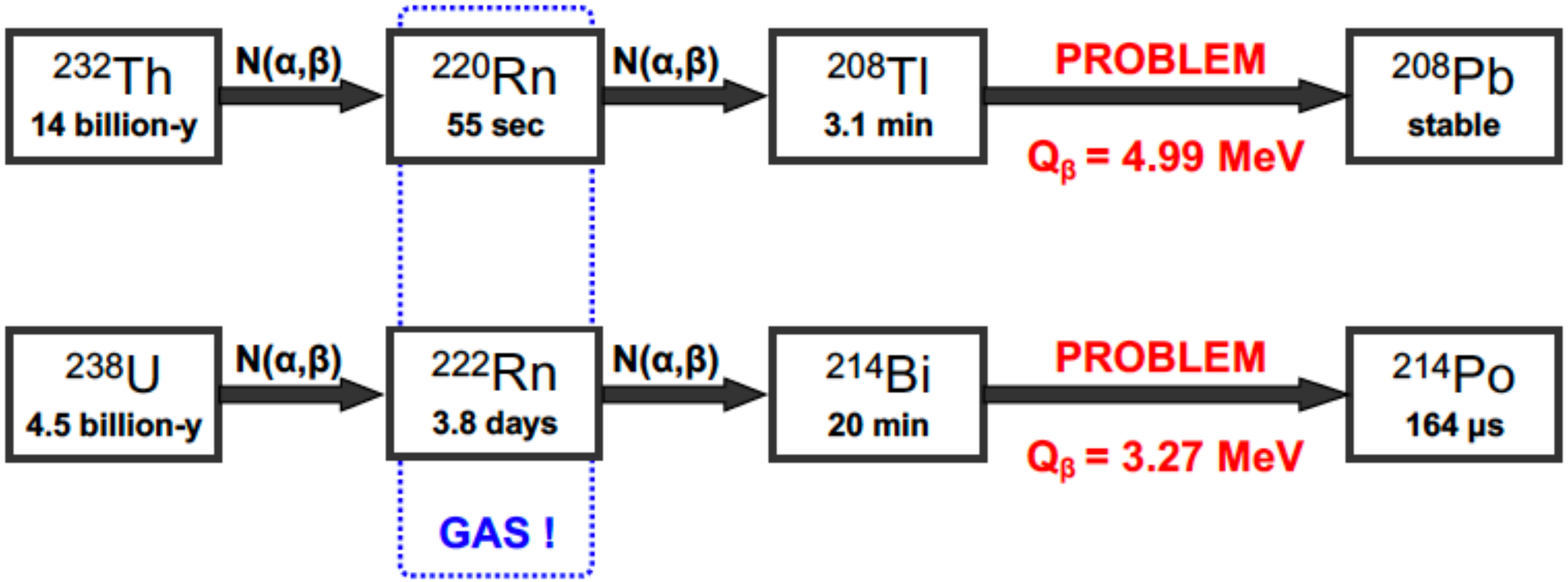
- Cosmic rays (underground)
- Natural radioactivity (clean materials, particle id and tagging)
- Standard Model $2\nu\beta\beta$ (energy resolution)

Underground Laboratories





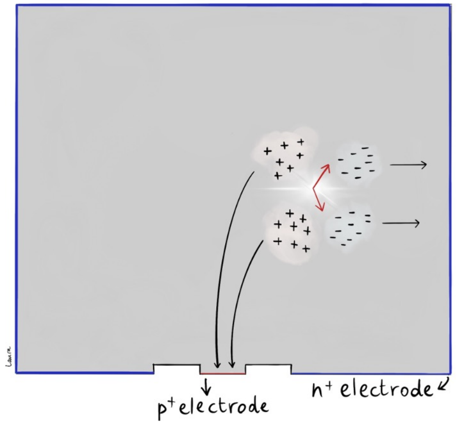
Natural Radioactivity



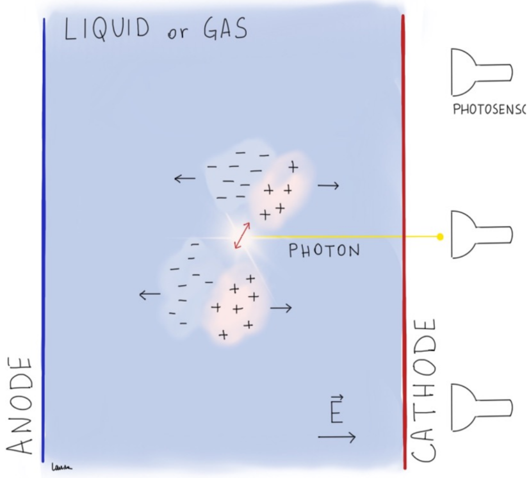
- Many other potential sources including cosmogenics, “degraded” alphas etc.
- Natural radioactivity falls very rapidly above ~3 MeV.
- What can be done ?
  - Extremely careful material selection.
  - Purification techniques.
  - Barriers against radon penetration.
  - Vetos & active shielding.
  - Background tagging/identification techniques - e.g. single-site ($0\nu\beta\beta$) versus multiple-site (γ)

Experimental Techniques

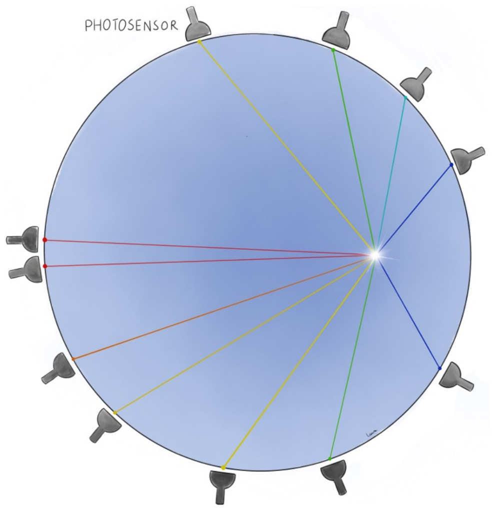
Ge Semiconductor detectors (^{76}Ge)



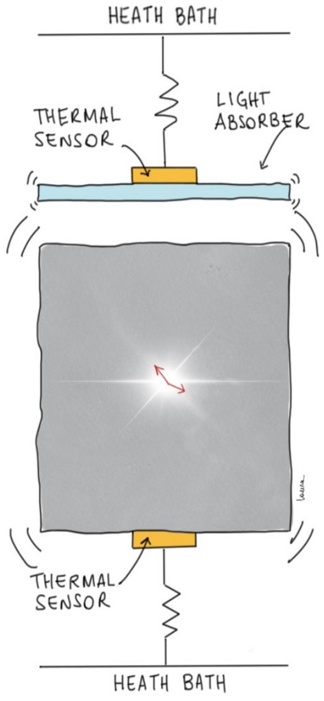
Xe Time Projection Chambers (^{136}Xe)



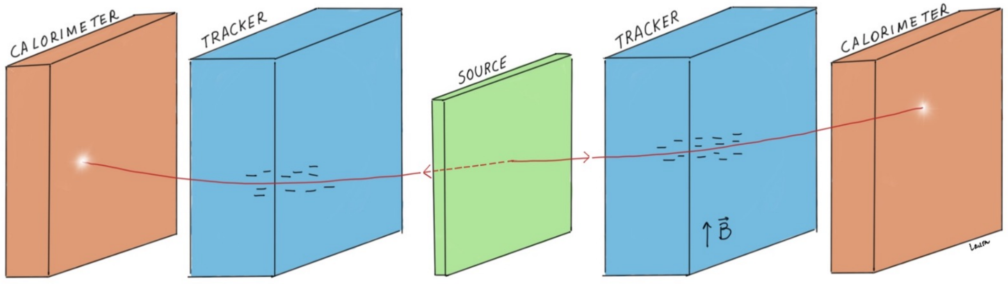
Large Liquid scintillator detectors (^{130}Te, ^{136}Xe)



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



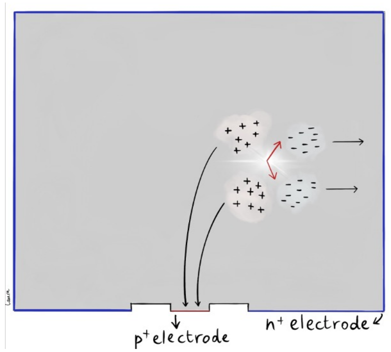
Passive source surrounded by detectors (^{100}Mo, ^{82}Se, ^{150}Nd, other)

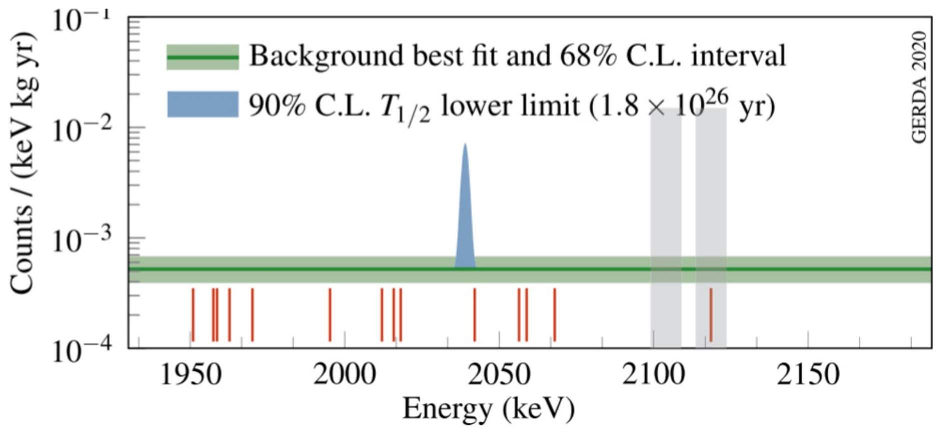


Drawings courtesy of Laura Manenti

Enriched HPGe in LAr

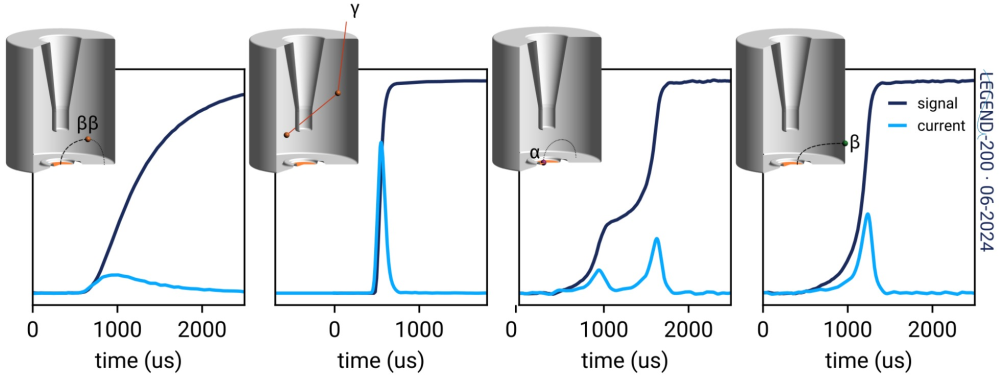
- ionization and charge drift
- $< 0.1\%$ energy resolution
- Ar shield and scintillation light
- advanced event topology

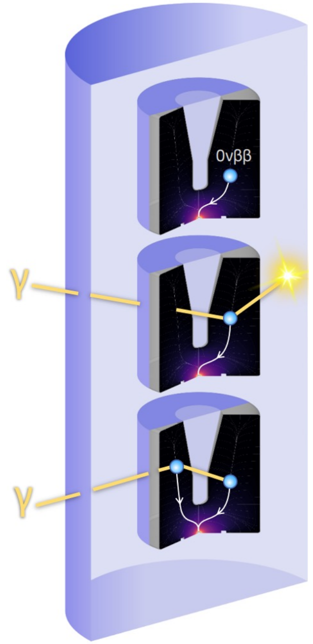




GERDA PRL 125 (2020)

- **GERDA/MAJORANA** (40 kg), lowest background
- **LEGEND-200** (200 kg) in data taking since 2023, good performance and background released at TAUP, first physics unblinding at _Neutrino'24 next week_!
- **LEGEND-1000** (1 t) designed to be reviewed next year, baseline design at LNGS, data taking by 2030

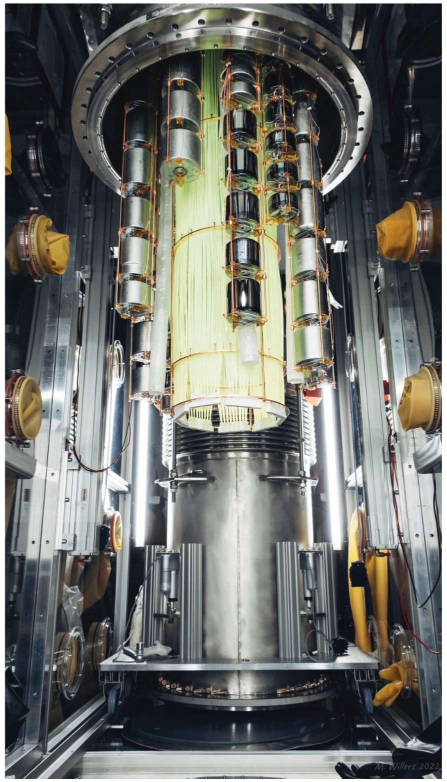




LEGEND

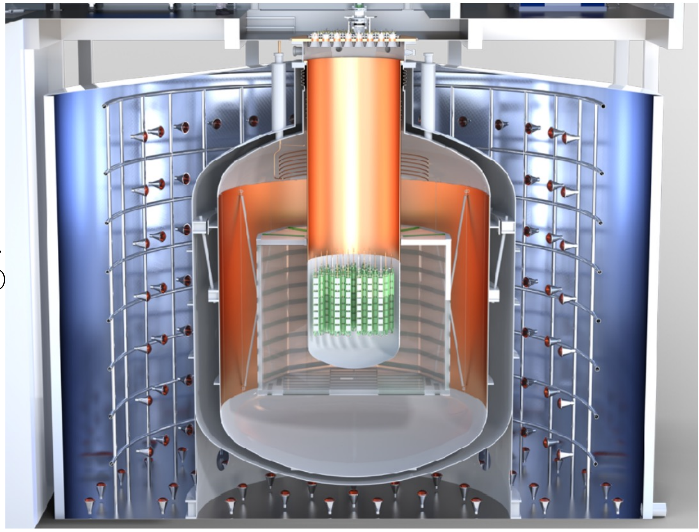
LEGEND-200

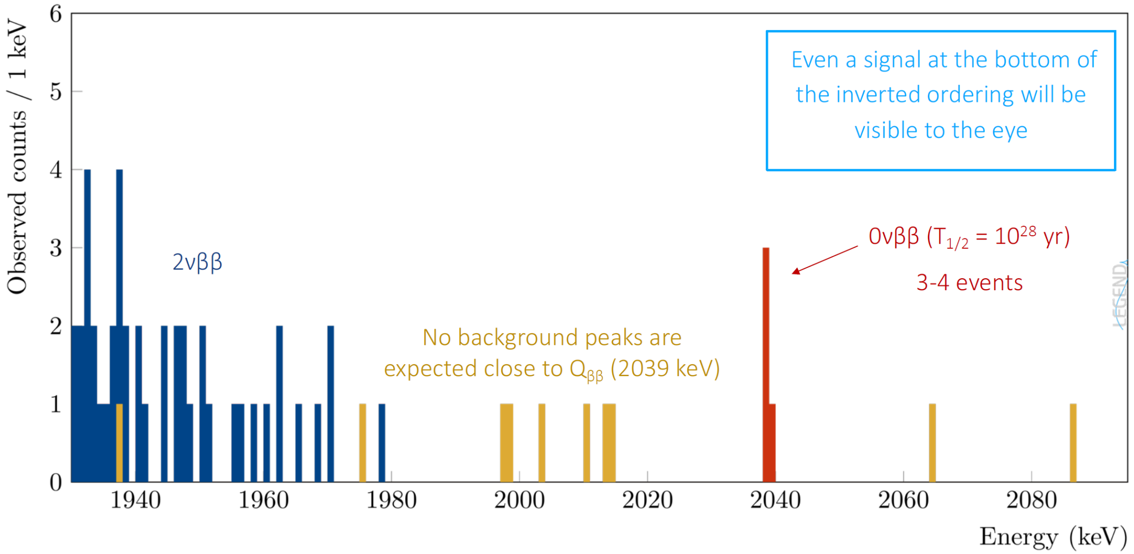
- 200kg ^{76}Ge enriched > 88%
- BG goal: < 0.5 cts/FWHM t yr)
- Physics run with 10 strings (142kg) since Mar-2023 at LNGS



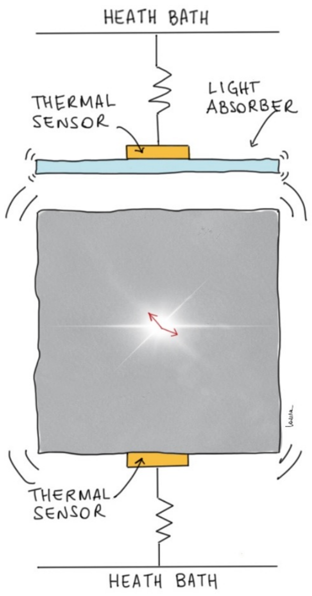
LEGEND-1000

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

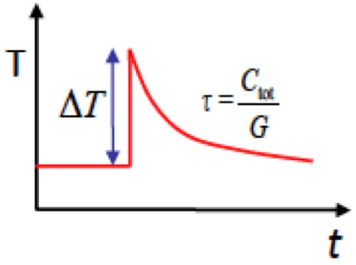




Cryogenic Calorimeters



$$\Delta T \cong \frac{E}{C_{tot}}$$



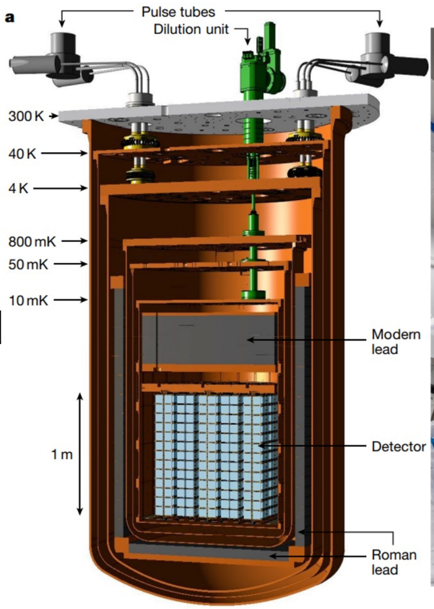
- temperature variation and scintillation light
- particle identification and good resolution
- array of enriched crystals operated at ~10 mK

CUORE

- 742 kg TeO_2 (206 kg ^{130}Te), 988 crystals
- 2 tonne years of exposure, still running at LNGS

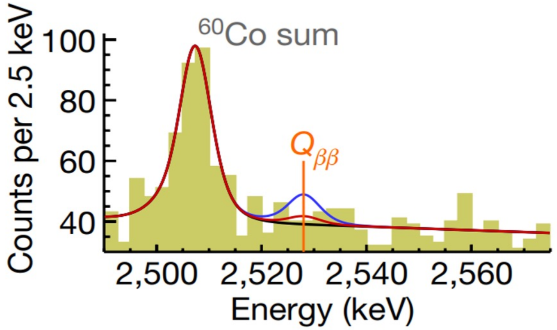
CUPID

- reusing CUORE existing infrastructure
- scintillating bolometer Li_2MoO_4 technology demonstrated by CUPID-Mo
- particle identification



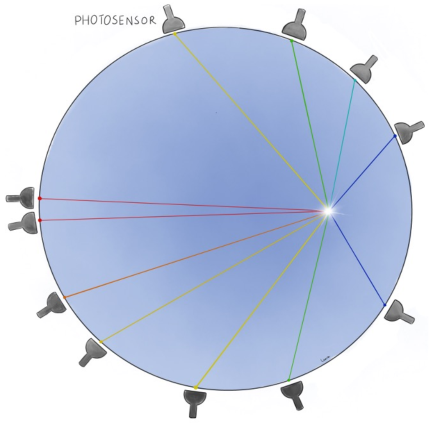
CUORE, Nature 604 (2022)

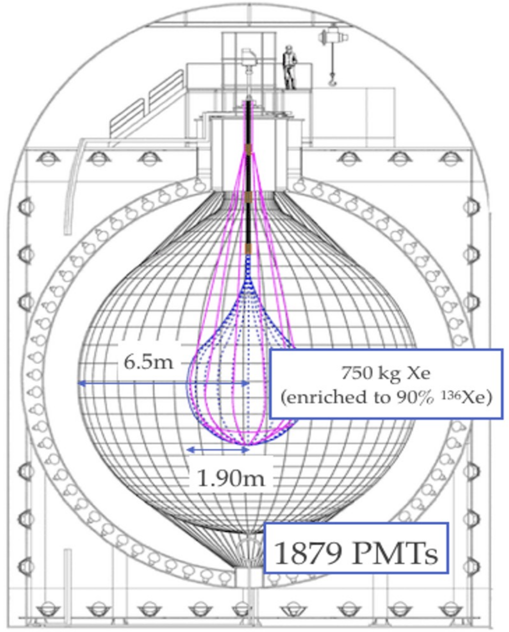
$$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25} \text{ yr}$$



Large loaded liquid scintillators

- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization



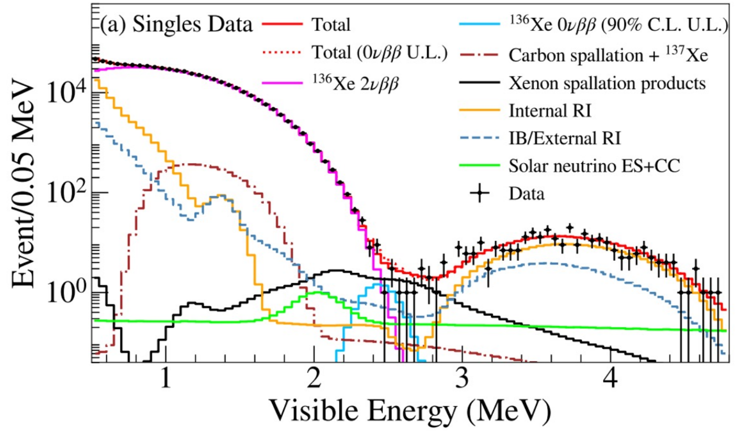


KamLAND-Zen-800@Kamioka
- 750 kg of ^{136}Xe in nylon balloon
- backgrounds: $2\nu\beta\beta$, cosmogenic, solar neutrinos, ^{214}Bi on balloon

KamLAND2-Zen@Kamioka
- new light concentrators and PMTs with higher quantum efficiency
- purer scintillator

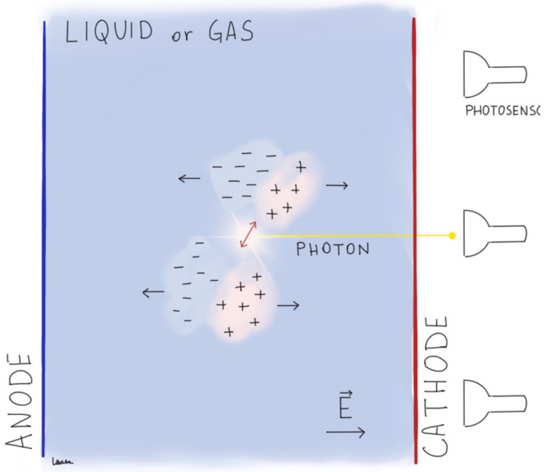
SNO+@SNOLab
- Te loaded scintillator up to 2.5-3%

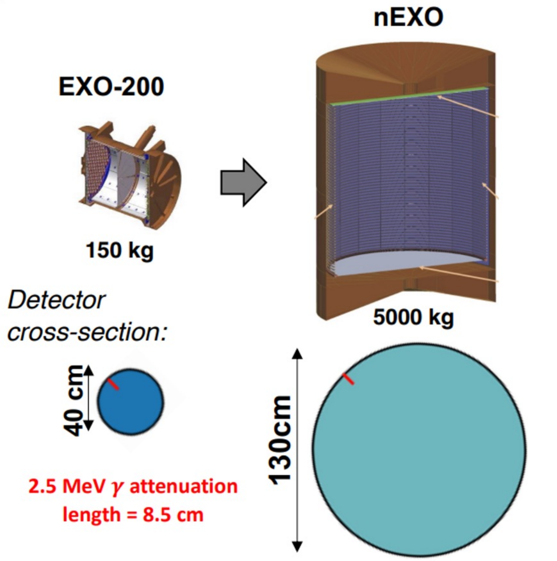
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at 90\% C.L.}$$

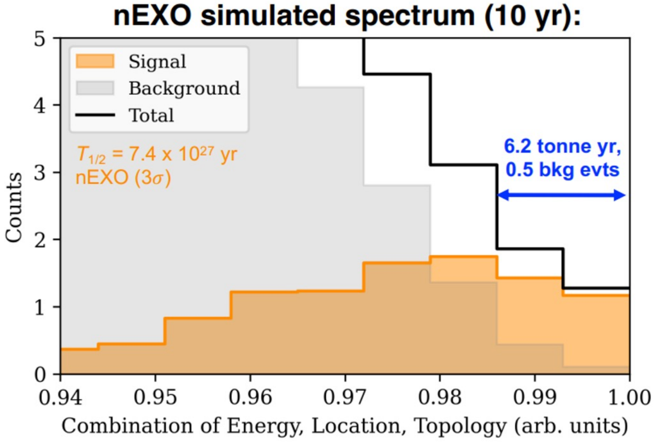


LXe time projection chambers

- ^{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





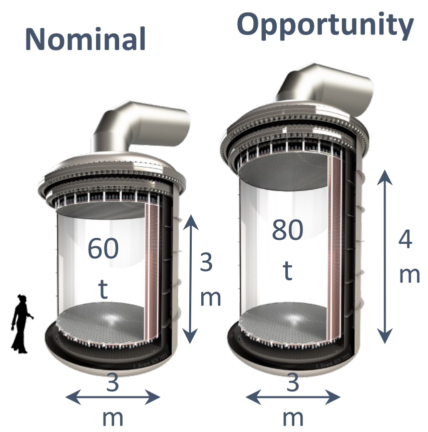


nEXO@SNOLAB

- builds on the EXO-200 experiment (completed in 2019)
- homogeneous, liquid enrXe time projection chamber scaled to **5 tonne total mass**
- dominant external backgrounds exponentially attenuated in central region
- preparing for DOE review next year

Also, natural LXe detectors for dark matter: XLZD

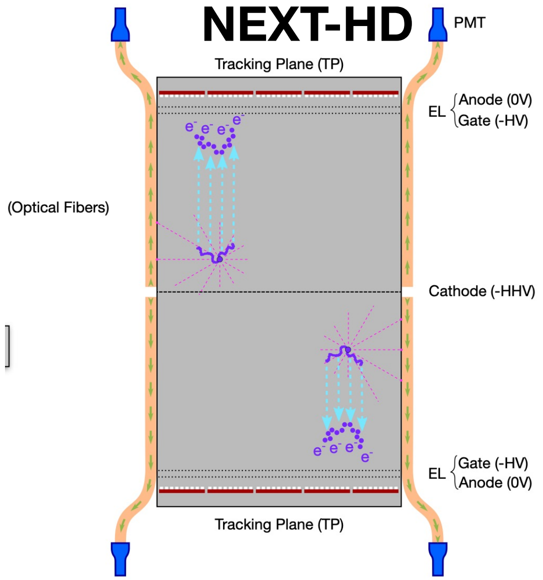
80t natural → 7t ^{136}Xe

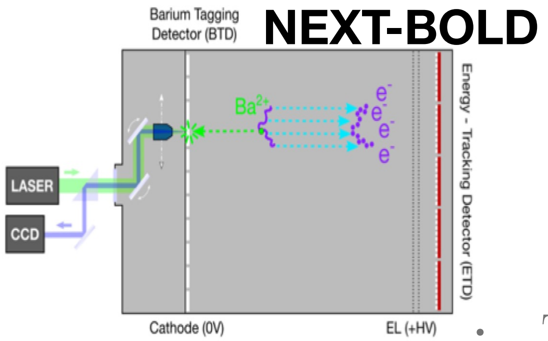


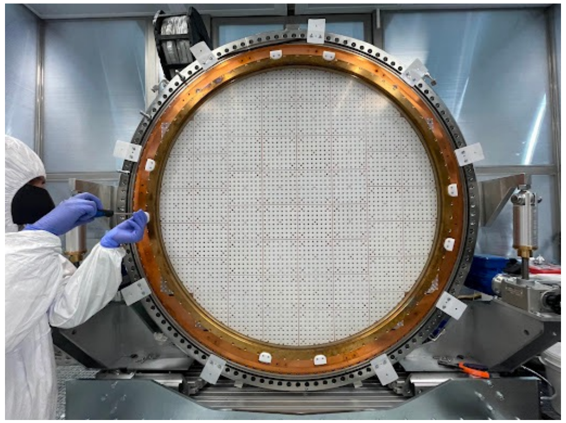
High-Pressure Gas ^{136}Xe time projection chamber

- Next-White demonstrated the technology:
  - ✓ Continuous ^{83m}Kr calibration
  - ✓ Sub-percent energy resolution FWHM
  - ✓ Powerful topology separation

- NEXT-100 under commissioning (data taking in summer 2024)
  - ✓ Will demonstrate scalability



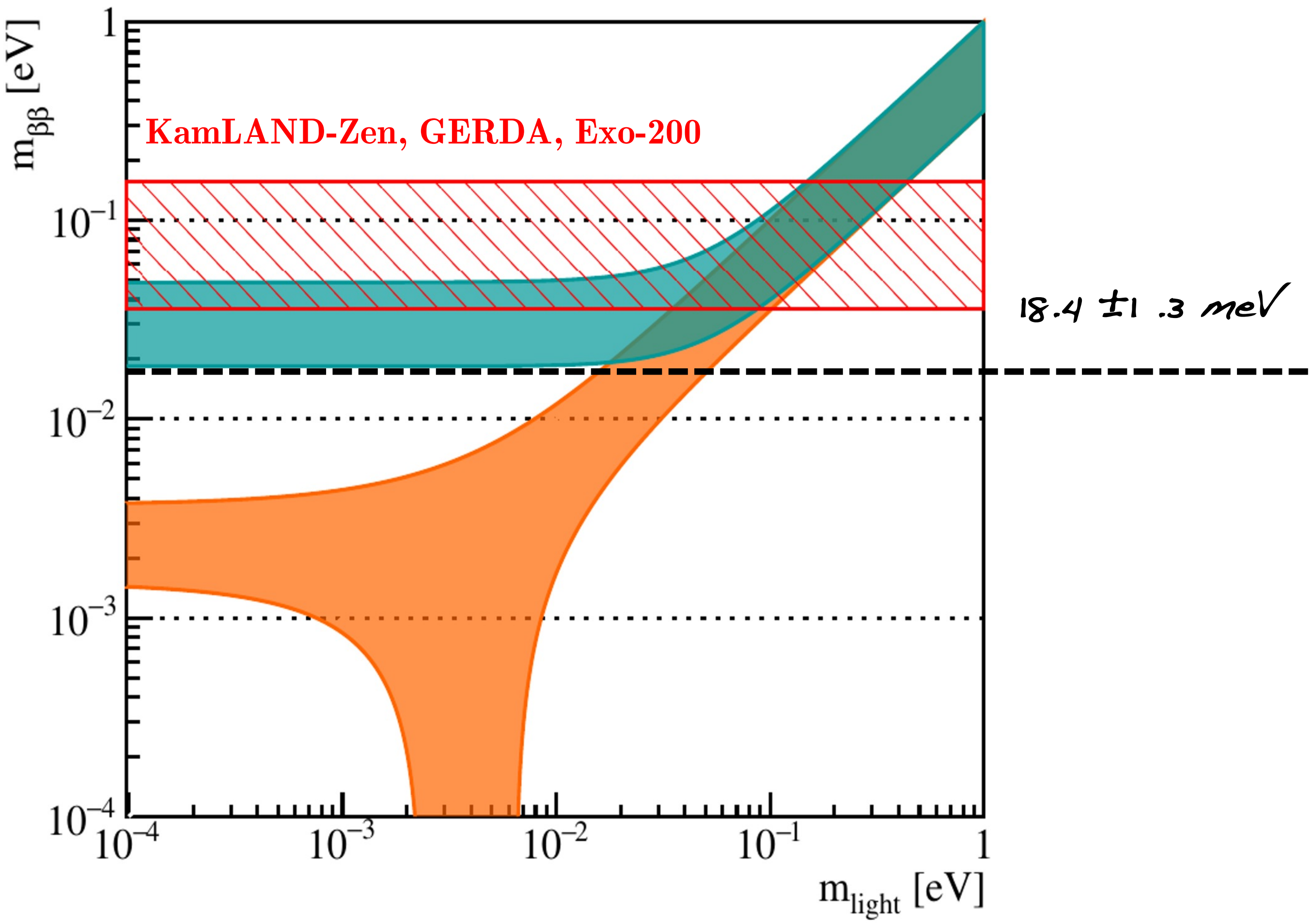


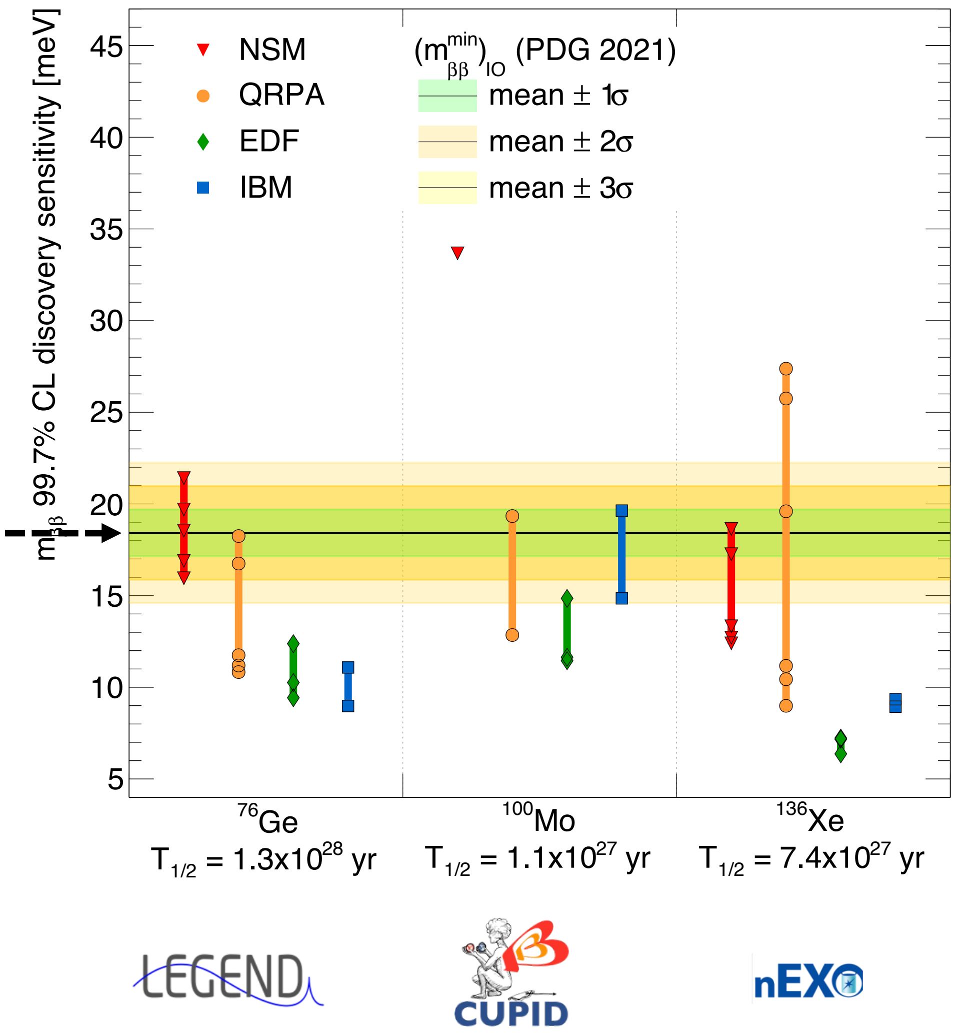


- Ton-scale plans:
  - ✓ NEXT-HD: Symmetric detector with reach of 10^{27} y
  - ✓ NEXT-BOLD: Add Ba tagging (bkg free!) for exploring beyond 10^{28} y

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

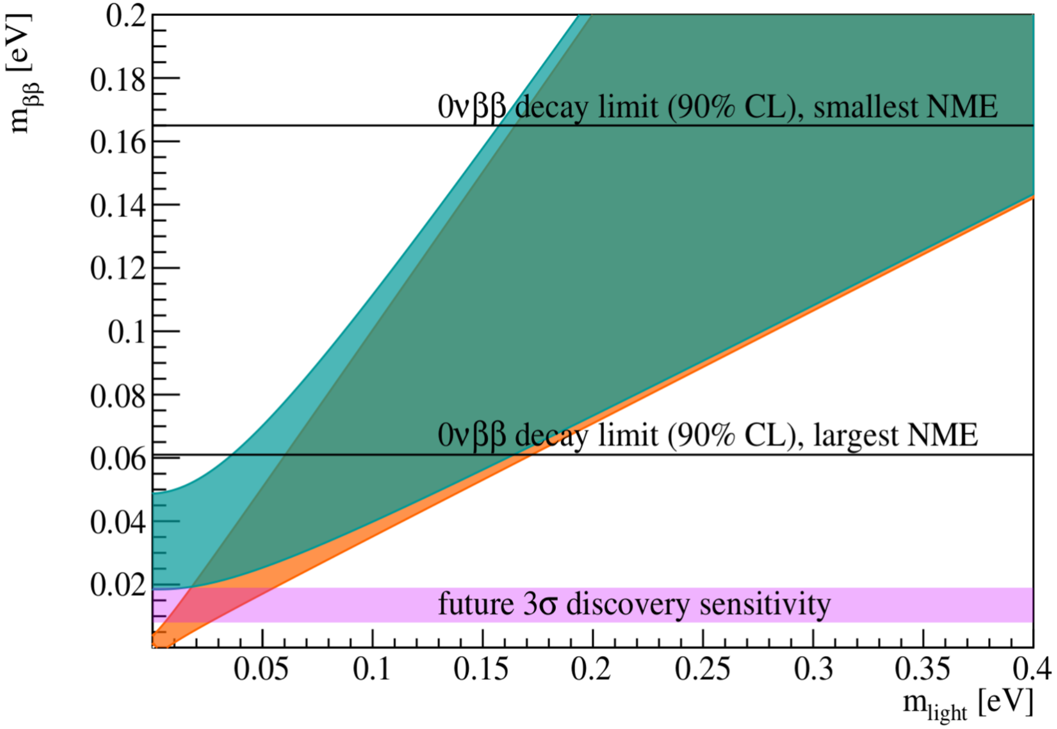
Best so far: $T_{1/2} > 10^{26}$ yr



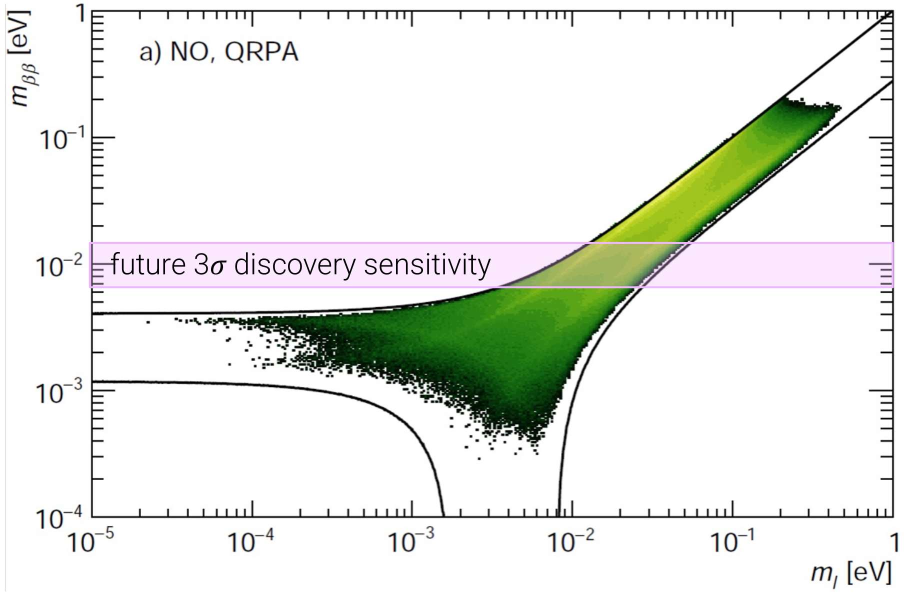


$0\nu\beta\beta$ with $m_{\beta\beta}$. Where are we heading?

- Significant part of Normal Ordering will be covered with next wave of experiments ("1 tonne")
- Beware of log-plots!

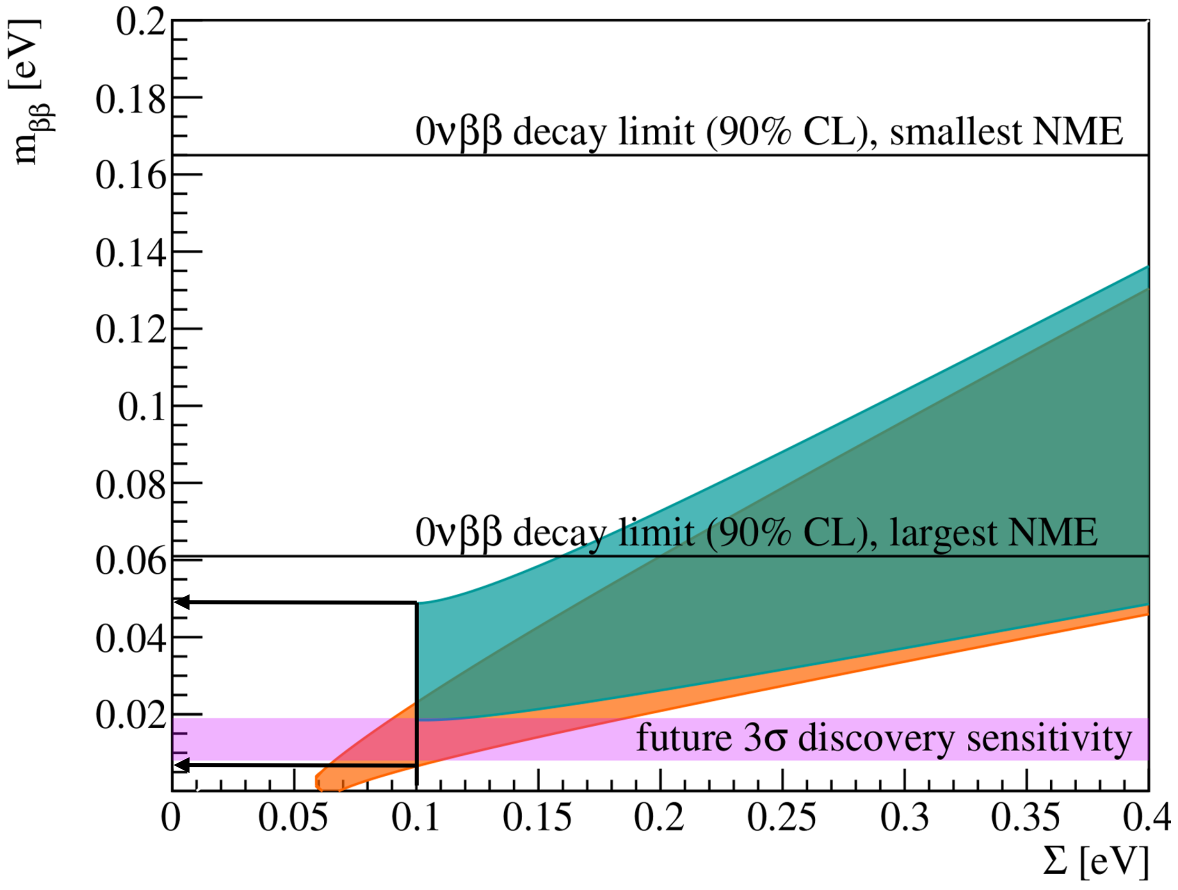


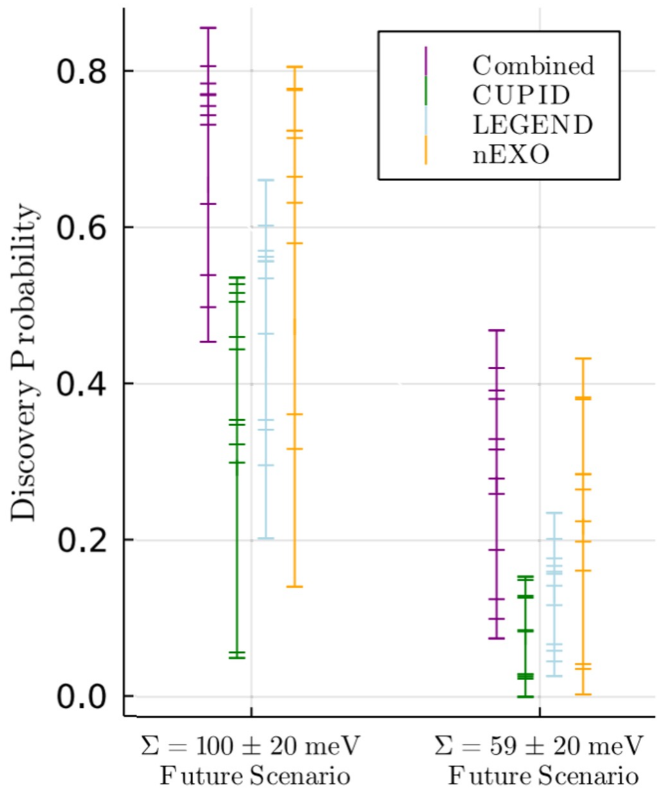
Potentially non equiprobable parameter space
(random phases would naturally favor large $m_{\beta\beta}$ values)



Agostini, Benato and Detwiler, PRD 96, 053001 (2017)

$0\nu\beta\beta$ and Cosmology



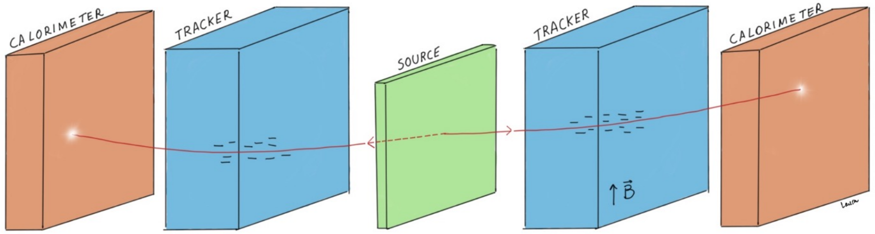


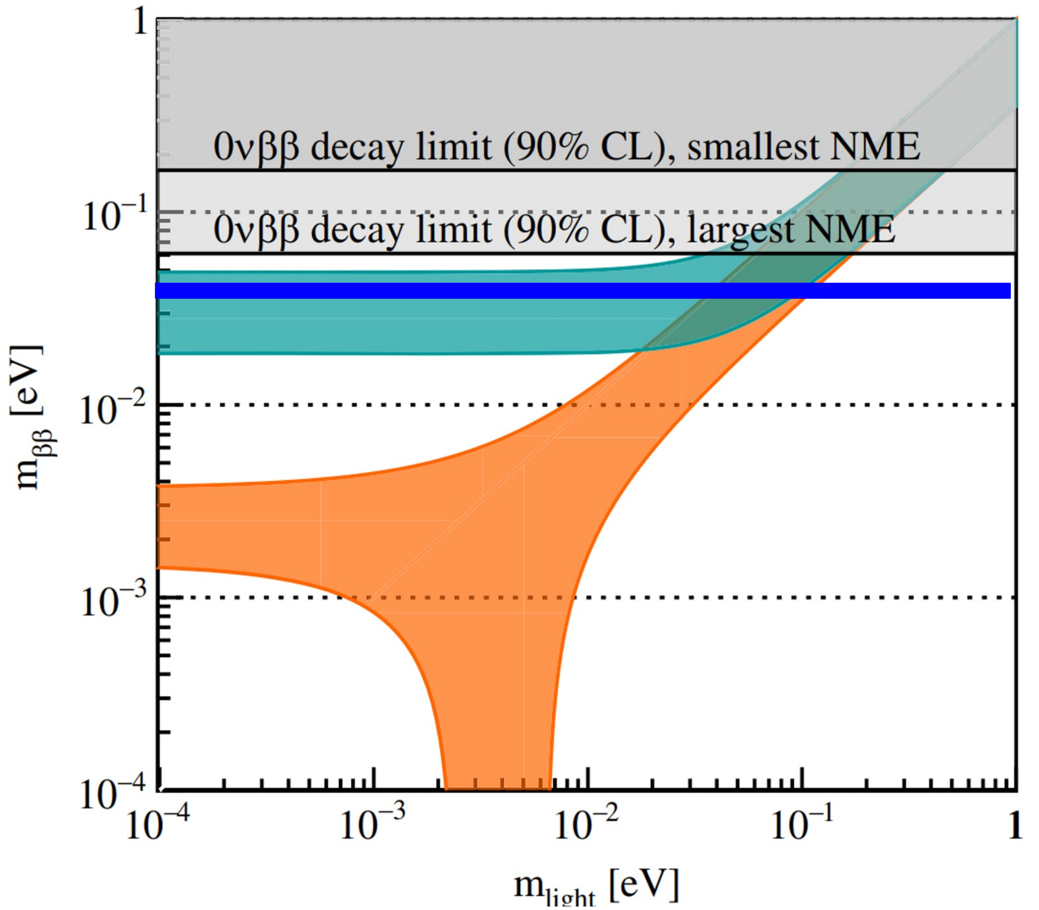
Scenario 1

$T_{1/2} < 10^{28}$ years: 100s events in ton-scale experiments

- O(10%) statistical uncertainty << NME uncertainties
- can probe decay mechanism by looking at individual electron energy distributions and angular correlations

supernemo collaboration





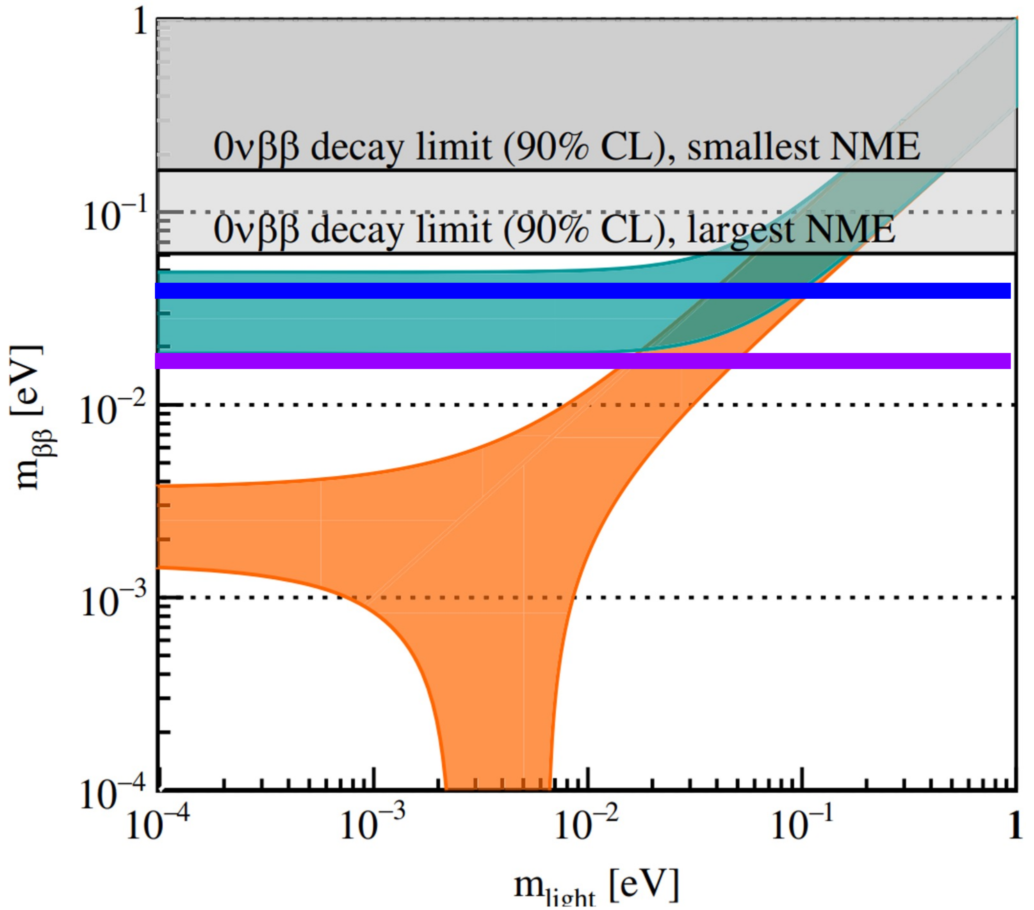
Scenario 2

$T_{1/2} < 10^{28}$ years: 100s events in ton-scale experiments

- O(10%) statistical uncertainty << NME uncertainties
- can probe decay mechanism

$T_{1/2}$ ~ 10^{28} years: ~10 events in ton-scale experiments

- statistical uncertainty ~ NME uncertainties
- multiple ton-scale experiments needed to confirm signal



Scenario 3

$T_{1/2} < 10^{28}$ **years: 100s events** in ton-scale experiments

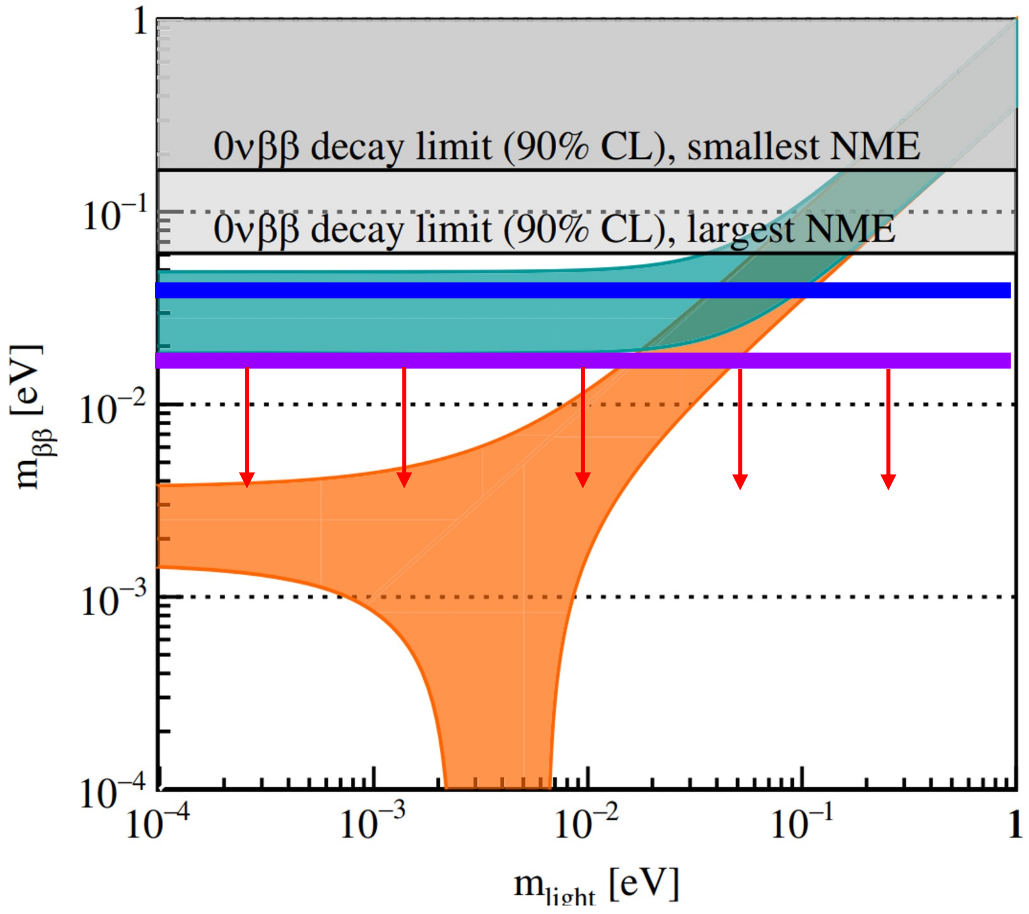
- O(10%) statistical uncertainty << NME uncertainties
- can probe decay mechanism

$T_{1/2} \sim 10^{28}$ **years: ~10 events** in ton-scale experiments

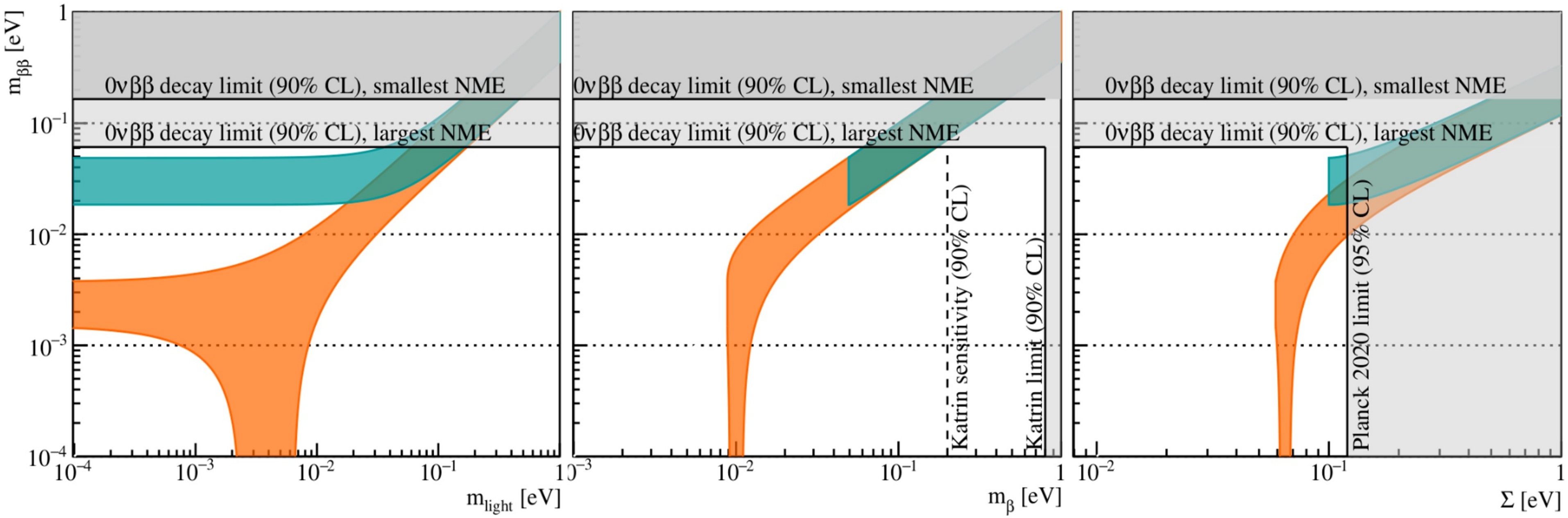
- statistical uncertainty ~ NME uncertainties
- multiple ton-scale experiments needed to confirm signal

$T_{1/2} > 10^{28}$ **years: < a few events** in ton-scale experiments

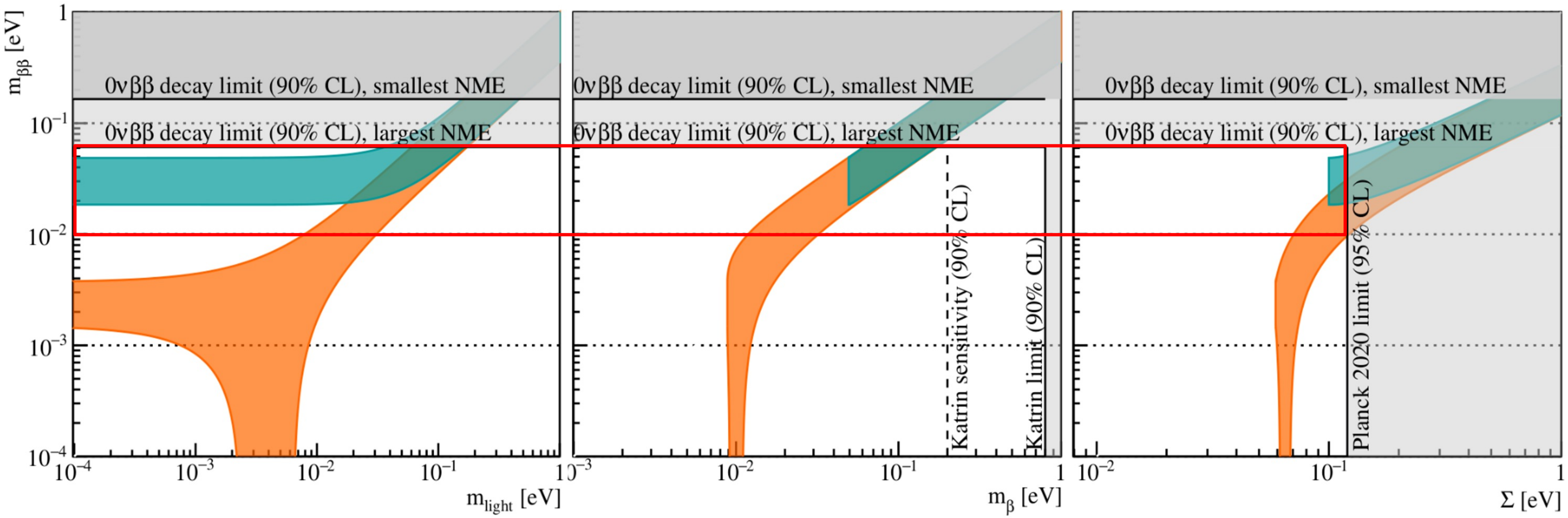
- R&D required to push further into NO, reduce cost
- technology diversity is a strength



Interplay between absolute neutrino mass experiments

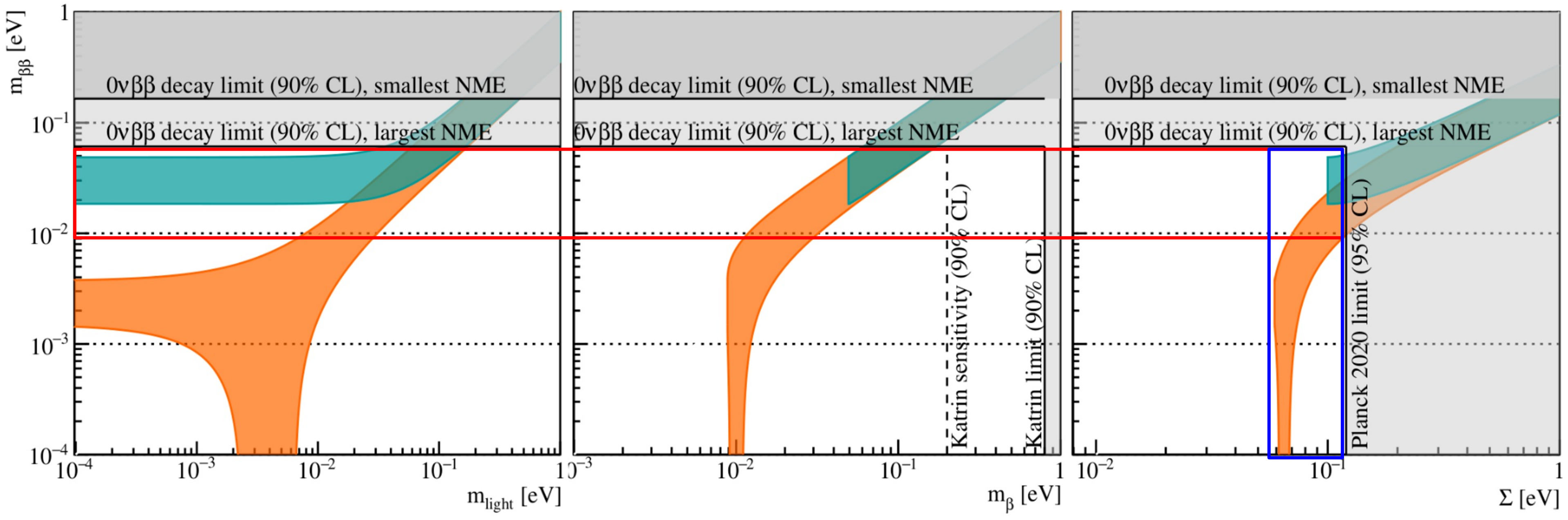


Interplay between absolute neutrino mass experiments



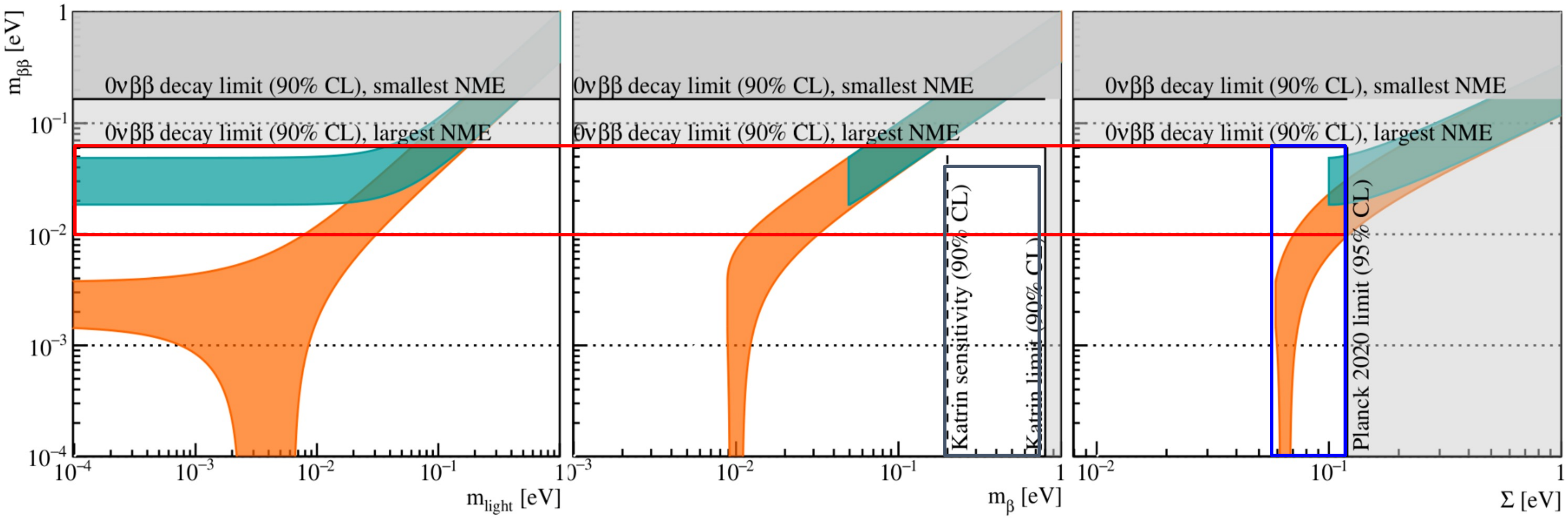
CUPID, LEGEND, nEXO, +… will explore $m_{\beta\beta}$ values till the bottom of the inverted ordering and beyond, with a good chance to discover matter-creation

Interplay between absolute neutrino 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 absolute neutrino 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

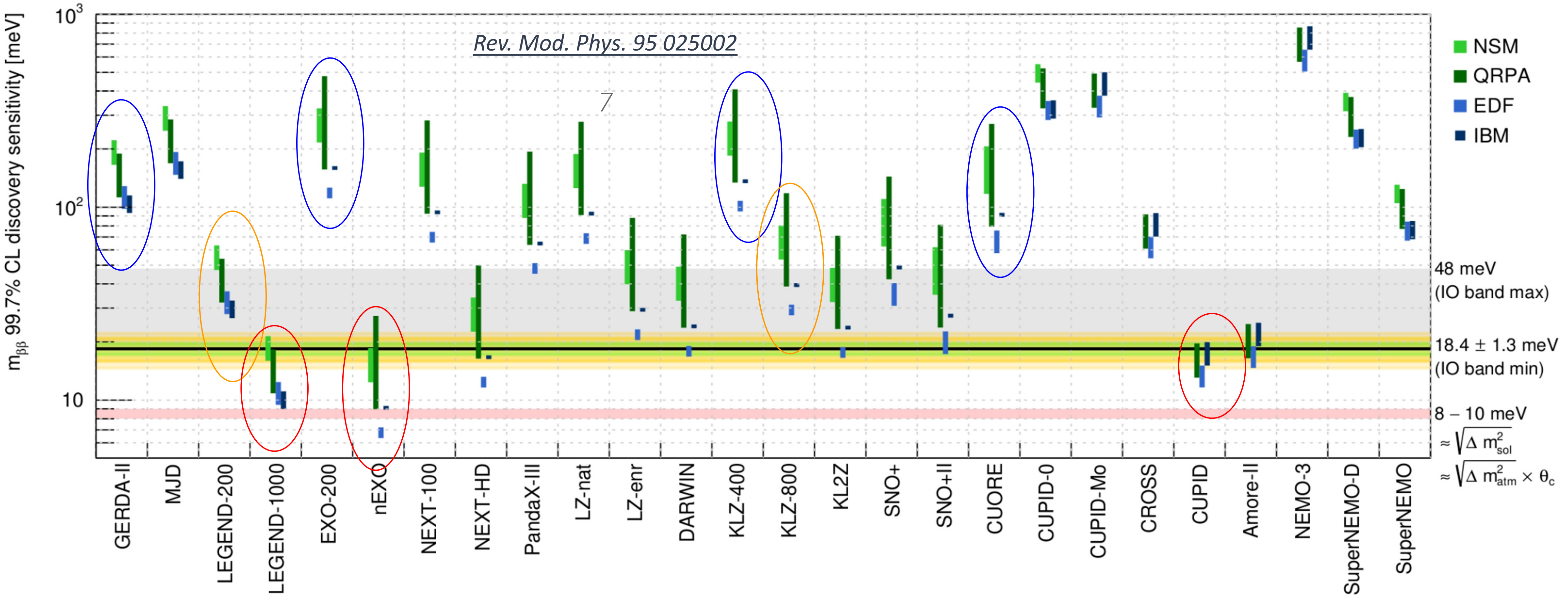
- Measuring m_{β} below 0.1 eV (Project-8, QTNM, PTOLEMY, ECHo…) and $m_{\beta\beta}$ and will allow Majorana CP-phases to be determined!

Outlook

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

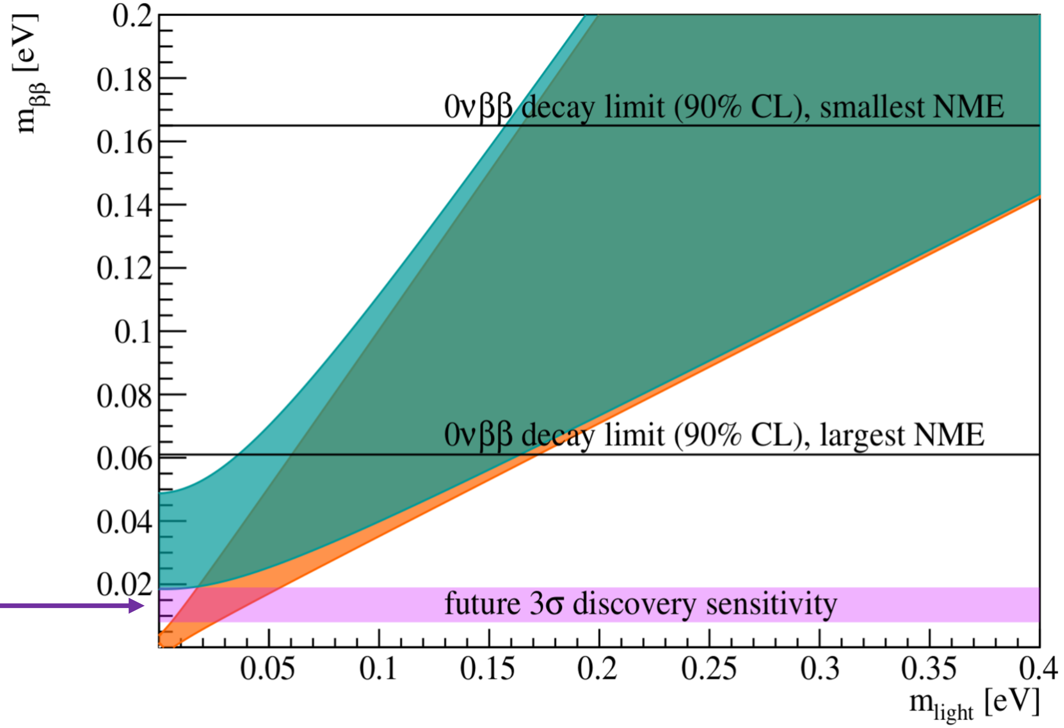
The two to watch: **LEGEND-200, KamLAND-Zen-800**

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



Concluding Remarks

- **$0\nu\beta\beta$** is the best way to probe **Lepton Number Violation, B-L** and its connection to preponderance of **matter** and **neutrino mass** generation mechanism
- Upcoming experiments are very well motivated scientifically – clear sensitivity targets



- 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 any **LNV** mechanism – open minded, **discovery-oriented** search.