

# NEUTRINOLESS DOUBLE BETA DECAY AND LEPTON NUMBER VIOLATION

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University of Amsterdam & Nikhef

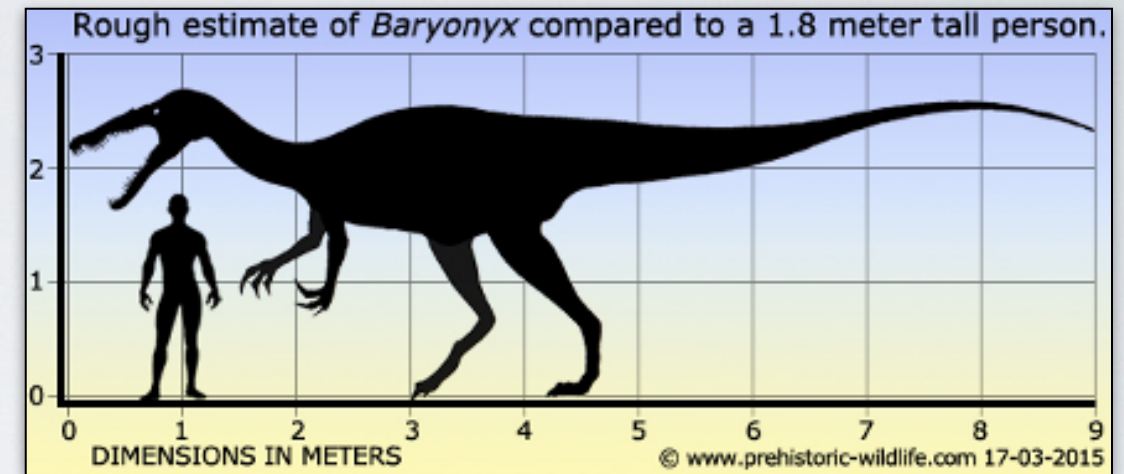


# The plan of attack

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
- Quarks carry baryon number  **$B = 1/3$**
- Nucleons and excited states (Delta etc)  **$B = 1$**
- Atomic nuclei have  **$B > 1$**  (atomic number)

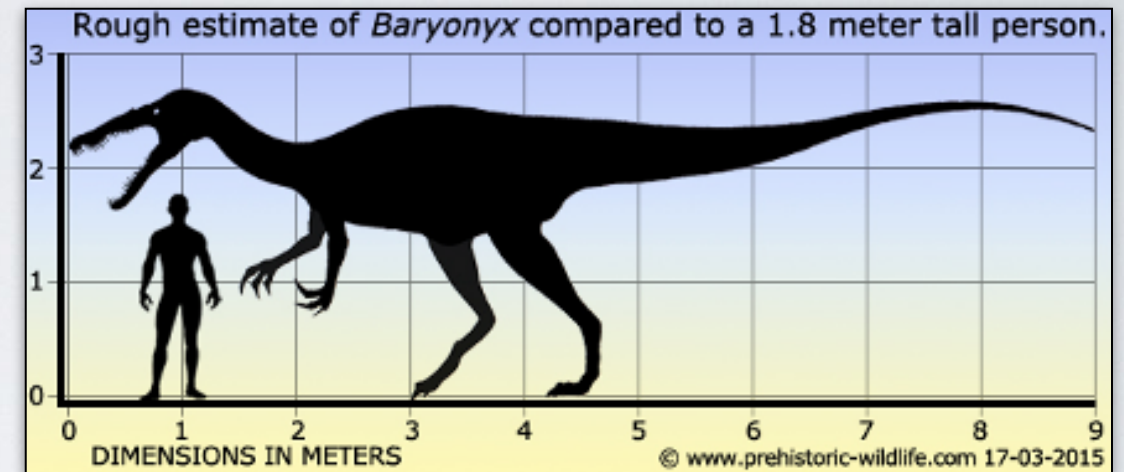




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- Leptons are spin 1/2 particles that do not feel strong interactions (no color charge)
- Name means '**fine/small/thin ones**' introduced by L. Rosenfeld



**'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?  $p \rightarrow e^+ + \pi^0 \rightarrow e^+ + 2\gamma$
- 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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**Accidental symmetry:** Symmetry that appears because terms that break it have too high dimension to appear in the Lagrangian

- **Illustration:** 1-flavor QED based on a local U(1) gauge symmetry  $\Psi_e \rightarrow e^{i\alpha(x)} \Psi_e$
- **Lagrangian:** 
$$\mathcal{L} = \bar{\Psi}_e (i\not{D} - m) \Psi_e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \dots$$
- 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)

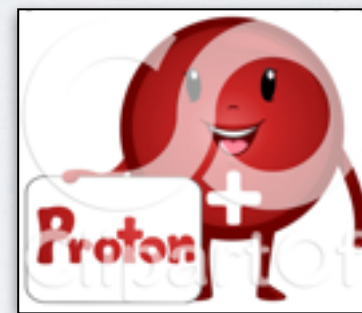


# A fortunate accident

- 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...

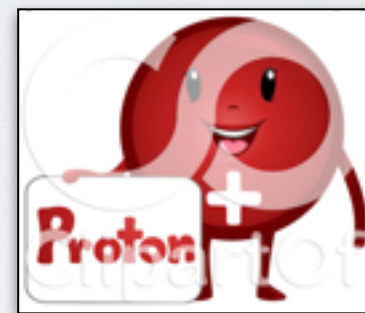


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## ***Baryon (B) and Lepton (L) number are classically conserved***

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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

$$\partial_\mu j_L^\mu = \partial_\mu j_B^\mu \sim \epsilon^{\alpha\beta\mu\nu} W_{\alpha\beta}^a W_{\mu\nu}^a$$

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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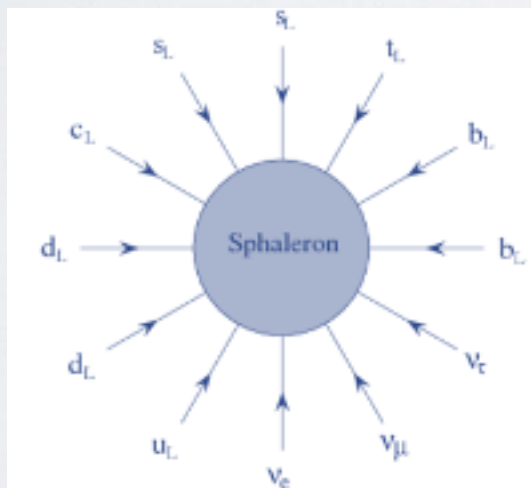
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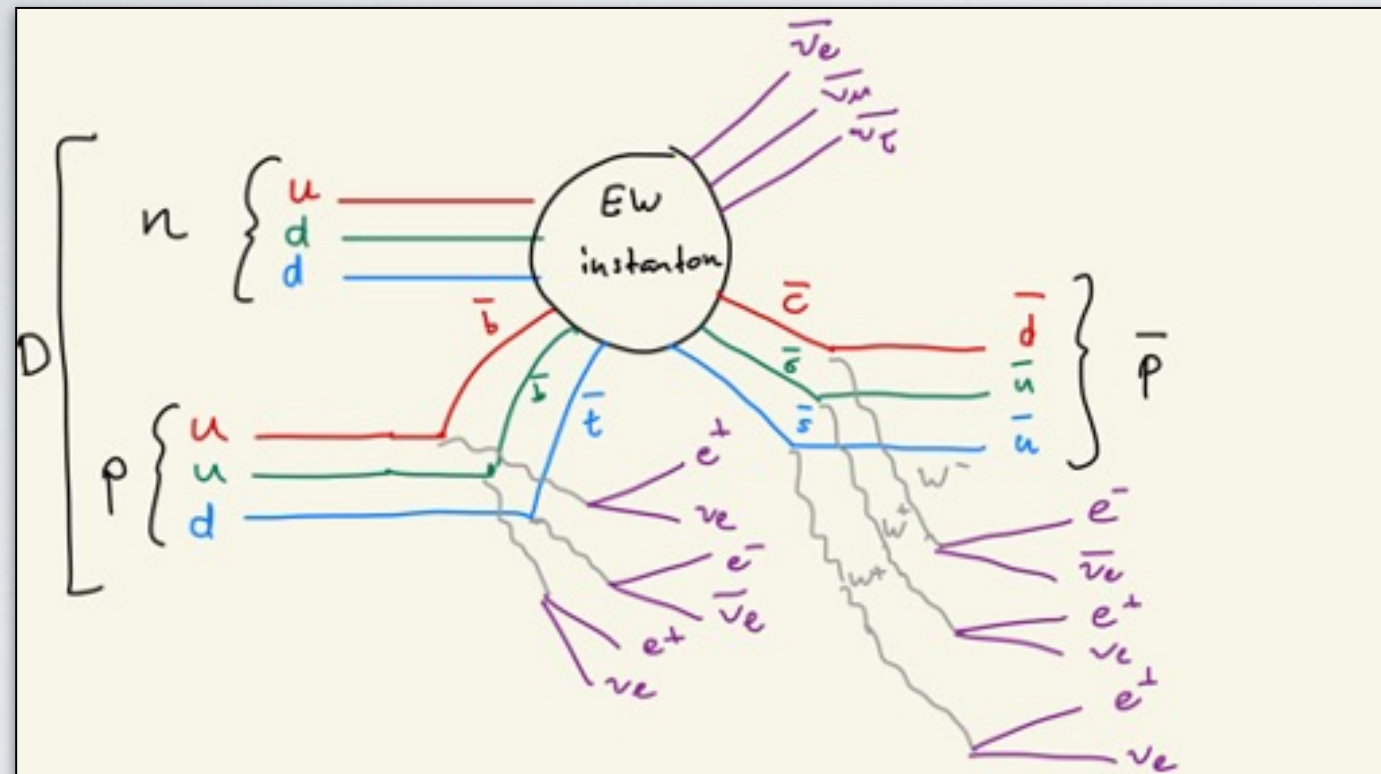
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**A murder most foul**



# But we are saved !!



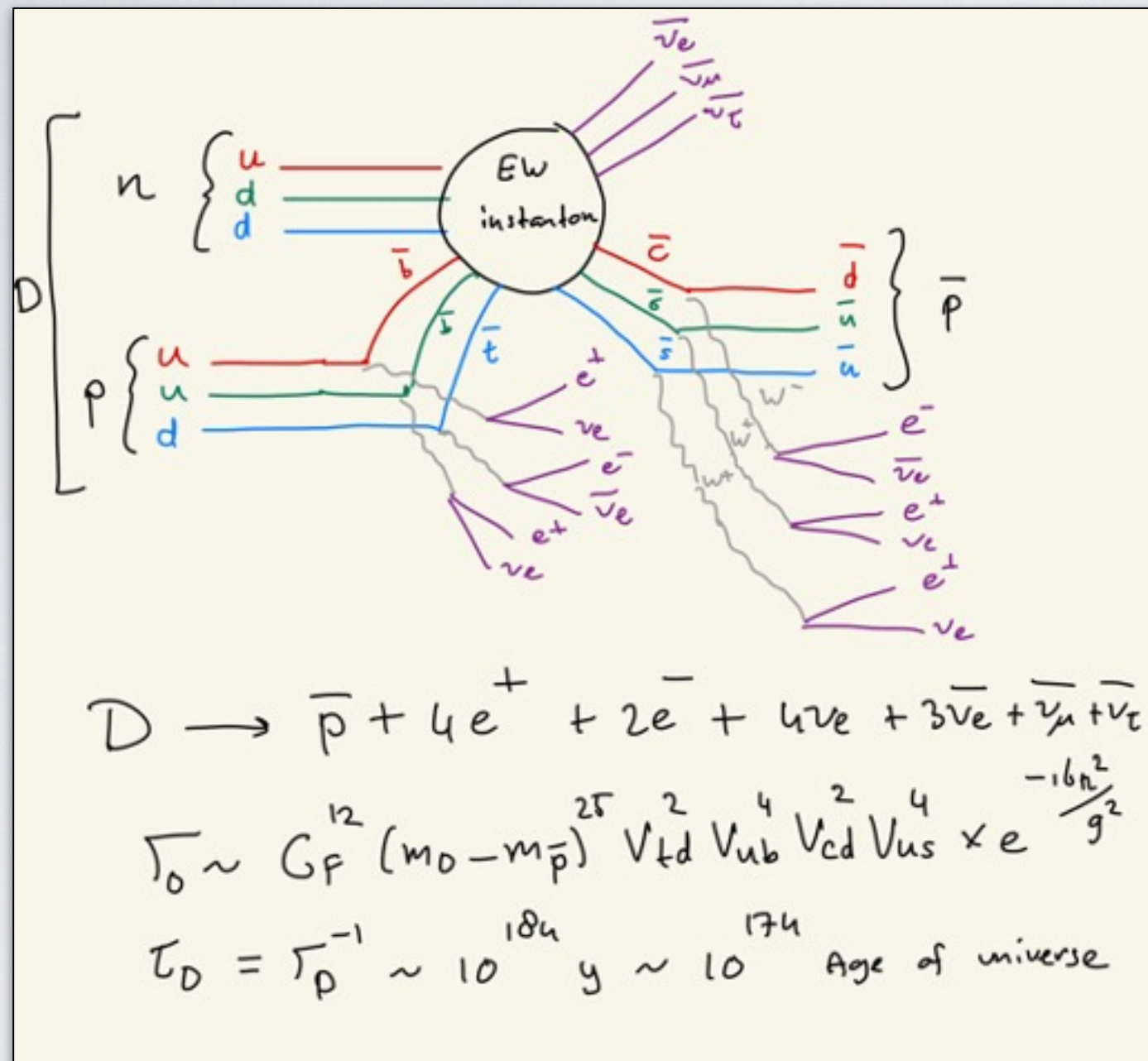
$$D \rightarrow \bar{p} + 4e^+ + 2e^- + 4\nu_e + 3\bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau$$

$$\Gamma_0 \sim G_F^{12} (m_D - m_{\bar{p}})^{25} V_{td}^2 V_{ub}^4 V_{cd}^2 V_{us}^4 \times e^{-\frac{16\pi^2}{g^2}}$$

$$\tau_D = \Gamma_0^{-1} \sim 10^{184} \text{ y} \sim 10^{174} \text{ Age of universe}$$

*inspired by Andrew Long*

# But we are saved !!



- 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

*inspired by Andrew Long*



# Why might there be extra L (or B) violation

## I. 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 baryogenesis (no new B or L violation at all)
- D. ....Thousand more scenarios

# Why might there be extra L (or B) violation

## 1. Where is the anti-matter ?



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## 2. No global symmetries in quantum gravity



+



Hawking  
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## 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

## I. 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  $m_\nu \ll m_e \ll m_p$

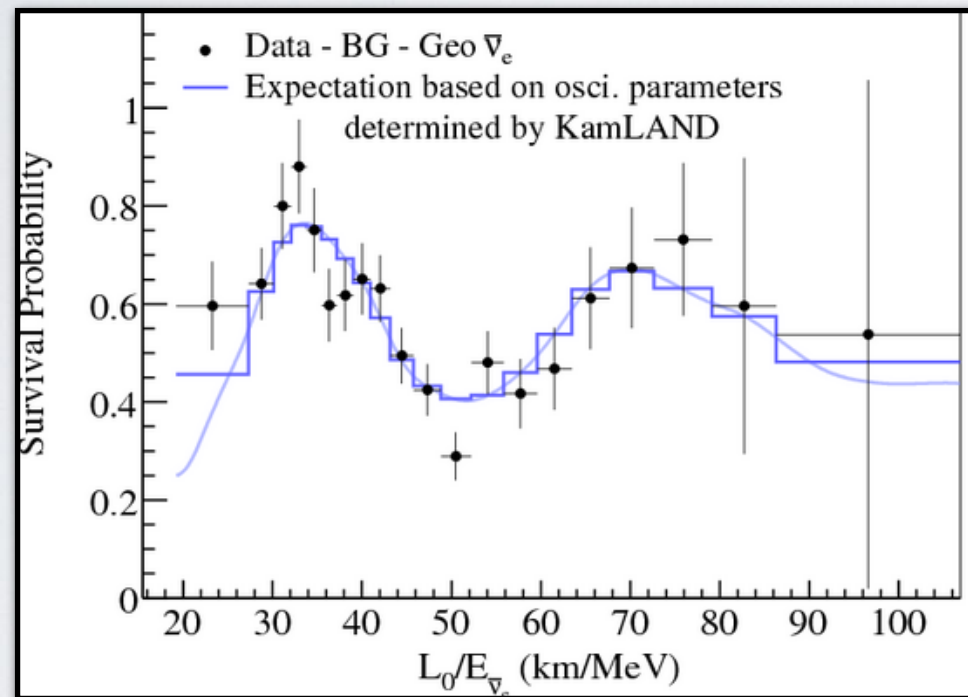
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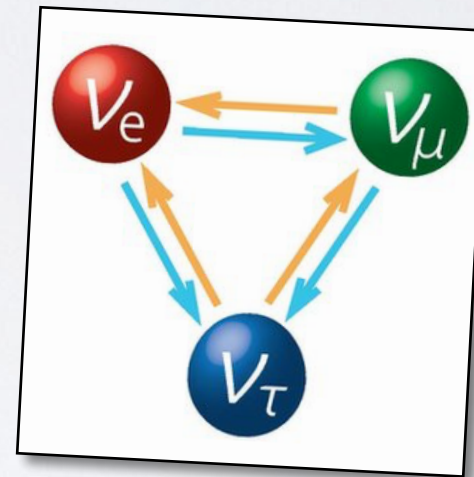
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$$m_\nu \ll m_e \ll m_p$$

- **But neutrinos do have mass !**



$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 \frac{\Delta m^2 L}{4E}$$



- Biggest mass splitting:  $|\Delta m| \simeq 0.05 \text{ eV}$       Smallest:  $|\delta m| \simeq 0.008 \text{ eV}$

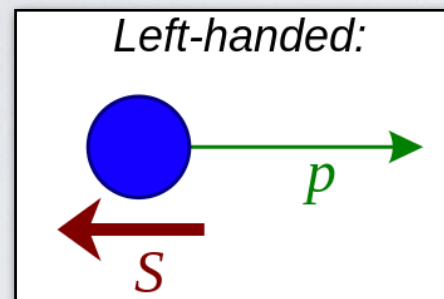
- Direct limits:  $m_{\nu_e} \leq 0.8 \text{ eV}$   
**KATRIN experiment**

- Cosmology  $\sum_{i=e,\mu,\tau} m_{\nu_i} \leq 0.12 \text{ eV}$

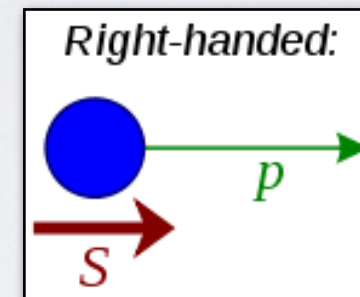


# Mass generation in the Standard Model

- 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



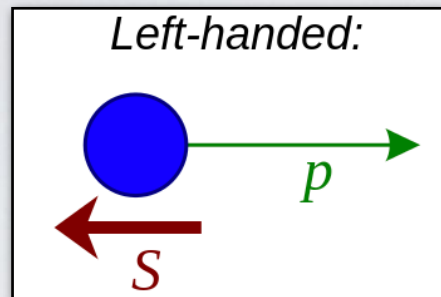
**Left-handed fields  
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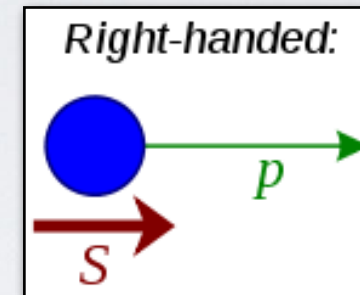
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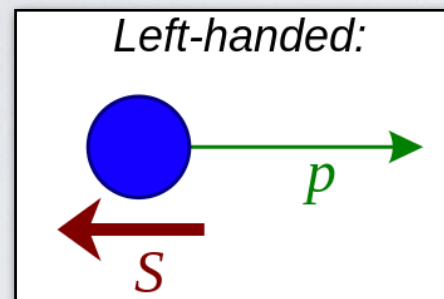
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- We cannot just write down a mass term:  $\mathcal{L} = -m_e \bar{e}_L e_R$
- This would violate ‘weak charge’ conservation (or SU(2) gauge invariance)

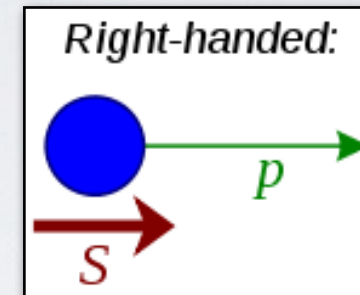


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- We cannot just write down a mass term:  $\mathcal{L} = -m_e \bar{e}_L e_R$
- This would violate 'weak charge' conservation (or SU(2) gauge invariance)
- The Standard Model overcomes this problem through the **Higgs** mechanism

$$\mathcal{L} = -y_e \bar{e}_L e_R \varphi \quad \longrightarrow \quad \mathcal{L} = -y_e \bar{e}_L e_R \mathbf{v} \quad m_e = y_e \mathbf{v}$$

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

# The puzzle of the neutrino mass

- **Easy fix:** Insert gauge-singlet right-handed neutrino  $\nu_R$

$$\mathcal{L} = -y_\nu \bar{\nu}_L \nu_R \varphi \qquad y_\nu \sim 10^{-12} \rightarrow m_\nu \sim 0.1 \text{ eV}$$

- Nothing really wrong with this....



# The puzzle of the neutrino mass

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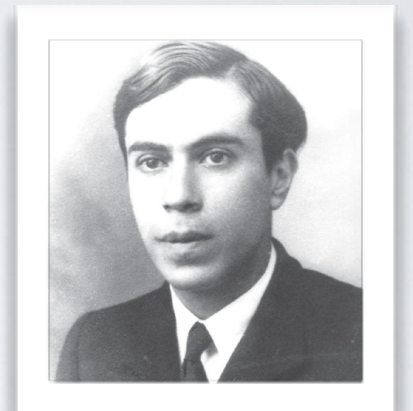
$$\mathcal{L} = -y_\nu \bar{\nu}_L \nu_R \varphi \quad y_\nu \sim 10^{-12} \rightarrow m_\nu \sim 0.1 \text{ eV}$$

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

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

*‘Everything that is not forbidden is compulsory’*

- 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)



Ettore Majorana

# The puzzle of the neutrino mass

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

Minkowski '77

- $|+|$  case: diagonalization leads to **2 mass eigenstates**

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

- A Majorana particle only has 2 degrees of freedom (Dirac particle has 4)



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

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



- 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**

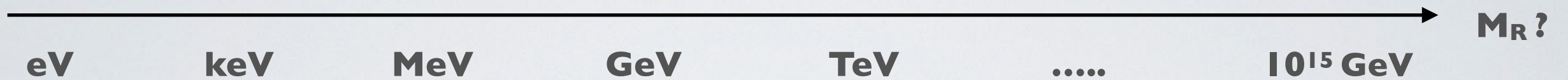


- If Yukawa coupling order 1 then  $m_1 \simeq \left| \frac{v^2}{M_R} \right| \rightarrow M_R \simeq 10^{15} \text{ GeV}$



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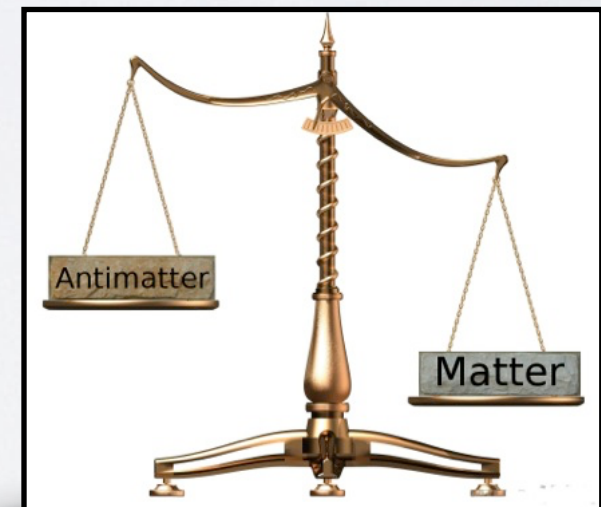
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Fukugita, Yanagadi '86
- **Thermal leptogenesis possible**  $M_R \geq 10^9 \text{ GeV}$  Davidson Ibarra '02



13.7 billion year



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

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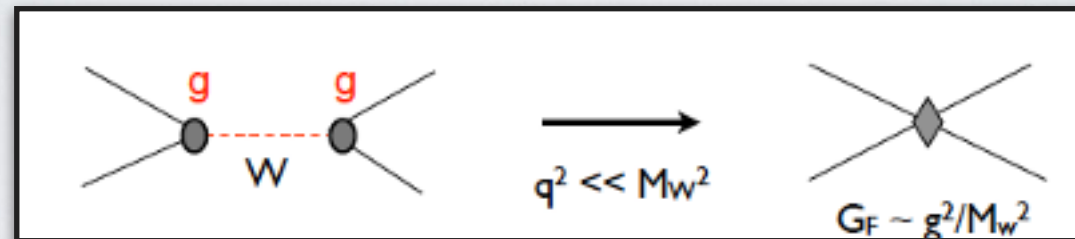
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- But also leptogenesis possible with **TeV** sterile neutrinos! Pilaftsis '97, Akhmedov et al '98  
See e.g. Shaposhnikov et al (many works)
- And even in the **MeV-GeV** range Drewes et al '21
- KeV sterile neutrino could be Dark Matter (but getting 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:



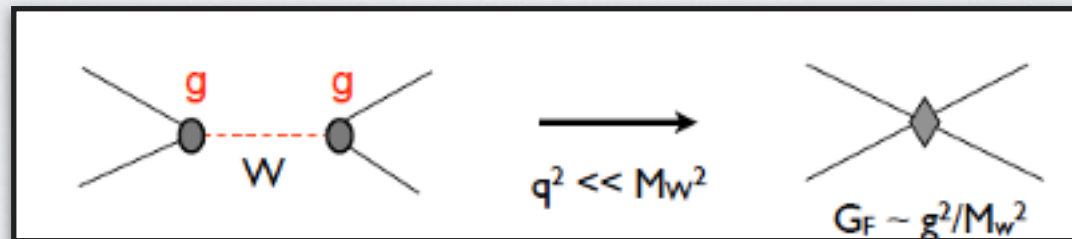
- **We don't need 'high-energy details' (the W-boson) at low energies**



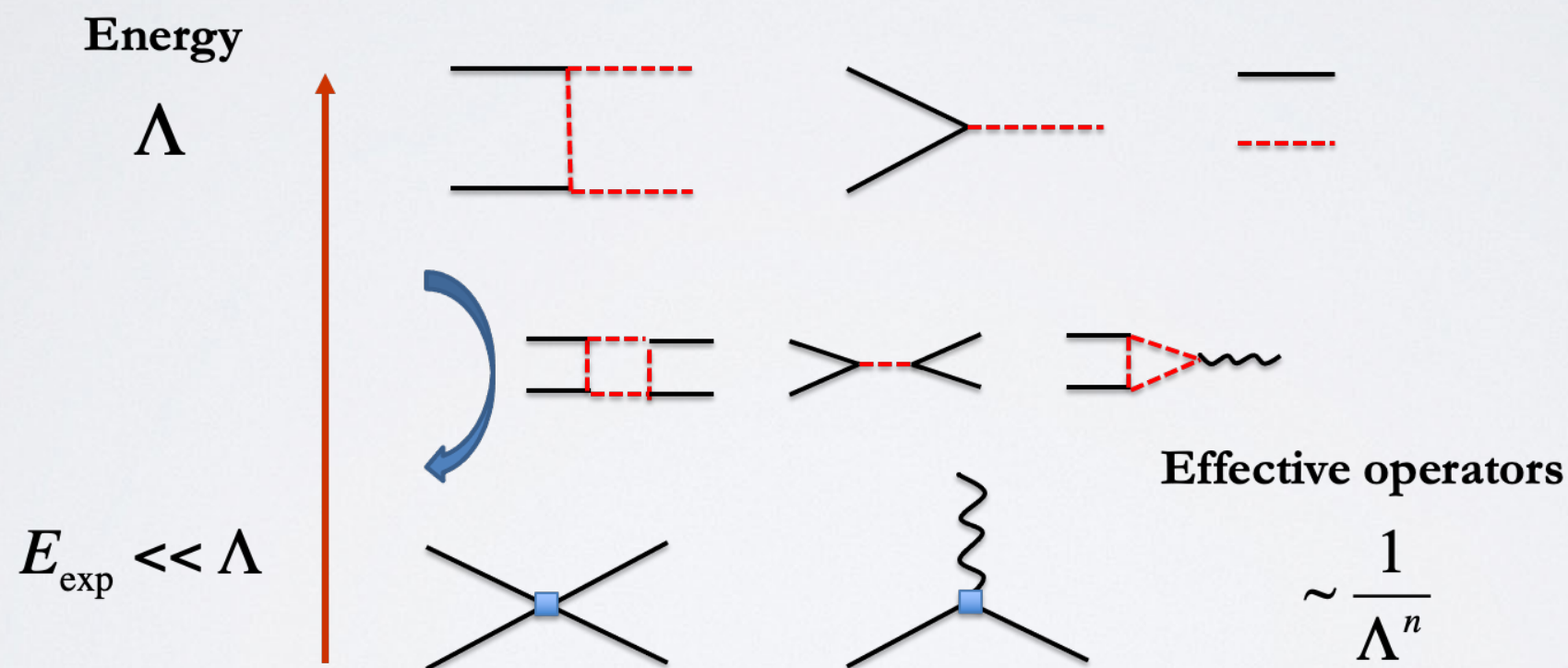
# The Standard Model as an EFT

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A la Fermi:



- **We don't need 'high-energy details' (the W-boson) at low energies**



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

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



# The Standard Model as an EFT

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- Let's just assume BSM physics lives at high scales



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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  $E/\Lambda$

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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  $E/\Lambda$
- Gauge symmetries are very restrictive: **only 1 type of dim-5 operator**

$$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L) \quad \text{Weinberg '79}$$

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

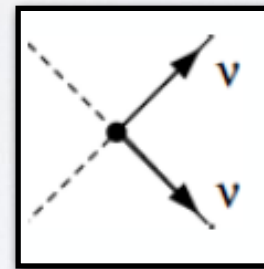
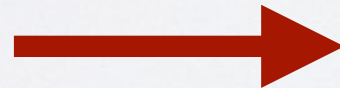
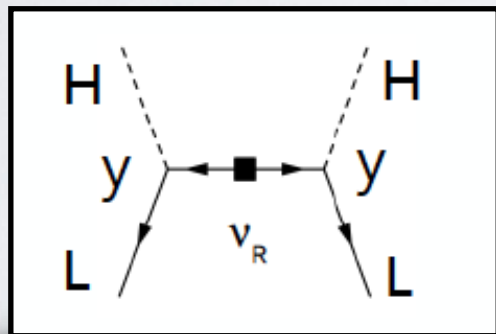


# Heavy-sterile neutrinos a UV completion

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



- 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**



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

$$c_5 = y_\nu^2$$

$$\Lambda = M_R$$

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

# The plan of attack

1. Baryon- and lepton-number foundations
- 2.  $0\nu\nu\beta$  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



1. A Dirac neutrino will only produce muons at target: no anti-muons
2. A Majorana neutrino could do it but it has to have a right-handed helicity

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- **Unfortunately this is hopeless experimentally!**

Fraction of right-handed neutrinos

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

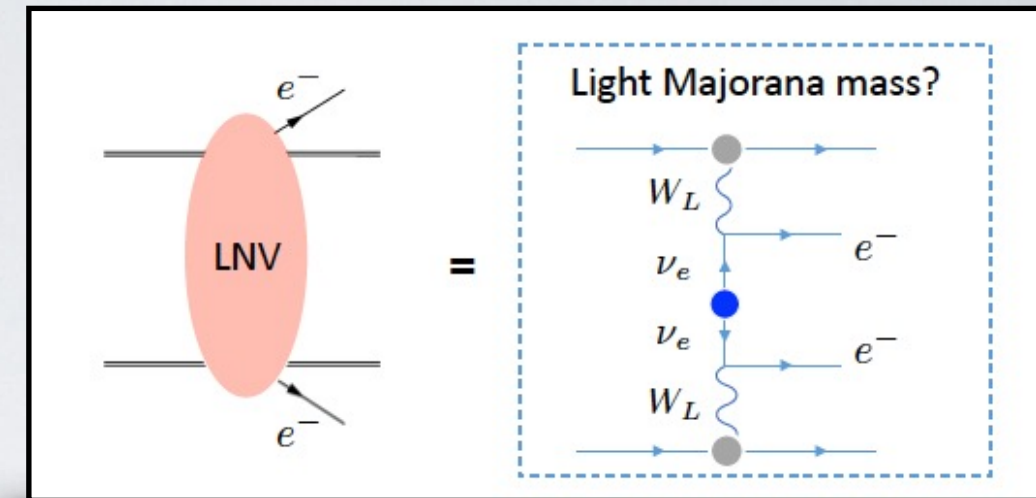


# Cut out the middle man

- Most promising way: look at 'neutrinoless' processes

$$K^- \rightarrow \pi^+ + e^- + e^- \quad pp \rightarrow e^+ + e^+ + \text{jets}$$

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

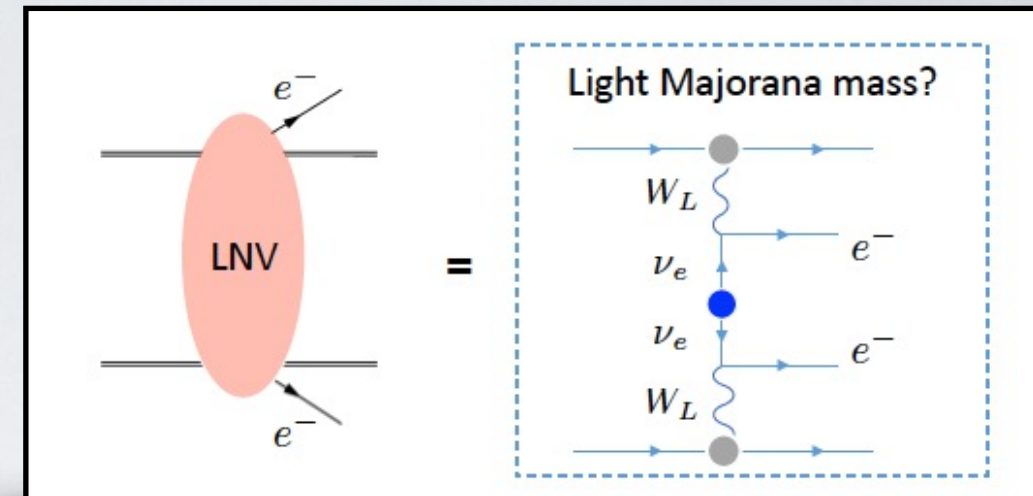
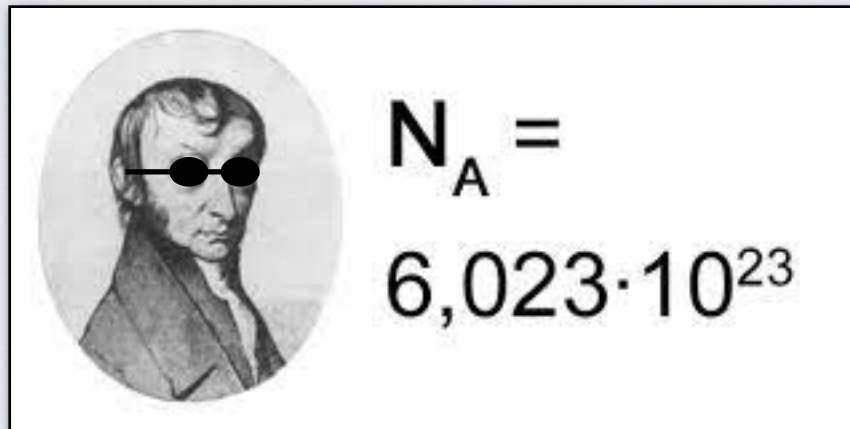


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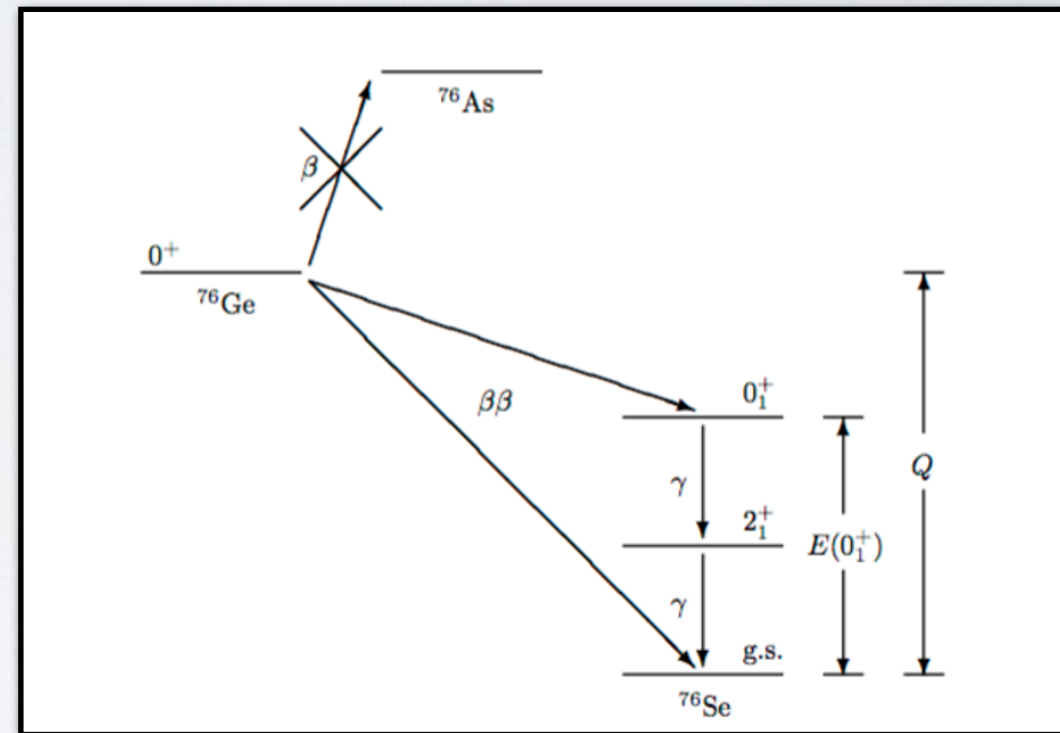
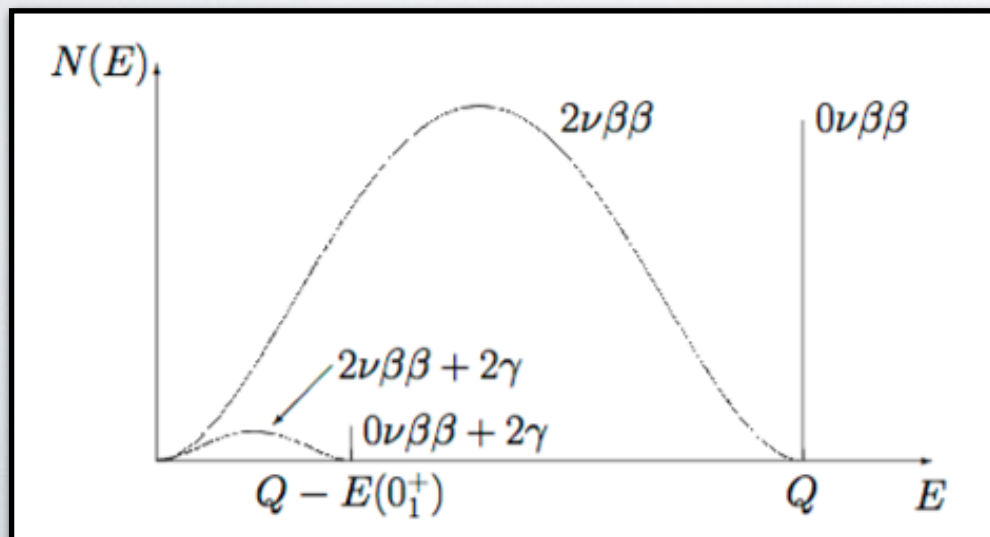
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- Isotopes protected from single beta decay
- Neutrinoless double beta decay from Standard Model

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

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



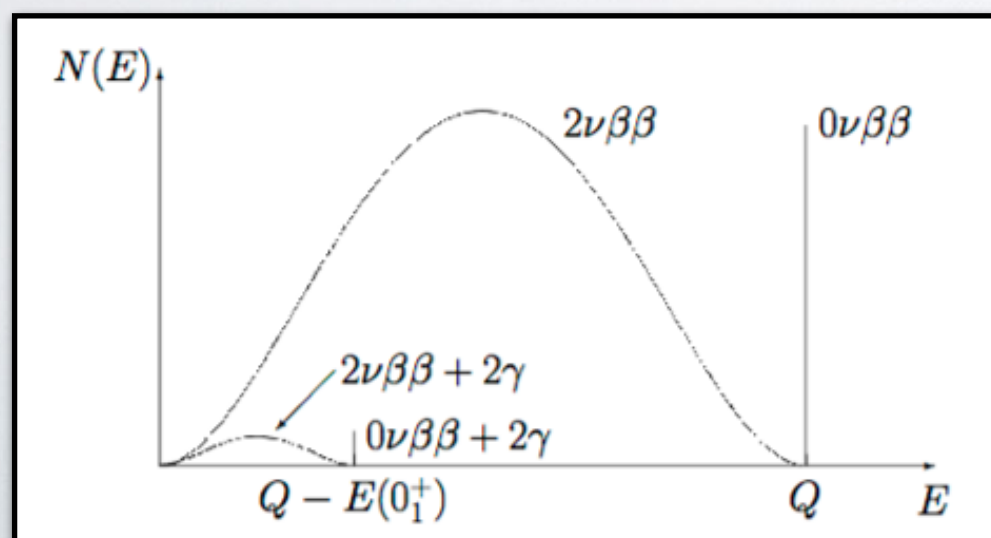
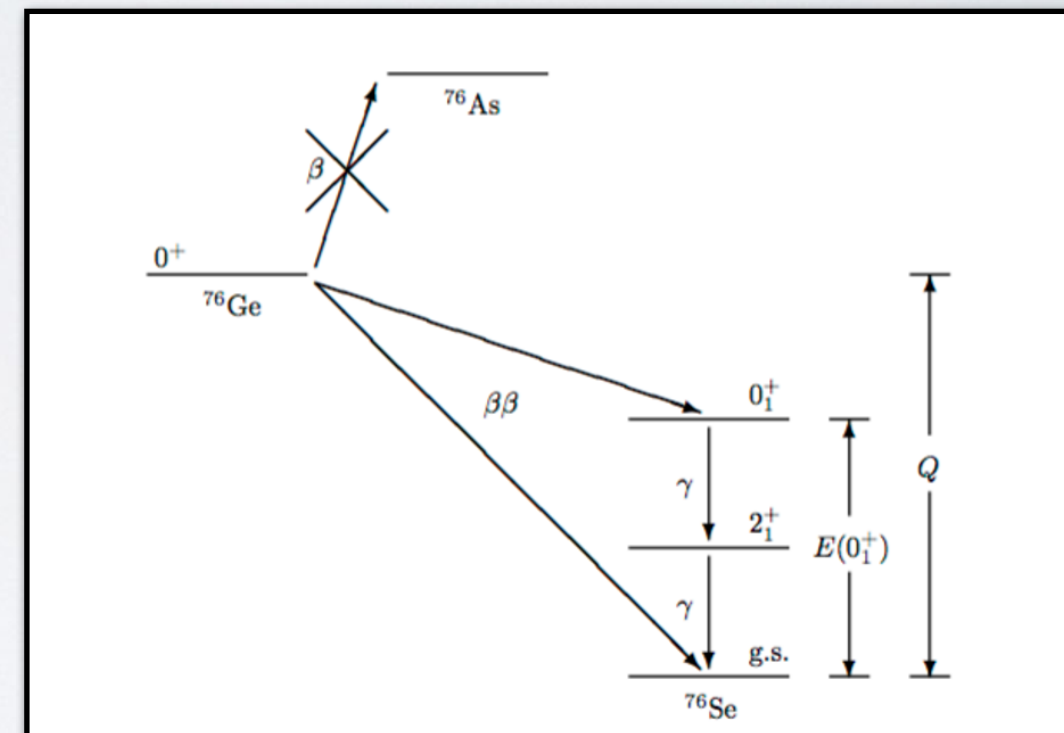
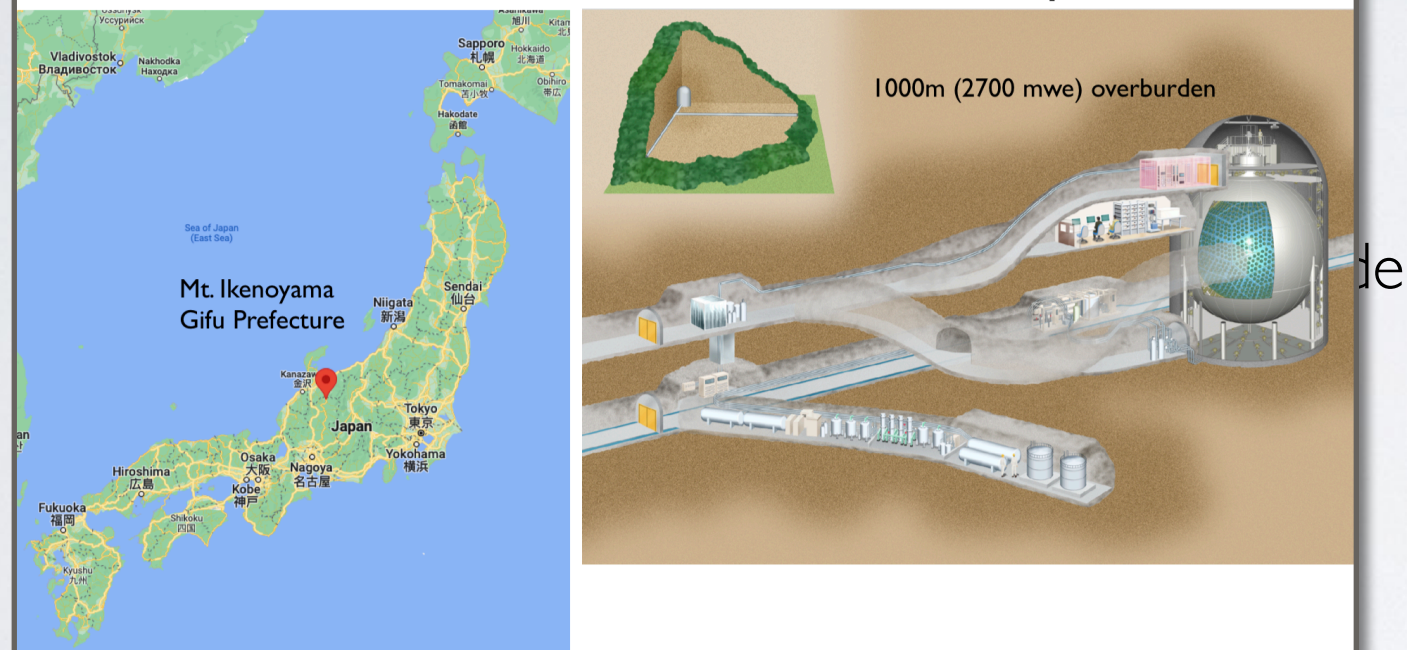
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$$X(Z, N) \rightarrow Y(Z + 2, N - 2) + e^- + e^-$$

KamLAND-Zen at Kamioka in Japan

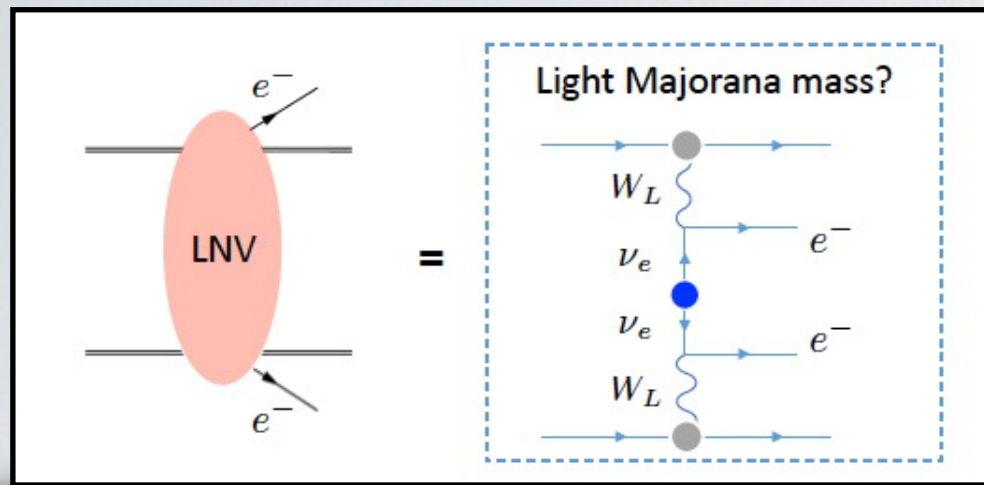


	Lifetime	Experiment	Year
$^{76}\text{Ge}$	$8.0 \cdot 10^{25} \text{ y}$	GERDA	2018
$^{130}\text{Te}$	$3.2 \cdot 10^{25} \text{ y}$	CUORE	2019
<b><math>^{136}\text{Xe}</math></b>	$2.2 \cdot 10^{26} \text{ y}$	KamLAND-Zen	2022

Note: age of universe  $\sim 10^{10}$  year



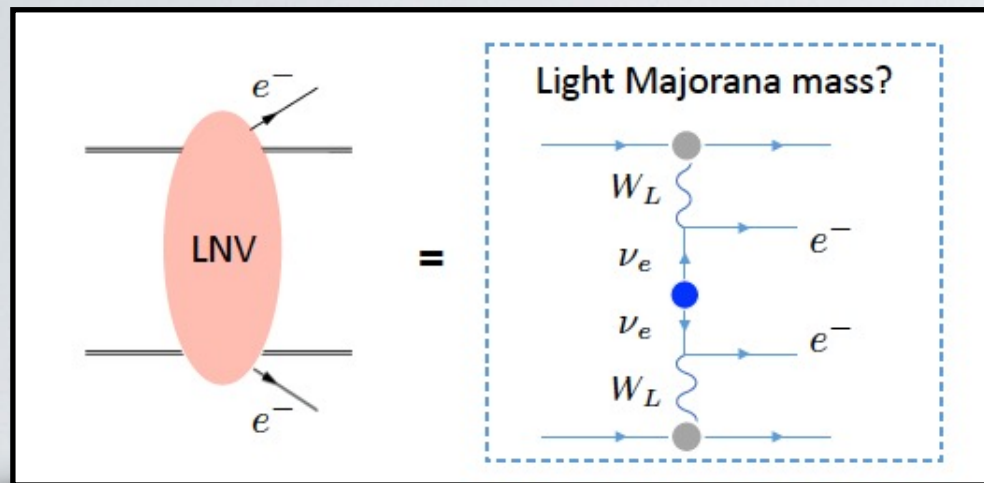
# Interpreting $10^{26}$ years....



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

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

# Interpreting $10^{26}$ years....



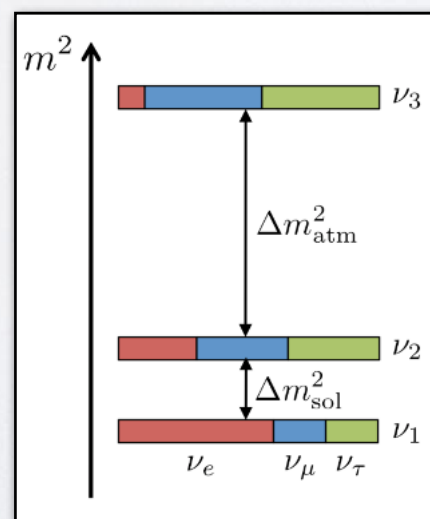
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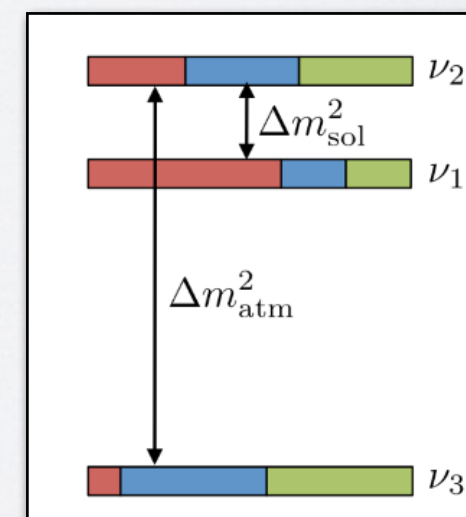
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- $c_{23}$  etc are neutrino mixing angles (**known** from oscillation experiments)
- Know the **mass splittings** but not the **absolute mass scale** nor **mass ordering**
- The **phases** are unknown (some hints for non-zero Dirac phase)

**Normal  
Hierarchy  
(NH)**

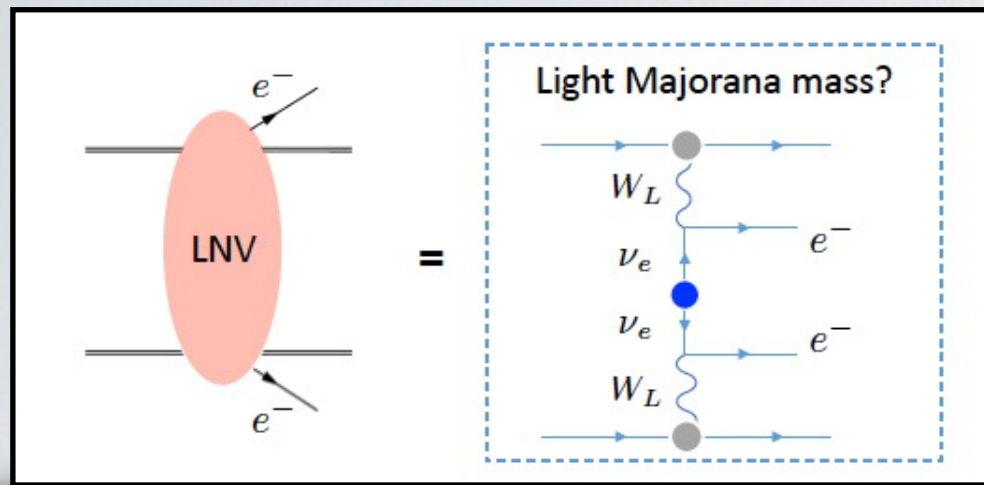


**Inverted  
Hierarchy  
(IH)**



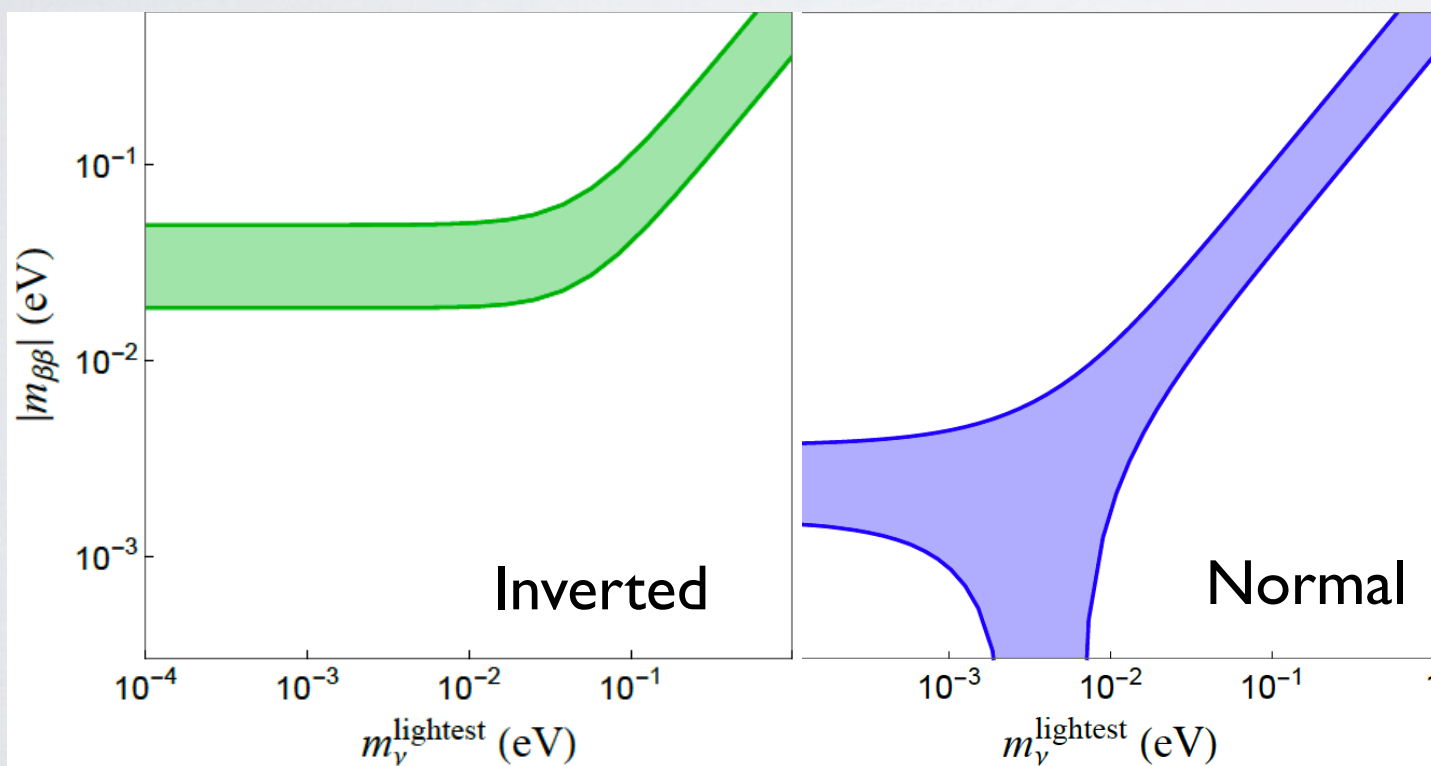


# Interpreting $10^{26}$ years....



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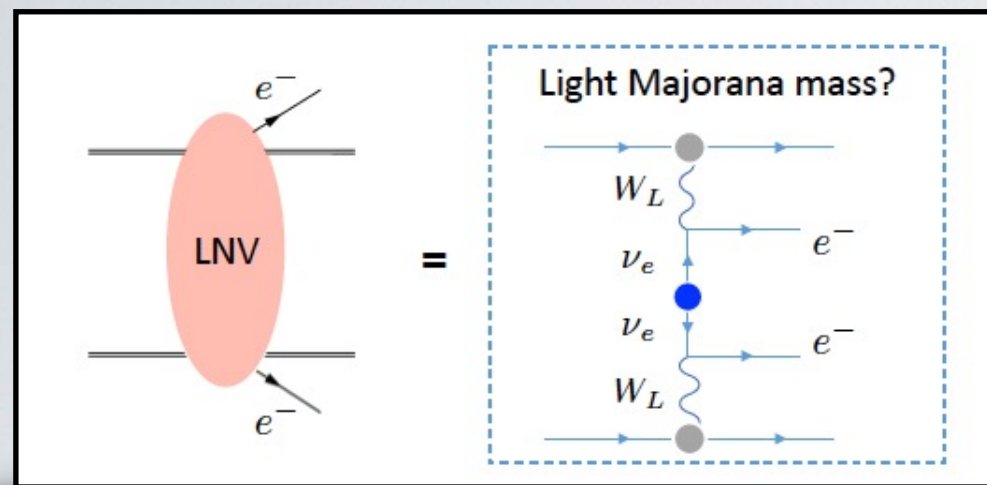
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Vary the lightest mass and the ordering  
Band from varying unknown phases

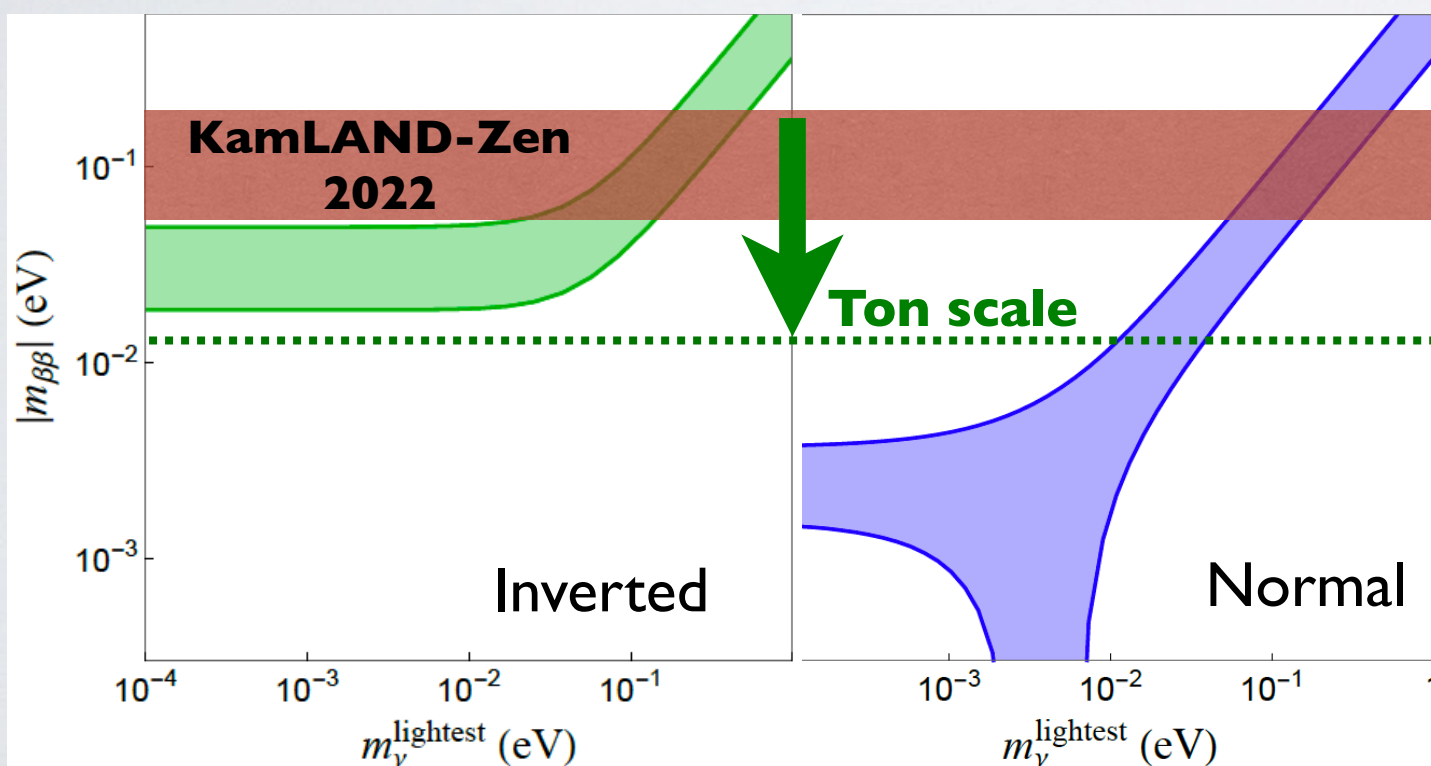
**How close are experiments ?**

# Interpreting $10^{26}$ years....



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

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**Very close !!**

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

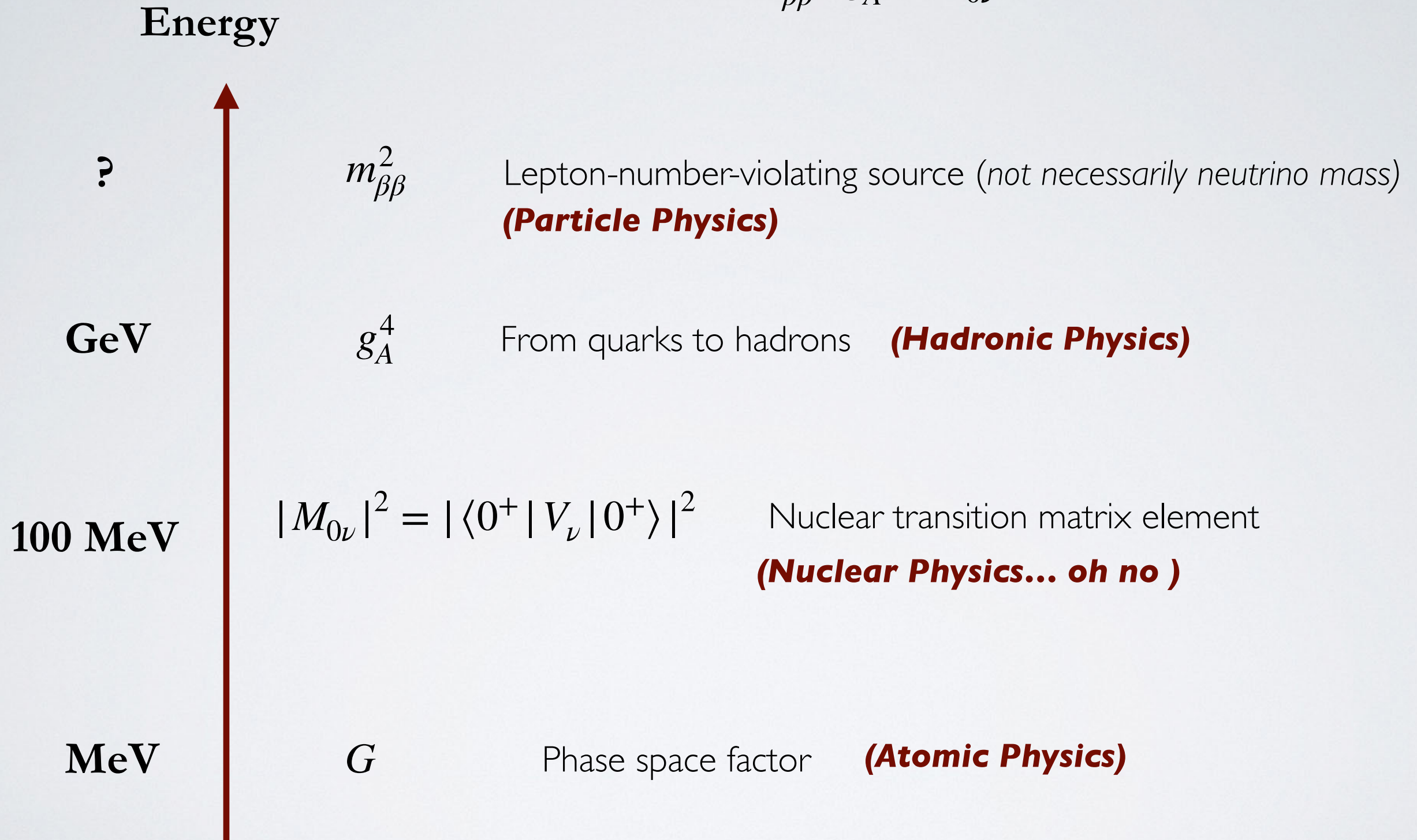
These experiments are probing energy scales up  $10^{14}$  GeV

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



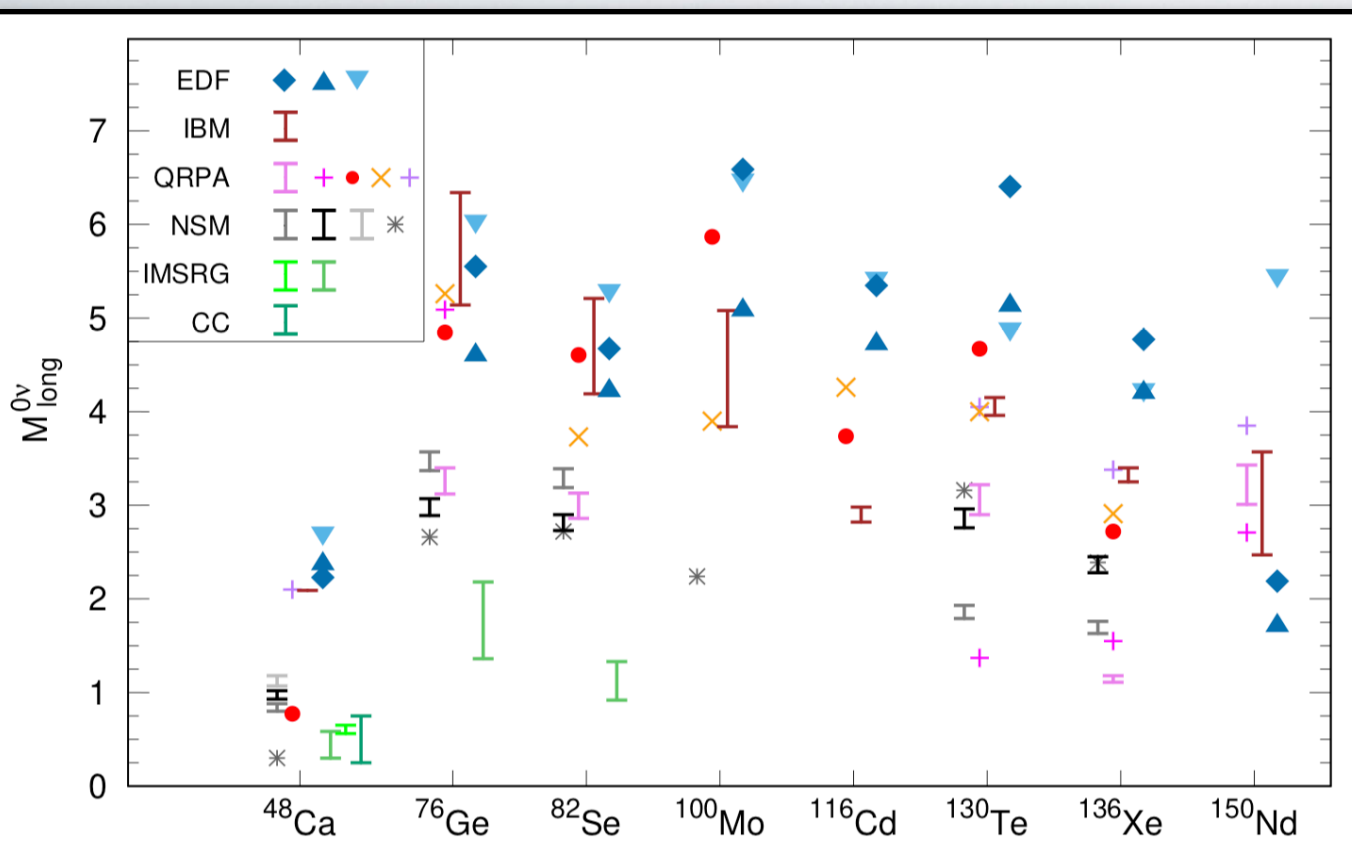
# Anatomy of a decay

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



# Predictions are hard, especially about the future

From: Menendez et al review '22



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

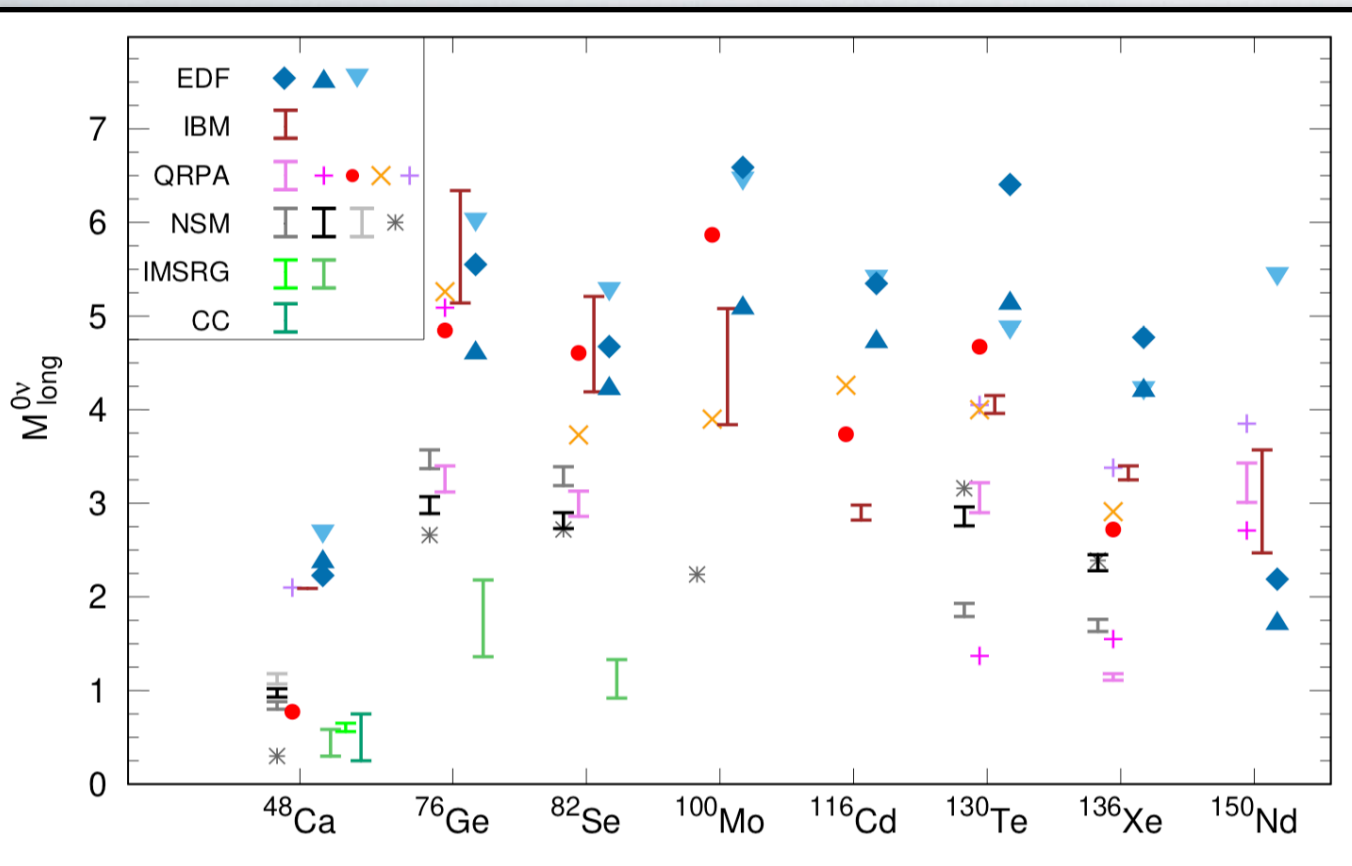
**Uncertainties factor 5 !  
So factor 25 on the life time !**

**Where is this coming from ?**



# Predictions are hard, especially about the future

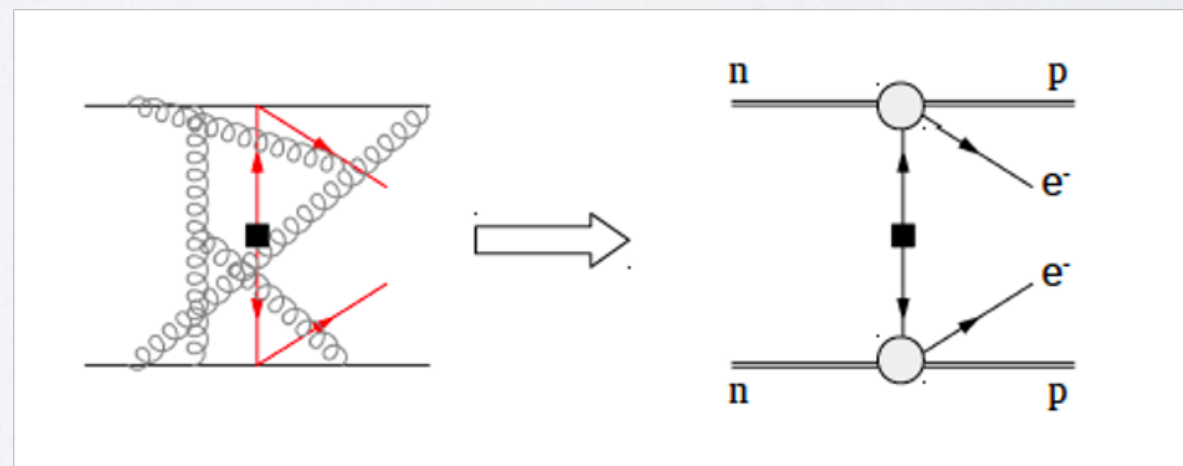
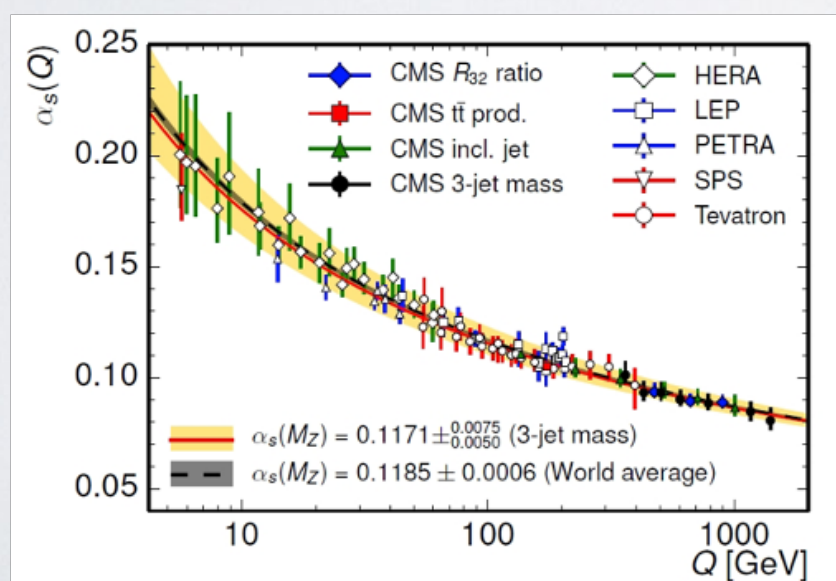
From: Menendez et al review '22



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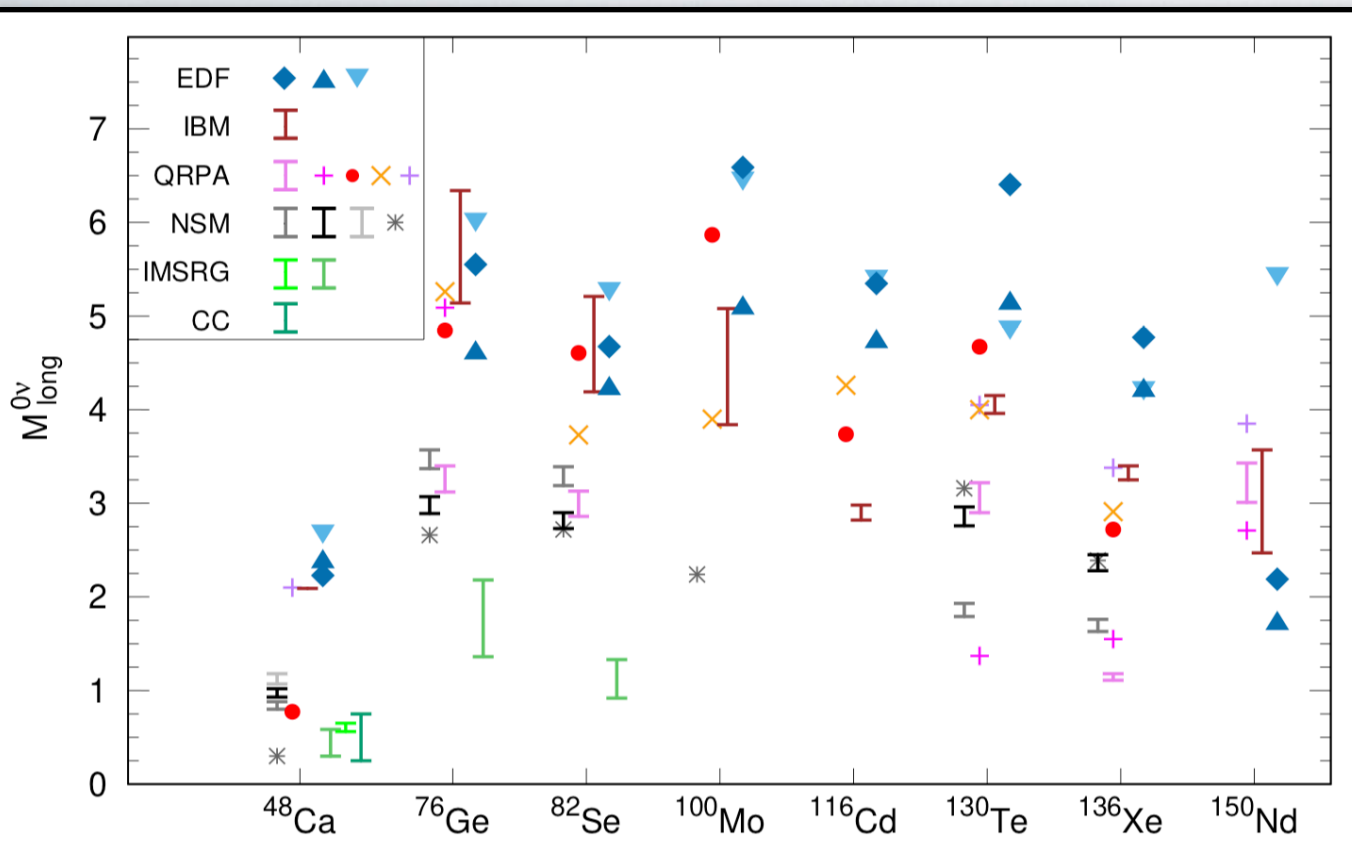
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From: Menendez et al review '22



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

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

**Where is this coming from ?**

- 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  $0\nu\beta\beta$  matrix elements**














# How to get nuclear physics from QCD

- Nuclear physics historically data-driven model-building enterprise (*semi-empirical 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-empirical 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: <i>Nucl.Phys.B</i> 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: <i>Phys.Lett.B</i> 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

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

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

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

# Chiral EFT in a nut-shell

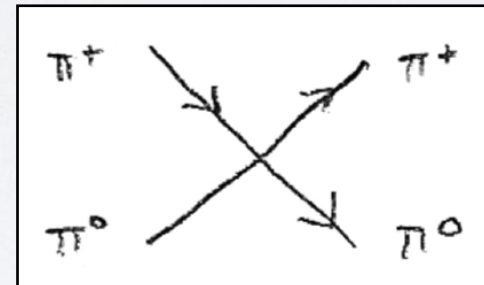
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$$m_\pi^2 \sim (m_u + m_d)$$

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

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



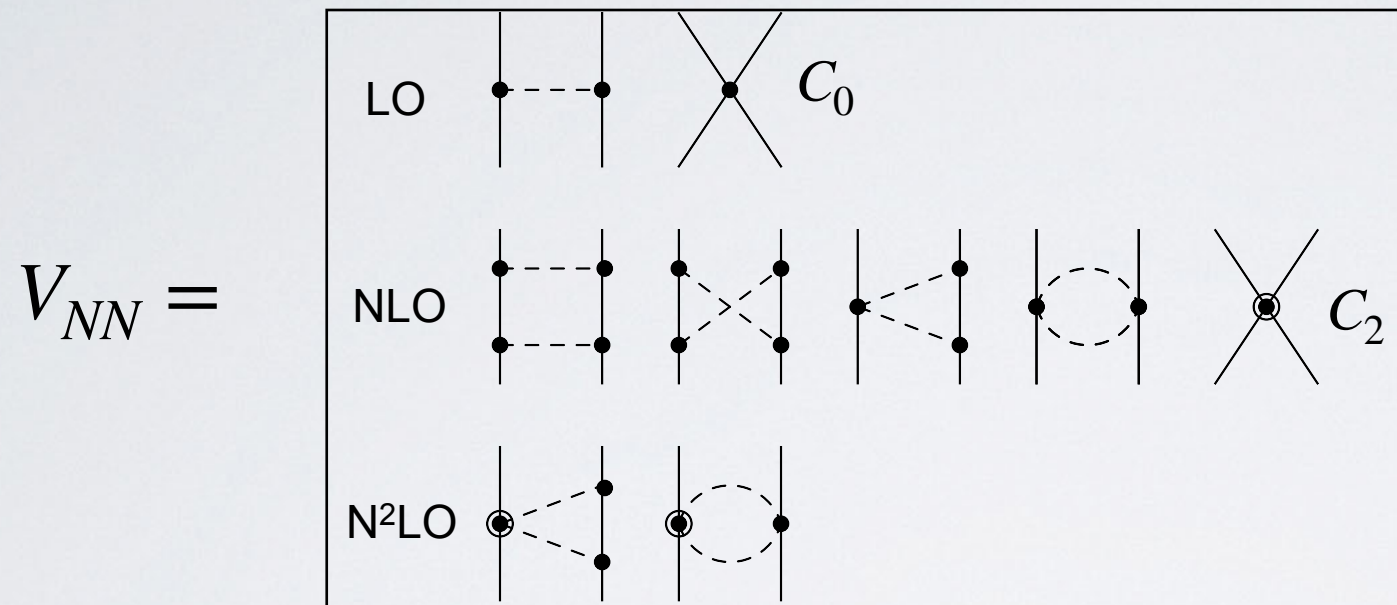
$$\sim (p \cdot p')$$

- Expansion parameter of chPT  $\frac{p}{\Lambda_\chi}$  where  $\Lambda_\chi \sim 1 \text{ GeV}$
- At higher-orders in the expansion more interactions appear  $\mathcal{L} = L_4 (\partial \pi)^4 \quad L_4 \sim \frac{1}{f_\pi^2 \Lambda_\chi^2}$
- 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



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

# Towards nuclear physics

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

$$V_{NN} =$$

LO			$C_0$			
NLO						$C_2$
N <sup>2</sup> LO						

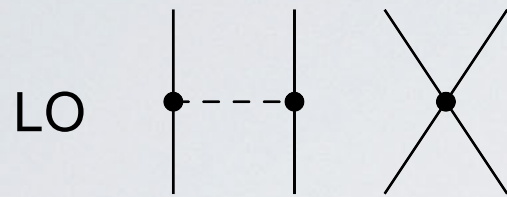
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And many more...

- 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)

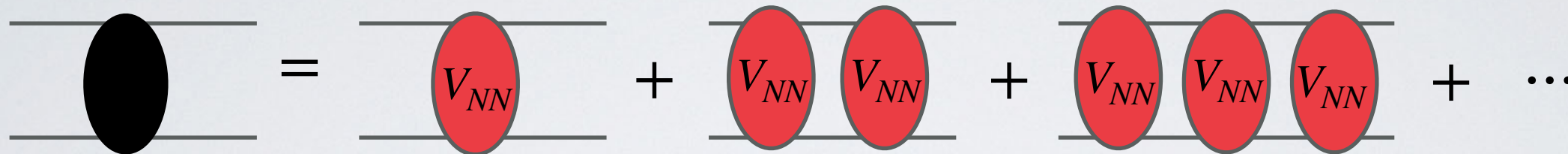
$$\begin{array}{c} \text{---} \\ \bullet \\ \text{---} \end{array} = \begin{array}{c} \text{---} \\ \text{red oval } V_{NN} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{red oval } V_{NN} \quad \text{red oval } V_{NN} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{red oval } V_{NN} \quad \text{red oval } V_{NN} \quad \text{red oval } V_{NN} \\ \text{---} \end{array} + \dots$$



# Example at leading order



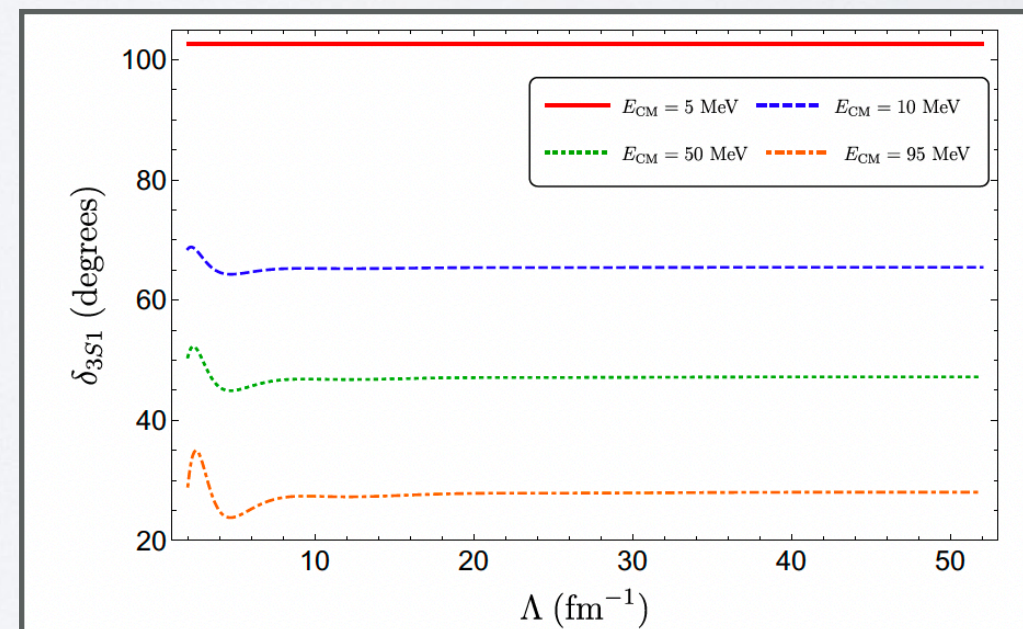
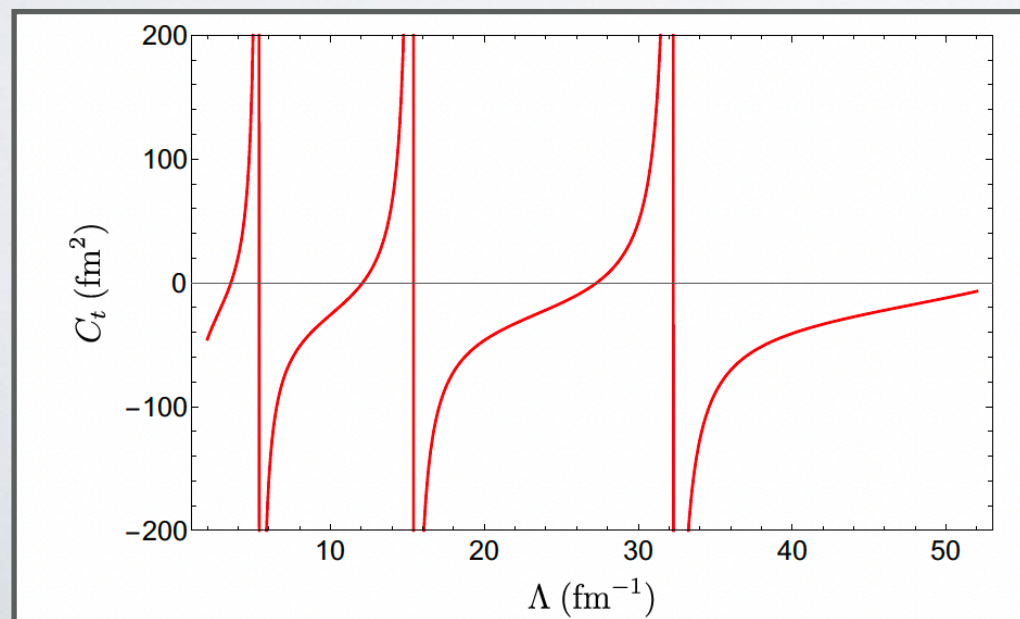
$$V_{NN} = C_0 - \frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$



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

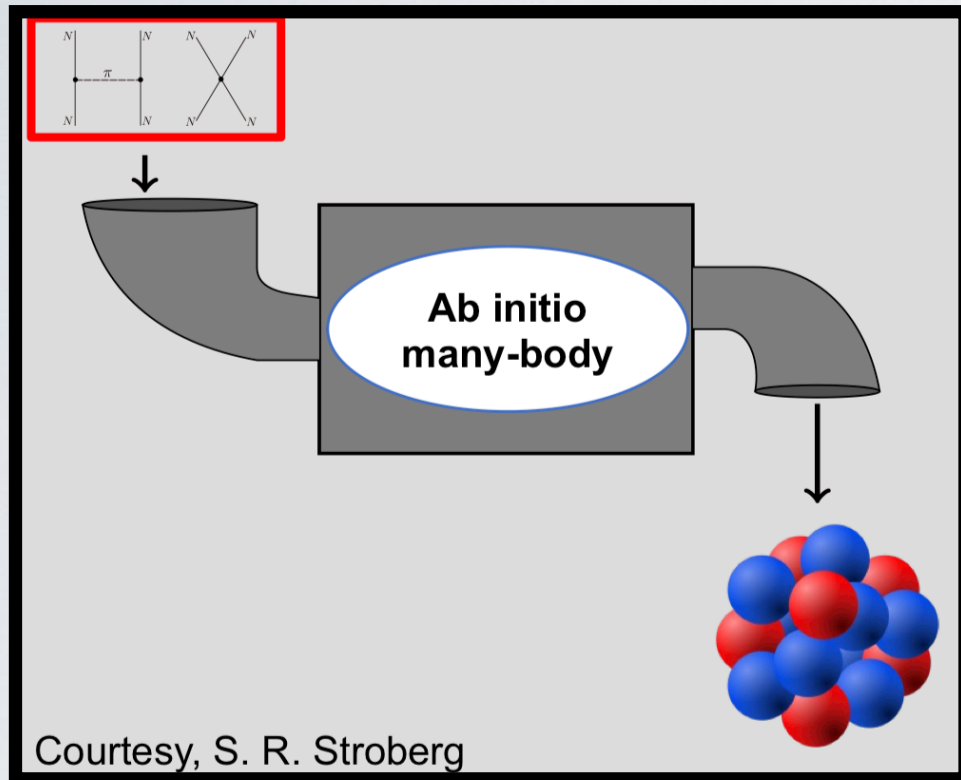
$$V_{NN} \rightarrow e^{-p^6/\Lambda^6} \times V_{NN} \times e^{-p'^6/\Lambda^6}$$

- Fit counter term  $C_0$  to nucleon-nucleon scattering data for each  $\Lambda$
- This is called ‘non-perturbative renormalization’ similar in spirit to what we do in any QFT



# State of the art

- Starting from chiral EFT  $\rightarrow$  derive nuclear properties + reactions



## *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](#)

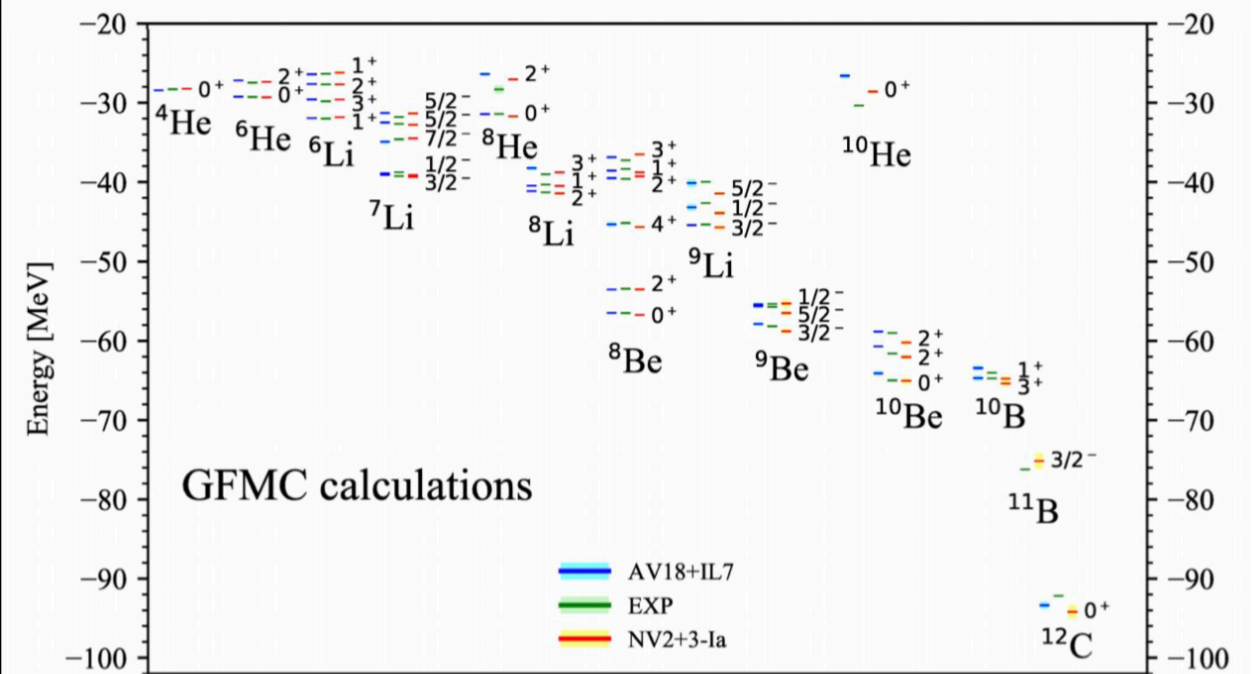
## LETTERS

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

nature  
physics

## Discrepancy between experimental and theoretical $\beta$ -decay rates resolved from first principles

Gysbers et al '20

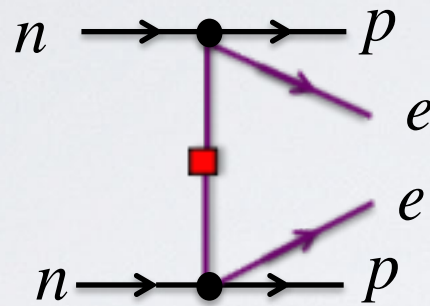


Piarulli et al. PRL 120, 052503 (2018)



# Chiral EFT for 0νbb

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



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

$$\mathbf{q} \sim k_F \sim m_\pi$$

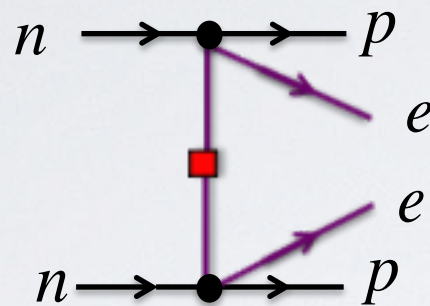
$$V_\nu = (2G_F^2 m_{\beta\beta}) \tau_1^+ \tau_2^+ \frac{1}{\mathbf{q}^2} \left[ (1 + 2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)} \right] \otimes \bar{e}_L e_L^c$$

- Note: the nucleons appear in a bound state and  $\mathbf{q}$  is a loop momentum

# Chiral EFT for $0\nu\beta\beta$

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

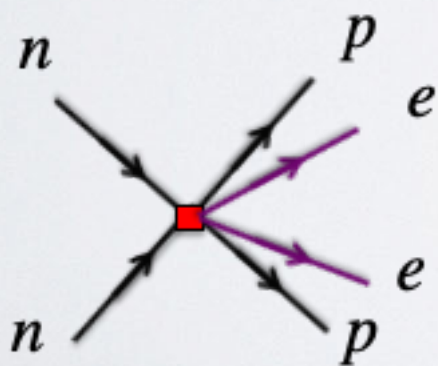
$$\nu_L \longleftrightarrow \text{[red square]} \longleftrightarrow \nu_L$$



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

$$\mathbf{q} \sim k_F \sim m_\pi$$

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



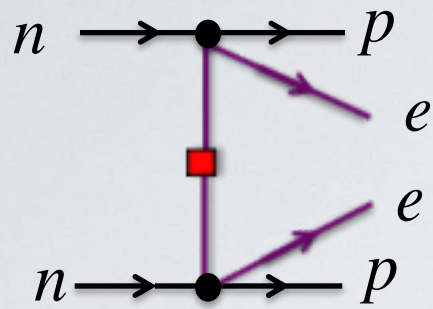
- Contributions from virtual hard neutrinos  $\mathbf{q} \sim \Lambda_\chi \sim 1 \text{ GeV}$
- Weinberg power counting then puts this at higher order

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

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

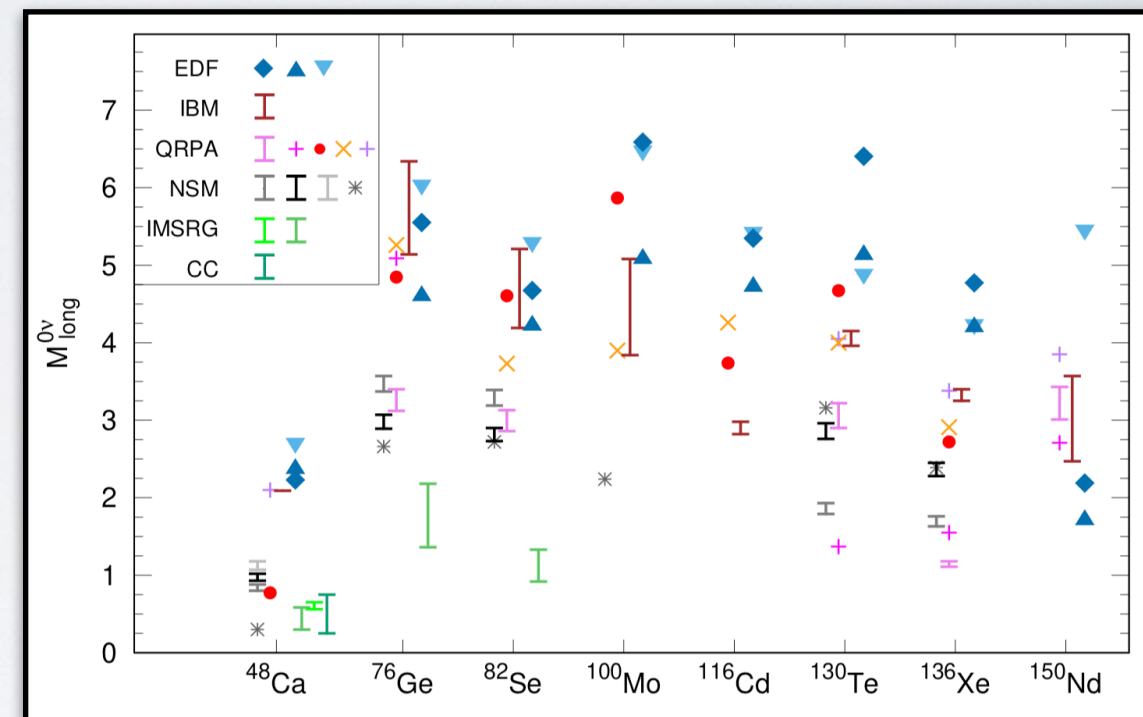


# The leading order process



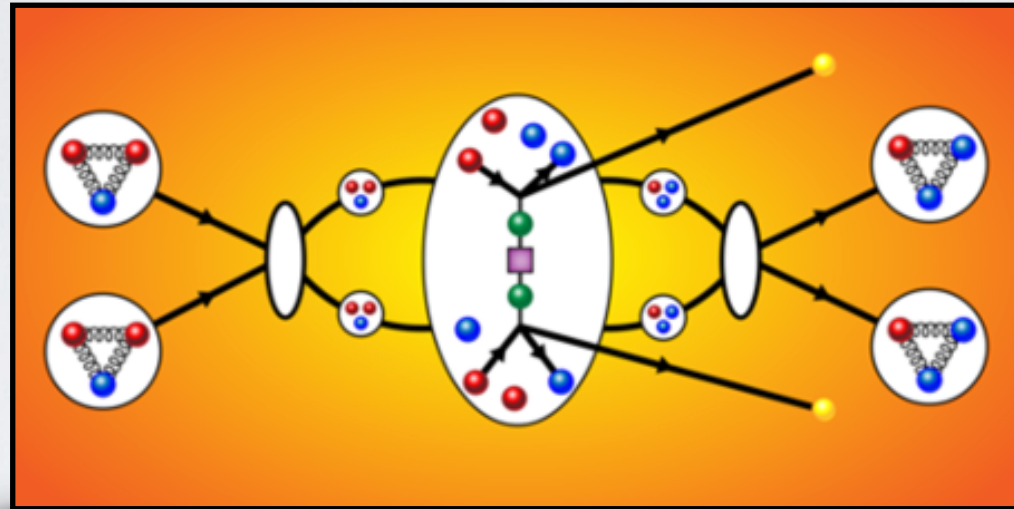
$$V_\nu = (2G_F^2 m_{\beta\beta}) \tau_1^+ \tau_2^+ \frac{1}{\mathbf{q}^2} \left[ (1 + 2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)} \right] \otimes \bar{e}_L e_L^c$$

- Leading-order  $0\nu\text{bb}$  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 $\rightarrow$ Proton-Proton

- Study simplest nuclear process:  $nn \rightarrow pp + ee$



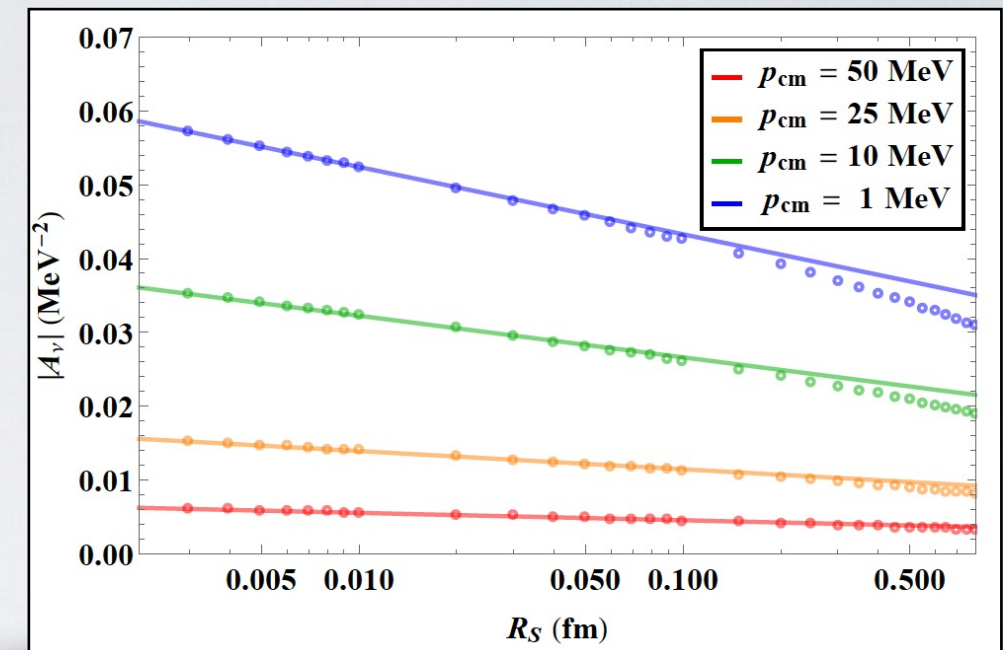
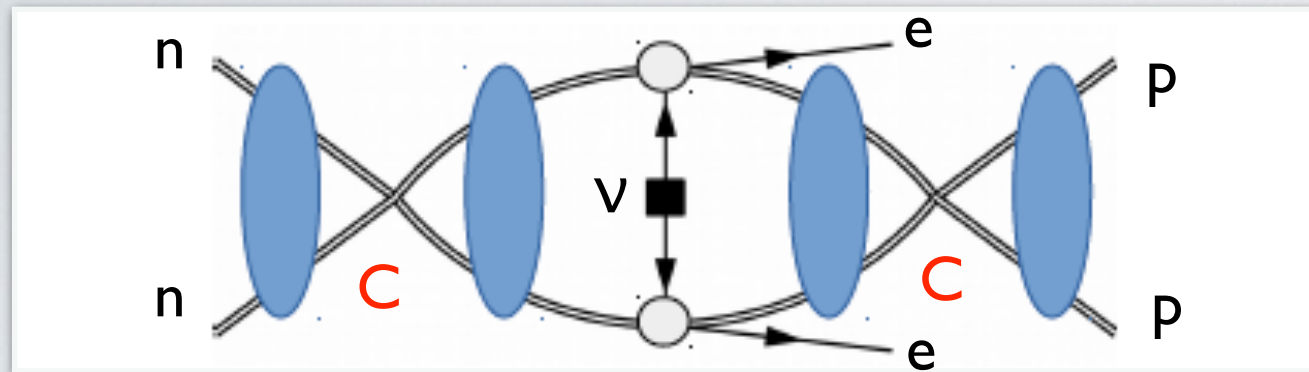
- Compute everything consistently from chiral EFT: wave function + currents
- Then insert the  $0\nu\beta\beta$  potential in renormalized wave function  $\longrightarrow$  **should be finite**

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

$$A_\nu = \langle \Psi_{pp} | V_\nu | \Psi_{nn} \rangle$$



# 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

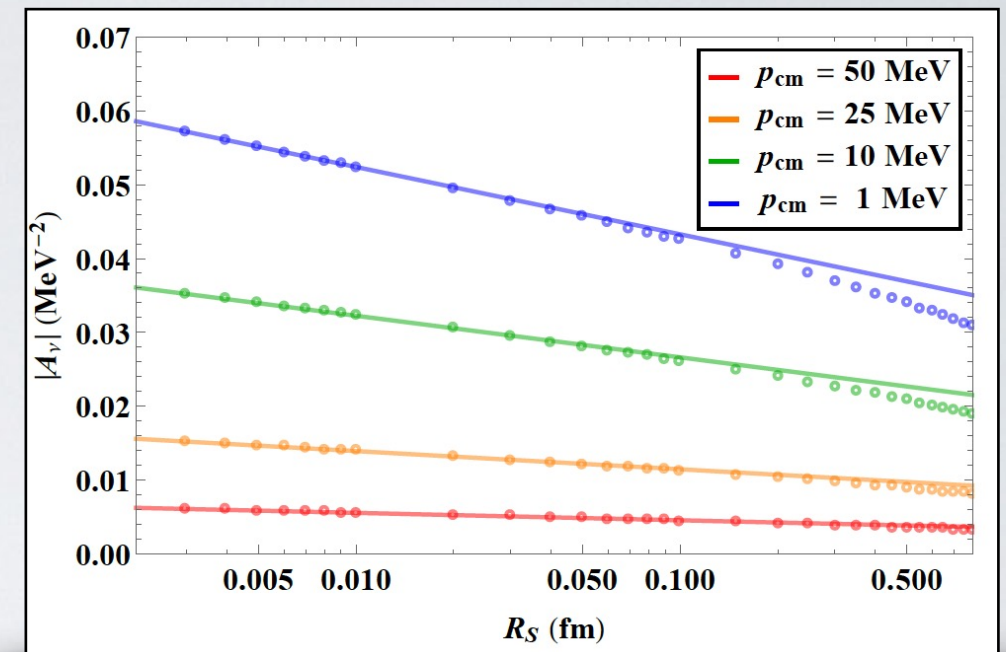
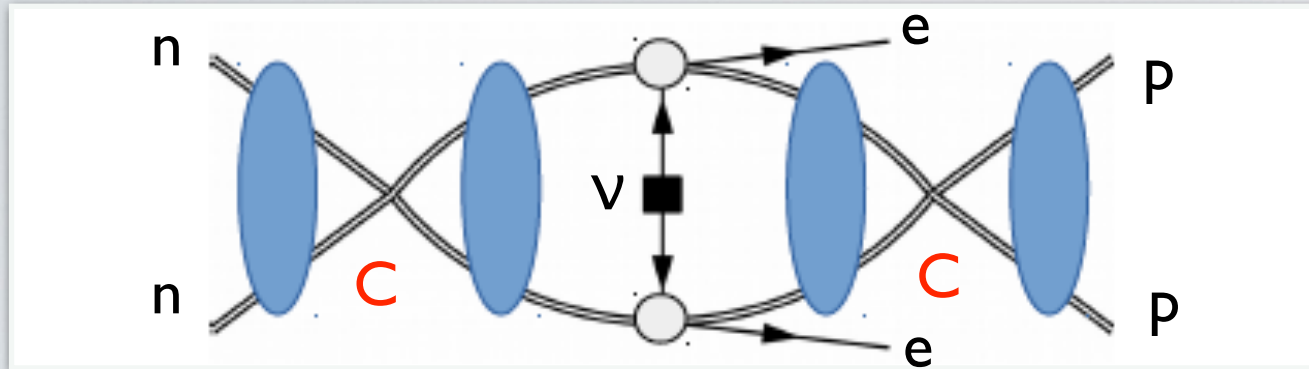
Open Access

## New Leading Contribution to Neutrinoless Double- $\beta$ 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

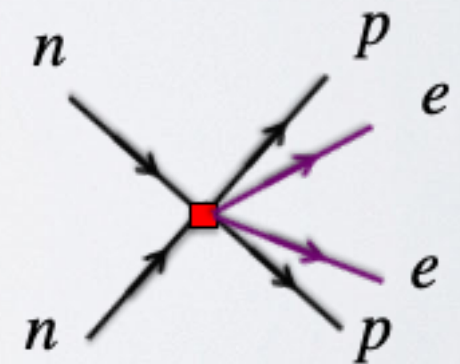
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$$\sim (1 + 2g_A^2) \left( \frac{m_N C_0}{4\pi} \right)^2 \left( \frac{1}{\epsilon} + \log \frac{\mu^2}{p^2} \right)$$

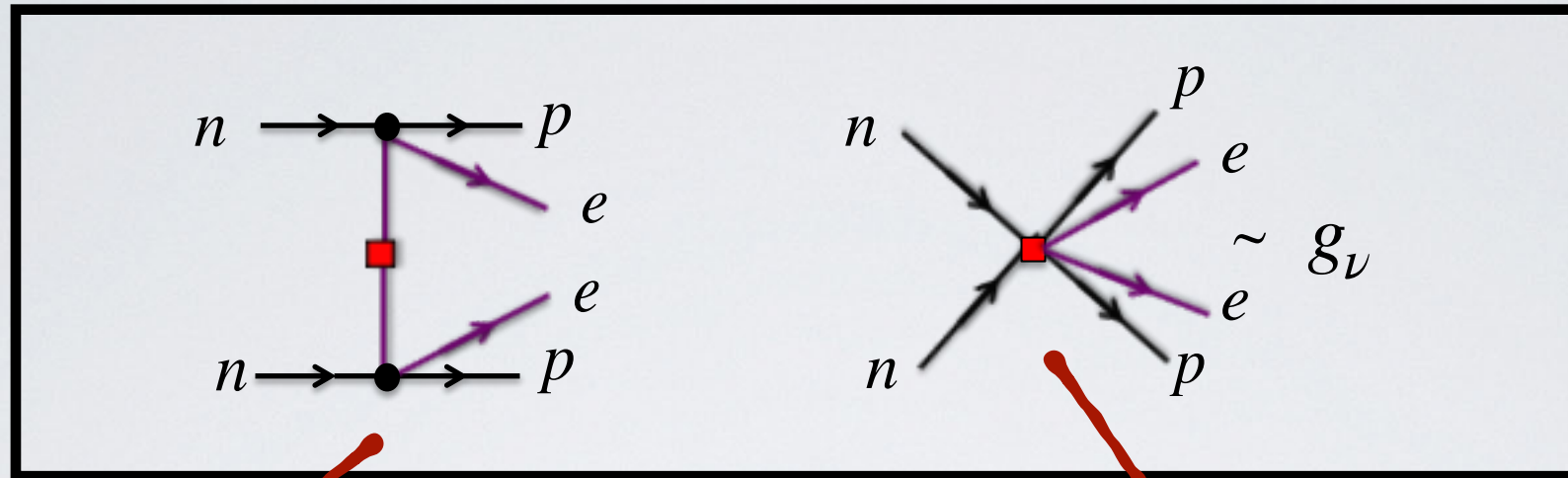
## New divergences

- Divergence indicates sensitivity to short-distance physics
- **Requires a leading order counter term**
- In the literature this is called '*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  $g_\nu$**

- 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

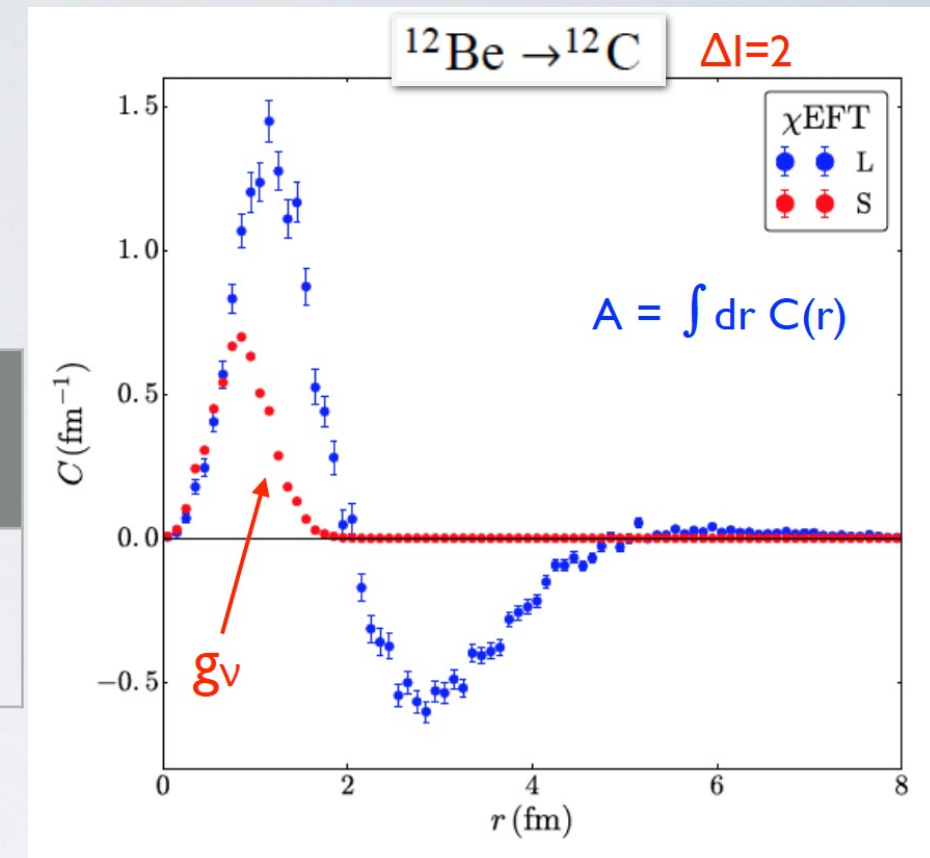
- 0vbb calculations have to be redone —> This is now happening !

# Impact on nuclear matrix elements

Pastore, Piarulli et al '19

- Use chiral potentials to generate wave functions

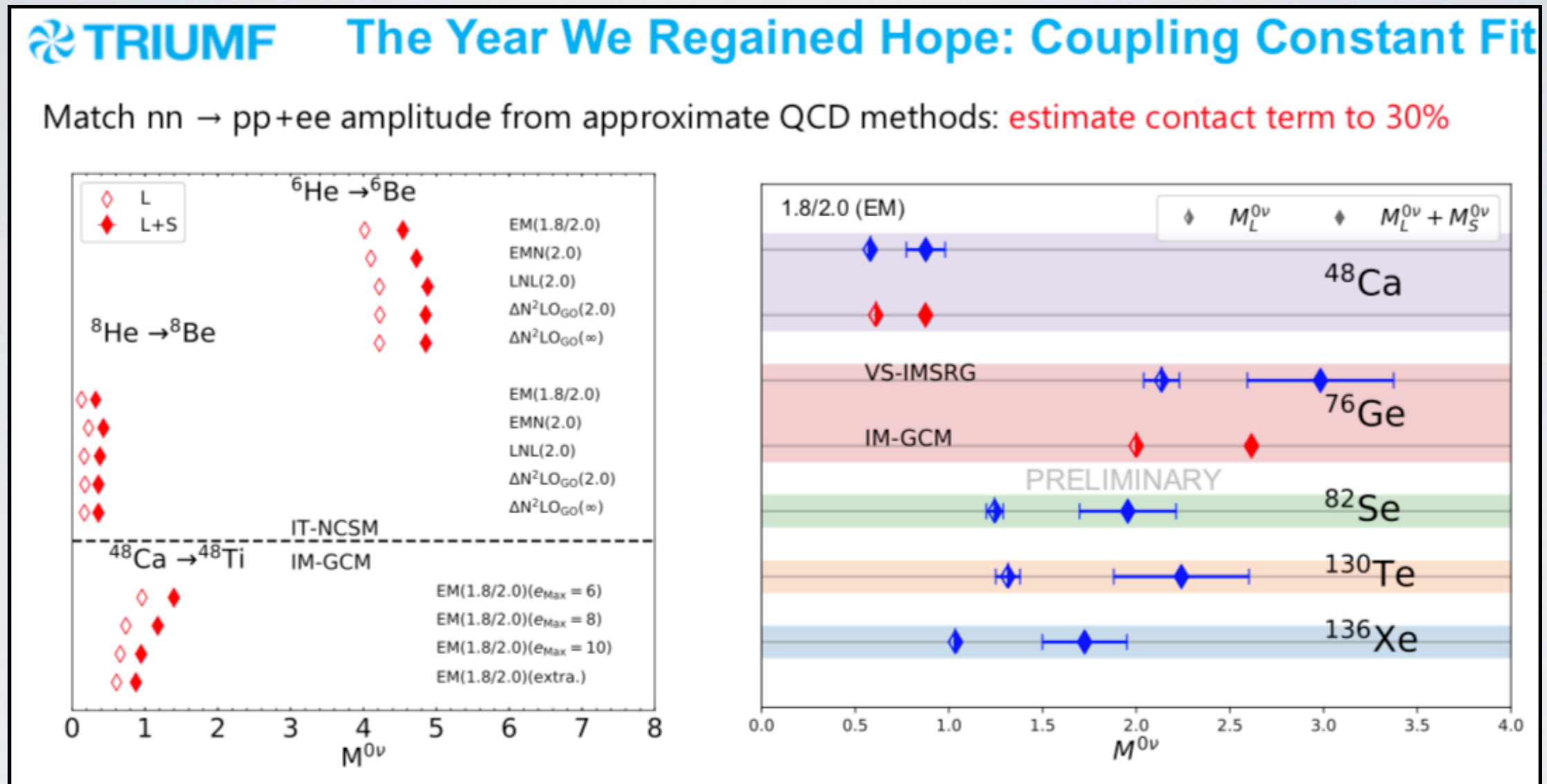
Nuclear matrix elements	Long Range	Short Range
$^{12}\text{Be} \rightarrow ^{12}\text{C} + e^- + e^-$	0.7	0.5



- **Short-distance effects are sizable and change matrix elements by almost 100%**
- **Caveat:** These are not nuclei of experimental interest



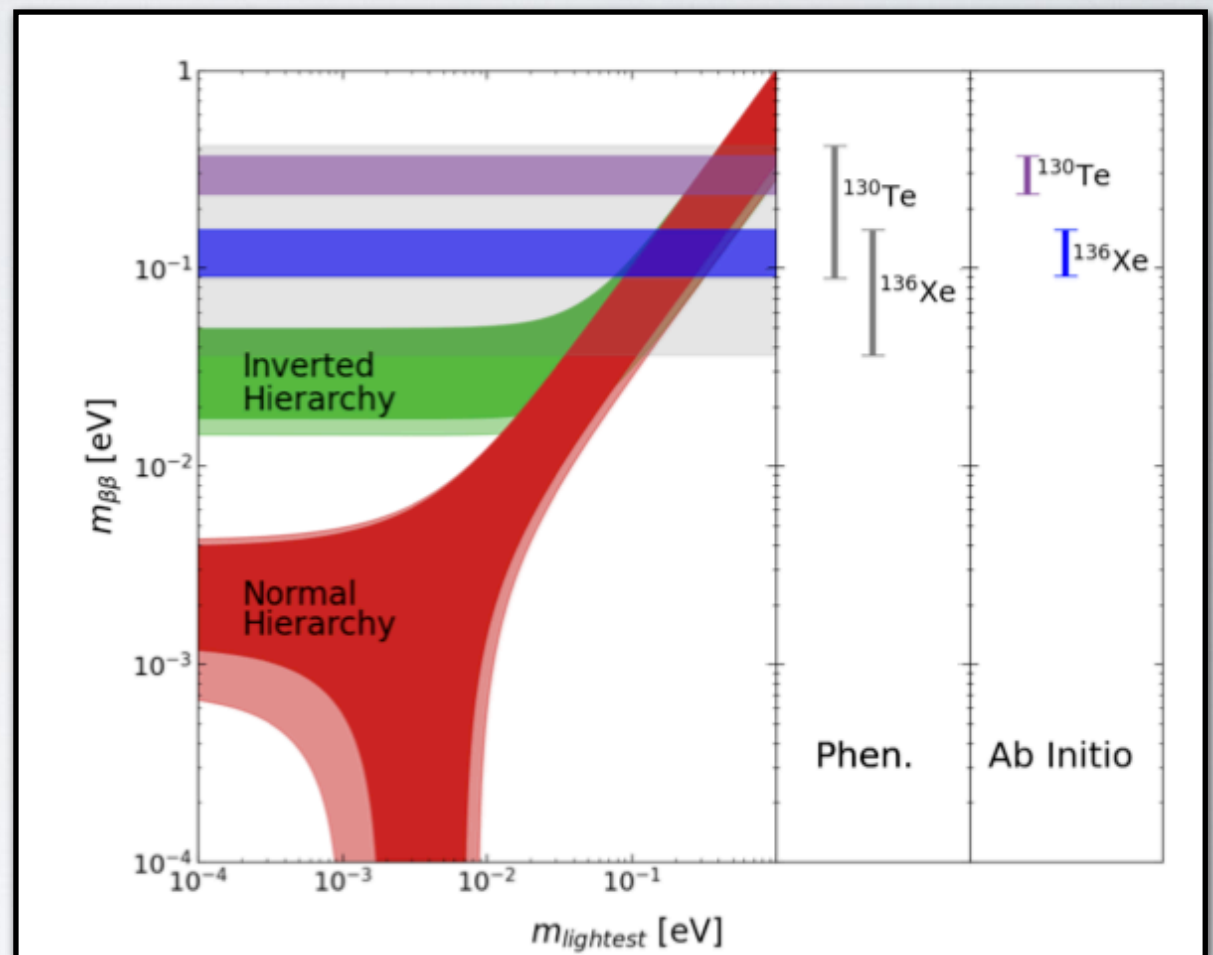
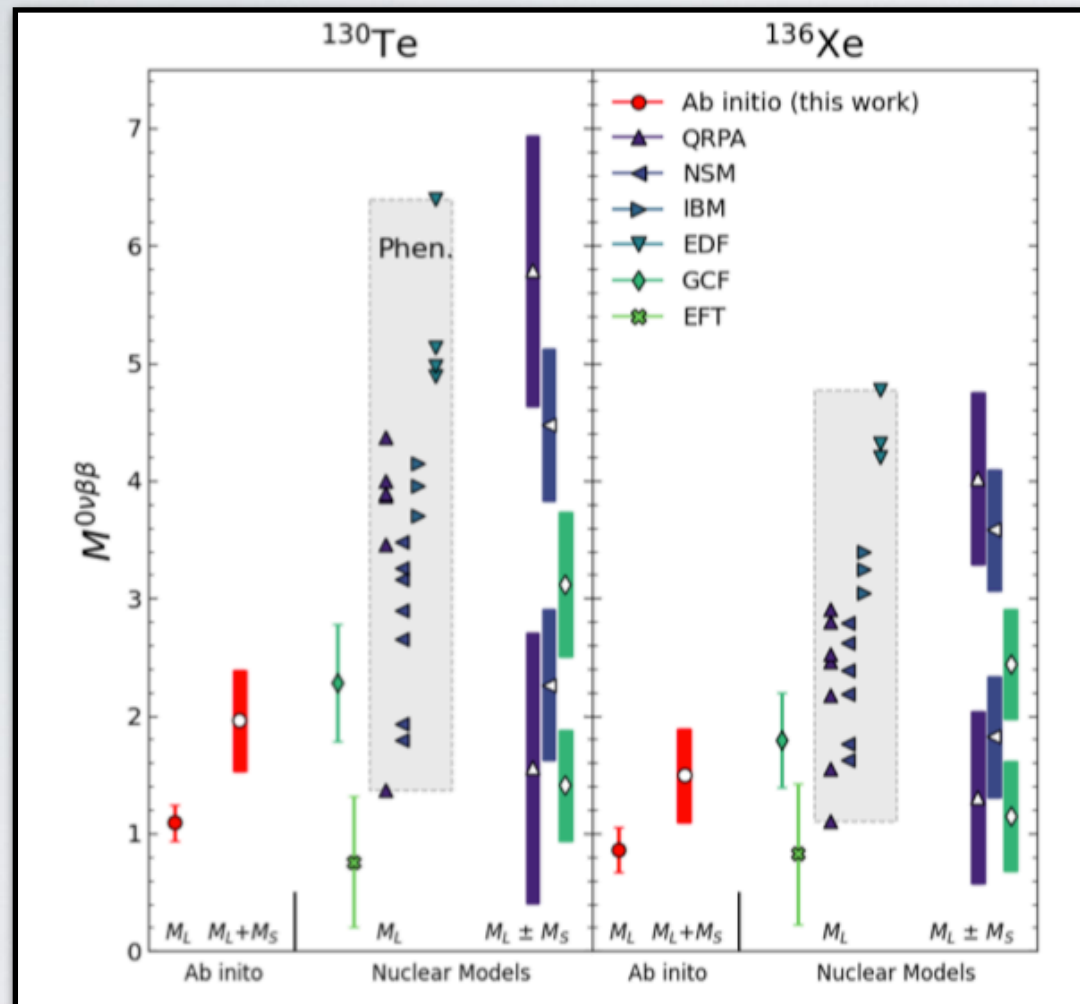
# Impact on realistic nuclei



- 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....



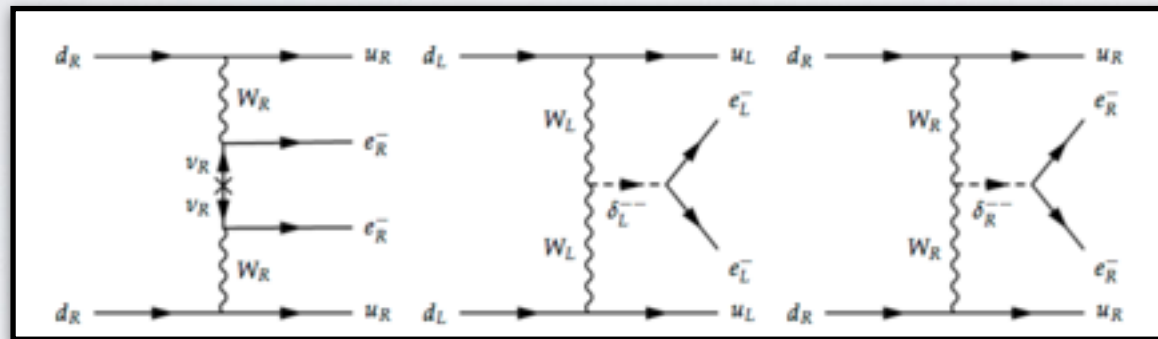
# The plan of attack

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* ....

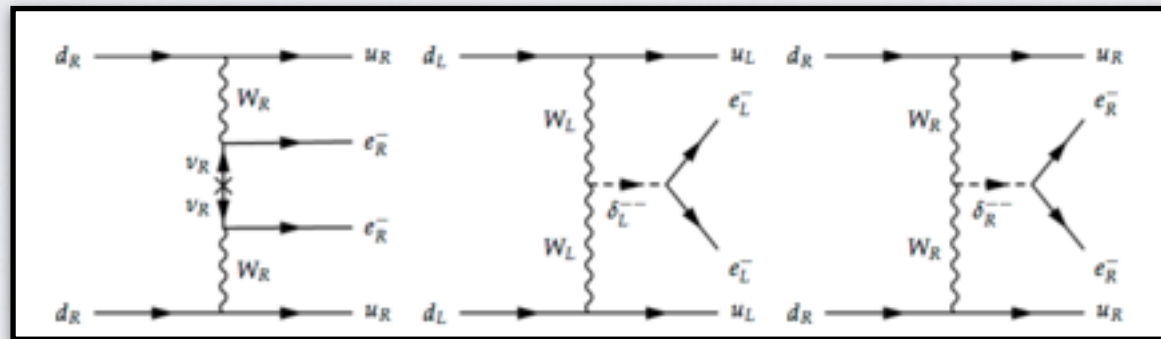


- No light neutrinos appear at all in these processes but **same observable signature**



# 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**
- If scale of LNV is high they can be captured by effective field theory techniques

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

- Disentangling the origin from  $0\nu\beta\beta$  measurements will be a **hard (luxury)** problem

# Higher-dimensional operators

- Effective operators appear at odd dimension (5, 7, 9, .....)

Kobach '16

# Dimension-five

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

- One operator
- Induces Majorana mass

# Dimension-seven

Lehman ‘14

1 :  $\psi^2 H^4 + \text{h.c.}$

$\mathcal{O}_{LEH}$	$\epsilon_{ij} \epsilon_{mn} (L^i C L^m) H^j H^n (H^\dagger H)$
---------------------	---

3 :  $\psi^2 H^3 D + \text{h.c.}$

$\mathcal{O}_{LHDn}$	$\epsilon_{ij} \epsilon_{mn} (L^i C \gamma_\mu \epsilon) H^j H^n D^\mu H^n$
----------------------	---

5 :  $\psi^4 D + \text{h.c.}$

$\mathcal{O}_{LL\partial D}^{(1)}$	$\epsilon_{ij} (\partial_\mu u) (L^i C D^\mu L^j)$
$\mathcal{O}_{LL\partial D}^{(2)}$	$\epsilon_{ij} (\partial_\mu u) (L^i C \partial^{\mu\nu} D_\nu L^j)$
$\mathcal{O}_{LQ\partial D}^{(1)}$	$(Q C \gamma_\mu d) (\tilde{L} D^\mu d)$
$\mathcal{O}_{LQ\partial D}^{(2)}$	$(\tilde{L} \gamma_\mu Q) (d C D^\mu d)$
$\mathcal{O}_{d\partial D D}$	$(\bar{d} \gamma_\mu d) (d C D^\mu d)$

2 :  $\psi^2 H^2 X + \text{h.c.}$

$\mathcal{O}_{LEH}^{(1)}$	$\epsilon_{ij} \epsilon_{mn} (L^i C L^m D^\mu L^j) H^n (D_\mu H^n)$
$\mathcal{O}_{LEH}^{(2)}$	$\epsilon_{mn} \epsilon_{jk} (L^i C L^m D^\mu L^j) H^n (D_\mu H^n)$

4 :  $\psi^2 H^2 X + \text{h.c.}$

$\mathcal{O}_{LEH}$	$\epsilon_{ij} \epsilon_{mn} (L^i C \gamma_\mu L^m) H^j H^n D^\mu H^n$
$\mathcal{O}_{LEH}$	$\epsilon_{ij} (\gamma^\mu \epsilon)_{mn} (L^i C \gamma_\mu L^m) H^j H^n D^\mu H^n$

6 :  $\psi^4 H + \text{h.c.}$

$\mathcal{O}_{LL\partial H}$	$\epsilon_{ij} \epsilon_{mn} (\partial_\mu L^i) (L^m C L^n) H^n$
$\mathcal{O}_{LL\partial H}^{(1)}$	$\epsilon_{ij} \epsilon_{mn} (\partial_\mu L^i) (Q^m C L^n) H^n$
$\mathcal{O}_{LL\partial H}^{(2)}$	$\epsilon_{mn} \epsilon_{jk} (\partial_\mu L^i) (Q^m C L^n) H^n$
$\mathcal{O}_{LL\partial H}$	$\epsilon_{ij} (\tilde{Q}_m d) (L^m C L^n) H^n$
$\mathcal{O}_{LQ\partial H}$	$\epsilon_{ij} (\tilde{L}_m d) (Q^m C Q^n) \tilde{H}^j$
$\mathcal{O}_{L\partial H H}$	$(d C d) (\tilde{L} d) H$
$\mathcal{O}_{L\partial H H}$	$(\tilde{L} d) (u C d) \tilde{H}$
$\mathcal{O}_{L\partial H H}$	$\epsilon_{ij} (L^i C \gamma_\mu \epsilon) (\partial^\mu u) H^j$
$\mathcal{O}_{Q\partial H H}$	$\epsilon_{ij} (u C Q^n) (d C d) \tilde{H}^j$

- 12  $\Delta L=2$  operators

# Dimension-nine

Li et al ‘20

Many many terms

19 4-quark 2-lepton operators after EWSB

Graesser et al ‘17 ‘18



# Higher-dimensional operators

- Effective operators appear at odd dimension (5, 7, 9, .....)

Kobach '16

Dimension-five	Dimension-seven	Dimension-nine														
$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H}) (\tilde{H}^T L)$ <ul style="list-style-type: none"> <li>One operator</li> <li>Induces Majorana mass</li> </ul>	<div>Lehman '14</div> <div>1: <math>\psi^2 H^4 + \text{h.c.}</math></div> <table> <tr> <td><math>\mathcal{O}_{LH}</math></td> <td><math>\epsilon_{ij} \epsilon_{mn} (L^i C L^m) H^j H^n (H^\dagger H)</math></td> </tr> </table> <div>3: <math>\psi^2 H^3 D + \text{h.c.}</math></div> <table> <tr> <td><math>\mathcal{O}_{LRD}</math></td> <td><math>\epsilon_{ij} \epsilon_{mn} (L^i C \gamma_\mu \epsilon) H^j H^m D^\mu H^n</math></td> </tr> </table> <div>5: <math>\psi^4 D + \text{h.c.}</math></div> <table> <tr> <td><math>\mathcal{O}_{LL\partial D}^{(1)}</math></td> <td><math>\epsilon_{ij} (\partial_\mu u) (L^i C D^\mu L^j)</math></td> </tr> <tr> <td><math>\mathcal{O}_{LL\partial D}^{(2)}</math></td> <td><math>\epsilon_{ij} (\partial_\mu u) (L^i C \partial^{\mu\nu} D_\nu L^j)</math></td> </tr> <tr> <td><math>\mathcal{O}_{LQ\partial D}^{(1)}</math></td> <td><math>(Q C \gamma_\mu d) (\tilde{L} D^\mu d)</math></td> </tr> <tr> <td><math>\mathcal{O}_{LQ\partial D}^{(2)}</math></td> <td><math>(\tilde{L} \gamma_\mu Q) (d C D^\mu d)</math></td> </tr> <tr> <td><math>\mathcal{O}_{d\partial D}</math></td> <td><math>(\bar{d} \gamma_\mu d) (d C D^\mu d)</math></td> </tr> </table> <div>• 12 <math>\Delta L=2</math> operators</div>	$\mathcal{O}_{LH}$	$\epsilon_{ij} \epsilon_{mn} (L^i C L^m) H^j H^n (H^\dagger H)$	$\mathcal{O}_{LRD}$	$\epsilon_{ij} \epsilon_{mn} (L^i C \gamma_\mu \epsilon) H^j H^m D^\mu H^n$	$\mathcal{O}_{LL\partial D}^{(1)}$	$\epsilon_{ij} (\partial_\mu u) (L^i C D^\mu L^j)$	$\mathcal{O}_{LL\partial D}^{(2)}$	$\epsilon_{ij} (\partial_\mu u) (L^i C \partial^{\mu\nu} D_\nu L^j)$	$\mathcal{O}_{LQ\partial D}^{(1)}$	$(Q C \gamma_\mu d) (\tilde{L} D^\mu d)$	$\mathcal{O}_{LQ\partial D}^{(2)}$	$(\tilde{L} \gamma_\mu Q) (d C D^\mu d)$	$\mathcal{O}_{d\partial D}$	$(\bar{d} \gamma_\mu d) (d C D^\mu d)$	<div>Li et al '20</div> <div>Many many terms</div> <div>19 4-quark 2-lepton operators after EWSB</div> <div>Graesser et al '17 '18</div>
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$\mathcal{O}_{d\partial D}$	$(\bar{d} \gamma_\mu d) (d C D^\mu d)$															

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

$$c_5 \sim y_e^2 \sim 10^{-10}$$

$$c_7 \sim y_e^1 \sim 10^{-5}$$

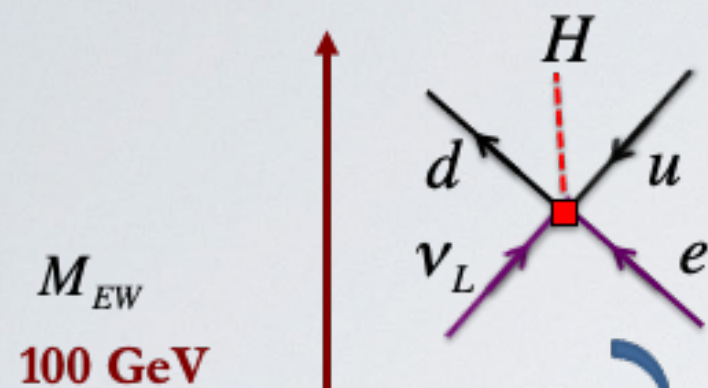
$$c_9 \sim y_e^0 \sim 1$$

- If scale is not too high:

$$\frac{v^2}{\Lambda^2} \sim y_e \rightarrow \Lambda \simeq (10 - 100) \text{ TeV}$$

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

# Example dim-7 operators

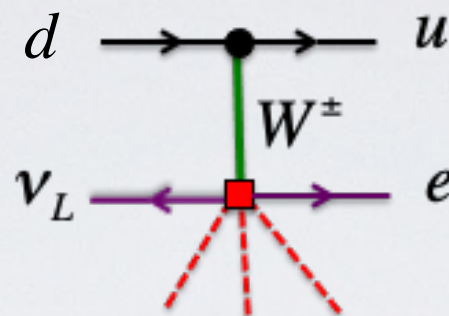
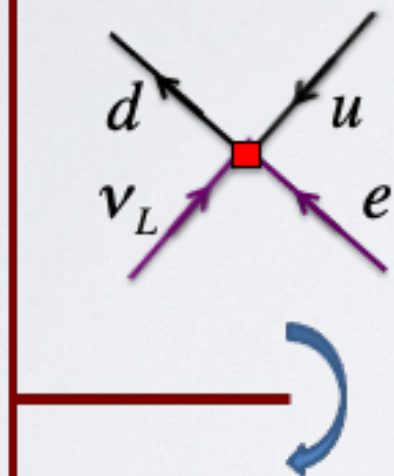


Integrate out heavy SM field and Higgs takes vev

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

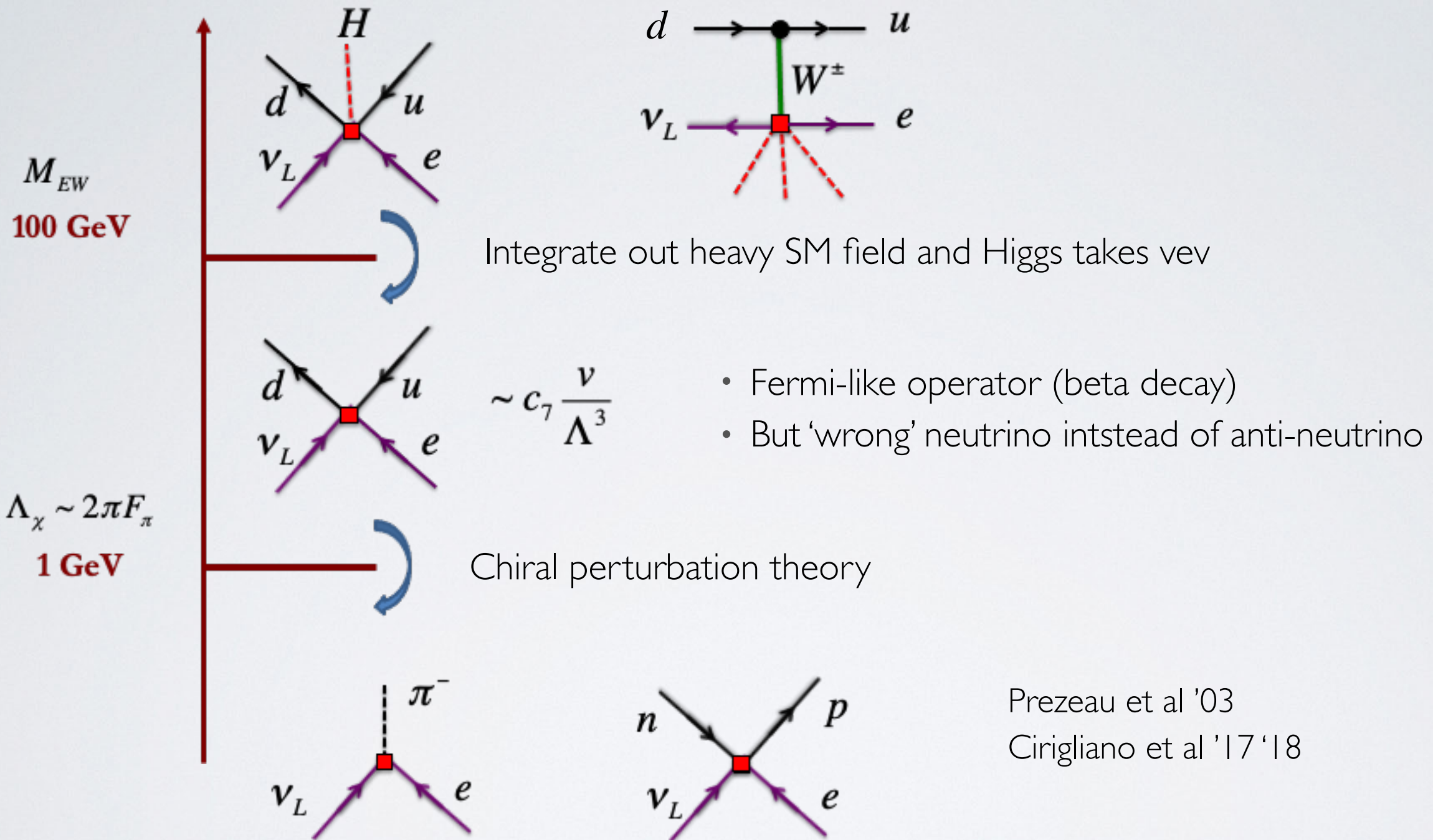
- Fermi-like operator (beta decay)
- But 'wrong' neutrino instead of anti-neutrino

$\Lambda_\chi \sim 2\pi F_\pi$   
1 GeV



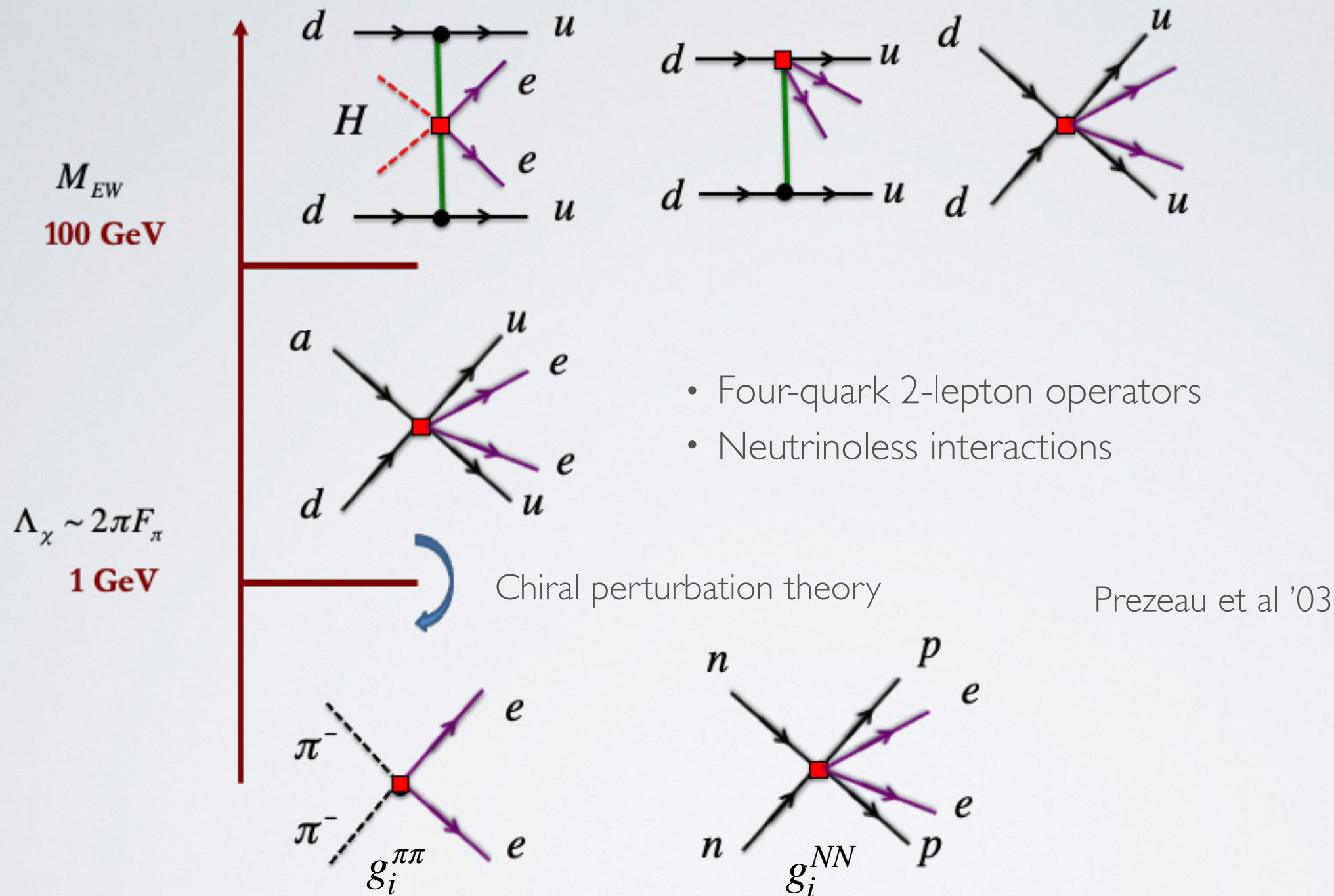


# Example dim-7 operators



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

# Example dim-9 operators



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

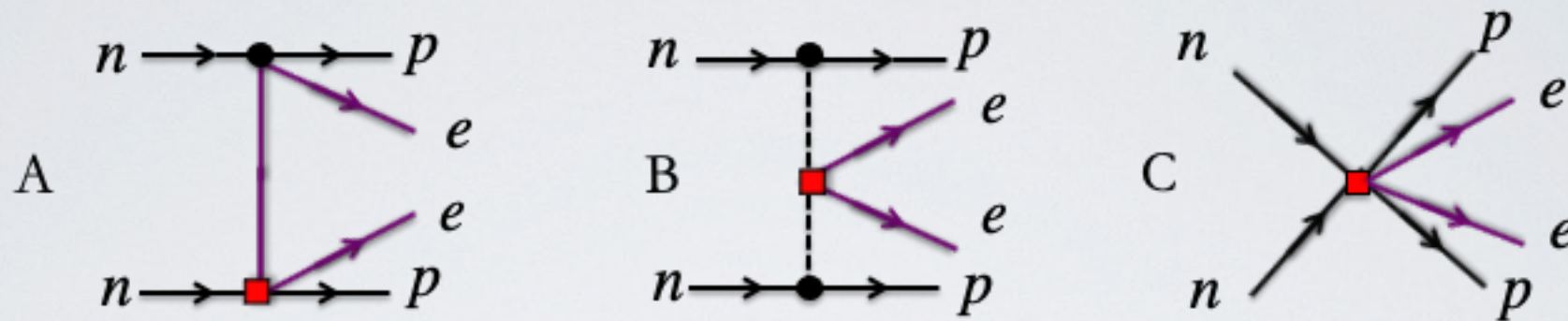
$$g_4^{\pi\pi} = -(1.9 \pm 0.2) \text{ GeV}^2$$

$$g_5^{\pi\pi} = -(8.0 \pm 0.6) \text{ GeV}^2$$

Nicholson et al '18



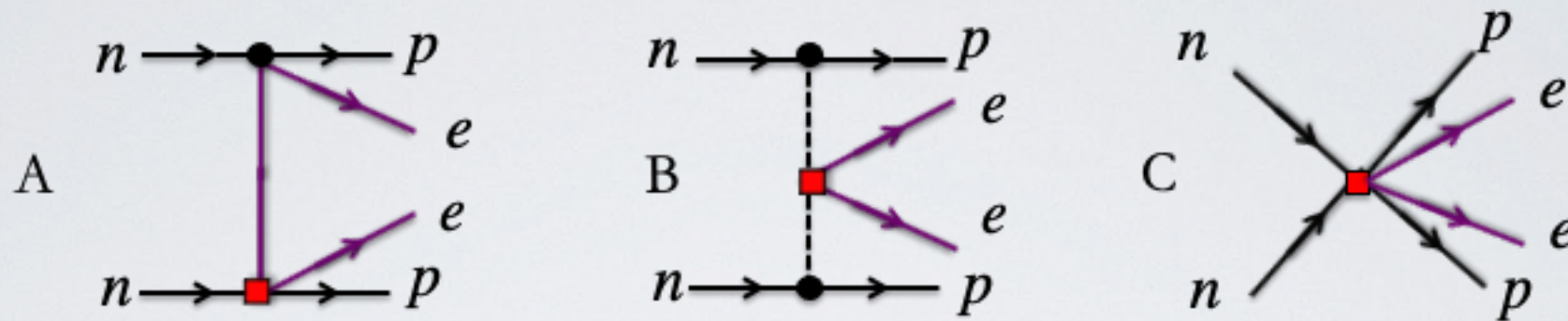
# New 0vbb topologies



- Straightforward to calculate generalized 0vbb transition current
- Need additional nuclear matrix elements (NMEs)

Cirigliano et al '17 '18

# New 0vbb topologies

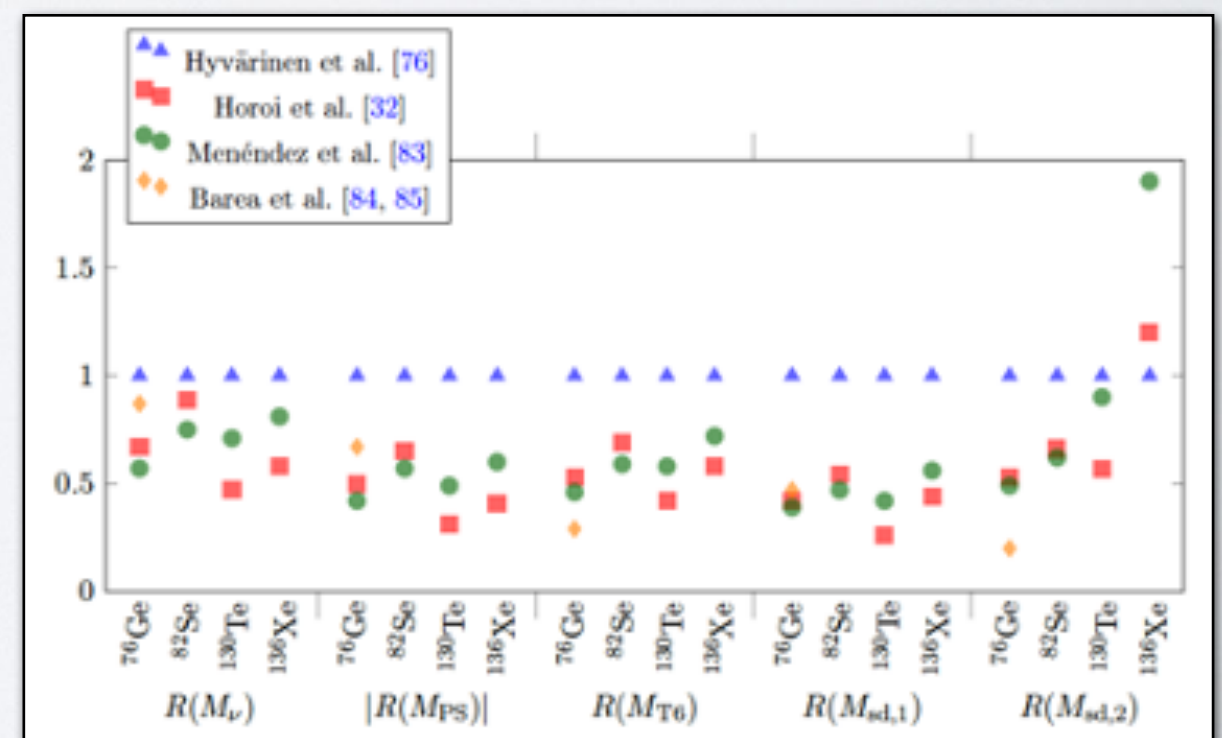


- Straightforward to calculate generalized 0vbb transition current Cirigliano et al '17 '18
- Need additional nuclear matrix elements (NMEs)
- **At leading-order in Chiral-EFT: 15 NMEs (all in literature)**
- Similar uncertainties as before

NMEs	<sup>76</sup> Ge				Hyvärinen/Suhonen '15 Menendez et al '17 '18 Barea et al '15 '18 Horoi/Neacsu '17
	[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		

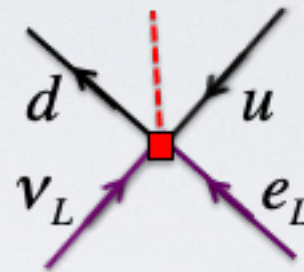
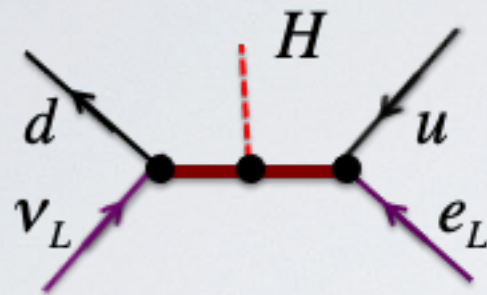
NMEs	<sup>76</sup> Ge			
	[74]	[31]	[81]	[82, 83]
$M_{F, sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT, sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT, sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT, sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T, sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T, sd}^{PP}$	0.32	0.00	0.02	0.38





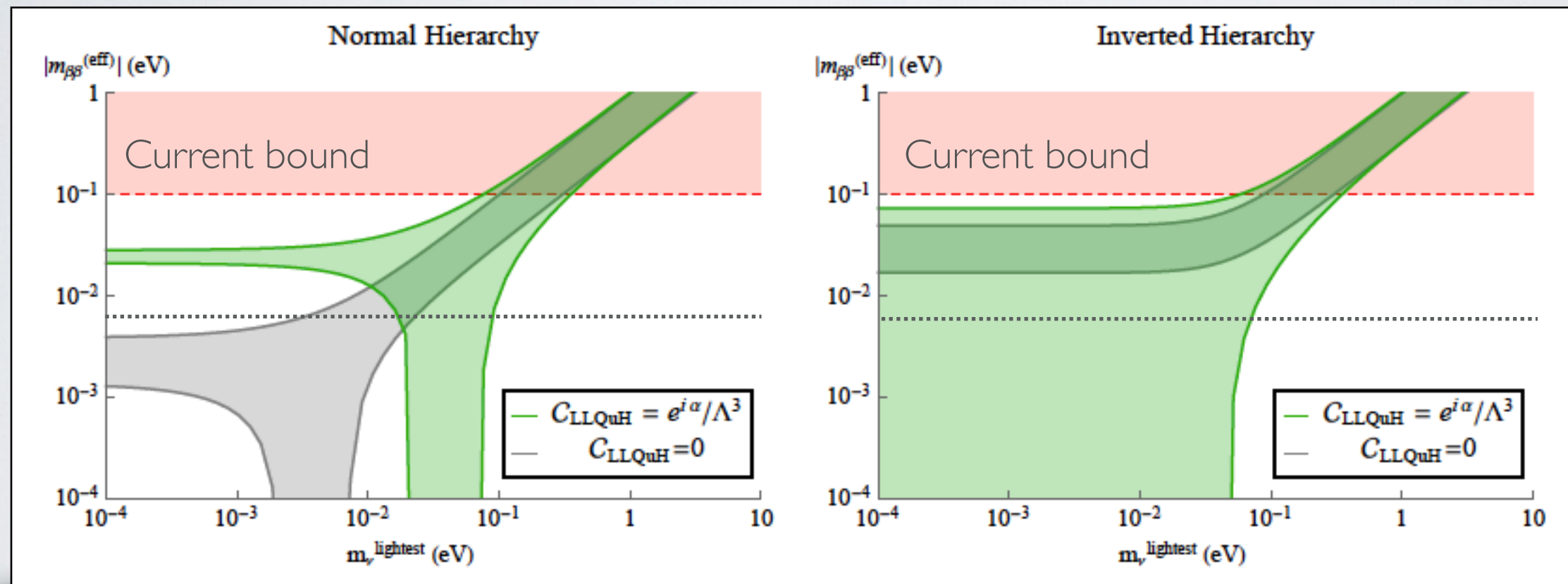
# Using the framework/tool

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



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

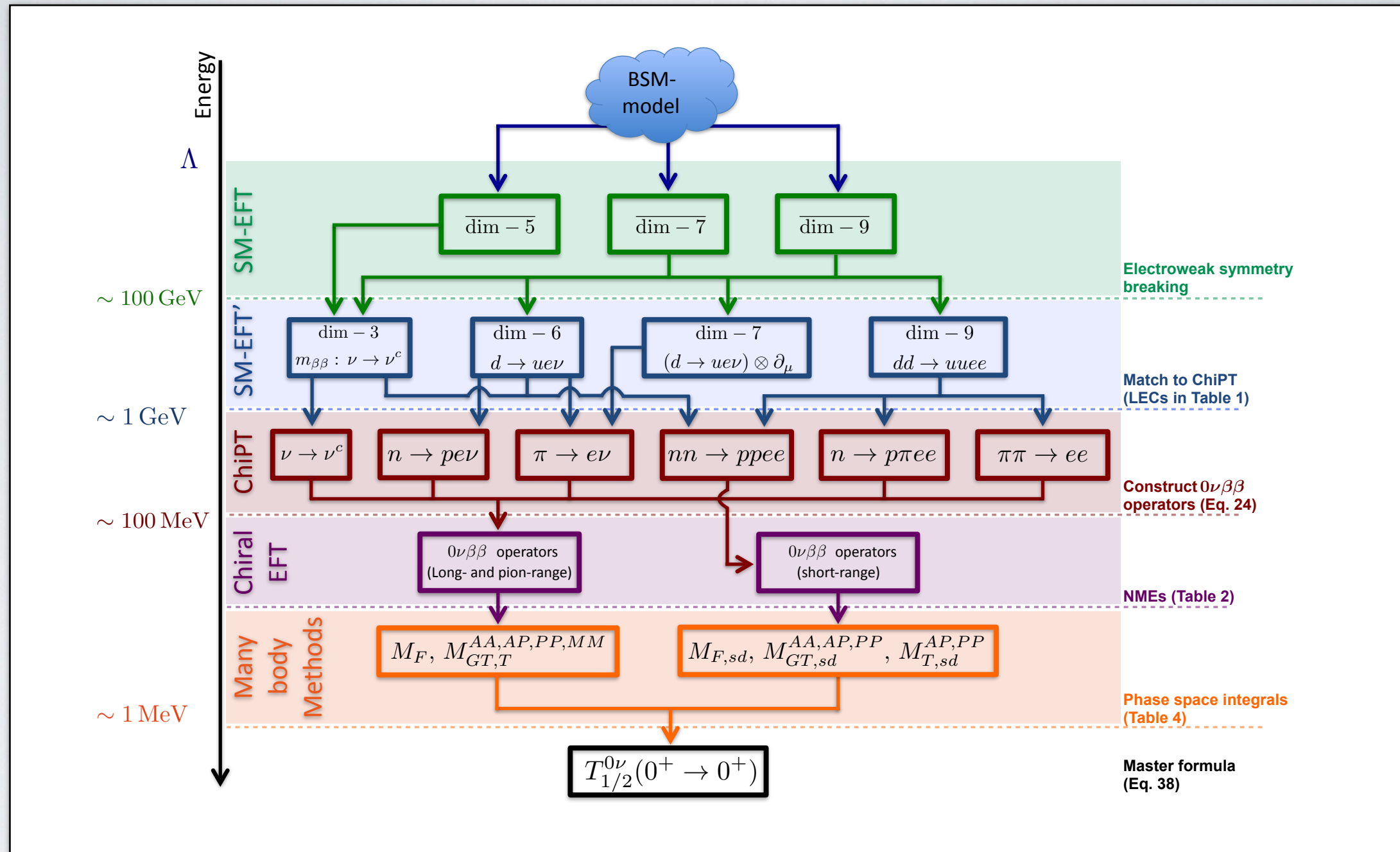
$$\Lambda = 400 \text{ TeV}$$



Ton-scale  
expectations

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

# The $0\nu\beta\beta$ metro map



- Open-access Python 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/>



# 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

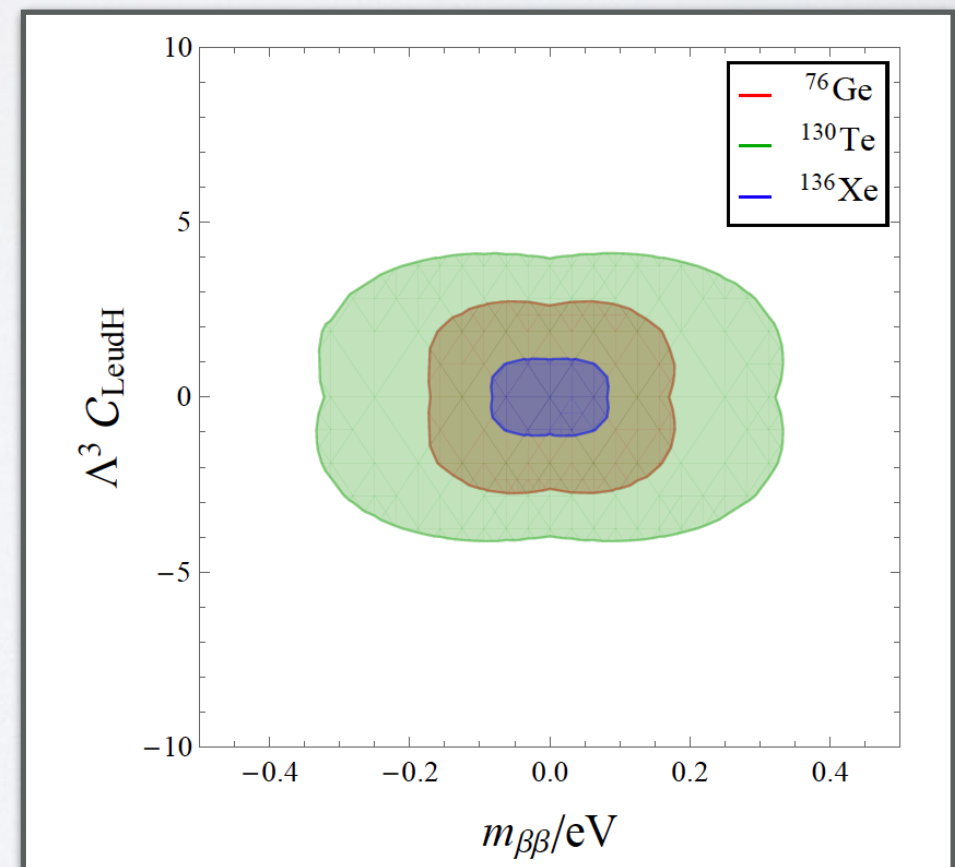
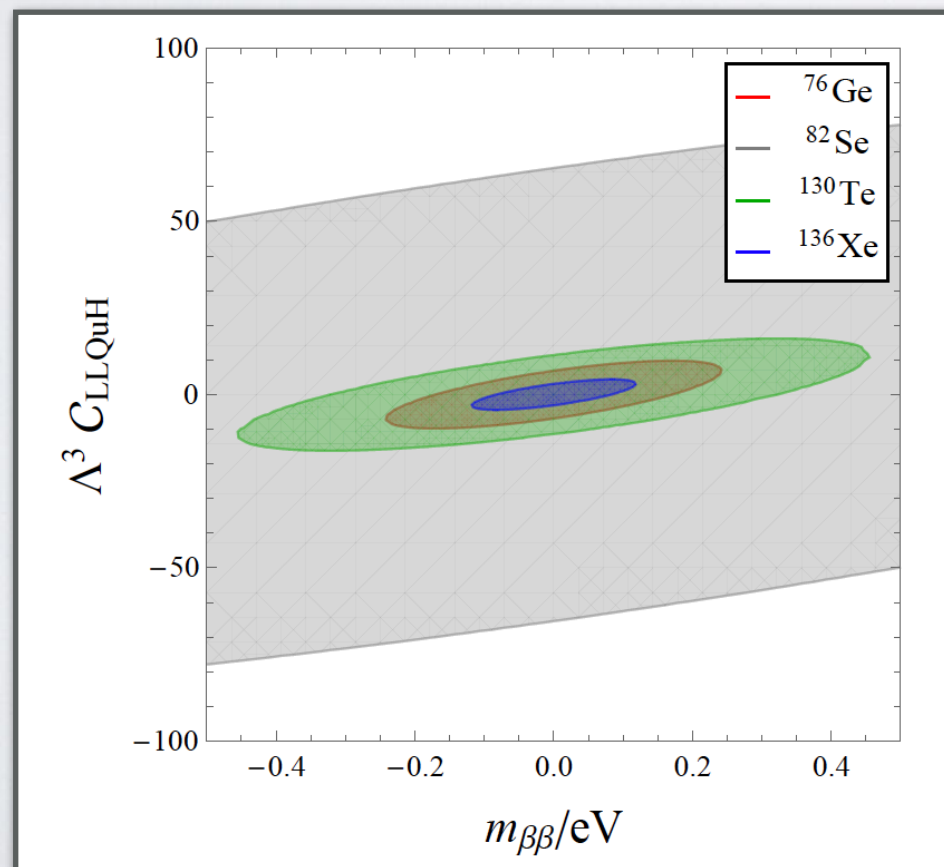
Deppisch/Pas '07, Lisi et al '15,  
Graf/Scholer '22

# 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

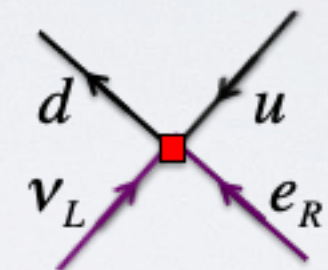




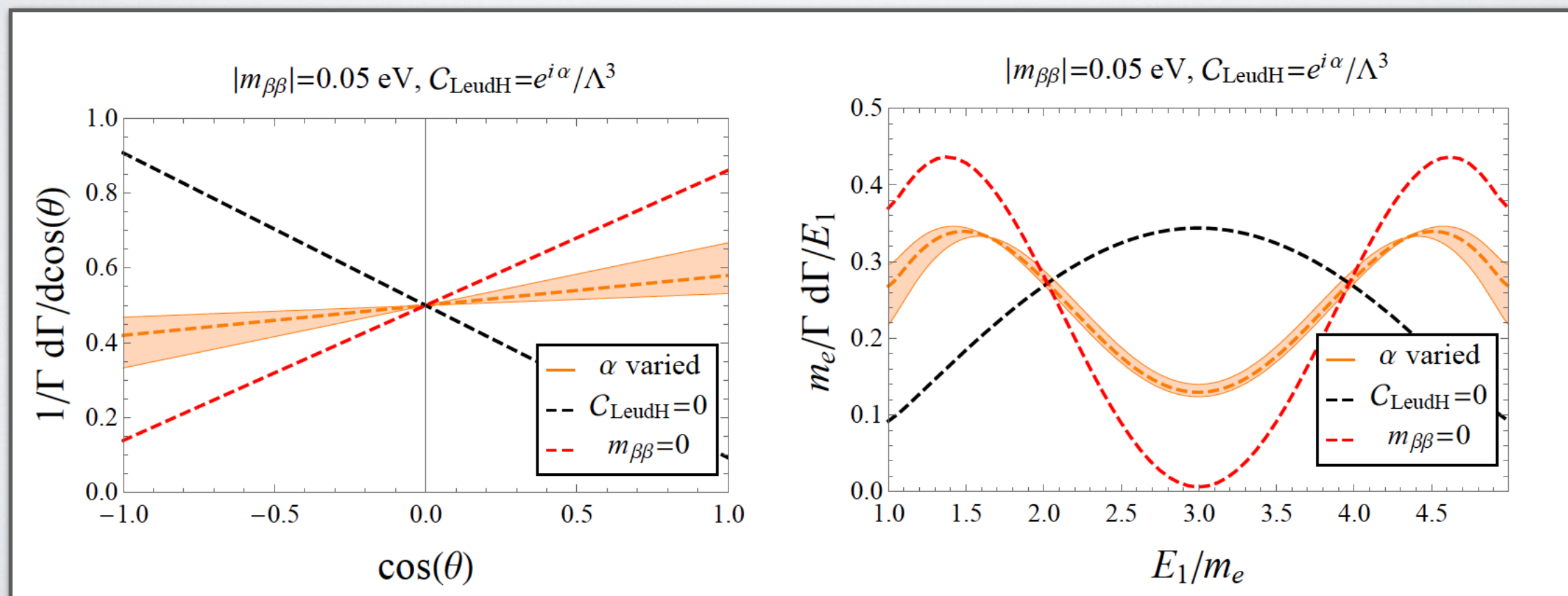
# Disentangling the source of LNV

- 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**



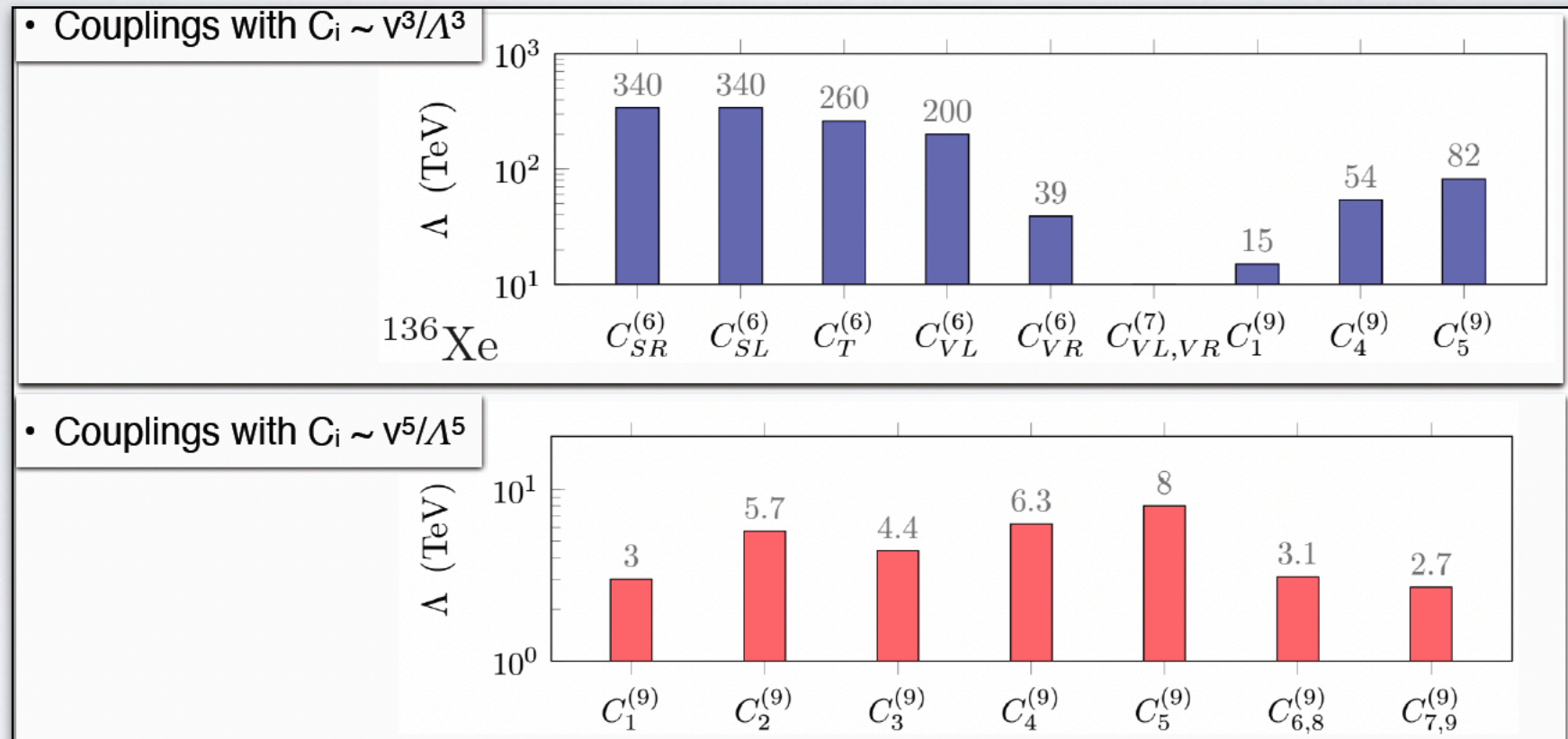


$C_7 \sim (v/\Lambda)^3 e^{i\alpha} \quad \Lambda \sim 50 \text{ TeV}$



# Take-aways

- $0\nu b\bar{b}$  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:

$$K^- \rightarrow \pi^+ + \mu^- + \mu^-$$

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

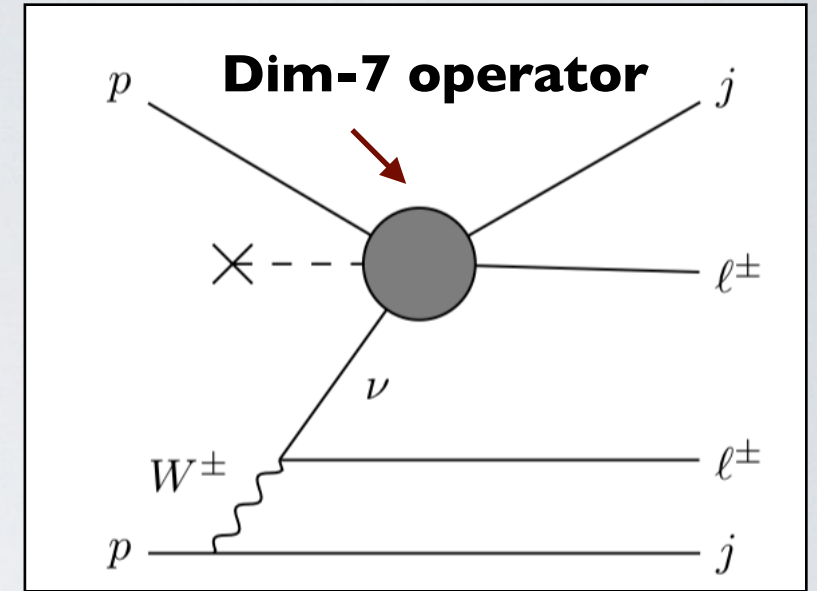
$$\mu^- + X(Z, N) \rightarrow e^+ + Y(Z - 2, N + 2)$$



# Complementary probes

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

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

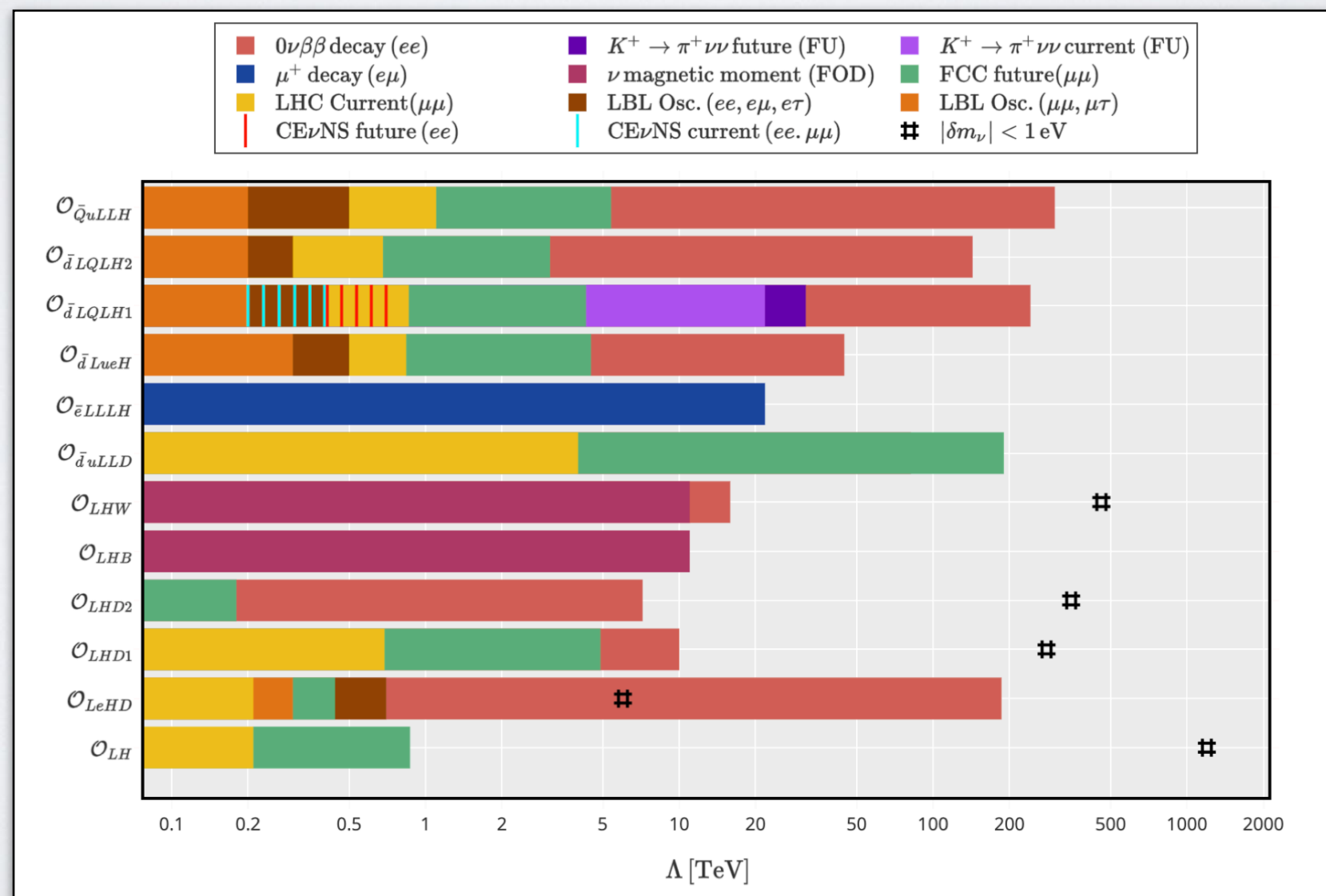
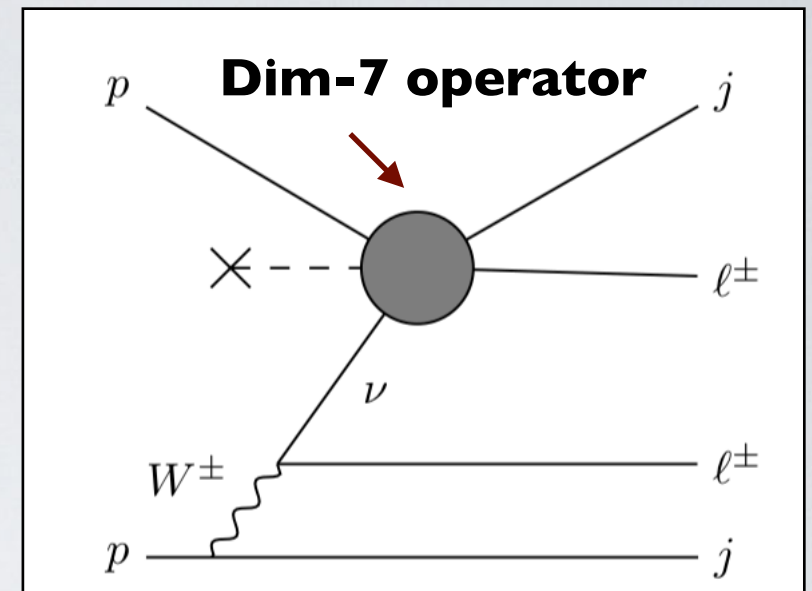


Operator	$\sigma(pp \rightarrow \mu^\pm \mu^\pm jj)$ (pb)		$\Lambda_{\text{LNV}}$ [TeV]	$\Lambda_{\text{LNV}}^{\text{future}}$ [TeV]
	LHC	FCC		
$\mathcal{O}_{\bar{Q}uLLH}$	$2.4 \times 10^{-4}$	0.11	1.1	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	$1.5 \times 10^{-5}$	$4.3 \times 10^{-3}$	0.68	3.1
$\mathcal{O}_{\bar{d}LQLH1}$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

# Complementary probes

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

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





# 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
  - ***Beyond EFTs (optional !)***

# Beyond effective field theory

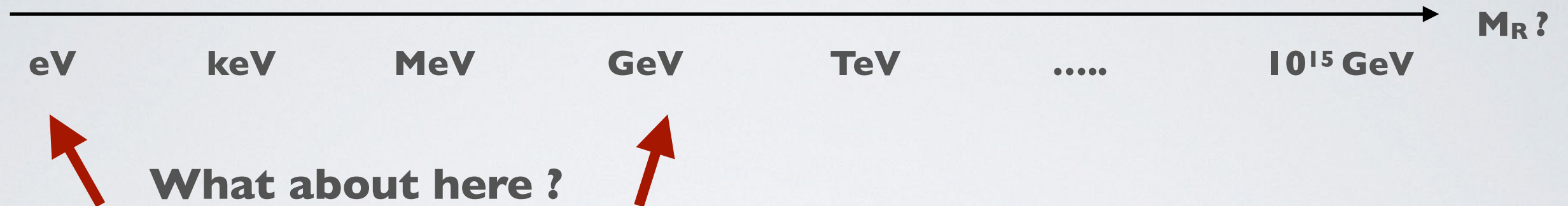
- EFT methods do not work in case of new light degrees of freedom
- Good example are sterile neutrinos





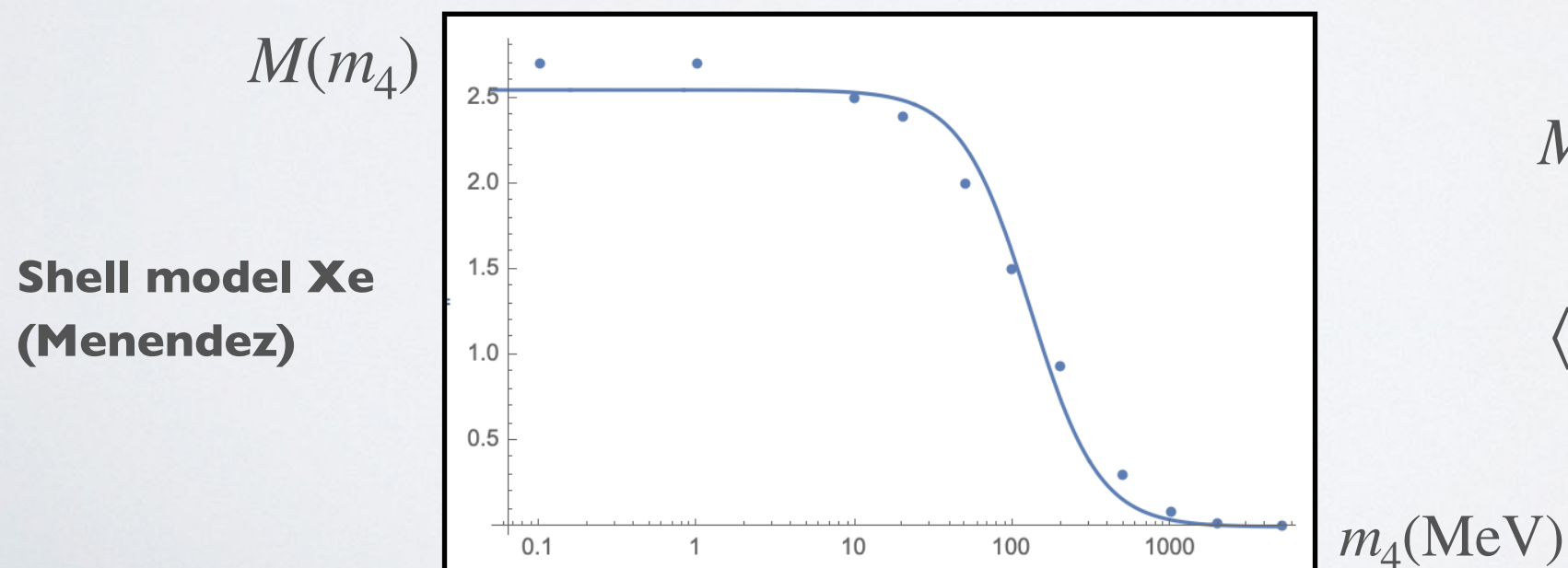
# Beyond effective field theory

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



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

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

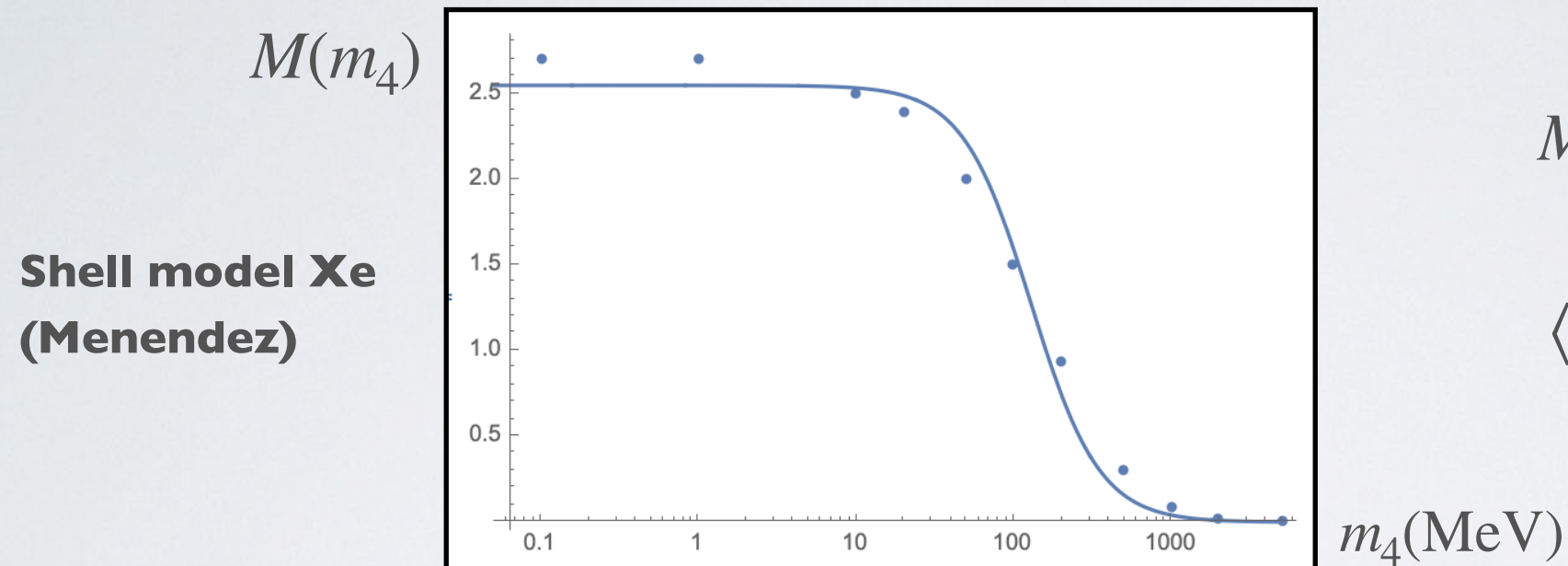


$$M(m_4) \sim \frac{1}{\langle p^2 \rangle + m_4^2}$$

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

# Current procedure in literature

- Compute nuclear matrix element computations for different neutrino masses



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

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

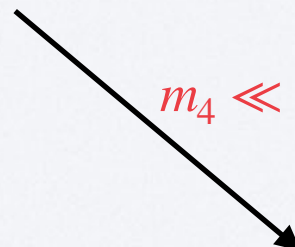
$$A_\nu \sim \sum_{i=1}^3 U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2}$$

$$m_4 \gg 100 \text{ MeV}$$



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

$$m_4 \ll 100 \text{ MeV}$$



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



# Revisit the light regime

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

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

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

# Revisit the light regime

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

• The first term depends on  $\sum_{i=1}^4 U_{ei}^2 m_i = M_{ee} = 0$   $M = \begin{pmatrix} 0 & \nu y_\nu \\ \nu y_\nu & M_R \end{pmatrix}$

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

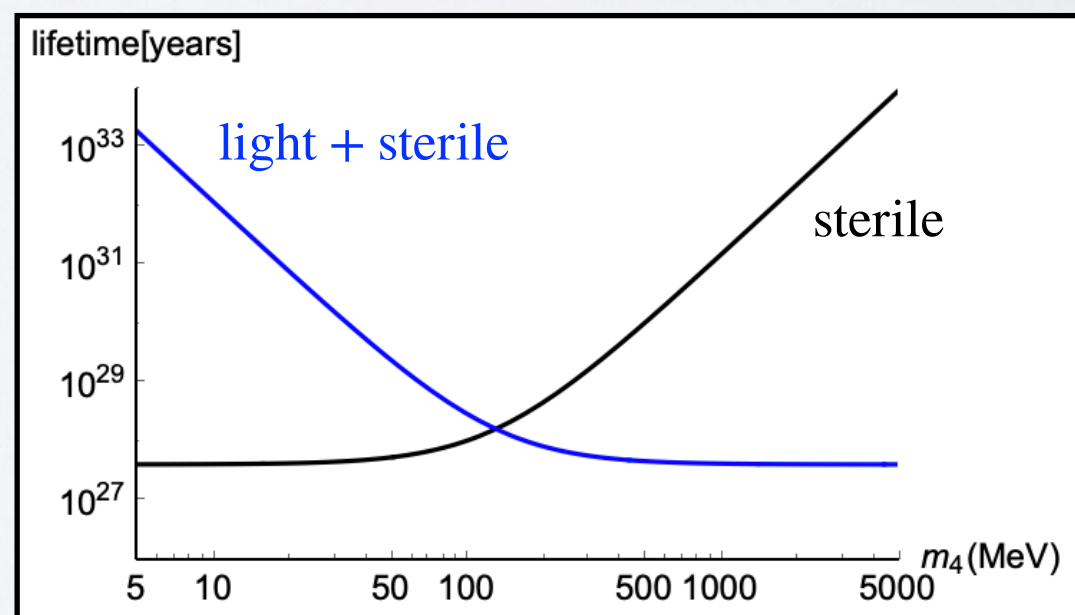
- The first term depends on  $\sum_{i=1}^4 U_{ei}^2 m_i = M_{ee} = 0$   $M = \begin{pmatrix} 0 & \nu y_\nu \\ \nu y_\nu & M_R \end{pmatrix}$

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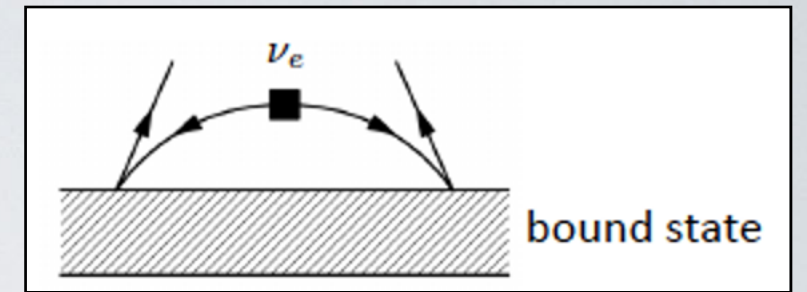
- Example in 3+1 model
- Cancellation between light + sterile contributions leads to

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



# Light extra neutrinos

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



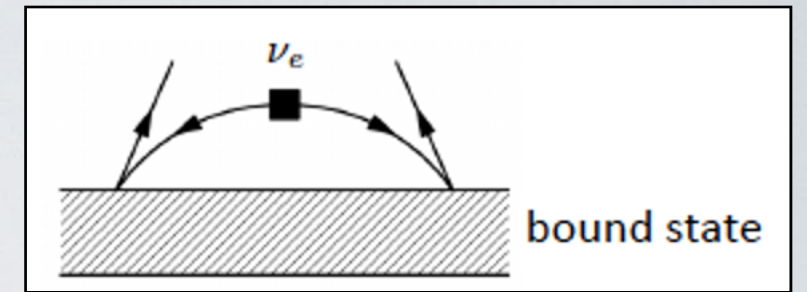
$$\sum_n \langle f | J_\mu | n \rangle \langle f | J^\mu | i \rangle \times \int \frac{d^3k}{(2\pi)^3} \frac{1}{E_\nu [E_\nu + (E_n - E_0) - i\epsilon]} \quad E_\nu = \sqrt{k^2 + m_i^2}$$

- 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 !  $\sim U_{ei}^2 m_i^3$  Dekens, JdV et al '23



# Light extra neutrinos

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

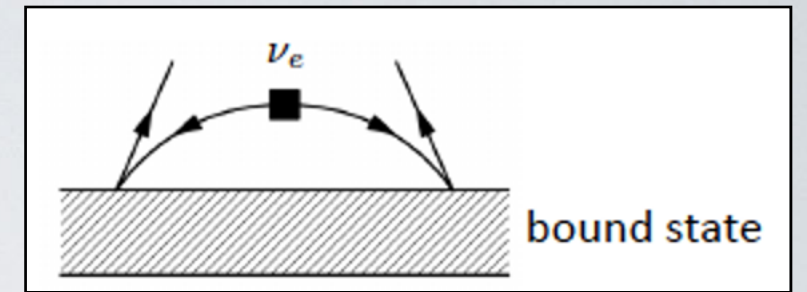


$$\sum_n \langle f | J_\mu | n \rangle \langle f | J^\mu | i \rangle \times \int \frac{d^3k}{(2\pi)^3} \frac{1}{E_\nu [E_\nu + (E_n - E_0) - i\epsilon]} \quad E_\nu = \sqrt{k^2 + m_i^2}$$

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- But become dominant in the GIM mechanism !  $\sim U_{ei}^2 m_i^3$  Dekens, JdV et al '23
- For  $m_4 \sim \text{MeV}$  we get new contributions  $\sim U_{ei}^2 m_i^2$
- For  $m_4 \ll \text{MeV}$  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

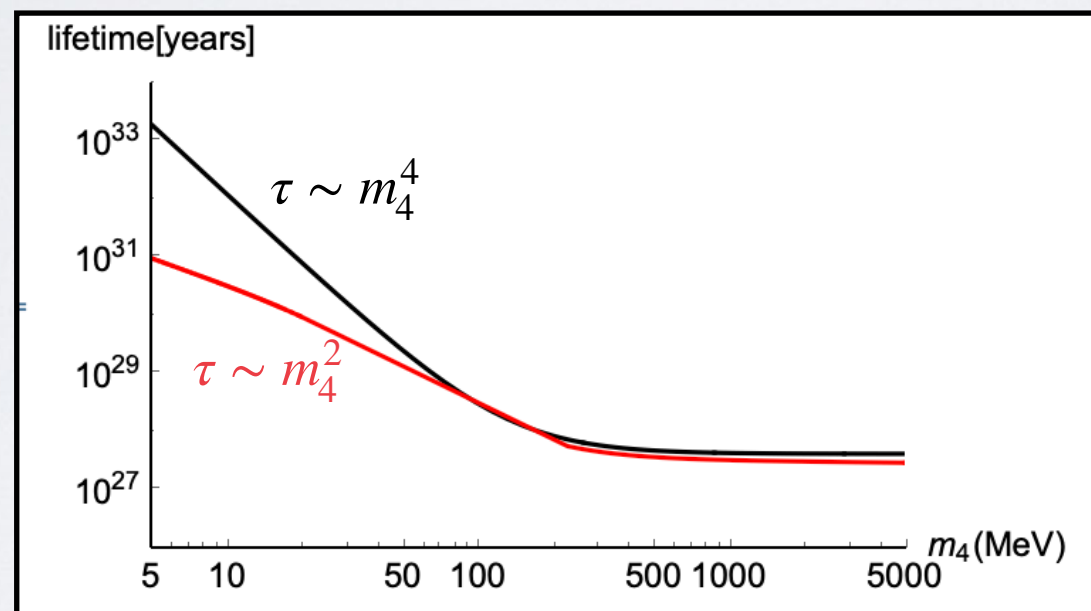
# Light extra neutrinos

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$$E_\nu = \sqrt{k^2 + m_i^2}$$



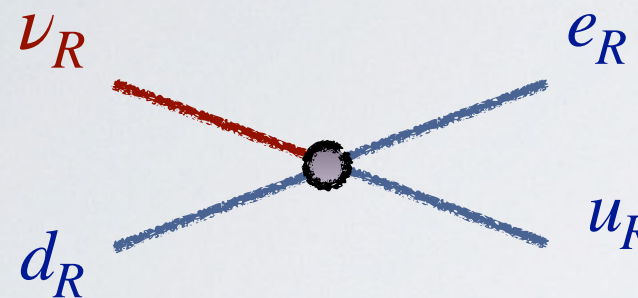
**100x larger decay rates**

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



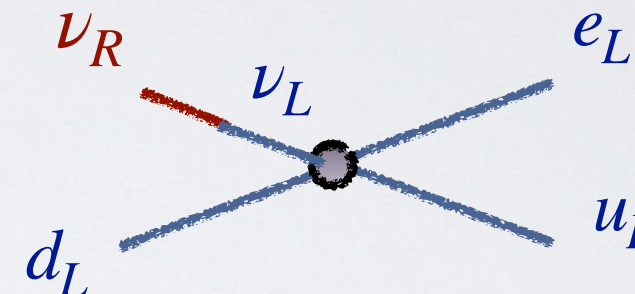
# Non-sterile sterile neutrinos ?

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



A Feynman diagram showing the production of a right-handed neutrino  $\nu_R$  (red line) from the annihilation of a right-handed electron  $e_R$  (blue line) and a right-handed down quark  $d_R$  (blue line). The interaction occurs through a right-handed  $W_R$  boson (black dot). The final state consists of a right-handed up quark  $u_R$  (blue line) and a right-handed neutrino  $\nu_R$  (red line).

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

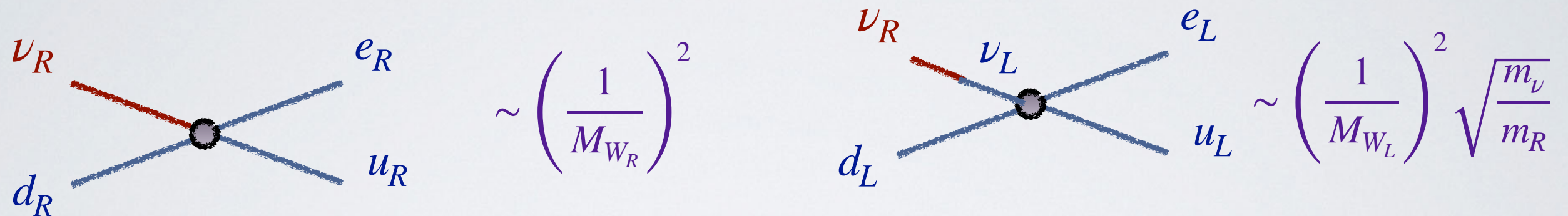


A Feynman diagram showing the production of a right-handed neutrino  $\nu_R$  (red line) from the annihilation of a left-handed electron  $e_L$  (blue line) and a left-handed down quark  $d_L$  (blue line). The interaction occurs through a left-handed  $W_L$  boson (black dot). The final state consists of a left-handed up quark  $u_L$  (blue line) and a left-handed neutrino  $\nu_L$  (blue line).

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

# 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  $SU_R(2)$



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

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

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

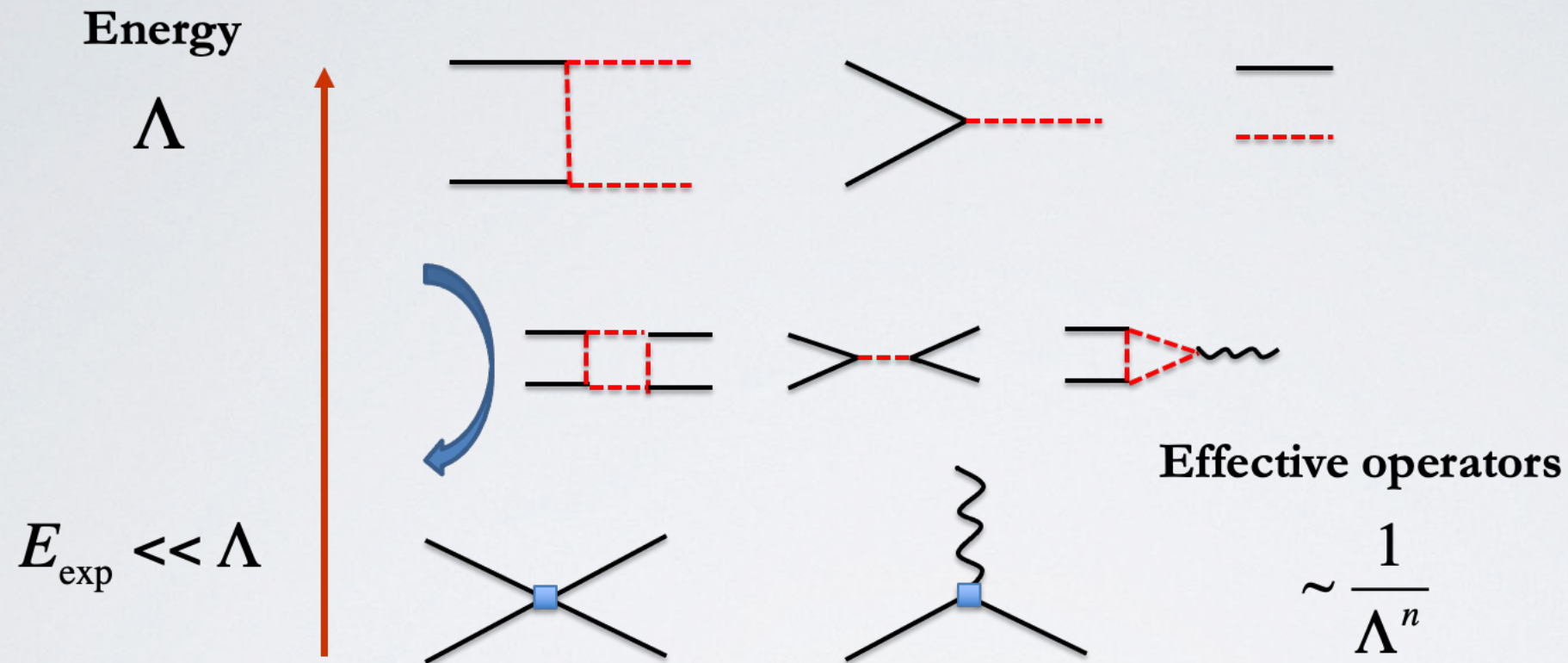
e.g. Ruiz, JdV et al '21

e.g. Azatov, Barducci et al '18



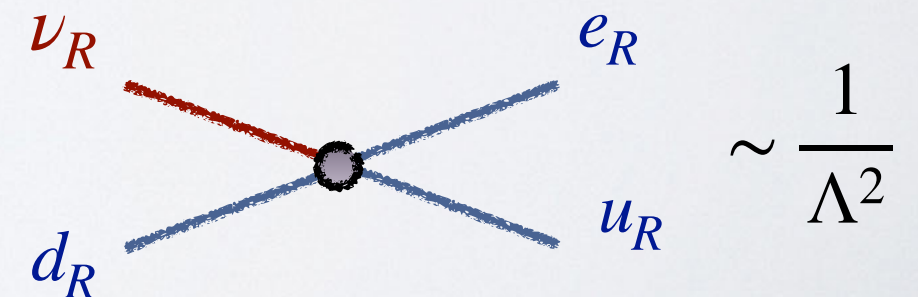
# Effective field theory

- Assume that non-standard interactions from decoupled sector



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

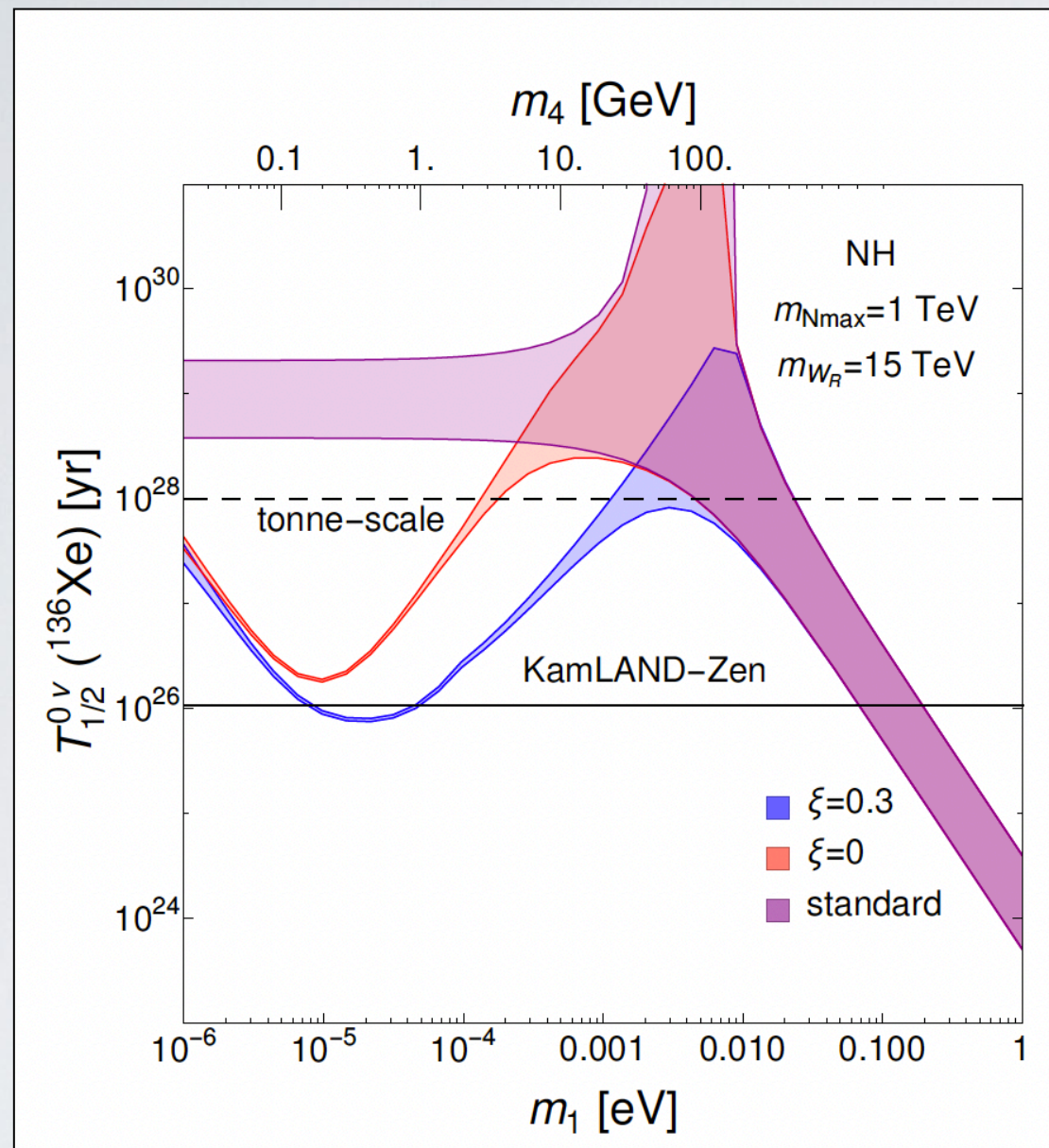
Class 1	$\psi^2 H^3$	Class 4	$\psi^4$
$\mathcal{O}_{L\nu H}^{(6)}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{du\nu e}^{(6)}$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$
Class 2	$\psi^2 H^2 D$	$\mathcal{O}_{Qu\nu L}^{(6)}$	$(\bar{Q}u)(\bar{\nu}_R L)$
$\mathcal{O}_{H\nu e}^{(6)}$	$(\bar{\nu}_R\gamma^\mu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



# An example: mLRSM + light right-handed neutrinos

Li, Ramsey-Musolf, Vasquez PRL '20

JdV, Li, Ramsey-Musolf, Vasquez '22



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

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

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

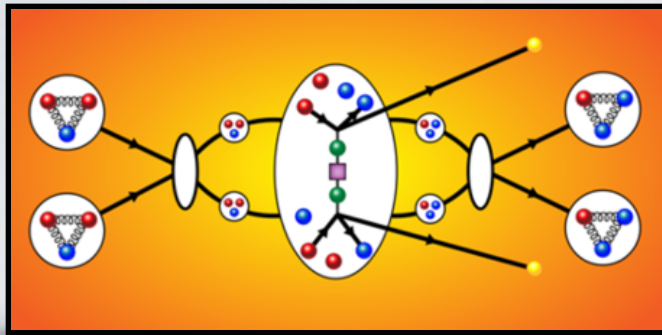
Normal Hierarchy

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



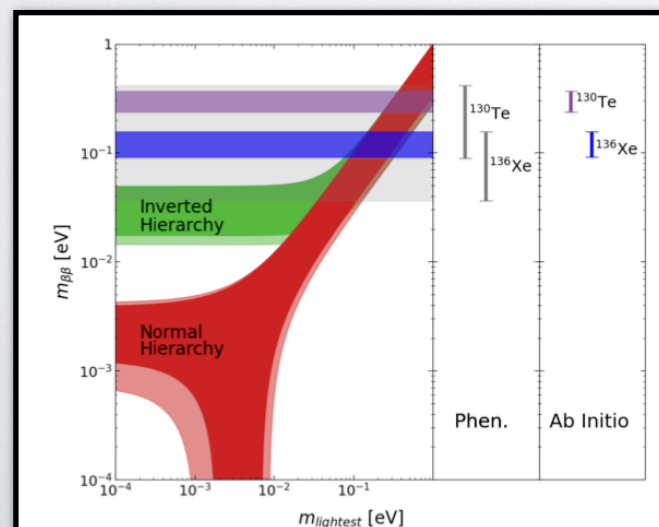
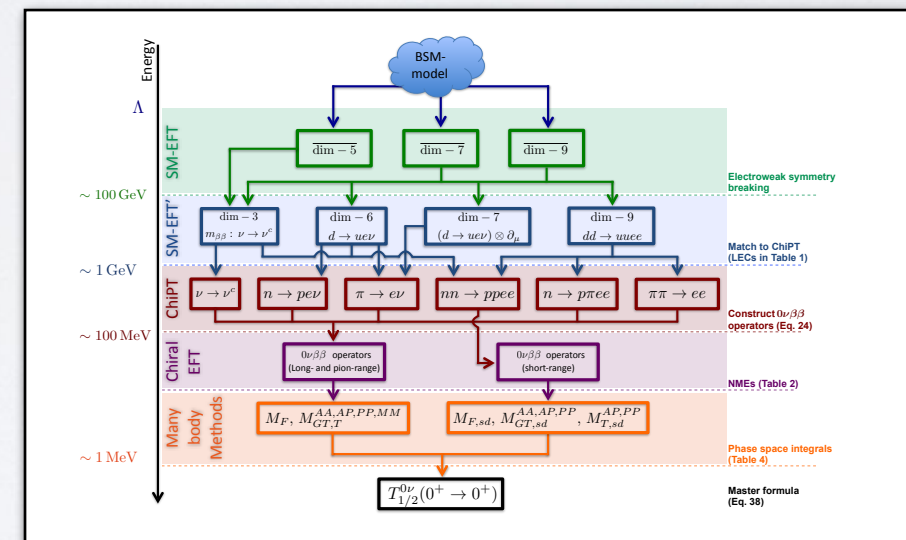
# Take-away

- Good motivations to think Lepton Number might not be an exact symmetry !
- **Neutrinoless double beta-decay extremely sensitive probe**
- There is an end goal !



- **Exciting experimental program**
- Theory improvements needed but good progress last 5 years
- Still a lot to do !

- End-to-End EFT framework for any LNV source
- Automized Python tool
- More tricky in case of light sterile neutrinos

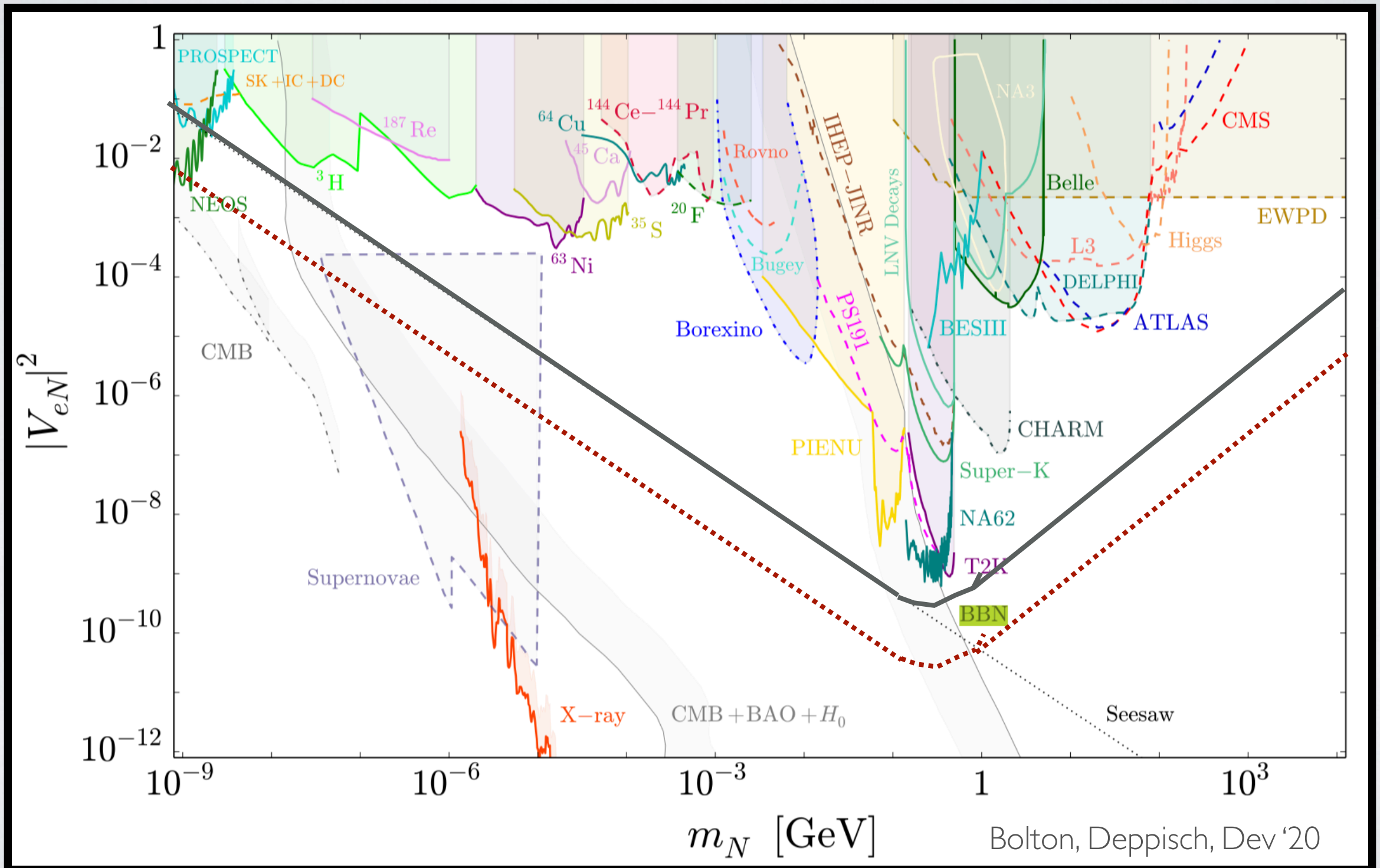


- We might find out soon if neutrinos are Majorana
- We might also have to wait a long time....

# Backup



# Naive $0\nu\beta\beta$ limits



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