NEUTRINOLESS DOUBLE BETA DECAY AND LEPTON NUMBER VIOLATION

Jordy de Vries
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The plan of attack

1. **Baryon- and lepton-number foundations**

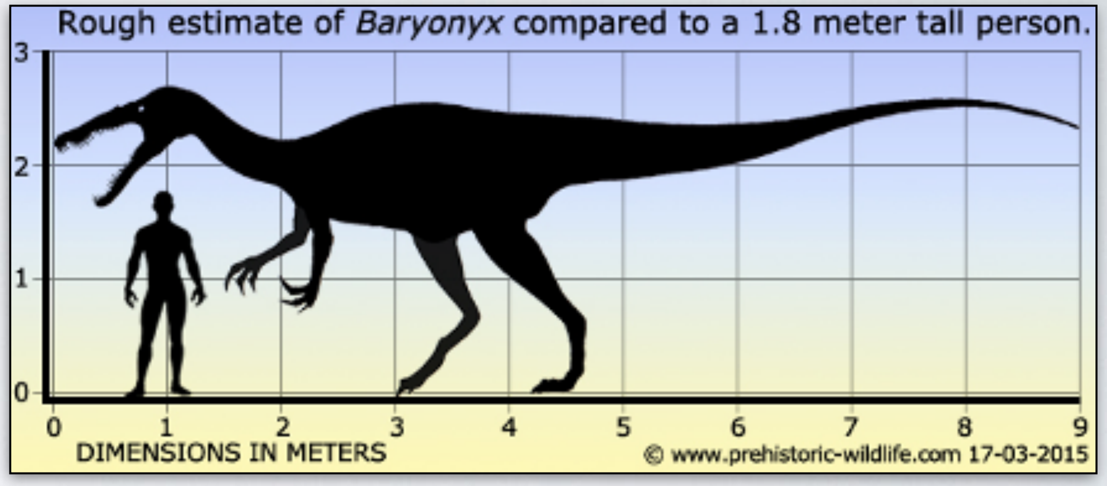
2. Neutrinoless double beta decay from light Majorana neutrino exchange

    - *Controlling nuclear matrix elements !*

3. Other lepton-number-violating mechanisms in effective field theory

Baryons and leptons

- Baryons are particles with a nonzero number of 'valence' quarks minus
- Name means 'heavy ones' introduced by A. Pais



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- Nucleons and excited states (Delta etc) **B=1**
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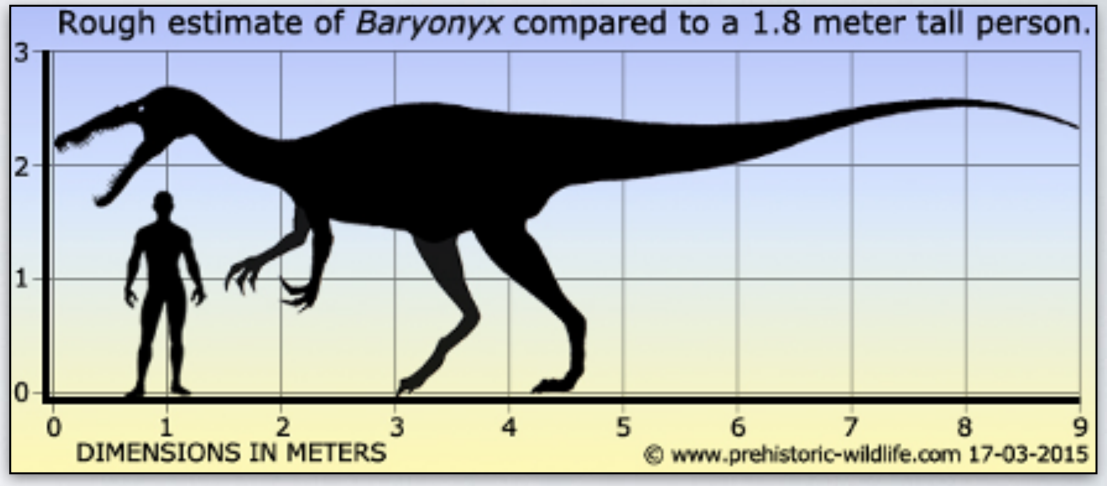

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- Leptons are spin 1/2 particles that do not feel strong interactions (no color charge)
- Name means '**fine/small/thin ones'** introduced by L. Rosenfeld

'Leptosaurus'

- Three charged leptons (electron, muon, tauon)
- Neutral leptons (neutrinos in 3 flavors)
- Neutrinos are probably the least understood particle of the Standard Model (hence this school…)
- All leptons carry L=1

A fortunate accident

- Why is the proton stable? $p \to e^+ + \pi^0 \to e^+ + 2\gamma$
- Because in the Standard Model B and L are **accidental symmetries**

Accidental symmetry: *Symmetry that appears because terms that break it have too high dimension to appear in the Lagrangian*

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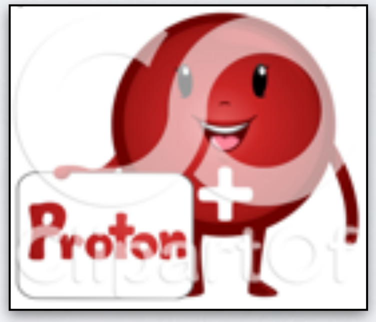
- ***Illustration:*** 1-flavor QED based on a local U(1) gauge symmetry $\Psi_e \rightarrow e^{i\alpha(x)}\Psi_e$
- ***Lagrangian:*** $\mathscr{L} = \bar{\Psi}_e(i\not{D} - m)\Psi_e - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \dots$
- The Lagrangian has an extra global symmetry not put in by hand $\Psi_e \rightarrow e^{i\beta}\Psi_e$
- There is an associated Noether current and conserved charge: number of (electrons - positrons)

A fortunate accident

- Standard Model is more complicated with more gauge symmetries and fields
- Once gauge symmetries and field contents are put in ‘by hand’

Baryon (B) and Lepton (L) number are classically conserved

- Proton stable as the lightest baryon
- Electron stable because it is the lightest…



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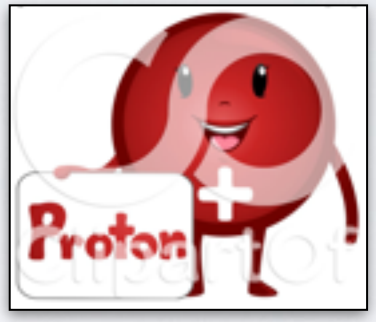

Some caveats and complications

- In vanilla SM, neutrinos are massless and 3 conserved lepton numbers $L_{e,\mu,\tau}$
- But neutrino oscillations require neutrino masses and break the individual lepton numbers

$$\nu_e \rightarrow \nu_{\mu,\tau}$$

- Neutrino mass mechanism is not known: while $L_{e,\mu,\tau}$ are broken total L is unclear
- **Focus on my lectures: how to determine if L is conserved or not**

More caveats

Baryon (B) and Lepton (L) number are classically conserved

- Not all classical symmetries survive quantum mechanics
- Turns out: B+L is an *anomalous* symmetry

$$\partial_\mu j^\mu_L = \partial_\mu j^\mu_B \sim \epsilon^{\alpha\beta\mu\nu} W^a_{\alpha\beta} W^a_{\mu\nu}$$

Weinberg '79

- Associated non-perturbative processes (aka electroweak instantons) cause **B+L**-violating processes (but conserve **B-L**). $\Delta B = \Delta L = \pm 3n$

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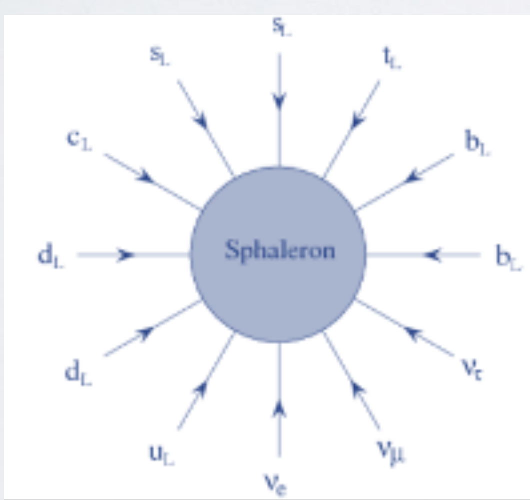
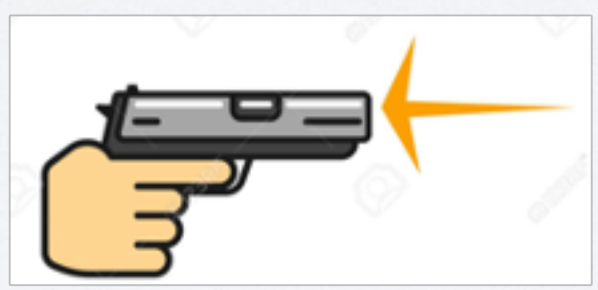
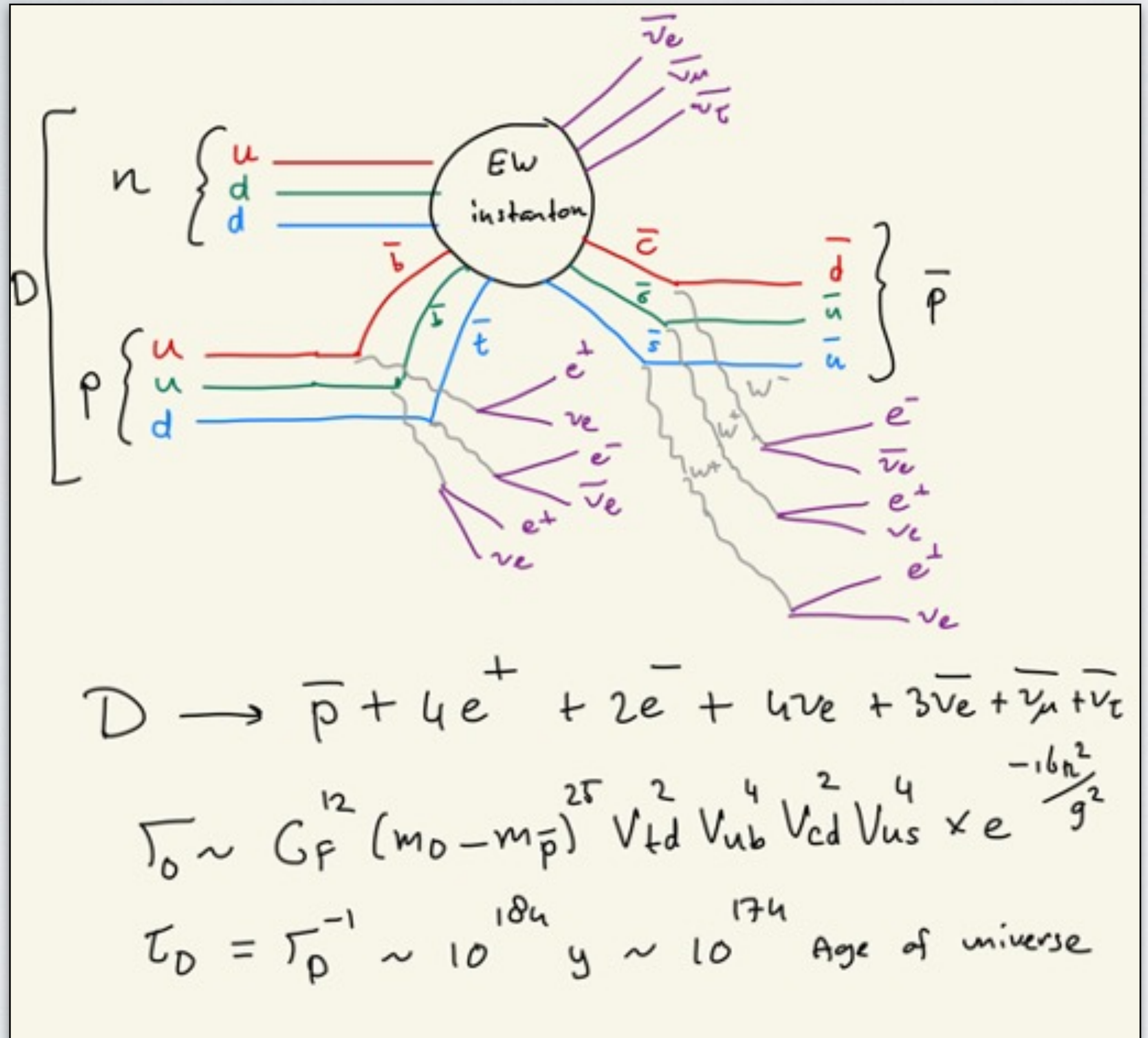




A murder most foul

But we are saved !!



inspired by Andrew Long

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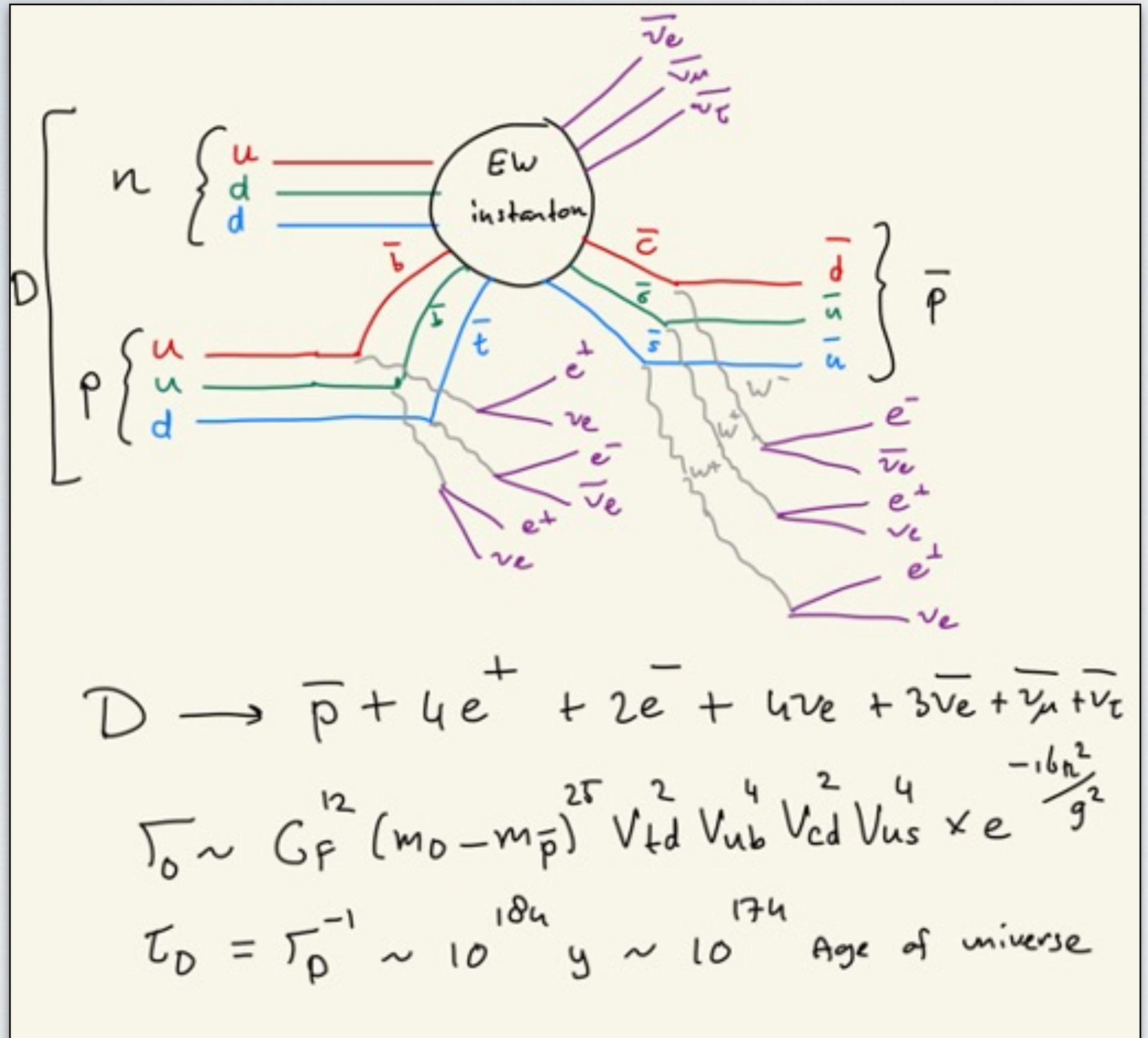

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- Suppression can be overcome at high temperatures (early universe)
- Then so-called electroweak sphalerons can transfer a nonzero L to a nonzero B
- Very important for models of **leptogenesis** that resolve the matter/antimatter asymmetry of the universe
- Not discussed in these lectures

Why might there be extra L (or B) violation

1. **Where is the anti-matter ?**

13.x billion years

But not guaranteed ! Many scenarios for **baryogenesis**

A. Leptogenesis (new L violation)
B. Post-sphaleron (new B violation)
C. Electroweak baryogengesis (no new B or L violation at all)
D. ………..Thousand more scenarios

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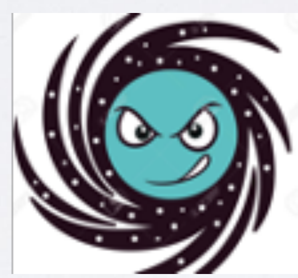
2. **No global symmetries in quantum gravity**

+



Hawking radiation

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Hawking radiation

3. **Nonzero neutrino masses suggest L violation**

4. **Standard Model is just a low-energy effective field theory (EFT)**

   Accidental symmetries broken by non-renormalizable terms

The plan of attack

1. **Baryon- and lepton-number foundations**

   A. *Neutrino masses as motivation for L violation*
   B. *EFT arguments to motivate L violation*

Neutrino masses

- In the original formulation of the Standard Model (Weinberg 1967) neutrinos were considered to be massless particles
- Not crazy: from beta decay experiments $m_\nu \ll m_e \ll m_p$

Neutrino masses

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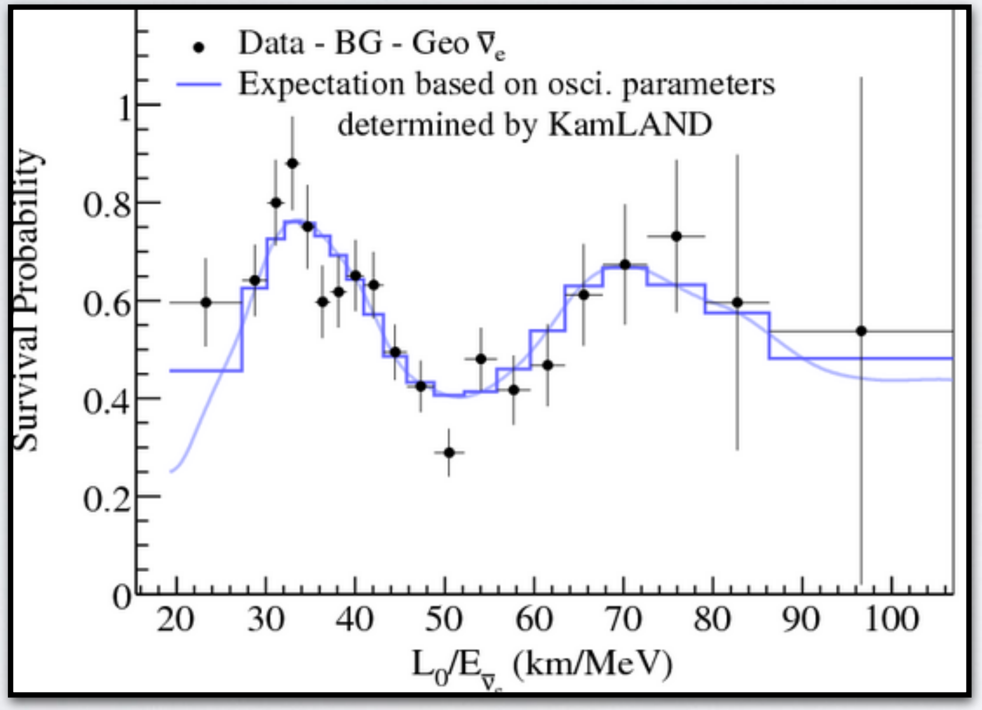
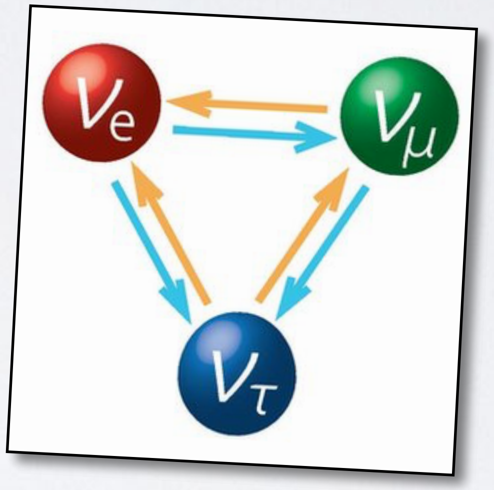
- Not crazy: from beta decay experiments $m_\nu \ll m_e \ll m_p$
- **But neutrinos do have mass !**



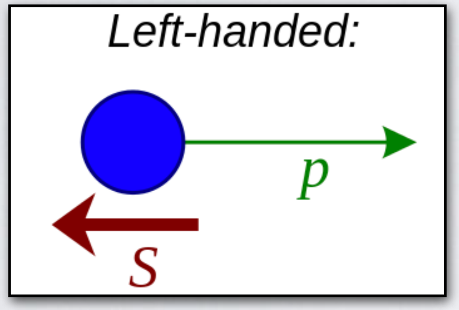
$$P(\nu_\mu \to \nu_e) \sim \sin \frac{\Delta m^2 L}{2E}$$

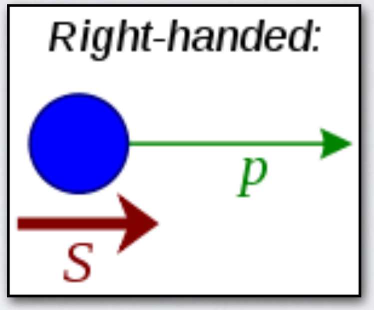


- Biggest mass splitting: $|\Delta m| \simeq 0.05\, eV$ Smallest: $|\delta m| \simeq 0.008\, eV$
- Direct limits: $m_{\nu_e} \leq 0.8\, eV$ **KATRIN experiment**
- Cosmology $\sum_{i=e,\mu,\tau} m_{\nu_i} \leq 0.12\, eV$

Mass generation in the Standard Model

- How does the electron get a mass in the Standard Model ?
- It's a bit **tricky**: a mass term connects a left-handed to a right-handed field





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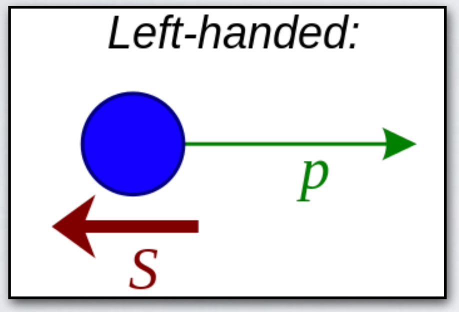

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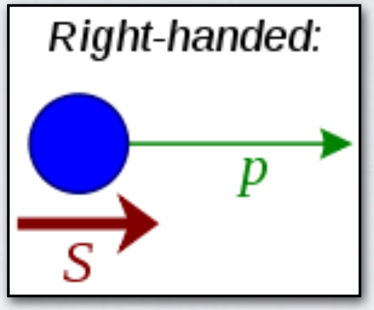

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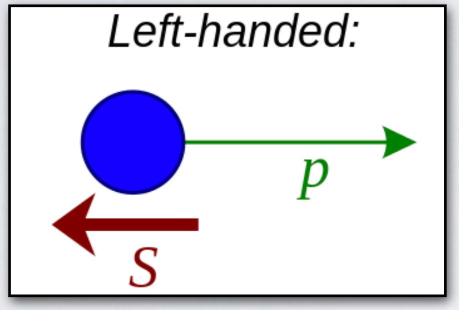

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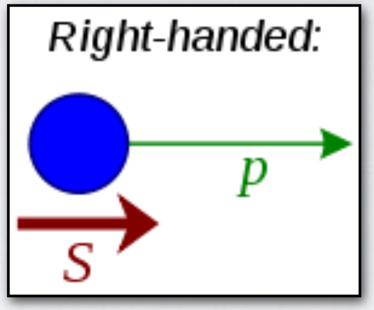

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- We cannot just write down a mass term: $\mathscr{L} = -m_e \bar{e}_L e_R$
- This would violate 'weak charge' conservation (or SU(2) gauge invariance)
- The Standard Model overcomes this problem through the **Higgs** mechanism

$$\mathscr{L} = -y_e \bar{e}_L e_R \varphi \longrightarrow \mathscr{L} = -y_e \bar{e}_L e_R \mathrm{v} \qquad m_e = y_e \mathrm{v}$$

- The scalar field has a weak charge and a nonzero value **v** in the vacuum (*spontaneous symmetry breaking*)

The puzzle of the neutrino mass

- **Easy fix:** Insert gauge-singlet right-handed neutrino ν_R

$$\mathscr{L} = -\, y_\nu \, \bar{\nu}_L \nu_R \, \varphi \qquad\qquad y_\nu \sim 10^{-12} \to m_\nu \sim 0.1\,\mathrm{eV}$$

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- Nothing really wrong with this…. **But nothing forbids a Majorana Mass term**

$$\mathscr{L} = -\, y_\nu \bar{\nu}_L \nu_R \varphi - M_R \, {\nu_R}^T C \nu_R$$

'Everything that is not forbidden is compulsary'

Ettore Majorana

- This is not allowed for any Standard Model particle !
- M_R not connected to electroweak scale: could be a **completely new scale**
- **Does this term exist in nature? How can we find out ?**
- Not the only way to generate neutrino masses! Can be done without right-handed neutrino's (see e.g. type-II seesaw with a new triplet scalar field)

The puzzle of the neutrino mass

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Minkowski '77

- 1+1 case: diagonalization leads to **2 mass eigenstates**

$\nu_{1,2}$ describe 2 massive Majorana neutrinos $\nu_i^c = \nu_i$ **Particle = anti-Particle**

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  - If M_R is significantly larger than a **few eV**: see-saw mechanism

$$m_1 \simeq \left| \frac{y_\nu^2 v^2}{M_R} \right| \qquad m_2 \simeq M_R \qquad \begin{aligned} \nu_1 &\simeq \nu_L - \theta \nu_R^c + \dots \\ \nu_2 &\simeq \nu_R + \theta \nu_L^c + \dots \end{aligned} \qquad |\theta| \simeq \sqrt{\frac{m_1}{m_2}}$$

- The mixing angle determines **strength of weak interactions** of heavy neutrinos

- Possible to get **larger mixing angles** in scenarios with more sterile neutrinos (see for instance linear or inverted see-saw scenarios)

Mass ranges

- **See-saw (variants) can work for essentially any right-handed scale**

$\longrightarrow$ **M_R ?**

eV keV MeV GeV TeV ..... 10^{15} GeV

- If Yukawa coupling order 1 then $$m_1 \simeq \left| \frac{v^2}{M_R} \right| \quad \rightarrow M_R \simeq 10^{15}\,\mathrm{GeV}$$

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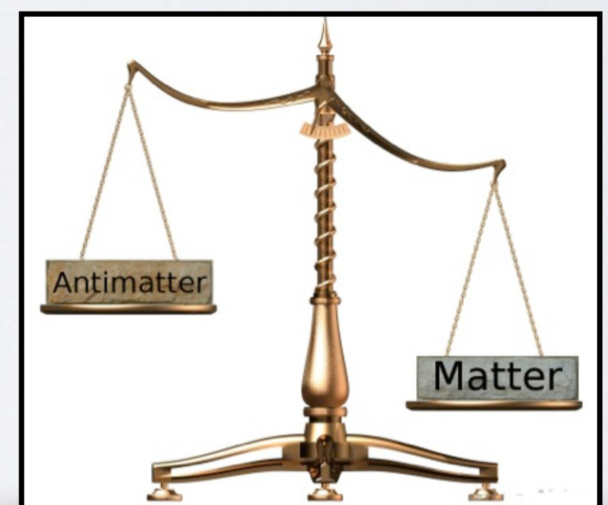
Fukugita, Yanagadi '86

- **Thermal leptogenesis possible** $M_R \geq 10^9\,\text{GeV}$ Davidson Ibarra '02

13.7 billion year



- Hard to test directly but smoking gun evidence:
neutrinos are Majorana + CPV in neutrino sector

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- But also leptogenesis possible with **TeV** sterile neutrinos! Pilaftsis '97, Akhmedov et al '98

- And even in the **MeV-GeV** range See e.g. Shaposhnikov et al (many works) Drewes et al '21

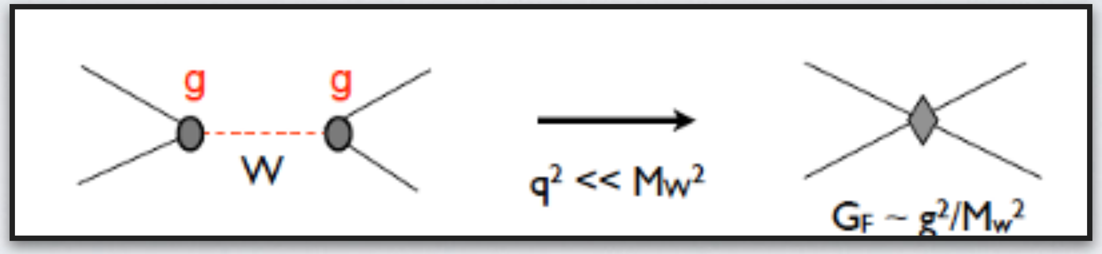
- KeV sterile neutrino could be Dark Matter (but getting more difficult) and essentially decoupled from neutrino mass generation Dodelson, Widrow '97 Shaposhnikov et al '05

- eV sterile neutrinos potentially related to short base-line anomalies

The Standard Model as an EFT

- **Let's be more agnostic:** assume as little as possible about BSM

A la Fermi:



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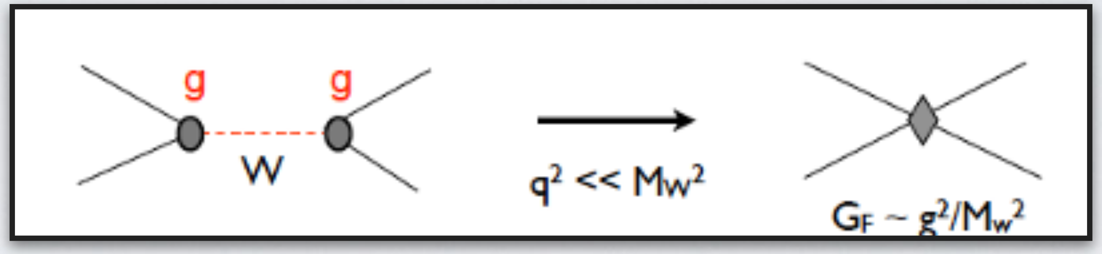

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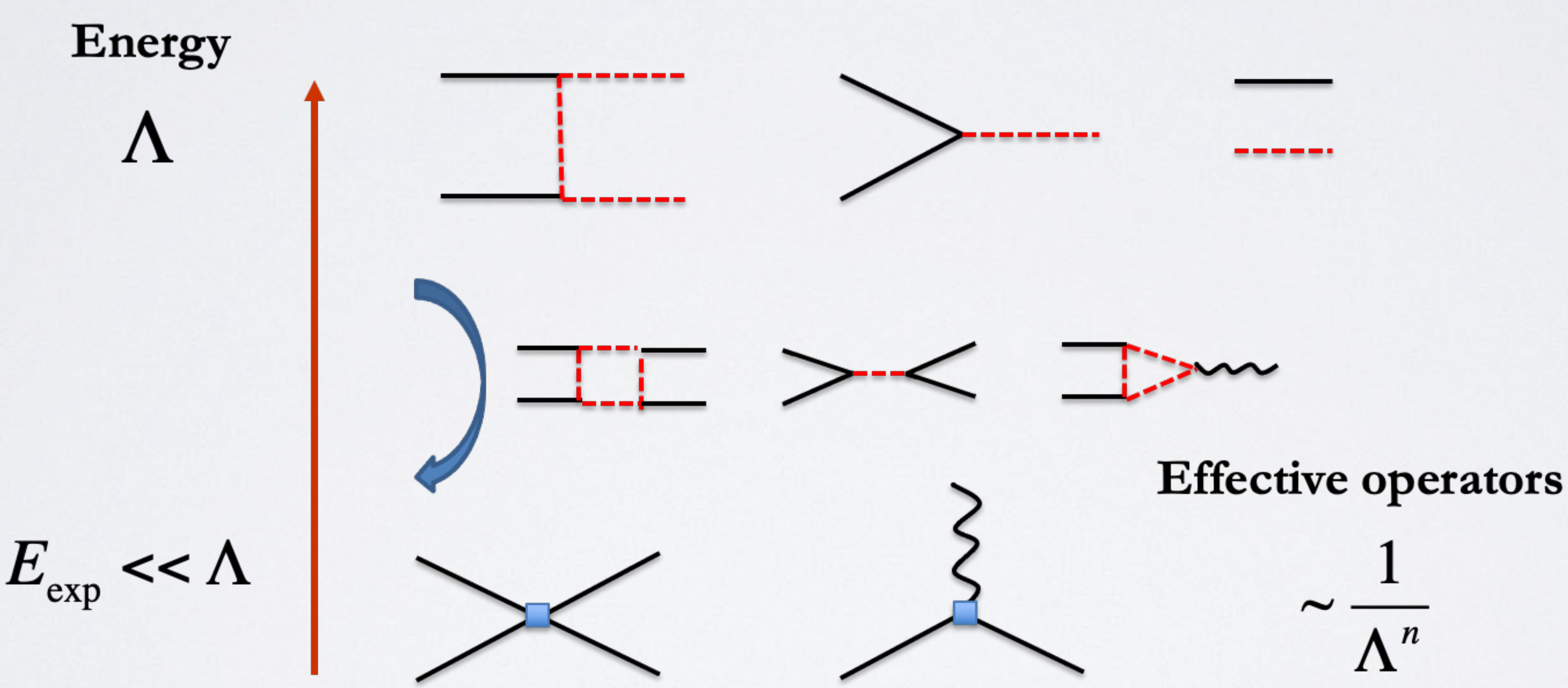

- **At low energies, effects from heavy physics captured by 'effective operators'**

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 + \cdots$$

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- The operators contain SM fields and obey crucial Lorentz and gauge symmetries
- For $E \ll \Lambda$ effects from higher-dim operators are suppressed by powers of E/Λ
- Gauge symmetries are very restrictive: **only 1 type of dim-5 operator**

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C \tilde{H}\right)(\tilde{H}^T L)$$

Weinberg '79

- Two lepton fields and no anti-leptons —> violate L by 2 units
- After electroweak symmetry breaking $\mathscr{L}_5 = c_5 \frac{v^2}{\Lambda} \nu_L^T C \nu_L$ (see-saw in EFT)
- **Neutrino Majorana masses are the first SM-EFT prediction !**

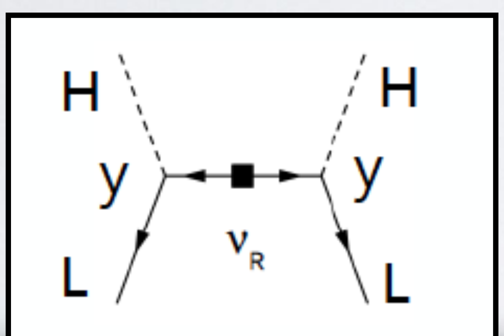
Heavy-sterile neutrinos a UV completion

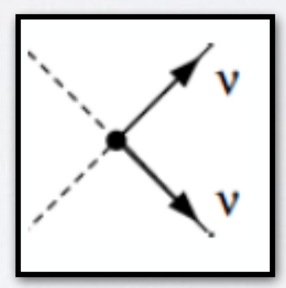
- **See-saw (variants) can work for essentially any right-handed scale**

eV **keV** **MeV** **GeV** **TeV** **.....** **10^{15} GeV** **M_R ?**

- For $m_R \geq 50$ TeV or so, we'll not be able to produce them this century

- But they leave a **footprint through quantum effects**





$$\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C \tilde{H}\right)(\tilde{H}^T L)$$

$$c_5 = y_\nu^2$$
$$\Lambda = M_R$$

- **So the SM-EFT captures these models (and others)**

The plan of attack

1. Baryon- and lepton-number foundations

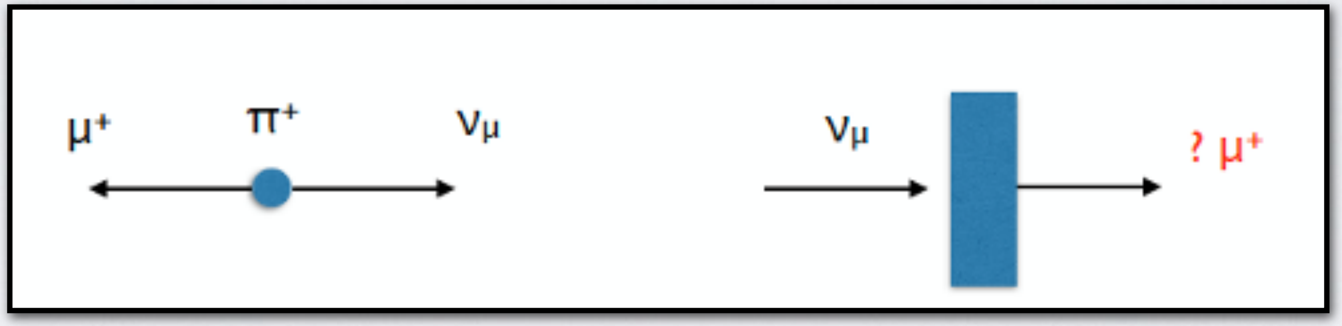
2. 0vvb from light Majorana neutrino exchange

   - *Controlling nuclear matrix elements !*

3. Other lepton-number-violating mechanisms in effective field theory

Key question of the field

- **Are neutrinos Majorana or not? Is Lepton number conserved or not ?**
- Consider an easy *Gedankenexperiment* (B. Kayser): generate neutrino beam from pion decays



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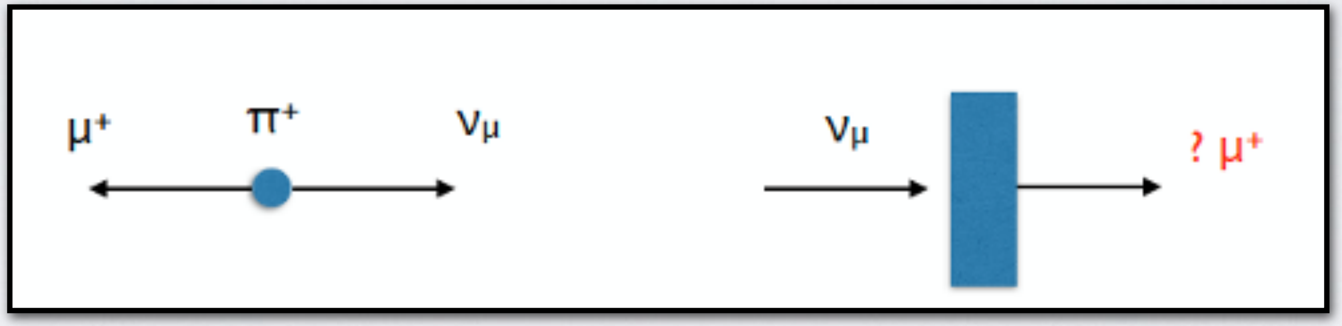

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- **Unfortunately this is hopeless experimentally!**

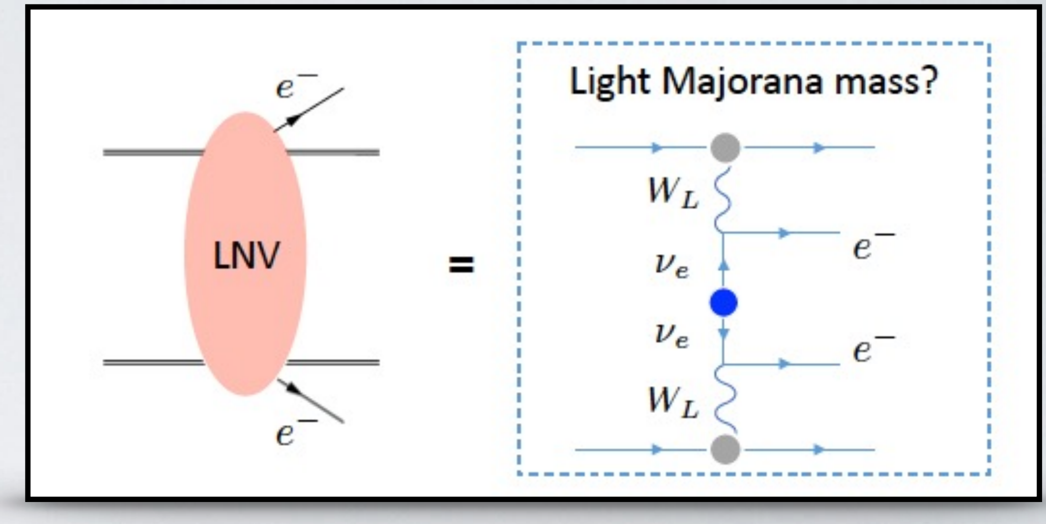
Fraction of right-handed neutrinos $\sim \left(\frac{m_\nu}{E_\nu}\right)^2 \simeq 10^{-18}$

Cut out the middle man

- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+ + \text{jets}$$

$$X(Z,N) \to Y(Z+2,N-2) + e^- + e^-$$



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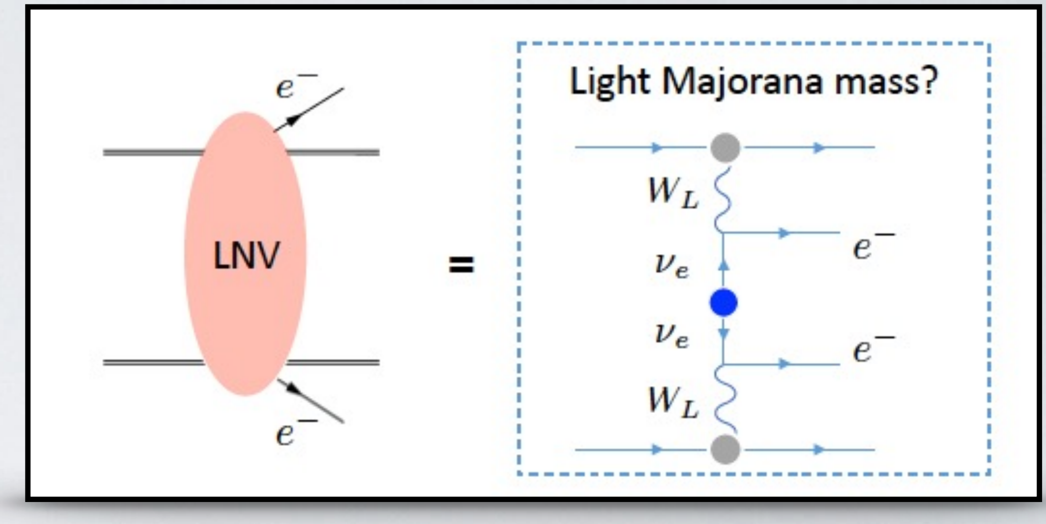

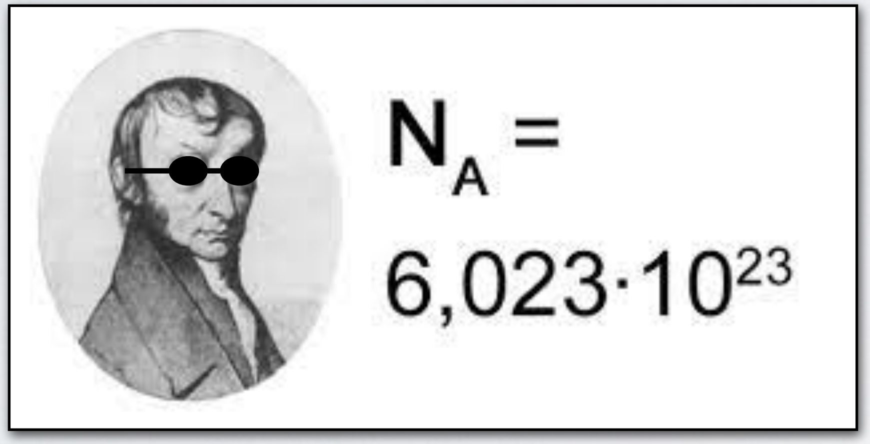

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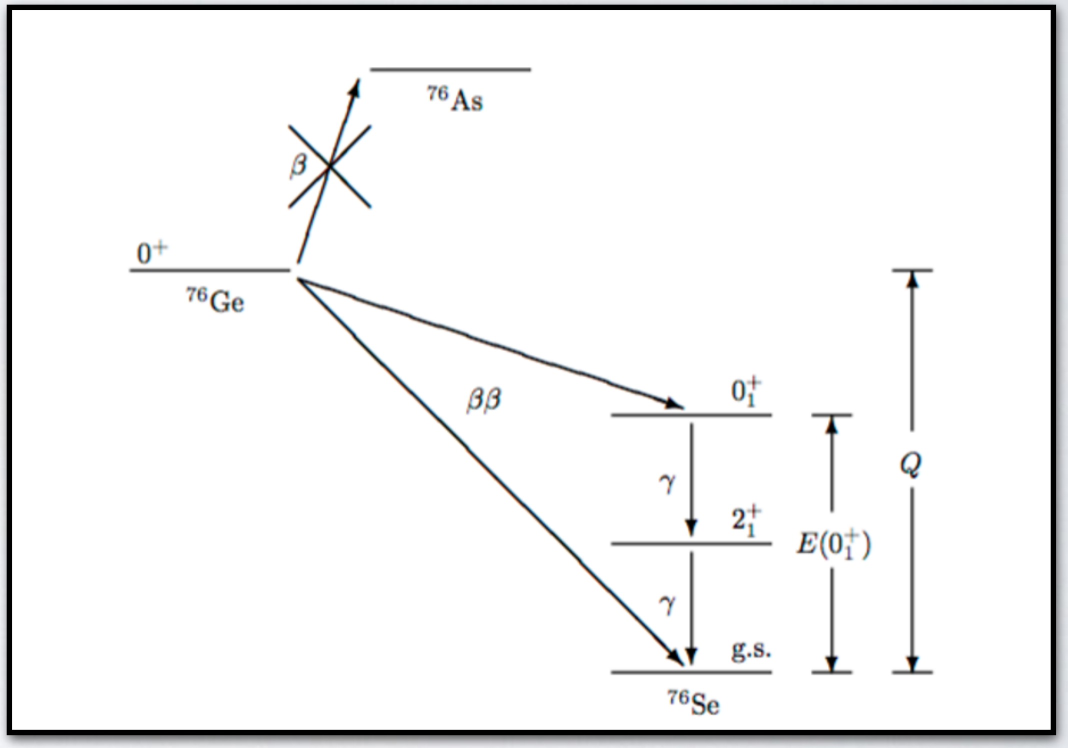
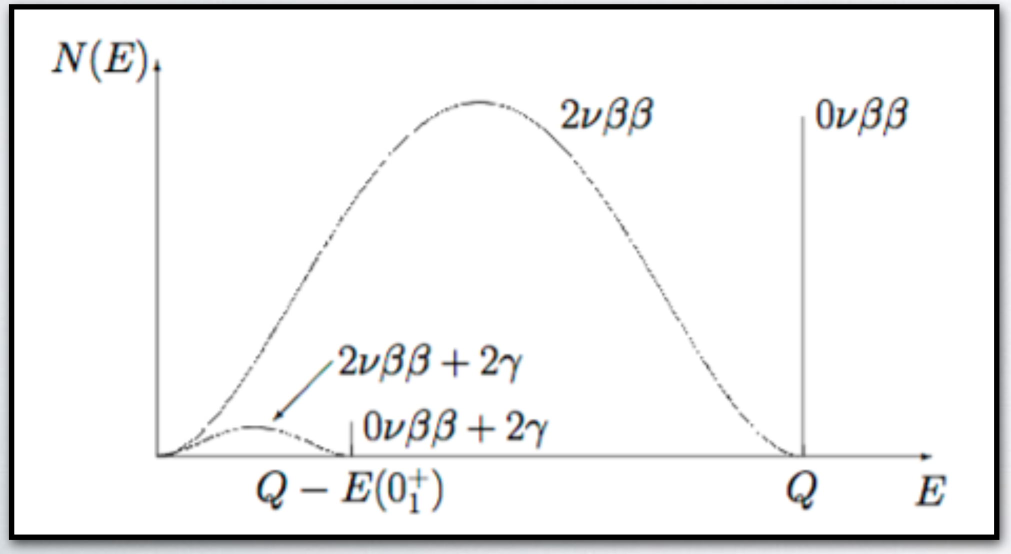


- Isotopes protected from single beta decay

- Neutrinofull double beta decay from Standard Model

$$X(Z,N) \to Y(Z+2,N-2) + 2e^- + 2\bar{\nu}_e$$

$$T_{1/2}^{2\nu}\left({}^{76}Ge \to {}^{76}Se\right) = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\ yr$$

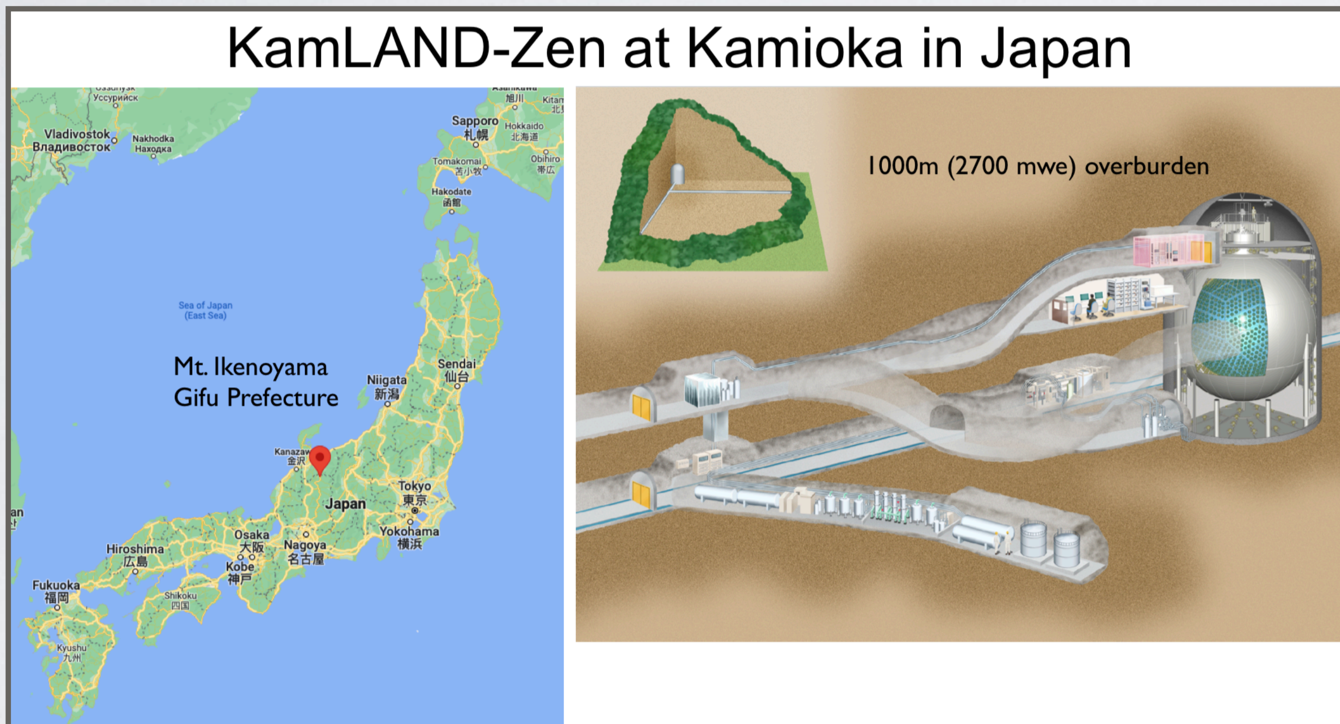


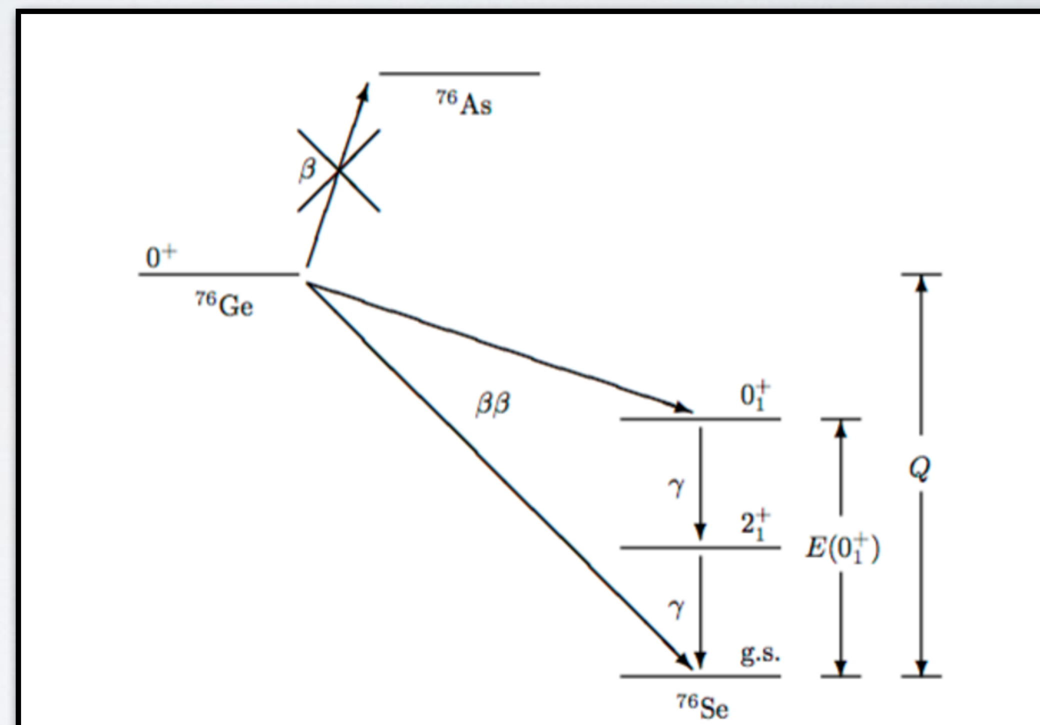
Cut out the middle man

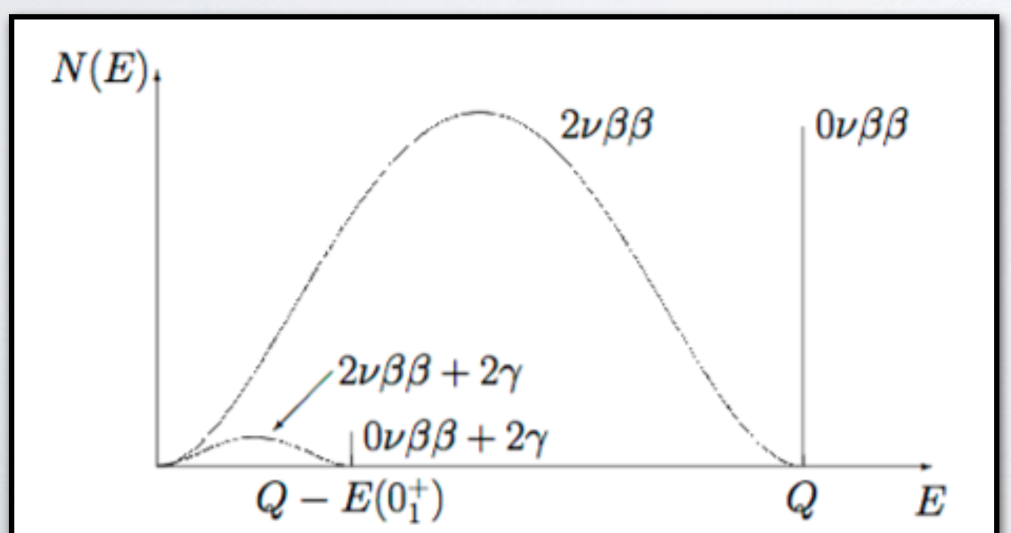
- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+ + \text{jets}$$

$$X(Z,N) \to Y(Z+2,N-2) + e^- + e^-$$



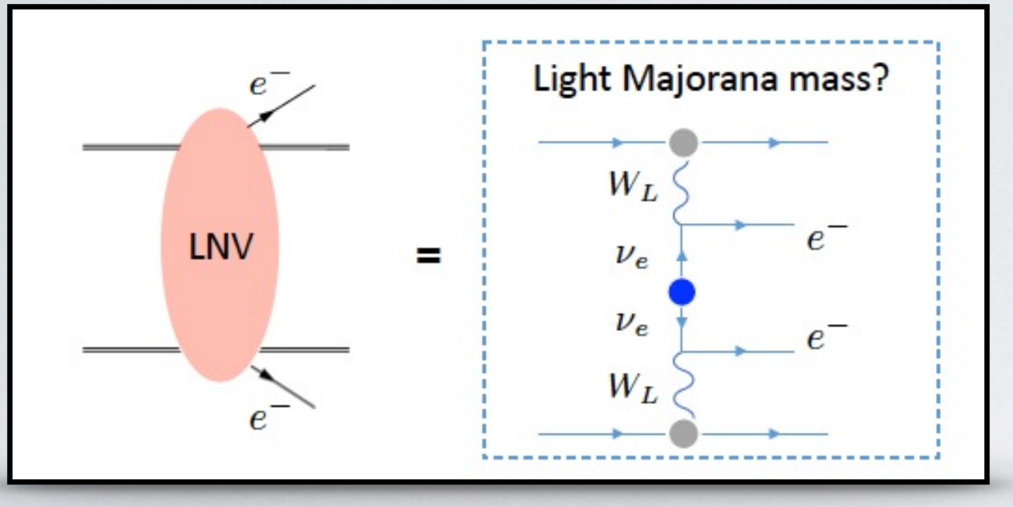




	Lifetime	Experiment	Year
76Ge	$8.0 \cdot 10^{25}\, y$	GERDA	2018
130Te	$3.2 \cdot 10^{25}\, y$	CUORE	2019
136Xe	$2.2 \cdot 10^{26}\, y$	KamLAND-Zen	2022

Note: age of universe ~ 10^{10} year

Interpreting 10^26 years….



$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2 \qquad m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

$$m_{\beta\beta} = m_1\, c_{12}^2 c_{13}^2 + m_2\, s_{12}^2 c_{13}^2 e^{2i\lambda_1} + m_3\, s_{13}^2 e^{2i(\lambda_2 - \delta_{13})}$$ = Effective neutrino mass

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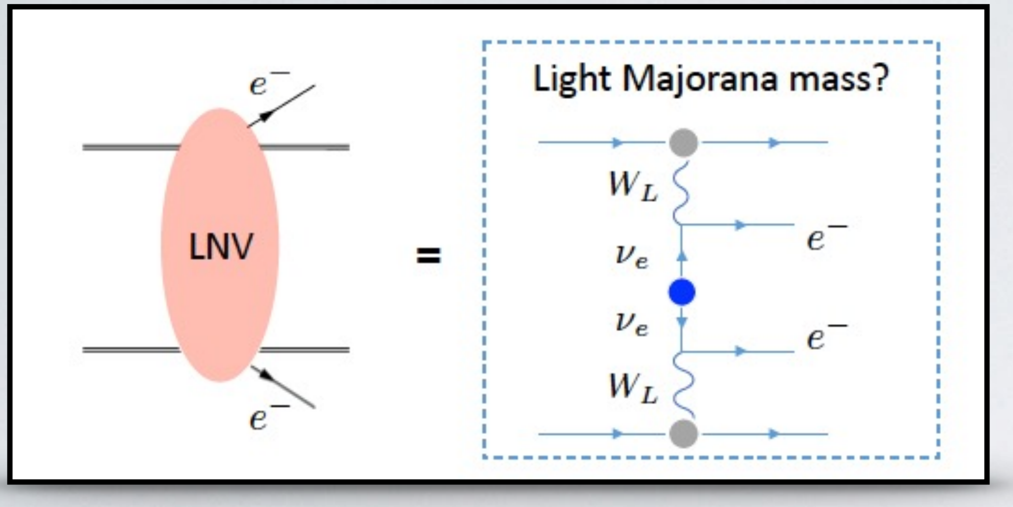

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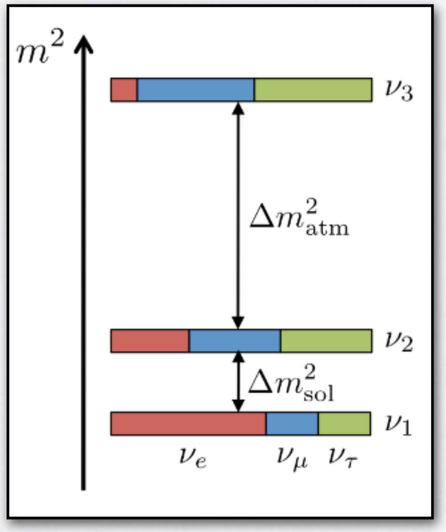
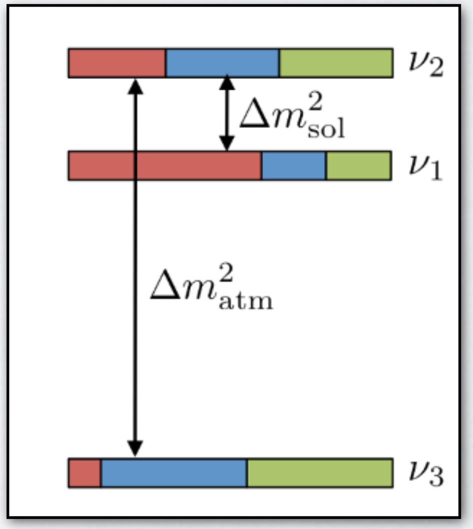
- c_{23} etc are neutrino mixing angles (**known** from oscillation experiments)
- Know the **mass splittings** but not the **absolute mass scale** nor **mass ordering**
- The **phases** are unknown (some hints for non-zero Dirac phase)

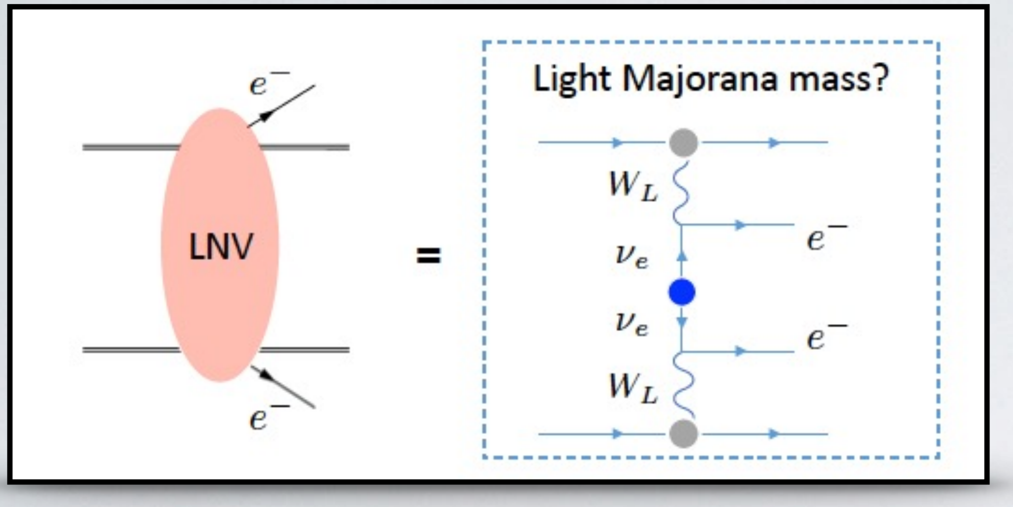
Normal Hierarchy (NH)



Inverted Hierarchy (NH)



Interpreting 10^{26} years....



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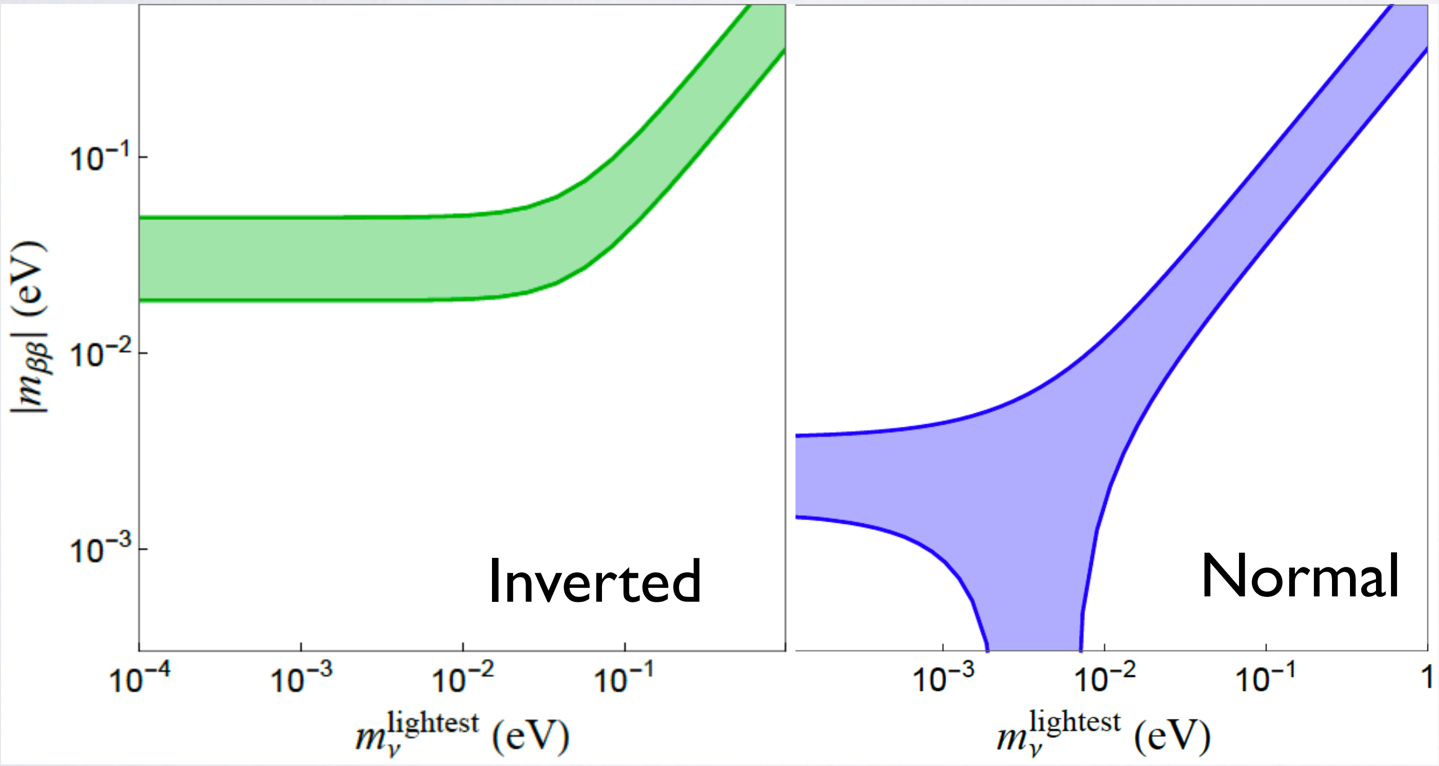
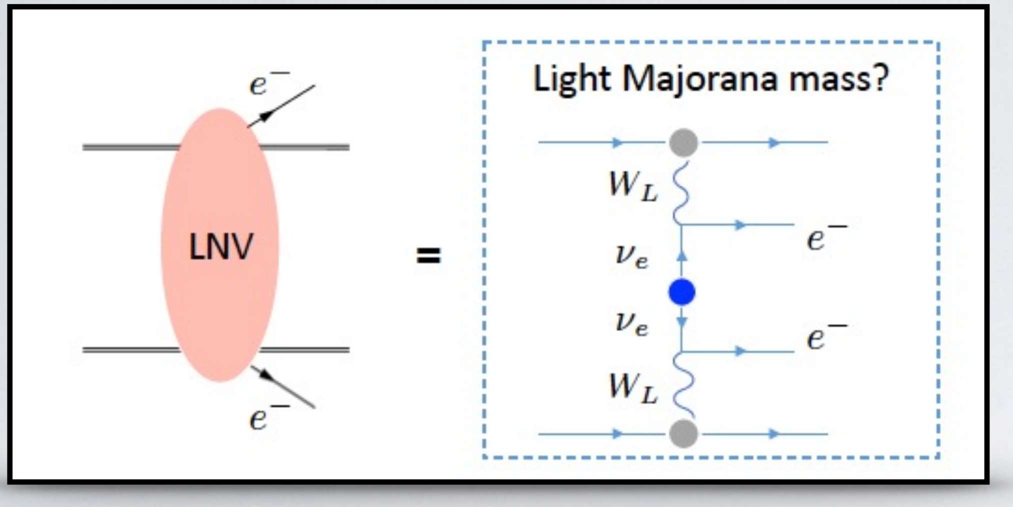


Vary the lightest mass and the ordering

Band from varying unknown phases

How close are experiments ?

Interpreting 10^{26} years....



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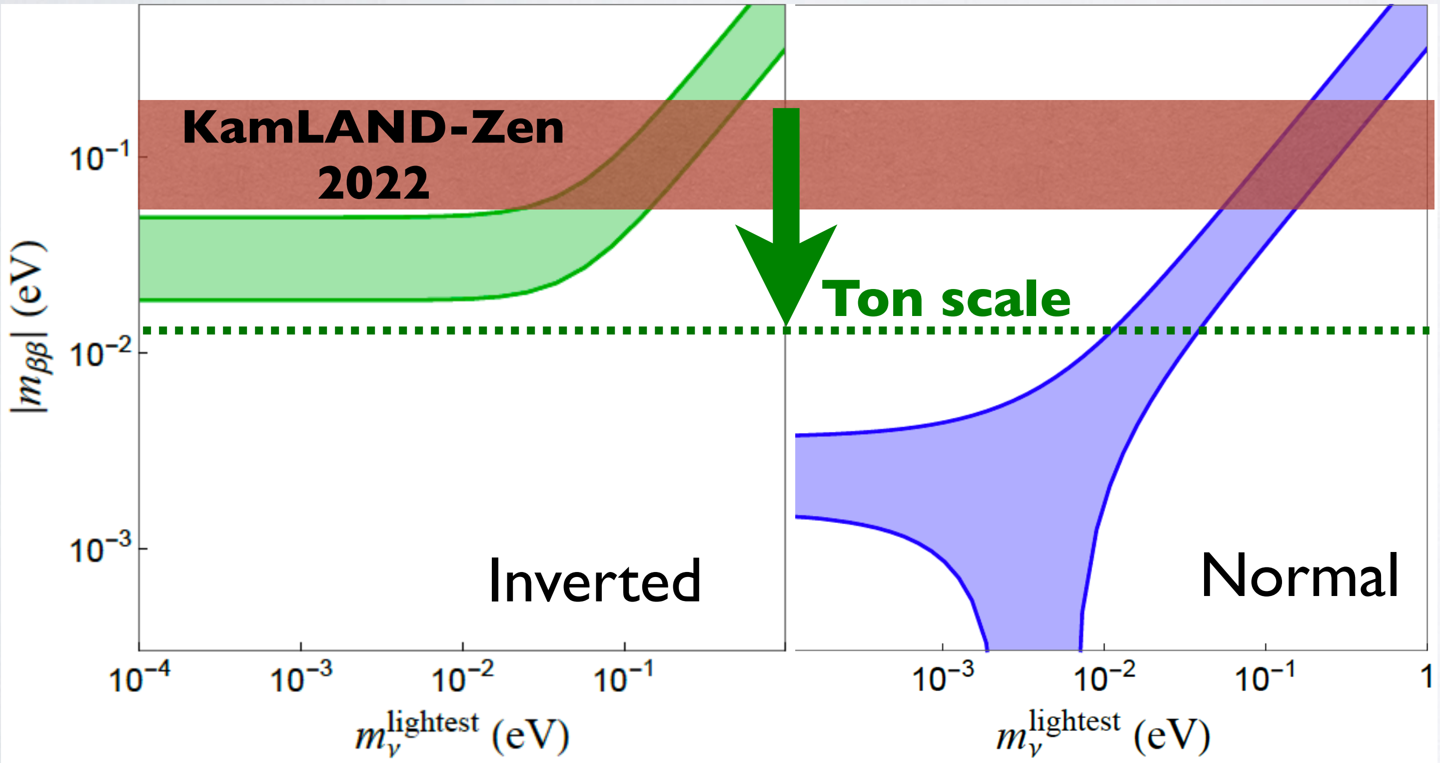


Very close !!

Next-generation discovery possible if inverted hierarchy or $m_{\rm lightest}$ >0.01 eV

These experiments are probing energy scales up 10^{14} GeV

There is a clear **end-game** for this search ! But it will require ~ **10^{30}** years sensitivity

Anatomy of a decay

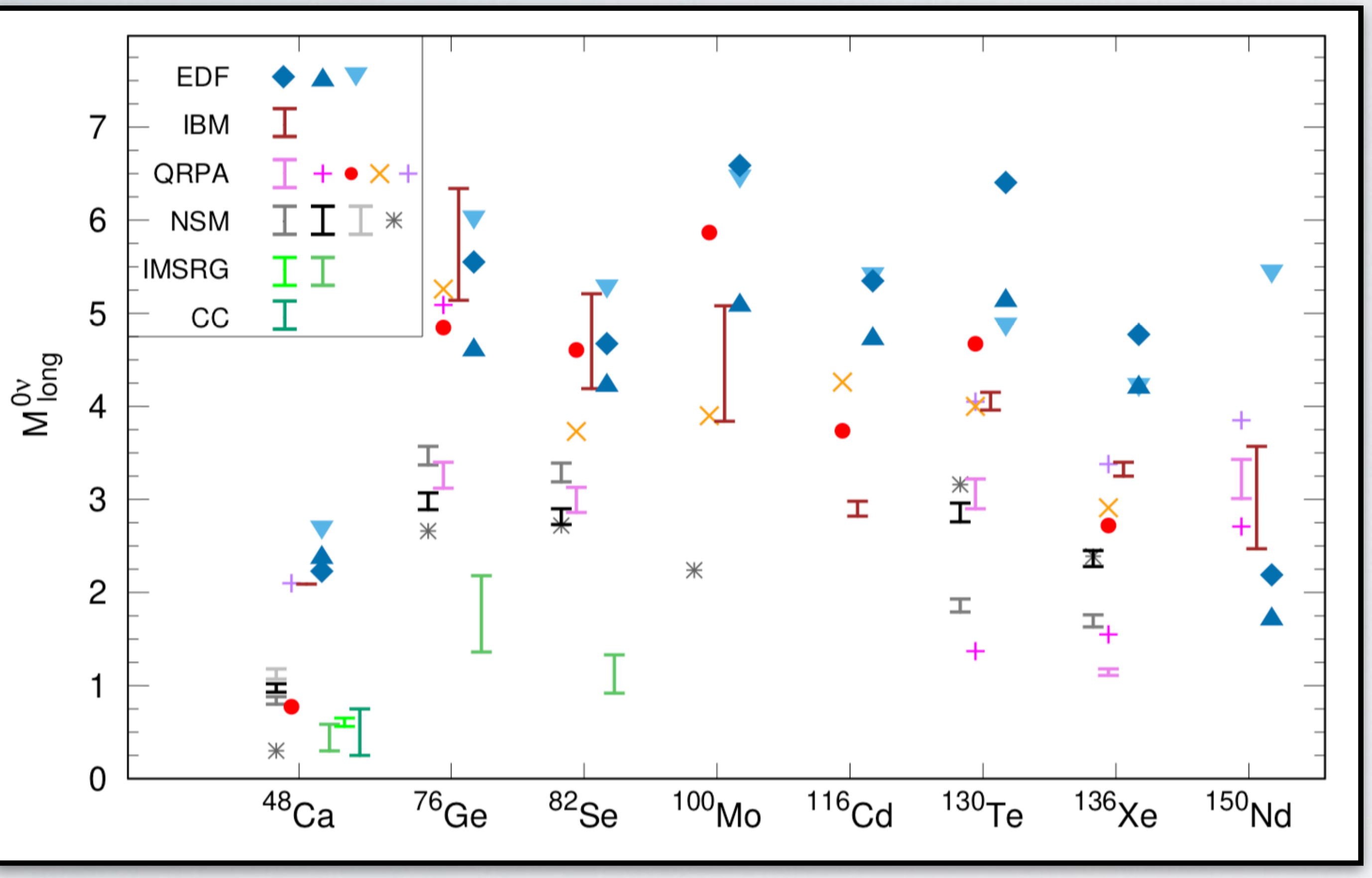
$$\Gamma^{0\nu} \sim m_{\beta\beta}^2 \cdot g_A^4 \cdot |M_{0\nu}|^2 \cdot G$$

Energy

?	$m_{\beta\beta}^2$	Lepton-number-violating source (*not necessarily neutrino mass*) ***(Particle Physics)***
GeV	g_A^4	From quarks to hadrons ***(Hadronic Physics)***
100 MeV	$\|M_{0\nu}\|^2 = \|\langle 0^+ \| V_\nu \| 0^+ \rangle\|^2$	Nuclear transition matrix element ***(Nuclear Physics... oh no)***
MeV	G	Phase space factor ***(Atomic Physics)***

Predictions are hard, especially about the future

From: Menendez et al review '22



$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2$$

Uncertainties factor 5 !
So factor 25 on the life time !

Where is this coming from ?

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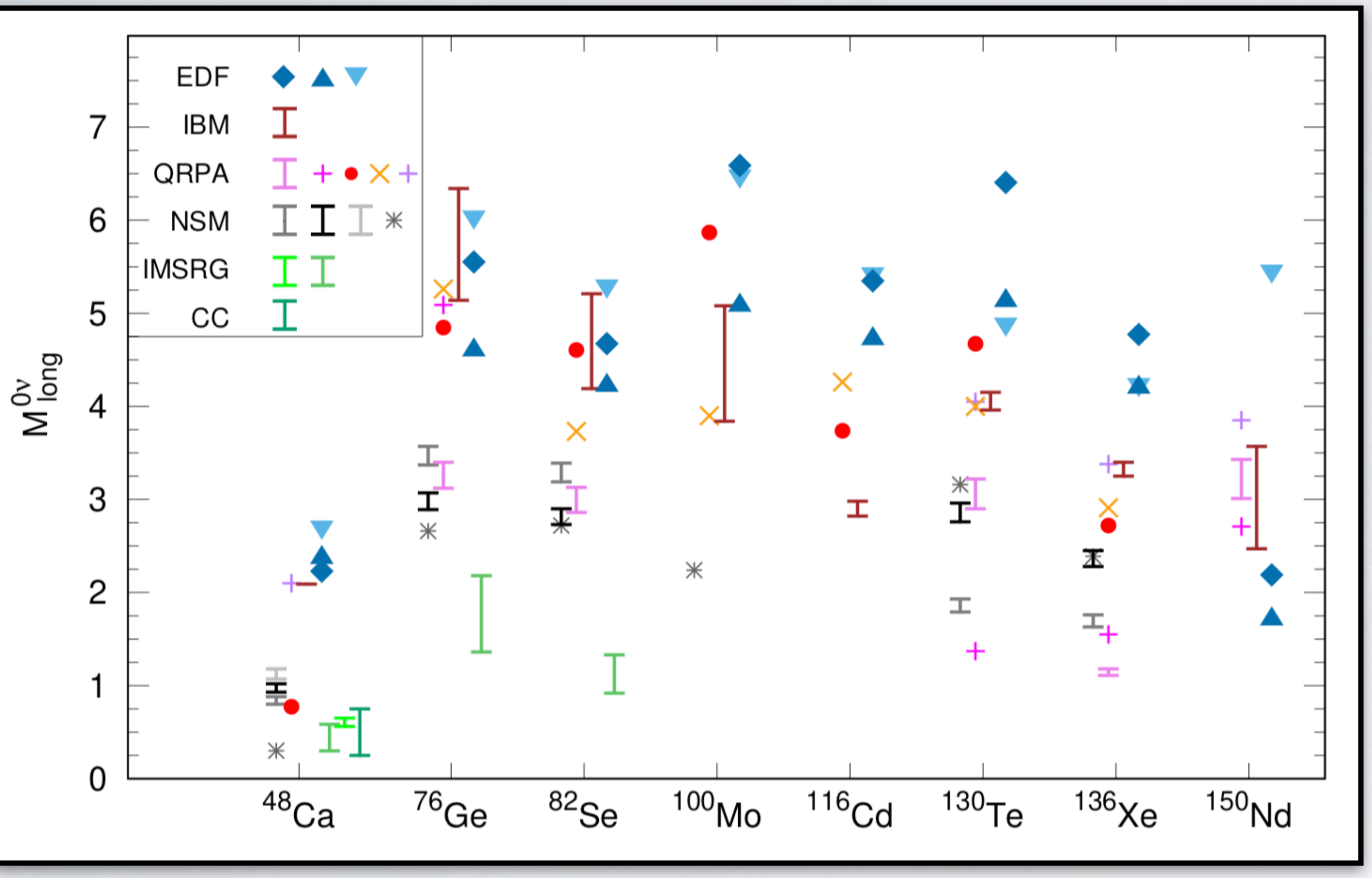

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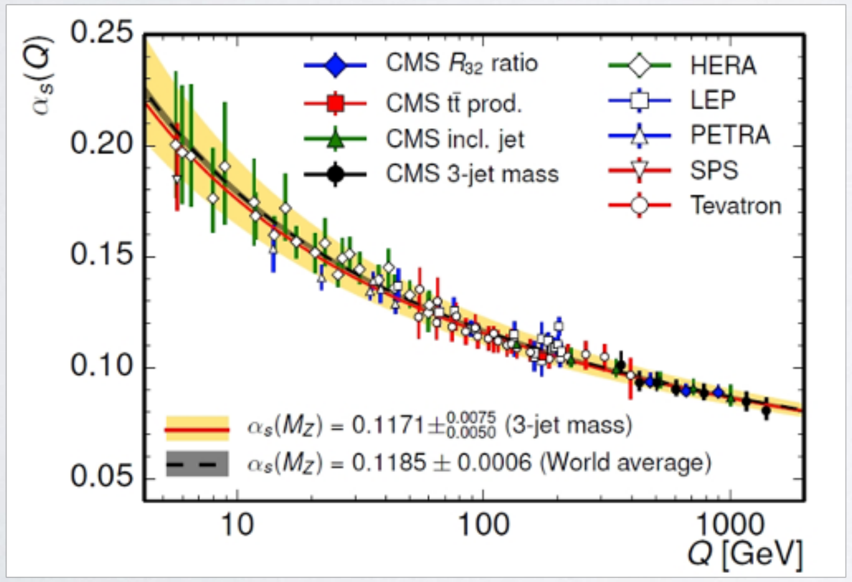

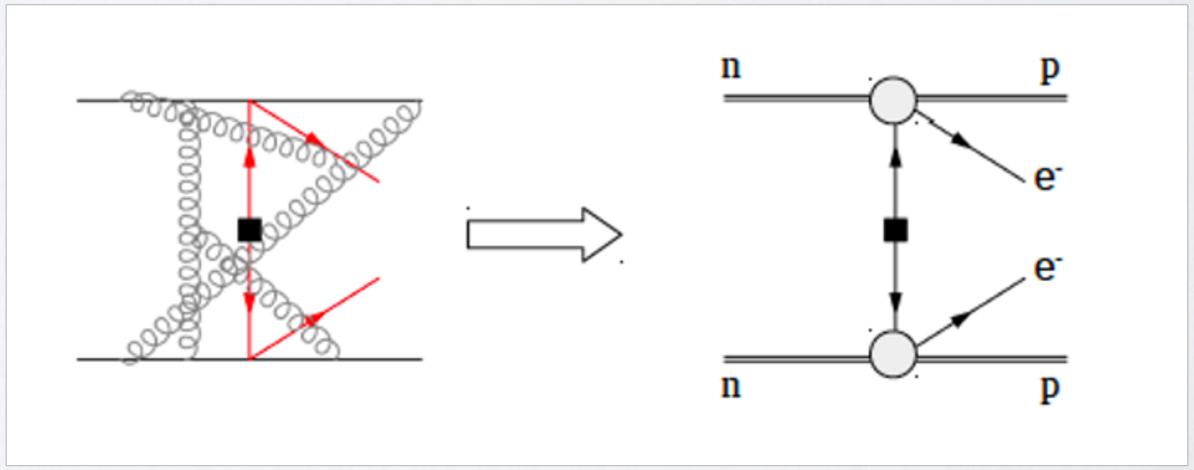

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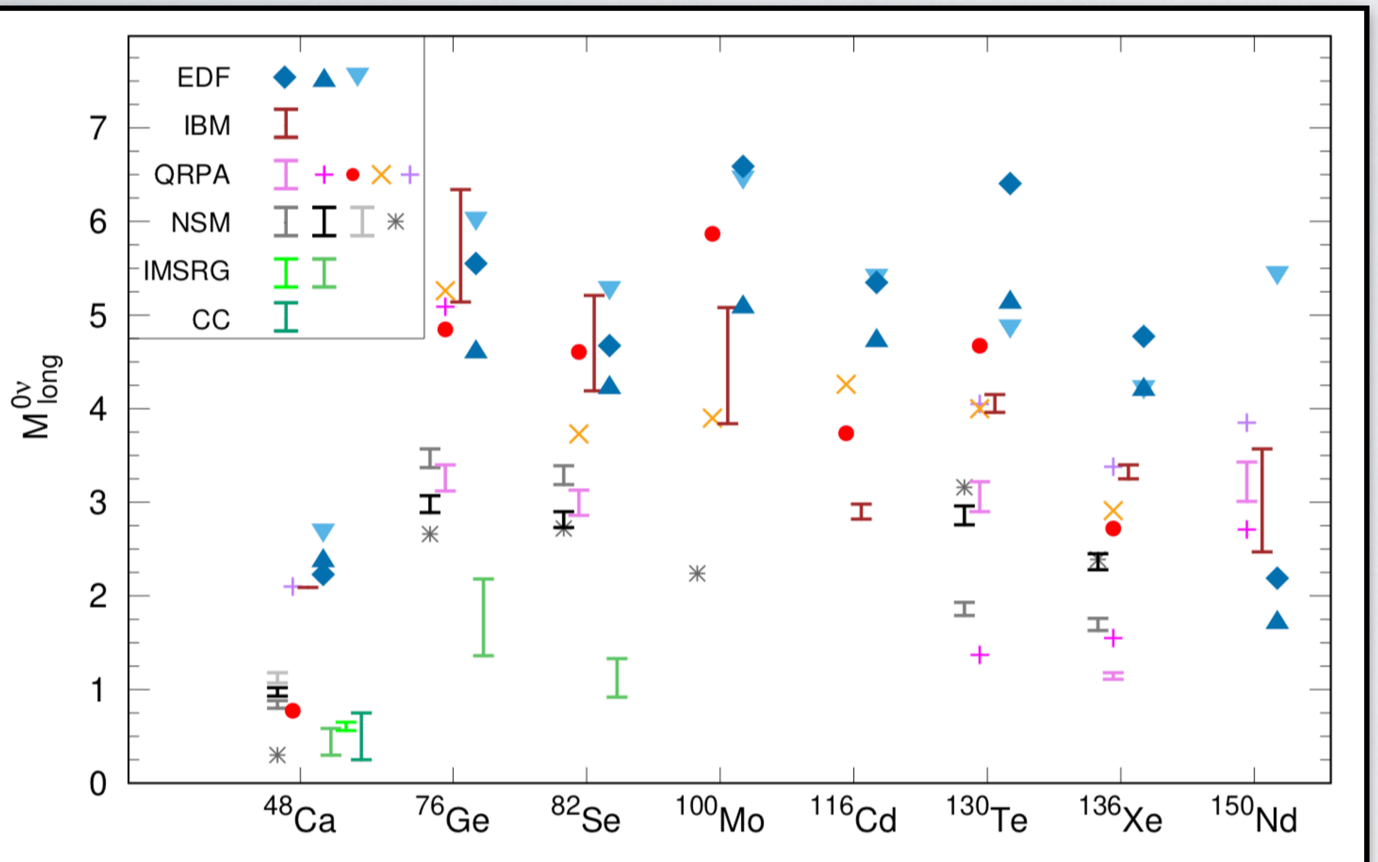

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Uncertainties factor 5 !
So factor 25 on the life time !

Where is this coming from ?

- First of all: nuclear many-body physics is simply difficult
- Many approximations without a clear 'power counting'
- Nuclear methods and codes are benchmarked on 'single-nucleon-currents' physics
- **Recent developments: ab initio computations of 0vbb matrix elements**

How to get nuclear physics from QCD

- Nuclear physics historically data-driven model-building enterprise (*semi-emperical mass formula, nuclear shell model, Nijmegen potential,* ……)
- Successful description but hard to learn general lessons and make predictions for something new (such as neutrinoless double-beta decay)
- Nuclear physics = stamp collecting ?

How to get nuclear physics from QCD

- Nuclear physics historically data-driven model-building enterprise (*semi-emperical mass formula, nuclear shell model, Nijmegen potential, ……*)

- Successful description but hard to learn general lessons and make predictions for something new (such as neutrinoless double-beta decay)

- In the 90's Weinberg wrote 2 extremely nice papers

Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces #3
Steven Weinberg (Texas U.) (Apr 1, 1991)
Published in: *Nucl.Phys.B* 363 (1991) 3-18
pdf DOI cite claim reference search 1,442 citations

Nuclear forces from chiral Lagrangians #4
Steven Weinberg (Texas U.) (Oct 9, 1990)
Published in: *Phys.Lett.B* 251 (1990) 288-292
DOI cite claim reference search 1,529 citations

- Describe the **nucleon-nucleon** force from **chiral perturbation theory**

- This is now a mature and sizable field where people describe large nuclei from ChPT.

Chiral EFT in a nut-shell

$$\mathscr{L}_{QCD} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R + \text{masses} \qquad q = \begin{pmatrix} u \\ d \end{pmatrix}$$

- Neglect light-quark masses: QCD has a global $SU_L(2) \times SU_R(2)$ symmetry
- Spontaneously broken to $SU_{isospin}(2)$ in the ground-state -> **3 Goldstone bosons** (pions)
- Pions are not exactly massless due to quark masses (**Pseudo-Goldstone bosons**)

$$m_\pi^2 \sim (m_u + m_d)$$

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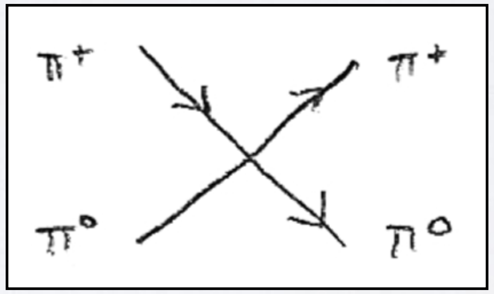
$$m_\pi^2 \sim (m_u + m_d)$$

- Chiral perturbation theory is **perturbative at low energies** due to Goldstone nature

$$\mathscr{L} = (\partial_\mu \pi)^2 + \frac{1}{f_\pi^2}(\pi \partial \pi)^2 + \dots$$



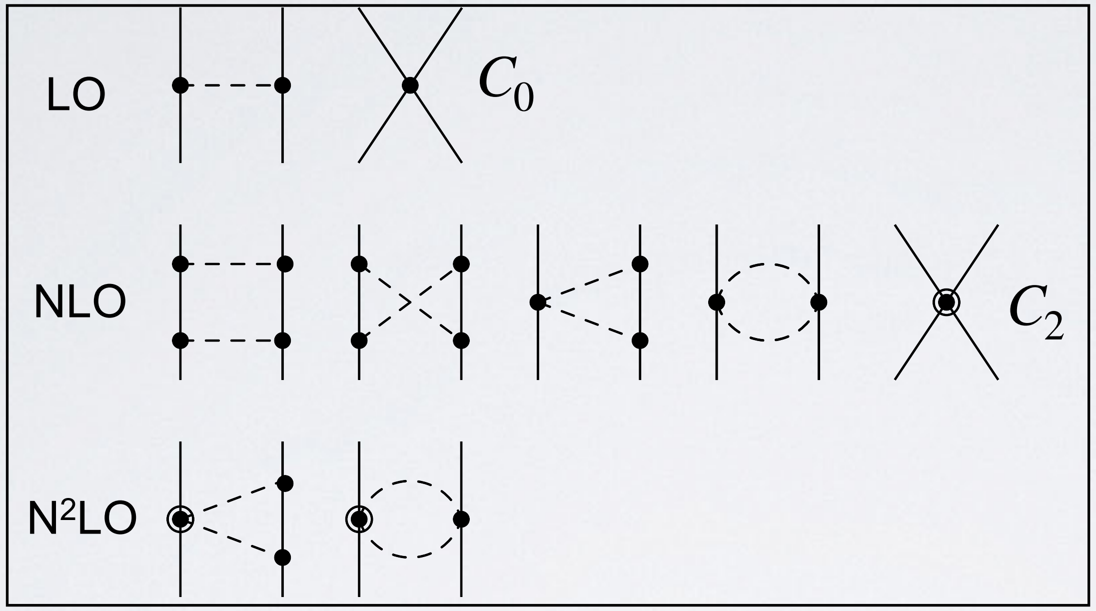
$\sim (p \cdot p')$

- Expansion parameter of chPT $\dfrac{p}{\Lambda_\chi}$ where $\Lambda_\chi \sim 1\,\text{GeV}$
- At higher-orders in the expansion more interactions appear $\mathscr{L} = L_4\,(\partial\pi)^4 \qquad L_4 \sim \dfrac{1}{f_\pi^2 \Lambda_\chi^2}$
- The coupling constants are **not predicted: fit to data or lattice QCD**

Towards nuclear physics

- Chiral perturbation theory can be extended to include nucleons
- Derive **nuclear potential** from the chiral Lagrangian

$V_{NN} =$



Weinberg
Van Kolck et al,
Epelbaum et al,
Machleidt et al,
And many more…

- Fit the coupling constants $C_{0,2}$ etc to **nucleon-nucleon data** --> predict the rest
- This describes an effective quantum field theory approach to nuclear physics

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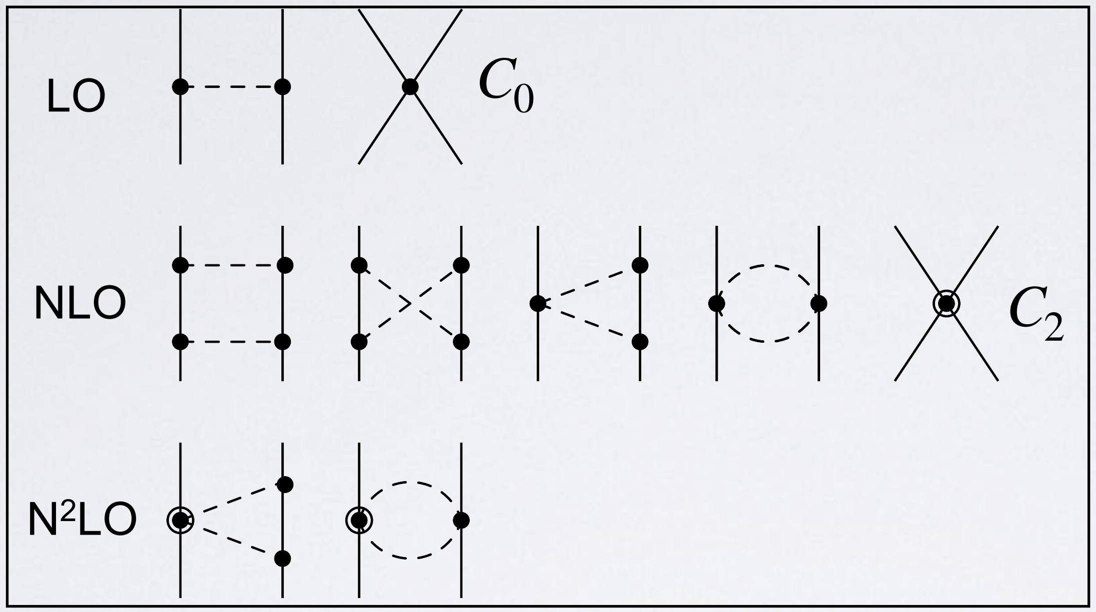

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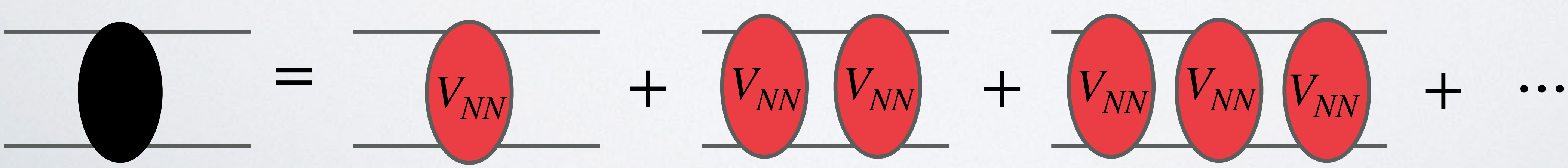
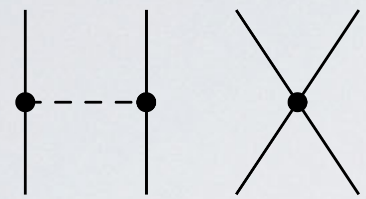
And many more…

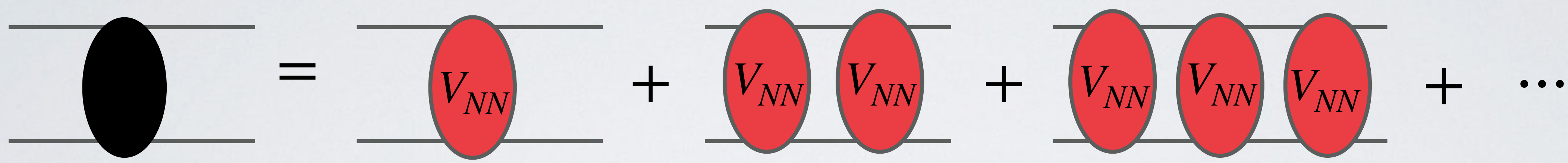
- Fit the coupling constants $C_{0,2}$ etc to **nucleon-nucleon data** --> predict the rest
- This describes an effective quantum field theory approach to nuclear physics
- Now nuclear forces are **not perturbative !** They lead to **bound states** !
- This is achieved by ‘resumming' the potential (solving a Schrodinger equation)



Example at leading order

LO 

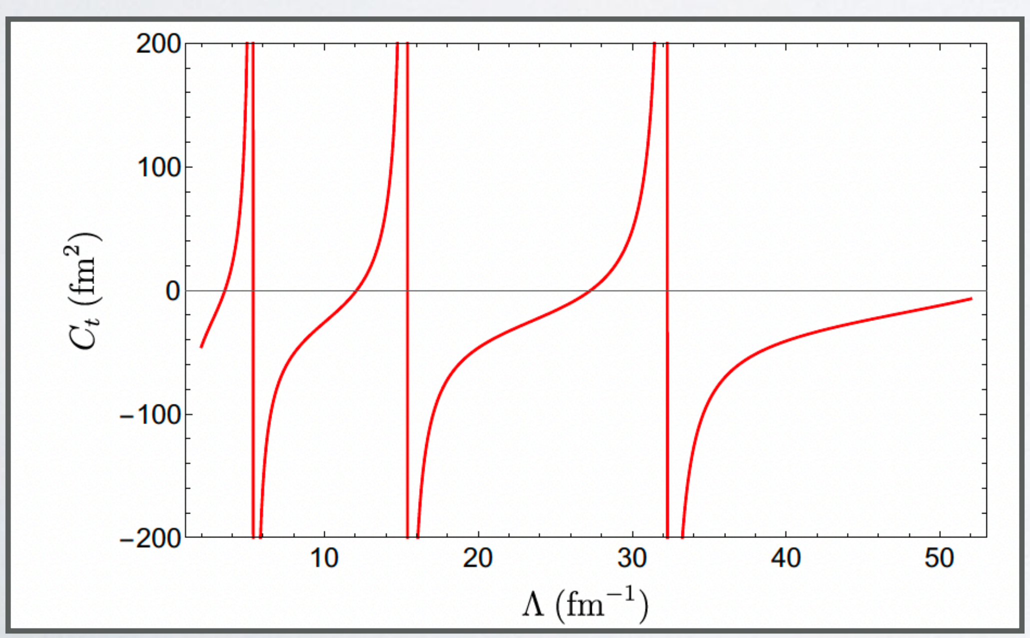
$$V_{\rm NN} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

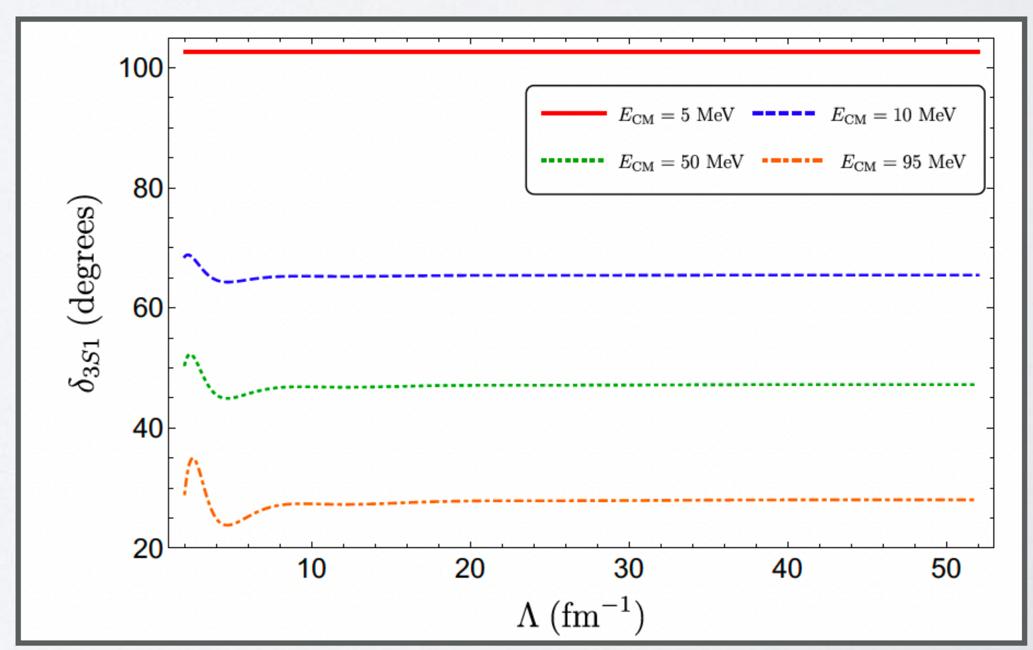


- Loops appearing here typically diverge and one has to **regulate**

$$V_{\rm NN} \to e^{-p^6/\Lambda^6} \times V_{\rm NN} \times e^{-p'^6/\Lambda^6}$$

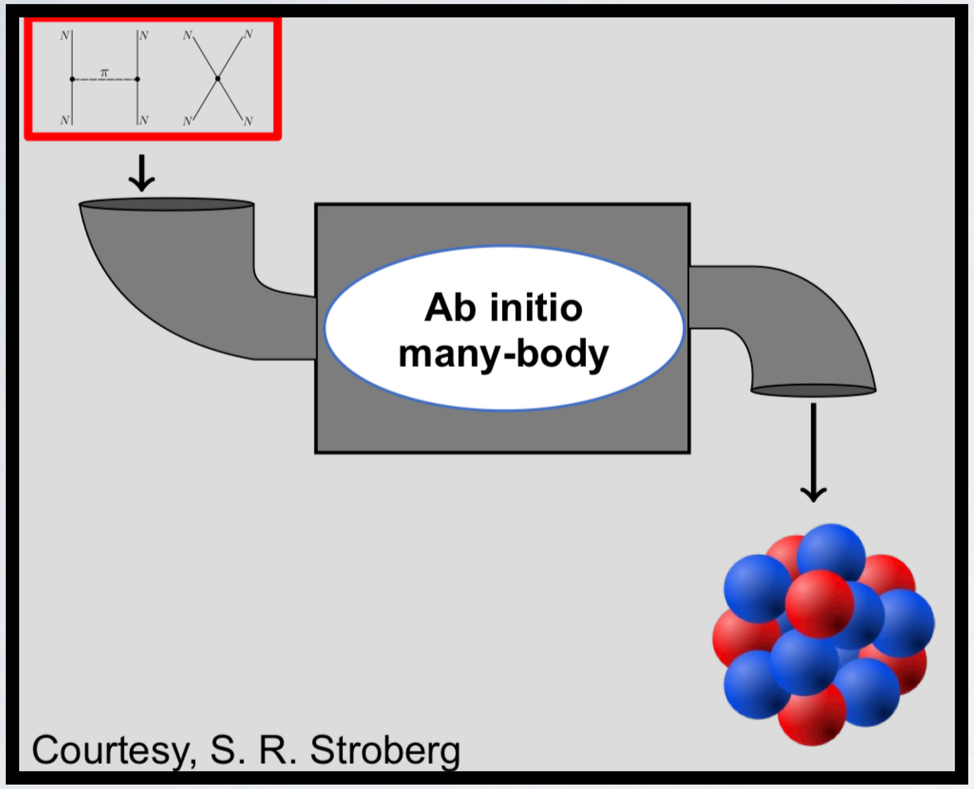
- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ
- This is called 'non-perturbative renormalization' similar in spirit to what we do in any QFT





State of the art

- Starting from chiral EFT —> derive nuclear properties + reactions



LETTERS

https://doi.org/10.1038/s41567-019-0450-7

nature physics

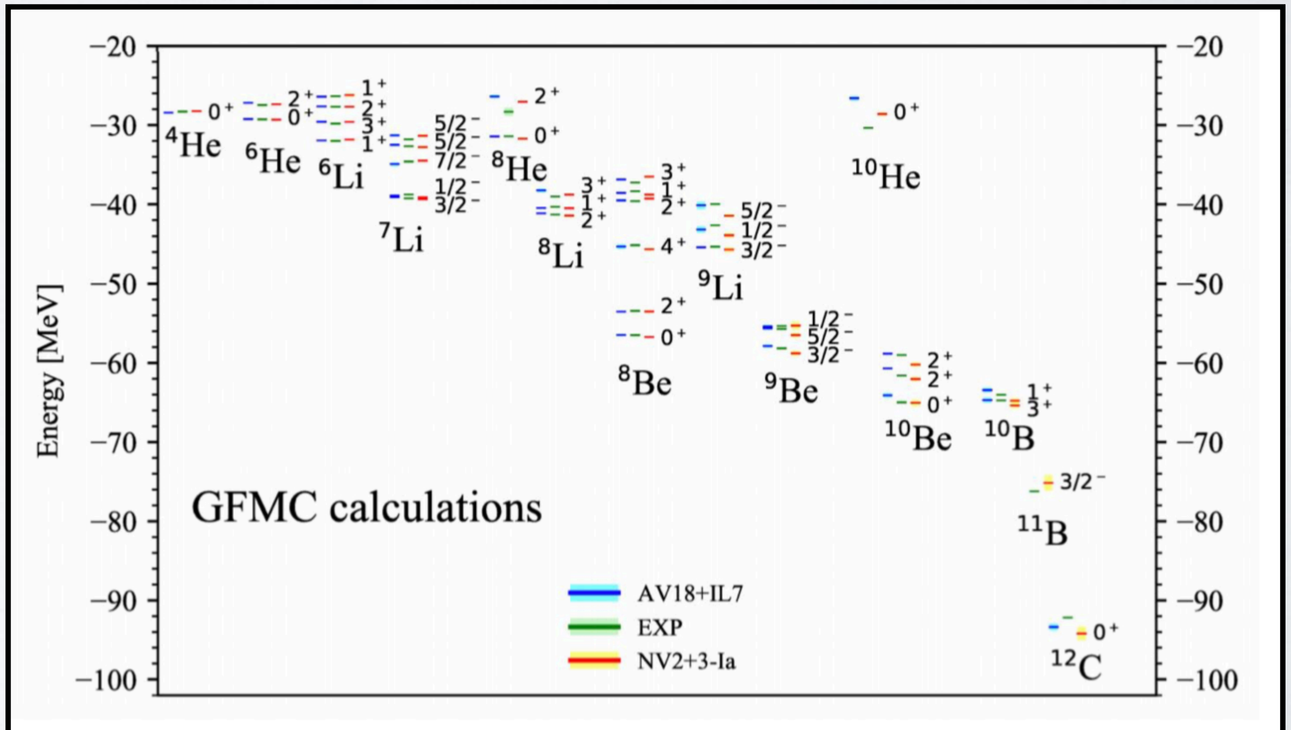
Discrepancy between experimental and theoretical β-decay rates resolved from first principles

Gysbers et al '20

Ab Initio Calculation of the Hoyle State

Evgeny Epelbaum, Hermann Krebs, Dean Lee, and Ulf-G. Meißner
Phys. Rev. Lett. **106**, 192501 – Published 9 May 2011

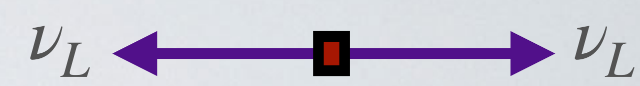
Physics See Viewpoint: The carbon challenge



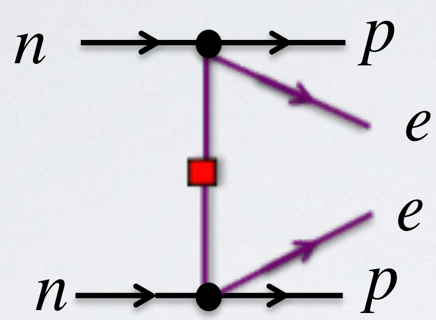
Piarulli et al. PRL 120, 052503 (2018)

Chiral EFT for 0vbb

- Neutrinos are still degrees of freedom in low-energy chiral EFT



- Compute neutrinoless double-beta decay processes in chiral expansion



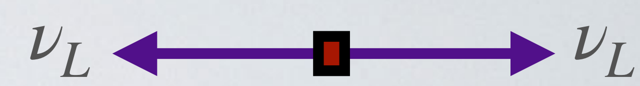
$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad \mathbf{q} \sim k_F \sim m_\pi$$

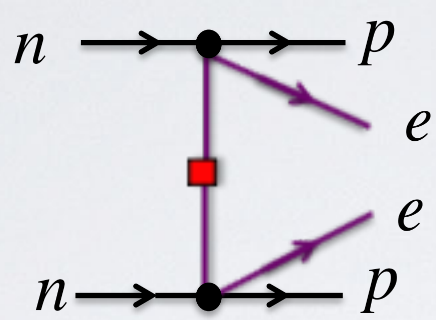
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+\frac{1}{\mathbf{q}^2}\left[(1+2g_A^2)+\frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right]\otimes \bar{e}_L e_L^c$$

- Note: the nucleons appear in a bound state and **q** is a loop momentum

Chiral EFT for 0vbb

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Compute neutrinoless double-beta decay processes in chiral expansion





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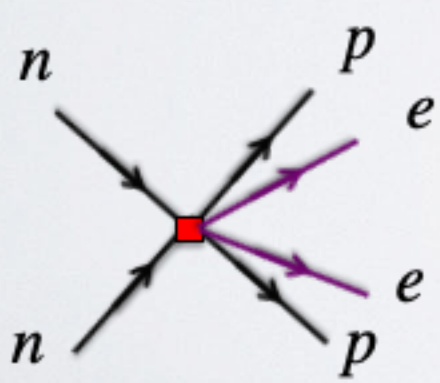
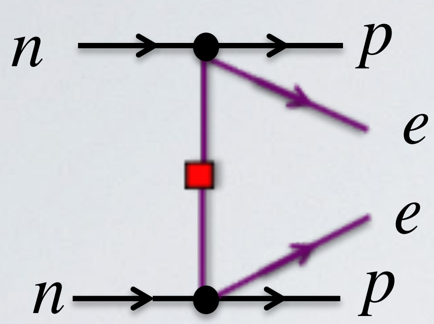


- Contributions from virtual hard neutrinos $\mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Weinberg power counting then puts this at higher order

$$V_\nu \sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$$

- Also loop diagrams etc at higher order (not today)

The leading order process



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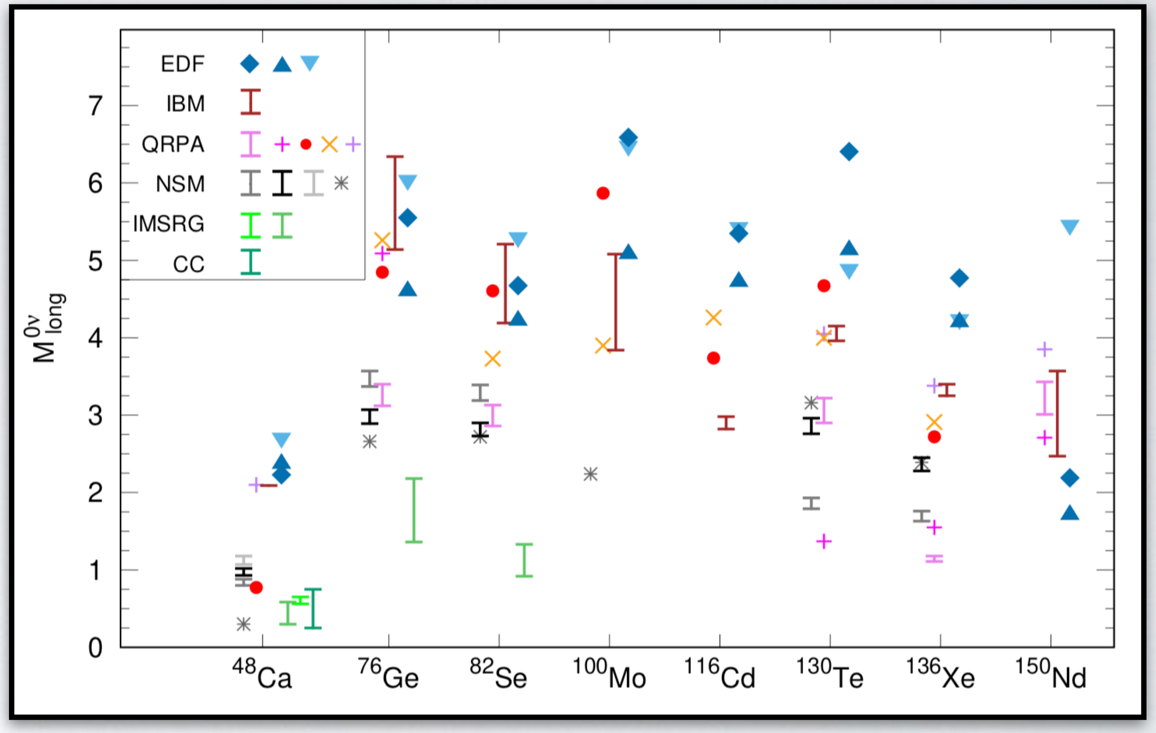
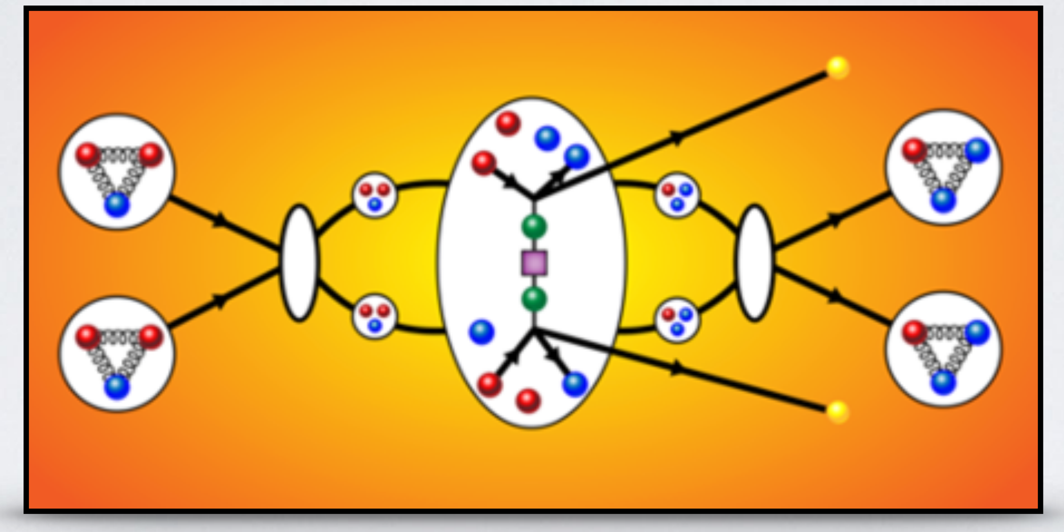
- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown $m_{\beta\beta}$
- Many-body methods disagree significantly
- Idea: see what happens for lighter systems
- **Not relevant for experiments but as a theoretical laboratory**



Neutron-Neutron → Proton-Proton

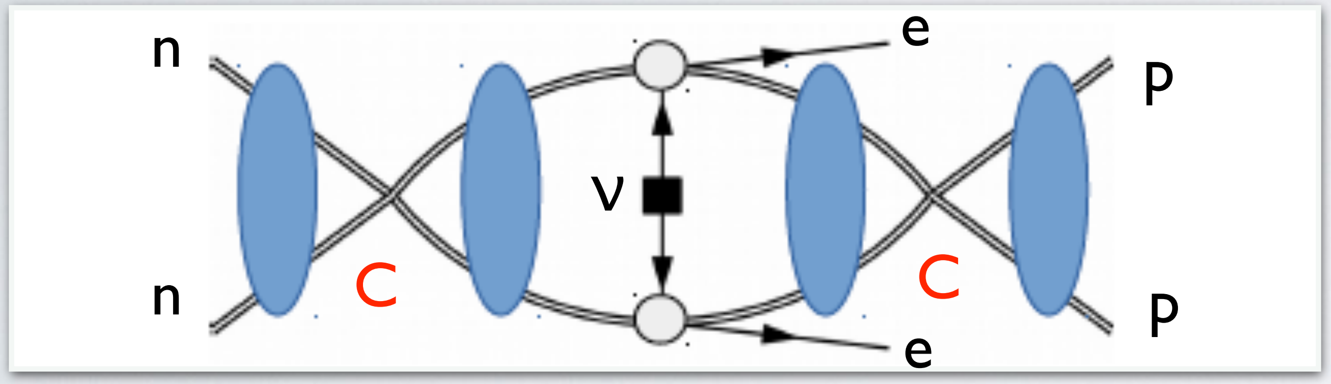
- Study simplest nuclear process: nn → pp + ee

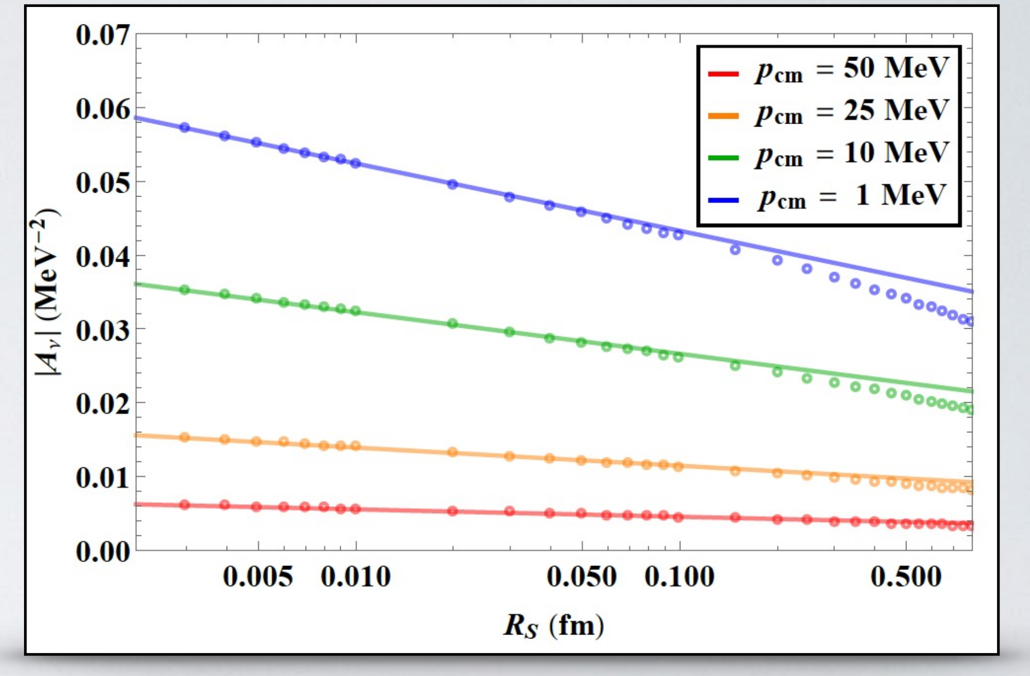


- Compute everything consistently from chiral EFT: wave function + currents
- Then insert the 0vbb potential in renormalized wave function —> **should be finite**

$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad\qquad A_\nu = \langle \Psi_{pp} | V_\nu | \Psi_{nn} \rangle$$

It doesn't work





$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\epsilon}+\log\frac{\mu^2}{p^2}\right)$$

New divergences

The leading order amplitude is not renormalized !


Featured in Physics | Editors' Suggestion | Open Access

New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck

Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

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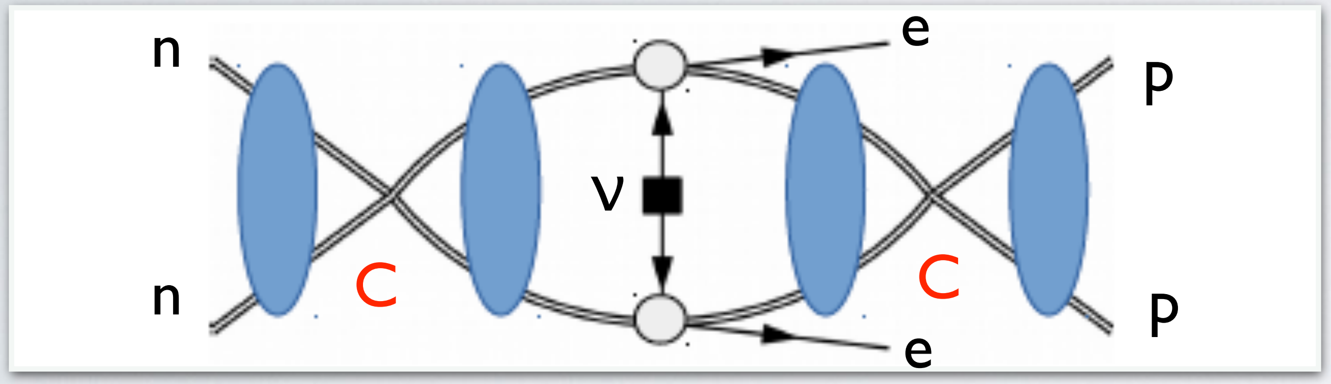
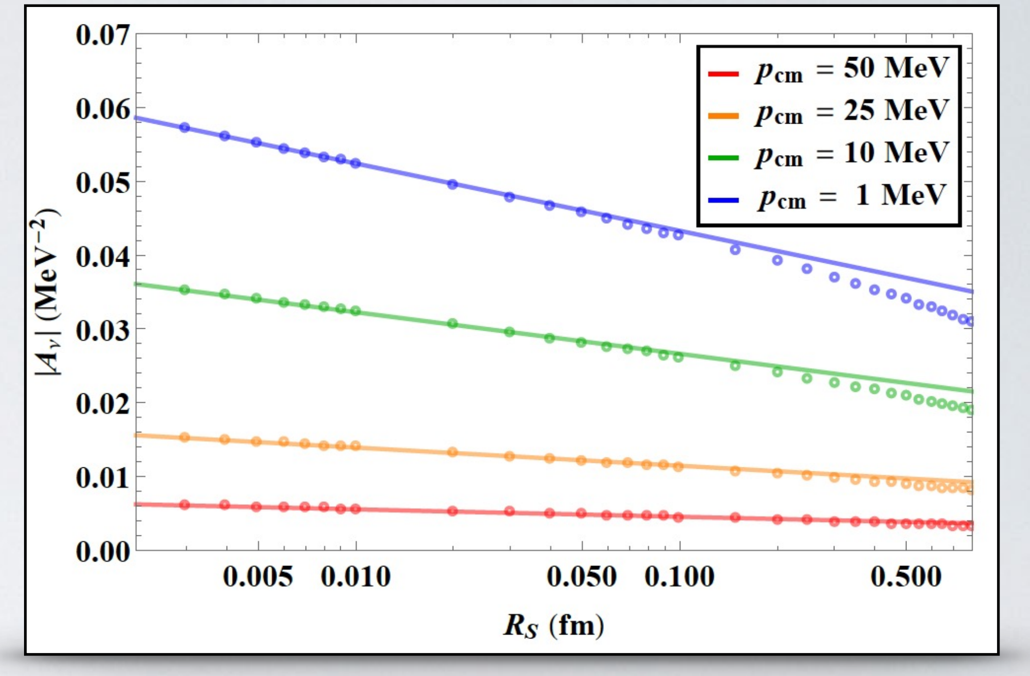
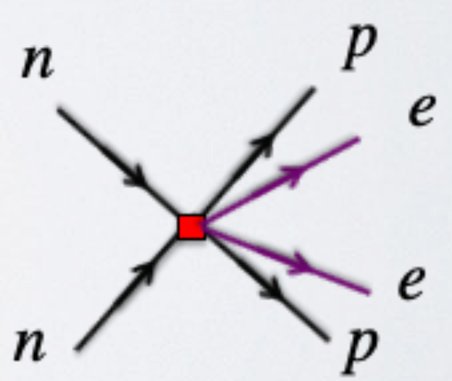




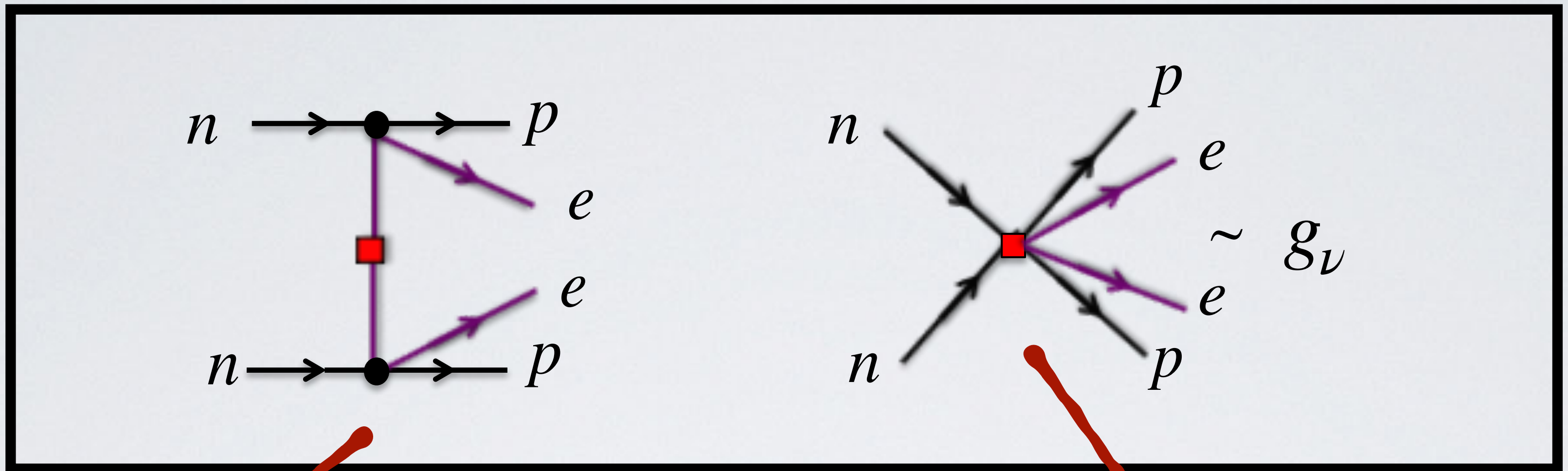
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

- Divergence indicates sensitivity to short-distance physics
- **Requires a leading order counter term**
- In the literature this is callled '*breakdown of Weinberg power counting*'



A new leading-order contribution



‘Long-range’ neutrino-exchange

‘Short-distance’ neutrino exchange
required by renormalization of amplitude

- **Short-distance piece depends on QCD matrix element** g_ν
- This was initially unknown but has now been determined (long story)

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC ’19 PRL ’21 JHEP ‘21
Davoudi, Kadam PRL ’21 Briceno et al ’19 ‘20
Richardson, Schindler, Pastore, Springer ‘21
Tuo et al. ‘19; Detmold, Murphy ’20 ‘22

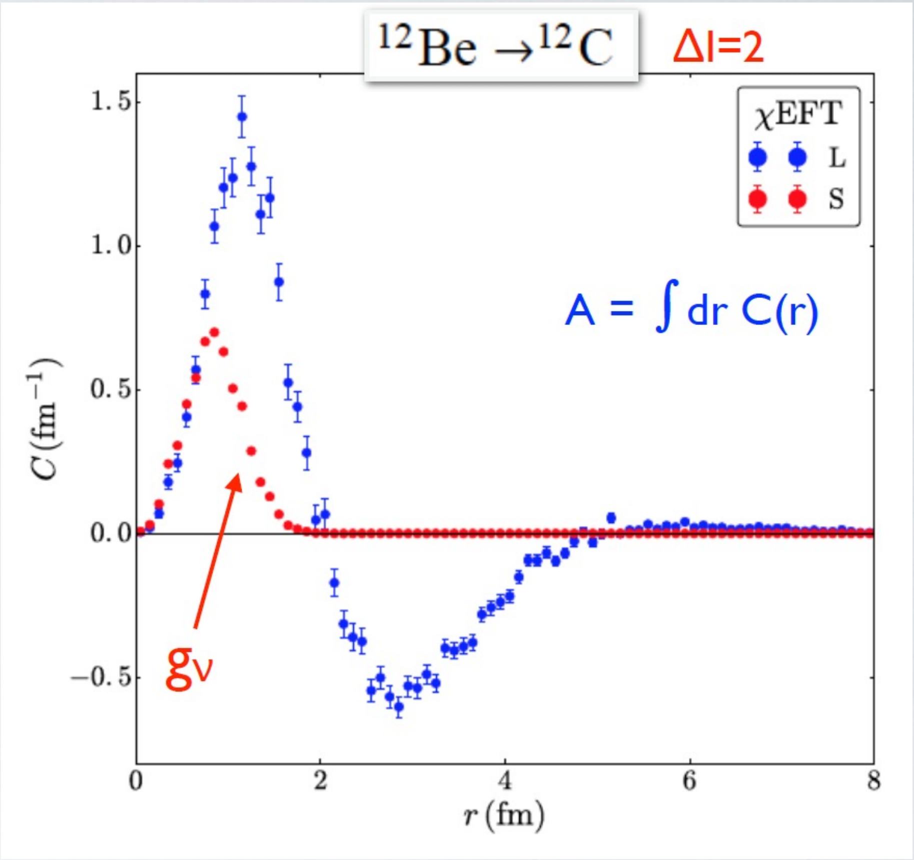
- 0vbb calculations have to be redone —> This is now happening !

Impact on nuclear matrix elements

Pastore, Piarulli et al '19

- Use chiral potentials to generate wave functions

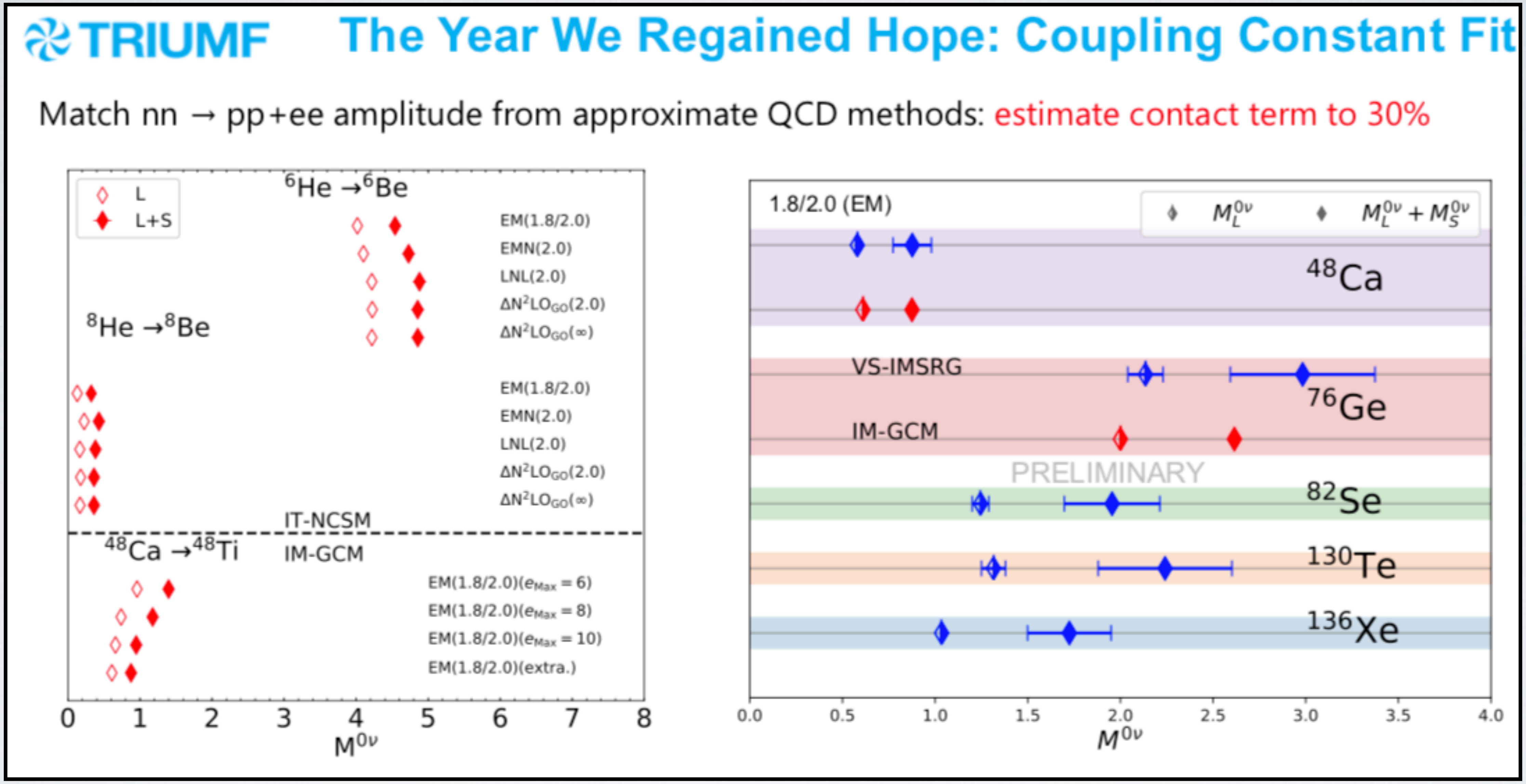
Nuclear matrix elements	Long Range	Short Range
$^{12}\mathrm{Be} \to {}^{12}\mathrm{C} + e^- + e^-$	0.7	0.5



- **Short-distance effects are sizable and change matrix elements by almost 100%**

- **Caveat:** These are not nuclei of experimental interest

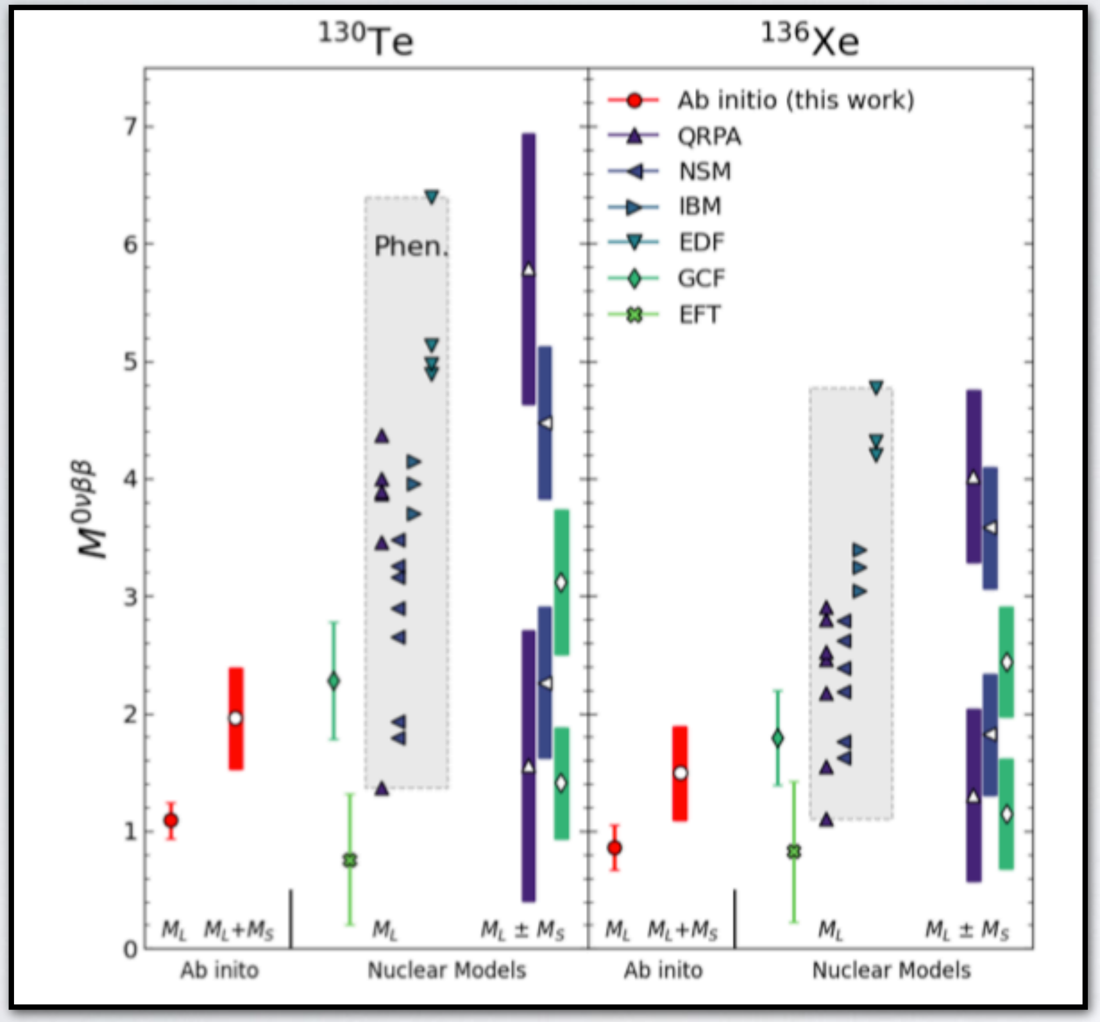
Impact on realistic nuclei

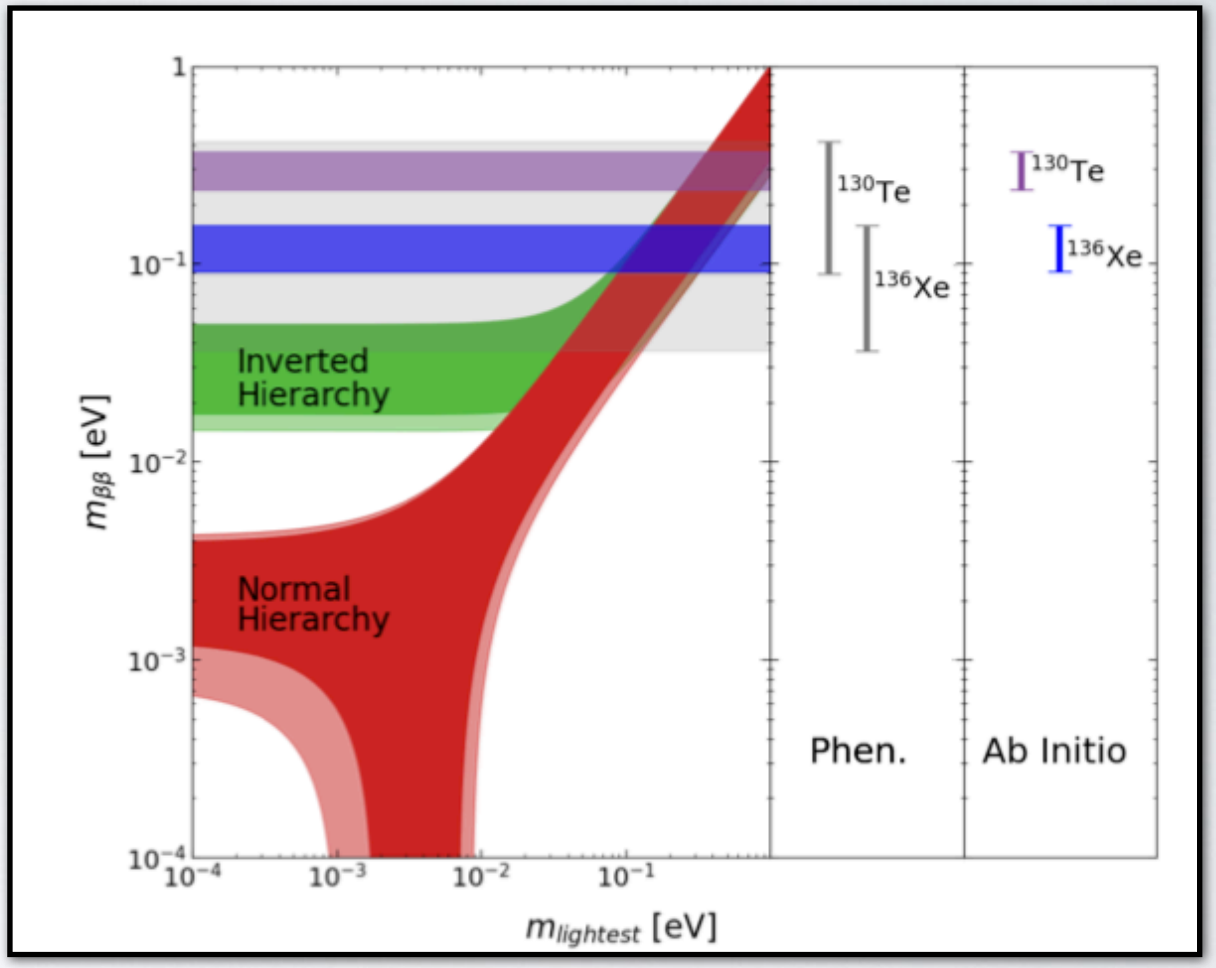


- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (2 months ago)
- The contact term enhances NMEs by 100% (Ca) to 70% (Xe) (factor 3-4 on the lifetime)
- Inclusion of contact term brings different computations **closer** together !

Impact on realistic nuclei

- Results from a few weeks ago 2307.15156 (Belley et al)





- **Still a lot to be done but there is now real path towards reliable predictions !**
- State-of-the-art calculations find rather small NME partially compensated by the new contact term
- Next-gen experiments will reach inverted hierarchy but normal hierarchy difficult….

The plan of attack

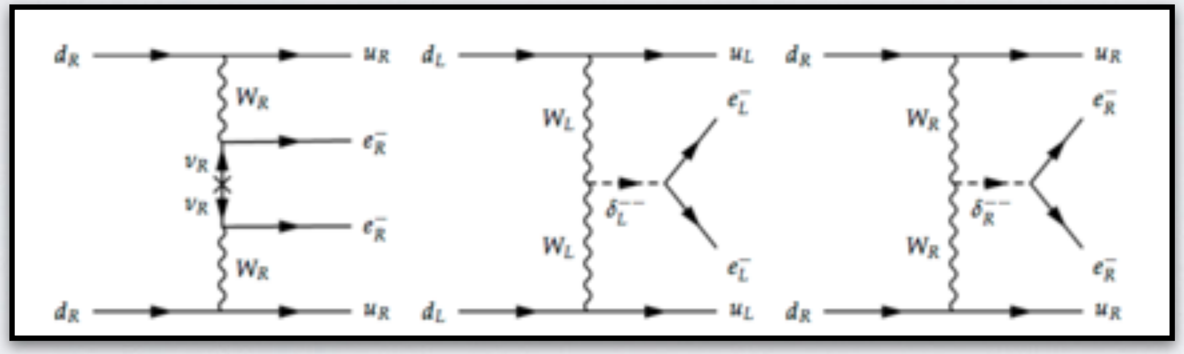
1. Baryon- and lepton-number foundations

2. Neutrinoless double beta decay from Majorana neutrino exchange

3. **Other mechanisms in effective field theory**

Beyond neutrino masses

- Neutrinoless double beta decay can be caused through other mechanisms !
- For instance in *left-right symmetric models, supersymmetry, leptoquarks* ….



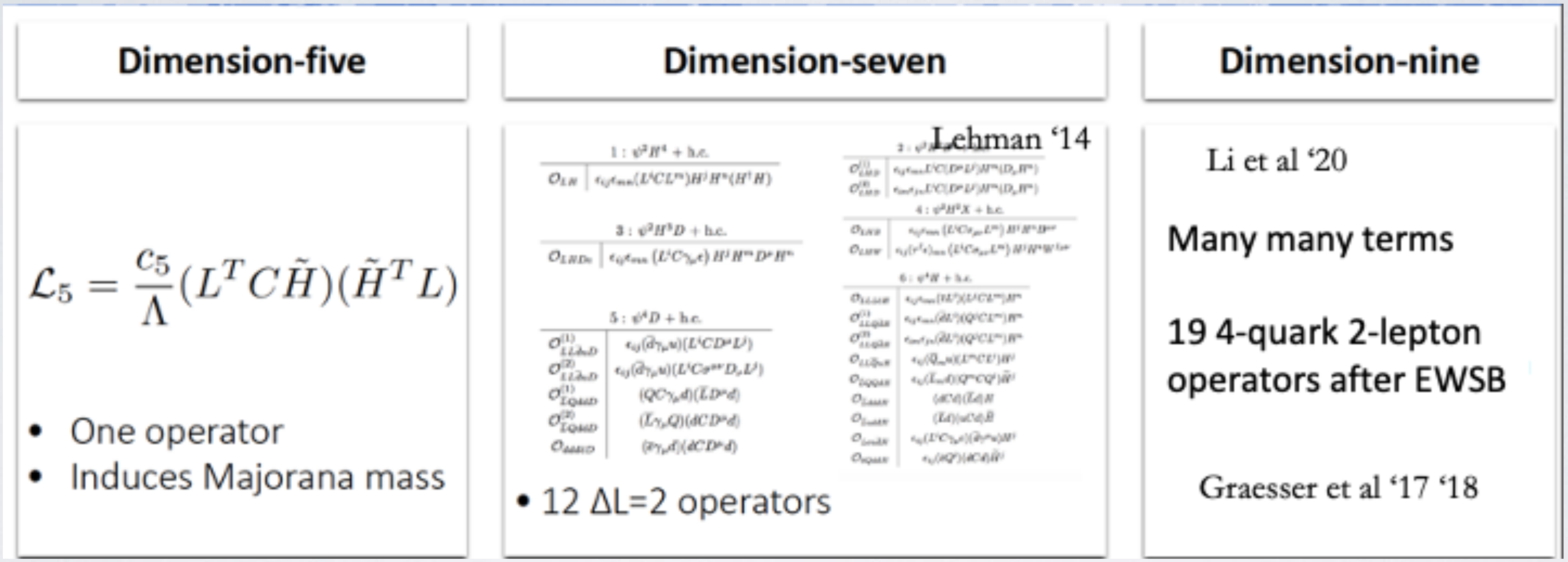
- No light neutrinos appear at all in these processes but **same observable signature**
- All these different processes can be captured by effective field theory techniques

$$\mathscr{L}_{LNV} = \frac{c_5}{\Lambda}\left(L^T C\tilde{H}\right)(\tilde{H}^T L) + \sum_i \frac{d_i}{\Lambda^3} O_{7i} + \sum_i \frac{f_i}{\Lambda^5} O_{9i} + \dots$$

- Disentangling the origin from 0vbb measurements will be a **hard (luxury)** problem

Higher-dimensional operators

- Effective operators appear at odd dimension (5, 7, 9, …..) Kobach '16



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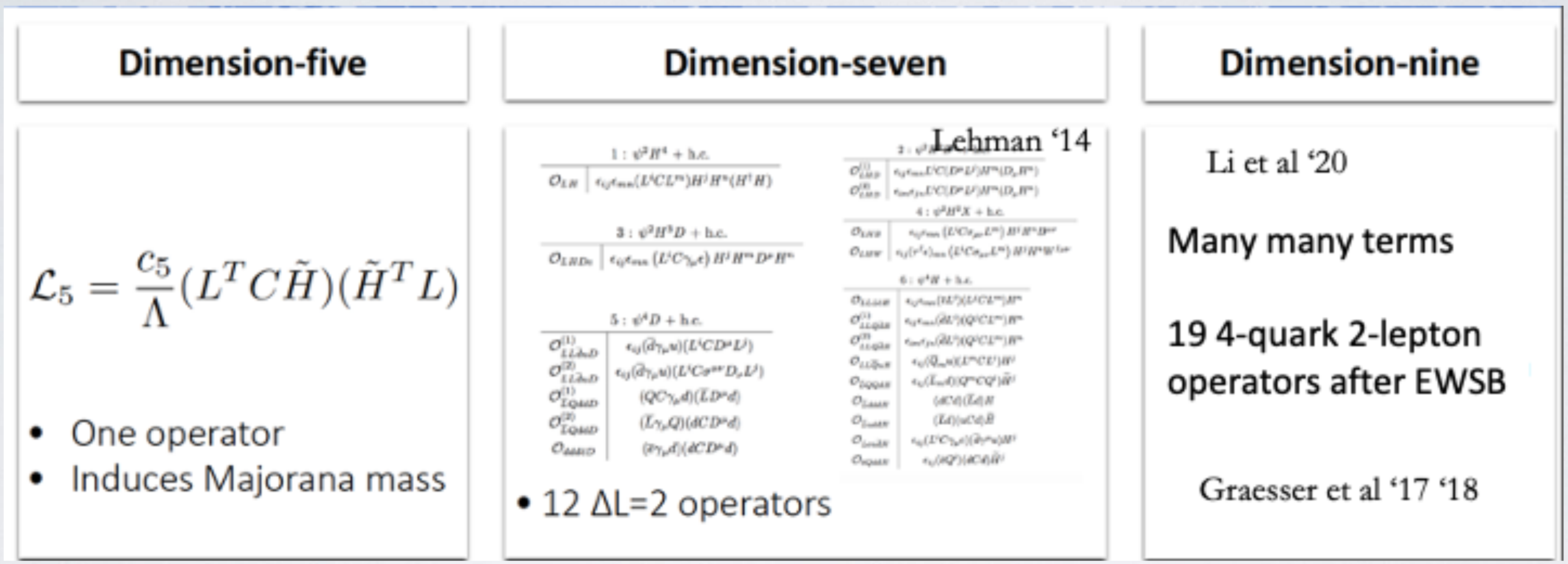


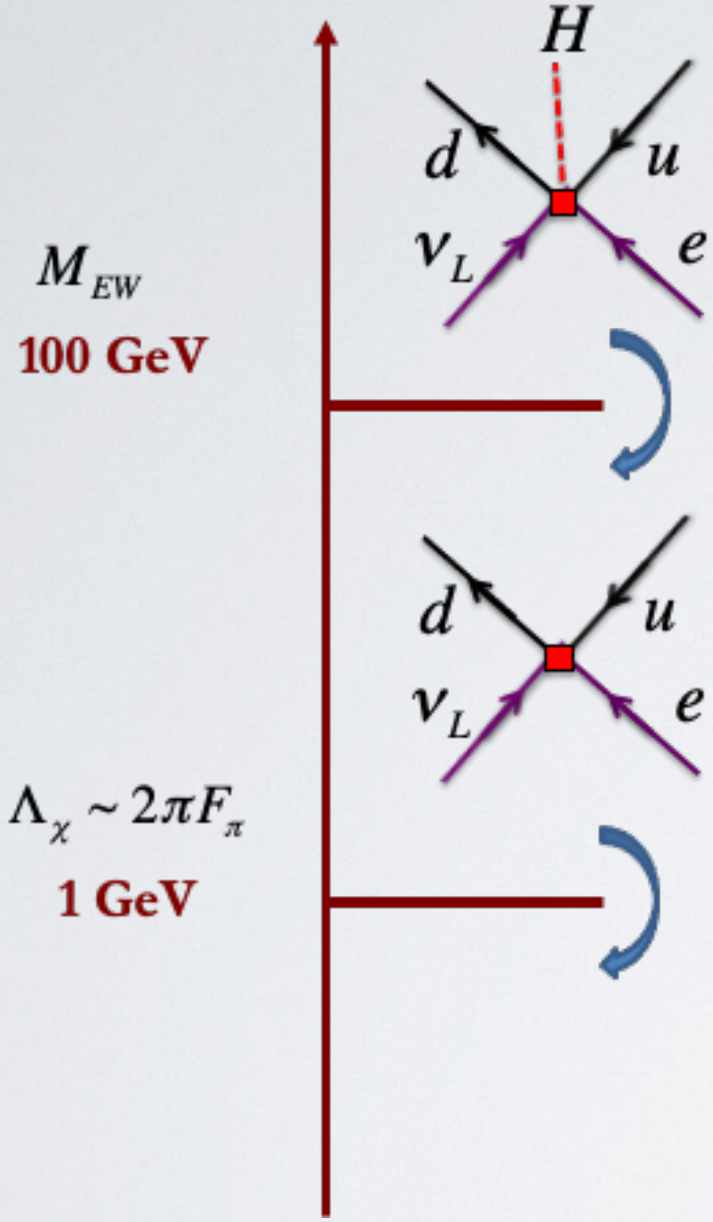
- Higher-dimensional terms only relevant if dim-5 operator are suppressed
- Example: in left-right symmetric models

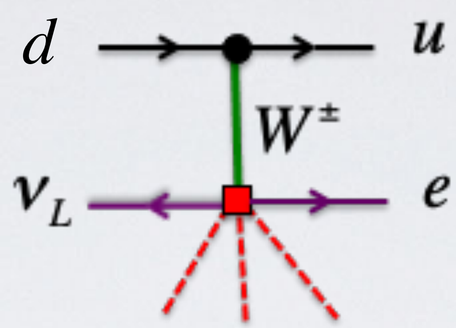
$$c_5 \sim y_e^2 \sim 10^{-10} \qquad c_7 \sim y_e^1 \sim 10^{-5} \qquad c_9 \sim y_e^0 \sim 1$$

- If scale is not too high: $$\frac{v^2}{\Lambda^2} \sim y_e \rightarrow \Lambda \simeq (10 - 100)\,\mathrm{TeV}$$

- **Dim-7 or dim-9 will dominate low-energy phenomenology !**

Example dim-7 operators



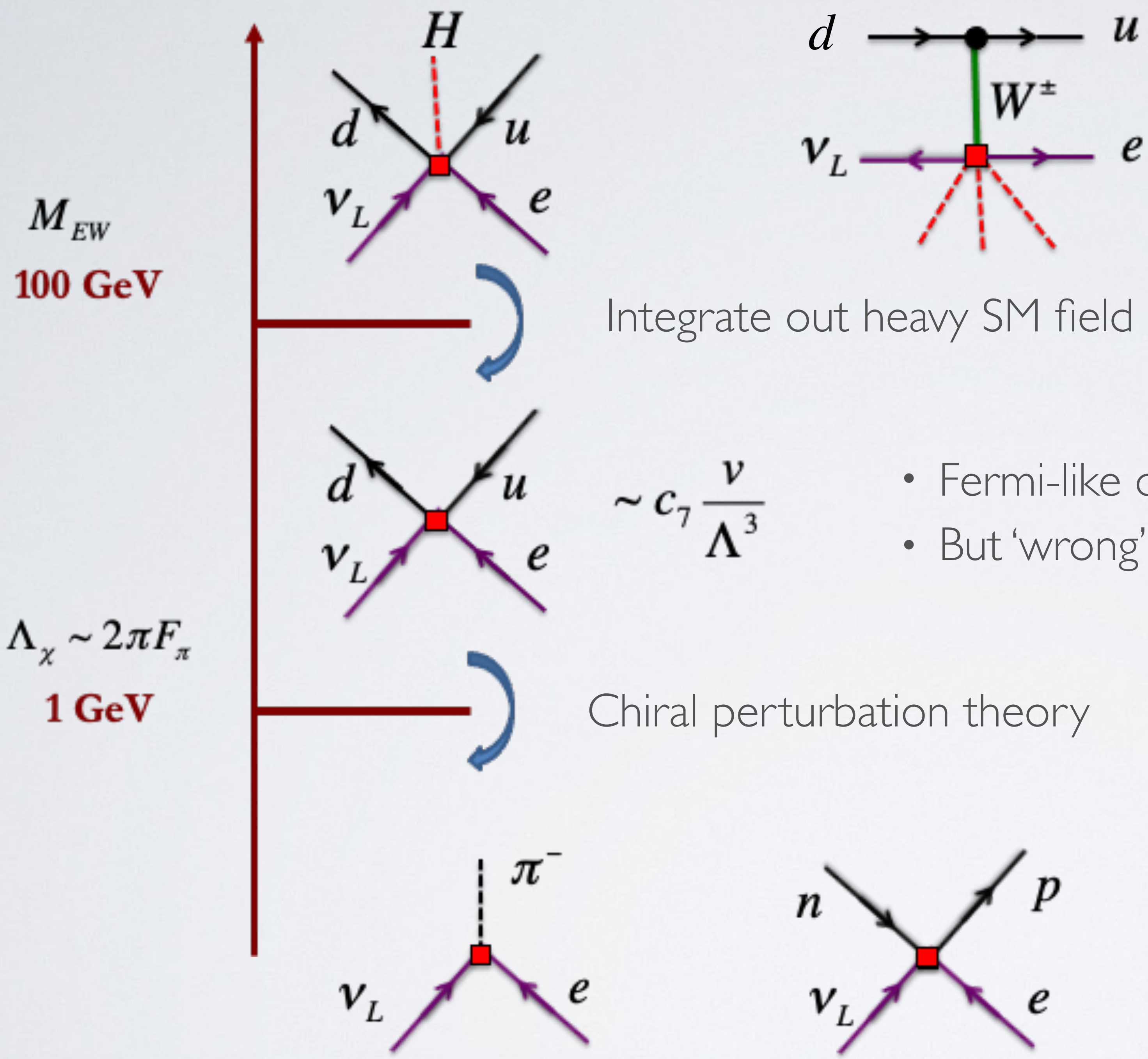


Integrate out heavy SM field and Higgs takes vev

$$\sim c_7 \frac{v}{\Lambda^3}$$

- Fermi-like operator (beta decay)
- But 'wrong' neutrino intstead of anti-neutrino

Example dim-7 operators



Integrate out heavy SM field and Higgs takes vev

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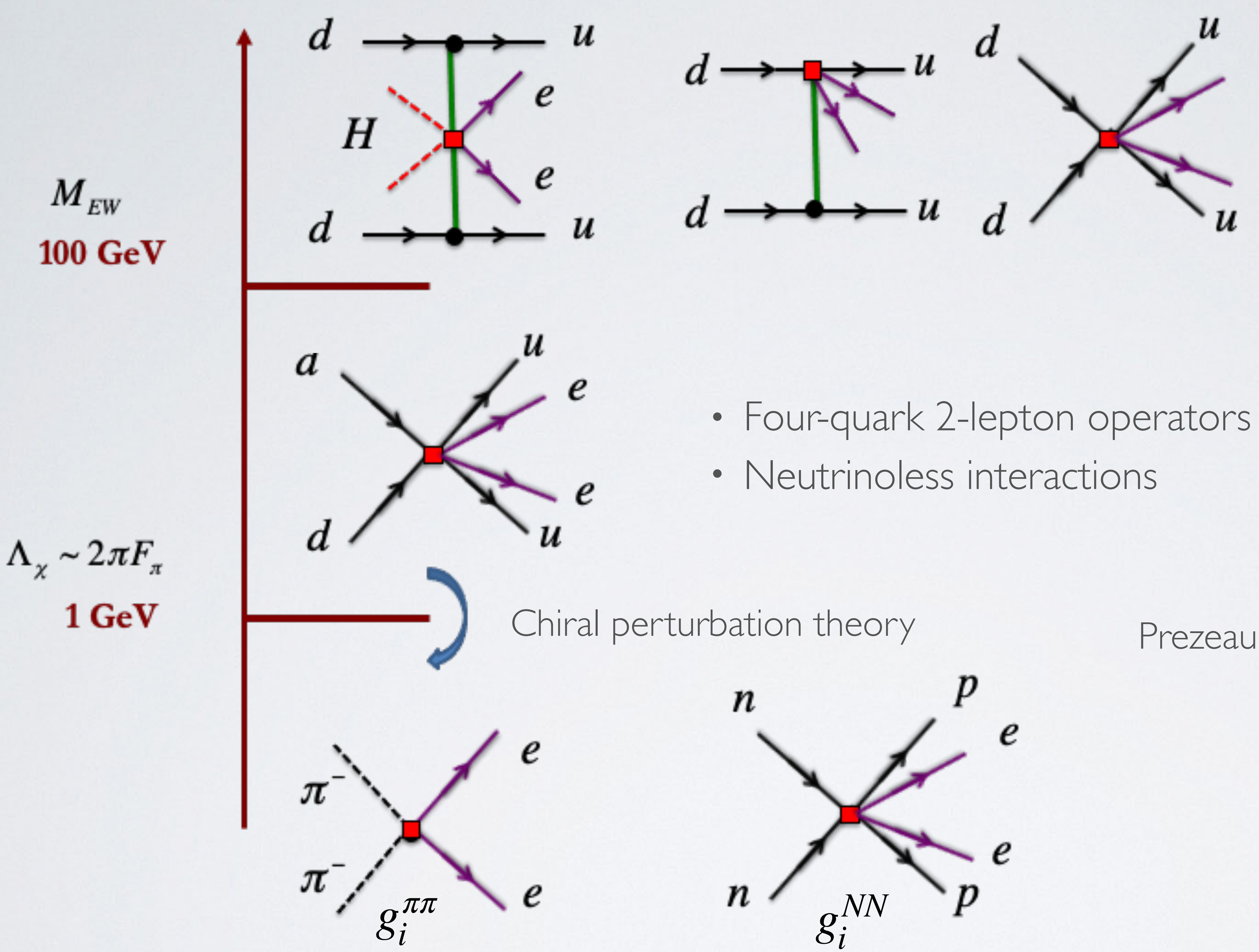
Chiral perturbation theory

Prezeau et al '03
Cirigliano et al '17 '18

Associated low-energy constants well known (nucleon charges $g_{A,S,T,V}$)

Example dim-9 operators



- Four-quark 2-lepton operators
- Neutrinoless interactions

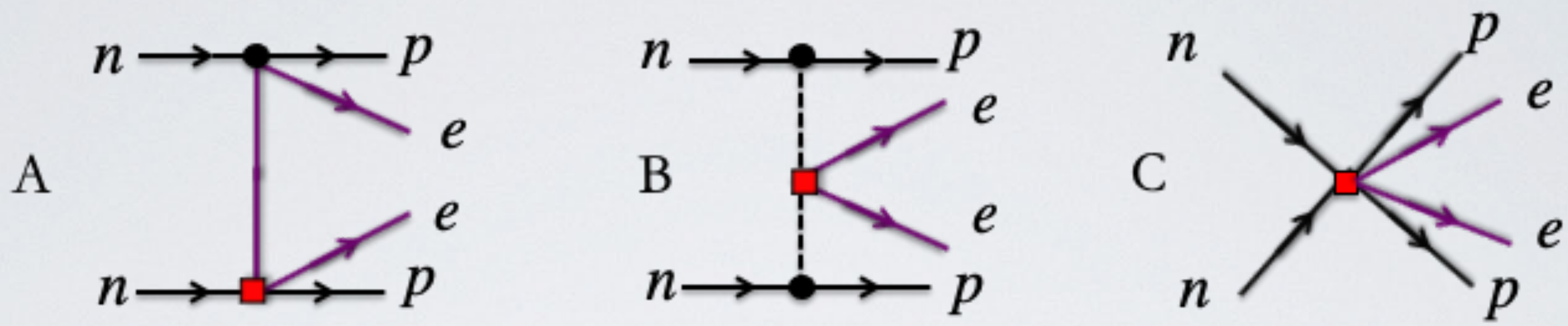
Prezeau et al ’03

- Pionic operators lead to leading-order neutrinoless double beta decay contributions !
- **Depend on four-quark matrix elements: great improvements by CalLat**

$$g_4^{\pi\pi} = -(1.9 \pm 0.2)\,\mathrm{GeV}^2 \qquad g_5^{\pi\pi} = -(8.0 \pm 0.6)\,\mathrm{GeV}^2$$

Nicholson et al ’18

New 0vbb topologies

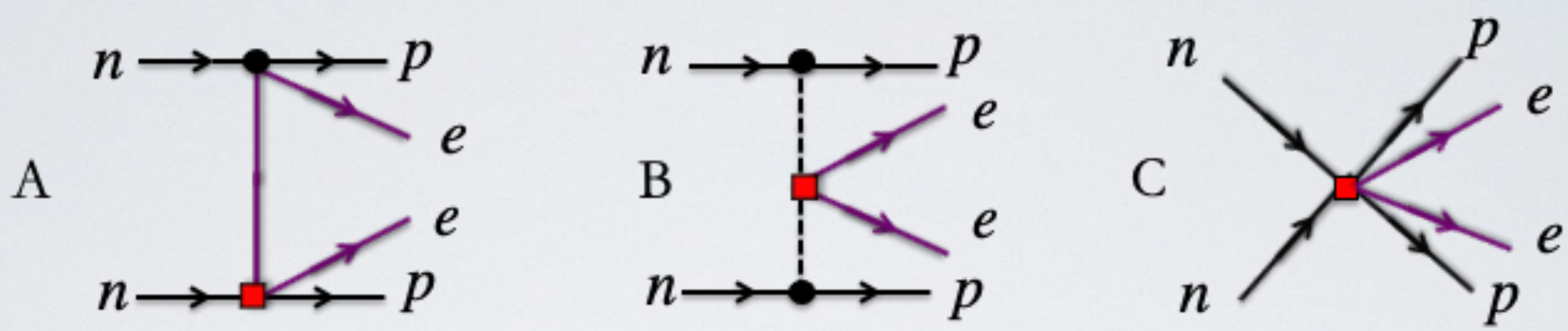


- Straightforward to calculate generalized 0vbb transition current

Cirigliano et al '17 '18

- Need additional nuclear matrix elements (NMEs)

New 0vbb topologies



- Straightforward to calculate generalized 0vbb transition current

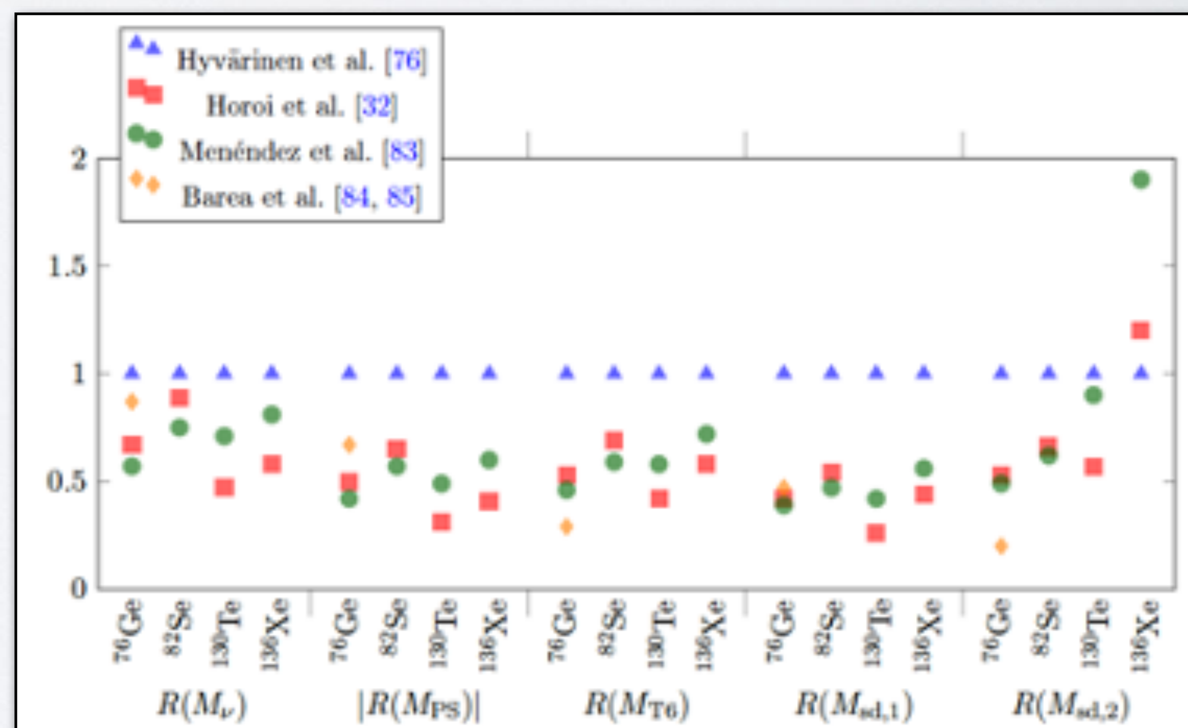
Cirigliano et al '17 '18

- Need additional nuclear matrix elements (NMEs)
- **At leading-order in Chiral-EFT: 15 NMEs (all in literature)**
- Similar uncertainties as before

NMEs	^{76}Ge [74]	[31]	[81]	[82,83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_T^{AA}	–	–	–	
M_T^{AP}	-0.35	0.01	-0.01	
M_T^{PP}	0.10	0.00	0.00	
M_T^{MM}	-0.04	0.00	0.00	

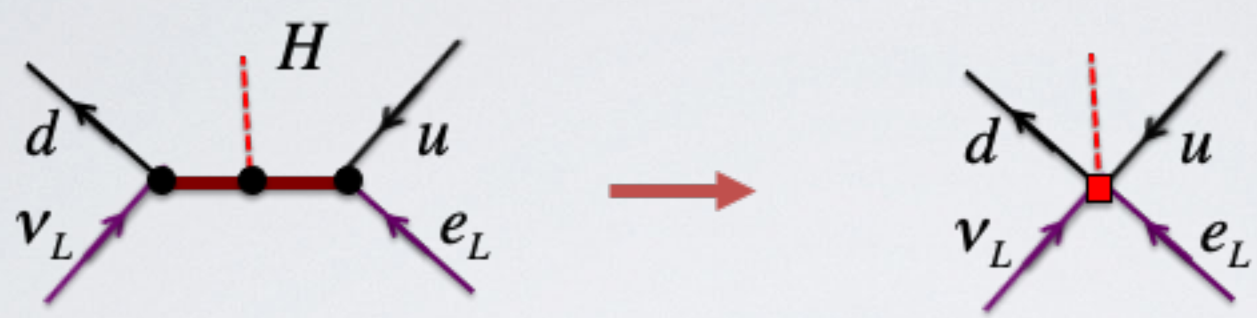
Hyvarinen/Suhonen '15
Menendez et al '17 '18
Barea et al '15 '18
Horoi/Neacsu '17

NMEs	^{76}Ge			
$M_{F,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,sd}^{PP}$	0.32	0.00	0.02	0.38



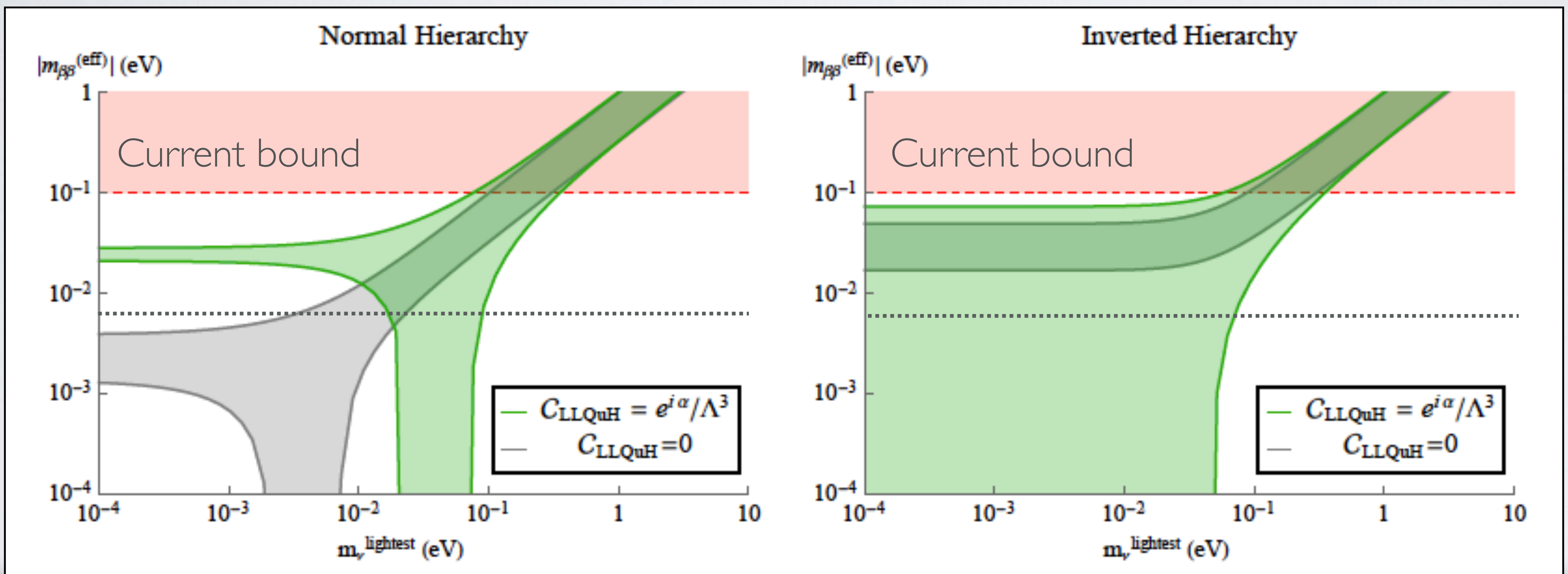
Using the framework/tool

- Example: a model of heavy leptoquarks with very large masses



$$C_7 \sim \frac{1}{\Lambda^3}$$

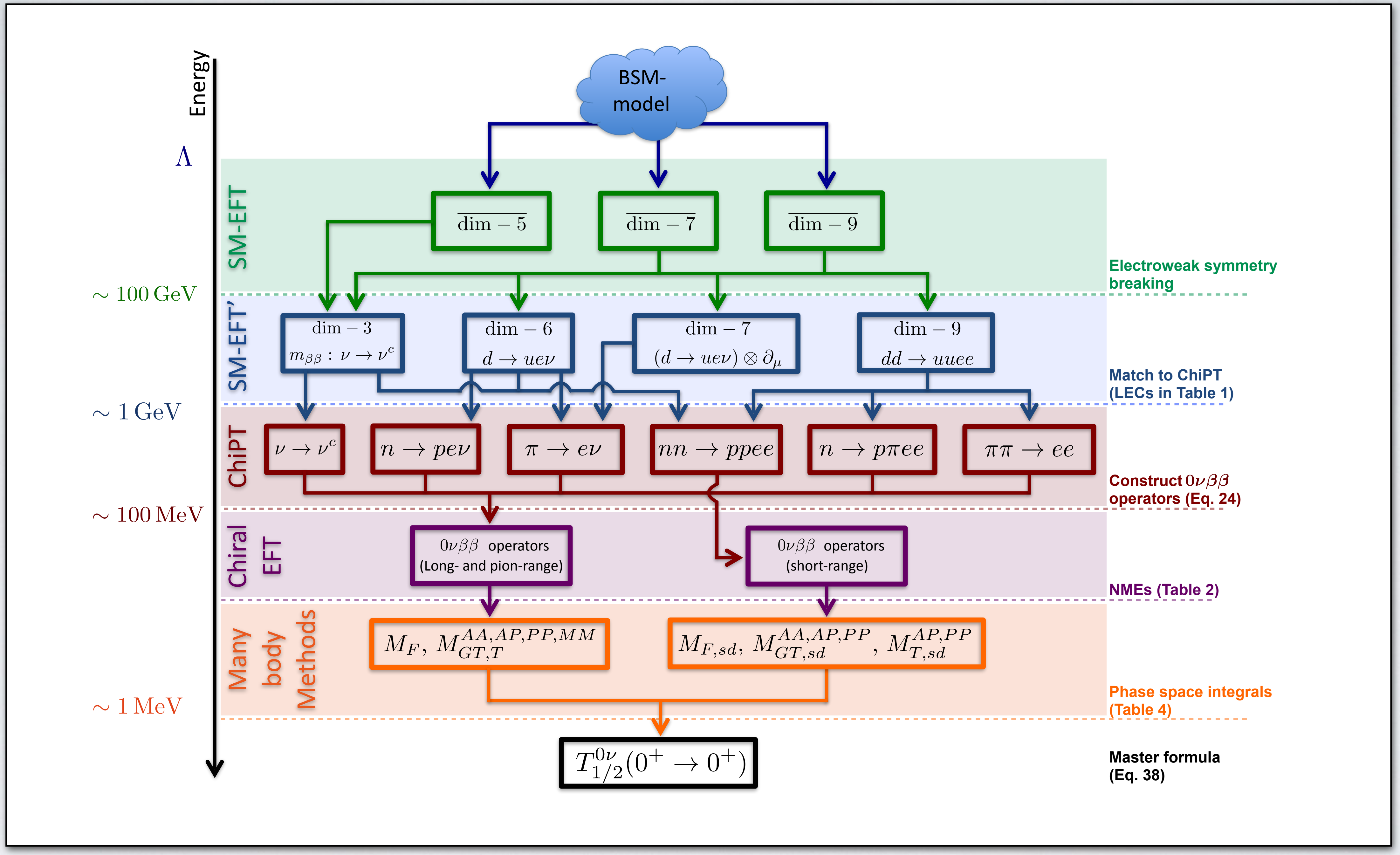
$$\Lambda = 400\ \text{TeV}$$



Ton-scale expectations

- **0vbb probes dim-7 operators at few hundred TeV**

The 0vbb metro map



- Open-access Phyton tool (***NuDoBe***) that automizes all of this in SM-EFT framework

download: https://github.com/OScholer/nudobe
online tool: https://oscholer-nudobe-streamlit-4foz22.streamlit.app/

Scholer, Graf, JdV' 23

Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?
- Example: ratios of decay rates of various isotopes

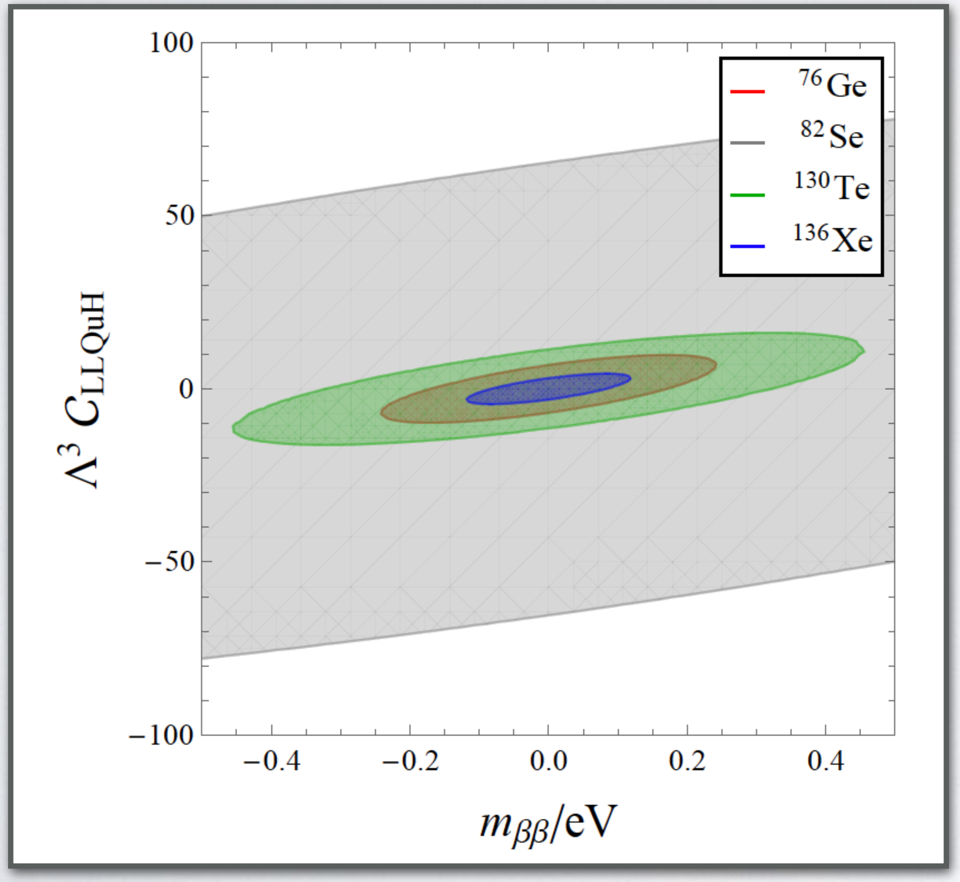
Deppisch/Pas '07, Lisi et al '15, Graf/Scholer '22

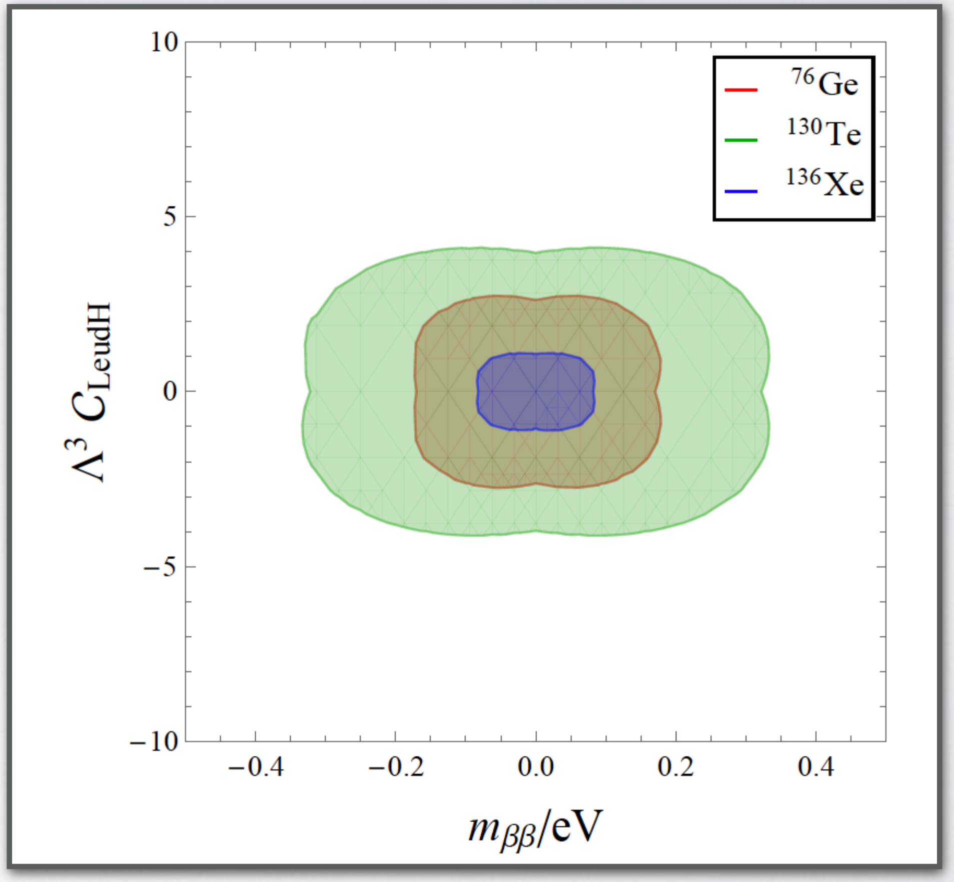
Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?
- Example: ratios of decay rates of various isotopes

Deppisch/Pas '07, Lisi et al '15

- **Unfortunately, different isotopes not too discriminating**
- Ratios suffer from nuclear/hadronic uncertainties

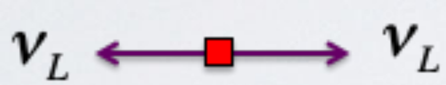


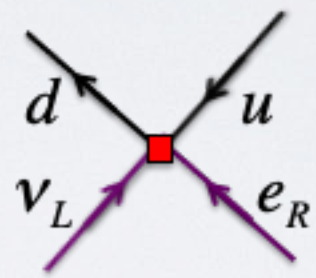


Disentangling the source of LNV

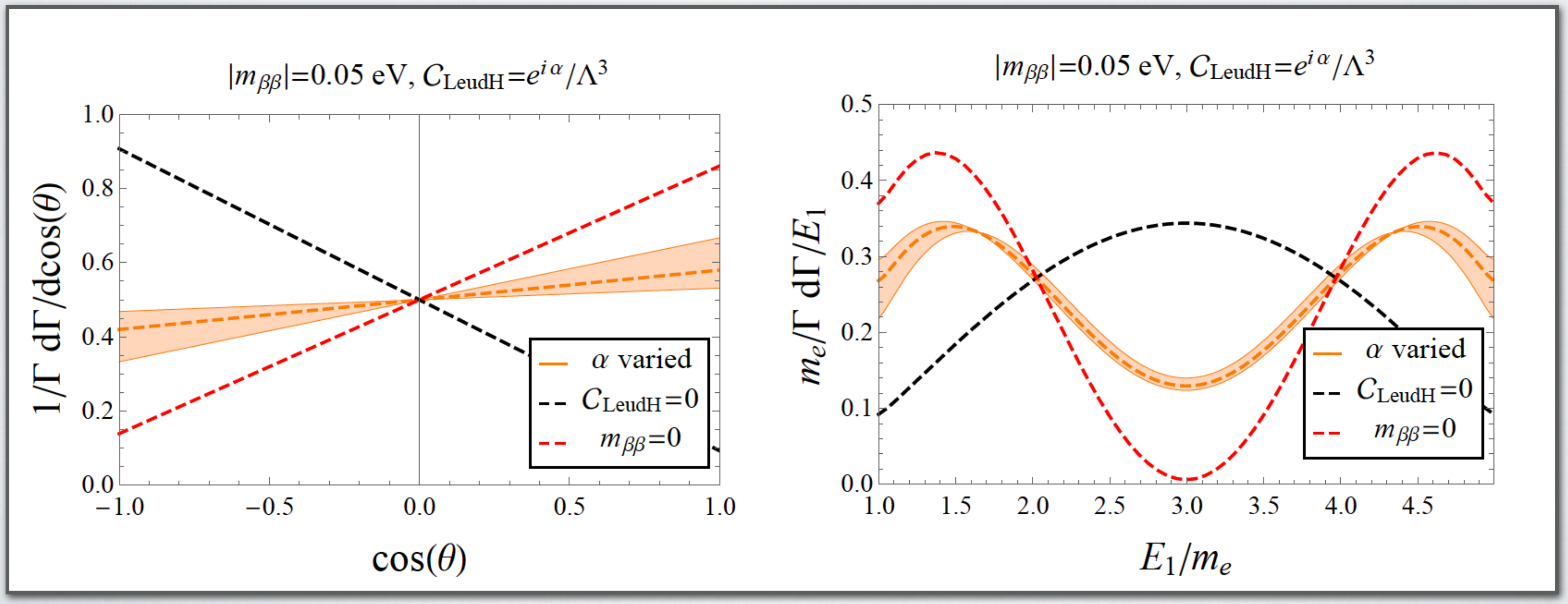
- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?

- **One could in principle measure angular&energy electron distributions**



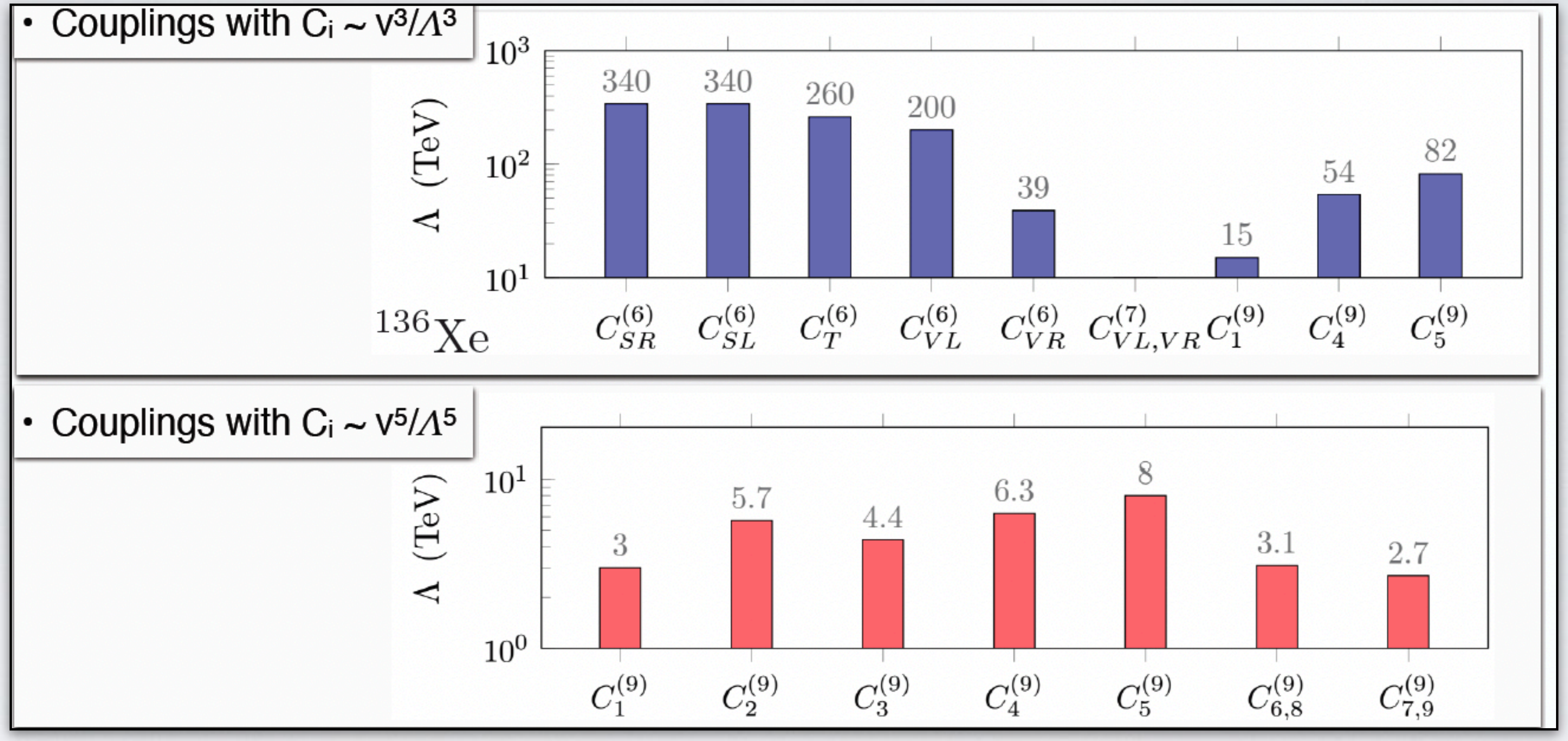


$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$ $\Lambda \sim 50\,\mathrm{TeV}$



Take-aways

- 0vbb very sensitive to new sources of L violation. Dim-5 operator up to GUT scales !



- But only in the electron-electron channel! No phase space to produce muons or tauons
- Other flavors can be tested in complementary experiments. Examples:

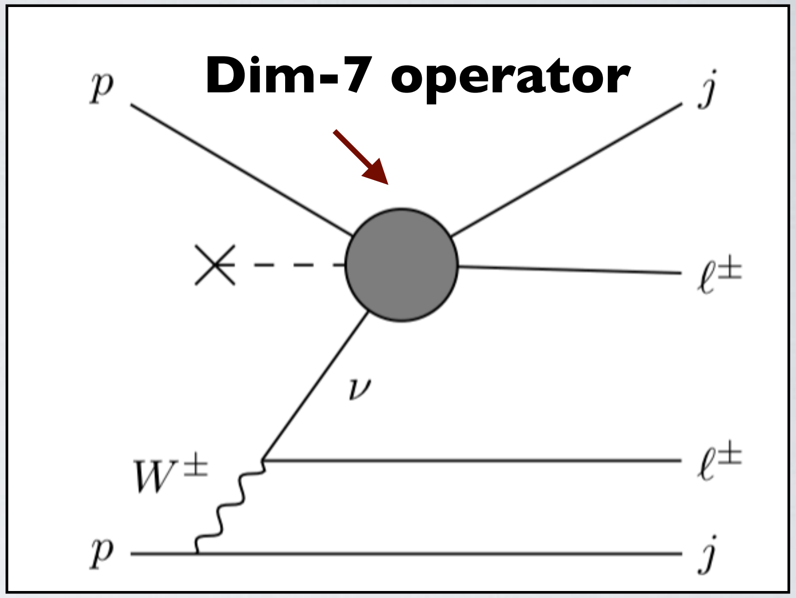
$$K^- \to \pi^+ + \mu^- + \mu^- \qquad pp \to \mu^+ + \mu^+ + \text{jets}$$

$$\mu^- + X(Z,N) \to e^+ + Y(Z-2,N+2)$$

Complementary probes

- Recent study of such probes by Fridell, Graf, Harz, Hati '23
- LNV at LHC or future colliders

$$pp \to \mu^+ + \mu^+ + \text{jets}$$



Operator	$\sigma(pp \to \mu^\pm\mu^\pm jj)$ (pb)		Λ_{LNV} [TeV]	$\Lambda_{\text{LNV}}^{\text{future}}$ [TeV]
	LHC	FCC		
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.1	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.68	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	0.86	4.3
$\mathcal{O}_{\bar{d}LueH}$	5.7×10^{-5}	0.035	0.84	4.5
$\mathcal{O}_{\bar{d}uLLD}$	0.64	210	4.0	19
$\mathcal{O}_{LDH2}$	2.7×10^{-12}	1.7×10^{-10}	0.050*	0.18
$\mathcal{O}_{LDH1}$	1.9×10^{-5}	0.061	0.69	4.9
$\mathcal{O}_{LeHD}$	1.2×10^{-8}	3.1×10^{-8}	0.21*	0.44
$\mathcal{O}_{LH}$	1.5×10^{-8}	2.0×10^{-6}	0.21*	0.87

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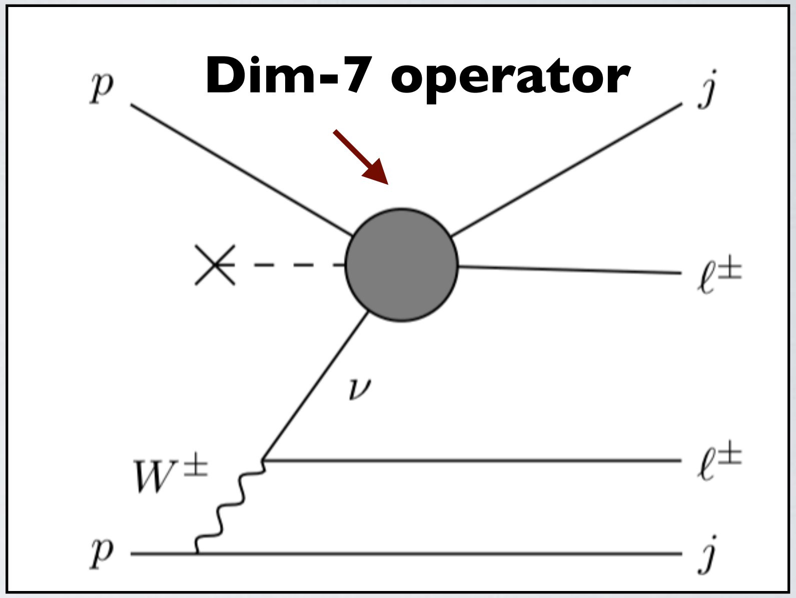
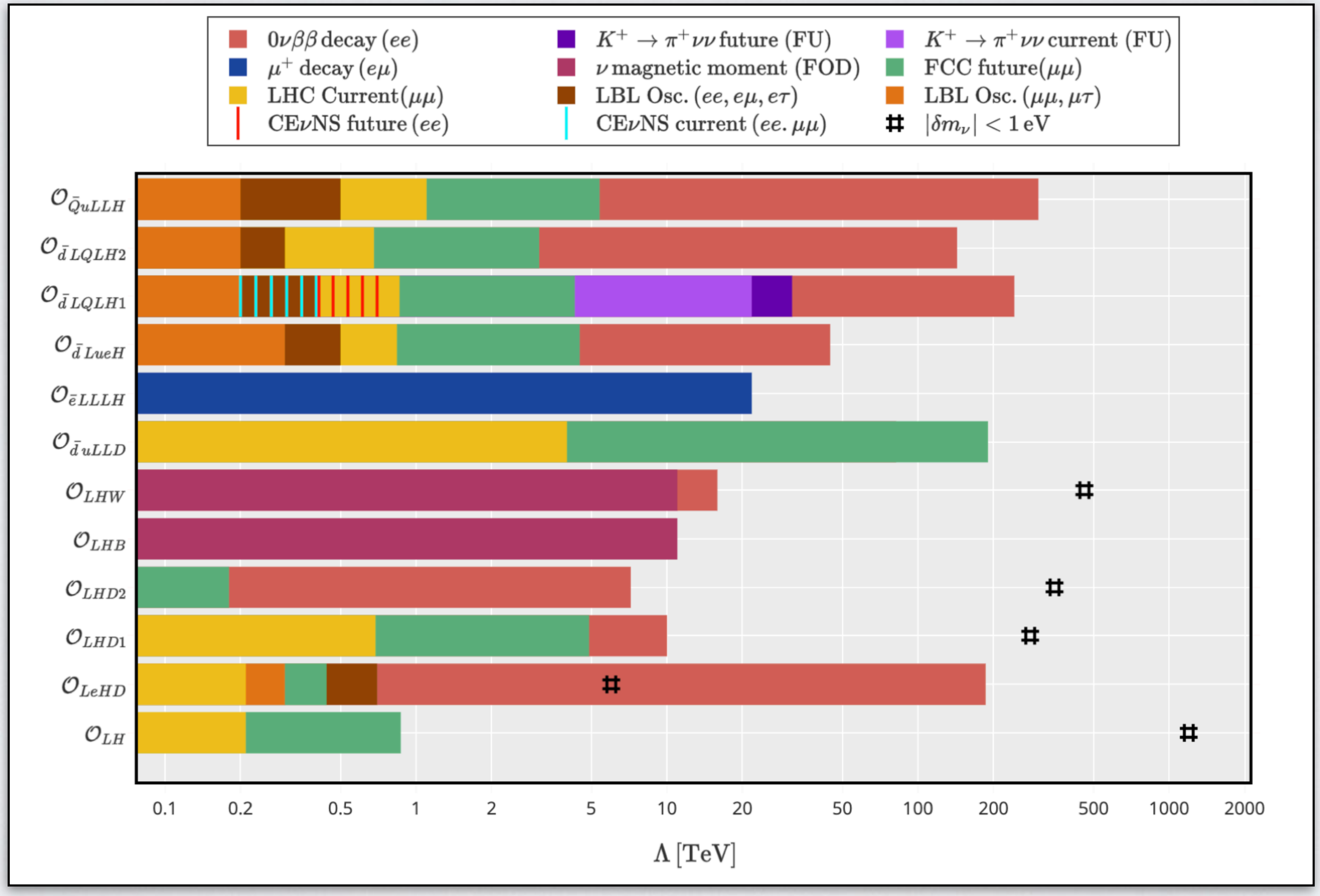


$$pp \to \mu^+ + \mu^+ + \text{jets}$$



Beyond effective field theory

- EFT methods do not work in case of new light degrees of freedom
- Good example are sterile neutrinos

Beyond effective field theory

- EFT methods do not work in case of new light degrees of freedom
- Good example are sterile neutrinos

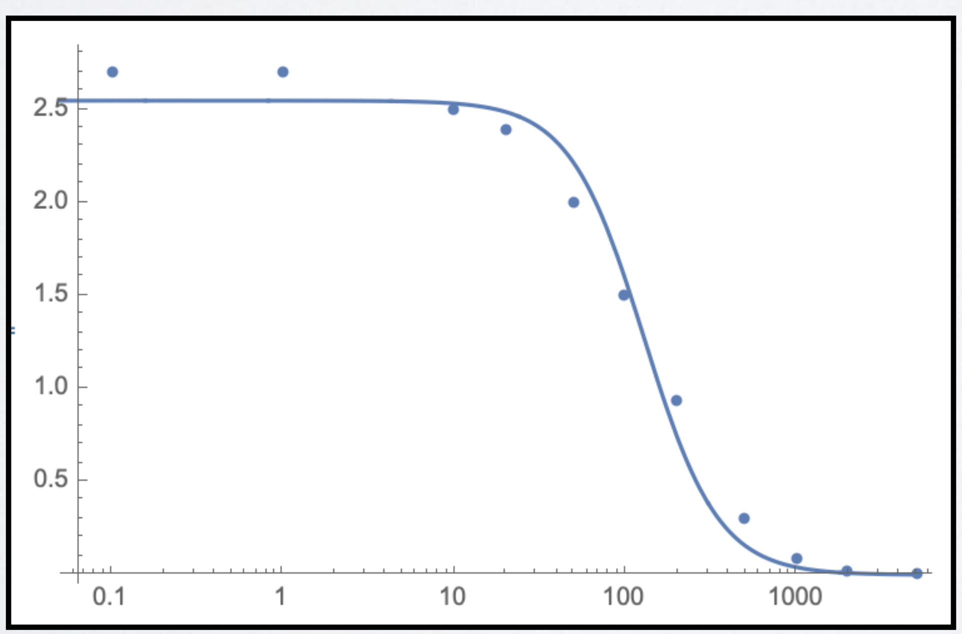
eV **keV** **MeV** **GeV** **TeV** **.....** **10^{15} GeV** **M_R ?**

What about here ?

- For masses below a GeV, the sterile neutrinos become explicit degrees of freedom

$$|M_{0\nu}(m_R)|^2 = |\langle 0^+ | V_\nu(m_R) | 0^+ \rangle|^2$$

$M(m_4)$



$m_4(\mathrm{MeV})$

Shell model Xe (Menendez)

$$M(m_4) \sim \frac{1}{\langle p^2 \rangle + m_4^2}$$

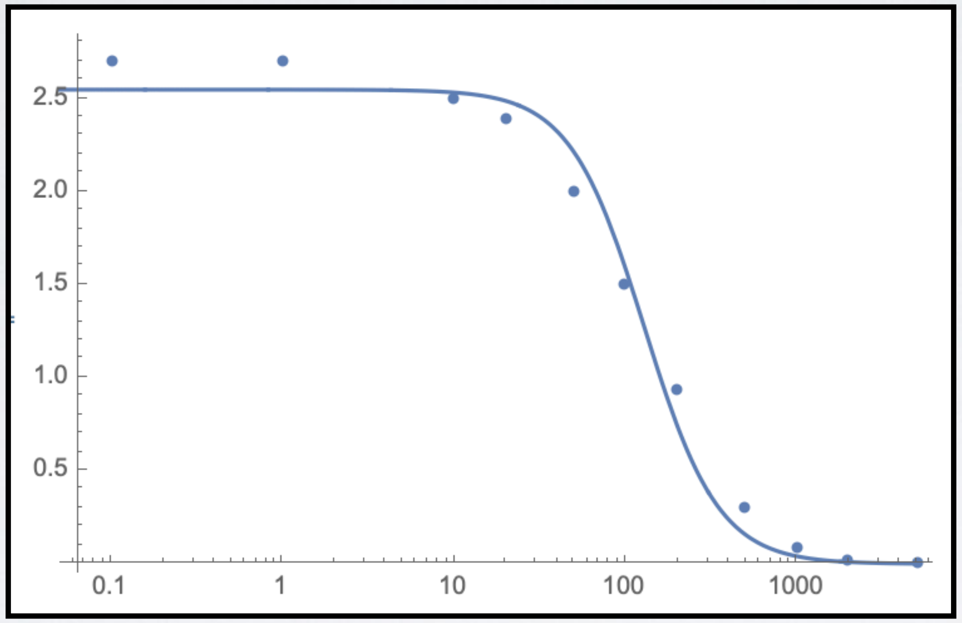
$$\langle p^2 \rangle \simeq (100\,\mathrm{MeV})^2$$

Current procedure in literature

- Compute nuclear matrix element computations for different neutrino masses

$M(m_4)$

Shell model Xe (Menendez)



$m_4(\mathrm{MeV})$

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$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \gg 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \frac{U_{e4}^2}{m_4}$$

$m_4 \ll 100\,\mathrm{MeV}$

$$A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle}$$

Revisit the light regime

$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \ll 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \mathcal{O}\left(\frac{m_i^3}{\langle p^2 \rangle^2} \right)$$

- The first term depends on $\sum_{i=1}^{4} U_{ei}^2 m_i = M_{ee}$

$$M = \begin{pmatrix} 0 & v y_\nu \\ v y_\nu & M_R \end{pmatrix}$$

Revisit the light regime

$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \ll 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \mathcal{O}\left(\frac{m_i^3}{\langle p^2 \rangle^2} \right)$$

- The first term depends on $\sum_{i=1}^{4} U_{ei}^2 m_i = M_{ee} = 0$ $\quad M = \begin{pmatrix} 0 & v y_\nu \\ v y_\nu & M_R \end{pmatrix}$
- **The 'GIM' mechanism for neutrinos !** (only valid if all steriles are light)
- The amplitude is strongly suppressed $A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i^3$ Blennow et al '10 JHEP

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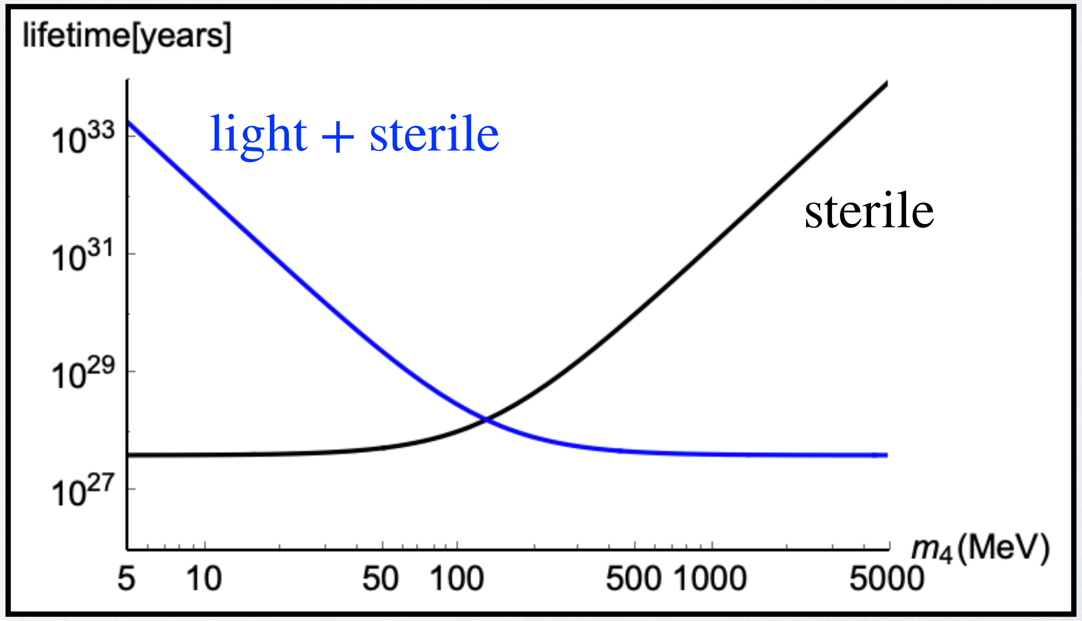
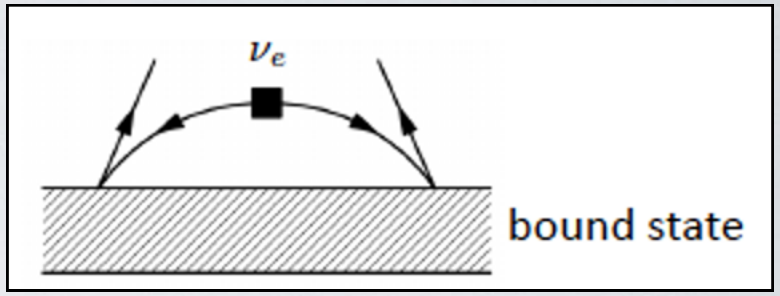
- The amplitude is strongly suppressed $A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i^3$ Blennow et al '10 JHEP
- Example in 3+1model
- Cancellation between light + sterile contributions leads to

$$\tau_{1/2} \sim m_4^4$$



Light extra neutrinos

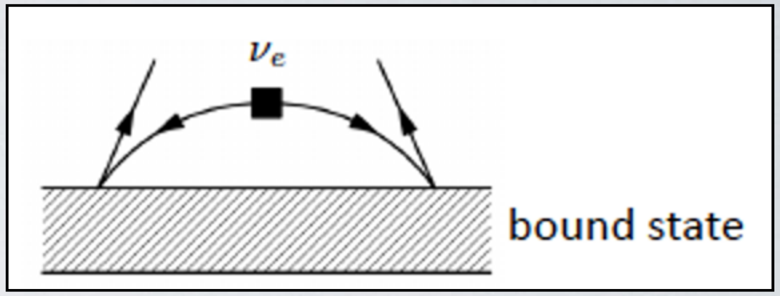


- Is there a way to avoid the GIM mechanism ?
- There are additional contributions from ‘ultra-soft’ neutrinos

$$\sum_n \langle f | J_\mu | n \rangle \langle f | J^\mu | i \rangle \times \int \frac{d^3k}{(2\pi)^3} \frac{1}{E_\nu [E_\nu + (E_n - E_0) - i\epsilon]} \qquad E_\nu = \sqrt{k^2 + m_i^2}$$

- The neutrinos see the nucleus as a whole and becomes sensitive to nuclear structure effects
- Depends on nuclear excited states. Normally these are tiny effects (5%)
- But become dominant in the GIM mechanism ! $\sim U_{ei}^2 m_i^3$

Light extra neutrinos



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- But become dominant in the GIM mechanism ! $\sim U_{ei}^2 m_i^3$
- For m4 ~ MeV we get new contributions $\sim U_{ei}^2 m_i^2$
- For m4 << MeV we get new contributions $\sim U_{ei}^2 m_i^3 \log \frac{(E_n - E_0)^2}{m_i^2}$
- These effects are not yet considered usual analysis of neutrinoless double beta decay

Light extra neutrinos

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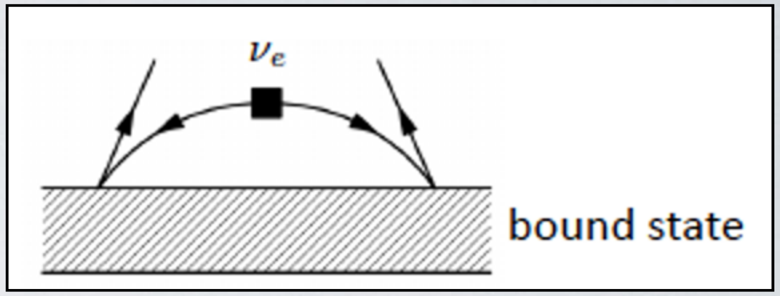
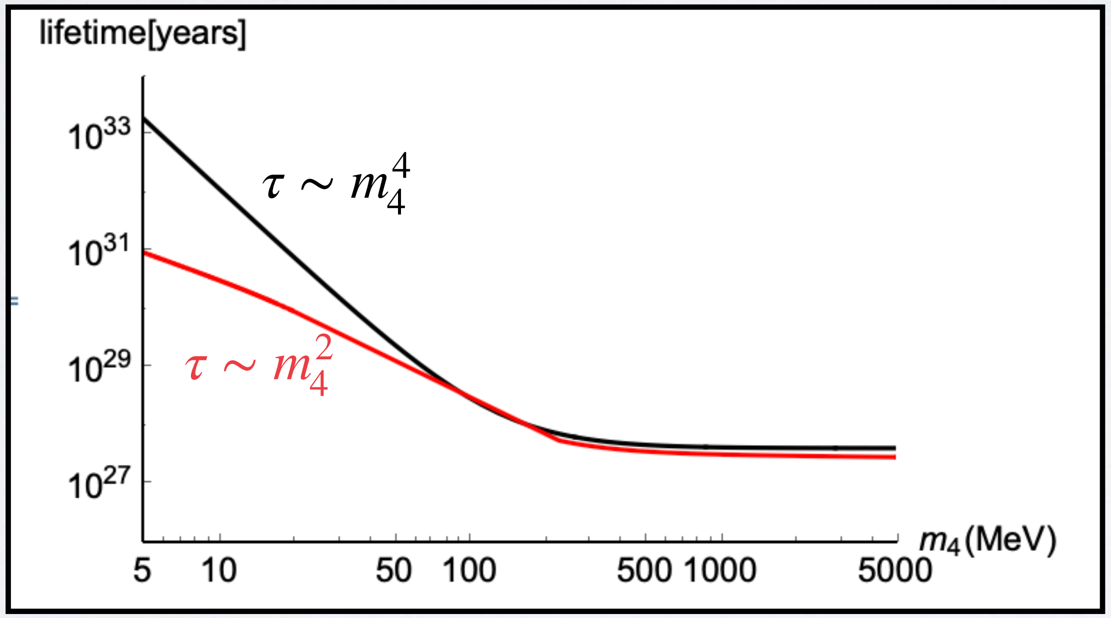
- There are additional contributions from 'ultra-soft' neutrinos



$$\sum_n \langle f|J_\mu|n\rangle\langle f|J^\mu|i\rangle \times \int \frac{d^3k}{(2\pi)^3}\frac{1}{E_\nu[E_\nu + (E_n - E_0) - i\epsilon]} \qquad E_\nu = \sqrt{k^2 + m_i^2}$$



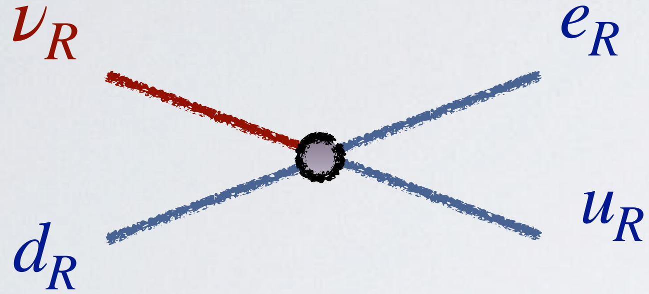
100x larger decay rates

Still small ;)

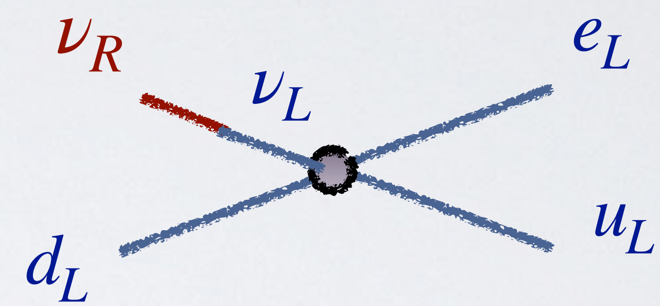
- Can play a role in realistic models 3+2 in linear/inverse seesaw
- Work in progress is to connect this models of leptogenesis

Non-sterile sterile neutrinos ?

- In various interesting scenarios sterile neutrinos only look sterile at low energies
- In left-right symmetric models: right-handed neutrinos charged under $SU_R(2)$



$$\sim \left(\frac{1}{M_{W_R}}\right)^2$$



$$\sim \left(\frac{1}{M_{W_L}}\right)^2 \sqrt{\frac{m_\nu}{m_R}}$$

- For allowed right-handed scales (M_{WR} > 5 TeV) this can lead to much larger interactions
- For GeV sterile states, non-standard interactions relevant up to

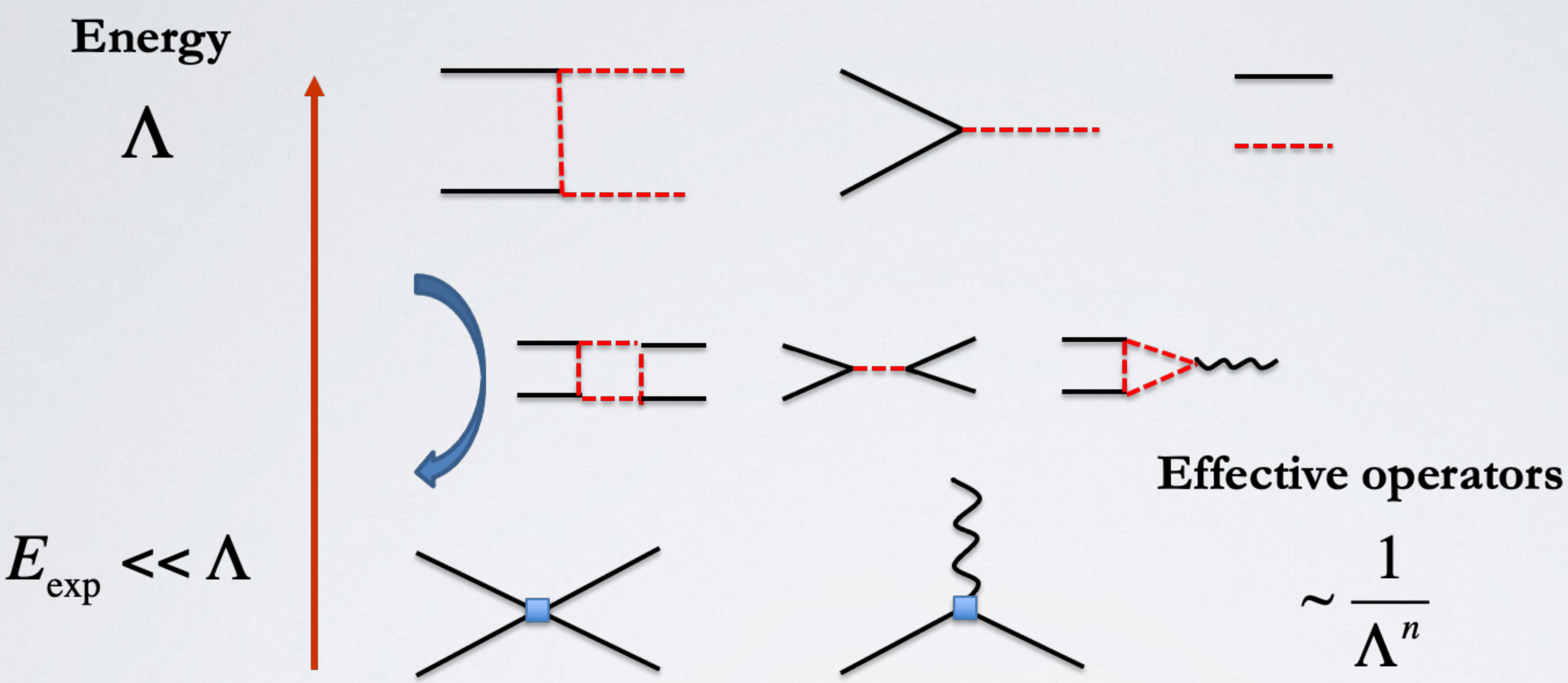
$$M_{W_R} \sim M_{W_L} \left(\frac{m_R}{m_\nu}\right)^{1/4} \sim 50\,\mathrm{TeV}$$

- This also happens in for instance Leptoquark scenarios and can even used in solutions to anomalies such as muon g-2 or flavor anomalies (not today)

e.g. Ruiz, JdV et al '21 e.g. Azatov, Barducci et al '18

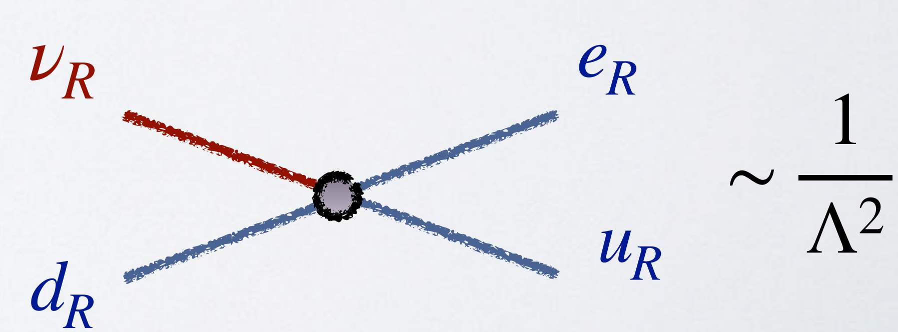
Effective field theory

- Assume that non-standard interactions from decoupled sector



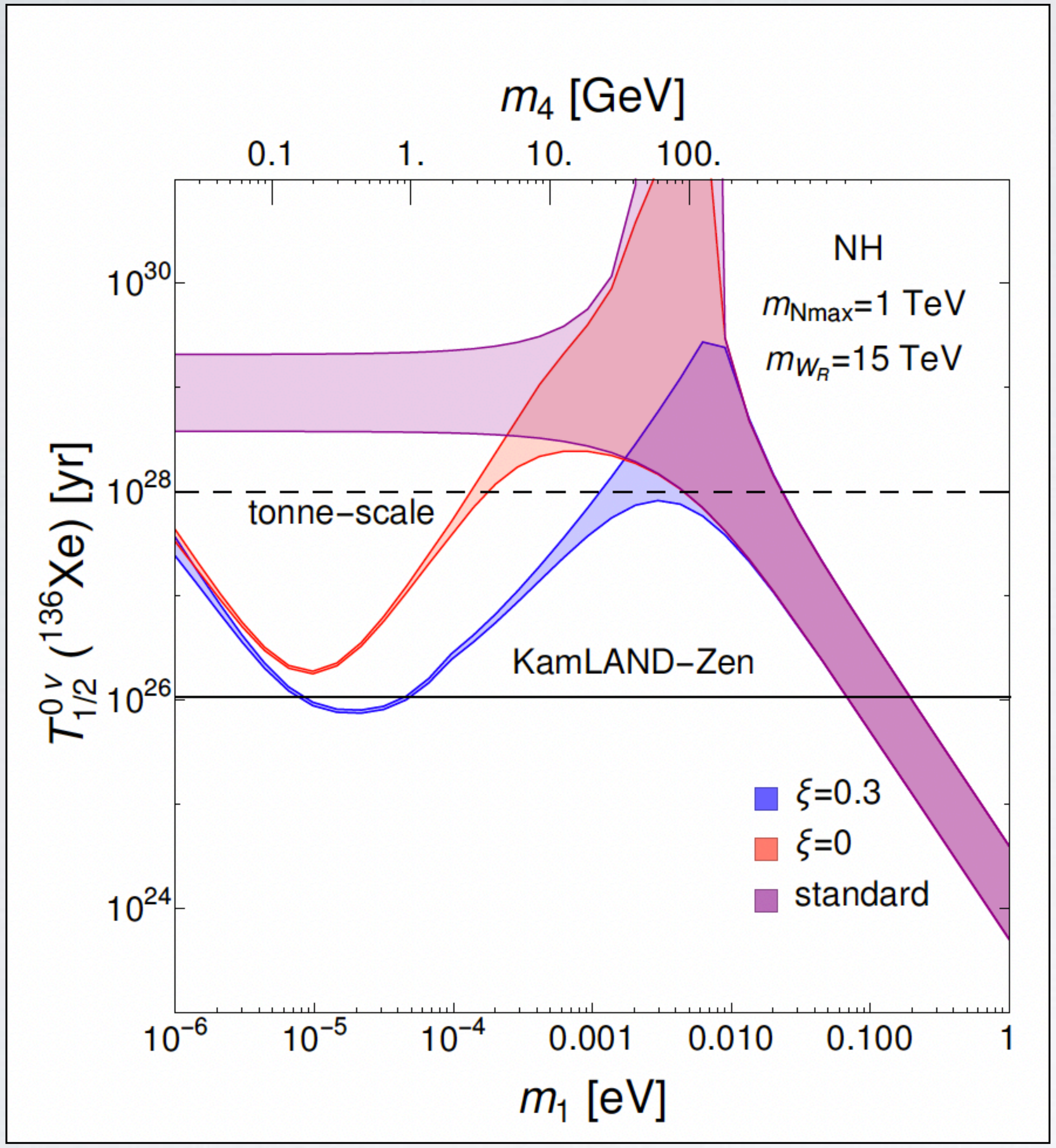
- Extend Standard Model EFT to include right-handed singlets: **nu**SMEFT

Class 1	$\psi^2 H^3$	Class 4	ψ^4
$\mathcal{O}^{(6)}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}^{(6)}_{du\nu e}$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$
Class 2	$\psi^2 H^2 D$	$\mathcal{O}^{(6)}_{Qu\nu L}$	$(\bar{Q}u)(\bar{\nu}_R L)$
$\mathcal{O}^{(6)}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger i D_\mu H)$	$\mathcal{O}^{(6)}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d))$
Class 3	$\psi^2 H^3 D$	$\mathcal{O}^{(6)}_{LdQ\nu}$	$(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}^{(6)}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$		



An example: mLRSM + light right-handed neutrinos

Li, Ramsey-Musolf, Vasquez PRL '20
JdV, Li, Ramsey-Musolf, Vasquez '22



$$M_{W_R} \simeq 15\,\text{TeV}$$

$$M_N(\text{light}) \in (0.1 - 1000)\,\text{GeV}$$

$$\xi \sim W_L - W_R\,\text{mixing}$$

Normal Hierarchy

- Large enhancements possible for 0vbb for parameter space not excluded elsewhere.
- Unfortunately, this is not automized yet although all formulae exist.
- Automizing more complicated due to more 'user input' (sterile masses + mixing)
- If someone is interested in helping out….

Feather-weight neutrinos

- **See-saw (variants) can work for essentially any right-handed scale**

- For masses below a GeV, the 0vbb matrix elements become mass dependent

$$|M_{0\nu}(m_R)|^2 = |\langle 0^+|V_\nu(m_R)|0^+\rangle|^2$$

Obese neutrinos

- **See-saw (variants) can work for essentially any right-handed scale**

- For $m_R \geq 50$ TeV or so, we'll **not be able to produce them this century**

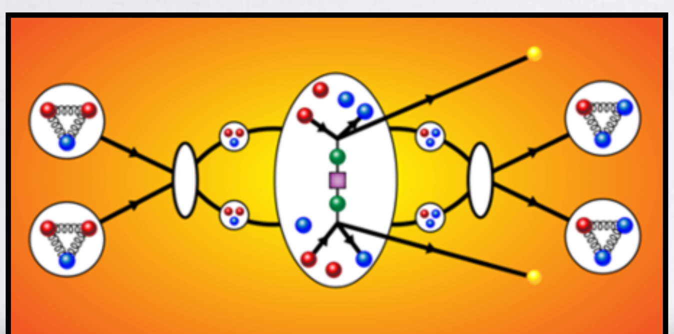
- **But good chance to see their quantum effects if they exist !!**

Summary and outlook

- Neutrino masses requires an explanation !!
- Good motivation for sterile neutrinos (also leptogenesis) but mass range unclear

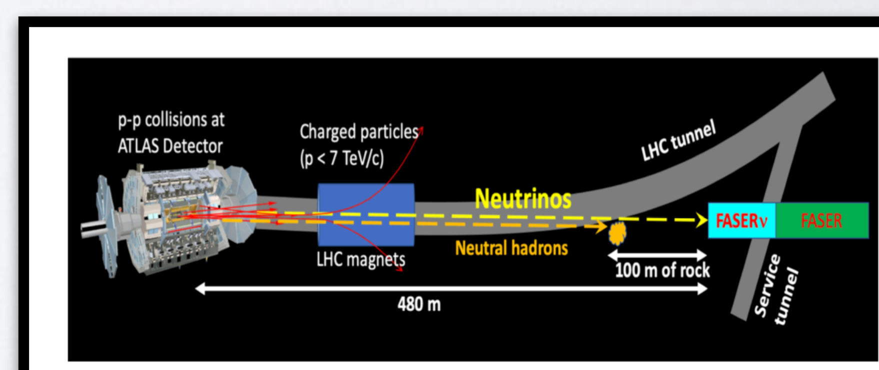
eV keV MeV GeV TeV ..... 10^{15} GeV → **M_R ?**

- **Excellent experimental prospects for large chunk of mass range**
- Neutrinoless double beta decay important for entire mass range



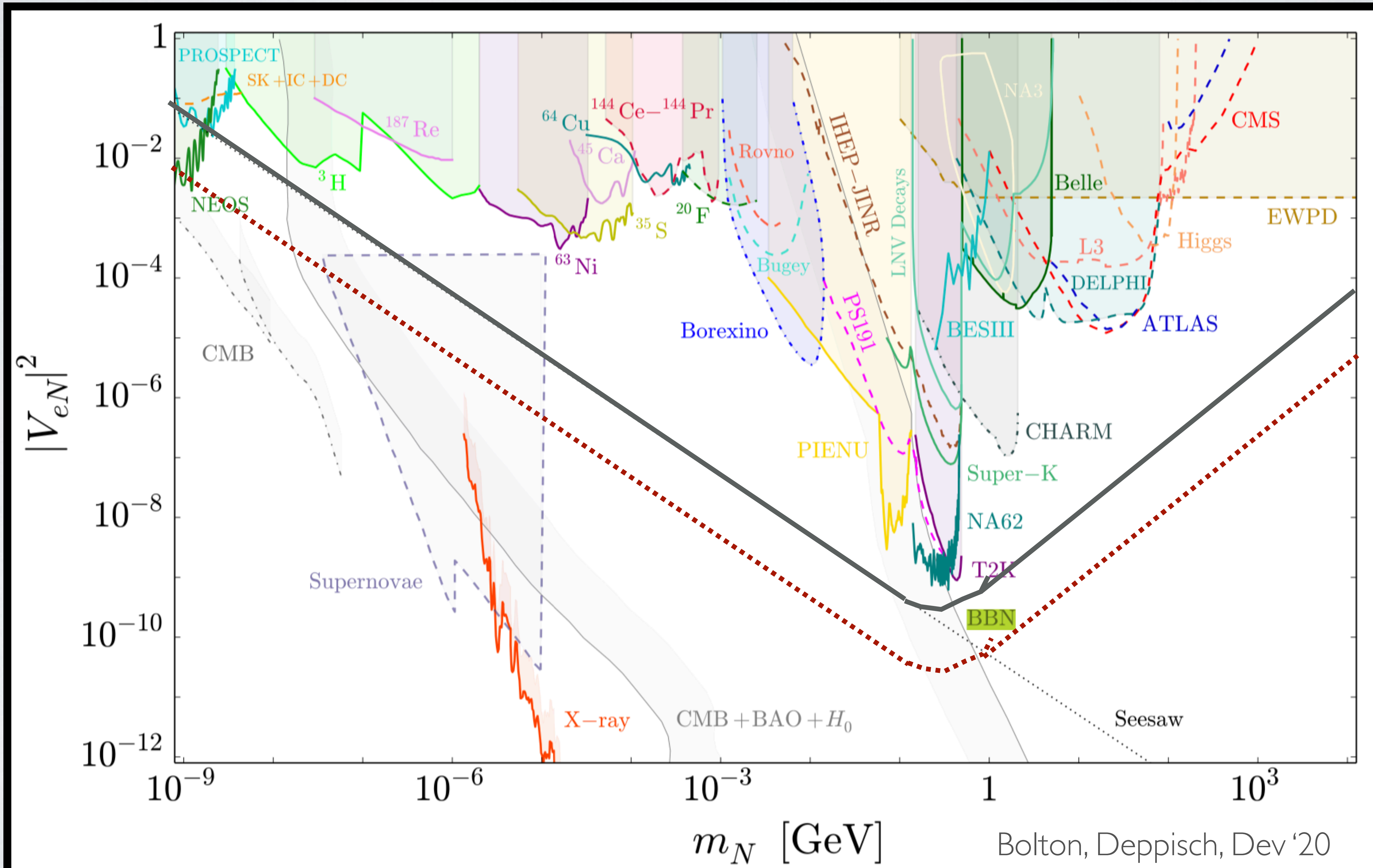
- **Exciting experimental program**
- Theory improvements needed but good progress last 5 years
- There is an end goal !

- **Great activity to find long-lived particles**
- We can detect sterile neutrinos at LHC and DUNE and other experiments (beta decay, oscillations)
- Unfortunately only in relative small mass range



Backup

Naive 0vbb limits



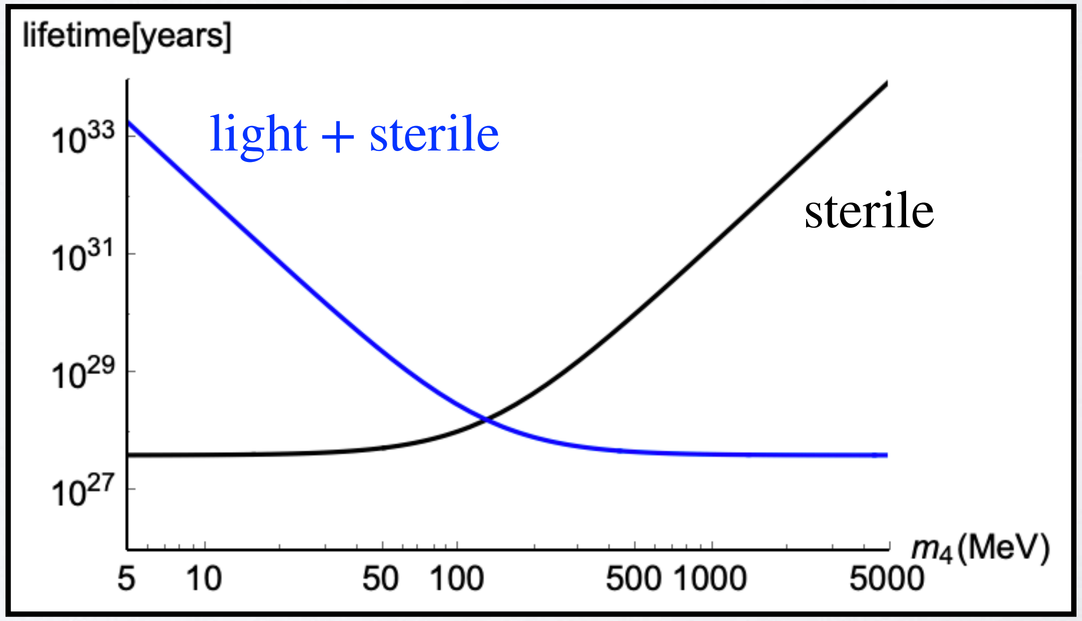
- Bounds can be weakened by considering **pseudo-Dirac** sterile neutrino pairs

Revisit the light regime

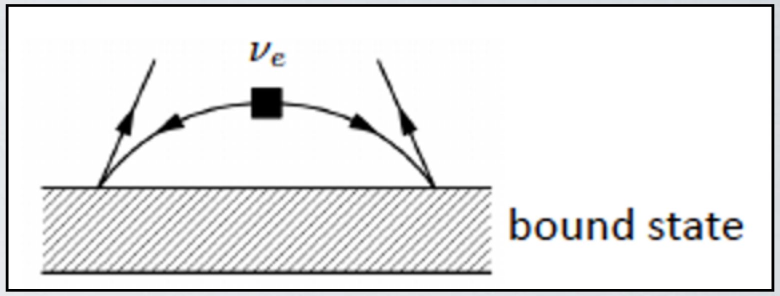
$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \ll 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \mathcal{O}\left(\frac{m_i^3}{\langle p^2 \rangle^2}\right)$$

- The first term depends on $\sum_{i=1}^{4} U_{ei}^2 m_i = M_{ee} = 0$ $\qquad M = \begin{pmatrix} 0 & v y_\nu \\ v y_\nu & M_R \end{pmatrix}$
- **The 'GIM' mechanism for neutrinos !** (only valid if all steriles are light)
- The amplitude is strongly suppressed $A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i^3$ Blennow et al '10 JHEP
- Example in 3+1model
- Cancellation between light + sterile contributions leads to

$$\tau_{1/2} \sim m_4^4$$



Light extra neutrinos



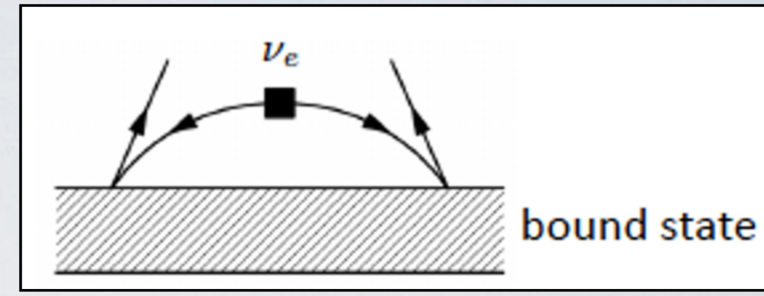
- Is there a way to avoid the GIM mechanism ?
- There are additional contributions from 'ultra-soft' neutrinos

$$\sum_n \langle f|J_\mu|n\rangle\langle f|J^\mu|i\rangle \times \int \frac{d^3k}{(2\pi)^3}\frac{1}{E_\nu[E_\nu + (E_n - E_0) - i\epsilon]} \qquad E_\nu = \sqrt{k^2 + m_i^2}$$

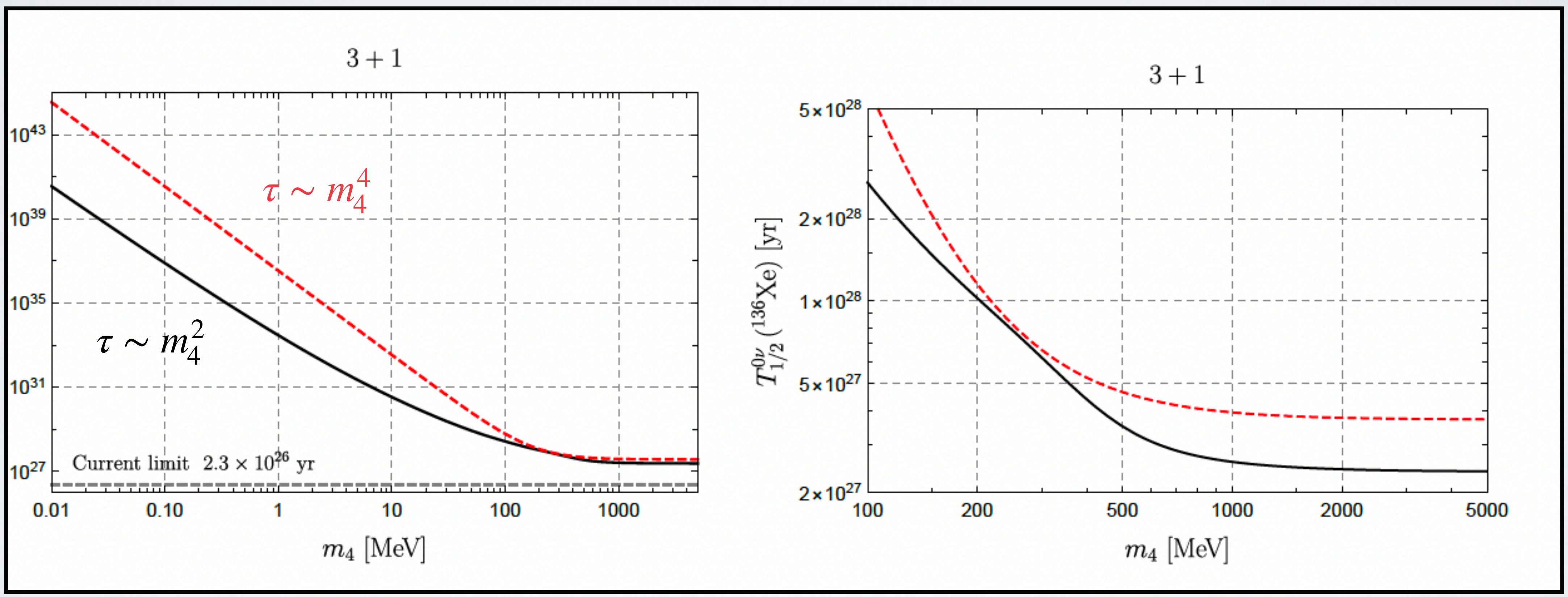
- Depends on nuclear excited states. Normally these are tiny effects (5%)
- But become dominant in the GIM mechanism ! $\sim U_{ei}^2 m_i^3$
- For m4 ~ MeV we get new contributions $\sim U_{ei}^2 m_i^2$
- For m4 << MeV we get new contributions $\sim U_{ei}^2 m_i^3 \log\frac{(E_n - E_0)^2}{m_i^2}$
- These effects are not considered in any analysis of neutrinoless double beta decay
- Javier Menendez computed for us the necessary matrix elements

Light extra neutrinos

- Is there a way to avoid the GIM mechanism ?
- There are additional contributions from 'ultra-soft' neutrinos
- Also include contributions from 'hard' neutrinos



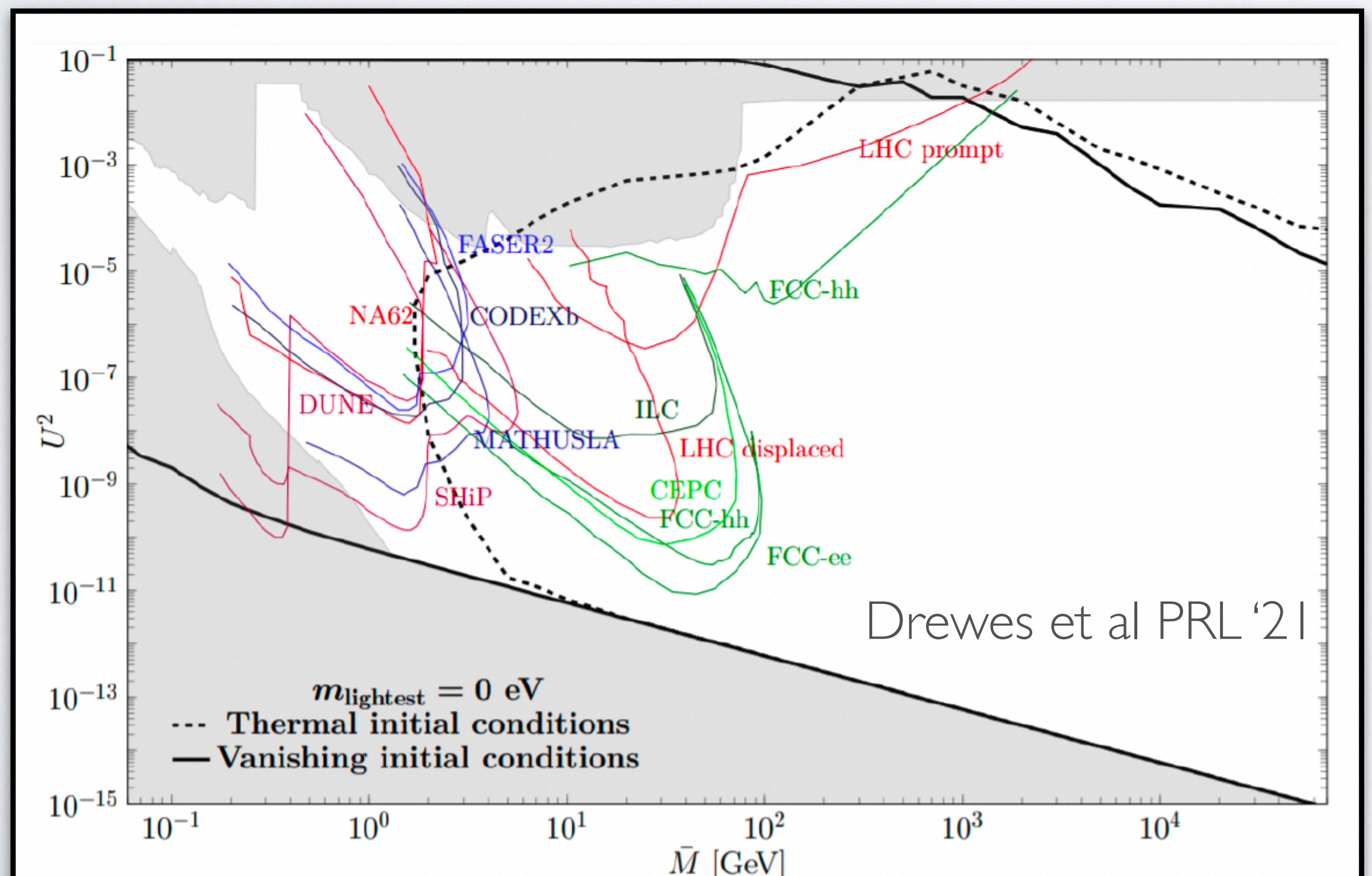
Lifetime in years



- **Work in progress: compute these corrections for realistic models**

Work in progress

- Our work has focused on hadronic/nuclear aspects: what drives 0vbb
- But we focused on toy neutrino models
- Ongoing work in collaboration with Marco Drewes (Louvain) and his group
- Use realistic 3+2 and 3+3 models + **leptogenesis**



- Compute 0vbb predictions for all viable points in parameter space

The associated symmetries

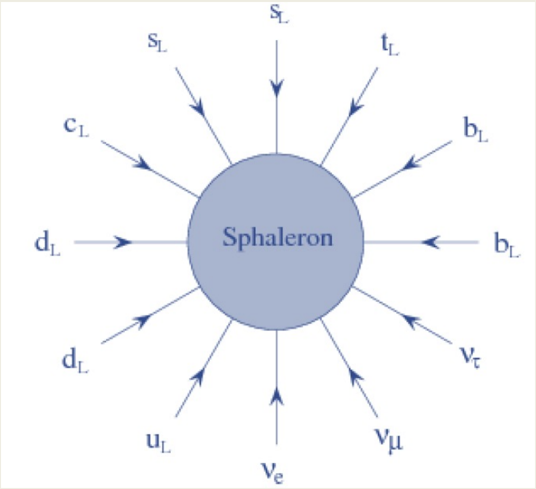
Important caveat II

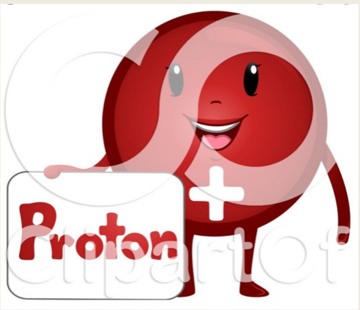
- Not all classical symmetries survive quantum mechanics
- **B+L** is an *anomalous* symmetry

$$\eth_\mu\, j_L^\mu = \eth_\mu\, j_B^\mu = 3\,\frac{g^2}{32\pi^2} W^a_{\mu\upsilon}\widetilde{W}^{a\;\mu\upsilon}$$

't Hooft 1976

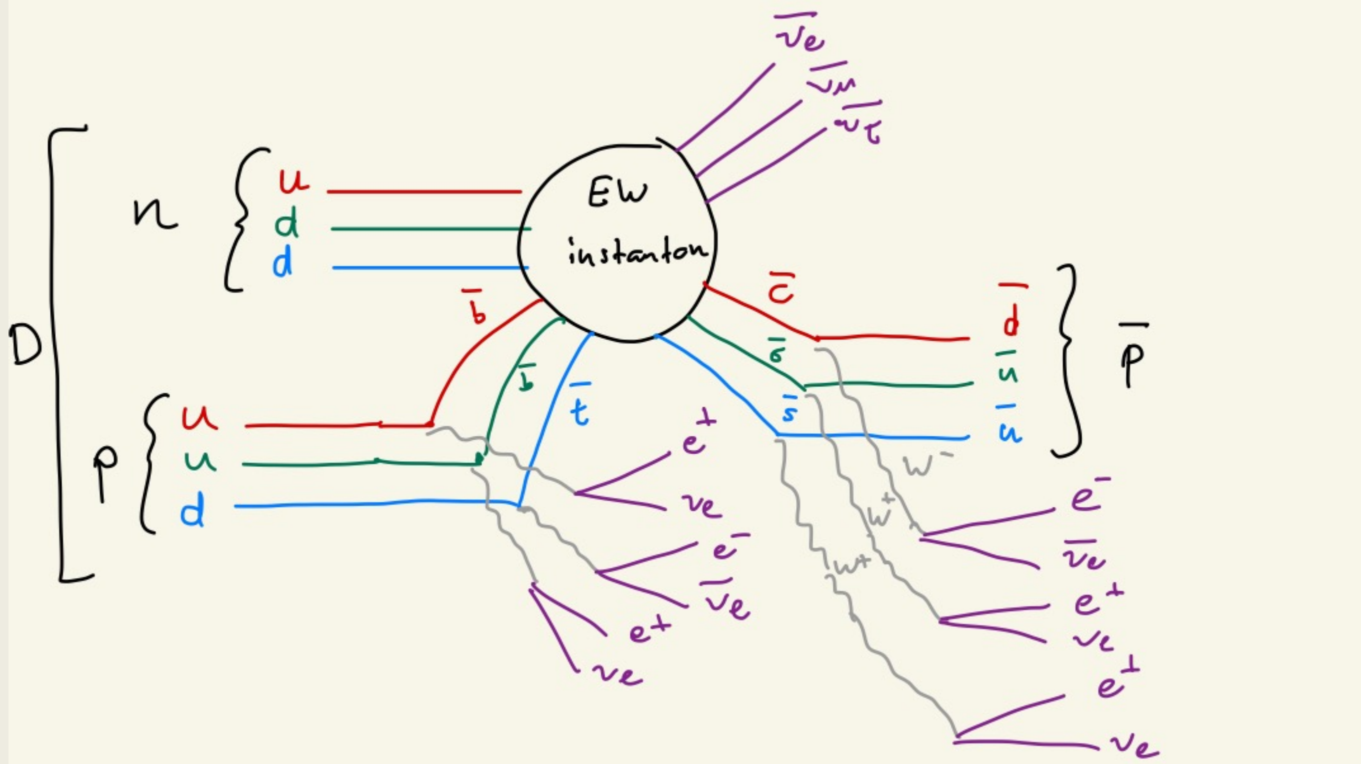
- These non-perturbative processes (aka electroweak instantons) cause **(B+L)-violating processes** (but conserve B-L) $\Delta B = \Delta L = \pm 3n$





A murder most foul

But we are saved !!



$$D \longrightarrow \bar{p} + 4e^{+} + 2e^{-} + 4\nu_e + 3\bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau$$

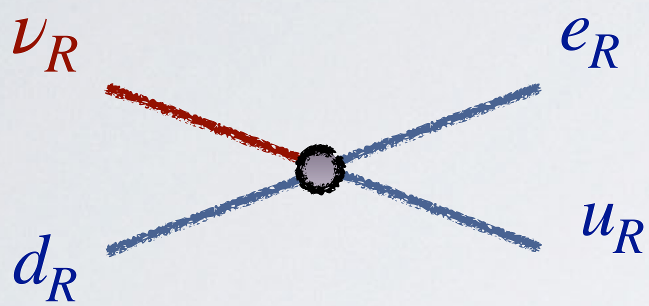
$$\Gamma_D \sim G_F^{12}\,(m_D - m_{\bar{p}})^{25}\, V_{td}^{2}\, V_{ub}^{4}\, V_{cd}^{2}\, V_{us}^{4} \times e^{-16\pi^2/g^2}$$

$$\tau_D = \Gamma_D^{-1} \sim 10^{184}\ y \sim 10^{174}\ \text{Age of universe}$$

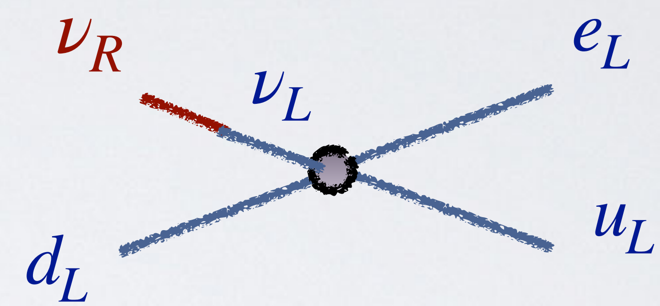
inspired by Andrew Long

Non-sterile sterile neutrinos ?

- In various interesting scenarios sterile neutrinos only look sterile at low energies
- In left-right symmetric models: right-handed neutrinos charged under $SU_R(2)$



$$\sim \left(\frac{1}{M_{W_R}}\right)^2$$



$$\sim \left(\frac{1}{M_{W_L}}\right)^2 \sqrt{\frac{m_\nu}{m_R}}$$

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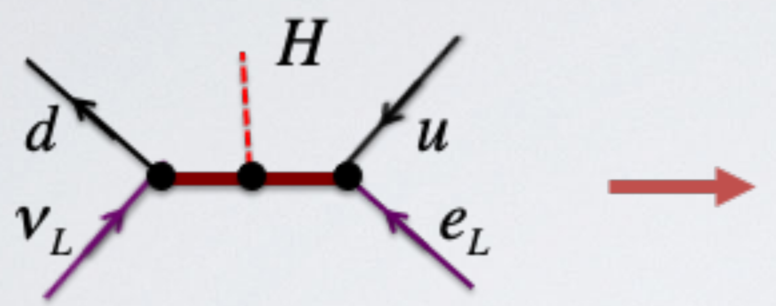
- This also happens in for instance Leptoquark scenarios and can even used in solutions to anomalies such as muon g-2 or flavor anomalies (not today)

e.g. Ruiz, JdV et al '21 e.g. Azatov, Barducci et al '18

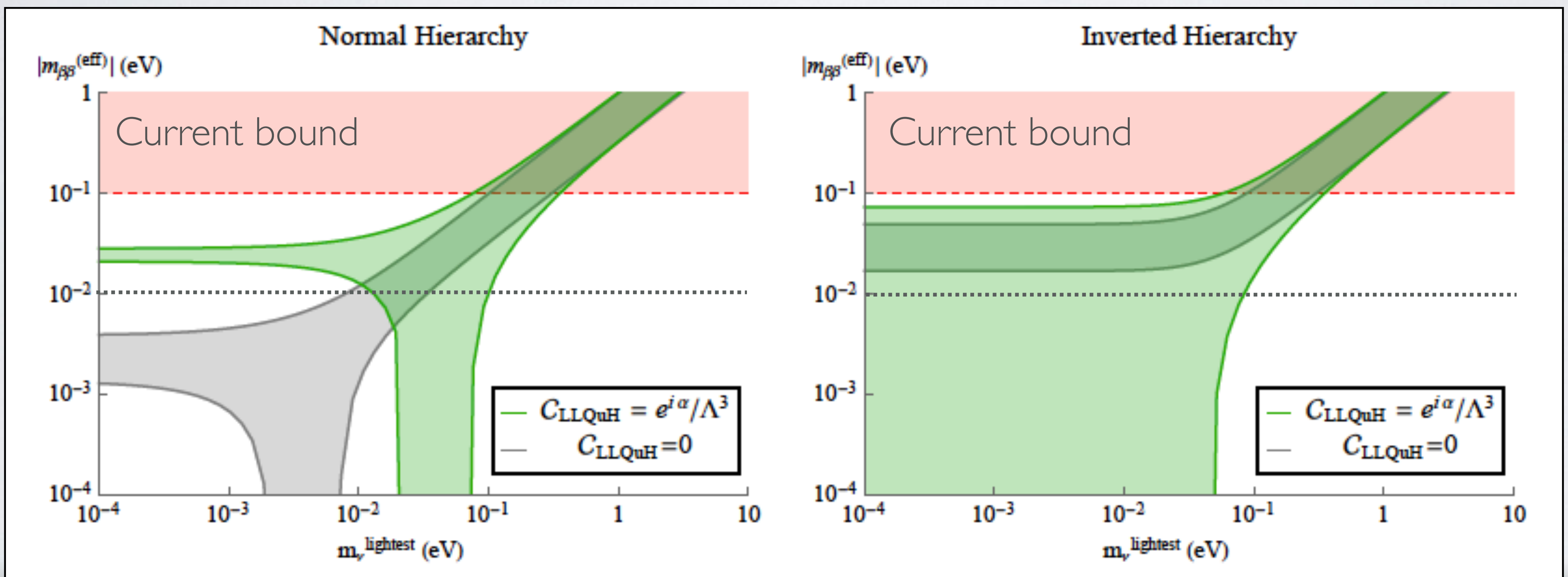
Using the framework

- Example: a model of heavy leptoquarks (LHC probes 1 TeV leptoquarks roughly)



$C_7 \sim (v/\Lambda)^3$

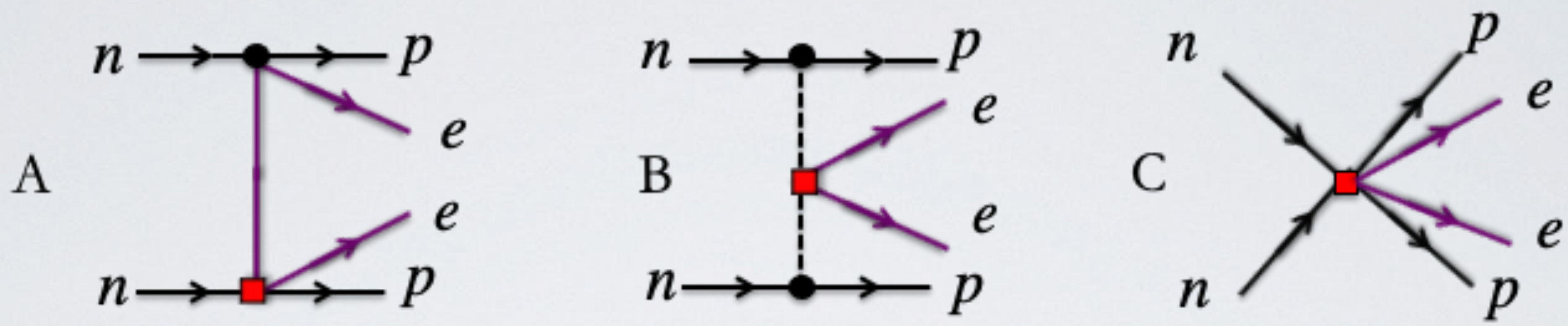
$\Lambda > 400\ TeV$



Ton-scale expectations

- Dramatic impact on 0vbb phenomenology !
- Sensitivity to 500-TeV new physics scales

New 0vbb topologies



- Straightforward to calculate generalized 0vbb transition current

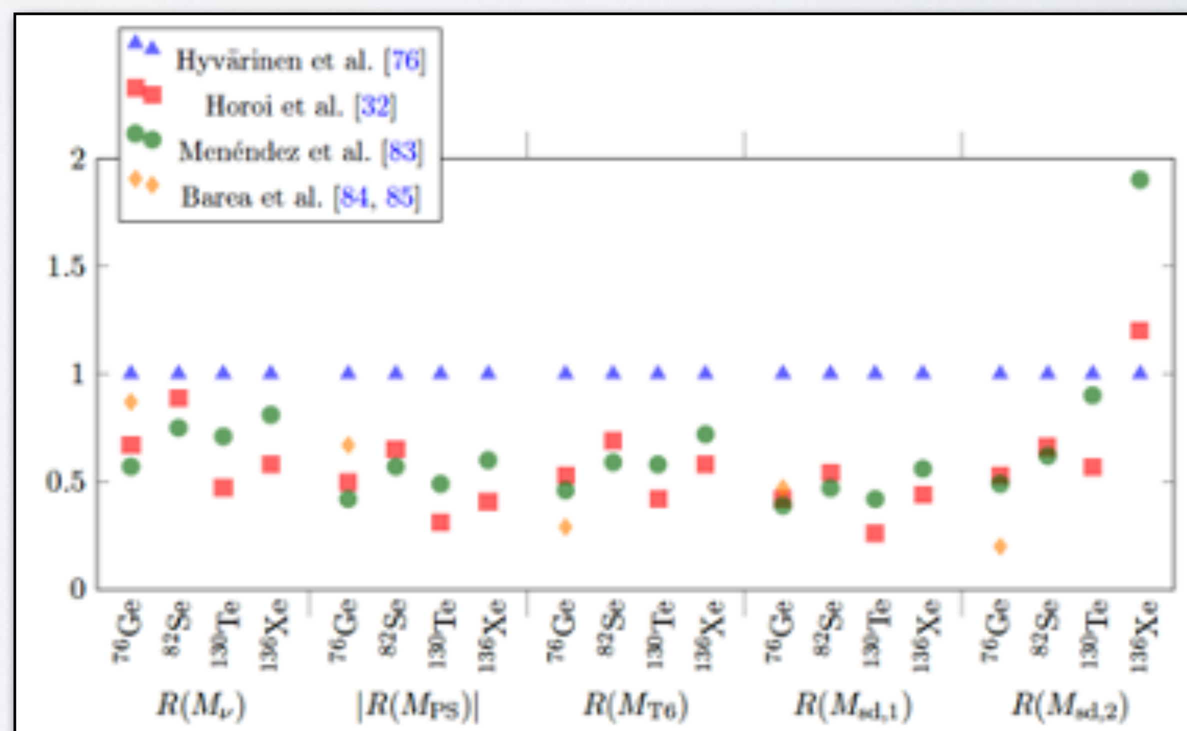
Cirigliano et al '17 '18

- Need additional nuclear matrix elements (NMEs)
- **At leading-order in Chiral-EFT: 15 NMEs (all in literature)**
- Similar uncertainties as before

NMEs	^{76}Ge [74]	[31]	[81]	[82, 83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_T^{AA}	–	–	–	
M_T^{AP}	-0.35	0.01	-0.01	
M_T^{PP}	0.10	0.00	0.00	
M_T^{MM}	-0.04	0.00	0.00	

NMEs	^{76}Ge			
$M_{F,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,sd}^{PP}$	0.32	0.00	0.02	0.38

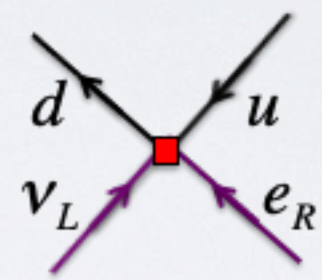
Hyvarinen/Suhonen '15
Menendez et al '17 '18
Barea et al '15 '18
Horoi/Neacsu '17



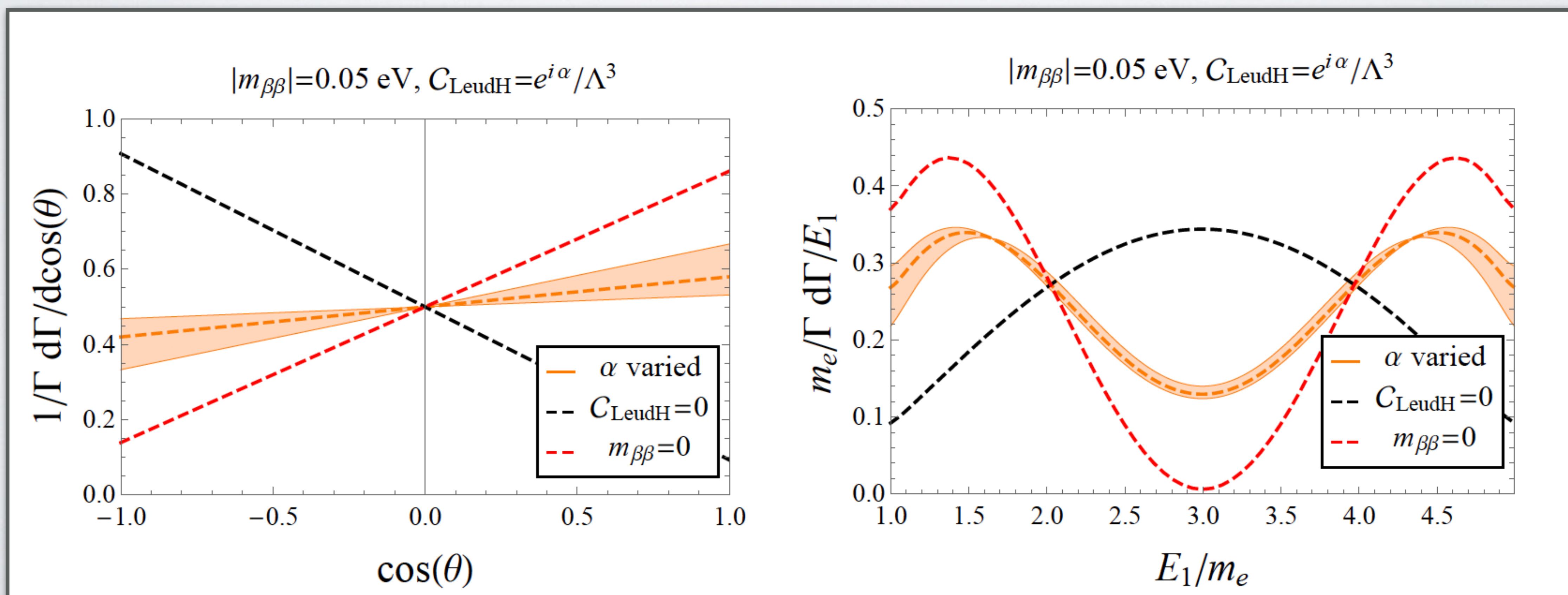
Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?

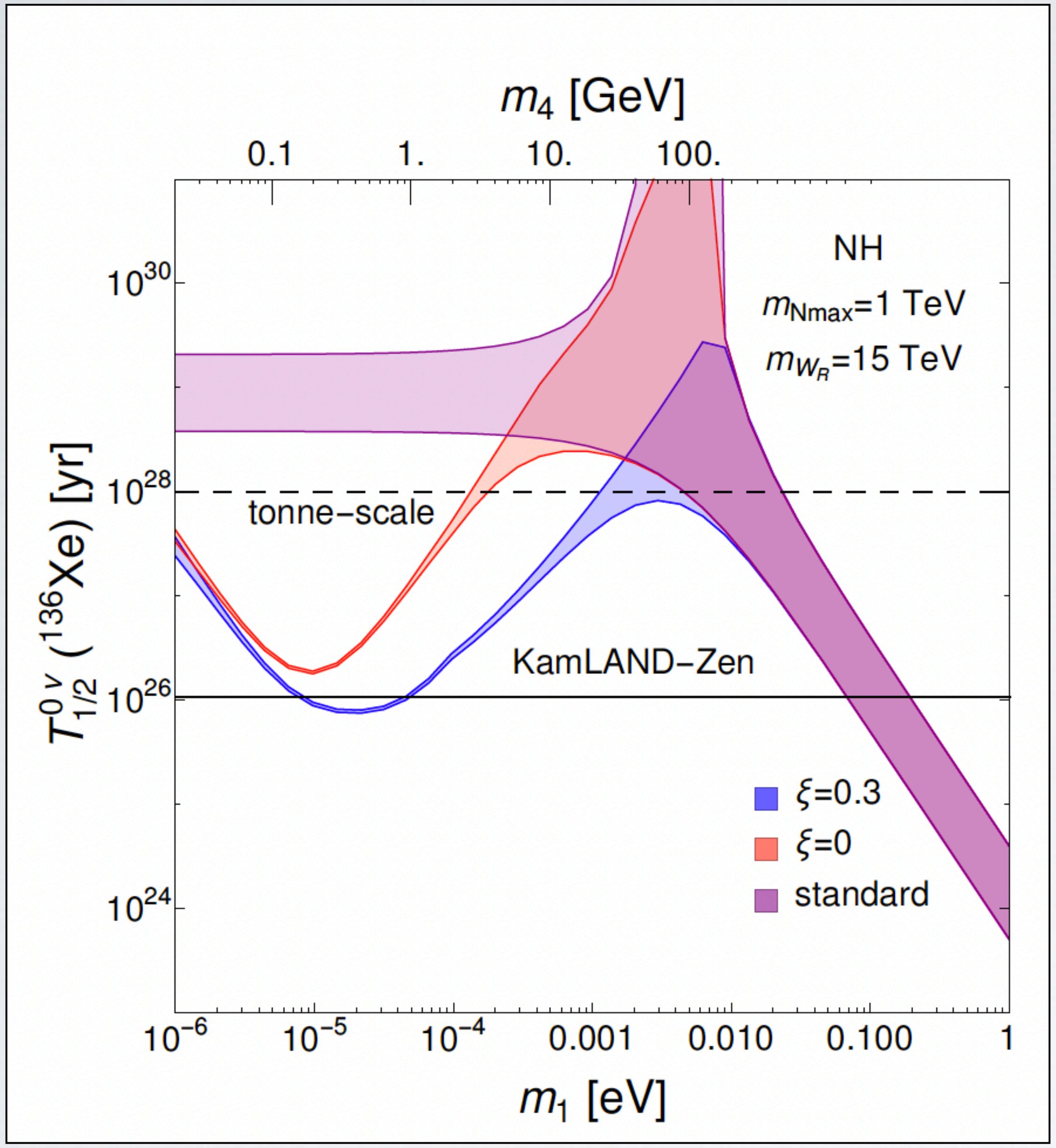
- **One could in principle measure angular&energy electron distributions**



$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$ $\Lambda \sim 50\,\mathrm{TeV}$



An example: mLRSM + light right-handed neutrinos



Li, Ramsey-Musolf, Vasquez PRL '20
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$\xi \sim W_L - W_R\,\text{mixing}$

Normal Hierarchy

- Large enhancements possible for 0vbb for parameter space not excluded elsewhere.
- Automizing more complicated due to more 'user input' (sterile masses + mixing)
- If someone is interested in helping out….