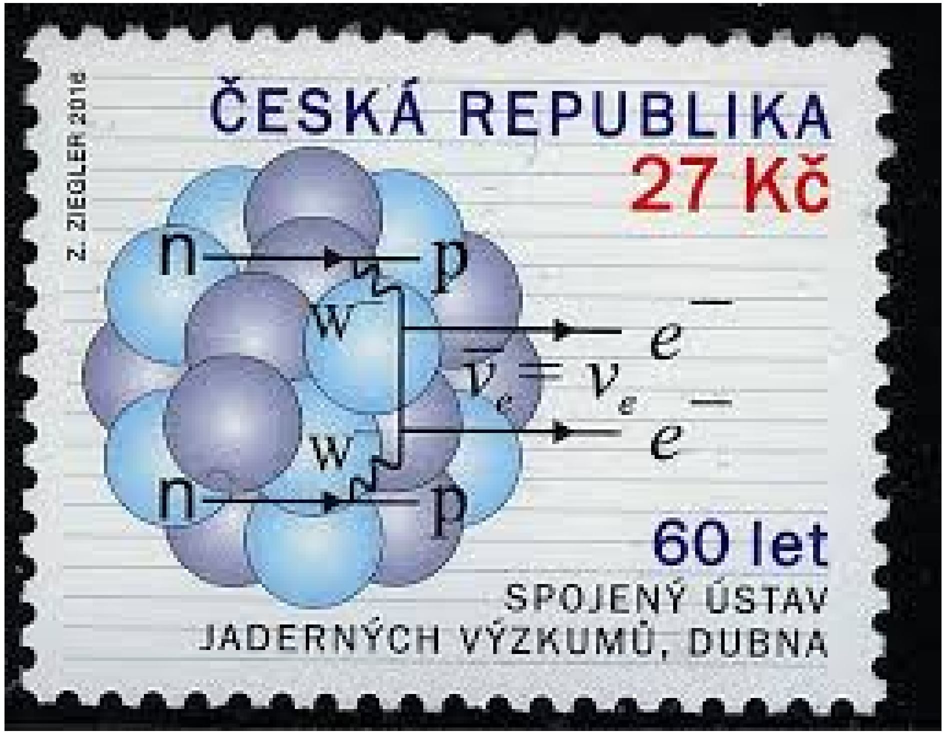
Model-Dependence in $0\nu\beta\beta$ Probes



André de Gouvêa – Northwestern University

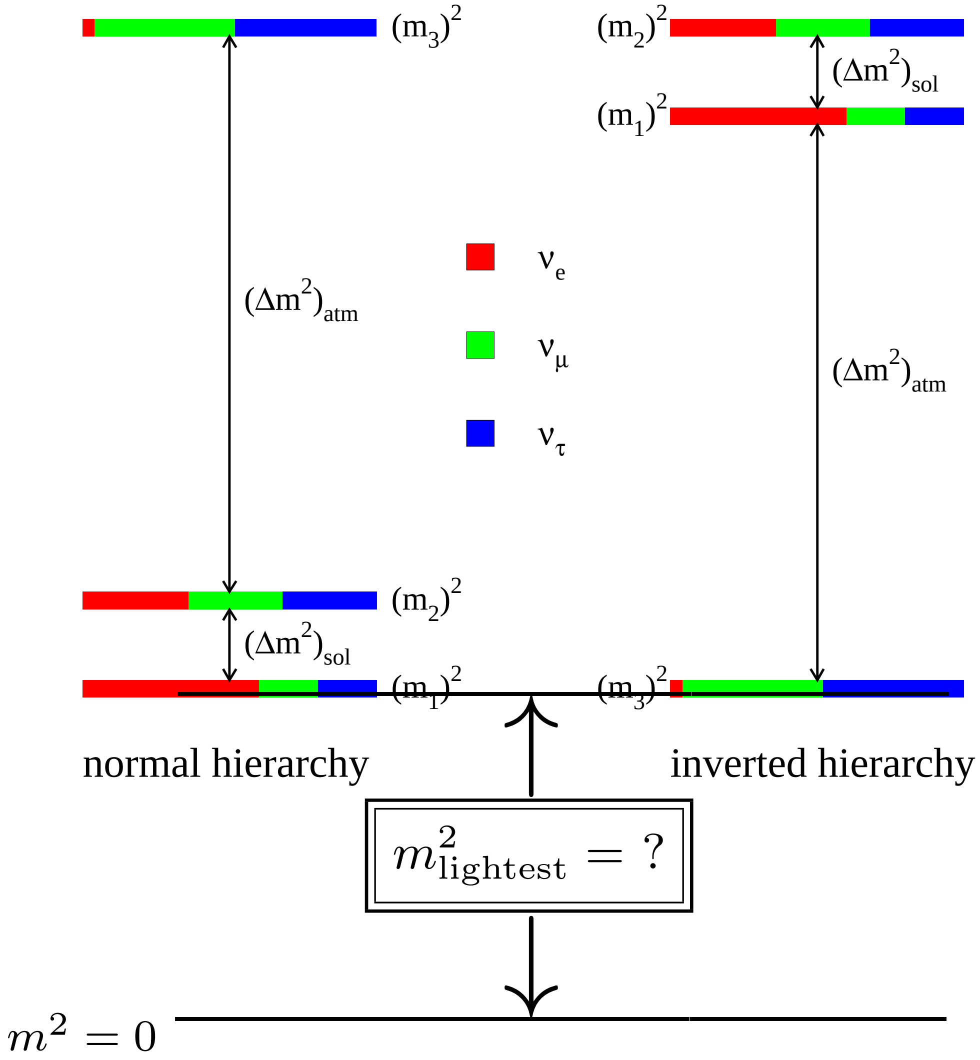
NF-CF Neutrino mass scale with beta decay kinematics, double beta decay, and cosmology

Community Summer Study – Snowmass – Seattle, July 17–26, 2022

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

[9 out of 10 theorists agree: "Best" Question in Neutrino Physics Today!]

And How Light is the Lightest Neutrino Anyway?



So far, we've only been able to measure neutrino mass-squared differences.

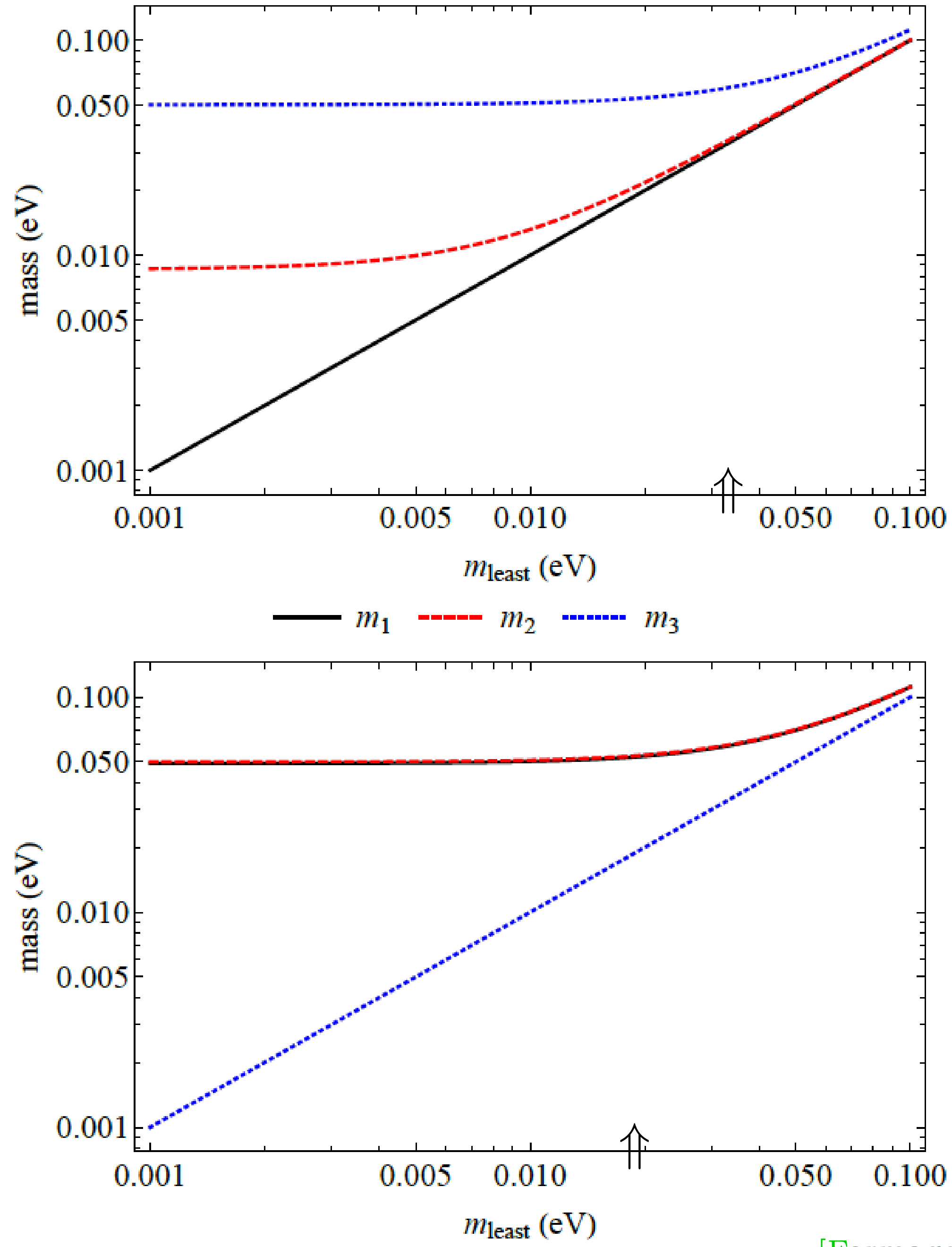
The lightest neutrino mass is only relatively poorly constrained.

qualitatively different scenarios allowed:

- $m^2_{\rm lightest} \equiv 0$;
- $m^2_{\rm lightest} \ll \Delta m^2_{12,13}$;
- $m^2_{\rm lightest} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations:

[Cosmology, β-Decay, $0\nu\beta\beta$]



($\Uparrow$: Cosmology Bound)

[Formaggio, AdG, Robertson, Phys.Rept. 914 (2021)]

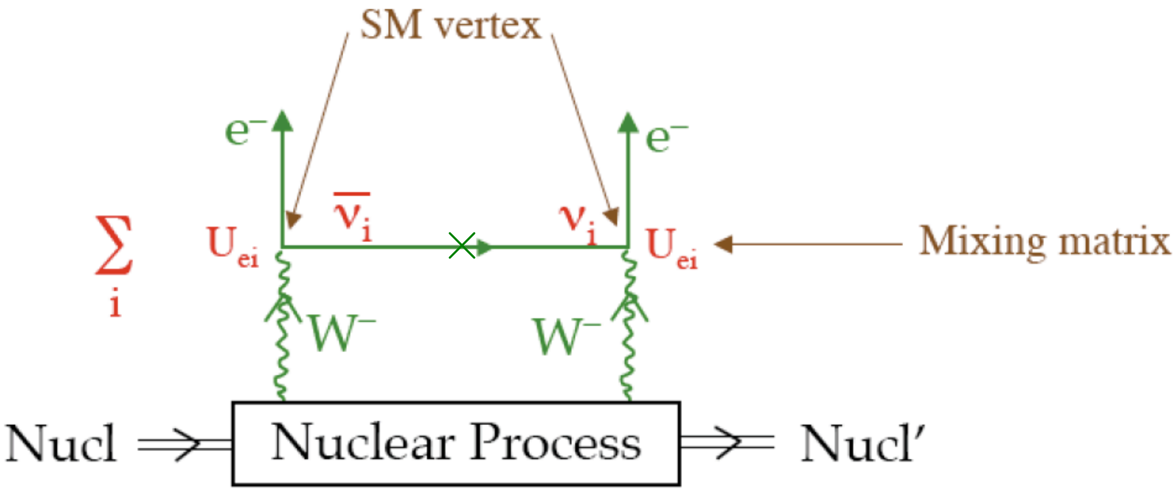
FIG. 4: Current best-fit values of the neutrino masses m_1, m_2, m_3 as a function of the lightest neutrino mass, for the normal mass-ordering (top) and the inverted mass ordering (bottom).

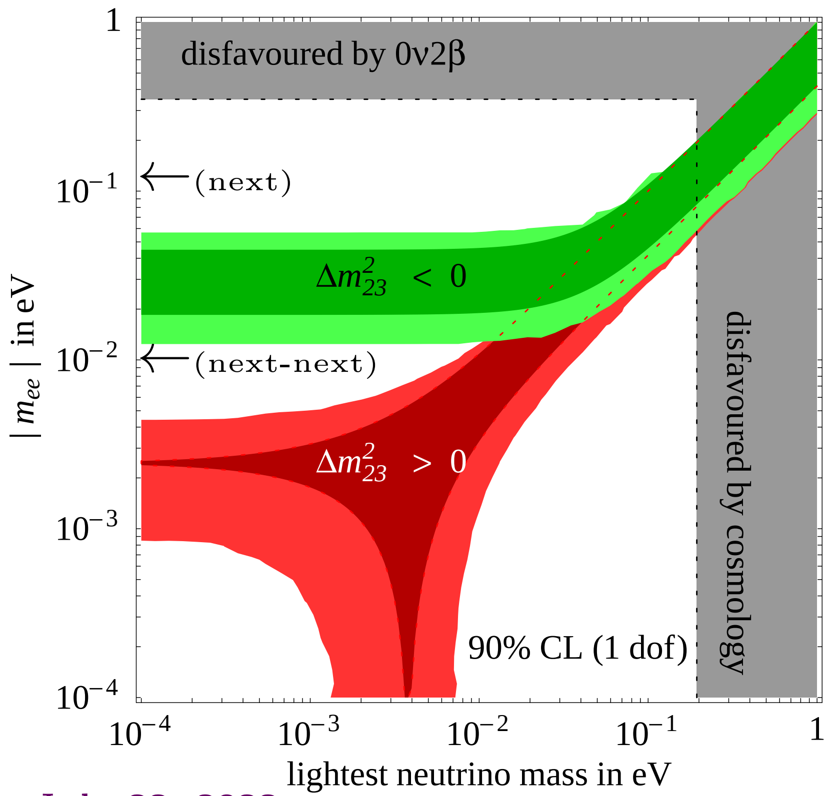
Searches for Lepton-Number Violation Depend on The Neutrino Masses

Best Bet: search for

Neutrinoless Double-Beta

Decay: $Z \to (Z+2)e^- e^-$





Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

$\Leftarrow$ **no longer lamp-post physics!**

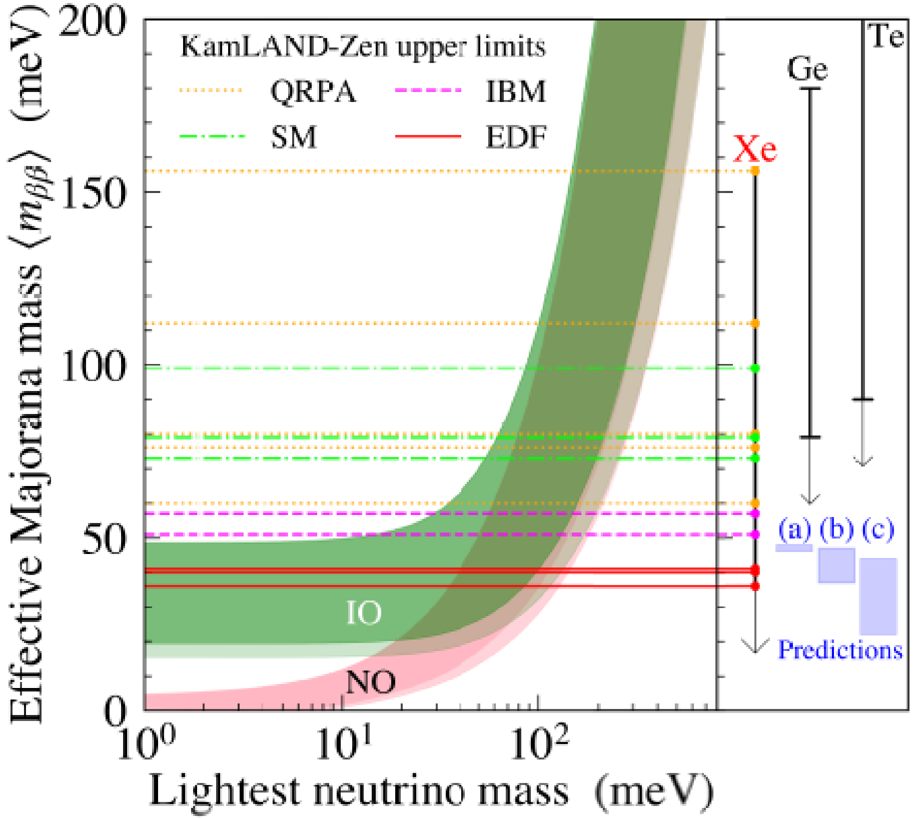


FIG. 4: Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass. The dark shaded regions are predictions based on best-fit values of neutrino oscillation parameters for the normal ordering (NO) and the inverted ordering (IO), and the light shaded regions indicate the 3σ ranges calculated from oscillation parameter uncertainties [23, 24]. The regions below the horizontal lines are allowed at 90% C.L. with ^{136}Xe from KamLAND-Zen (this work) considering an improved phase space factor calculation [25, 26] and commonly used nuclear matrix element estimates, EDF [27–29] (solid lines), IBM [30, 31] (dashed lines), SM [32–34] (dot-dashed lines), QRPA [35–39] (dotted lines). The side-panel shows the corresponding limits for ^{136}Xe, ^{76}Ge [40], and ^{130}Te [41], and theoretical model predictions on $\langle m_{\beta\beta} \rangle$, (a) Ref. [2], (b) Ref. [3], and (c) Ref. [4] (shaded boxes), in the IO region.

Lots of Experimental Activity!

Moving Towards Ton-Scale Expts.

(LEGEND, CUPID, nEXO, etc)

[KamLAND-Zen Coll. (Abe *et al*), 2203.02139 [hep-ex]]

Caveats: $0\nu\beta\beta$ searches and informing neutrino properties

- Non-observation does not imply the neutrinos are Dirac fermions ("you can't prove a negative");
- Only informs the neutrino masses if the neutrinos are Majorana fermions;
- Model-dependent, indirect probe of neutrino masses. While a nonzero rate for $0\nu\beta\beta$ implies neutrinos are massive Majorana fermions, the connection to nonzero neutrino masses can be very indirect. How do we learn that we are measuring what we think we are measuring?
- Real life is hard. Large uncertainties in translating the half-life to the effective neutrino mass (nuclear matrix elements).

Comments on the "funnel" region, $m_{\beta\beta}=0$

- $m_{\beta\beta}=\sum_i U_{ei}^2 m_i$. Sum of three complex numbers. It can vanish if they define a triangle in the complex plane. Easy to see this only happens in the Normal Ordering.

- This possibility can be ruled out by other experiments. For example, we could learn that $m_{\rm least}>0.01$ eV. Other example, in some theoretical models, $m_{\beta\beta}=0$ is not an option (e.g., in models where $m_{\rm least}$ vanishes.)

- However, $m_{\beta\beta}$ very small is not "fine-tuning." $m_{\beta\beta}\equiv m_{ee}$:

$$m_\nu=\left(\begin{array}{ccc} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau}\end{array}\right)$$

It is easy to imagine a hierarchy to the elements of the mass matrix (remember, e.g., $m_e\ll m_\mu\ll m_\tau$).

Another example: Everyone's Favorite Neutrino Mass Model

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

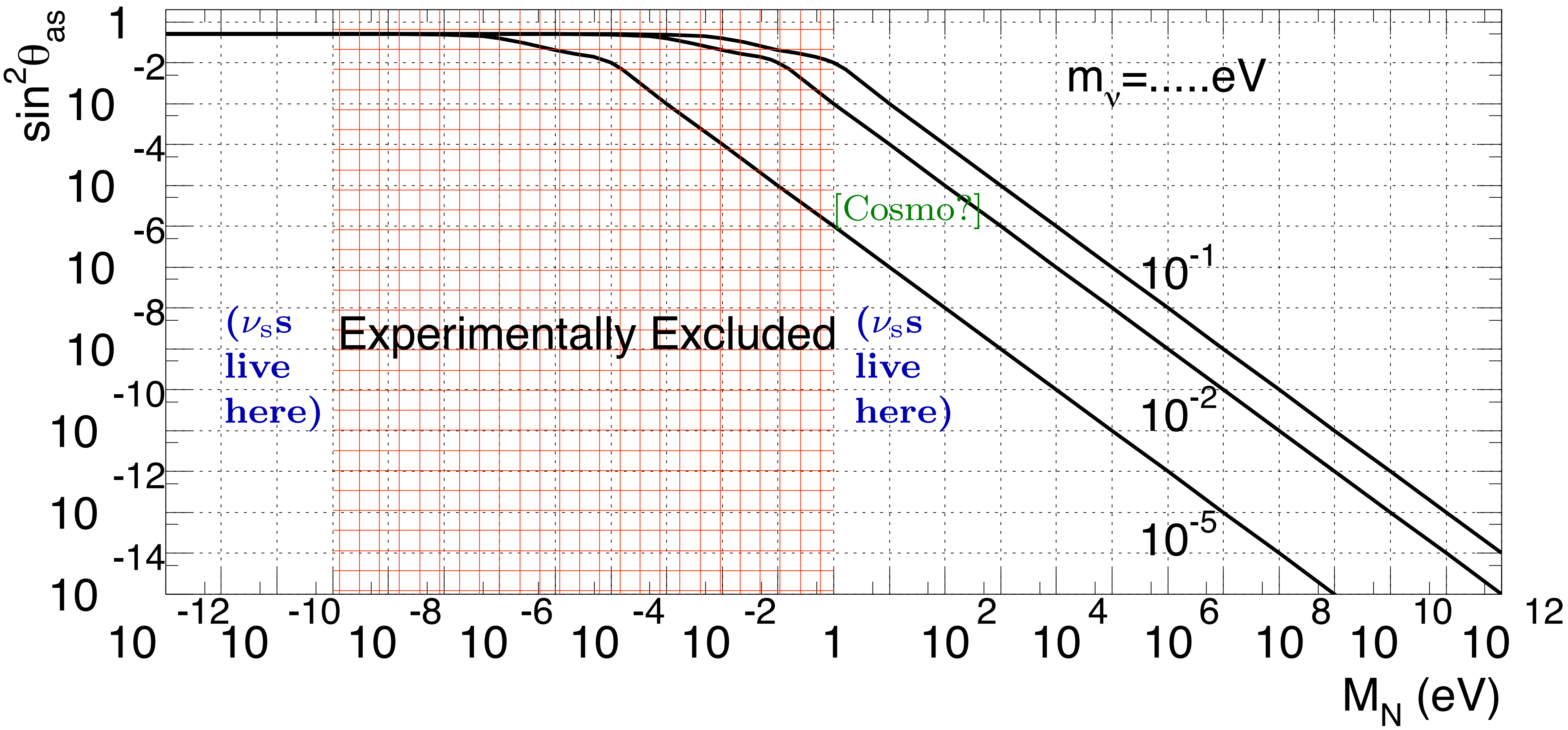
where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

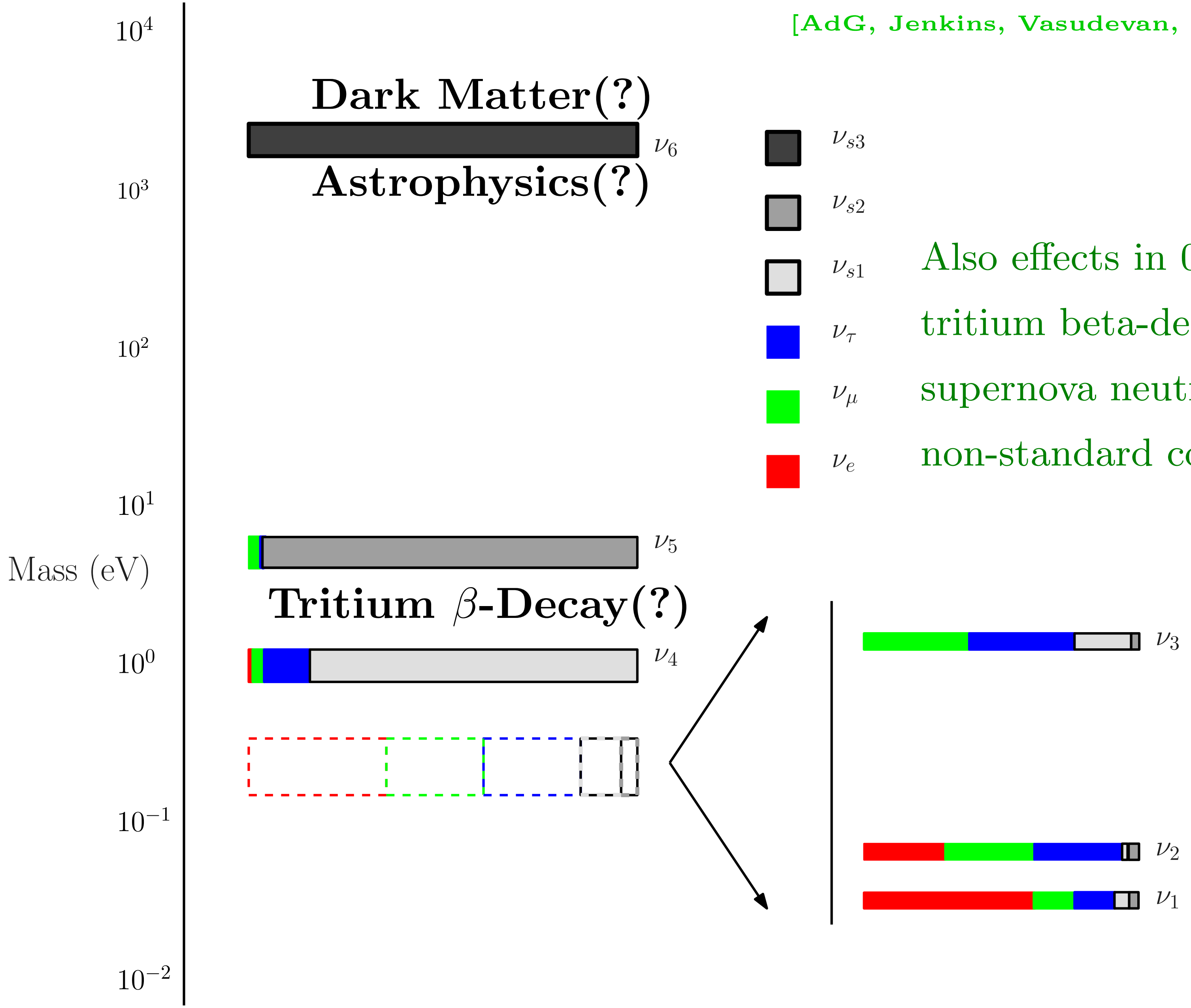
Constraining the Seesaw Lagrangian

$\theta_{as}^2 \sim m_{\rm light}/M_{\rm heavy}$



Theoretical upper bound: $M_N < 7.6 \times 10^{24}$ eV $\times \left(\frac{0.1 \text{ eV}}{m_\nu}\right) \Rightarrow\Rightarrow\Rightarrow$

[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]



Also effects in $0\nu\beta\beta$,
tritium beta-decay,
supernova neutrino oscillations,
non-standard cosmology.

Neutrinoless Double-Beta Decay

The exchange of Majorana neutrinos mediates lepton-number violating neutrinoless double-beta decay, $0\nu\beta\beta$: $Z \to (Z+2)e^-e^-$.

For light enough neutrinos, the amplitude for $0\nu\beta\beta$ is proportional to the effective neutrino mass

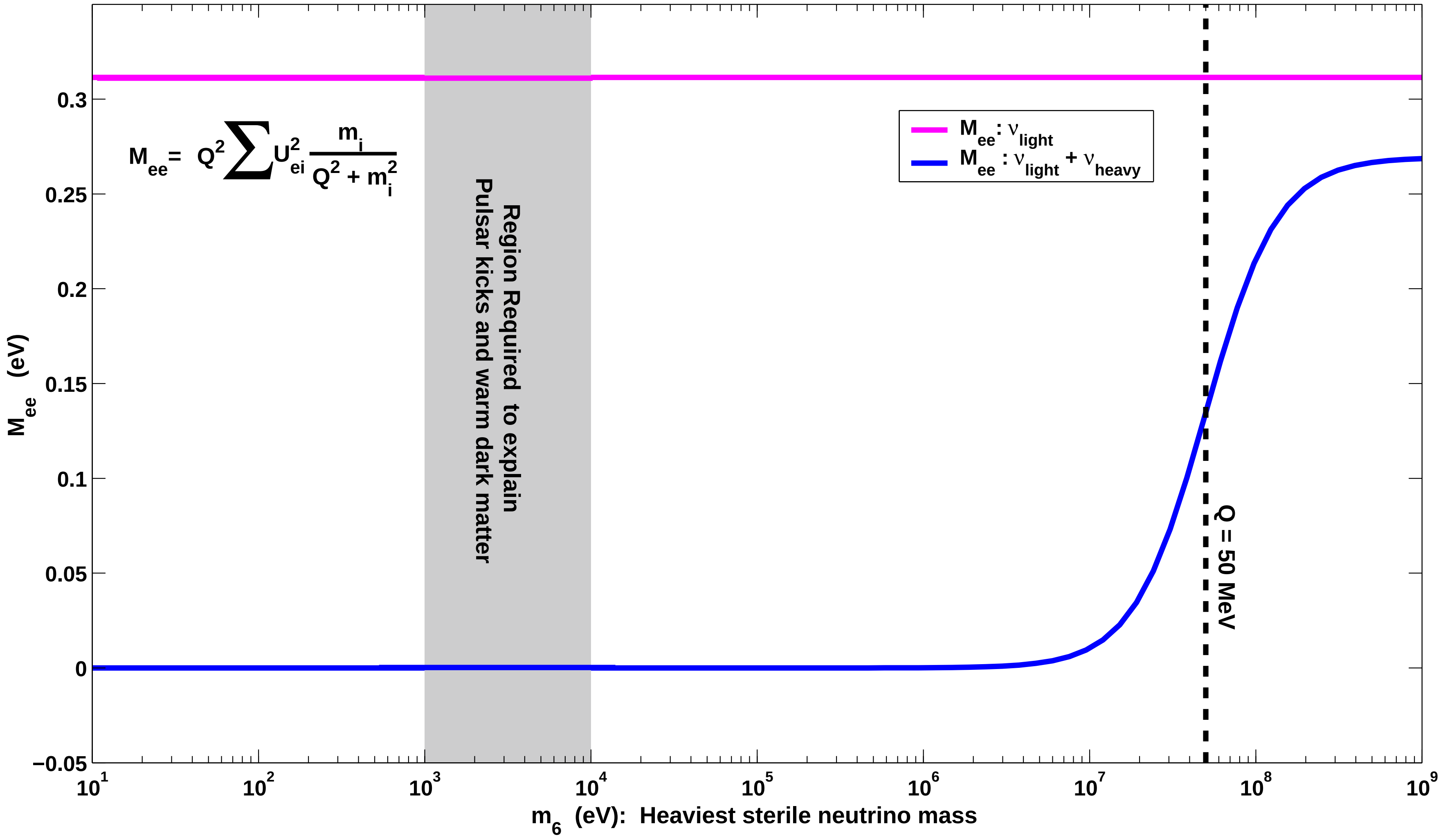
$$m_{ee} = \left|\sum_{i=1}^{6} U_{ei}^2 m_i\right| \sim \left|\sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{i=1}^{3} \vartheta_{ei}^2 M_i\right|.$$

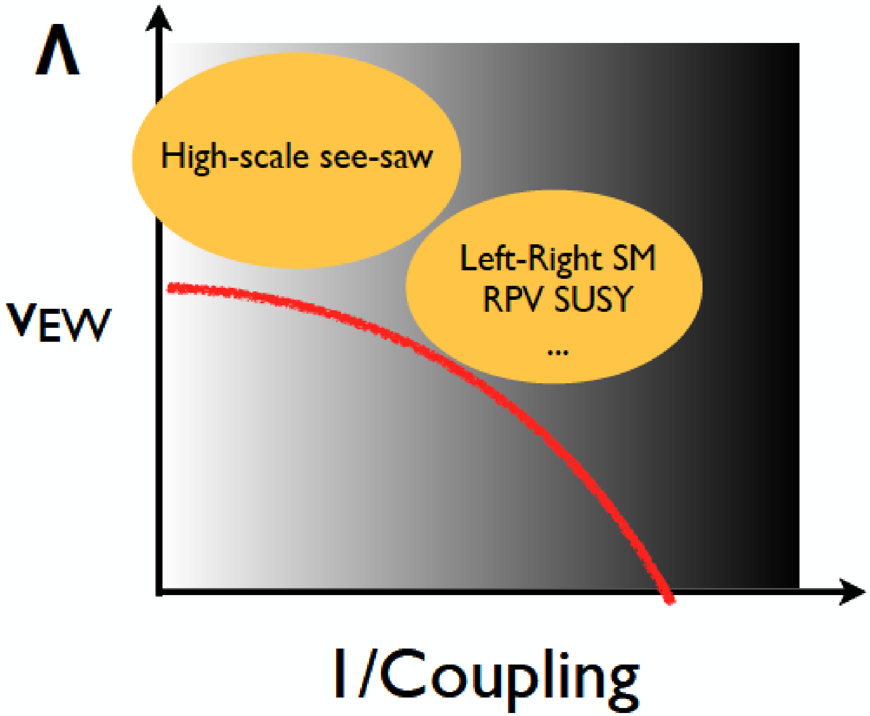
However, upon further examination, $m_{ee} = 0$ in the low-energy seesaw.
The contribution of light and heavy neutrinos exactly cancels!
This remains a good approximation as long as $M_i \ll 100$ MeV.

$$\left[\mathcal{M} = \begin{pmatrix} 0 & \mu^{\rm T} \\ \mu & M \end{pmatrix} \quad \rightarrow \quad m_{ee} \text{ is identically zero!} \right]$$

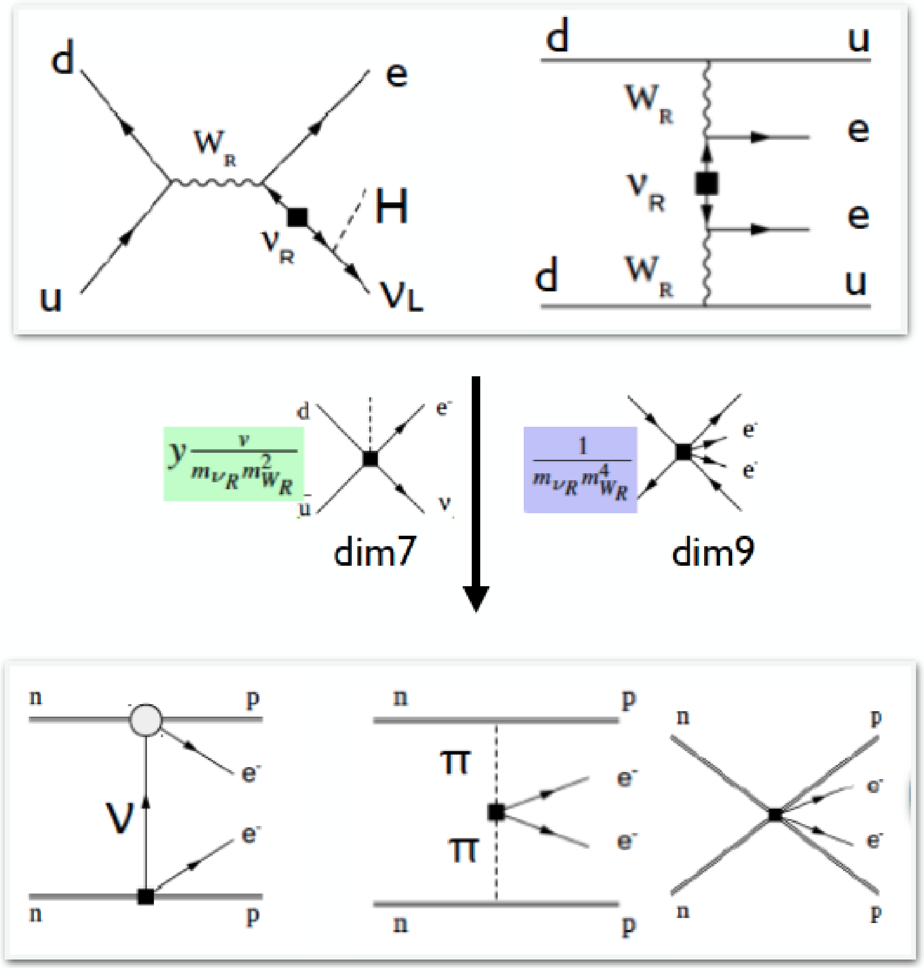
(lack of) sensitivity in $0\nu\beta\beta$ due to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]





These contributions can compete if scale is not too high (10-100 TeV) and lead to new mechanisms at the nuclear scale



[talk by V. Cirigliano, RP Plenary Session (07/21)]

There are many, many more, different ways to give neutrinos Majorana masses!

E.g., Higher Order Neutrino Masses from $\Delta L = 2$ Physics

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, in general, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_1$	$(LH)(LH)$	$6\times10^{10-11}$

$\mathcal{O}_2$	$(LL)(LH)e^c$	$4\times10^{6-7}$
$\mathcal{O}_{3_a}$	$(LL)(QH)d^c$	$2\times10^{4-5}$
$\mathcal{O}_{3_b}$	$(LQ)(LH)d^c$	$1\times10^{7-8}$
$\mathcal{O}_{4_a}$	$(L\overline{Q})(LH)\overline{u^c}$	$4\times10^{8-9}$
$\mathcal{O}_{4_b}$	$(LL)(\overline{Q}H)\overline{u^c}$	$2-7$
$\mathcal{O}_8$	$(LH)\overline{e^c}\overline{u^c}d^c$	$6\times10^{2-3}$

$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_5$	$(L\overline{H})(LH)(QH)d^c$	$6\times10^{4-5}$
$\mathcal{O}_6$	$(LH)(L\overline{H})(\overline{Q}H)\overline{u^c}$	$2\times10^{6-7}$
$\mathcal{O}_7$	$(LH)(QH)(\overline{Q}H)\overline{e^c}$	$4\times10^{1-2}$
$\mathcal{O}_9$	$(LL)(LL)e^ce^c$	$3\times10^{2-3}$
$\mathcal{O}_{10}$	$(LL)(LQ)e^cd^c$	$6\times10^{2-3}$
$\mathcal{O}_{11_a}$	$(LL)(QQ)d^cd^c$	$3-30$
$\mathcal{O}_{11_b}$	$(LQ)(LQ)d^cd^c$	$2\times10^{3-4}$

$\mathcal{O}_{12_a}$	$(L\overline{Q})(L\overline{Q})\overline{u^c}\overline{u^c}$	$2\times10^{6-7}$
$\mathcal{O}_{12_b}$	$(LL)(\overline{Q}\overline{Q})\overline{u^c}\overline{u^c}$	$0.3-0.6$
$\mathcal{O}_{13}$	$(L\overline{Q})(LL)\overline{u^c}e^c$	$2\times10^{4-5}$
$\mathcal{O}_{14_a}$	$(LL)(Q\overline{Q})\overline{u^c}d^c$	10^{2-3}
$\mathcal{O}_{14_b}$	$(L\overline{Q})(LQ)\overline{u^c}d^c$	$6\times10^{4-5}$
$\mathcal{O}_{15}$	$(LL)(L\overline{L})d^c\overline{u^c}$	10^{2-3}
$\mathcal{O}_{16}$	$(LL)e^cd^c\overline{e^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{17}$	$(LL)d^cd^c\overline{d^c}\overline{u^c}$	$0.2-2$

$\mathcal{O}_{18}$	$(LL)d^cu^c\overline{u^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{19}$	$(LQ)d^cd^c\overline{e^c}\overline{u^c}$	$0.1-1$
$\mathcal{O}_{20}$	$(L\overline{Q})d^c\overline{u^c}\overline{e^c}\overline{u^c}$	$4-40$
$\mathcal{O}_s$	$e^ce^cu^cu^c\overline{d^c}\overline{d^c}$	10^{-3}

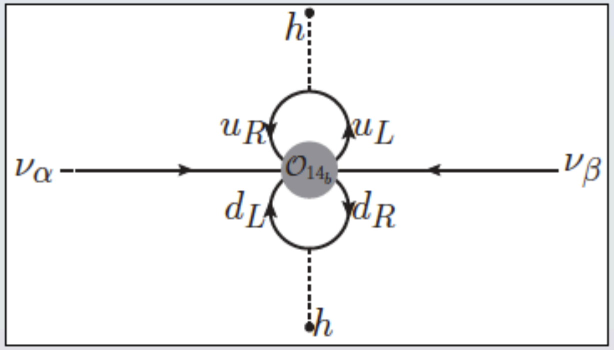
- Ignore Lorentz, $SU(3)_C$ structure
- $SU(2)_L$ contractions denoted with parentheses
- Λ indicates range in which $m_\nu \in [0.05\text{ eV}, 0.5\text{ eV}]$

hep-ph/0106054; K.S. Babu & C.N. Leung
arXiv:0708.1344; A. de Gouvêa & J. Jenkins
arXiv:1212.6111; P.W. Angel, et al.
arXiv:1404.4057; A. de Gouvêa, at al.

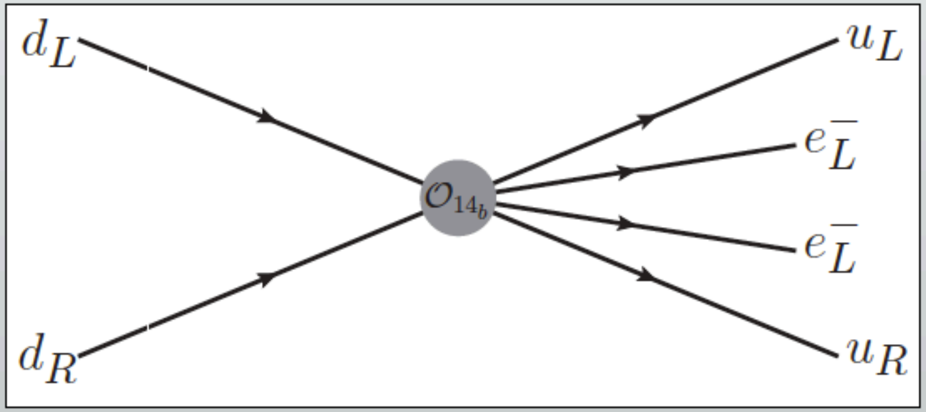
LNV from Effective Operators

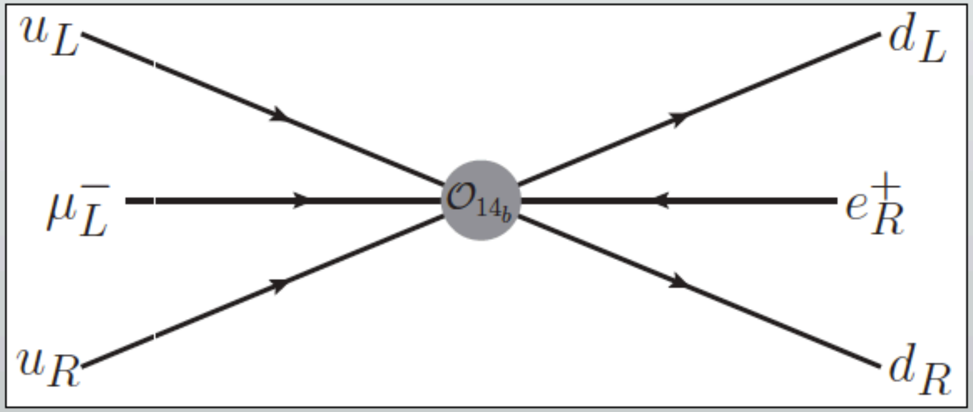
What do these operators do? Consider $\mathcal{O}_{14b}=(LQ)(LQ)u^c d^c$.

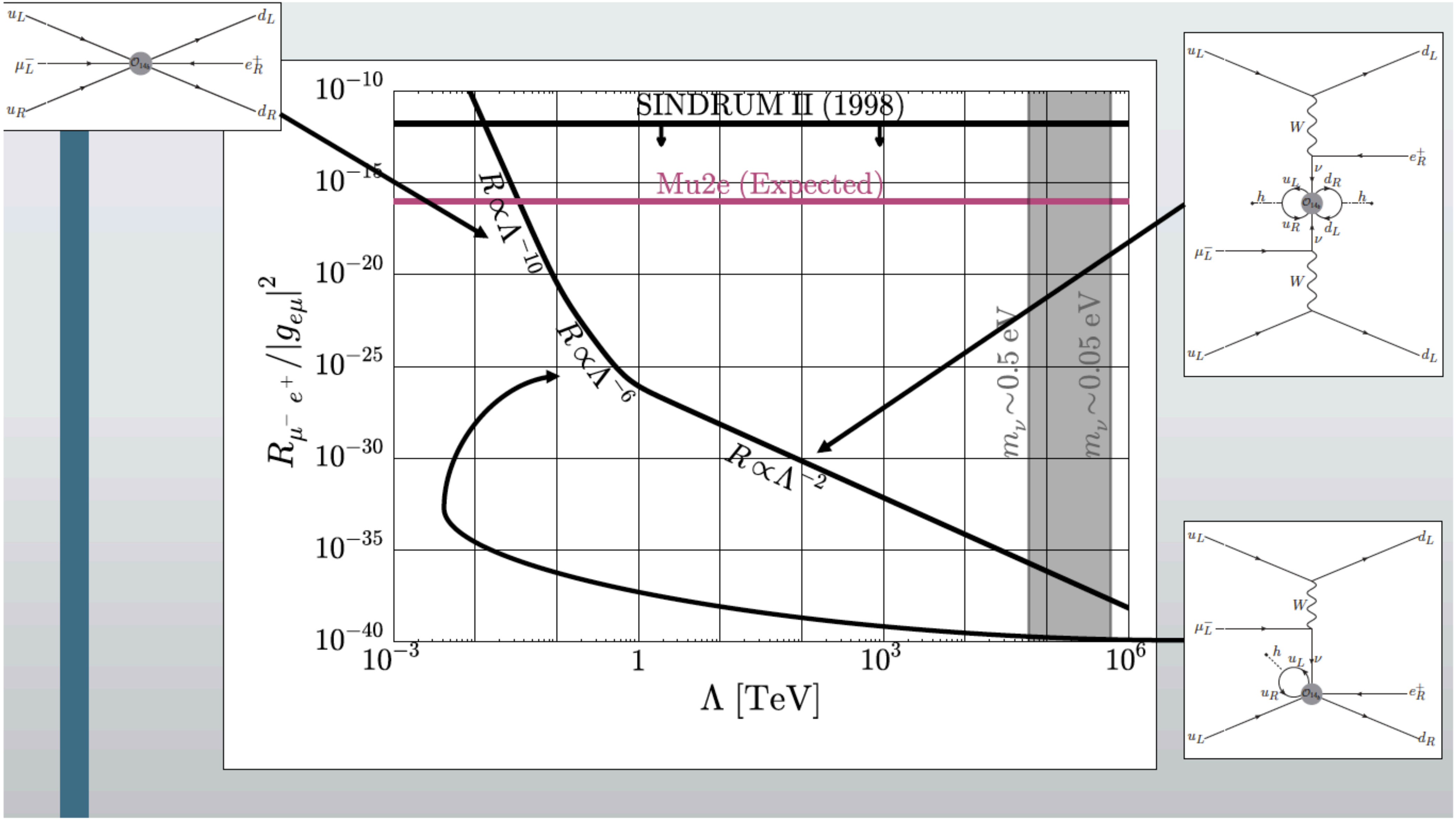
- They generate neutrino masses:

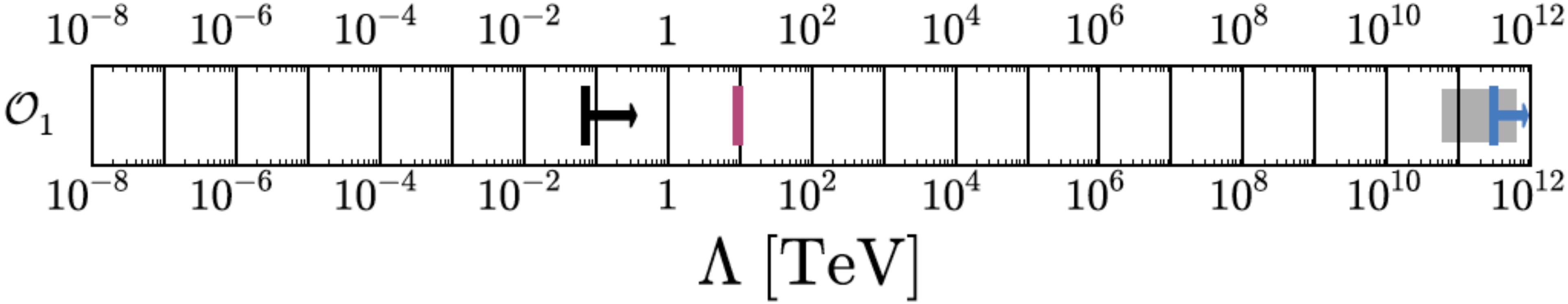


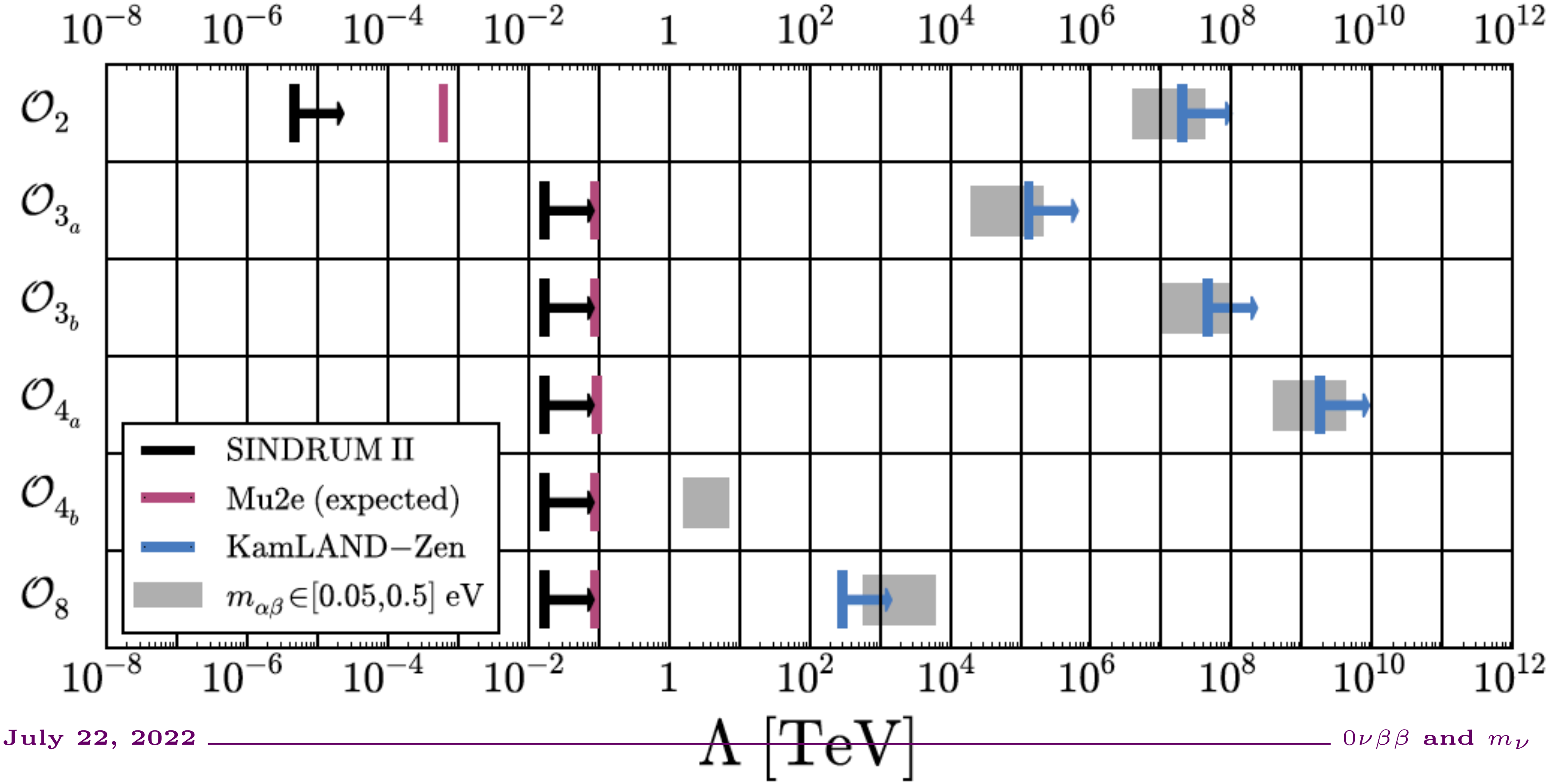
- They generate various LNV phenomena:

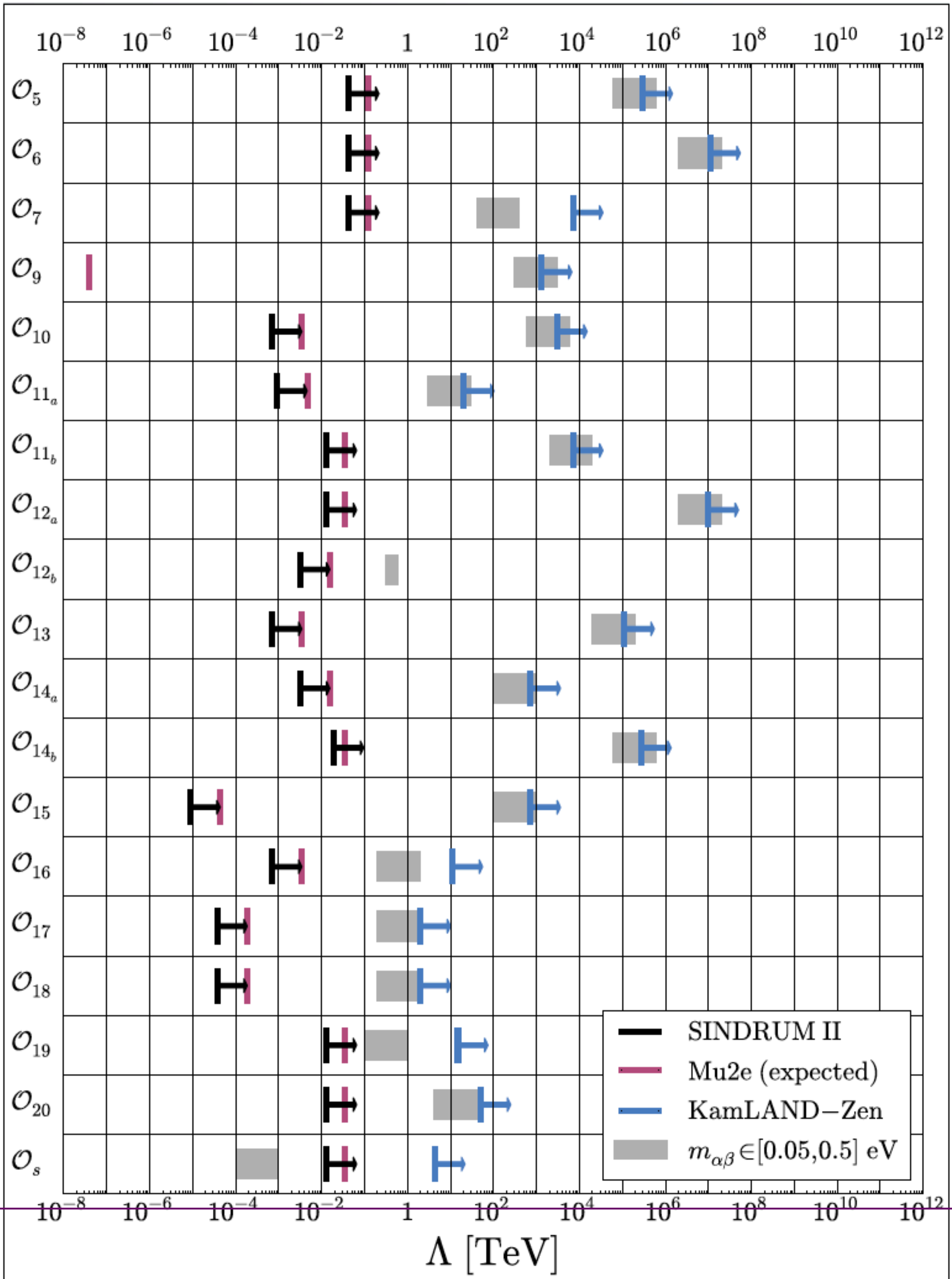




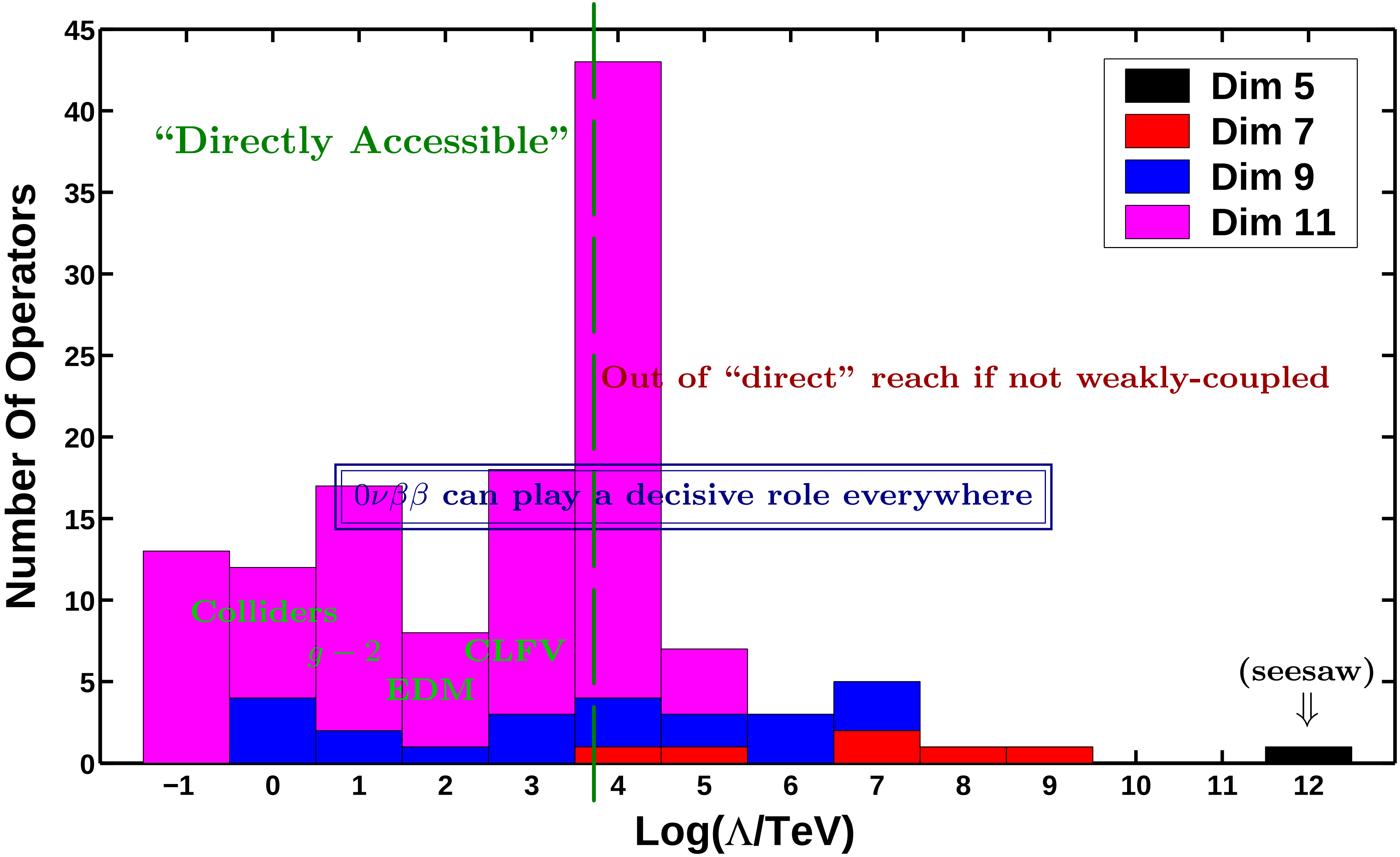

SINDRUM II (1998)
Mu2e (Expected)
R∝Λ^−10
R∝Λ^−6
R∝Λ^−2
m_ν~0.5 eV
m_ν~0.05 eV
R_{μ⁻e⁺}/|g_{eμ}|²
Λ [TeV]
u_L
d_L
μ_L^−
e_R^+
u_R
d_R
W
ν
h


10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12}
$\mathcal{O}_1$
Λ [TeV]


10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12}
$\mathcal{O}_2$
$\mathcal{O}_{3_a}$
$\mathcal{O}_{3_b}$
$\mathcal{O}_{4_a}$
$\mathcal{O}_{4_b}$
$\mathcal{O}_8$
SINDRUM II
Mu2e (expected)
KamLAND−Zen
$m_{\alpha\beta} \in [0.05, 0.5]$ eV
Λ [TeV]



10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12}
$\mathcal{O}_5$
$\mathcal{O}_6$
$\mathcal{O}_7$
$\mathcal{O}_9$
$\mathcal{O}_{10}$
$\mathcal{O}_{11_a}$
$\mathcal{O}_{11_b}$
$\mathcal{O}_{12_a}$
$\mathcal{O}_{12_b}$
$\mathcal{O}_{13}$
$\mathcal{O}_{14_a}$
$\mathcal{O}_{14_b}$
$\mathcal{O}_{15}$
$\mathcal{O}_{16}$
$\mathcal{O}_{17}$
$\mathcal{O}_{18}$
$\mathcal{O}_{19}$
$\mathcal{O}_{20}$
$\mathcal{O}_s$
SINDRUM II
Mu2e (expected)
KamLAND−Zen
$m_{\alpha\beta}\in[0.05,0.5]$ eV
Λ [TeV]


Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled
0νββ can play a decisive role everywhere
Colliders
g − 2
EDM
CLFV
(seesaw)
Number Of Operators
Log(Λ/TeV)
0
5
10
15
20
25
30
35
40
45
−1
0
1
2
3
4
5
6
7
8
9
10
11
12

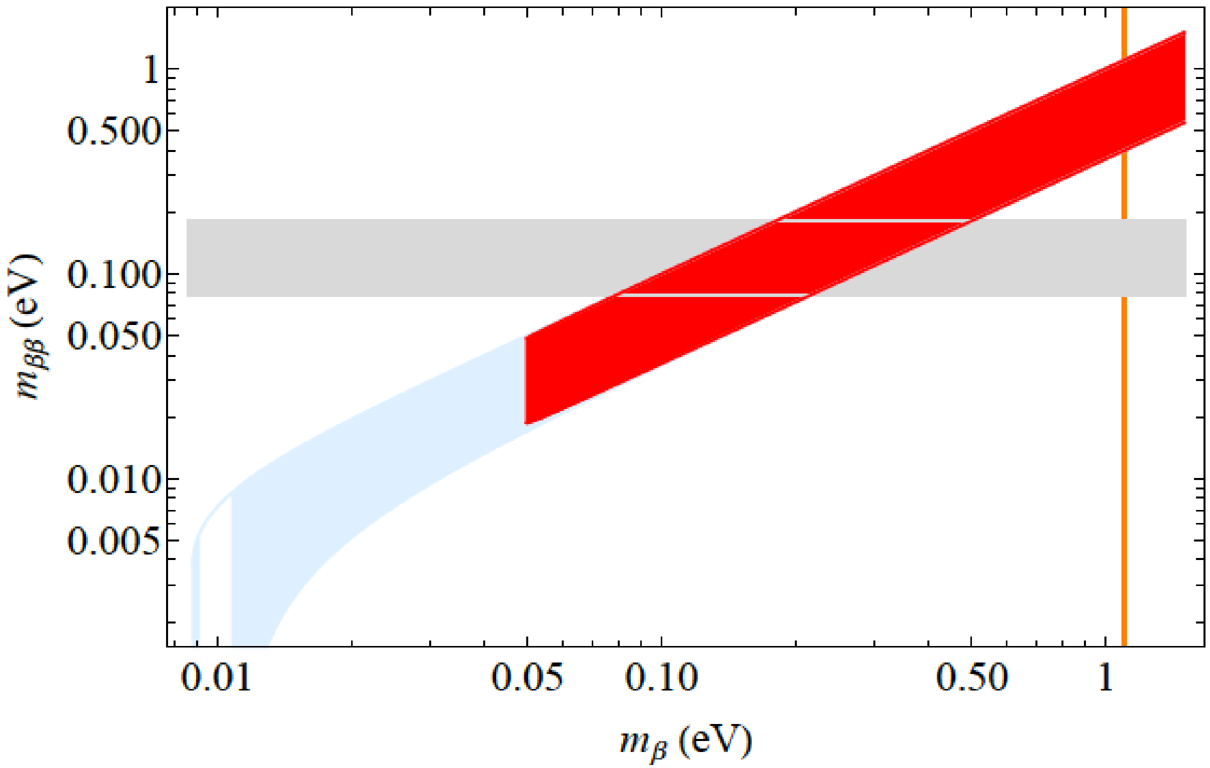


FIG. 5: $m_{\beta\beta}$ as a function of m_β, for both the normal (lighter, blue) and inverted (darker, red) mass orderings. The bands are a consequence of allowing for all possible values of the relative Majorana phases. For everything else, we use the current best-fit values of the oscillation parameters from [29]. The whited-out region inside the light-blue contour is meant to highlight the values of m_β for which $m_{\beta\beta}$ can vanish exactly. We assume the neutrinos are Majorana fermions. If neutrinos are Dirac fermions, $m_{\beta\beta} = 0$. The grey, horizontal band corresponds to the 95% CL upper bound on $m_{\beta\beta}$ from GERDA [37]. The width of the band is a consequence of uncertainties in the nuclear matrix element for the neutrinoless double-beta decay of ^{76}Ge. The vertical line corresponds to the current 90% upper bound on m_β [56].

[Formaggio, AdG, Robertson, Phys.Rept. 914 (2021)]

Concluding Remarks

- Searches for $0\nu\beta\beta$ are the most promising way to learn about the nature of neutrinos.
  - However, not guaranteed to make a discovery, even if the neutrinos are Majorana fermions. (Flavor effects, new physics "cancellations.")
  - It is wise to consider other possibilities. $\mu^- \to e^+$-conversion is an excellent second-best. Independently, it is wise to search everywhere!
- Searches for $0\nu\beta\beta$ can provide non-trivial information on the neutrino mass ordering and the absolute values of the neutrino masses.
  - However, they are an indirect probe of neutrino masses. There aren't any real neutrinos here. It is right there in the name!
  - After a discovery is made, deciding the connection between $0\nu\beta\beta$ and m_ν will be the next big challenge.
  - Other m_ν probes – cosmic surveys, β-decay – can help a lot.
- What if the neutrinos are Dirac fermions?