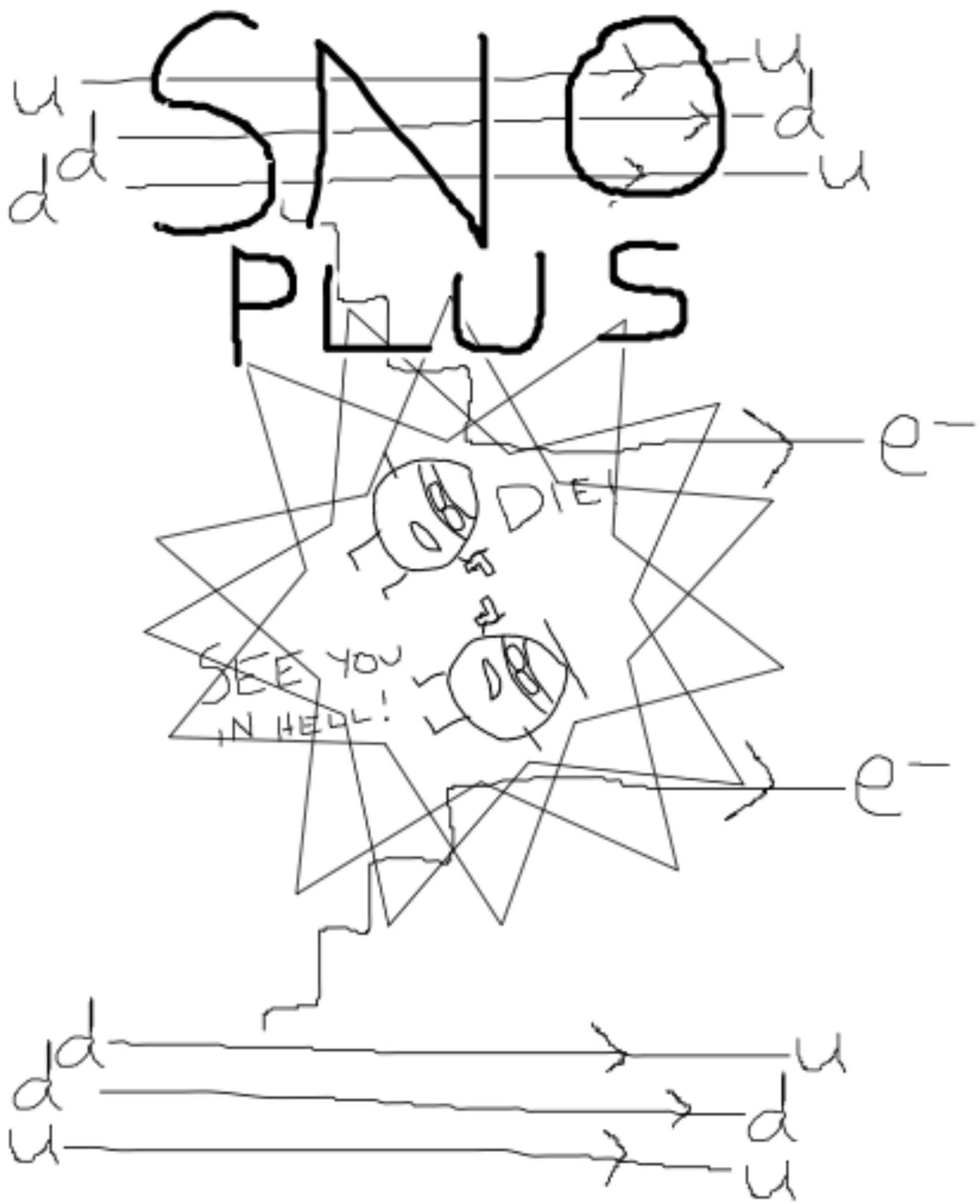
Neutrinoless Double Beta Decay $0\nu\beta\beta$ – part 3

Prof Jeanne Wilson

TRISEP 2024, Sudbury



Credit: A Mastbaum

Outline

Lecture 1

- What is double beta decay?
  - SEMF splitting
  - Known isotopes
- 2 neutrino double beta decay
- Neutrinoless double beta decay
  - Theory
  - Dirac and Majorana neutrinos
  - See-saw mechanism

Lecture 2

- Half-life / rate
  - Phase space
  - Matrix elements
- Experimental considerations
  - Challenges
  - Backgrounds
- Experiment examples

Lecture 3

- Neutrino mass
- Lobster plots
- Limits vs Discovery
- Alternative mechanisms and probing new physics
- $\beta^+\beta^+$ decays
- Future prospects

PMNS matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- Dirac phase is a CP violating phase that is measured in lepton number conserving processes, such as neutrino oscillations.
- Majorana phases are those which are only accessible through lepton number violating processes.

Dirac Phase

Majorana Phase

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

Effective Majorana Neutrino Mass

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

- $\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right| = \left|\sum_i |U_{ei}|^2 e^{2i\alpha_i} m_i\right|$

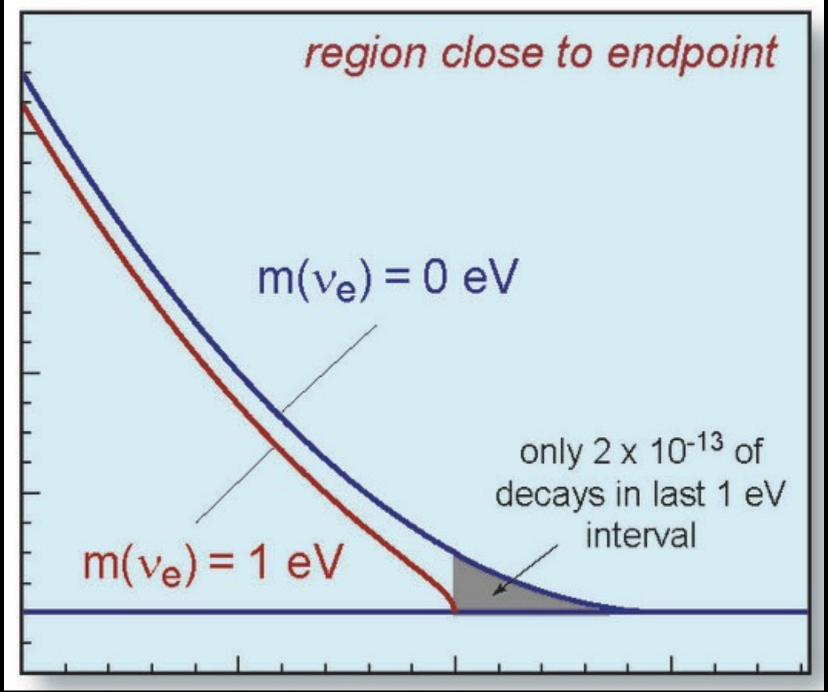
- $\langle m_{\beta\beta}\rangle$ is a linear combination of the neutrino masses
- Note – presence of majorana phases in sum means cancellations are possible
    - Complete cancellation for a Dirac neutrino since it is equivalent to two degenerate Majorana neutrinos with opposite CP phases

Direct neutrino Mass measurement

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

- ${m_\nu}^2 = \sum_i |U_{ei}|^2 m_i^2$
- an effective neutrino mass-squared associated with the charged-current processes involving the charged-lepton (e^-)

$$m_\beta^2 = m_1^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2$$



PMNS matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

Dirac Phase

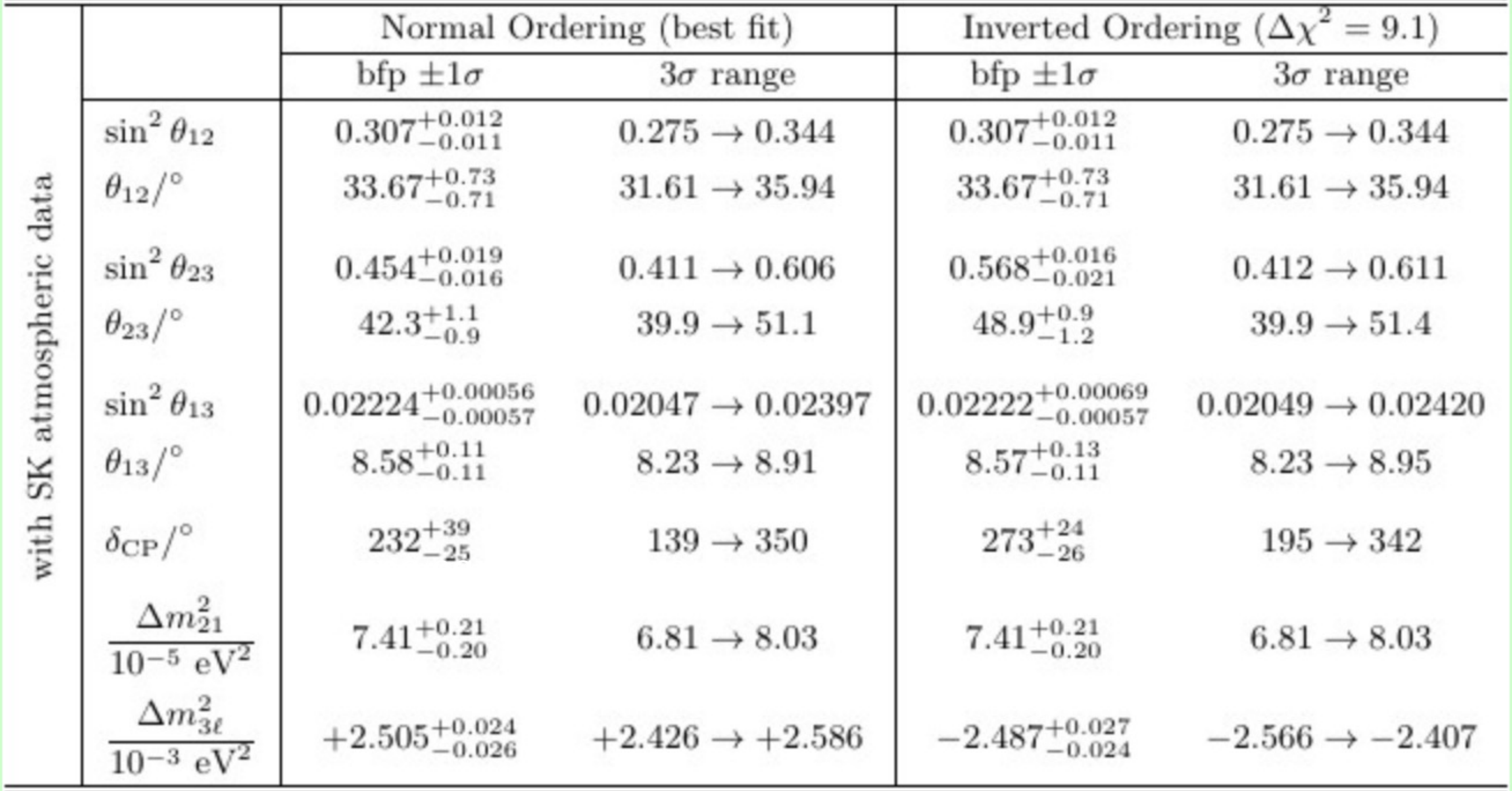
Majorana Phase

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13} m_1 + e^{2i\alpha}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + e^{2i(\beta-\delta_{CP})}\sin^2\theta_{13} m_3$$

Neutrino Mass

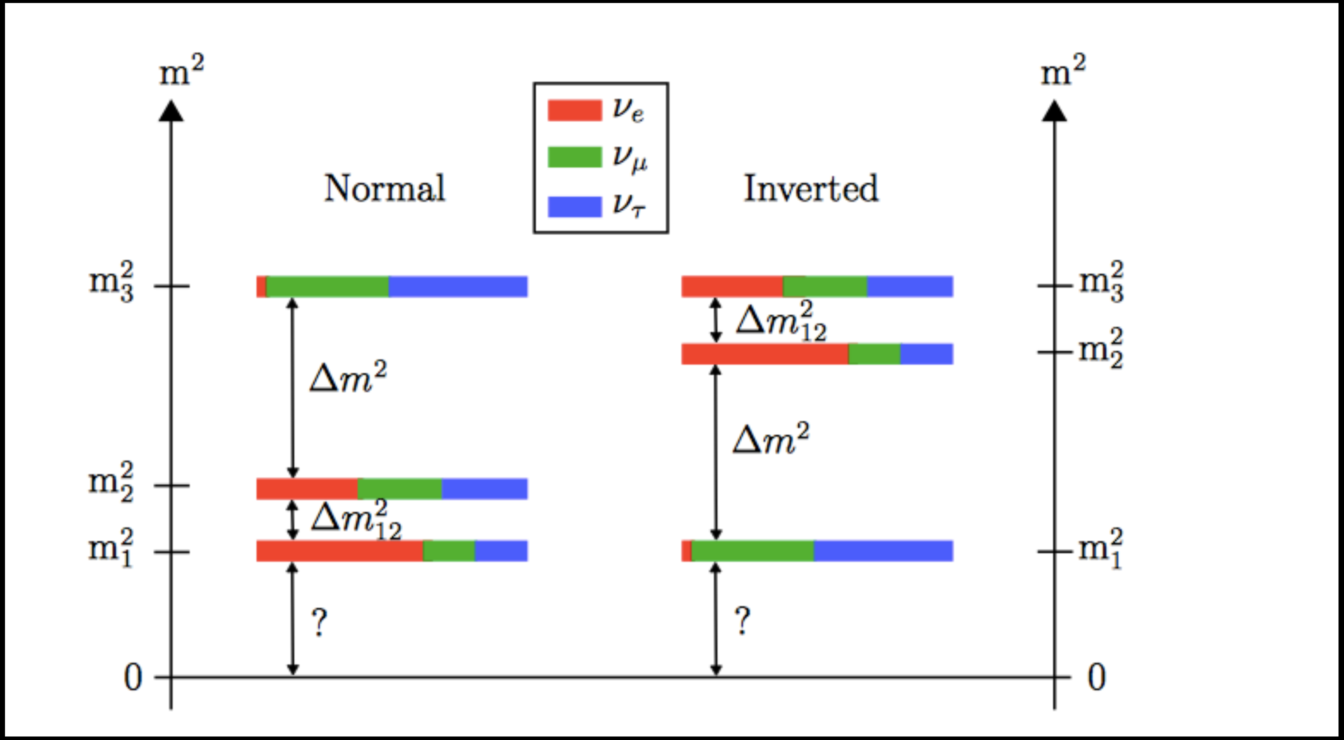
NuFit5.3

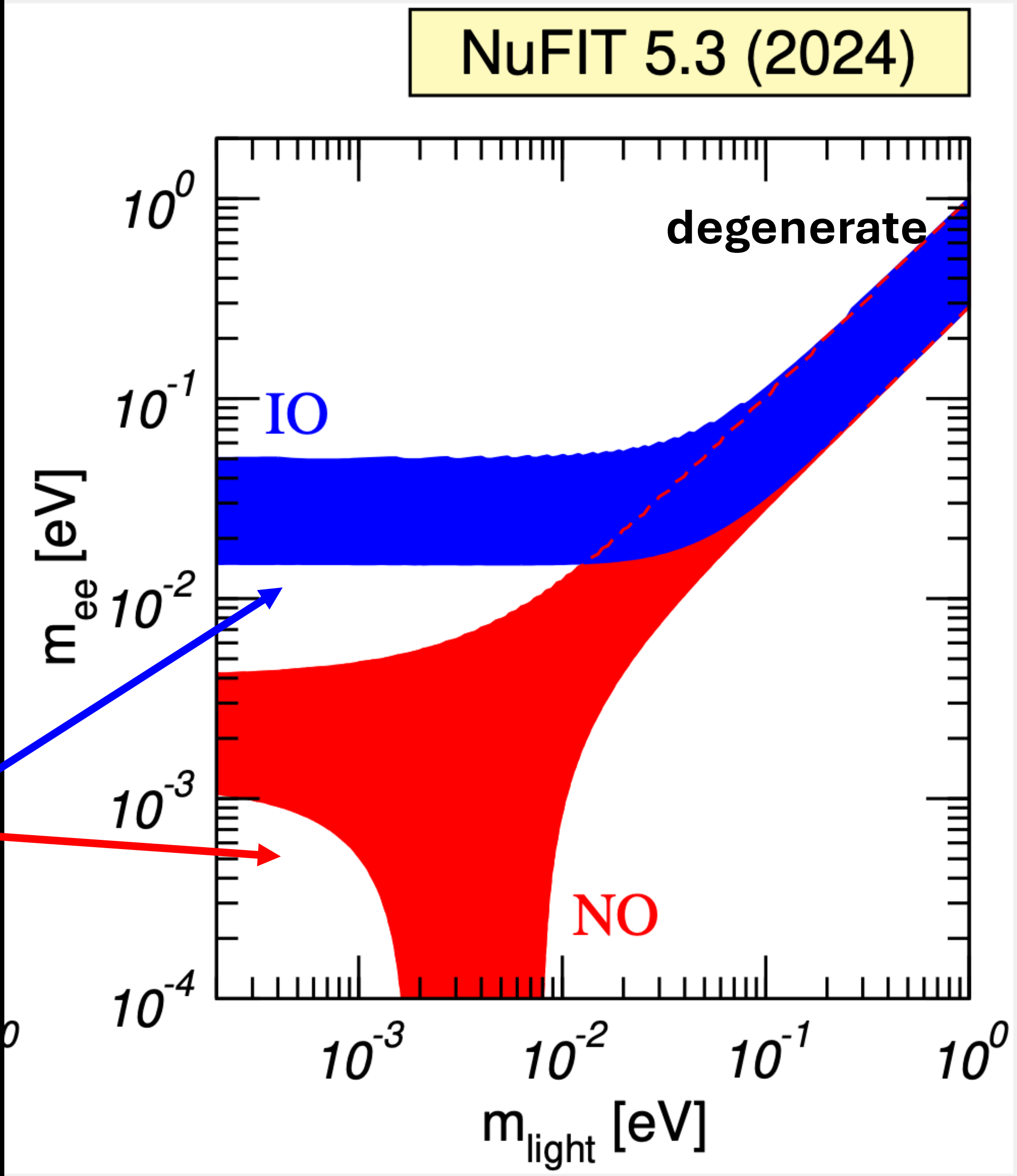


		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{\mathrm{CP}}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

$$m_{\beta\beta} = 0.69 m_1 + 0.72 m_2 e^{2i\alpha} + 0.02 m_3 e^{2i(\beta-\delta_{CP})}$$

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13} m_1 + e^{2i\alpha}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + e^{2i(\beta-\delta_{CP})}\sin^2\theta_{13} m_3$$





Normal ordering

m_1 & m_2 small, m_3 bigger

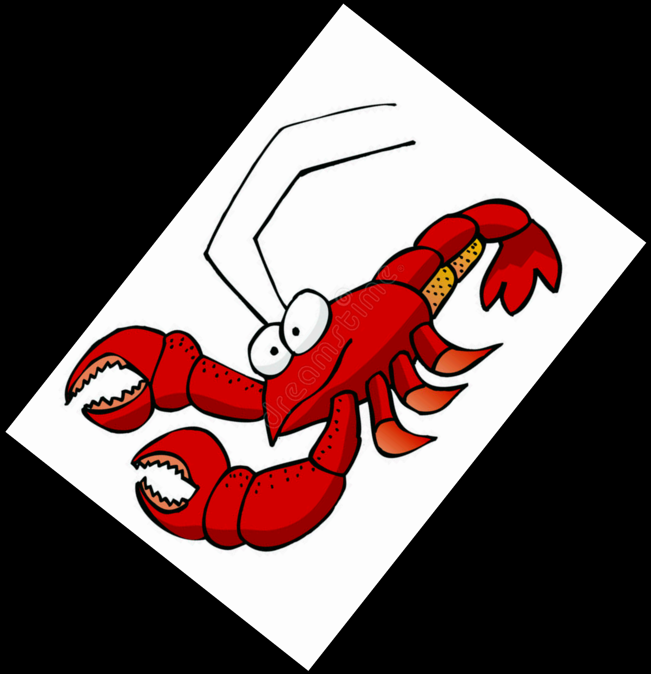
Inverted ordering

m_3 small, m_1 & m_2 bigger

$$m_{\beta\beta} = 0.69 m_1 + 0.72 m_2 e^{2i\alpha} + 0.02 m_3 e^{2i(\beta-\delta_{CP})}$$

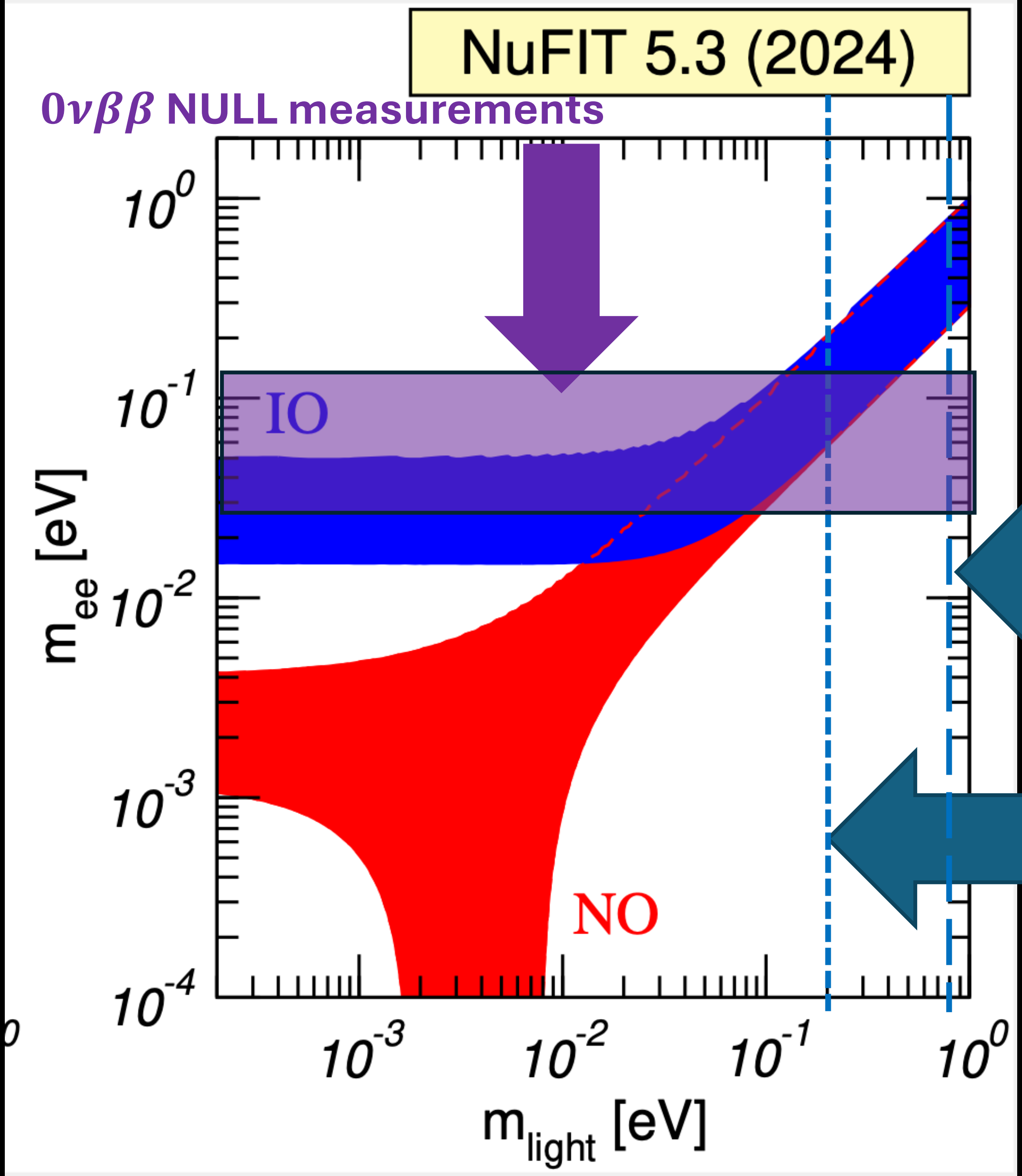
2σ allowed regions

Lobster Plots

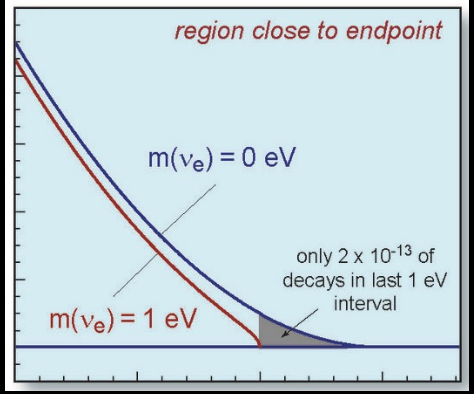


Shape constrained by bounds on Δm^2 from oscillation measurements

KamLAND-Zen
https://arxiv.org/pdf/2406.11438

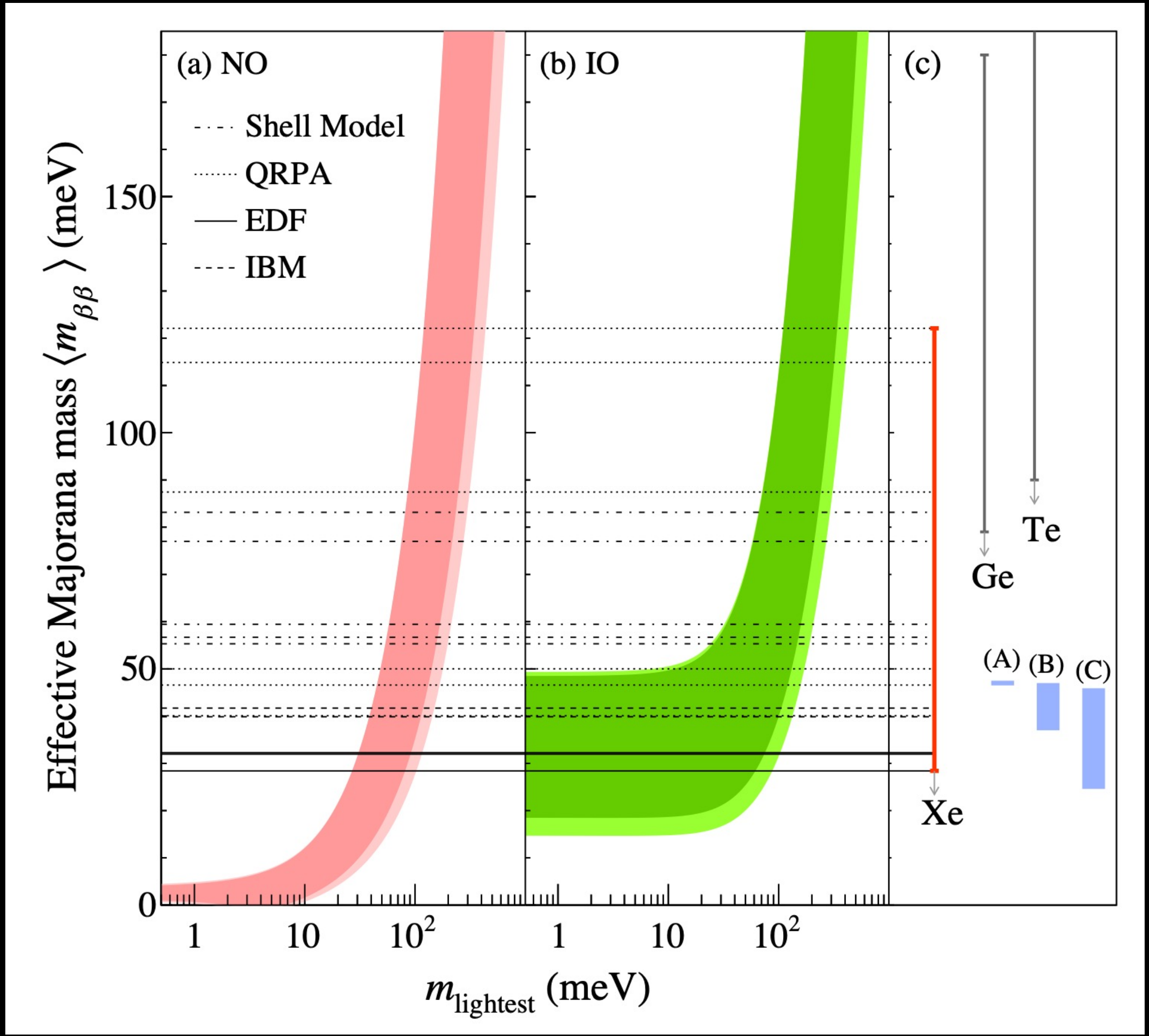


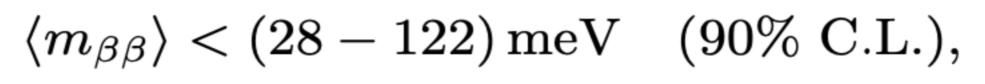
Katrin $m_\nu < 0.9\ eV$
Nat. Phys. **18**, 160–166 (2022)



Cosmology
pdglive.lbl.gov
$\sum m_\nu < 0.12$eV

KamLAND-Zen latest results



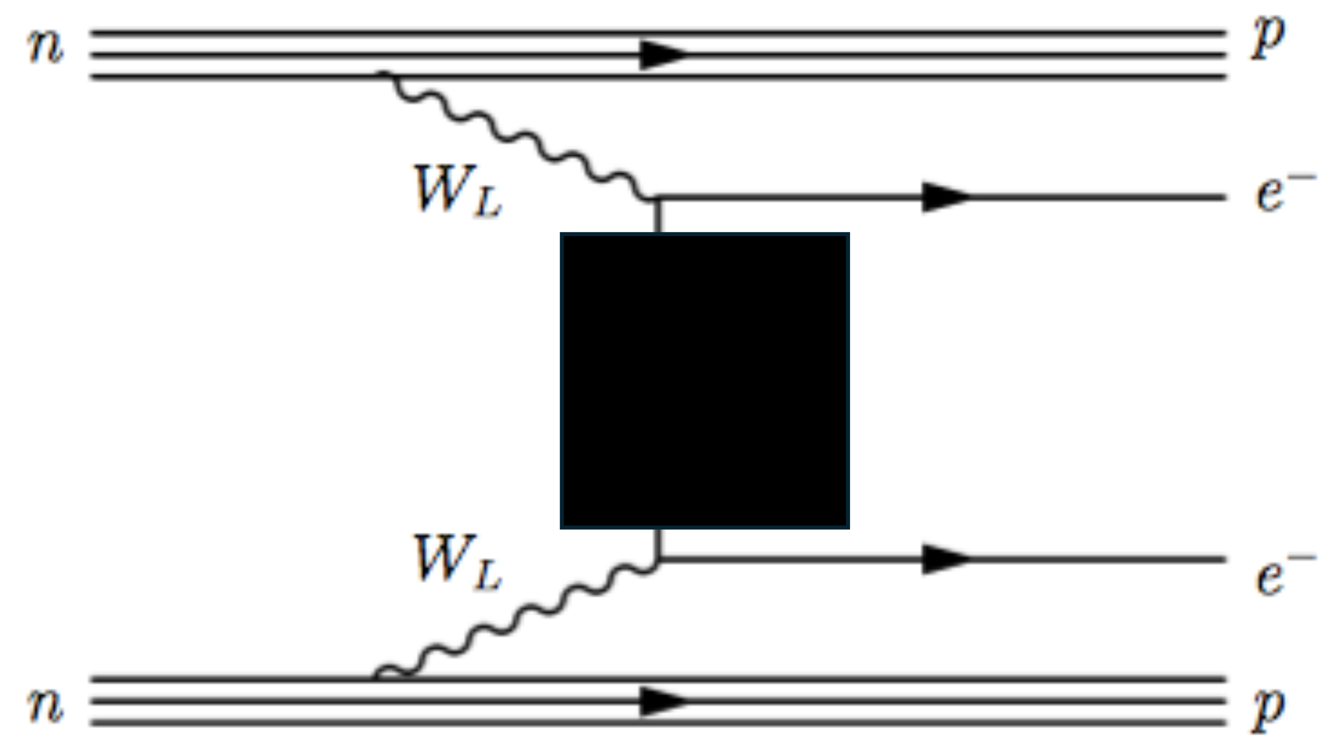


$$\langle m_{\beta\beta} \rangle < (28 - 122)\,\text{meV} \quad (90\%\ \text{C.L.}),$$

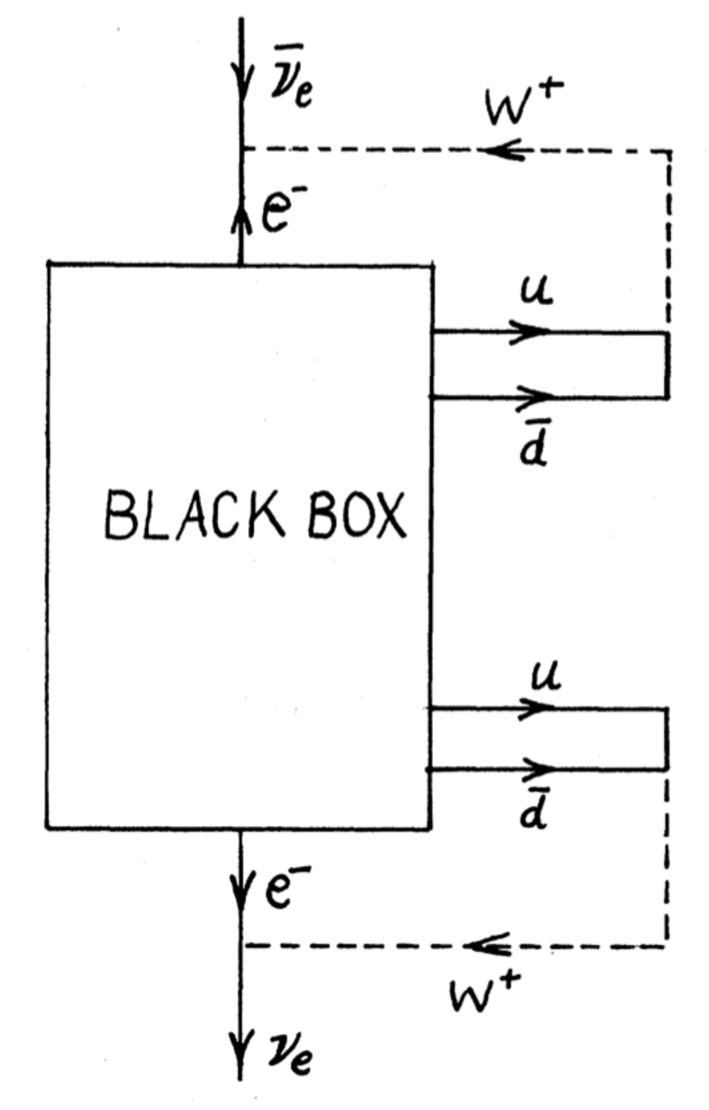
https://arxiv.org/pdf/2406.11438

$0\nu\beta\beta$

If we just observe the final products, we can't be sure what's happening inside this black box:



Schechter Valle Theorem



$\bar{\nu_e} \rightarrow \nu_e$

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.25.2951
Schechter & Valle, PRD 25, 11, 1981

The existence of any 0νββ mode would imply an effective Majorana mass term.

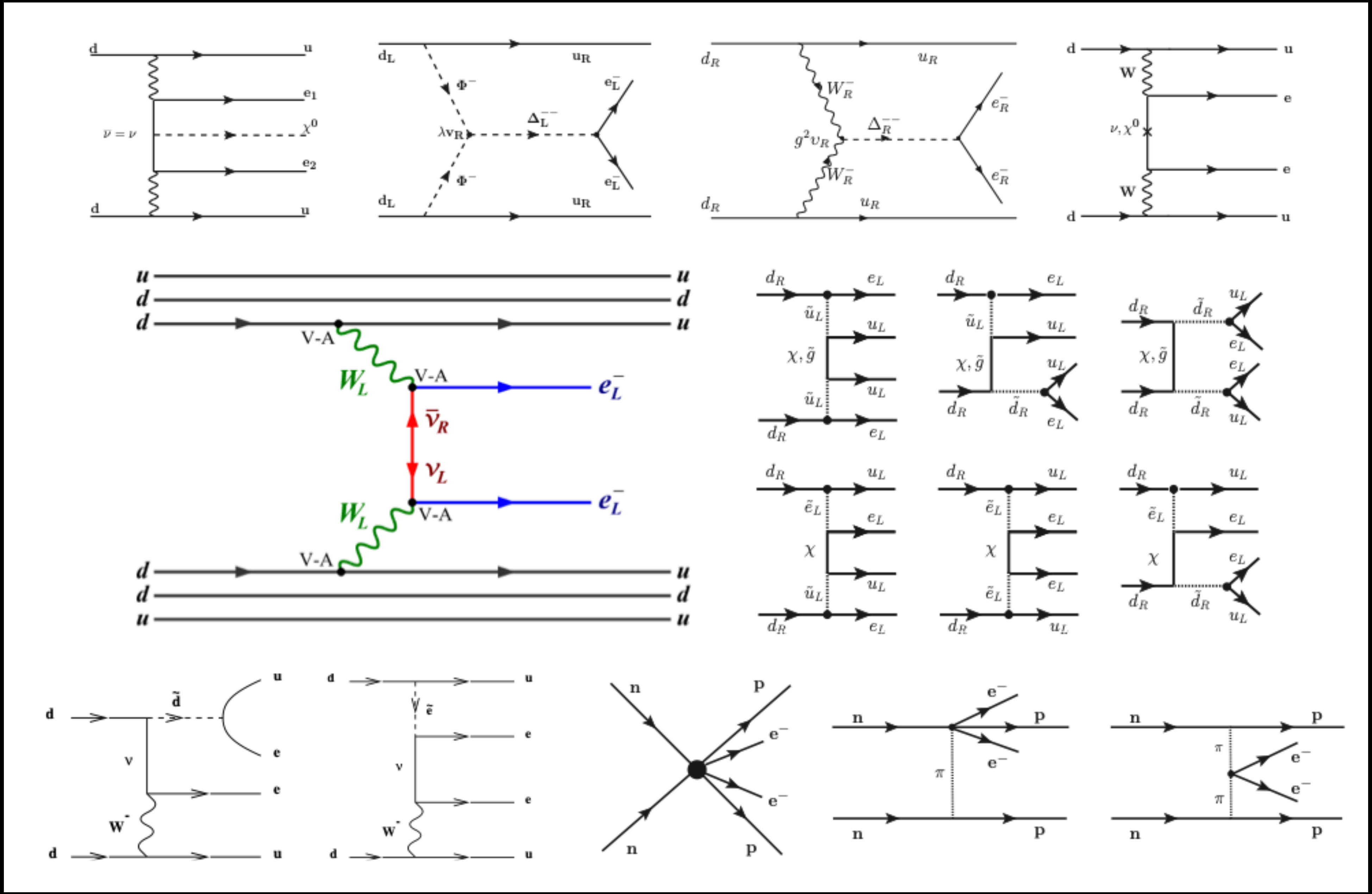
$0\nu\beta\beta$ is the golden channel to test the Majorana nature of the neutrino

$\beta\beta$ as a probe for new physics

- Possible BSM physics mechanisms:
  - New particles - either bosons or fermions – could be emitted in the decay, replacing one or both of the $2\nu\beta\beta$ neutrinos
  - Theories where fundamental symmetries are violated such as Lorentz covariance or Pauli's exclusion principle
  - Non-standard interactions, like right-handed leptonic currents and strong neutrino self-interactions

- If new particles or new physics involved this would affect the phase space of the two electrons emitted in the $\beta\beta$ decay
  - Changes to summed $2\nu\beta\beta$ spectrum
  - $0\nu\beta\beta$ energy could become a continuum

Credit: Martti Nirkko



Exotic $0\nu\beta\beta$ mechanisms

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2\eta^2$$

Lepton violation parameter

- Light neutrino mass mechanism most popular. $\eta = m_{\beta\beta}$
  - Minimal scenario, connection with neutrino oscillations
- Majoron emission $\eta = \langle g_{\chi^0} \rangle$
- Right-handed currents $\eta = \langle \lambda, \eta \rangle$

New Boson - Majoron

- Neutrinos are Majorana particles with small masses arising from the spontaneous breakdown of the global B–L symmetry. In these models, a massless Goldstone boson should exist = Majoron

J. Phys. G: Nucl. Part. Phys. **51** (2024) 023001 Topical Review

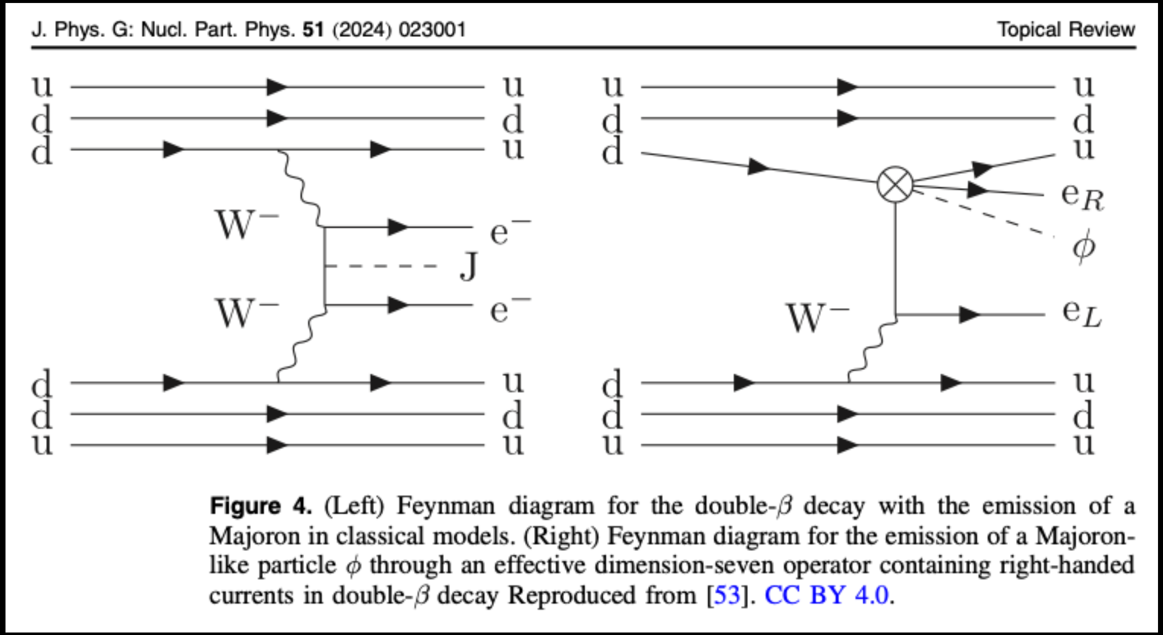


Figure 4. (Left) Feynman diagram for the double-β decay with the emission of a Majoron in classical models. (Right) Feynman diagram for the emission of a Majoron-like particle ϕ through an effective dimension-seven operator containing right-handed currents in double-β decay Reproduced from [53]. CC BY 4.0.

J. Phys. G: Nucl. Part. Phys. **51** (2024) 023001 Topical Review

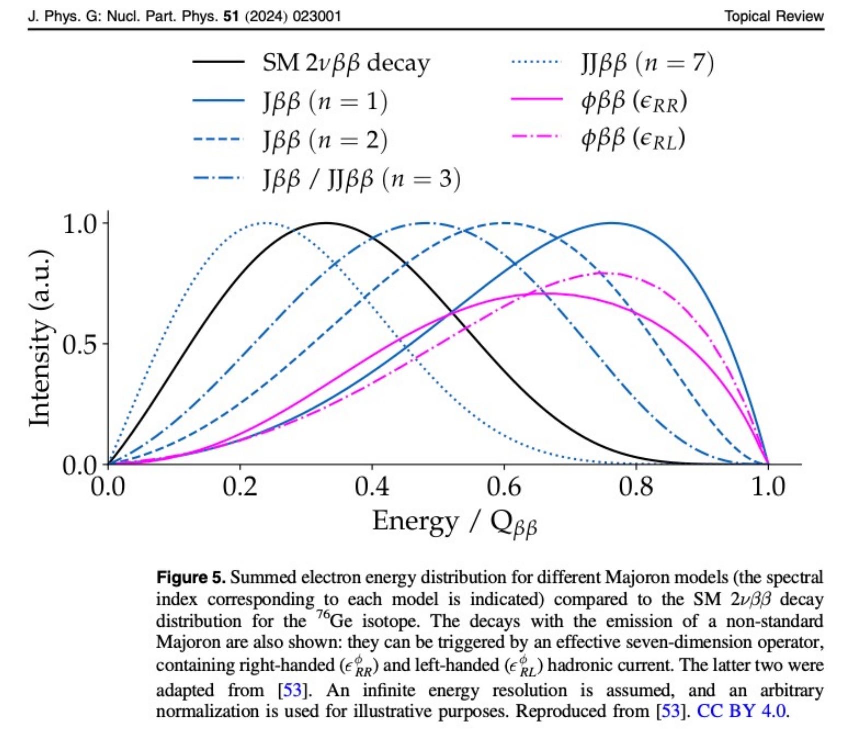


Figure 5. Summed electron energy distribution for different Majoron models (the spectral index corresponding to each model is indicated) compared to the SM $2\nu\beta\beta$ decay distribution for the ^{76}Ge isotope. The decays with the emission of a non-standard Majoron are also shown: they can be triggered by an effective seven-dimension operator, containing right-handed (ϵ^{ϕ}_{RR}) and left-handed (ϵ^{ϕ}_{RL}) hadronic current. The latter two were adapted from [53]. An infinite energy resolution is assumed, and an arbitrary normalization is used for illustrative purposes. Reproduced from [53]. CC BY 4.0.

- If emitted, the Majorons would escape any detector and carry away part of the decay energy

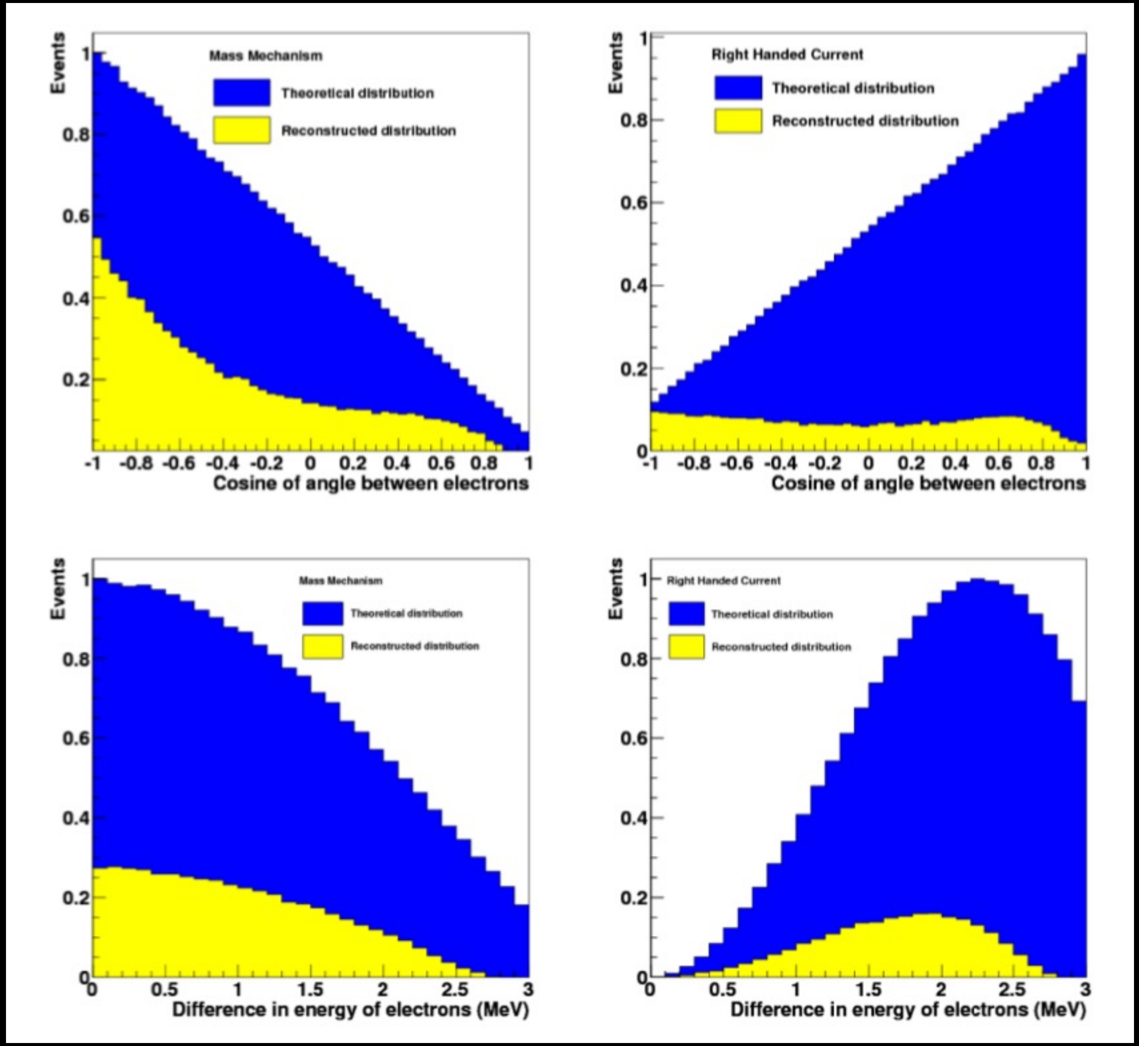
  → summed electron energy becomes continuous spectrum (like for $2\nu\beta\beta$)

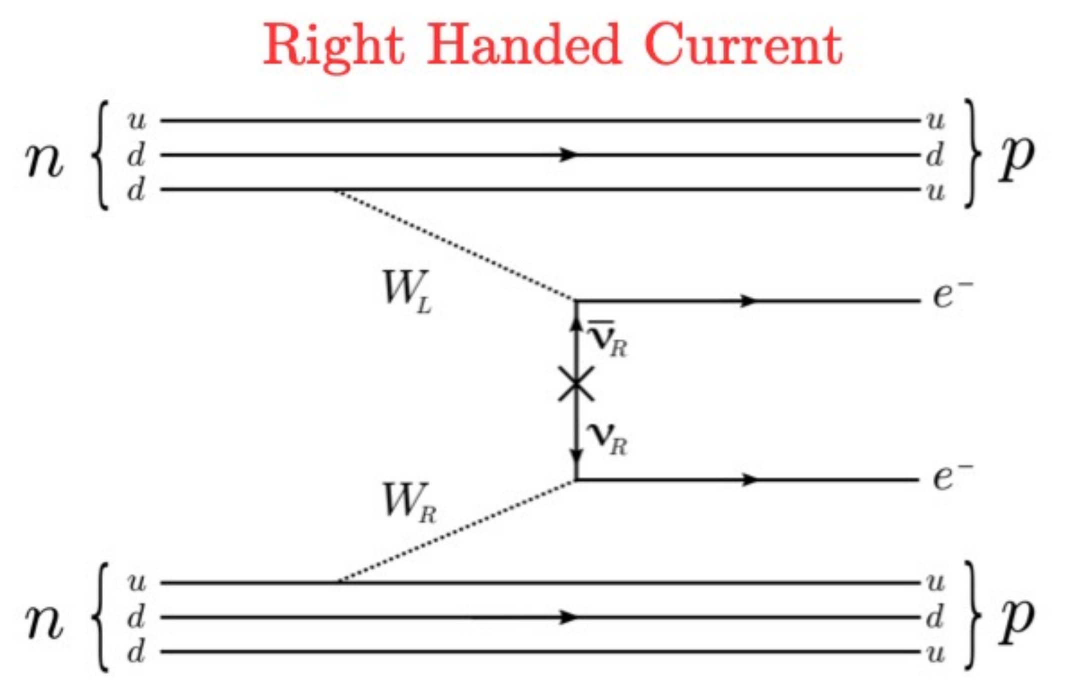
  → exact spectrum shape determined by phase space via the effective neutrinos-Majoron interaction Lagrangian – parameterise with spectral index η

Right Handed EW Currents

- Mediated by a right-handed W boson
  - SM only has left-handed chiral states, add right handed or mixed state W boson into the Lagrangian
  - 2 electrons seen in final state, virtual ν interacts at second vertex without needing helicity flip
  - $\eta = \langle \lambda, \eta \rangle$
    - λ is a new physics parameter representing right chiral state coupling of the right-handed quarks to the right-handed leptons
    - η is for right-handed quarks coupling to the left-handed leptons
- Changes to $2\nu\beta\beta$ decay rate and spectral shape

Right Handed EW Currents





Angular distributions of the $0\nu\beta\beta$ emitted electrons are different from those predicted for light neutrino exchange mechanism

- Mechanism can be distinguished in tracking experiments
- Plots from NEMO-3

New underlying physics changed mass interpretation

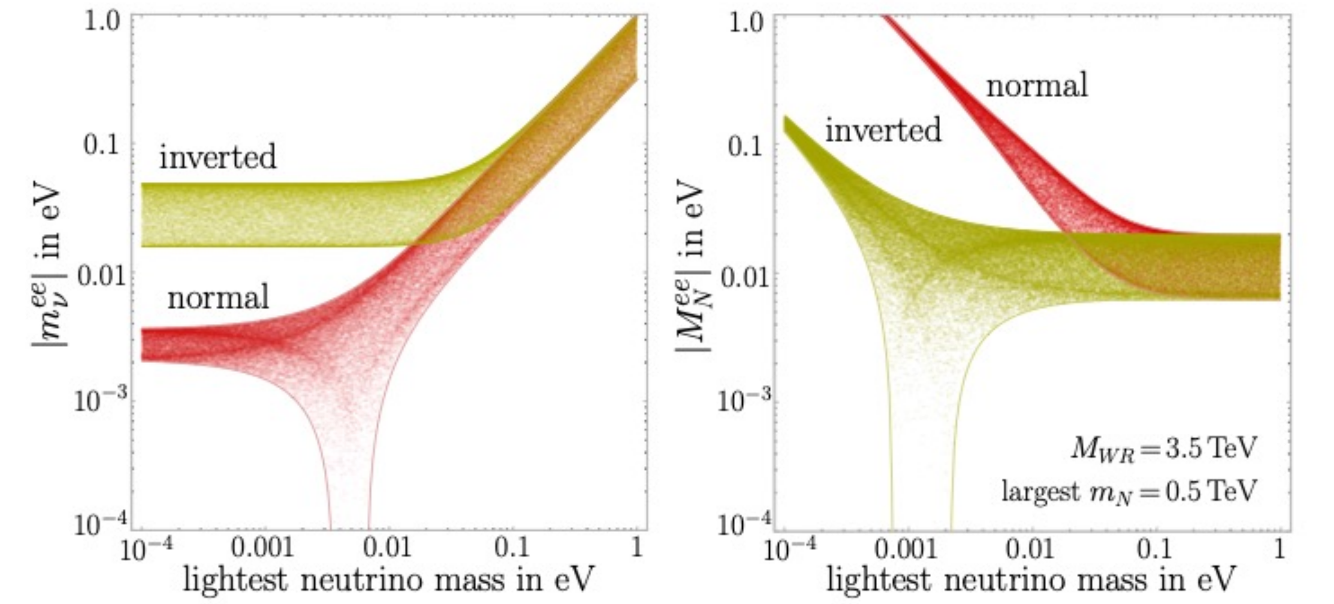


Fig. 1. The canonical contribution (left) from light neutrino mass and the new physics part (right), with $|M_N^{ee}|$ *defined in Eq.* (12). *The mixing angles are fixed at* $\{\theta_{12}, \theta_{23}, \theta_{13}\} = \{35^\circ, 45^\circ, 7^\circ\}$, *while the Dirac and Majorana phases vary in the interval* $[0, 2\pi]$.

← Also not a lobster!

https://arxiv.org/pdf/1011.3522

Impact of Left-right symmetry models that could be
Within LHC reach

New Fermion – Sterile neutrino

- Sterile neutrinos are neutral and right-handed SM singlet fermions that interact with ordinary matter only through mixing with the active neutrinos
- Sterile neutrinos with masses below few MeV could be produced in $\beta\beta$ decays
- The presence of a massive sterile neutrino in the final state affects the kinematics of the decay

  → endpoint of the summed electron energy distribution is shifted to $Q_{\beta\beta} - m_N$, m_N= sterile neutrino mass.

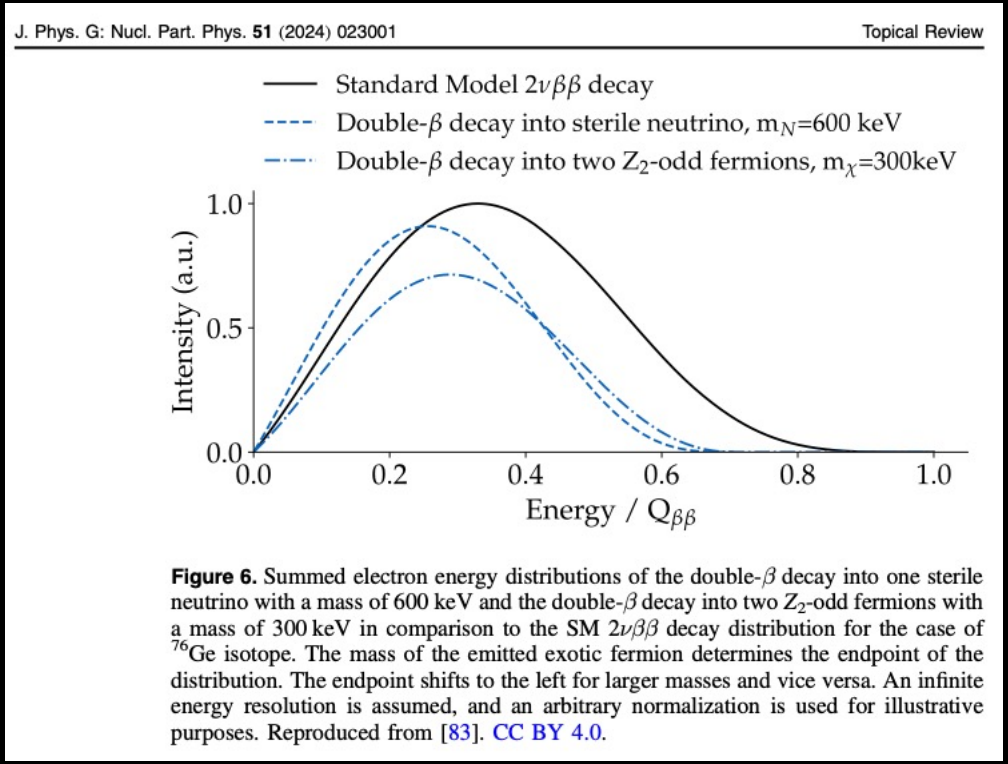

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Figure 6. Summed electron energy distributions of the double-β decay into one sterile neutrino with a mass of 600 keV and the double-β decay into two Z_2-odd fermions with a mass of 300 keV in comparison to the SM $2\nu\beta\beta$ decay distribution for the case of ^{76}Ge isotope. The mass of the emitted exotic fermion determines the endpoint of the distribution. The endpoint shifts to the left for larger masses and vice versa. An infinite energy resolution is assumed, and an arbitrary normalization is used for illustrative purposes. Reproduced from [83]. CC BY 4.0.

Lorentz Violation

- Lorentz invariance is one of the fundamental symmetries of the SM of particle physics
- Symmetry is broken at Planck scale in many theories of quantum gravity
- Suppressed effects could arise at lower energy scales, modifying the $2\nu\beta\beta$ spectral shape

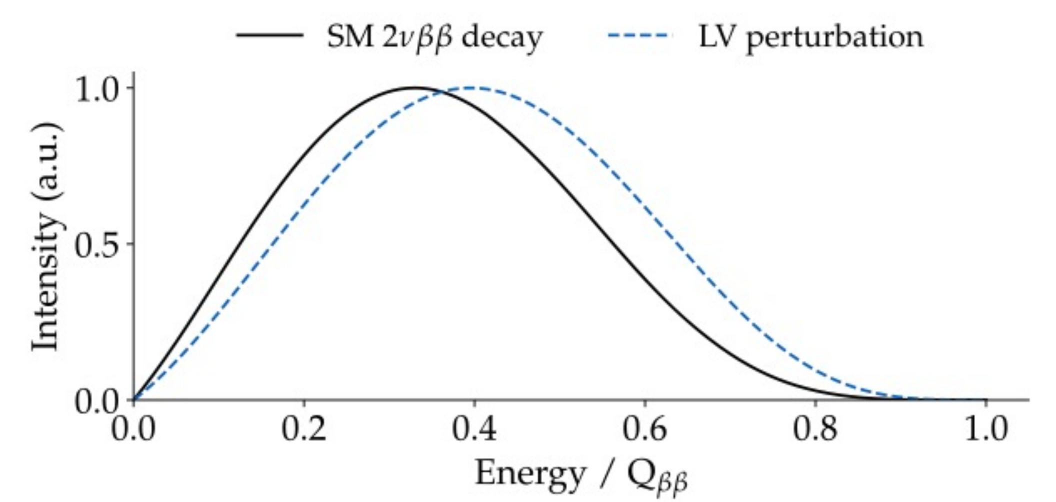
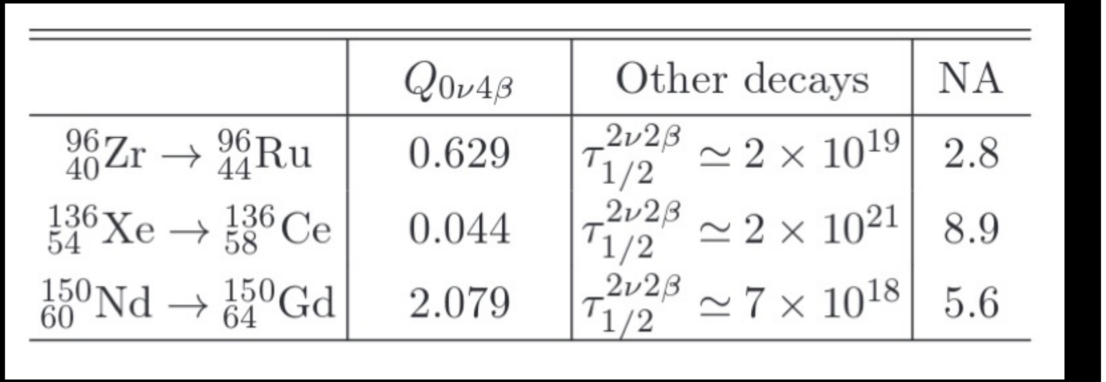


Figure 7. Summed electron energy distribution of the $2\nu\beta\beta$ decay in the SM and the perturbation term introduced by Lorentz violation (LV) for the isotope ^{76}Ge. An infinite energy resolution is assumed, and an arbitrary normalization is used for illustrative purposes.

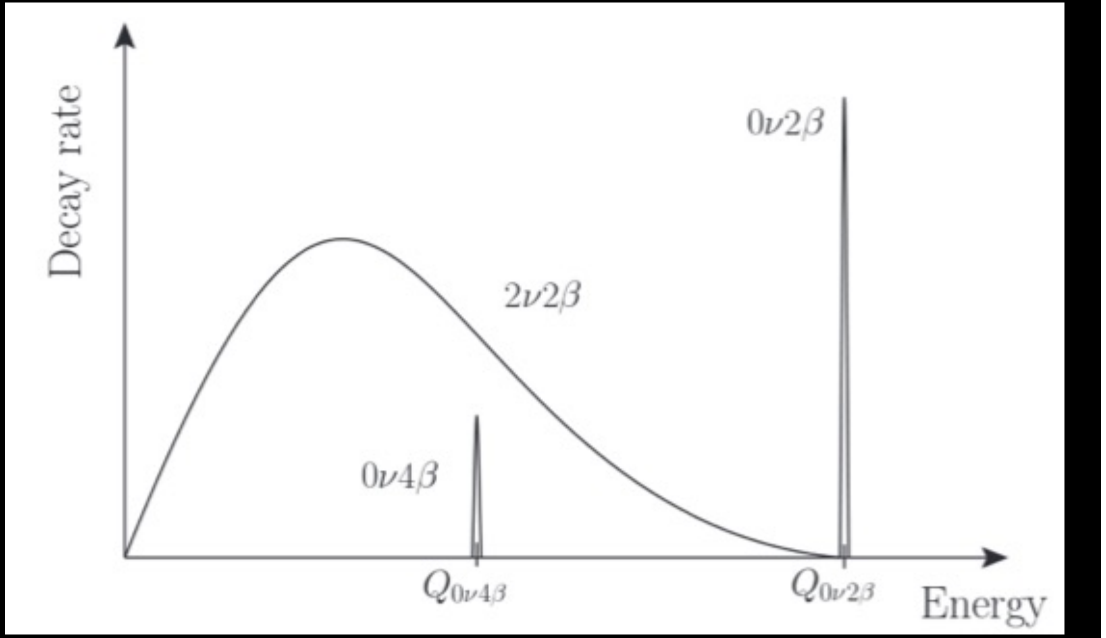
Is LNV only possible with Majorana particles?

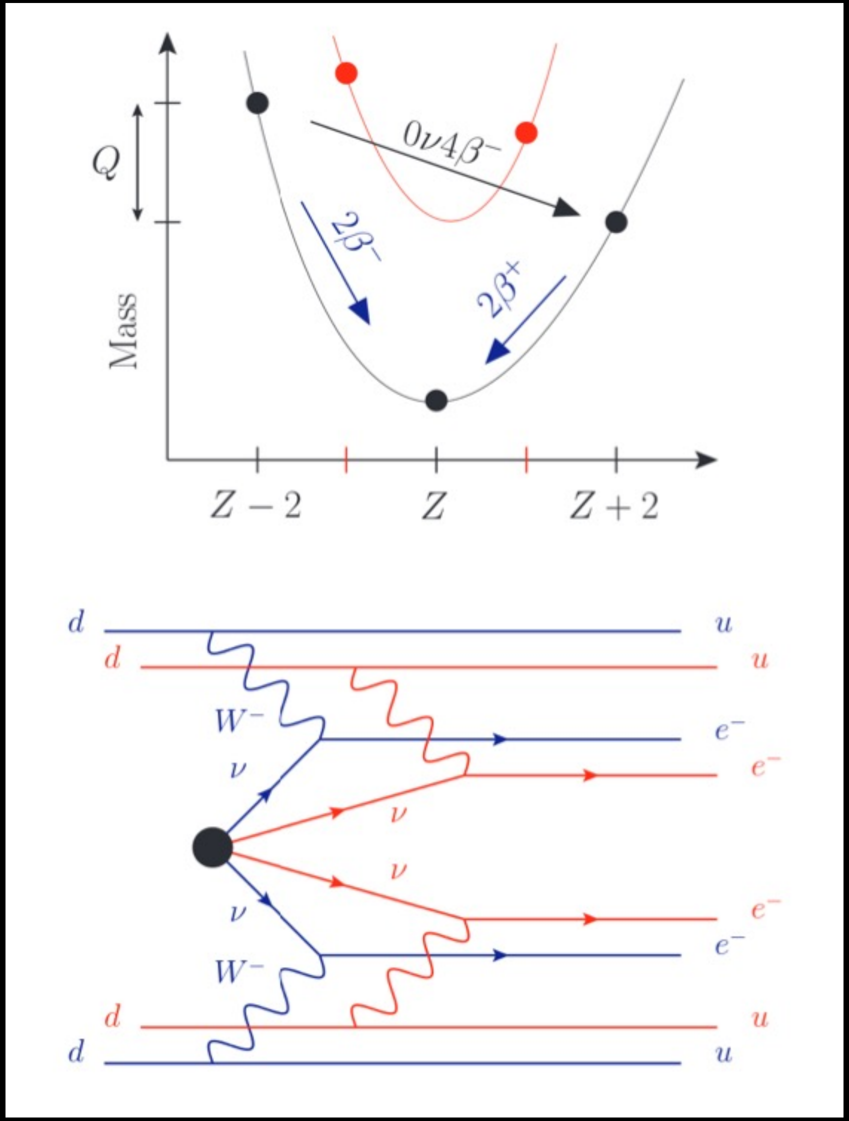
Quadruple Beta Decay

3 candidates:



	$Q_{0\nu4\beta}$	Other decays	NA
$^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6





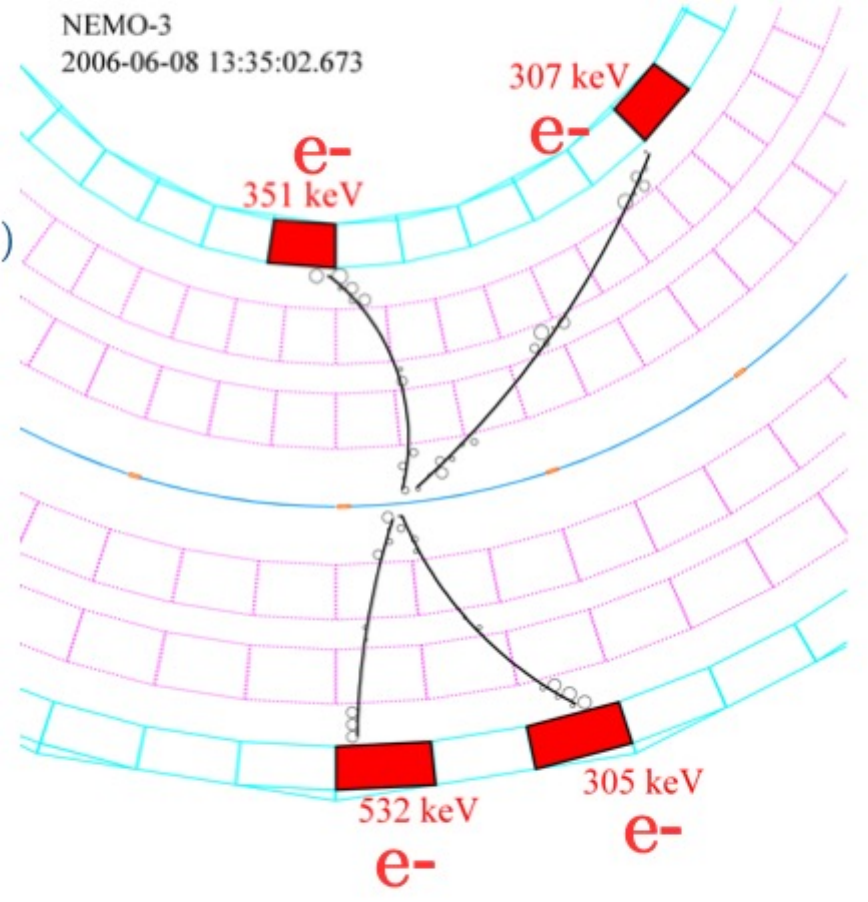
Heeck and Rodejohann Europhys. Lett. 103, 32001 (2013)

Neutrinos are Dirac, $0\nu\beta\beta$ is forbidden in this model

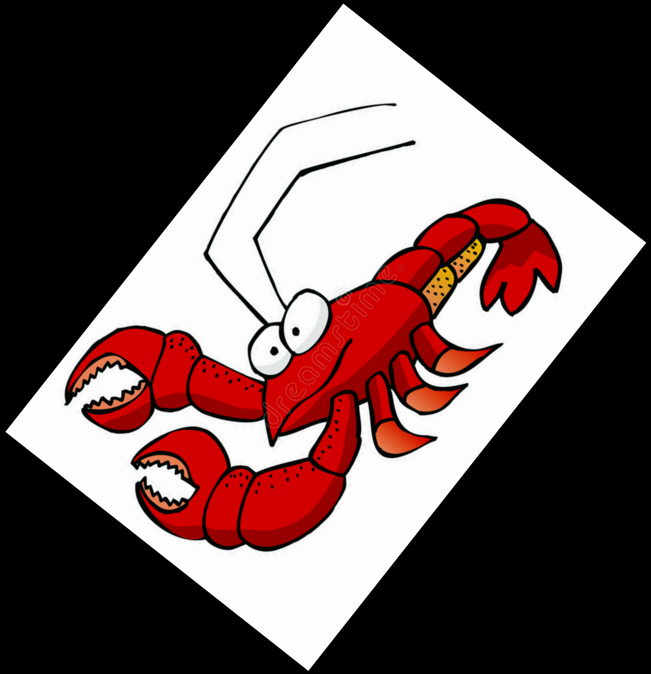
Quadruple Beta Decay

NEMO-3 search in ^{150}Nd
$Q_{4\beta} = 2.079\text{MeV}$

$T_{1/2}^{0\nu4\beta} > (1.1 - 3.2)\times10^{21}$ years



Lobster Plots



Shape constrained by bounds on Δm^2 from oscillation measurements

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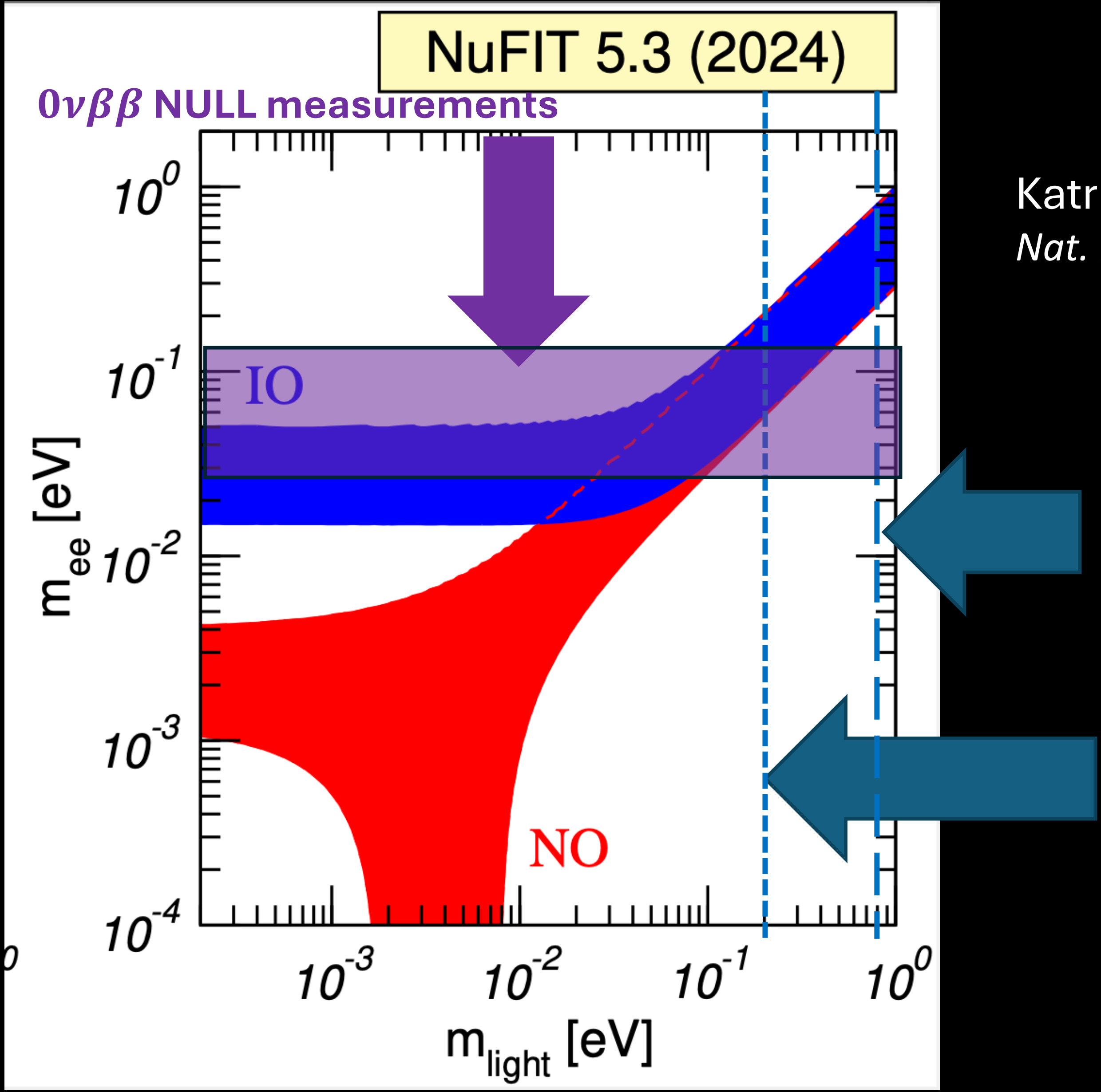
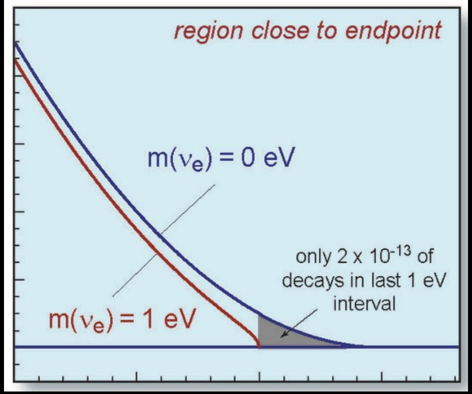


$0\nu\beta\beta$ NULL measurements

Katrin $m_\nu < 0.9\ eV$
Nat. Phys. **18**, 160–166 (2022)

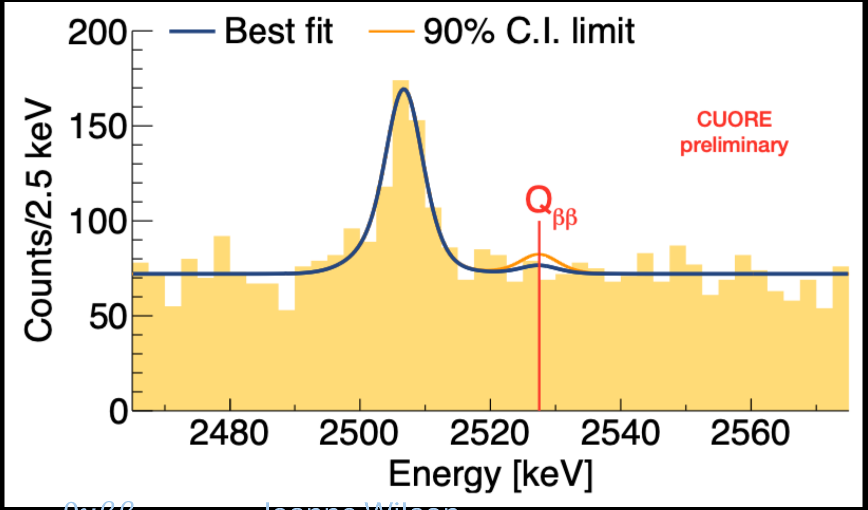


Cosmology
pdglive.lbl.gov
$\sum m_\nu < 0.12$eV

Setting Limits vs Discovery

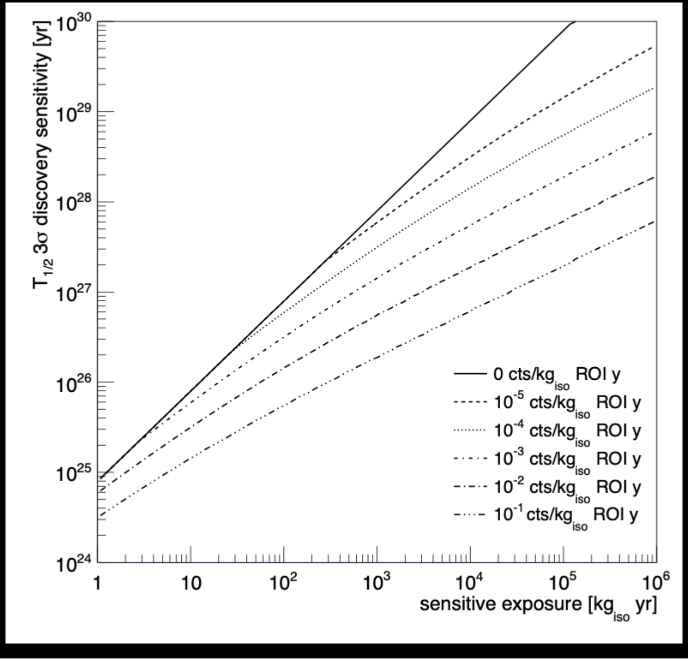
- Place a limit on half-life if there is no evidence of a signal above the observed background, genera use 90% $C.L.$
- Sensitivity limit ($T_{1/2} >$) scales wit exposure $\sqrt{(mass \times time)}$ and increases with decreasing background

Not the same limits

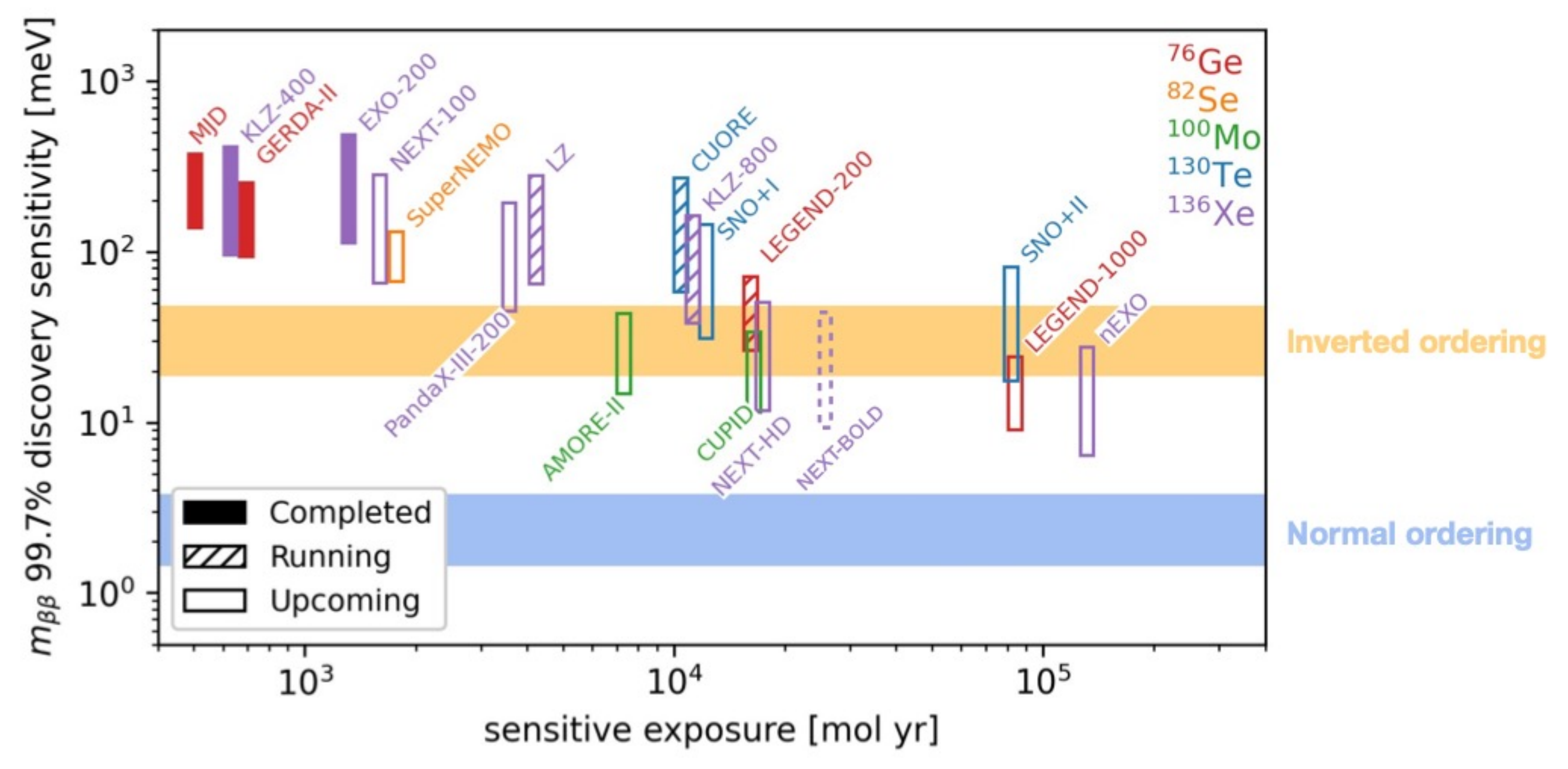


- Claim discover 3σ bove expected b
- very sensitivity = al e of $T_{1/2}$ $m_{\beta\beta}$) for which experiment has 50% chance to measure a signal with significance of at least 3σ

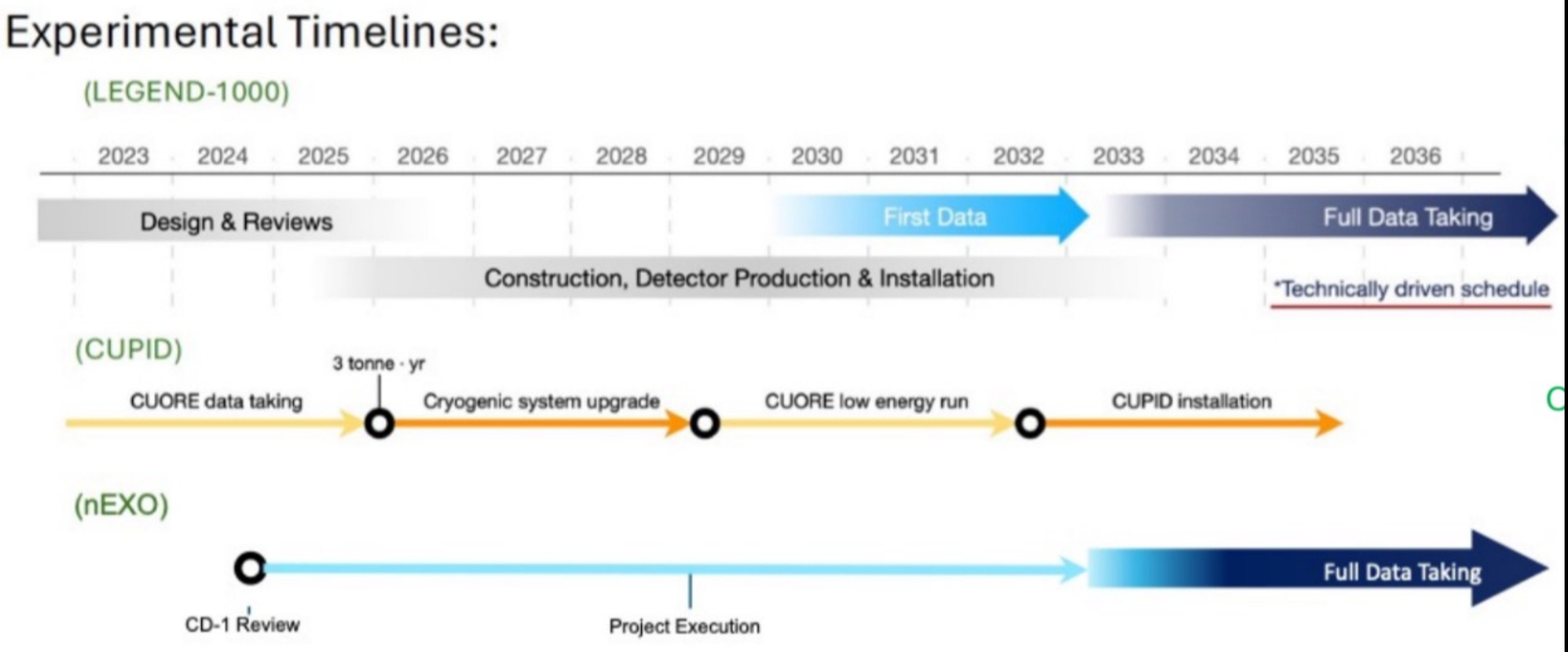
Definitions can vary between collaborations



Comparing Experiments

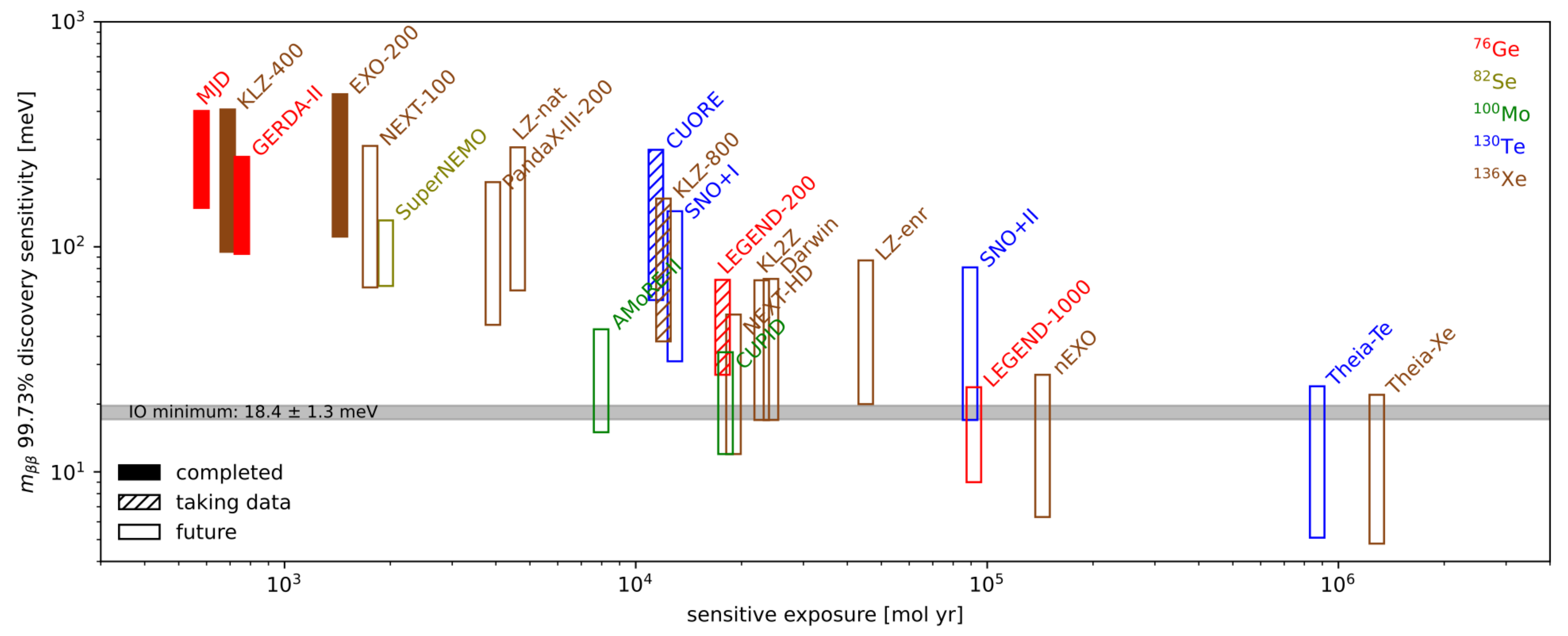


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)



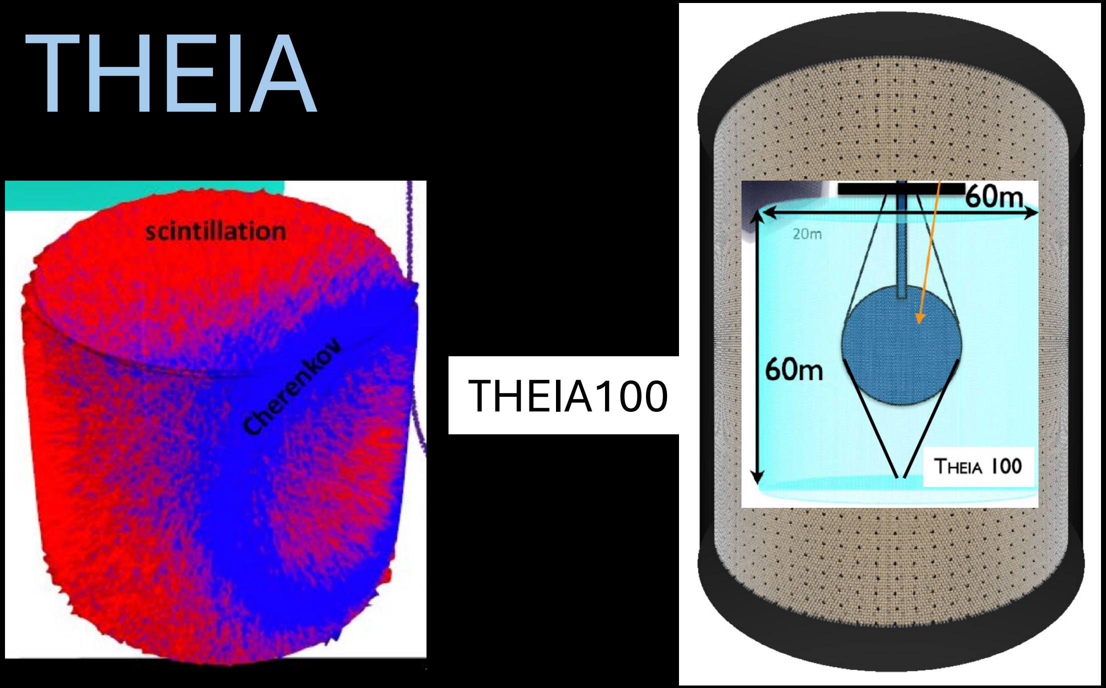
Experimental Timelines:

Beyond the Inverted Ordering



https://arxiv.org/pdf/2304.03451

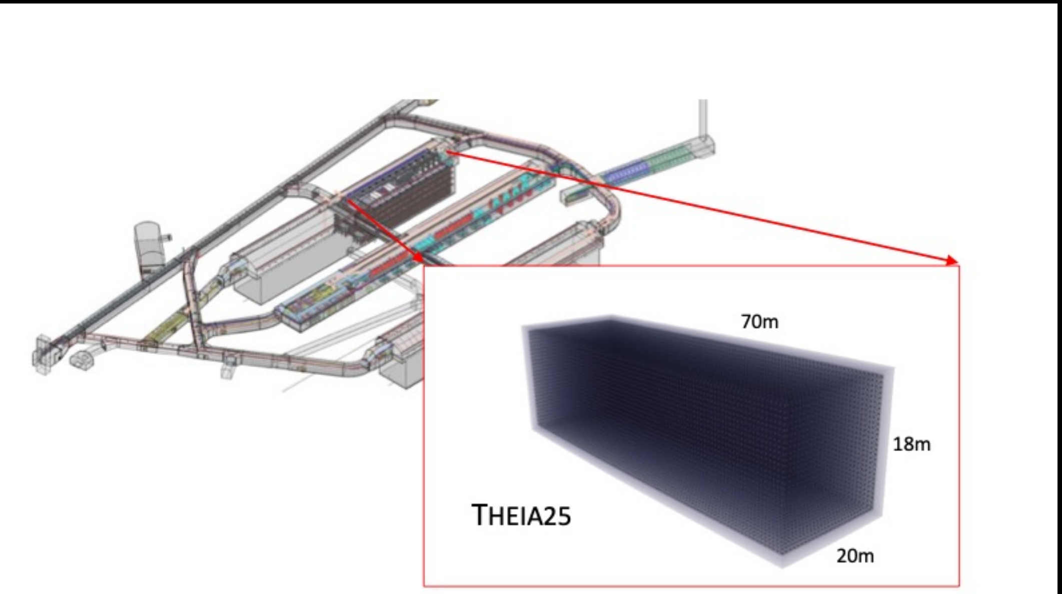
THEIA



Hybrid optical neutrino detector with Rich physics programme

Combine topology of Cherenkov light with light yield and low threshold of scintillation.

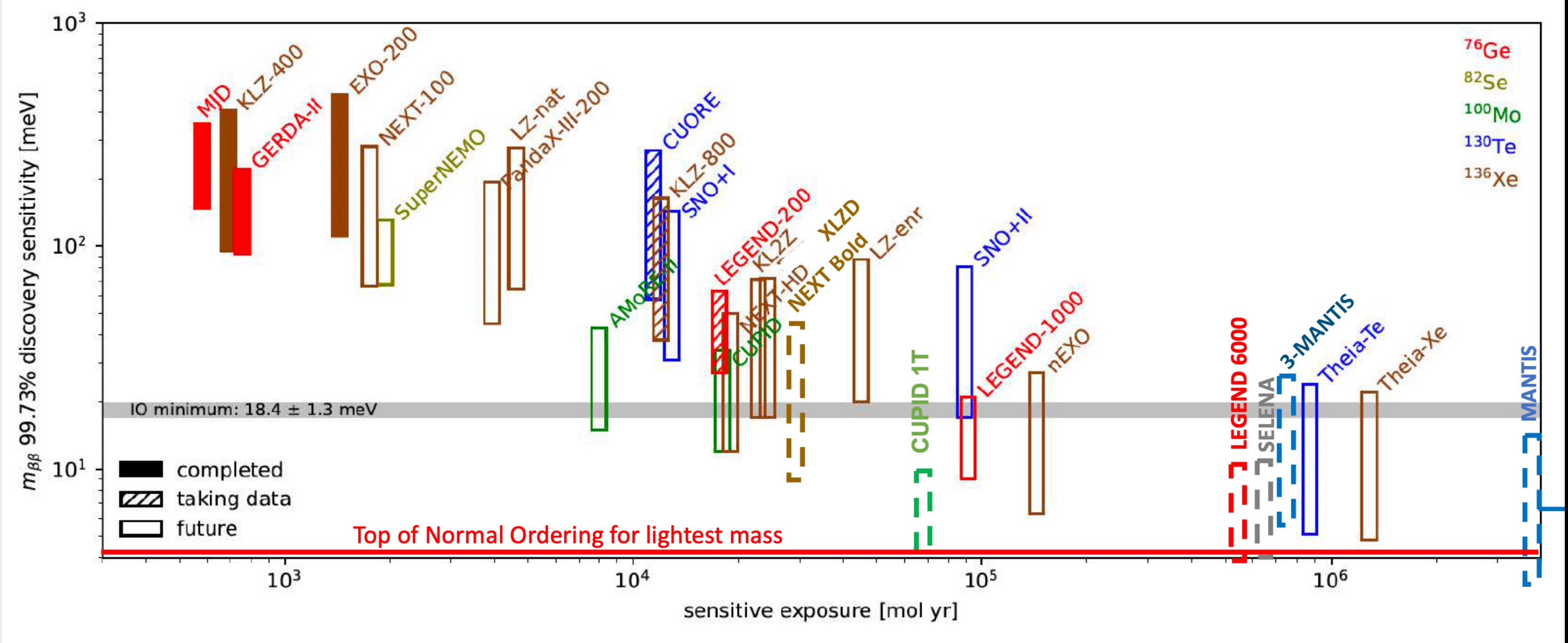
- Water based liquid scintillators (WbLS) or slow scintillators
- Fast photon detectors (eg LAPPDs)
- Spectral sorting with dichroic filters



THEIA25 would fit in a DUNE ‘cavern of opportunity’

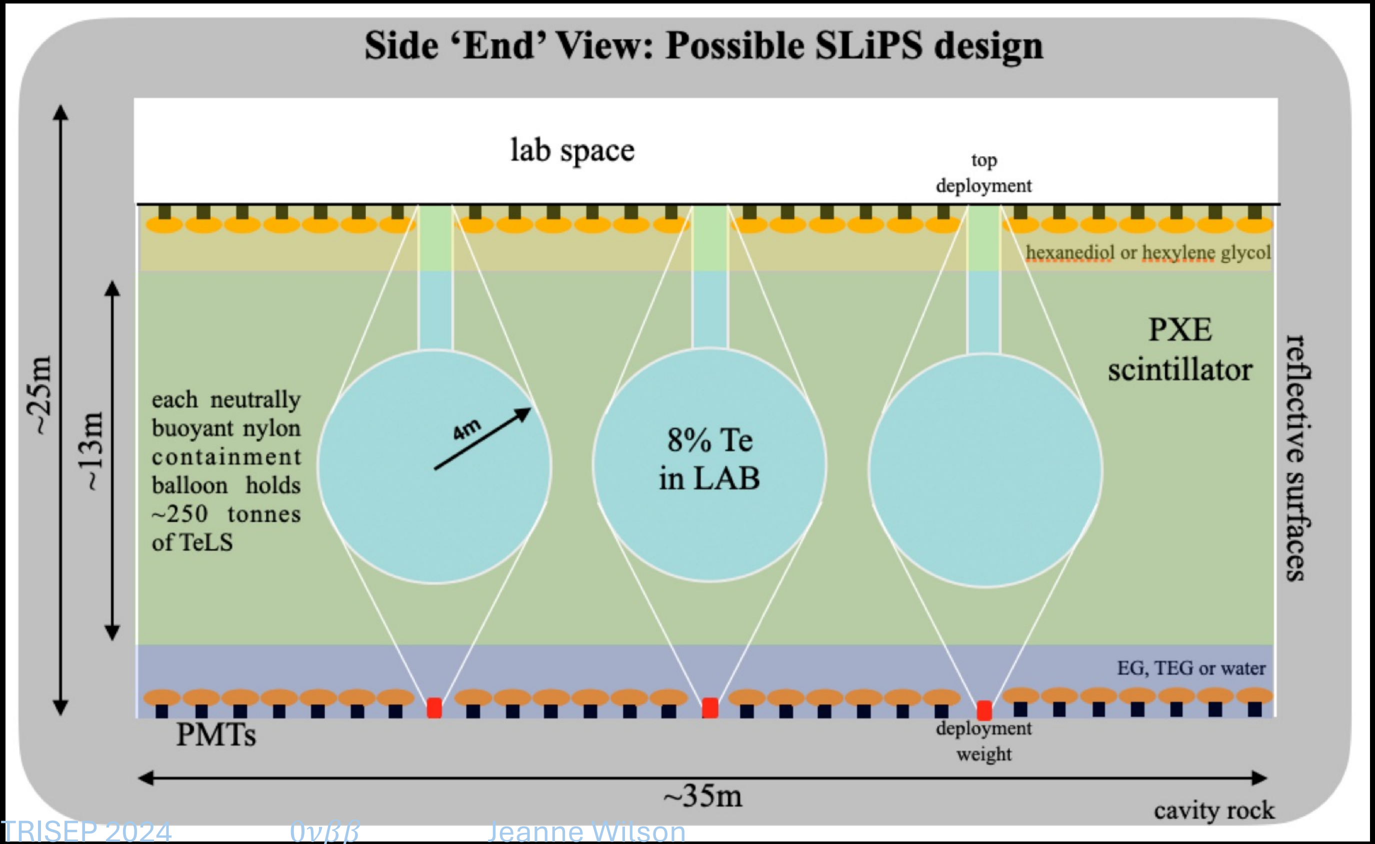
THEIA100 better for $0\nu\beta\beta$ search:

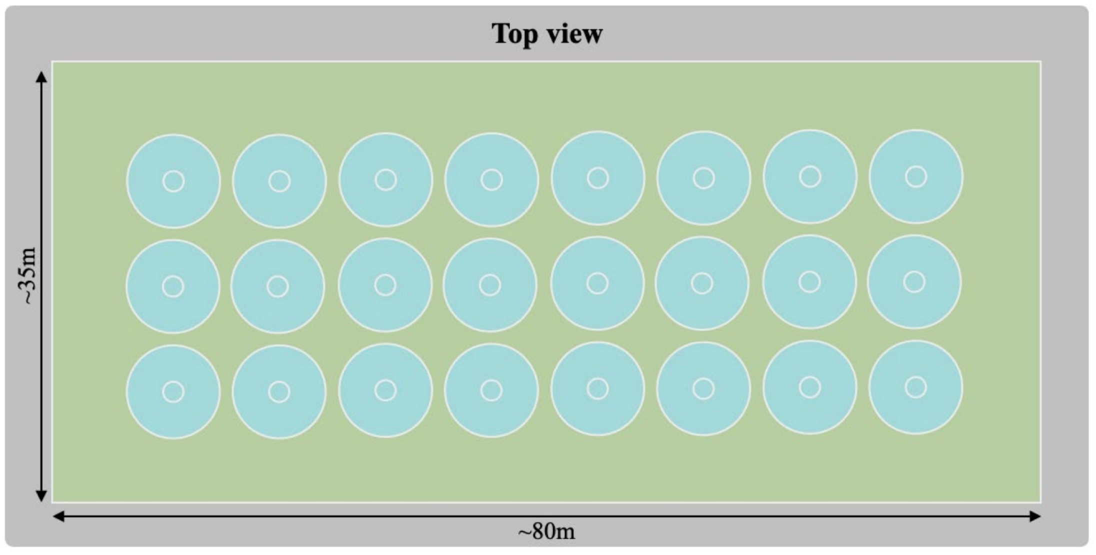
- Load natural Te or enriched ^{136}Xe inside a balloon of Liquid scintillator within the larger WbLS detector.

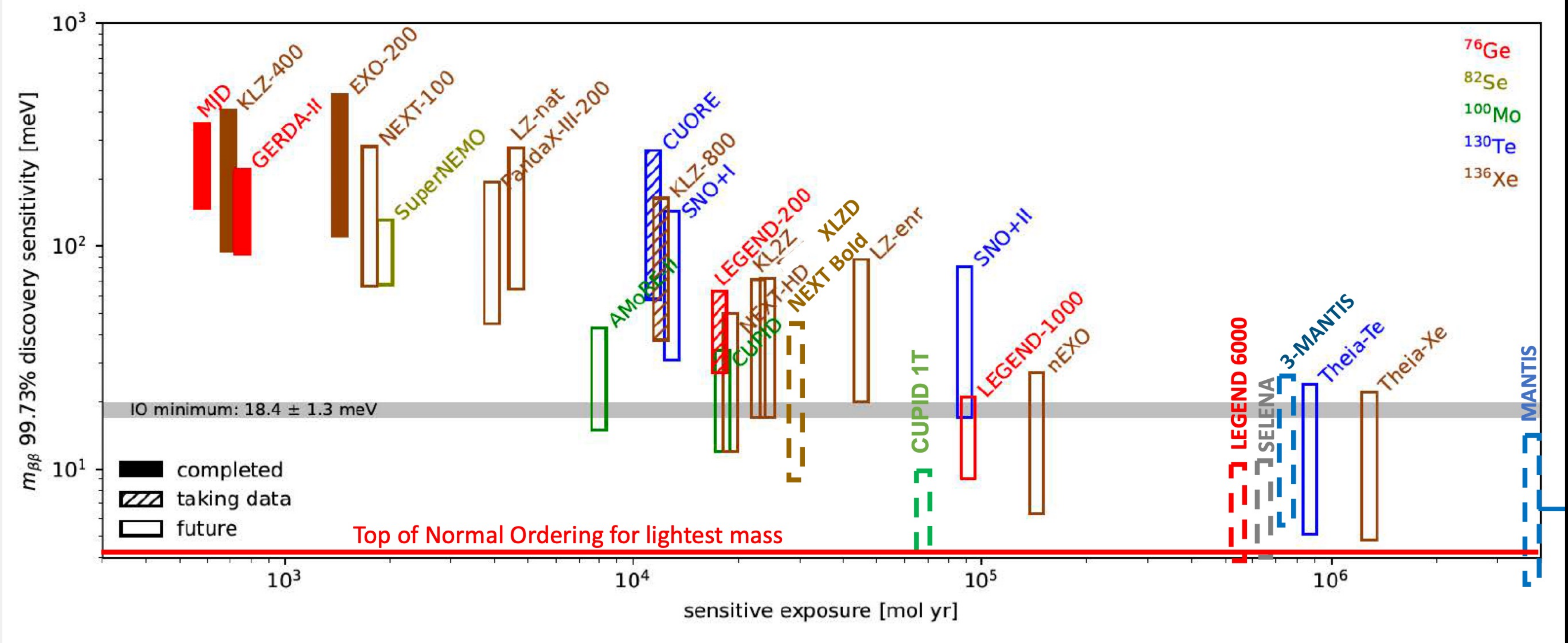

10^3
10^2
10^1
10^3
10^4
10^5
10^6
$m_{\beta\beta}$ 99.73% discovery sensitivity [meV]
sensitive exposure [mol yr]
^{76}Ge
^{82}Se
^{100}Mo
^{130}Te
^{136}Xe
MJD
KLZ-400
GERDA-II
EXO-200
NEXT-100
SuperNEMO
LZ-nat
PandaX-III-200
CUORE
KLZ-800
SNO+I
AMoRE-II
LEGEND-200
KL2Z
NEXT-HD
CUPID
XLZD
NEXT Bold
LZ-enr
SNO+II
LEGEND-1000
nEXO
CUPID 1T
LEGEND 6000
SELENA
3-MANTIS
Theia-Te
Theia-Xe
MANTIS
IO minimum: 18.4 ± 1.3 meV
completed
taking data
future
Top of Normal Ordering for lightest mass

MANTIS

- Modular Approach for $N\beta\beta$ with Tellurium In Scintillator
- ^{130}Te high isotopic abundance -> cheapest isotope to load (~<$2M / ton)
- Challenge is to get to high loading without blocking light, and maintaining radioactive purity


Side 'End' View: Possible SLiPS design


Top view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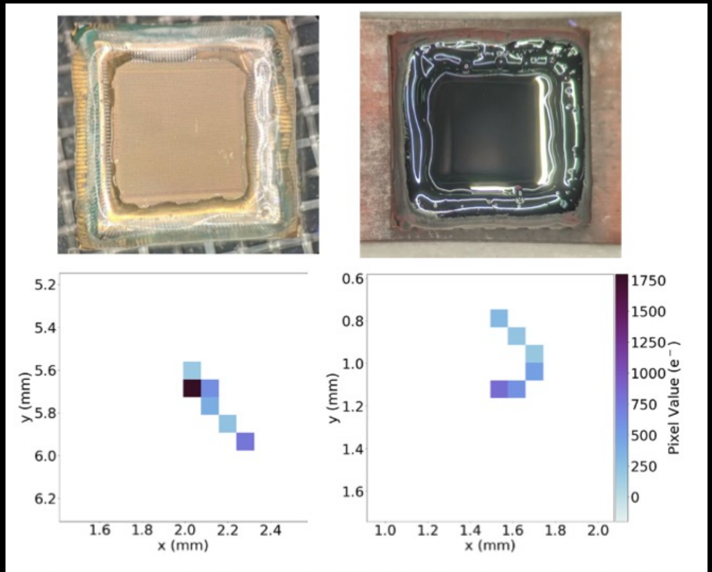
CUPID 1T
SNO+II
LEGEND-1000
nEXO
LEGEND 6000
SELENA
3-MANTIS
Theia-Te
Theia-Xe
MANTIS

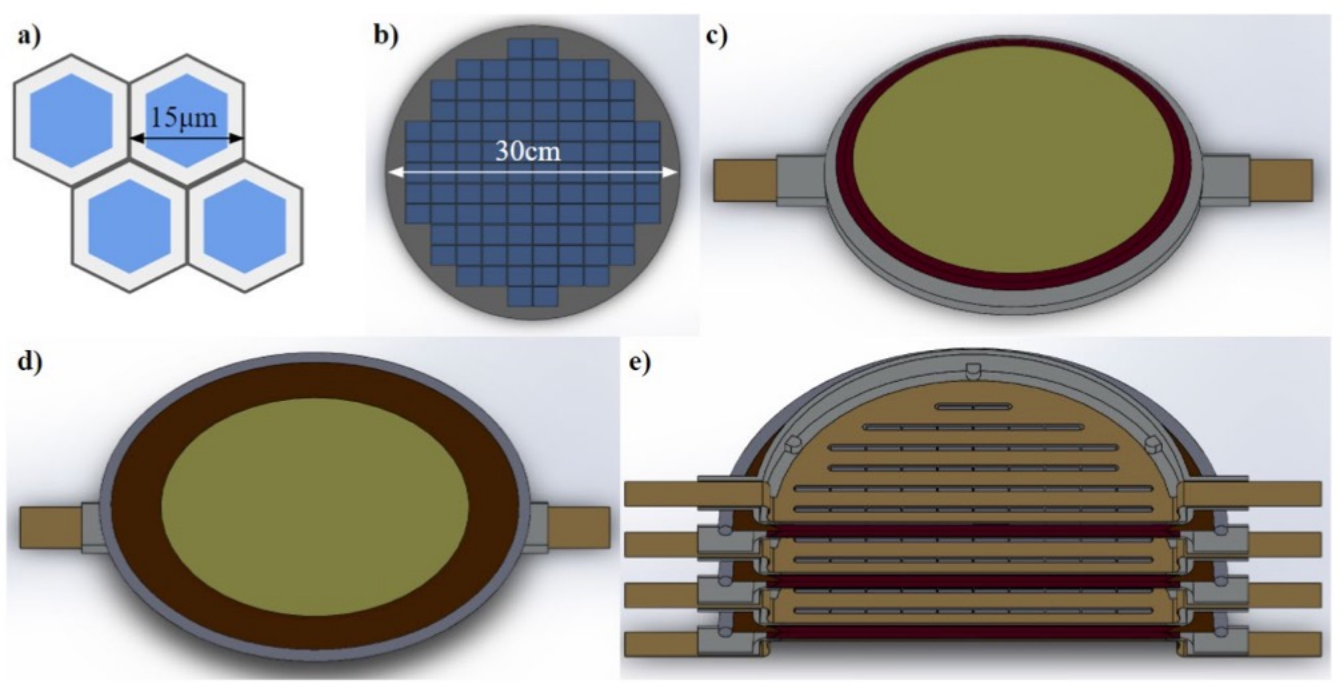
Selena

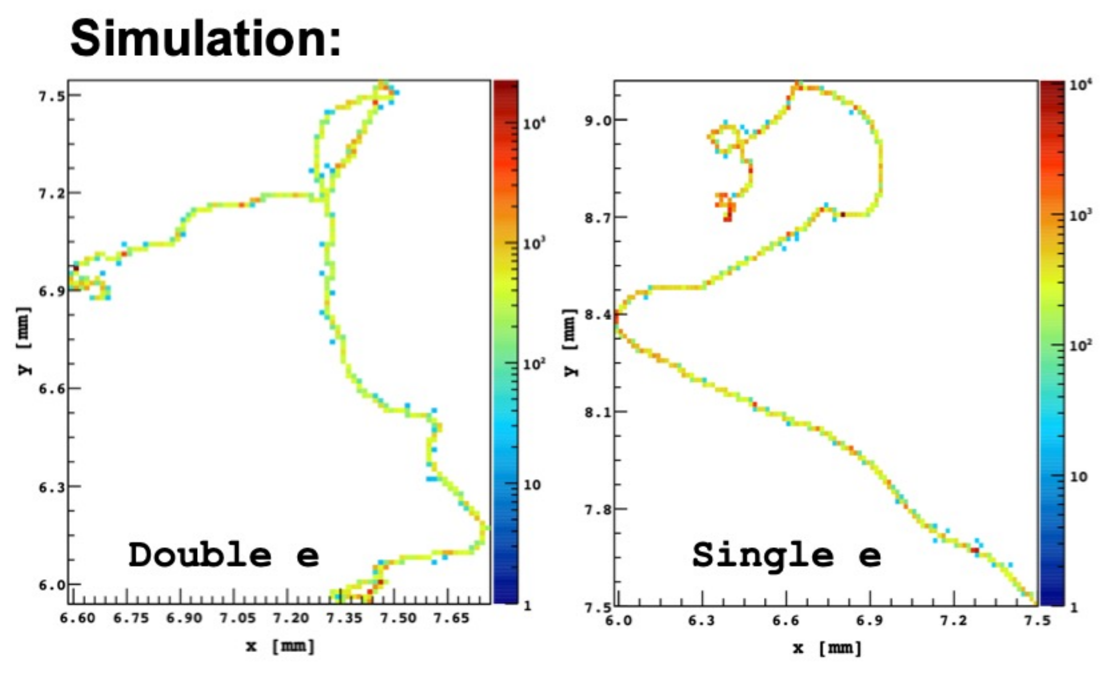
arXiv: 2203.08779

- 10-ton ^{82}Se target with exquisite spatial resolution
- Large-area hybrid CMOS images with ~5mm thick layers of amorphous ^{82}Se
- Currently in R&D stage with small pixelated devices



Demonstration of ~MeV electron tracks!





Simulation:

Summary – lecture 3

- Current bounds on effective Majorana neutrino mass
  - Oscillations (Δm^2), β-endpoint, cosmology, $0\nu\beta\beta$ non-observation limits
- Other underlying mechanisms for $0\nu\beta\beta$ and new physics ($2\nu\beta\beta$ sensitivity)
- Limits vs discovery potential
- Comparing experiments
  - Mass sensitivities of some of the experiments we have discussed
- Future ideas for probing below inverted ordering mass range

Final thoughts

- There is clear theoretical motivation for $0\nu\beta\beta$ but so far no experimental evidence
- Require ton-scale experiments to see the process if neutrino mass ordering is inverted
  - Many challenges – requires huge investment and large-scale international collaborations
- >>Multi-ton-scale experiments needed to see the process if neutrino mass is normally ordered
  - Need to build on the best elements of existing experiments (isotopes, location, shielding, materials)
  - Advances in technology also required, R&D
- Strong argument for multiple isotope measurements
- Even if we do observe $0\nu\beta\beta$, more work required to understand underlying mechanism and hence neutrino absolute mass