NEUTRINOLESS DOUBLE BETA DECAY AND THE NATURE OF NEUTRINO MASSES

Jordy de Vries
University of Amsterdam & Nikhef

Tiny masses

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

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass.

John Updike's Cosmic Gall
(1960)

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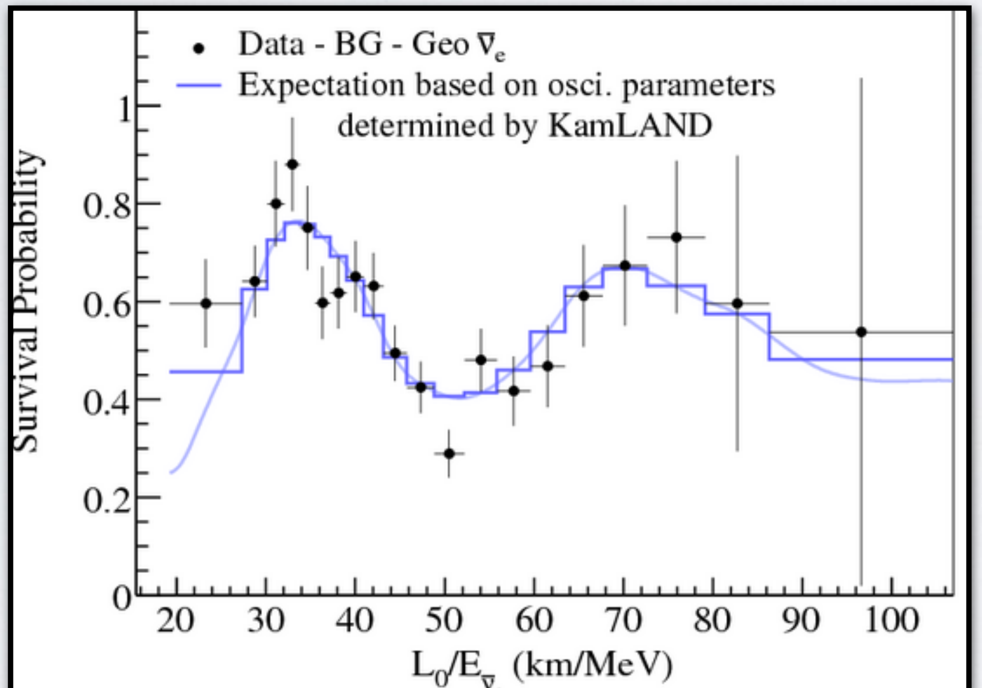
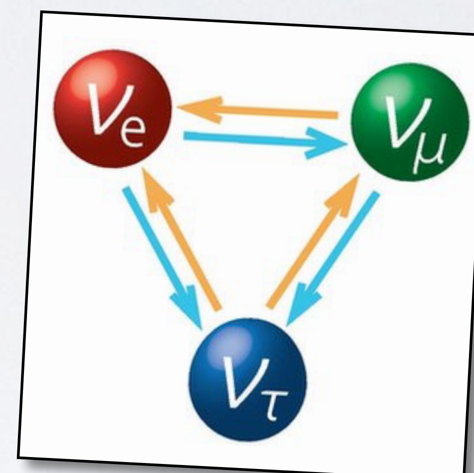


$$P(\nu_\mu \to \nu_e) \sim \sin \frac{\Delta m^2 L}{2E}$$



- 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 (DESI 2024) $\sum m_{\nu_i} \leq 0.15\, eV(IH)$
  $\sum m_{\nu_i} \leq 0.11\, eV(NH)$

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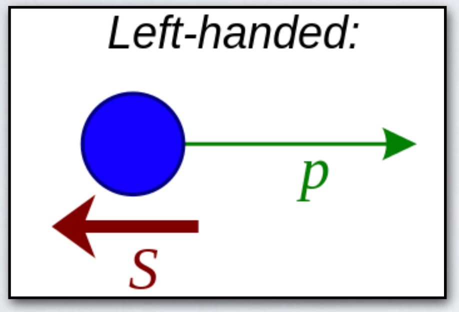
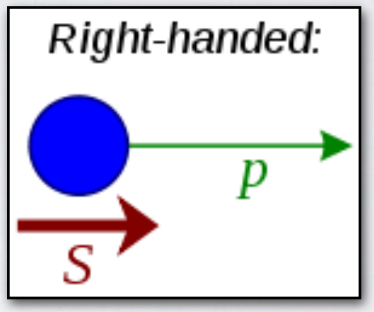
- **The problem of neutrino masses points towards new fields/new scales/new symmetries**

Mass generation in the Standard Model

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



Left-handed fields have a 'weak' charge



Right-handed fields have no 'weak' charge

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- This would violate 'weak charge' conservation (or SU(2) gauge invariance)

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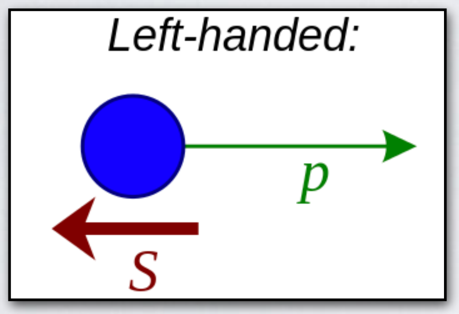

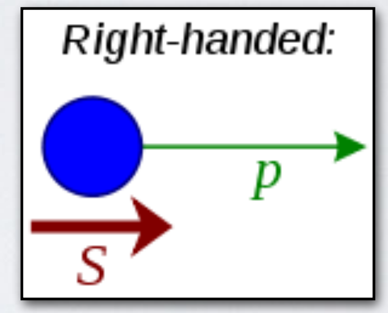

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- We cannot just write down a mass term: $\mathscr{L} = -m_e \bar{e}_L e_R$
- This would violate 'weak charge' conservation (or SU(2) gauge invariance)
- The Standard Model overcomes this problem through the **Higgs** mechanism

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

- 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 υ_R

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

- Nothing really wrong with this….

- **The υ-nightmare scenario**

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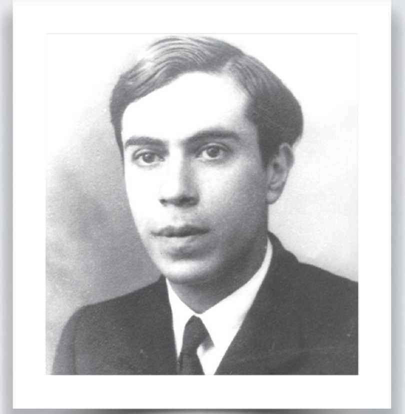
$$\mathscr{L} = -\, y_\nu \bar{\nu}_L \nu_R \varphi - M_R \nu_R{}^T C \nu_R$$

'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**

- Footnote: by far 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)

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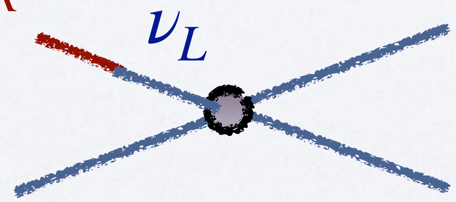
- 1+1 case: diagonalization leads to **Majorana** mass eigenstates $\qquad \nu_i^c = \nu_i$
- If M_R is significantly larger than active neutrino masses: **see-saw mechanism**

$$m_1 \simeq \left| \frac{y_\nu^2 v^2}{M_R} \right| \ll m_2 \simeq M_R$$

Active neutrino + heavier sibling (sterile neutrino)

- **Sterile neutrinos**



$$\sim G_F \sqrt{\frac{m_1}{m_2}} \ll G_F$$

The puzzle of the neutrino mass

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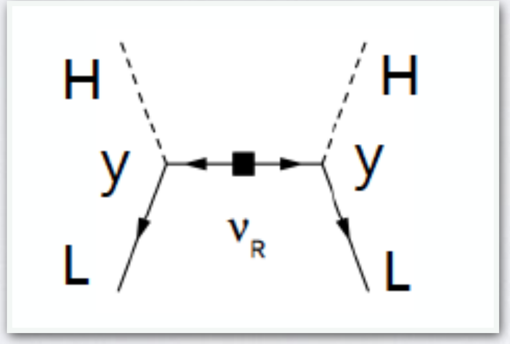
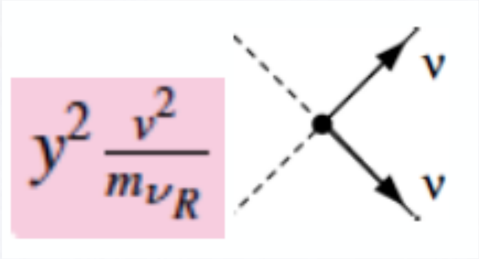
- If M_R is significantly larger than electroweak scale: **integrate it out**





- Obtain dimension-5 SMEFT operator that lead to **active neutrino Majorana mass**

$$\mathscr{L}_5 = C_5 \left(L^T C \tilde{H}\right)(\tilde{H}^T L)$$

Weinberg '79

- Weinberg operator describes many 'high-scale' mechanisms

Are neutrino masses BSM ?

- A question to fight about at dinner tonight
- Not uncommon opinion: ***Standard Model can be redefined to include neutrino masses***

Are neutrino masses BSM ?

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- Not uncommon opinion: ***Standard Model can be redefined to include neutrino masses***

- ***But which mechanism?***

A) $\mathscr{L} = -y_\nu \bar{\nu}_L \nu_R \varphi$

B) $\mathscr{L} = C_5 \left(L^T C \tilde{H}\right)(\tilde{H}^T L)$

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

D) ……………

- *Footnote: B and C/D are not exclusive*

Jordy de Vries
@Jordy_de_Vries

In the Standard Model of particle physics, neutrinoless double beta decay rates are

zero	37,8%
non-zero	14,4%
This is a BSM question	**47,8%**

270 stemmen · Eindresultaten

9:59 p.m. · 19 sep. 2022

David McKeen @davemckeen · 19 sep. 2022
This is the right question!
1

George T. Fleming 傅樂明 @GeorgeFleming · 20 sep. 2022
In the Electroweak Standard Model, as written by Weinberg, neutrinos are massless.

The plan of attack

1. Introduction to Majorana neutrinos and 0vbb

2. **0vbb from light Majorana neutrino exchange**
    - *Controlling nuclear matrix elements !*

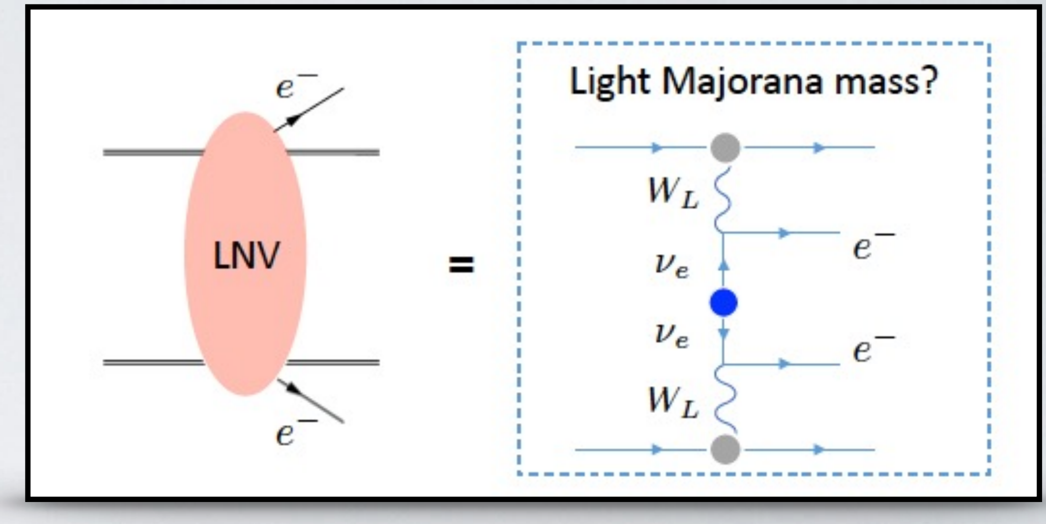
3. Other sources of lepton number violation

Probes of lepton number violation

- Most promising way: look at `neutrinoless' processes

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

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



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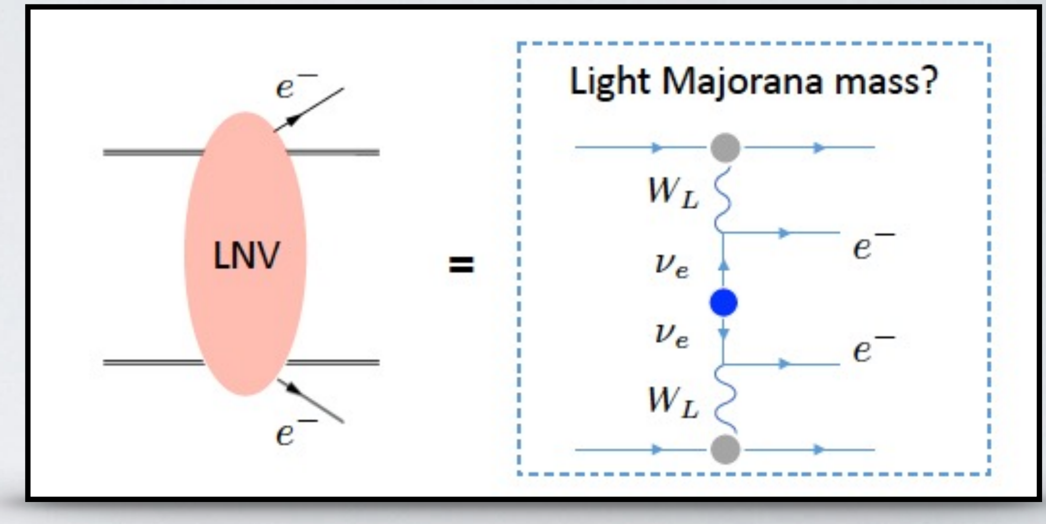

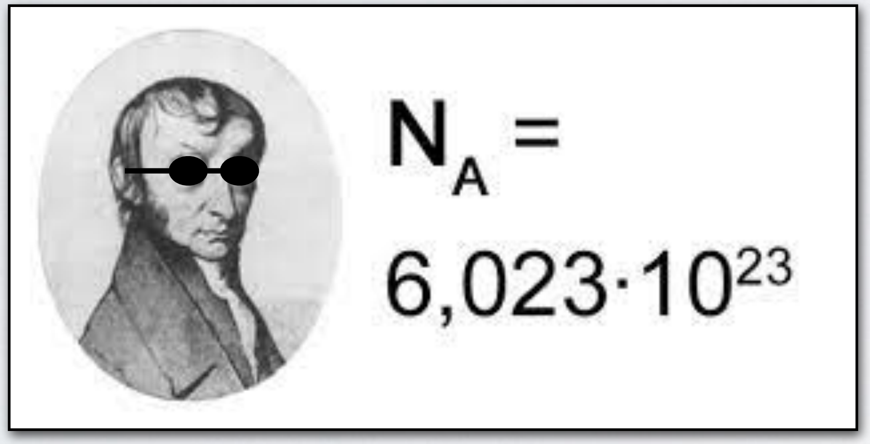

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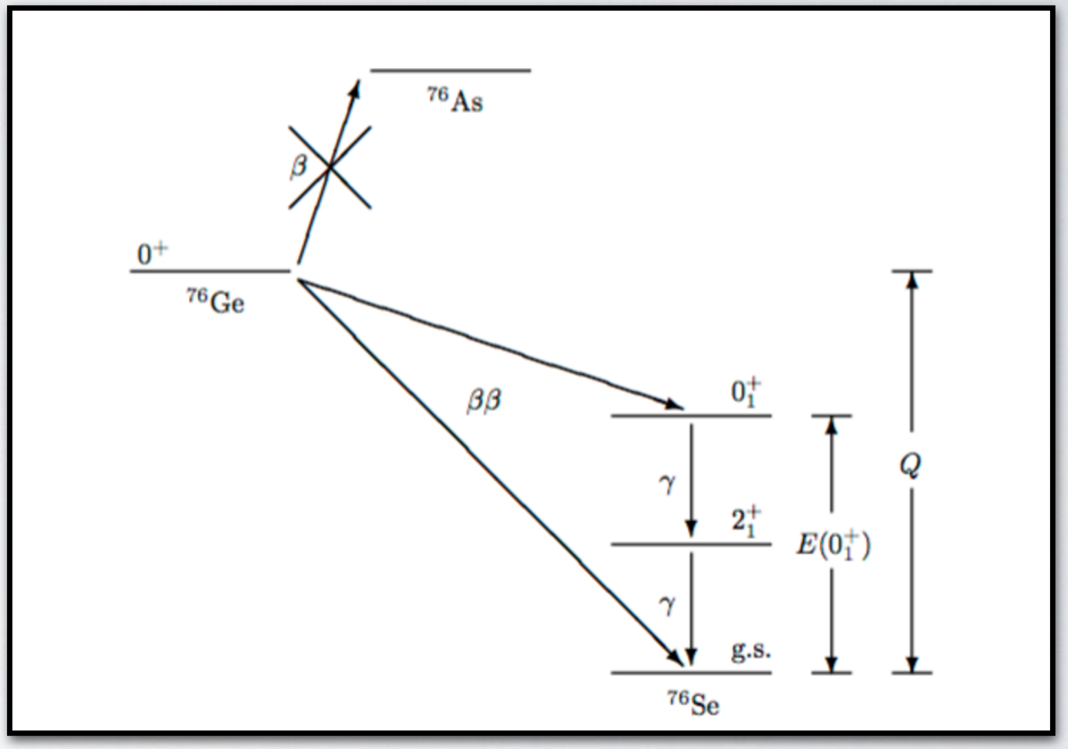
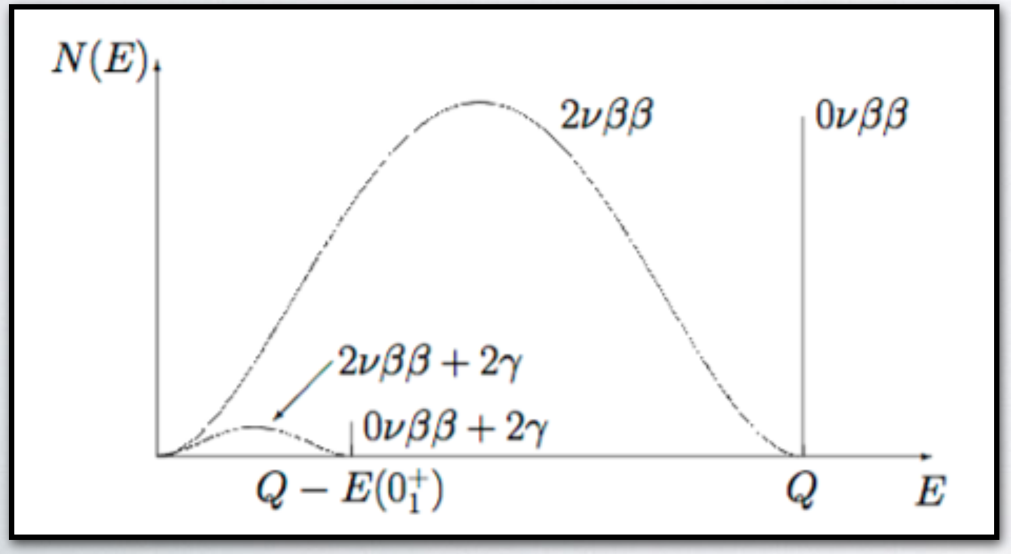


- Isotopes protected from single beta decay

- Neutrinofull double beta decay from Standard Model

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

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



	Lifetime	Experiment	Year
76Ge	$8.0 \cdot 10^{25}\, y$	GERDA	2018
130Te	$3.2 \cdot 10^{25}\, y$	CUORE	2019
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Note: age of universe ~ 10^{10} year

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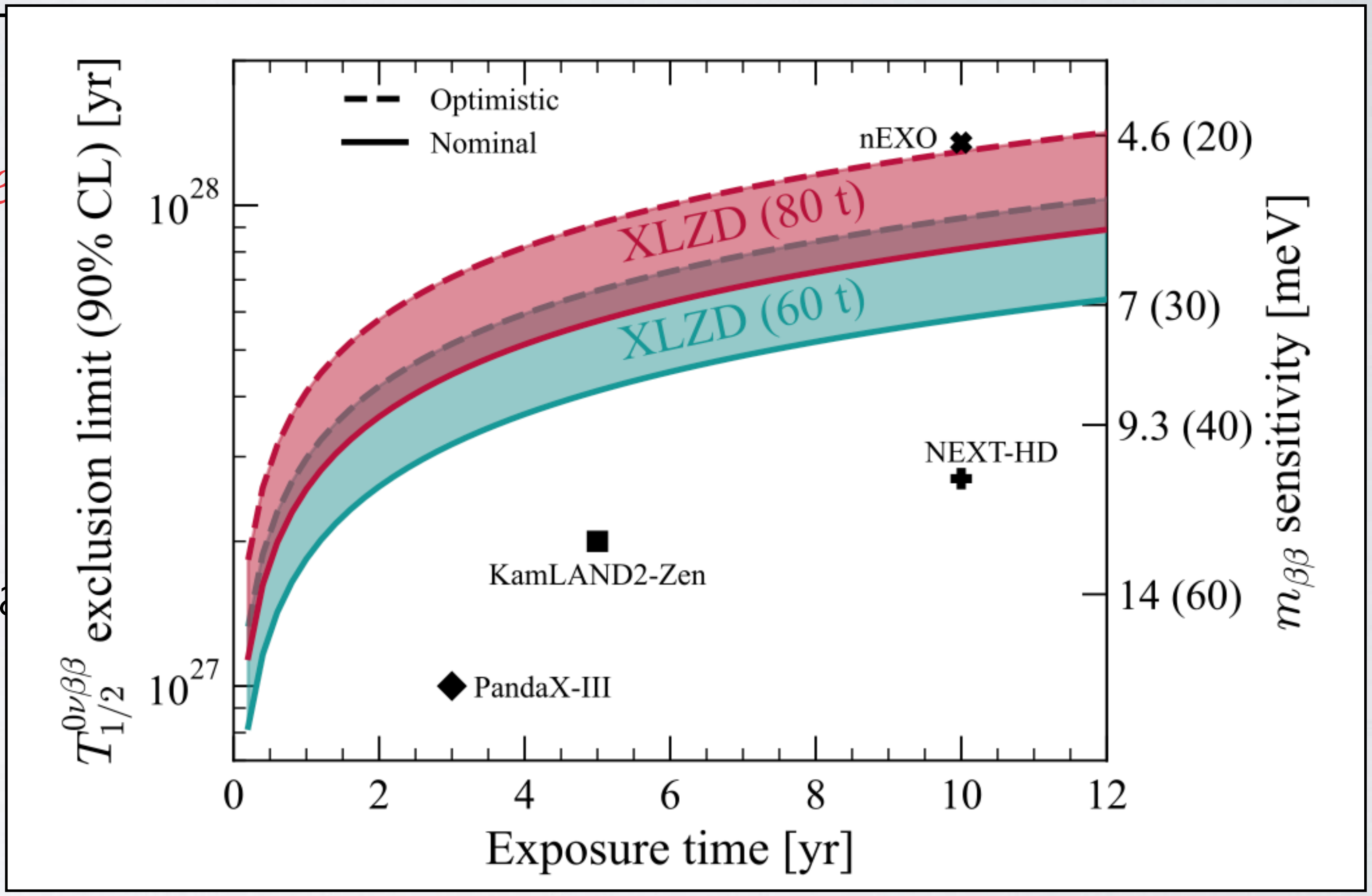

Figure from XLZD collaboration, 2410.19016

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- Neutrinofull double beta decay from Standa

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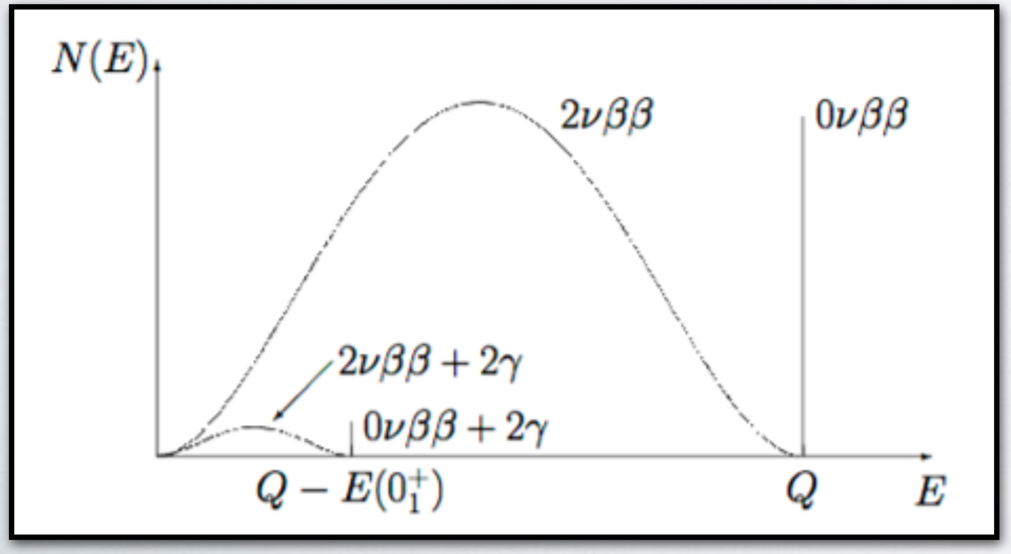

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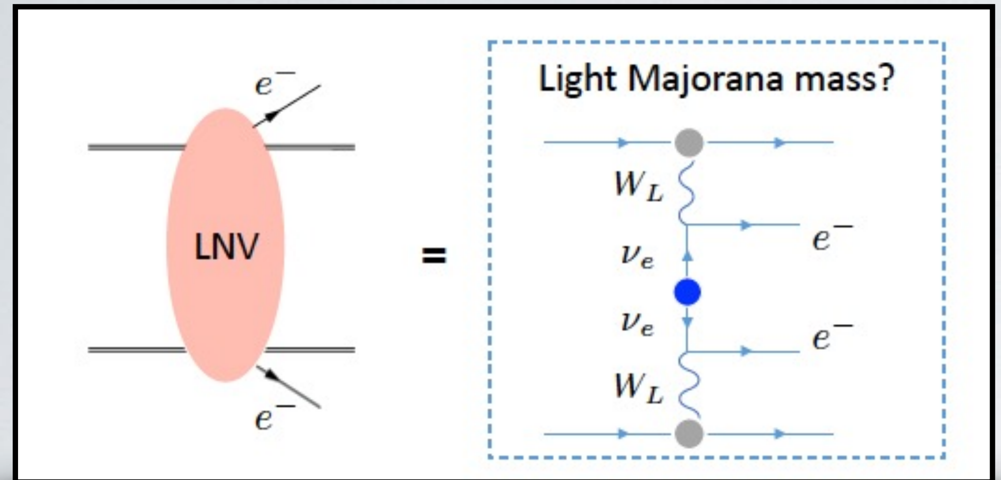
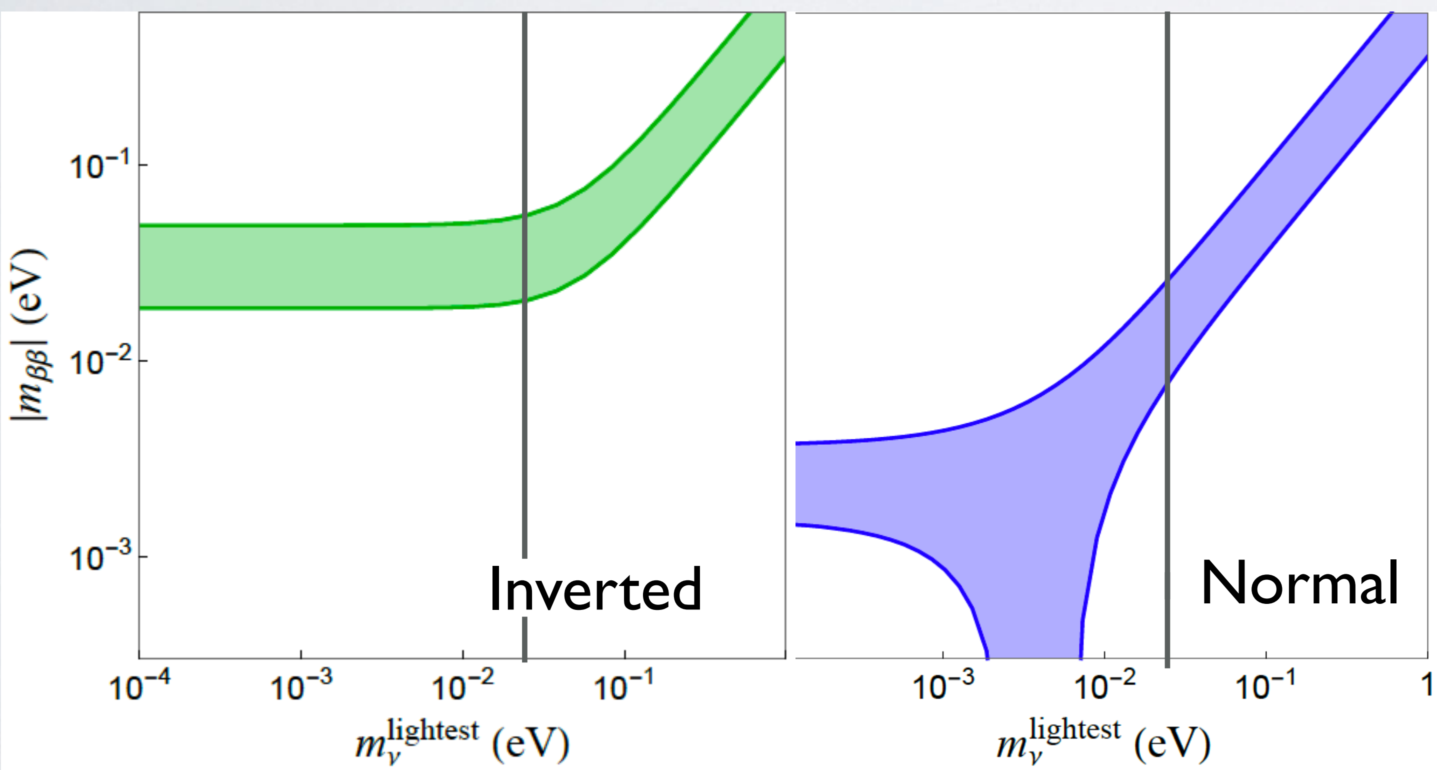
Interpreting 10^{26} years….



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

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

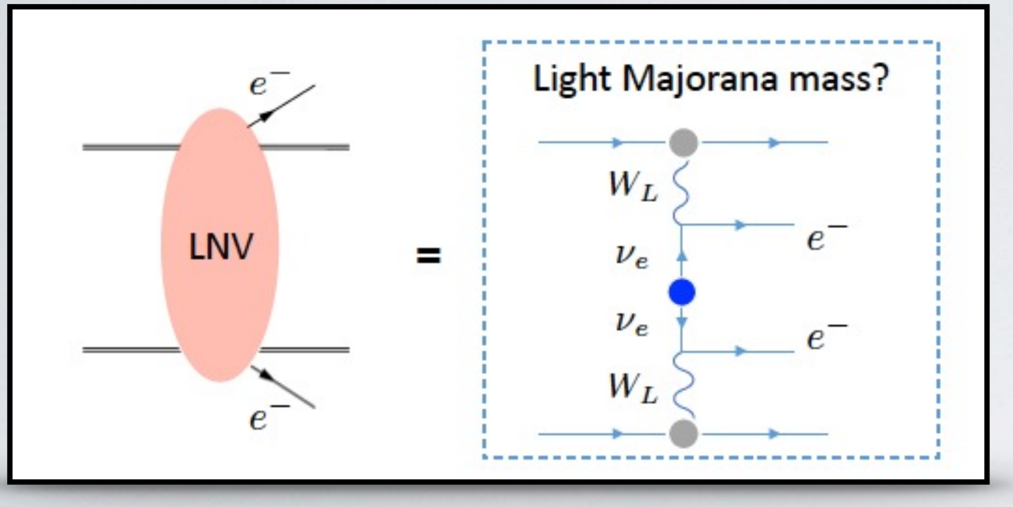


Vary the lightest mass and the ordering

Band from varying unknown phases

How close are experiments ?

Interpreting 10^{26} years....



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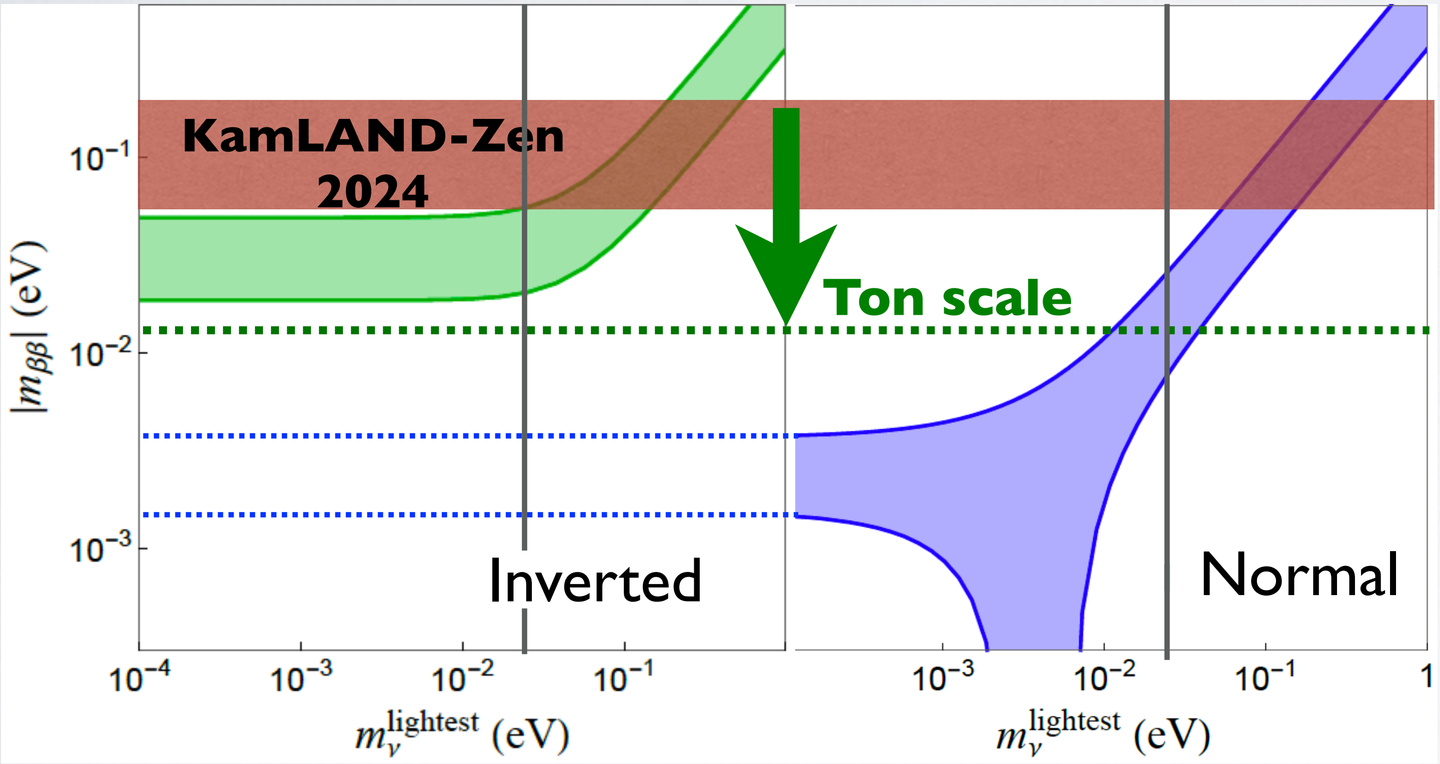


Quite close !!

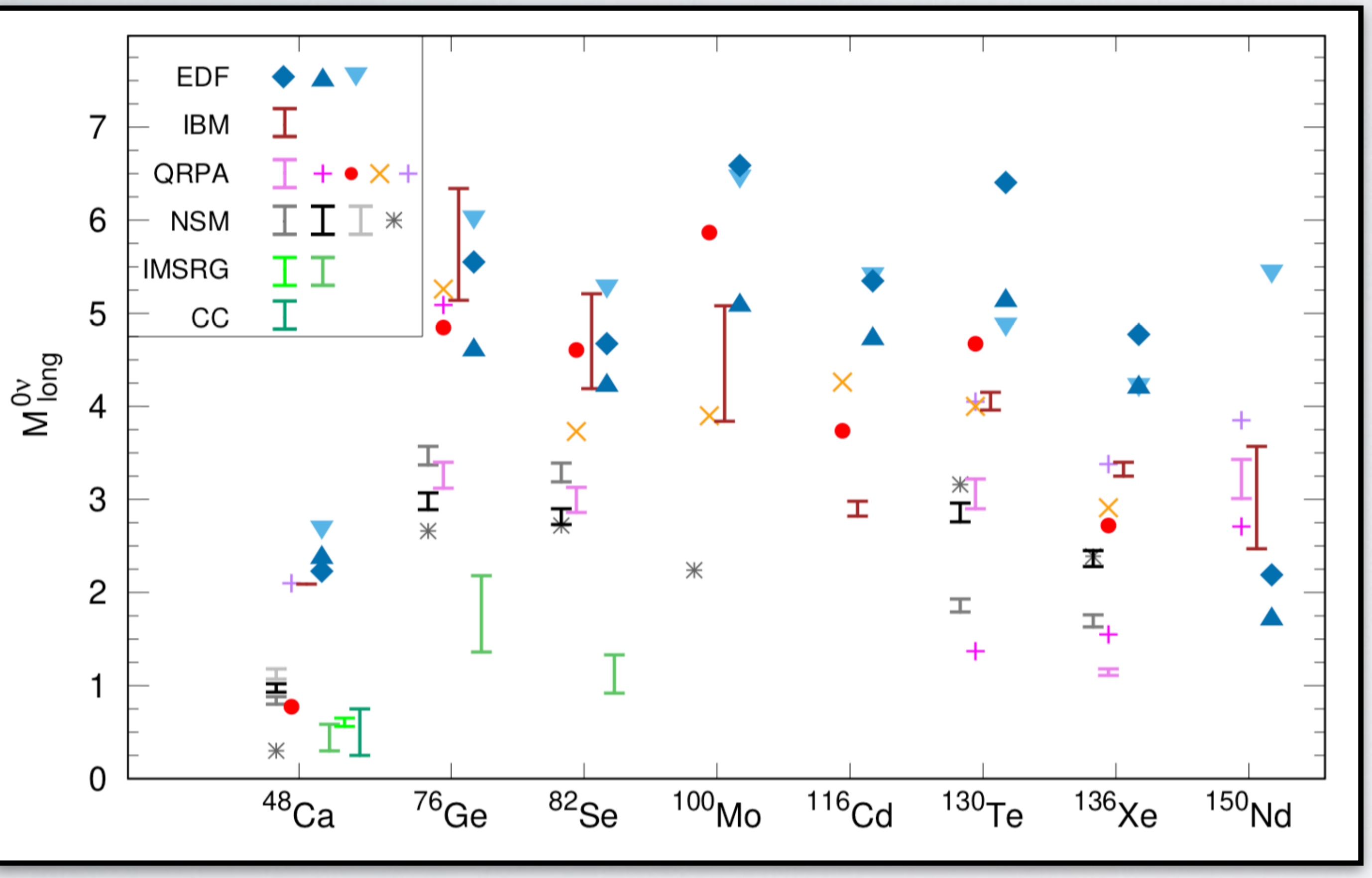
Next-generation discovery possible if inverted hierarchy or m_{lightest} >0.01 eV

Note: **FUNNEL OF DESPAIR** and **THE DEAD ZONE**

See Denton & Gehrlein '23 for the likelihood that we live in the funnel

Predictions are hard, especially about ~~the future~~ nuclei

From: Menendez et al review '22



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

Where is this coming from ?

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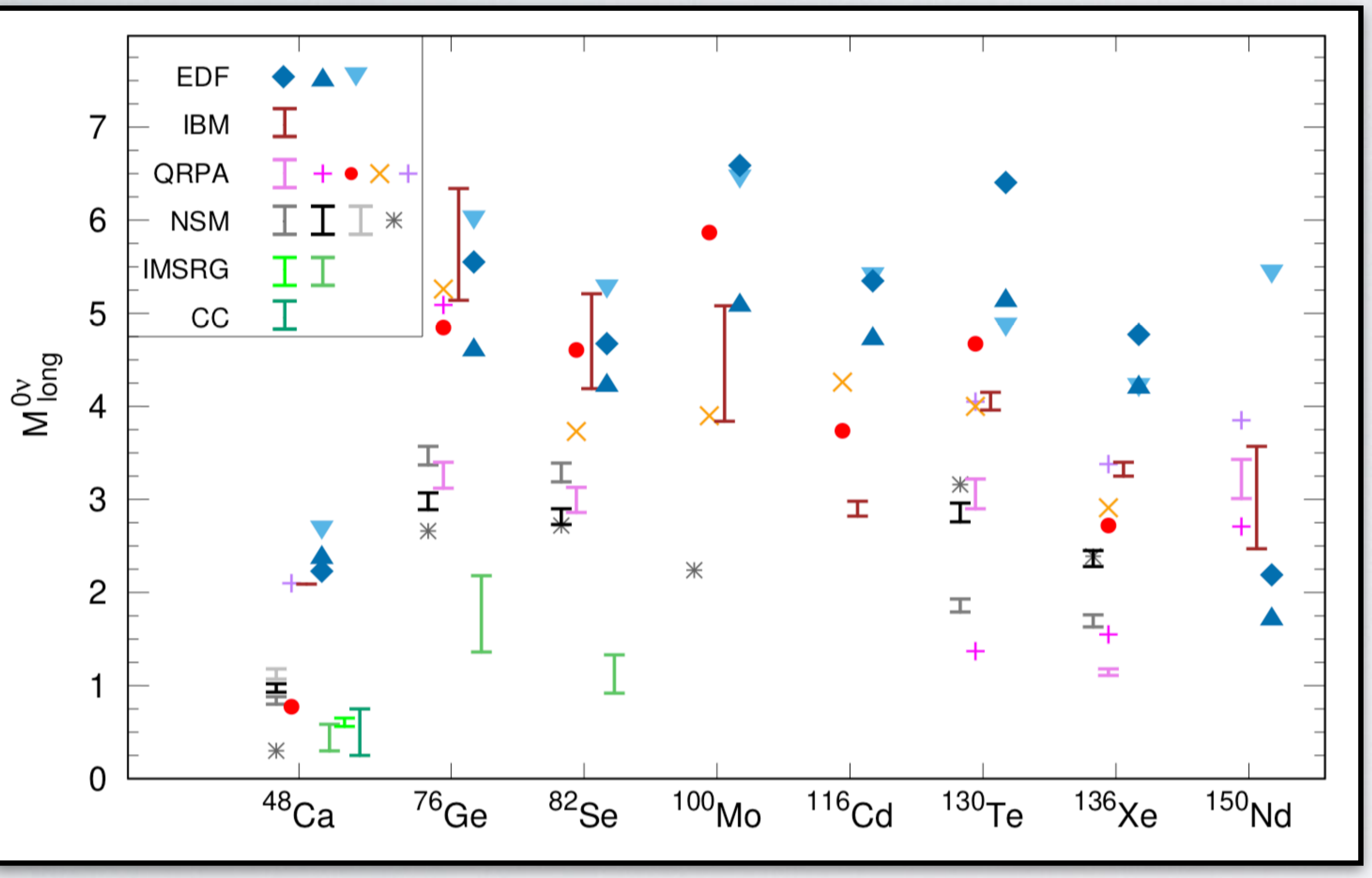

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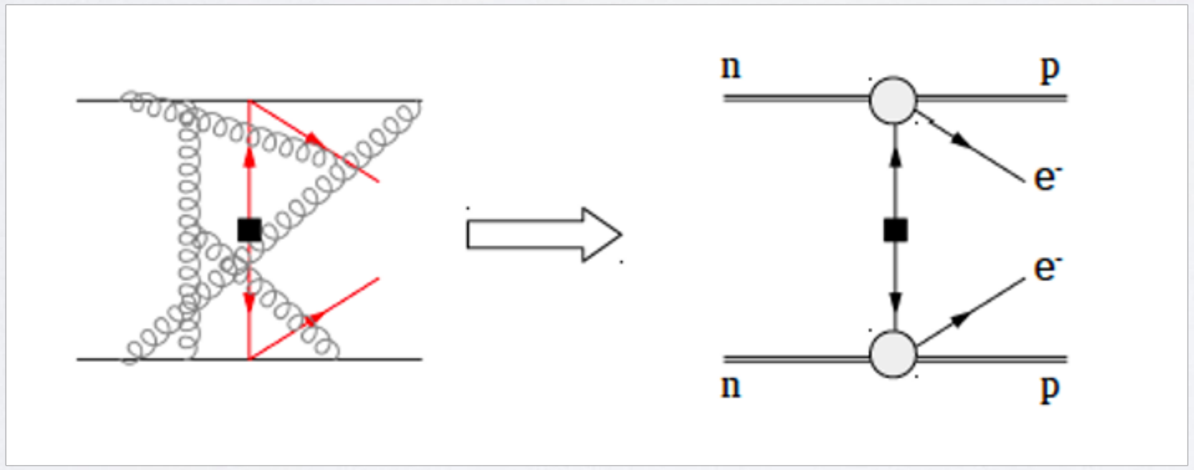

- Large nuclei —> complicated many-body nuclear matrix elements
- Nuclear methods and codes are benchmarked on 'single-nucleon-currents' physics

Nuclear physics from QCD

- In the 90's Weinberg (who else) wrote 2 very 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

[Submitted on 16 Feb 2025]

Steven Weinberg: A Scientific Life

C.P. Burgess, F. Quevedo

Weinberg used similar tools to compute the inter-nucleon forces implied at low energies by generalizing the effective theory governing low-energy pion interactions to include nonrelativistic nucleons [85–87] (see also [88]). By so doing he enabled the calculation of *ab initio* nuclear energy levels for the first time, at least for light nuclei involving comparatively few protons and neutrons. Nuclear physicists at the time were instead fitting data from nuclear measurements with models in which meson exchange between nucleons assumed phenomenological couplings.

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Published in: *Nucl.Phys.B* 363 (1991) 3-18
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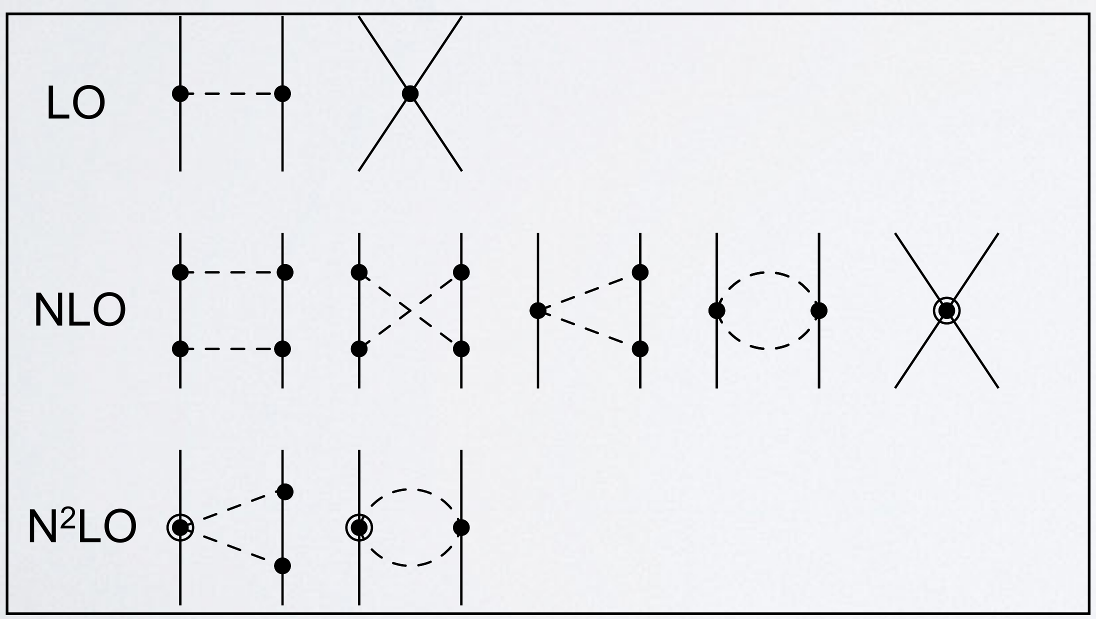
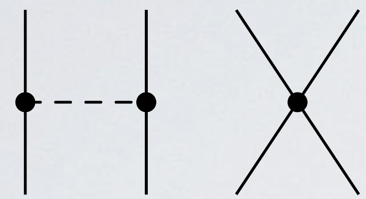
- Describe the **nucleon-nucleon** force from **chiral perturbation theory**



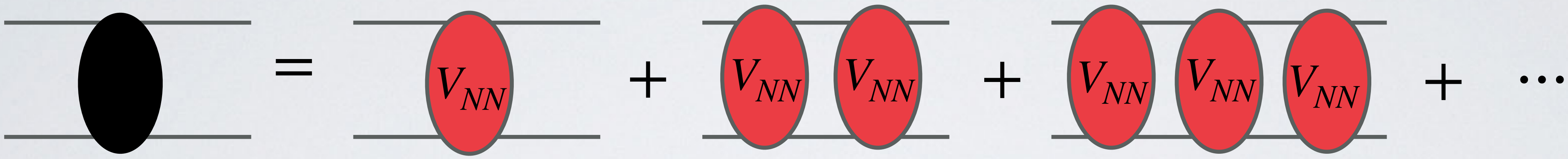
- Effective field theory description of nuclear forces and currents
- Systematic expansion
- Nuclei from solving Schrodinger-like equations
- Wilson coefficient (low-energy constants fitted to few-nucleon data) -> predict larger systems

Developed by van Kolck, Meißner, Epelbaum, Machleidt and many others ….

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** (typically numerically)

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

- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ

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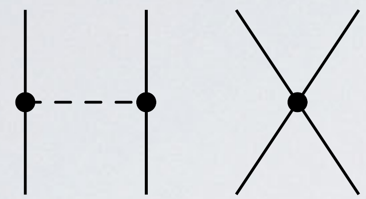
LO 

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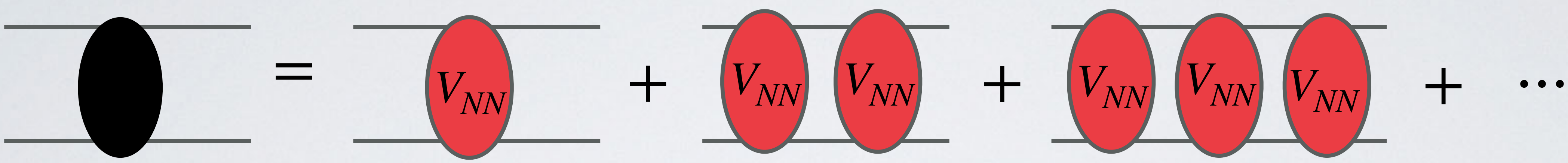

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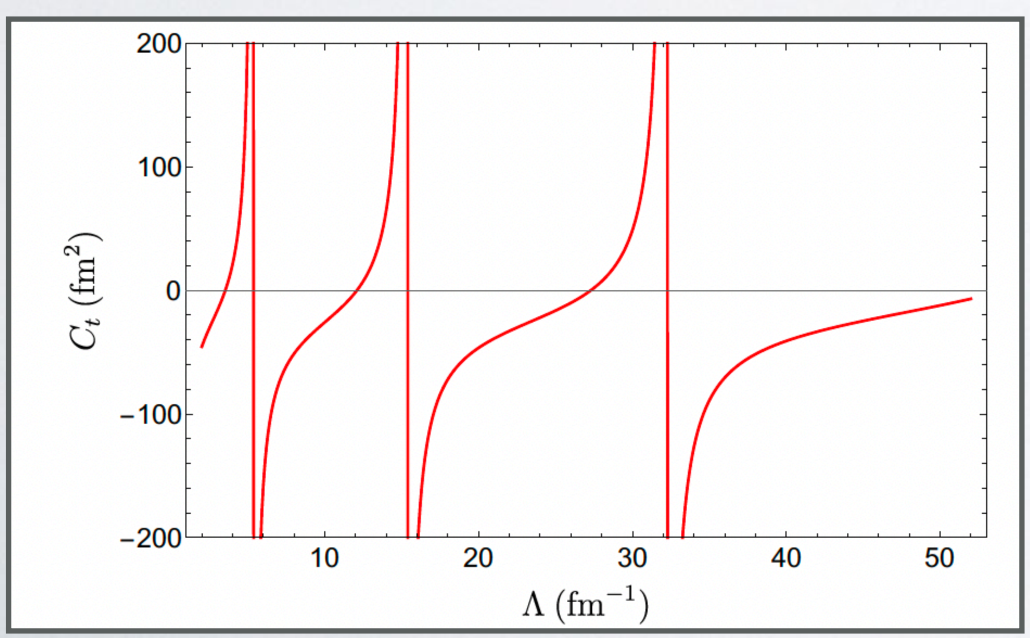
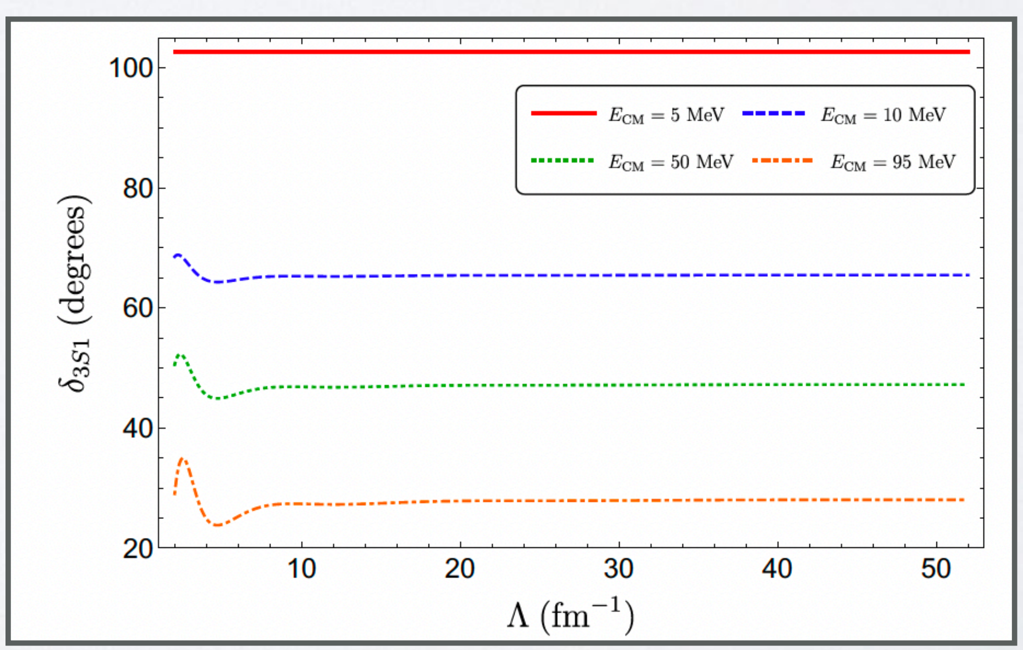
$$V_{\rm NN} \to e^{-p^6/\Lambda^6} \times V_{\rm NN} \times e^{-p'^6/\Lambda^6}$$

- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ
- This is called 'non-perturbative renormalization'. This is now down at very high order.
- Use nucleon-nucleon + three-nucleon data to fit constants —> predict nuclear physics





Nogga, Timmermans, van Kolck '05

Some successes (not by me)

- Chiral EFT —> derive nuclear properties + reactions —> equation of state + neutron stars

LETTERS

nature physics

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

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

Gysbers et al '20

ARTICLES

nature physics

https://doi.org/10.1038/s41567-022-01715-8

Check for updates

OPEN

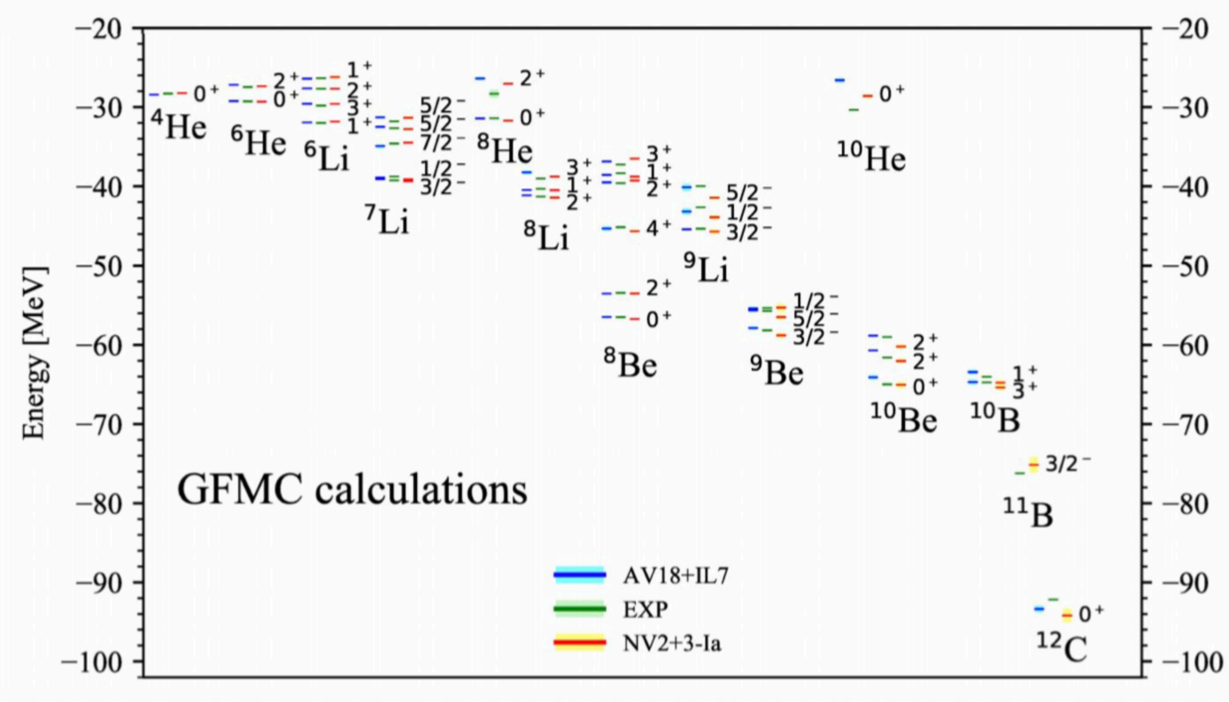
Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Hu et al '22

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

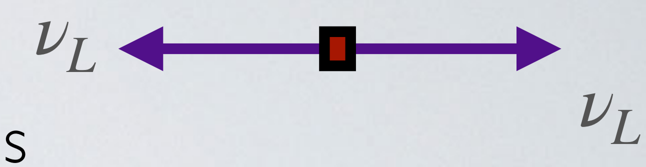
Physics See Viewpoint: The carbon challenge

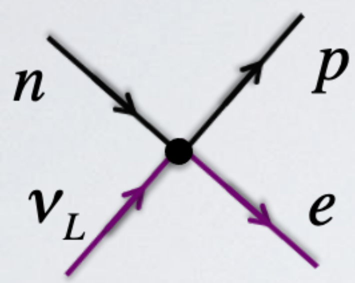


Piarulli et al. PRL 120, 052503 (2018)

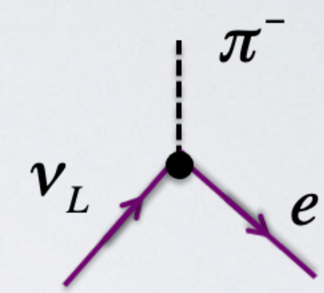
Light Majorana neutrinos (standard mechanism)

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Basically just use low-energy chiral Lagrangian with weak interactions



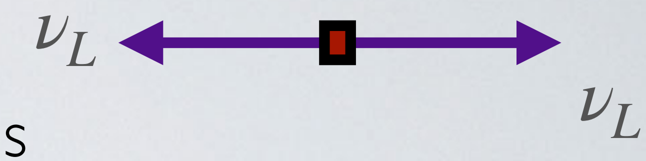


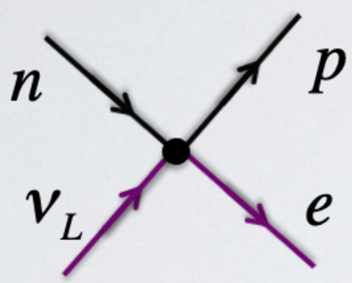
$$L_{\chi,Fermi} = G_F f_\pi \left(\partial_\mu \pi^- \, \bar{e}_L \gamma^\mu \nu_L \right)$$
$$+ G_F \, \bar{p} \left(\gamma^\mu - g_A \gamma^\mu \gamma^5 \right) n \, \bar{e}_L \gamma^\mu \nu_L + \cdots$$



Light Majorana neutrinos (standard mechanism)

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Basically just use low-energy chiral Lagrangian with weak interactions





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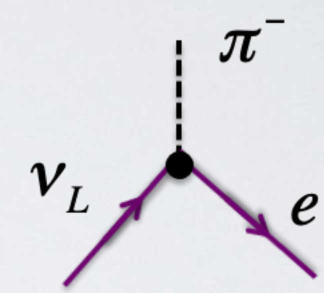
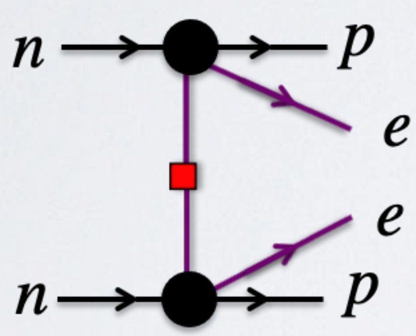


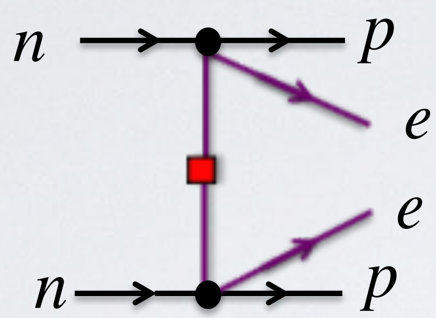


$$V_\nu(^1S_0) = (2G_F^2 m_{\beta\beta}) \tau_1^+ \tau_2^+ \frac{1}{\mathbf{q}^2} \left[(1 + 2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)} \right] \otimes \bar{e}_L e_L^c$$

- This is the leading-order 'neutrino potential'.
- Then insert this 'potential' between nuclear wave functions $A_\nu = \langle \Psi_f | V_\nu | \Psi_i \rangle$
- Note: the nucleons appear in a bound state and **q** is a loop momentum

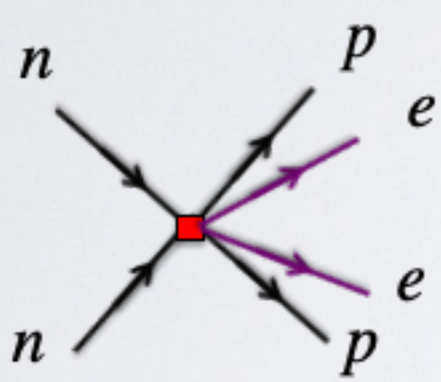
Light Majorana neutrinos (standard mechanism)

- Leads to 'long-range' nn → pp + ee



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

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

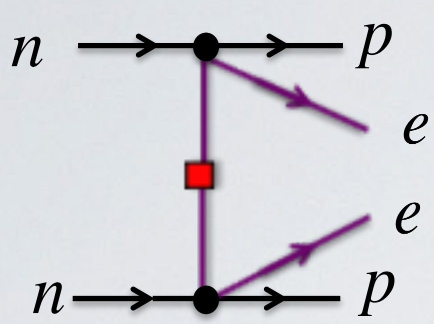


- Contributions from virtual hard neutrinos $\mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Naive-dimensional analysis tells us this is NNLO

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

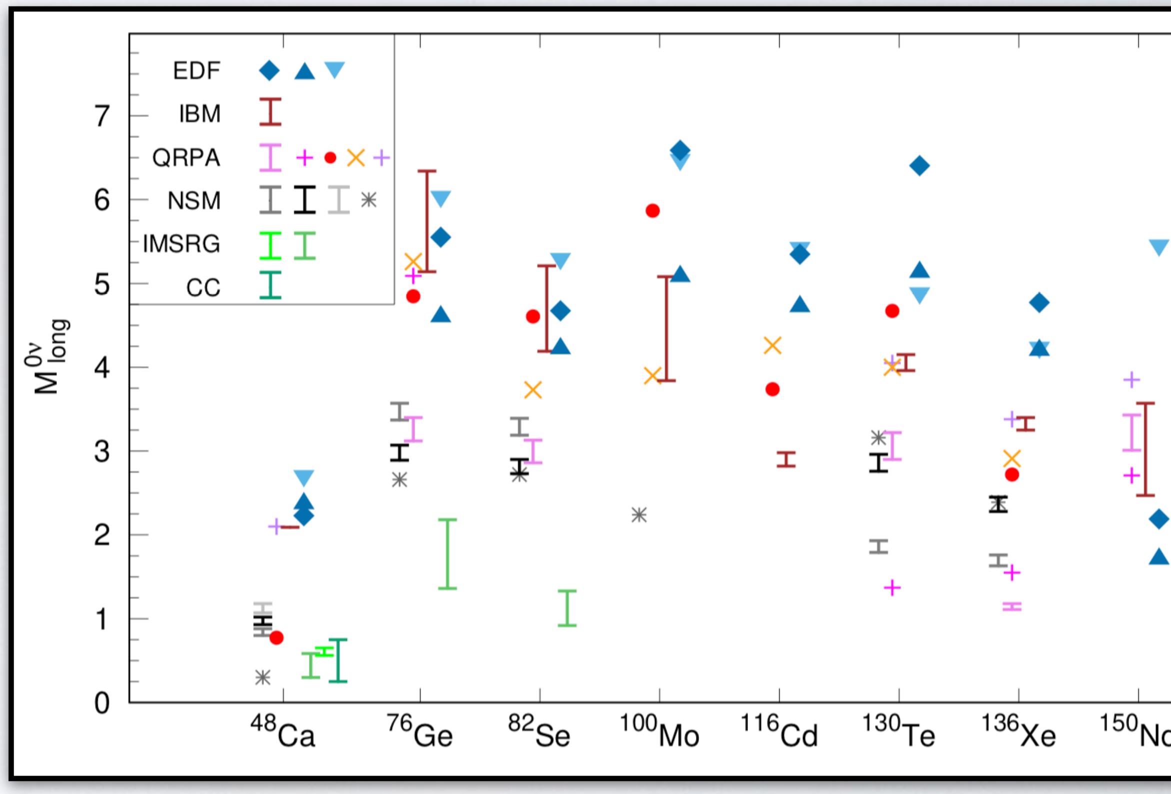
- Loops and other corrections at higher order in chiral EFT expansion

Leading-order transition currents



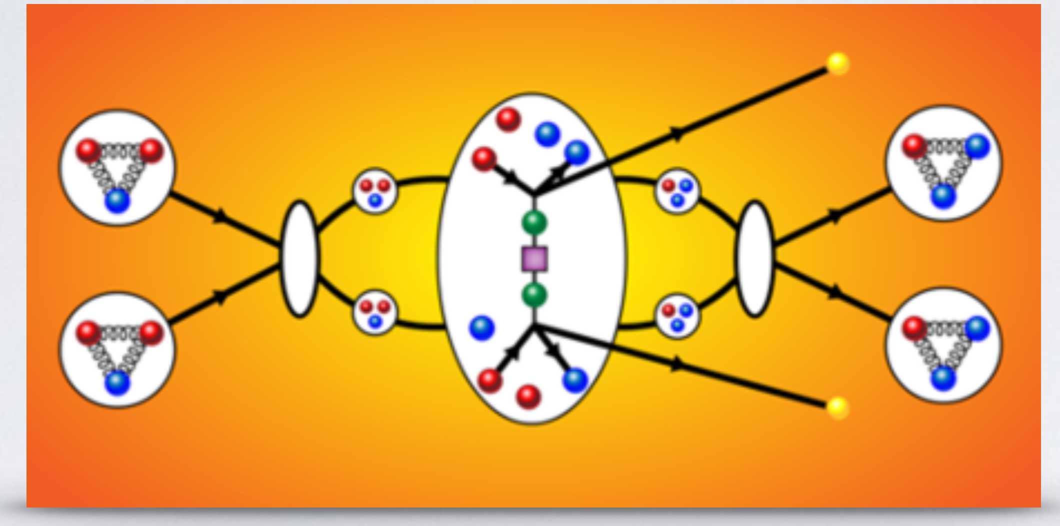
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+\frac{1}{\mathbf{q}^2}\left[(1+2g_A^2)+\frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right]\otimes \bar{e}_L e_L^c$$

- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown is $m_{\beta\beta}$
- ***Many-body methods disagree significantly***
- Original idea: study simpler nuclear systems
- **Not relevant for experiments but as a theoretical laboratory**



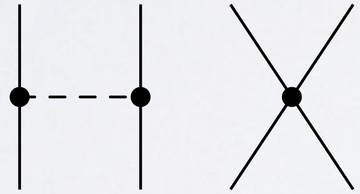
Neutron-Neutron → Proton-Proton

- Study simplest nuclear process: nn → pp + ee



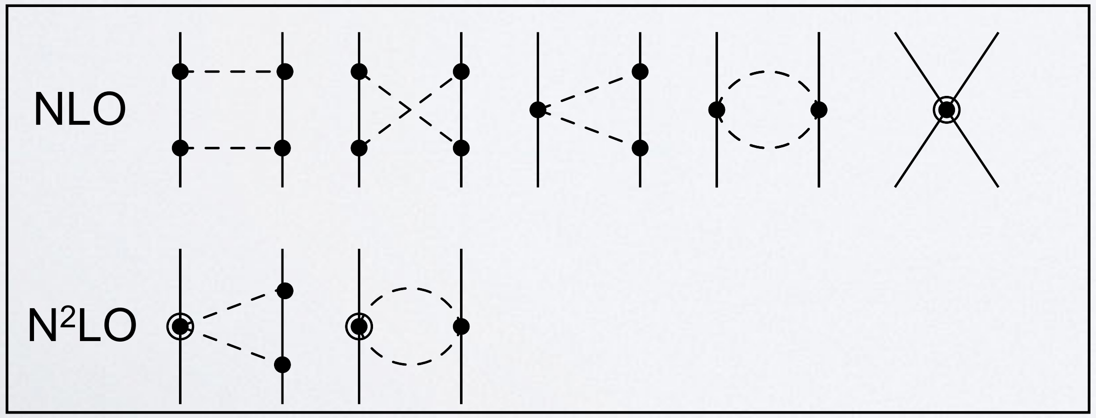
- Derive wave functions from chiral effective field theory

LO



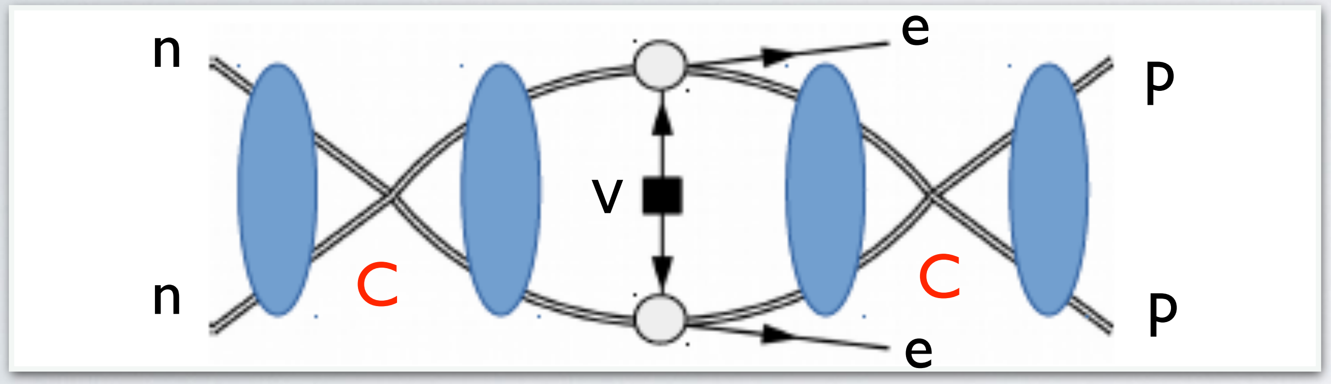
$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

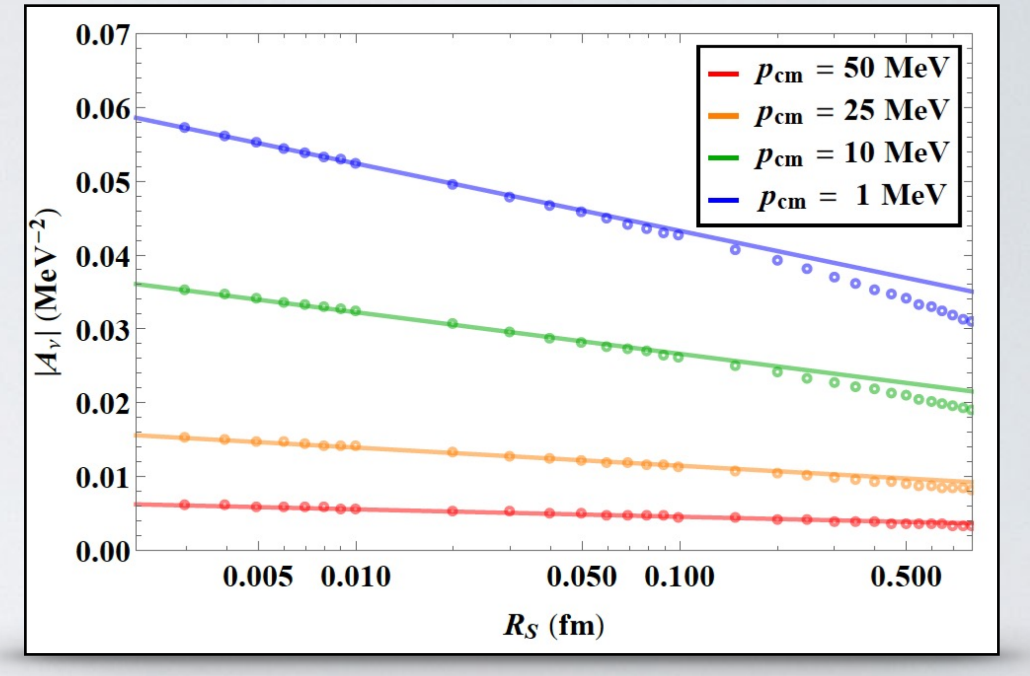
Weinberg 90' 91'



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

It doesn't work



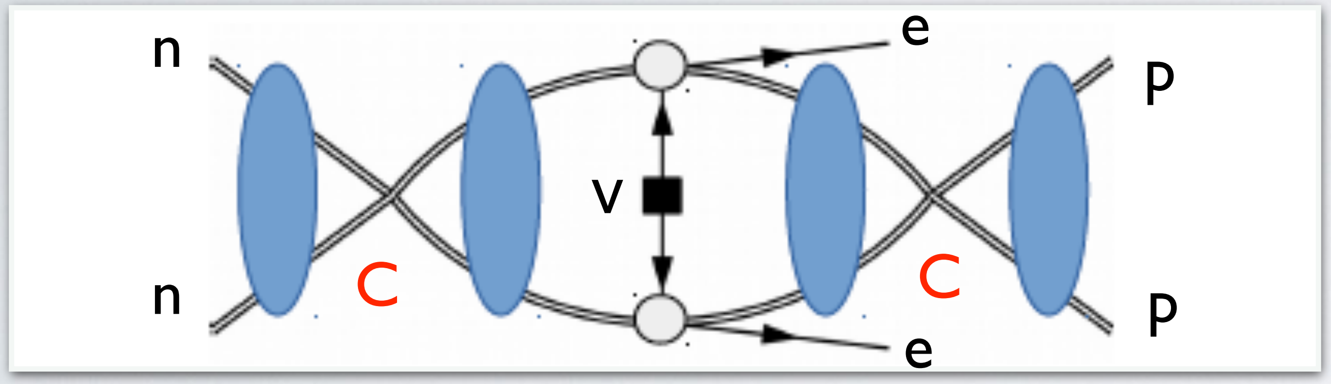


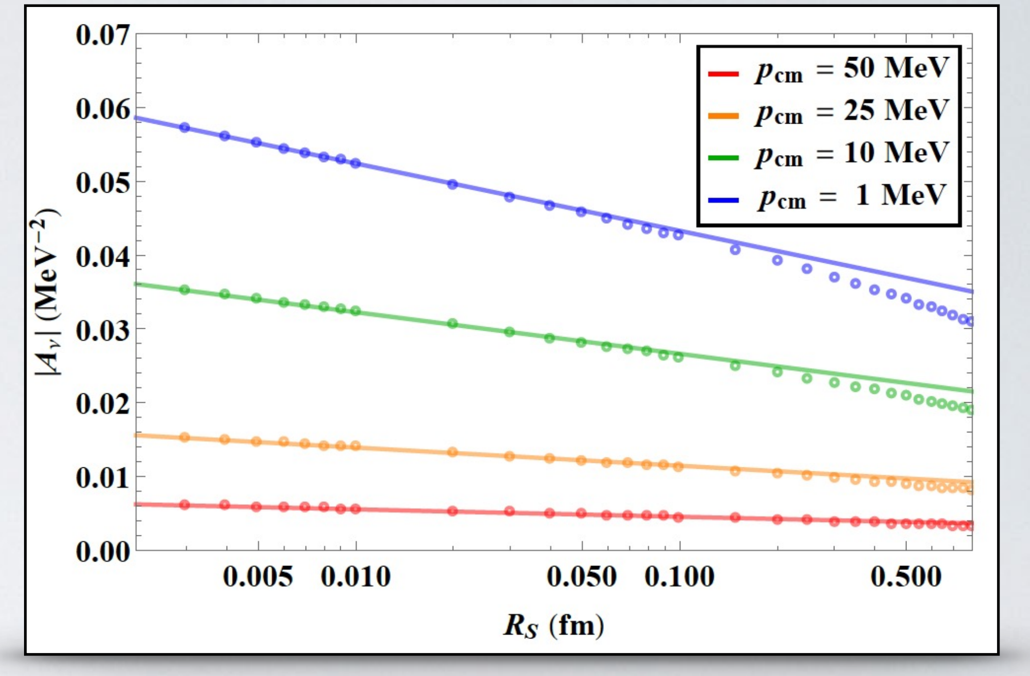
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\epsilon} + \log \frac{\mu^2}{p^2}\right)$$

New divergences

The leading order amplitude is not renormalized !

It doesn't work

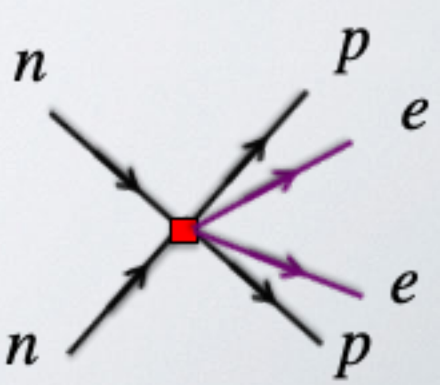




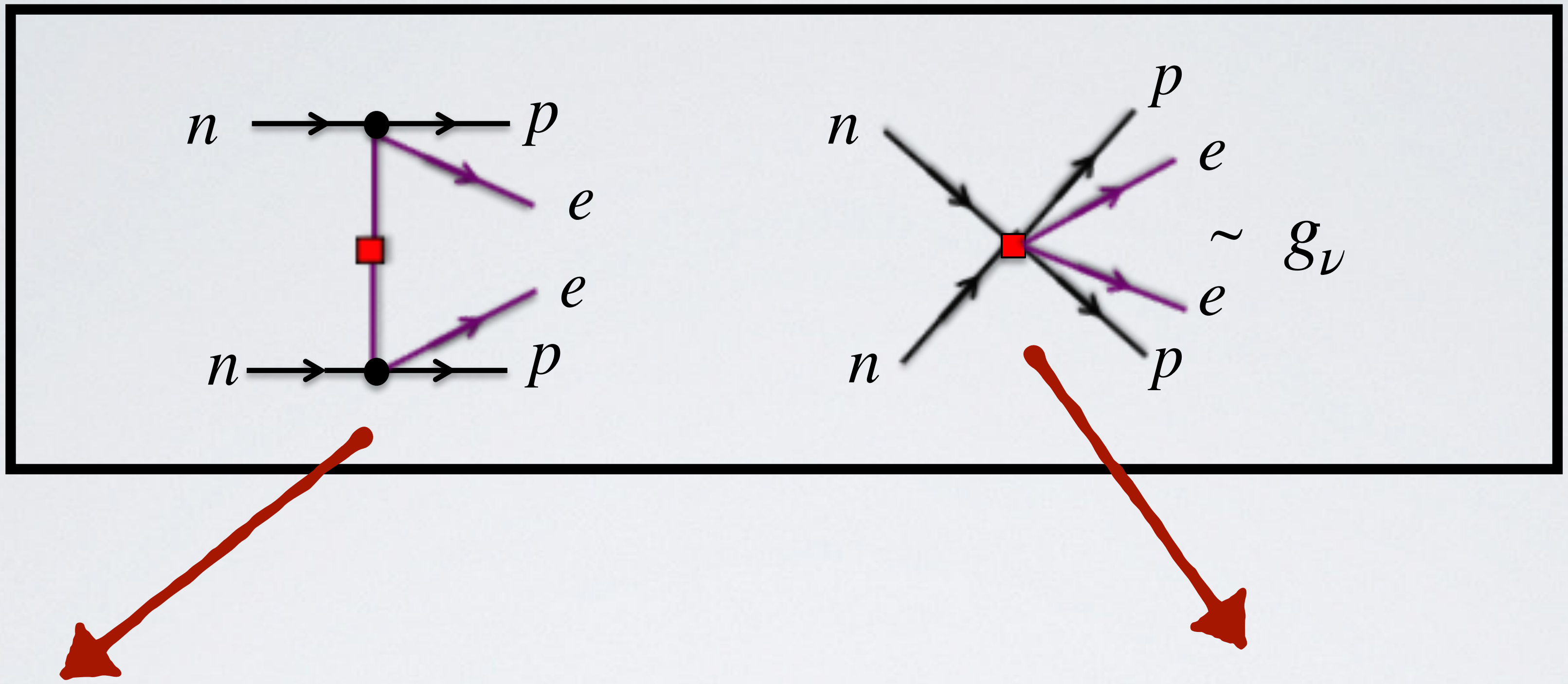
$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\epsilon}+\log\frac{\mu^2}{p^2}\right)$$

New divergences

- **Logarithmic regulator dependence**
- Divergence indicates sensitivity to short-distance physics (hard-neutrino exchange)
- Suggest to add a counter term: a short-range nn → pp + ee operator
- Literature: *'breakdown of Weinberg power counting'*



A new leading-order contribution



'Long-range' neutrino-exchange

'Short-distance' neutrino exchange required by renormalization of amplitude

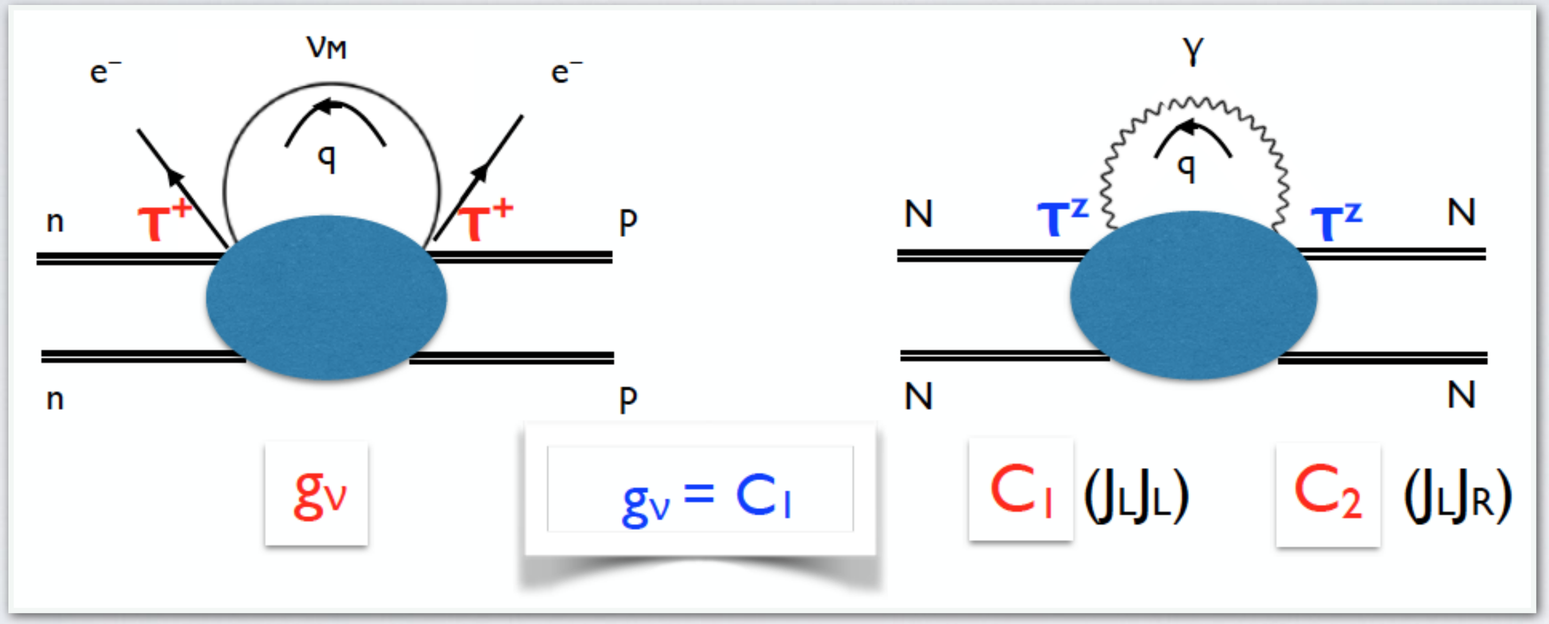
- **Short-distance piece depends on QCD matrix element** g_ν
- This was initially unknown but has now been determined (long story for a technical talk)

  Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC '19 PRL '21 JHEP '21
  Davoudi, Kadam PRL '21 Briceno et al '19 '20
  Van Groffier '24
  Richardson, Schindler, Pastore, Springer '21
  Tuo et al. '19; Detmold, Murphy '20 '22
  Yang, Zhao '23 '24

- 0vbb calculations have to be redone —> This is now happening by many groups

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions

A connection to electromagnetism

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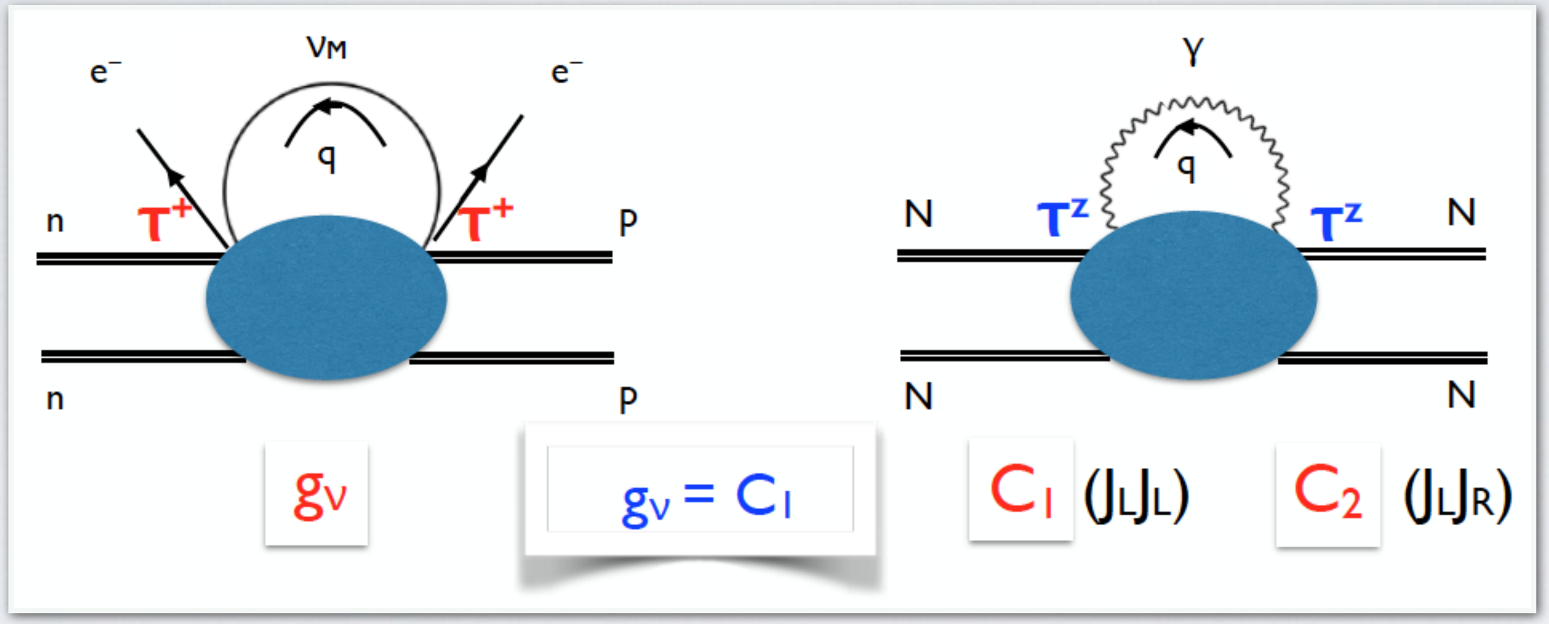


Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions

- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **g_ν~C_1** only

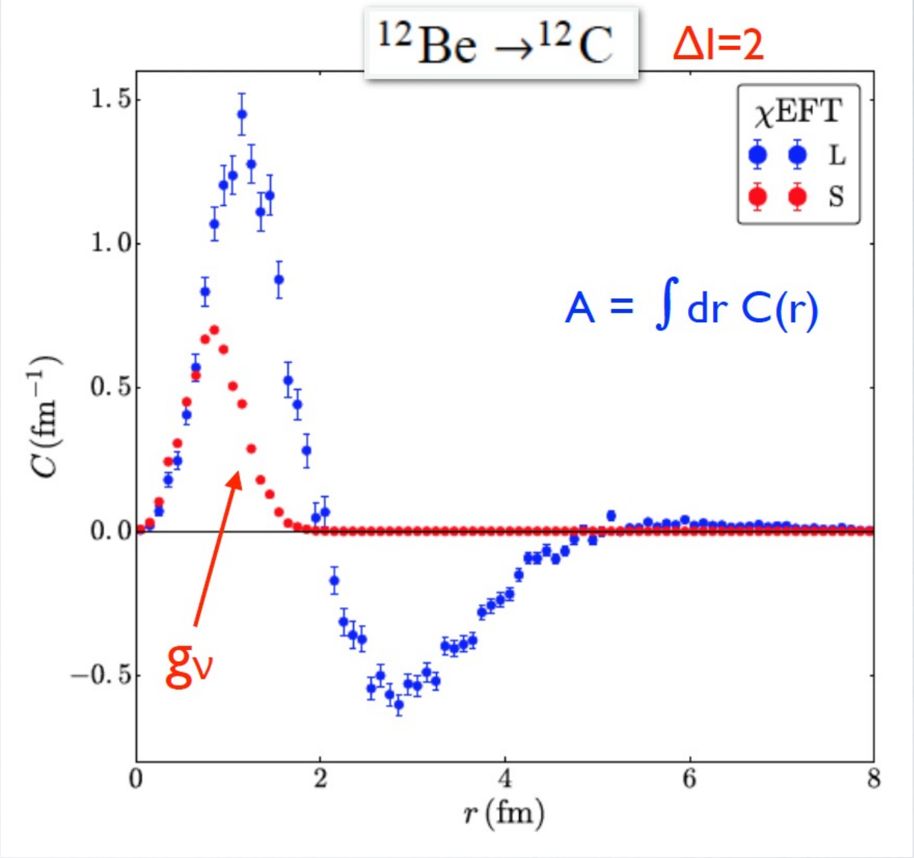
- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer PRC'21

- This seems to work surprisingly well Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL '21

Van Groffier '24 Yang, Zhao PLB '23 '24

Impact on nuclear matrix elements

Pastore, Piarulli et al '19

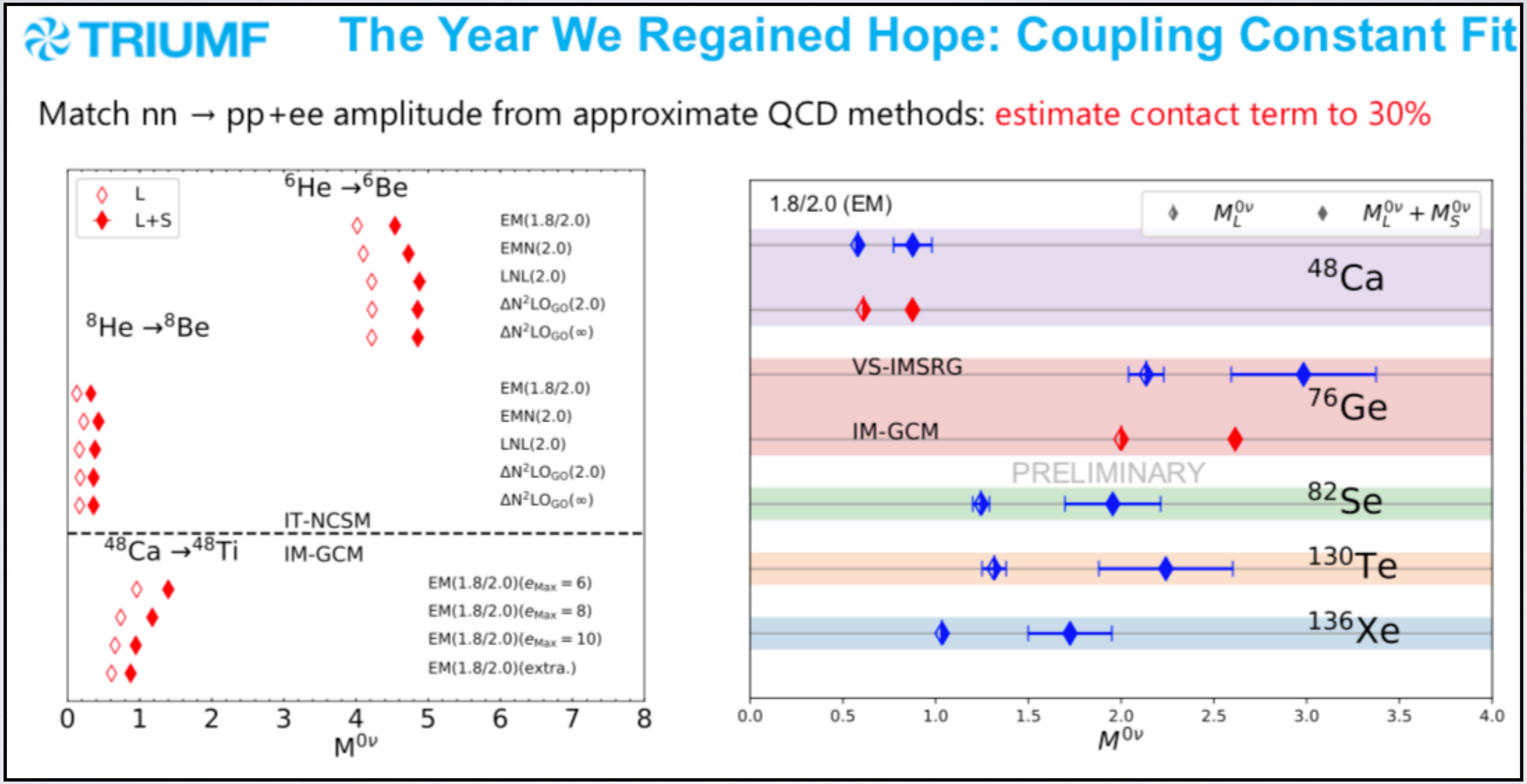


- Use VMC + Norfolk chiral potentials for wave functions

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

- Short-distance effects are sizable and change matrix elements by O(1)
- **Caveat:** These are not nuclei of experimental interest
- **Can we do better ?**

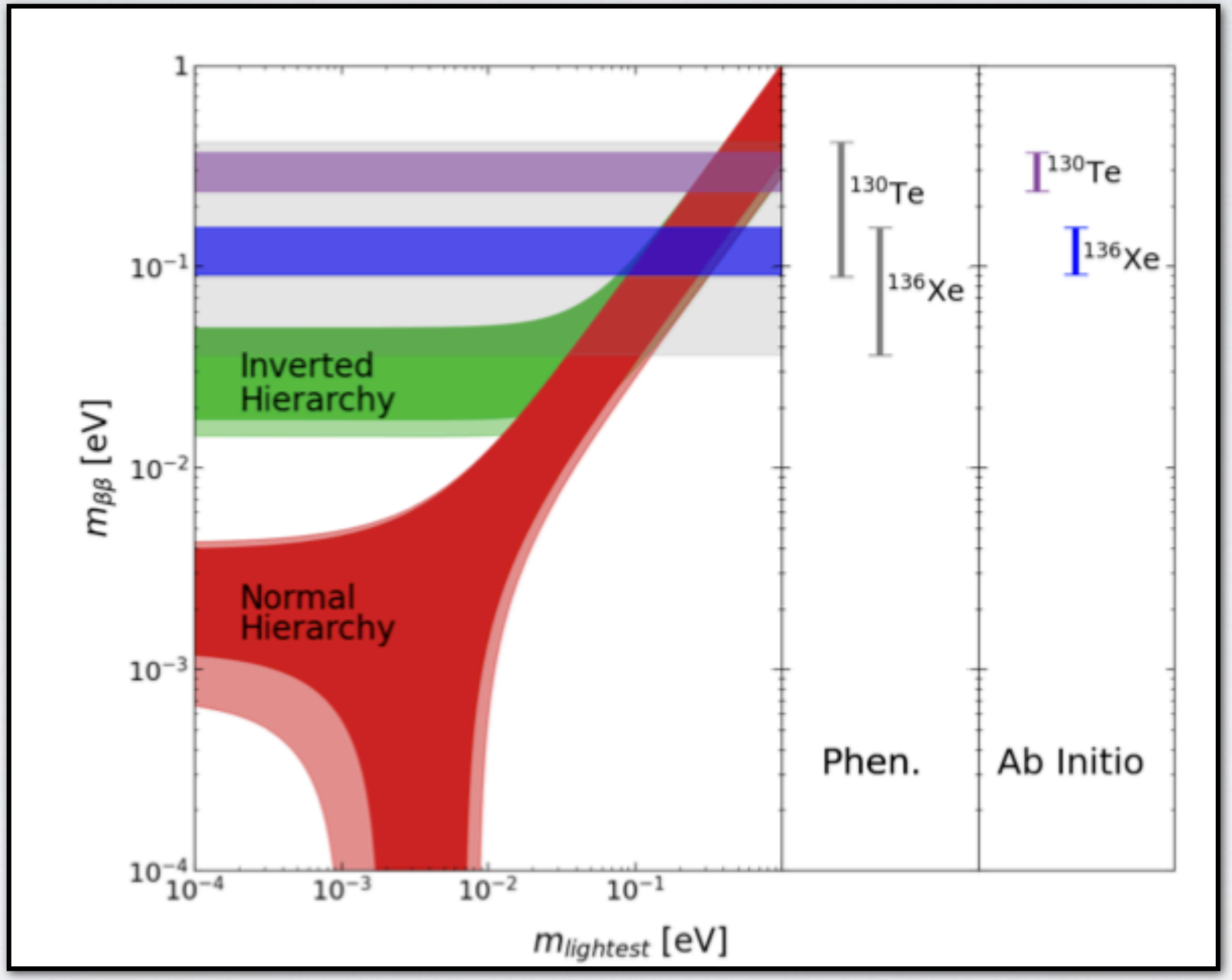
Impact on realistic nuclei



- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (2024)
- The contact term enhances NMEs by 100% (Ca) to 70% (Xe) (factor 3-4 on the lifetime)

Impact on realistic nuclei

- Results from 2307.15156 (Belley et al) and PRL 132, 182502 (2024) + papers from ’21 ’22

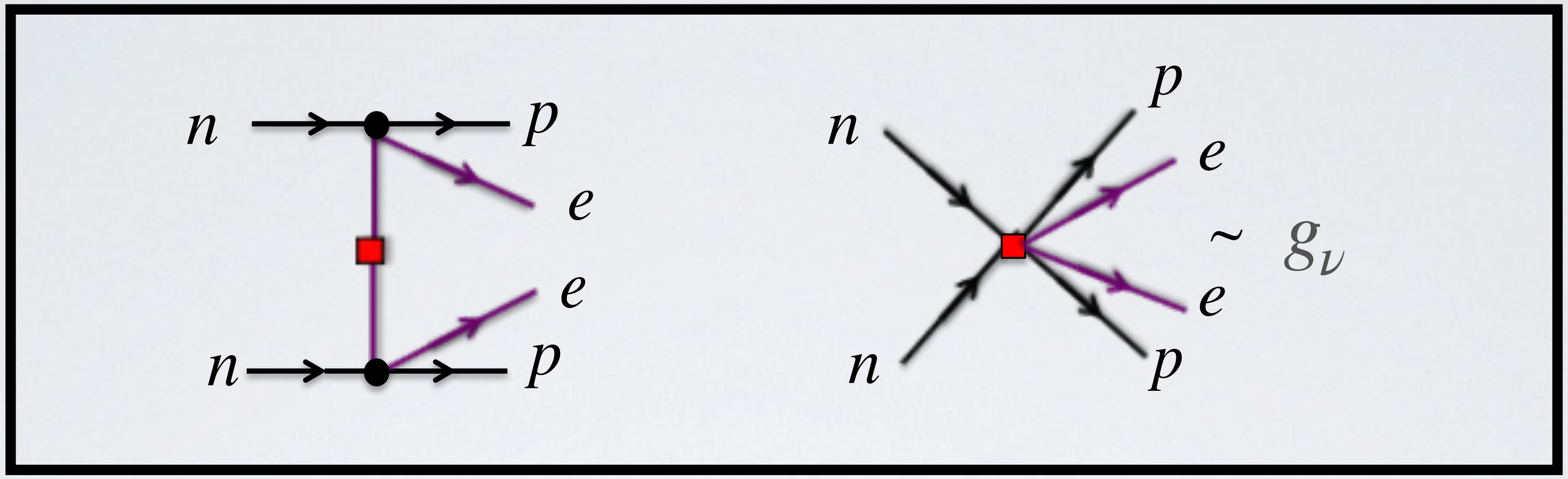


- Ab initio calculations find rather small NME **compensated** by contact term
- Counter term leads to smaller model dependence: uncertainties at 30-40% level

- Not clear to me how to connect chiral EFT to phenomenological nuclear models

Higher-order corrections

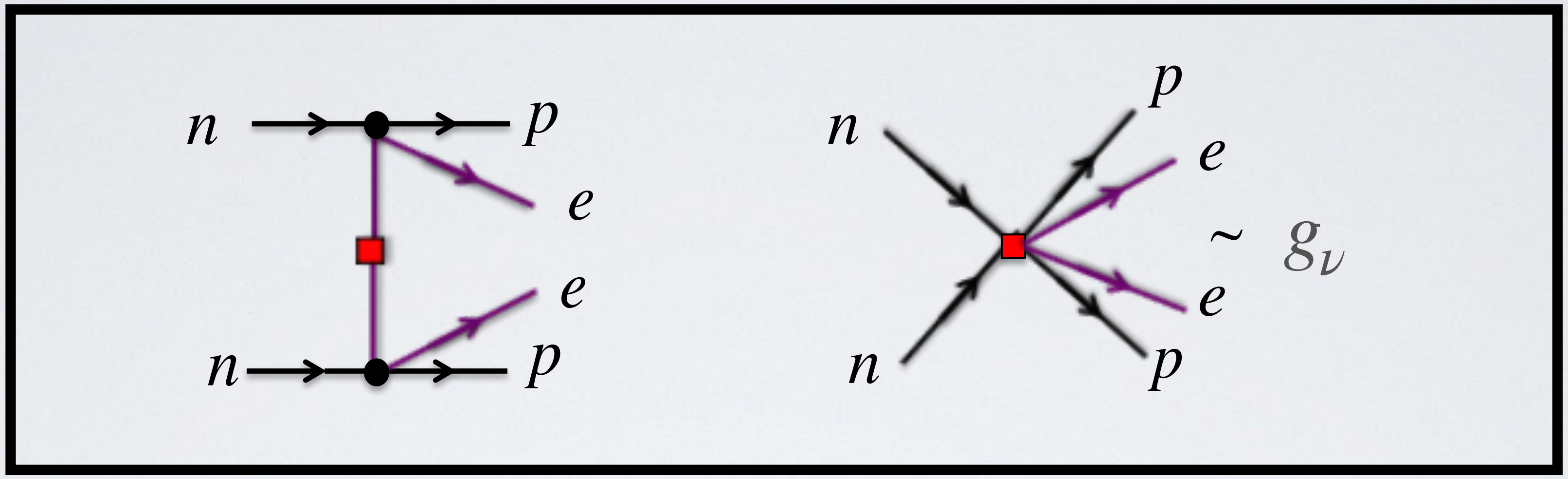
- It seems now that the leading-order 0vbb current contains 2 terms



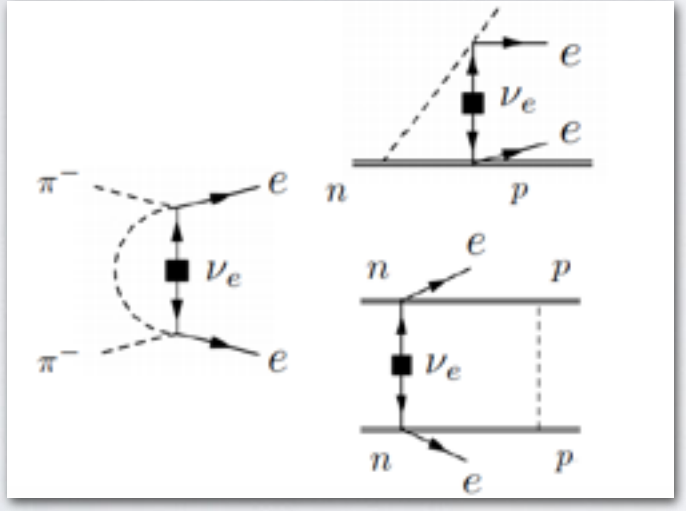
- **Are there more surprises ?**

Higher-order corrections

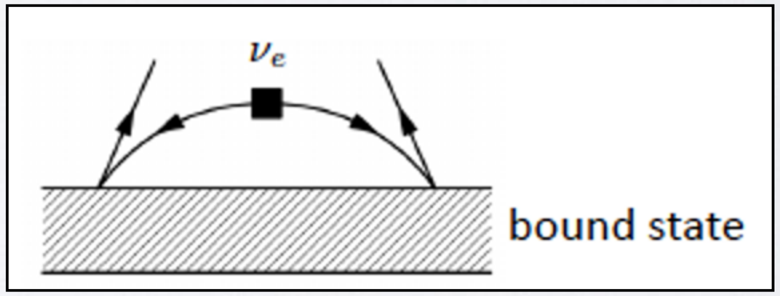
- It seems now that the leading-order 0vbb current contains 2 terms



- At NNLO we get additional contributions from loops



'Soft' neutrinos



'Ultra-soft' neutrinos

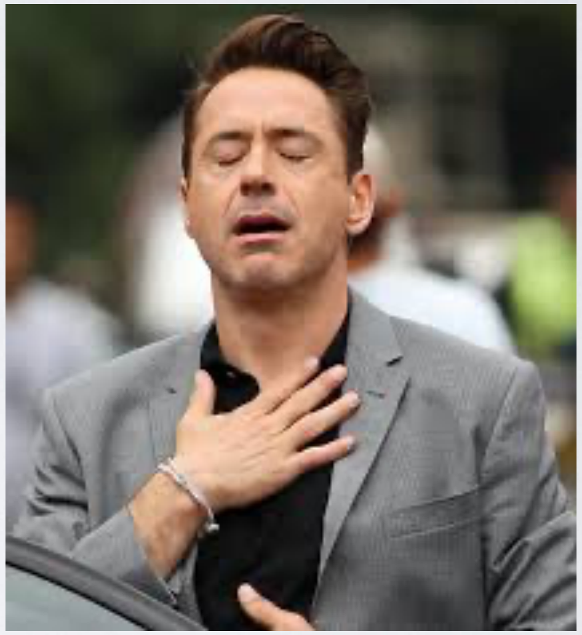
- Ultrasoft depends on nuclear structure

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

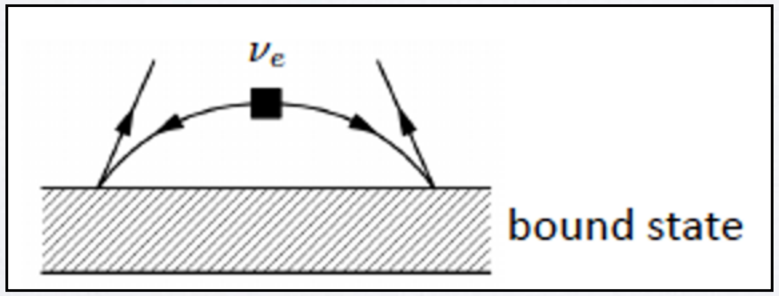
Higher-order corrections in the nuclear shell model

- Soft loops (Cirigliano et al '17) and ultrasoft (JdV et al '24) calculated in chiral EFT
- Implemented by Javier Menendez and collaborators (2408.03374) in Shell Model

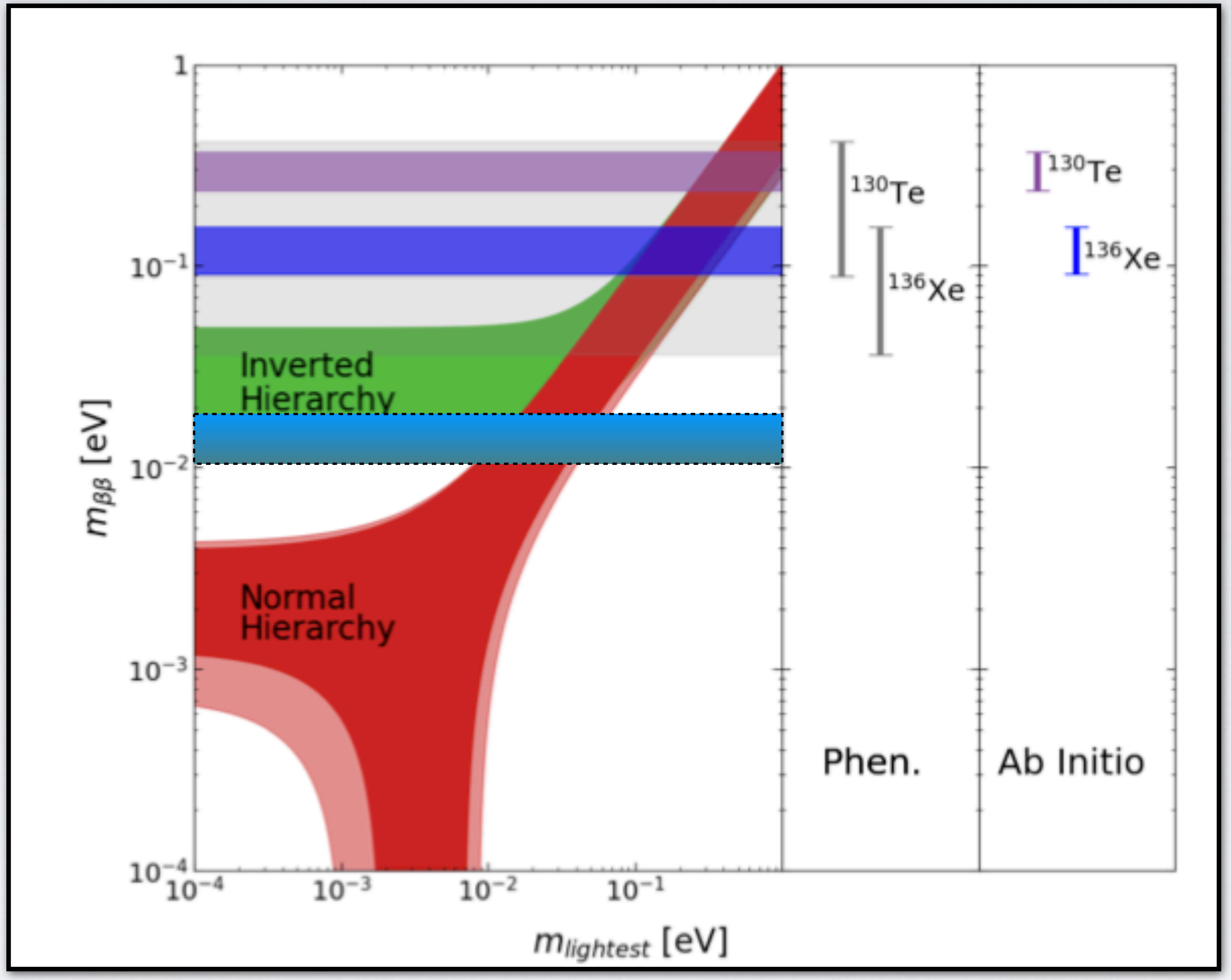
Nucleus	NSM			
	LO		N^2LO	
	L	S	usoft	loops
^{48}Ca	0.92(14)	0.43(20)	0.01(3)	0.05(7)
^{76}Ge	3.57(25)	0.97(48)	-0.26(0)	0.05(16)
^{82}Se	3.38(20)	0.91(43)	-0.24(1)	0.05(15)
^{96}Zr				
^{100}Mo				
^{116}Cd				
^{124}Sn	2.79(63)	1.06(52)	-0.21(5)	0.06(16)
^{130}Te	2.68(79)	1.07(50)	-0.20(7)	0.06(16)
^{136}Xe	2.26(53)	0.86(41)	-0.17(5)	0.05(13)



- Confirms that these effects are relatively small (usoft -10% corrections roughly)



Intermediate summary



- NMEs are still a big problem but there has been progress

- ***Next-gen experiments to reach inverted hierarchy but normal hierarchy remains difficult (unless m_l ~ 0.01 eV)***

Measuring nuclear matrix elements

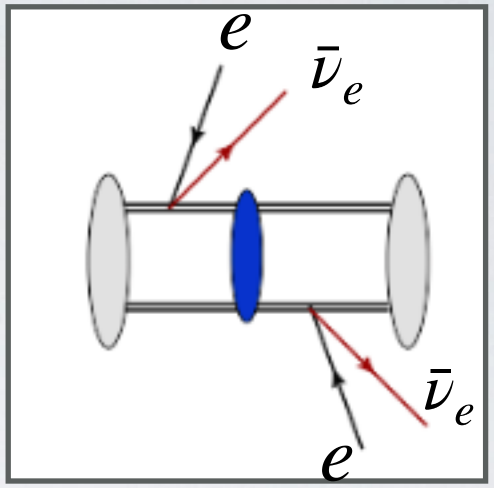
- Can't we extract NMEs from data on 2nubb ?

$$T_{\nu\nu} \sim G_F^2 \left(M_{GT}^K L_{11} \cdot L_{22} - M_{GT}^L L_{12} \cdot L_{21} \right)$$

Kotila '12
Simkovic et al '19

$$M_{GT}^{K,L} \sim \sum_n G_n \frac{E_n - \frac{1}{2}(E_i + E_f)}{[E_n - \frac{1}{2}(E_i + E_f)]^2 - \epsilon_{K,L}^2}$$

$$G_n \sim \langle \Psi_f | \sigma\tau^+ | n \rangle \cdot \langle n | \sigma\tau^+ | \Psi_i \rangle$$



- The dominant amplitude is sensitive to very different nuclear physics ! **No info for 2nubb**

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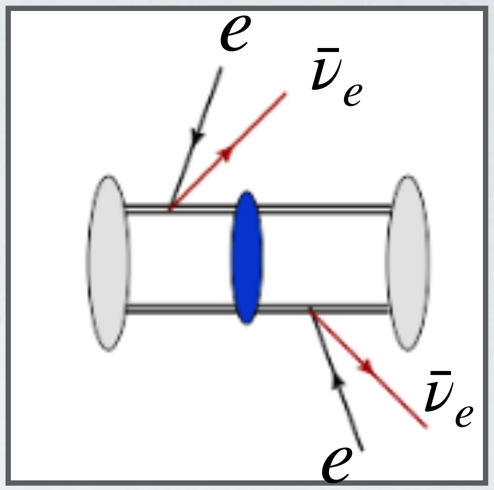
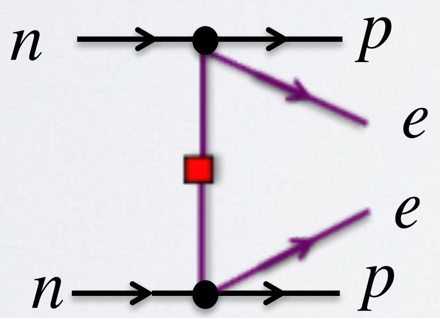
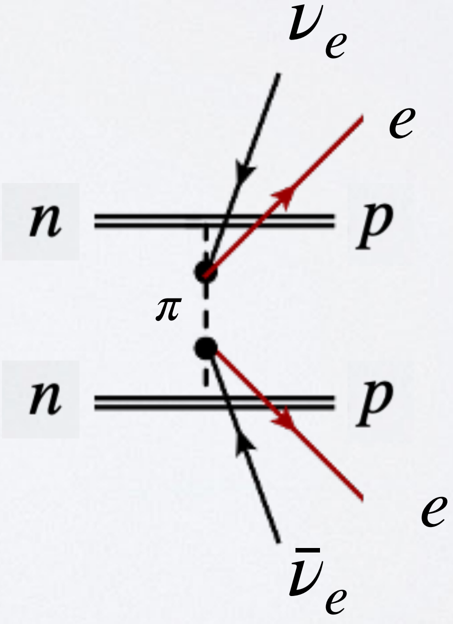


- The dominant amplitude is sensitive to very different nuclear physics ! **No info for 2nubb**

- But there are additional 2nubb contributions at *next-to-leading-order in chiral EFT* el Morabit et al '24



versus



- Modifies the total rate (but uncertainties too large) but also the **electron spectrum**

Measuring nuclear matrix elements

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$$T_{\nu\nu} \sim G_F^2 \left(M_{GT}^K L_{11} \cdot L_{22} - M_{GT}^L L_{12} \cdot L_{21} \right)$$

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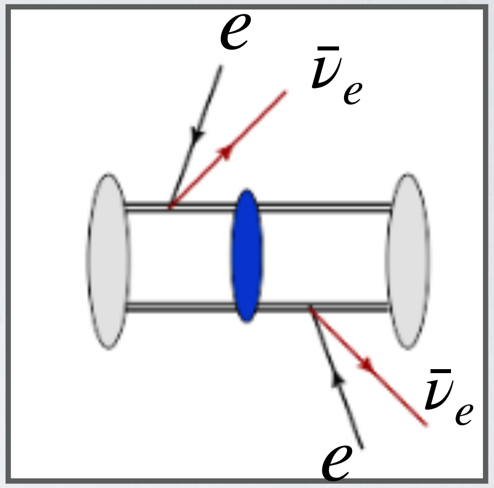

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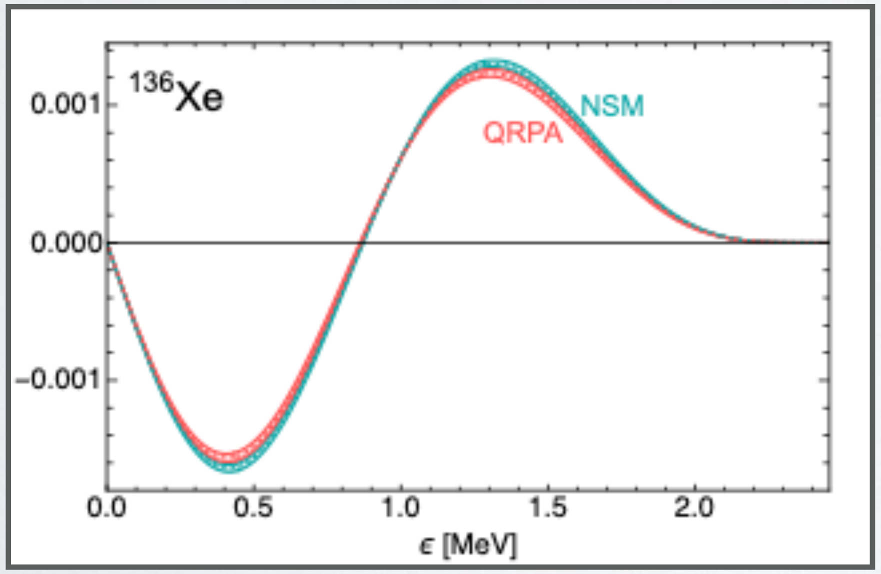
$\frac{1}{\Gamma}\frac{d\Gamma}{d\epsilon}$



- Extracting the nuclear matrix elements requires <% accurate spectrum measurements (not impossible at next-gen 0vbb and DM experiments)
- Also worries about radiative corrections….
- Interesting: but more work is needed
- Collaboration with XenonNT

The plan of attack

1. Introduction to Majorana neutrinos and 0vbb

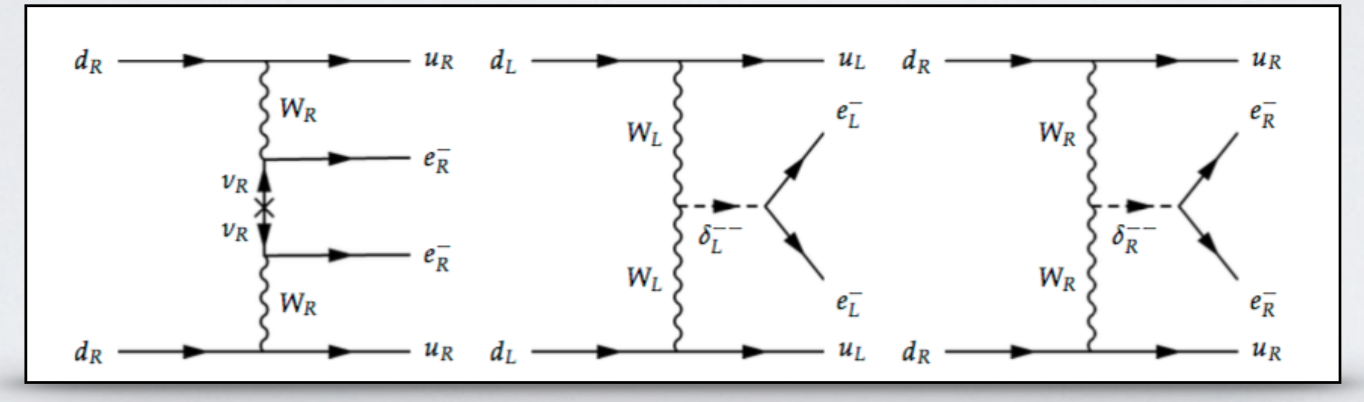
2. 0vbb from light Majorana neutrino exchange

    - *Controlling nuclear matrix elements !*

3. **Other sources of lepton number violation**

Other mechanism of 0vbb

- **Many beyond-the-SM model induce different 0vbb mechanism**
- Examples: Left-right symmetry, supersymmetry, leptoquarks, …….



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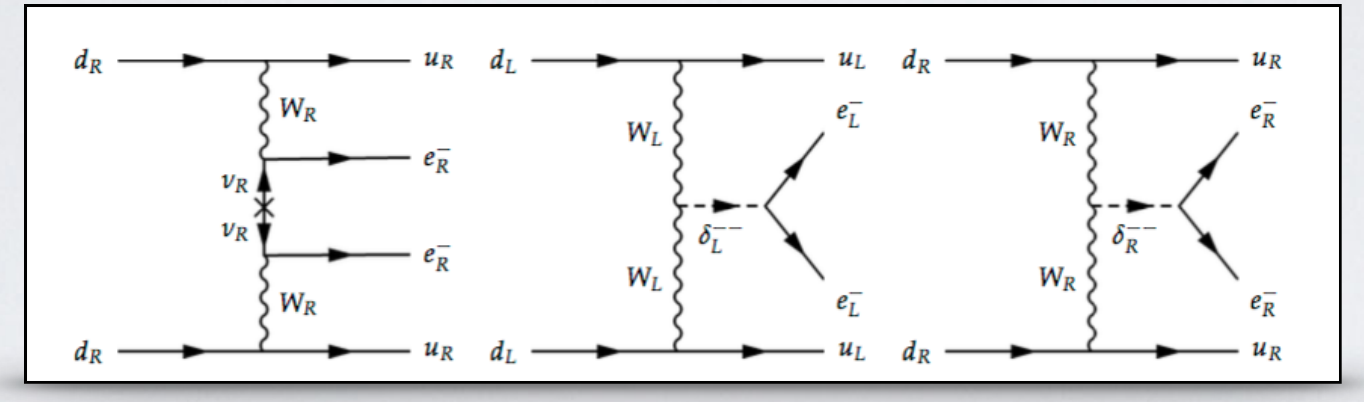
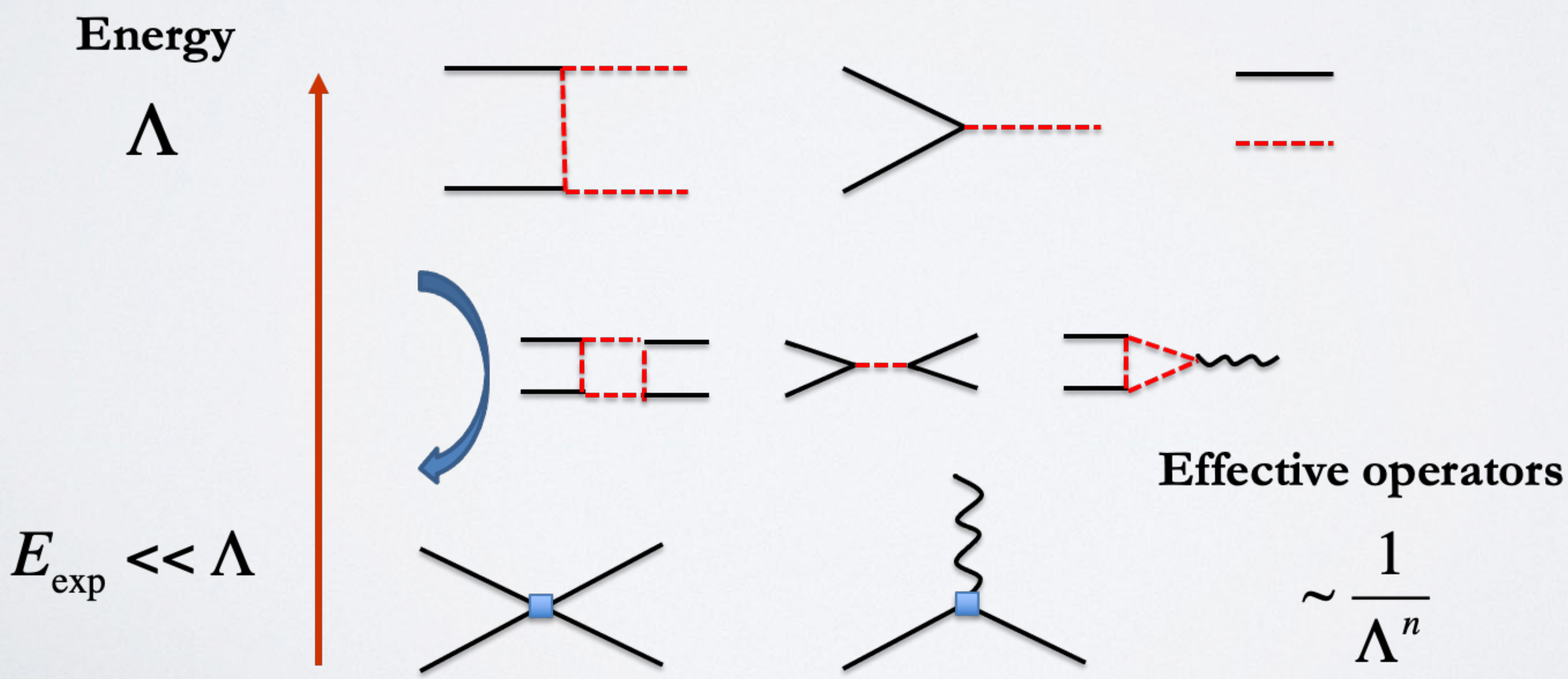
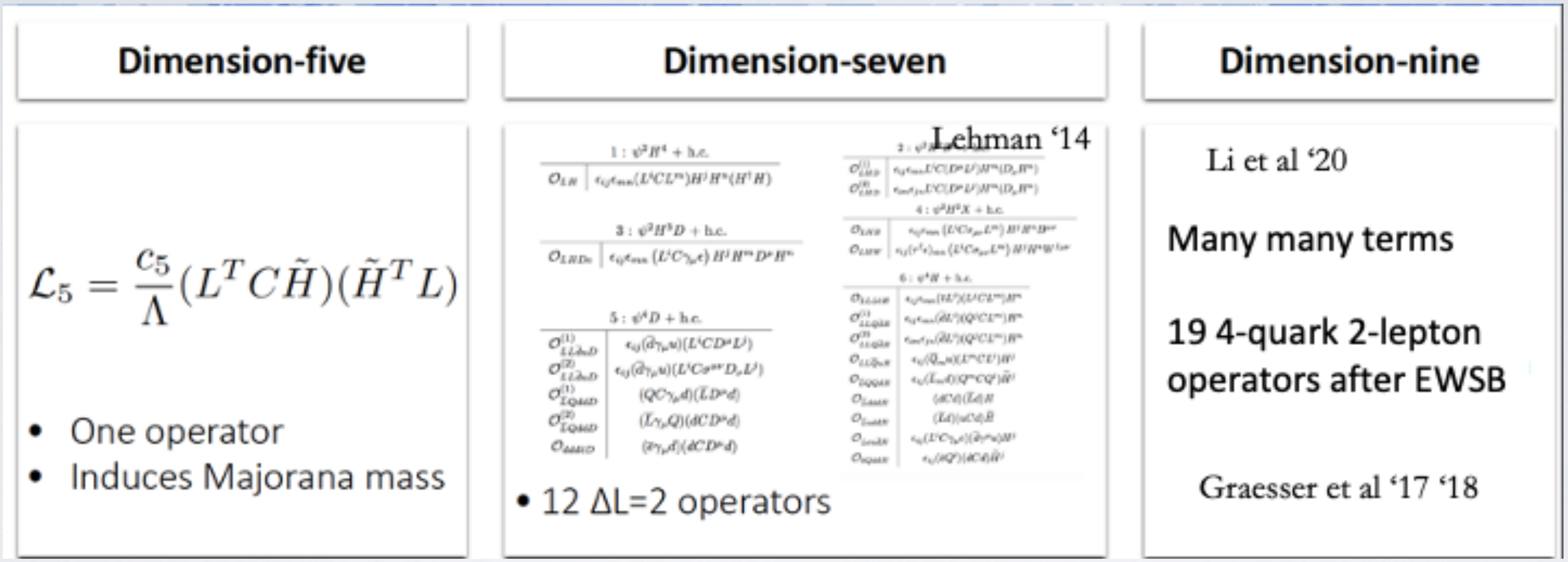


- **If new fields are heavy, can use effective field theory !**



Higher-dimensional operators

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



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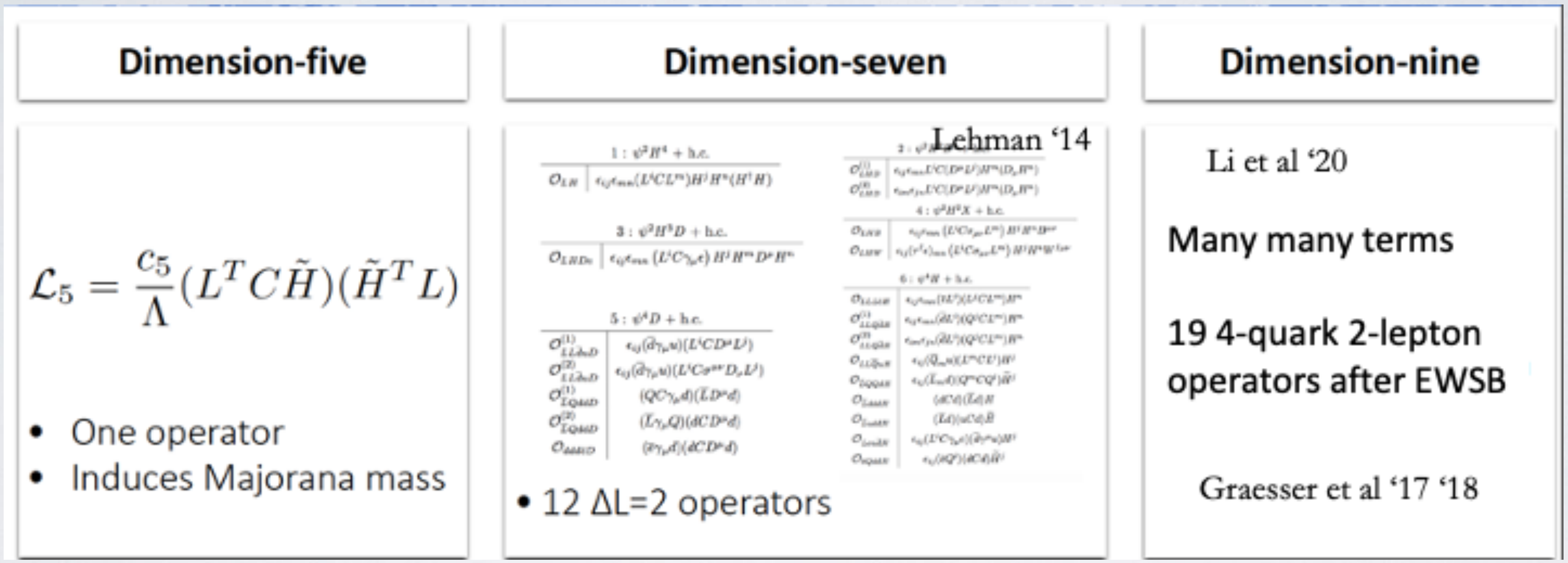


- Higher-dimensional terms relevant if dim-5 operator are suppressed

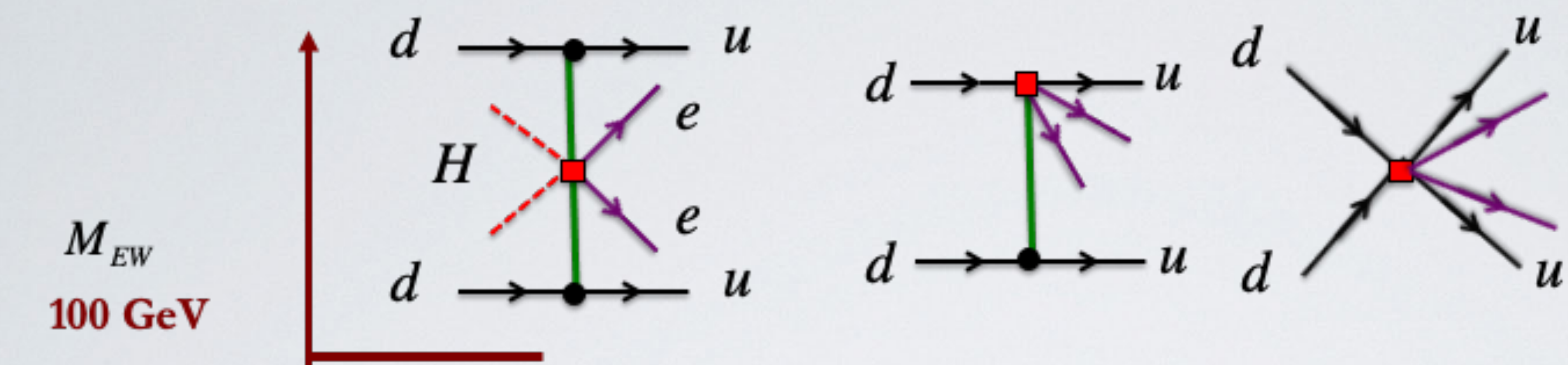
- Example: in left-right symmetric models

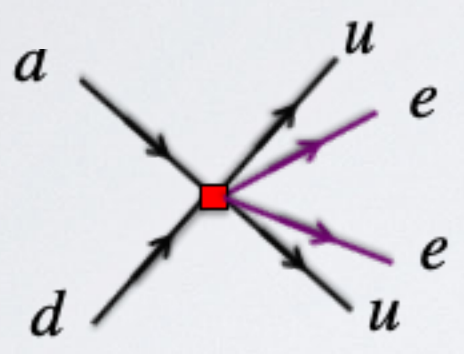
$$c_5 \sim y_e^2 \sim 10^{-10} \qquad c_7 \sim y_e^1 \sim 10^{-5} \qquad c_9 \sim y_e^0 \sim 1$$

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

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

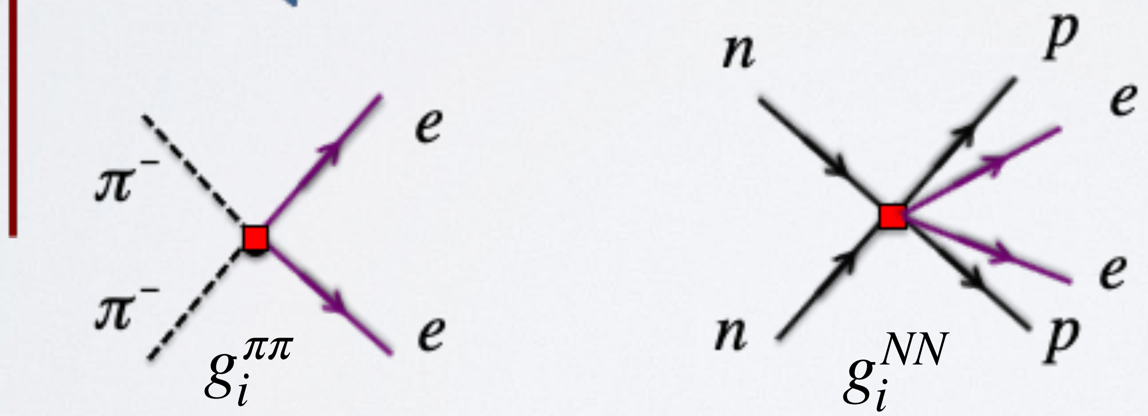
Some examples





- Four-quark 2-lepton operators
- Neutrinoless interactions

Chiral perturbation theory

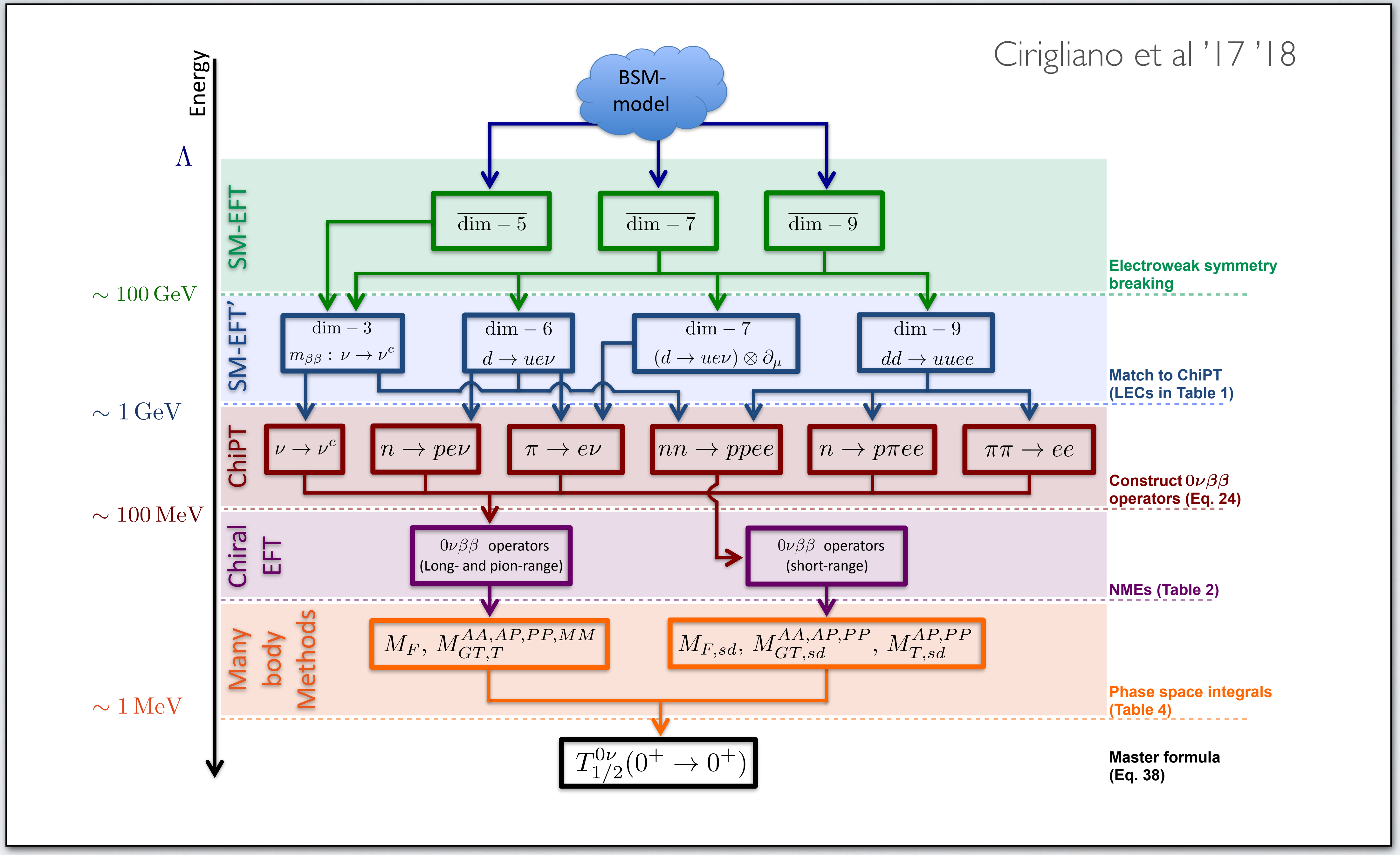


- Pionic operators lead to leading-order neutrinoless double beta decay contributions !
- **Depend on four-quark matrix elements: lattice QCD**

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

Nicholson et al '18

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

Using the framework

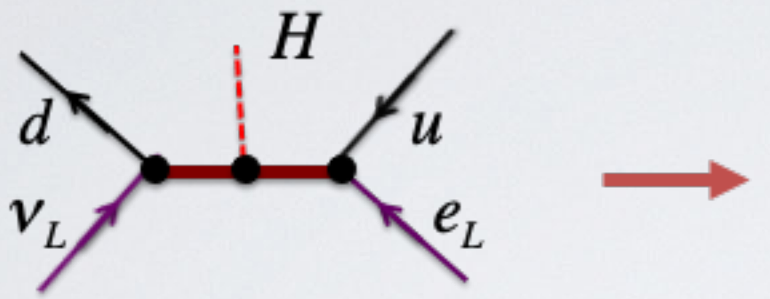
- Example: a model of heavy leptoquarks (LHC probes 1 TeV leptoquarks roughly)

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

$\Lambda > 400\ TeV$

Using the framework

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



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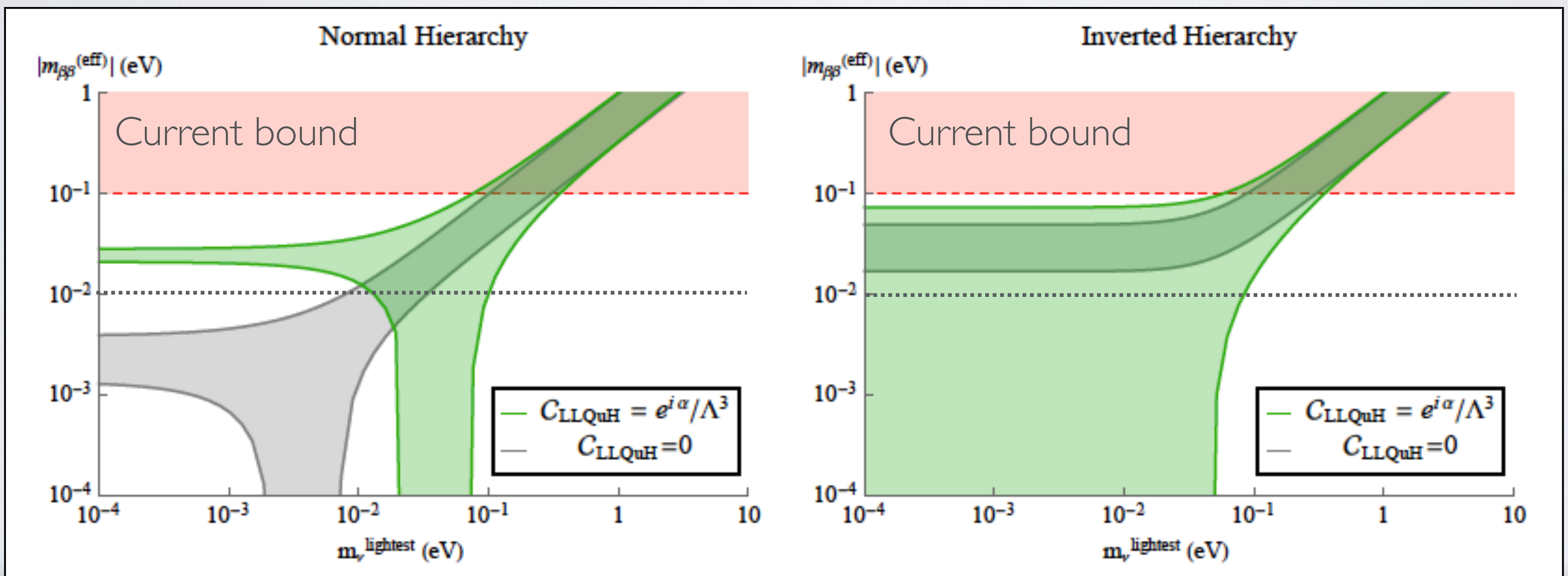


Ton-scale expectations

- Can lead to very different 0vbb phenomenology (**populate the 'dead zone'**)
- Sensitivity to 500-TeV new physics scales

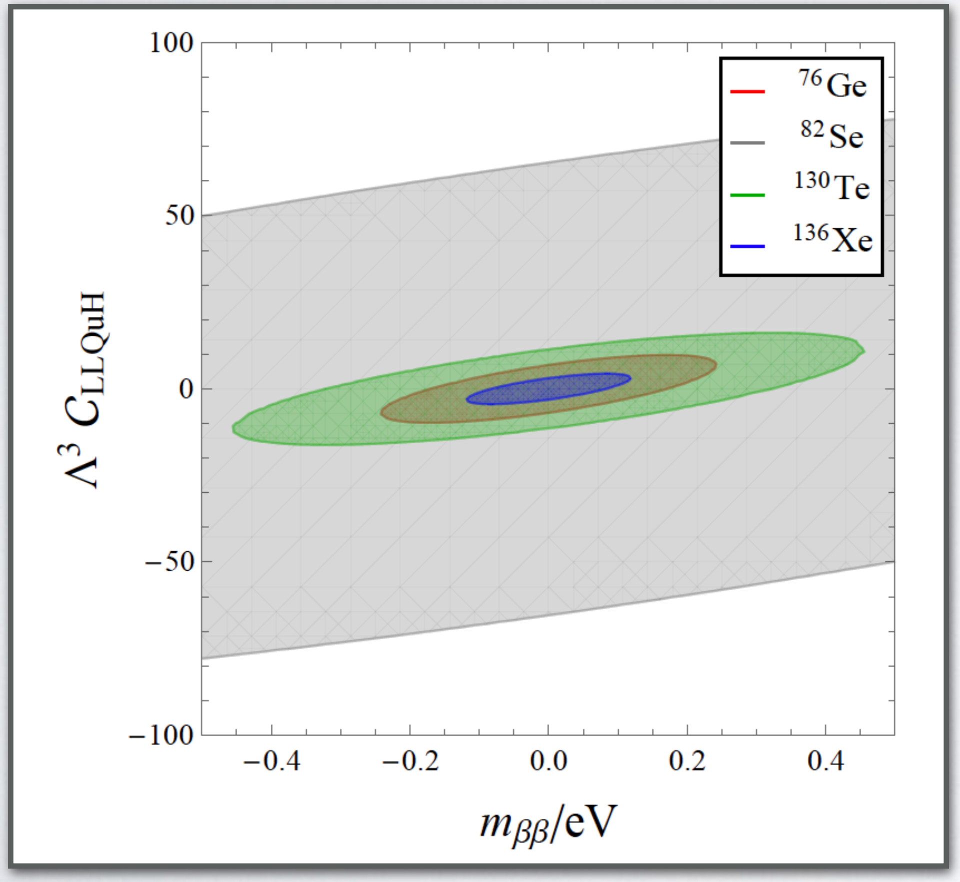
Disentangling the source of LNV

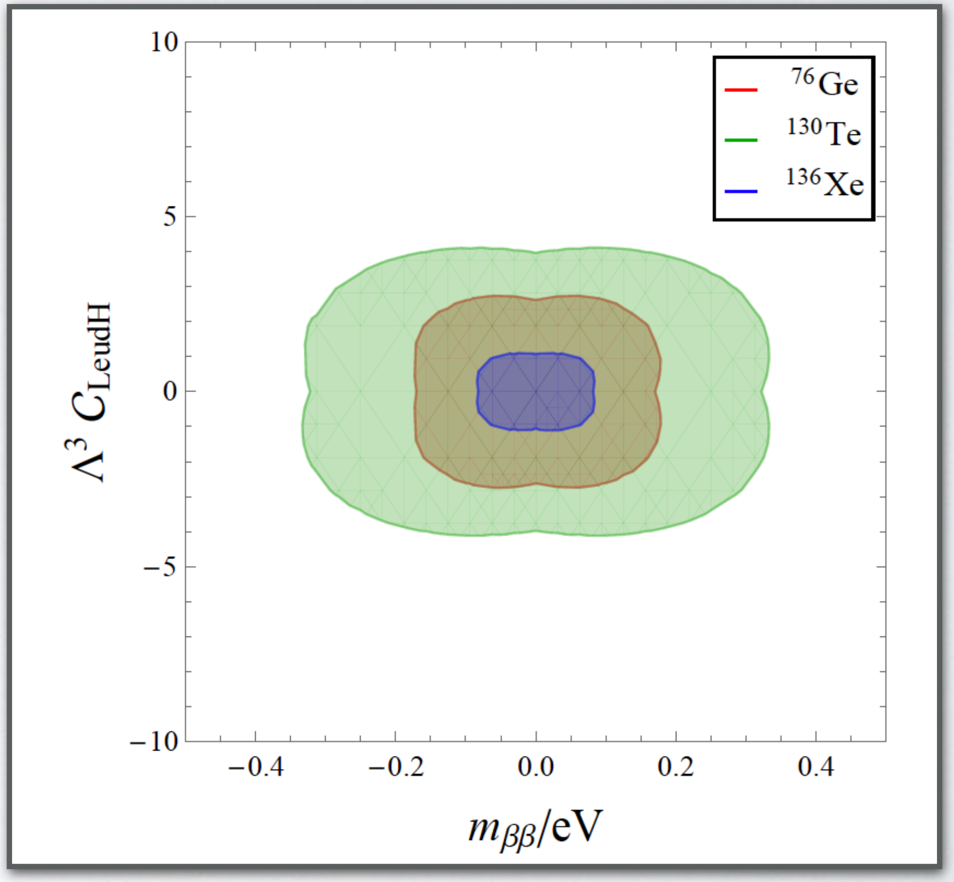
- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?
- Example: ratios of decay rates of various isotopes

Deppisch/Pas '07, Lisi et al '15

Scholer/Graf ' 22

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

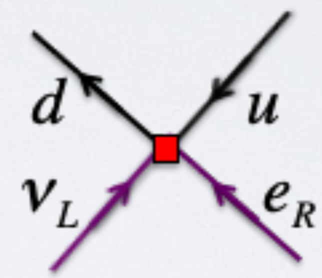




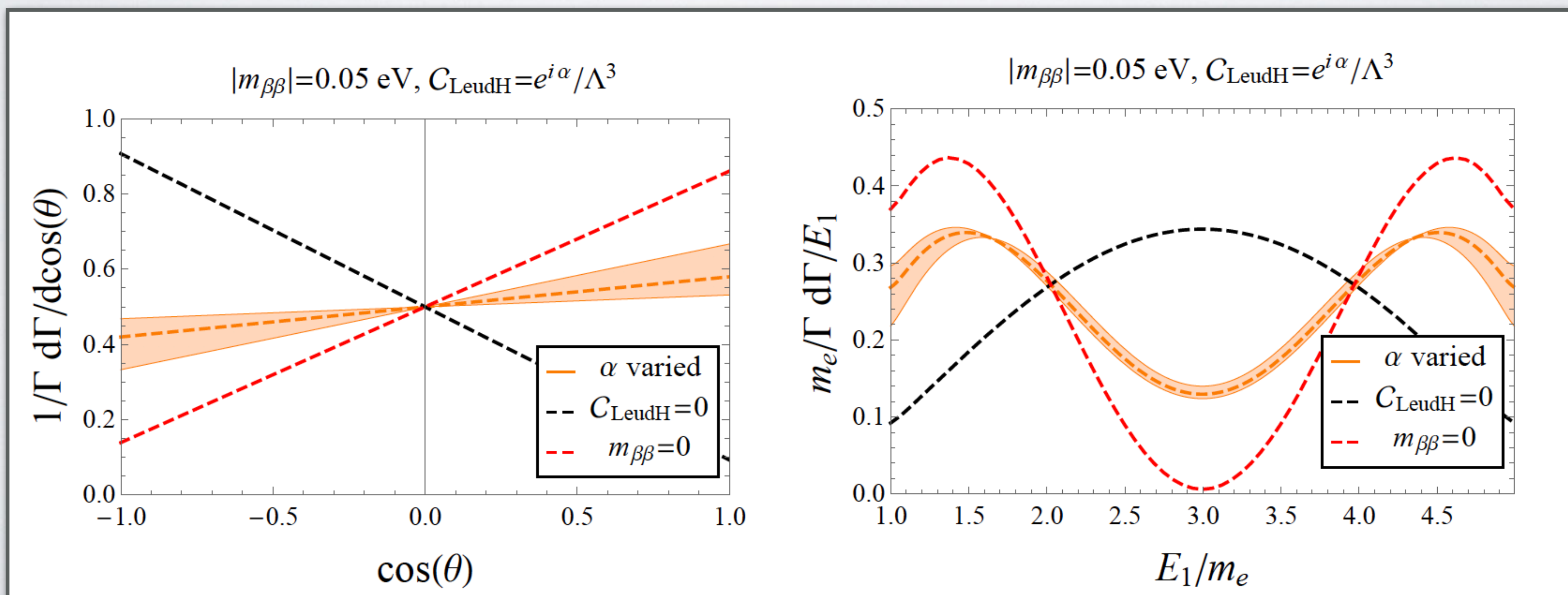
Disentangling the source of LNV

- 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**



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

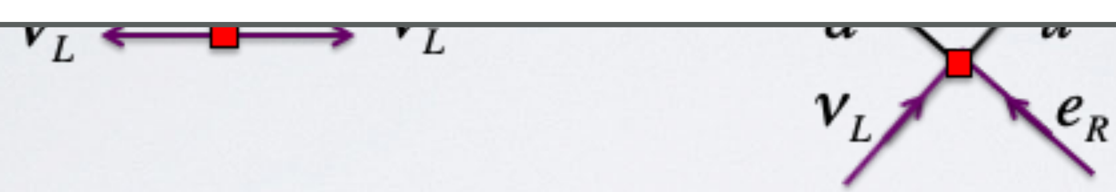


Disentangling the source of LNV

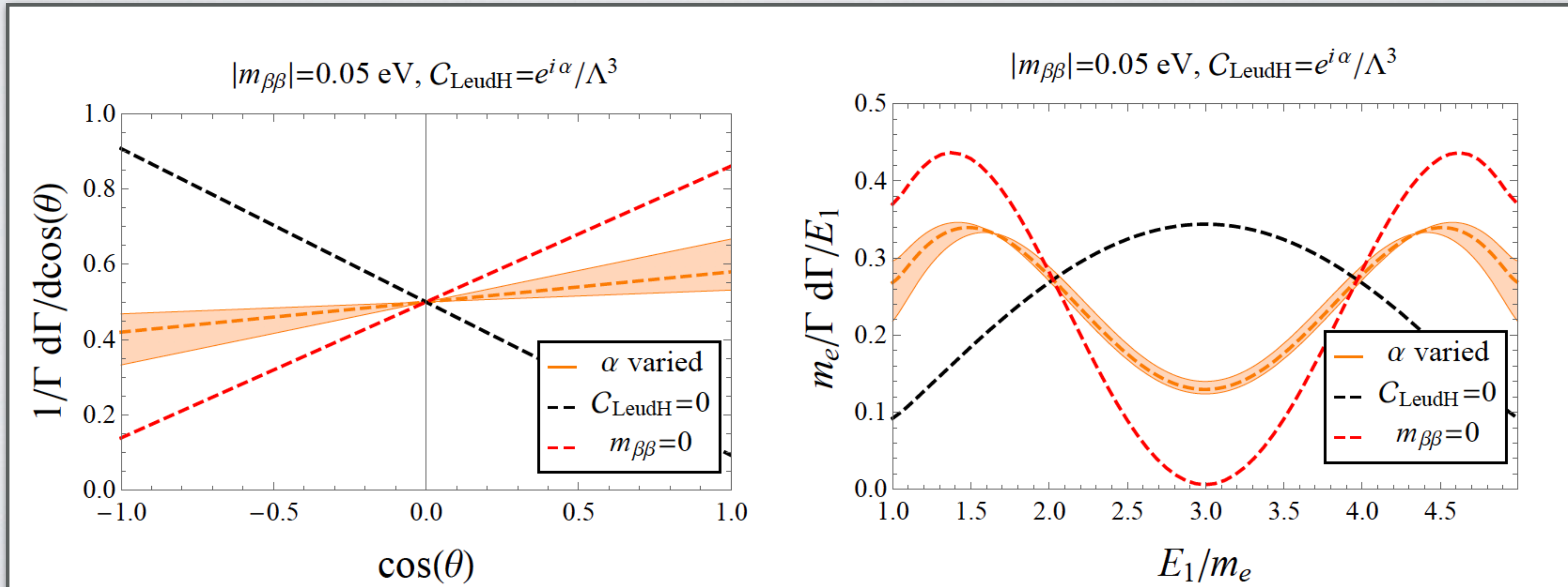
- A single measurement can be from any LNV operator
- Can v
- **One c … butions**

[Submitted on 14 Feb 2025]

Reconstructing neutrinoless double beta decay event kinematics in a xenon gas detector with vertex tagging

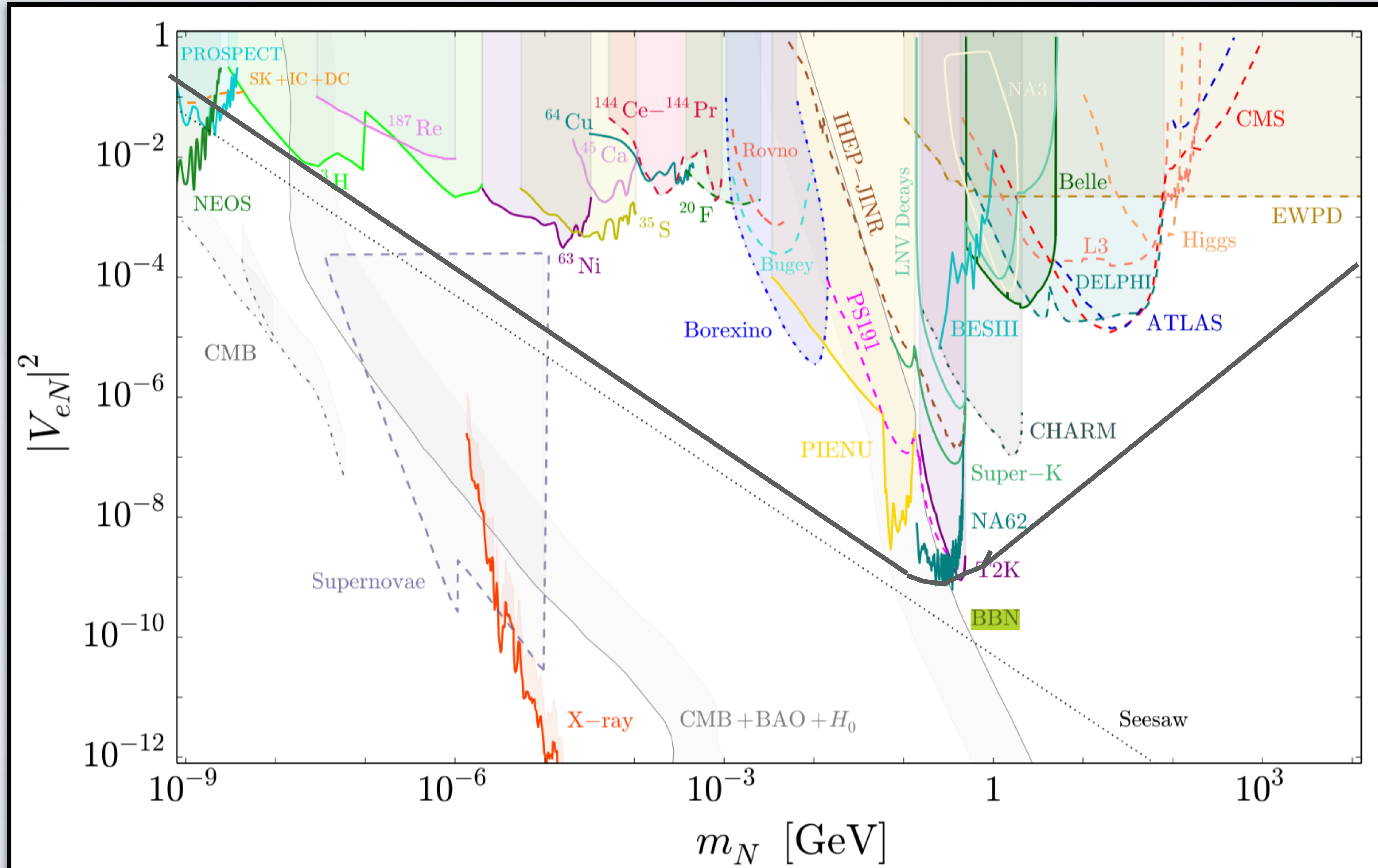


$\Lambda \sim 50\,\mathrm{TeV}$



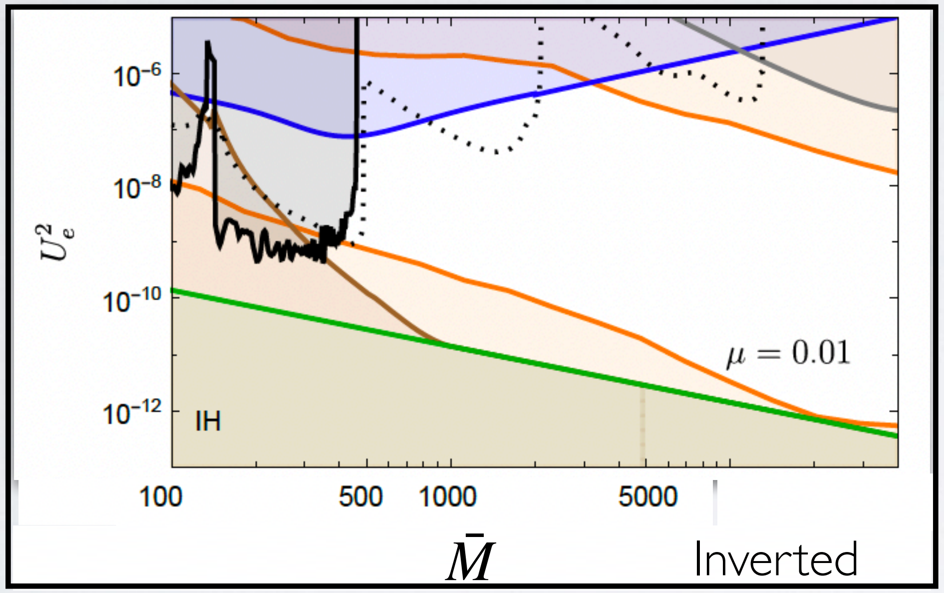
And more .....

- Neutrinoless double beta decay great test for ***light sterile neutrinos***



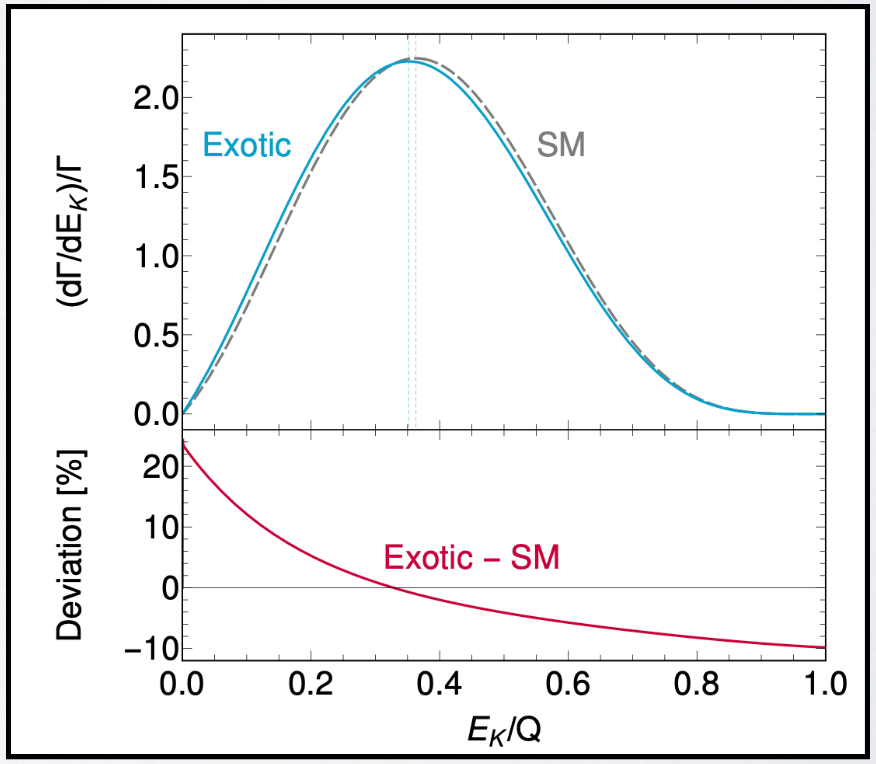
And more …..

- Neutrinoless double beta decay great test for ***light sterile neutrinos***
- Provide a test for *low-scale leptogenesis* (and indirect high-scale leptogenesis) Harz et al ‘ 15



Akhmedov/Rubakov/Smirnov ’98
Pilaftsis/Underwood ’03
Asaka/Shaposhnikov ’05
Drewes et al ’16 ‘24

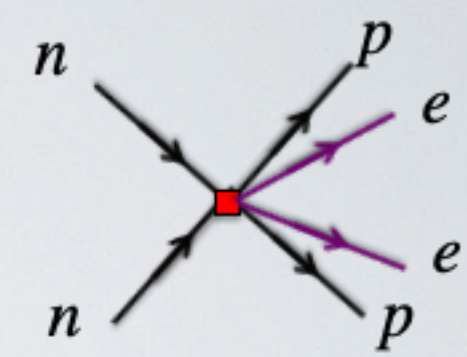
- And data on two-neutrino doublebeta decay can be used as a BSM test
- It’s just a great observable !



Deppisch, Graf, Simkovic, PRL ‘20 El Morabit et al ‘24

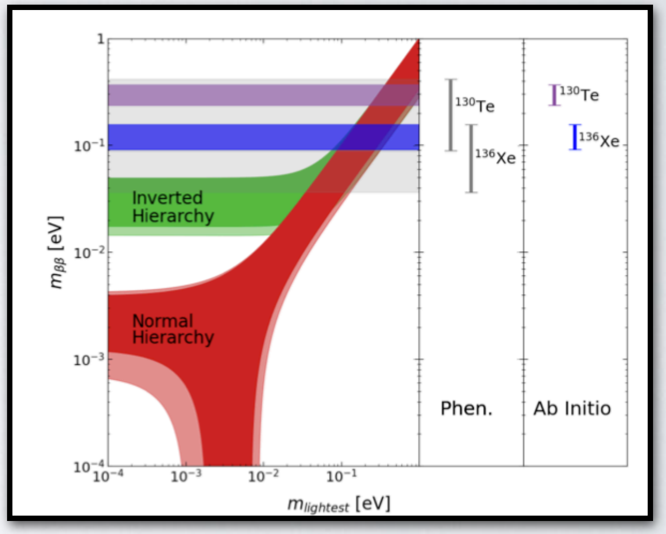
Concluding remarks

- **Neutrinoless double beta decay best way to determine if neutrinos are Majorana states**



- ***Heroic experimental effort!*** Hadronic/Nuclear theory to interpret data

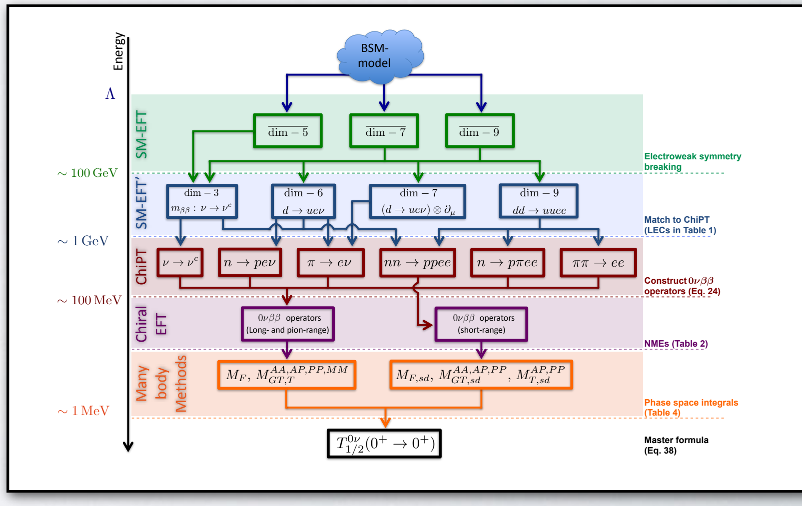
- Progress from EFT + lattice + nuclear structure



- New findings: standard mechanism depends on short-distance physics
  Impacts ab initio calculations of heavy nuclear decays

- End-to-End EFT framework for high-scale LNV source (easy to use)

- New work on impact of light sterile neutrinos (not today)



Backup

This is perhaps not fair

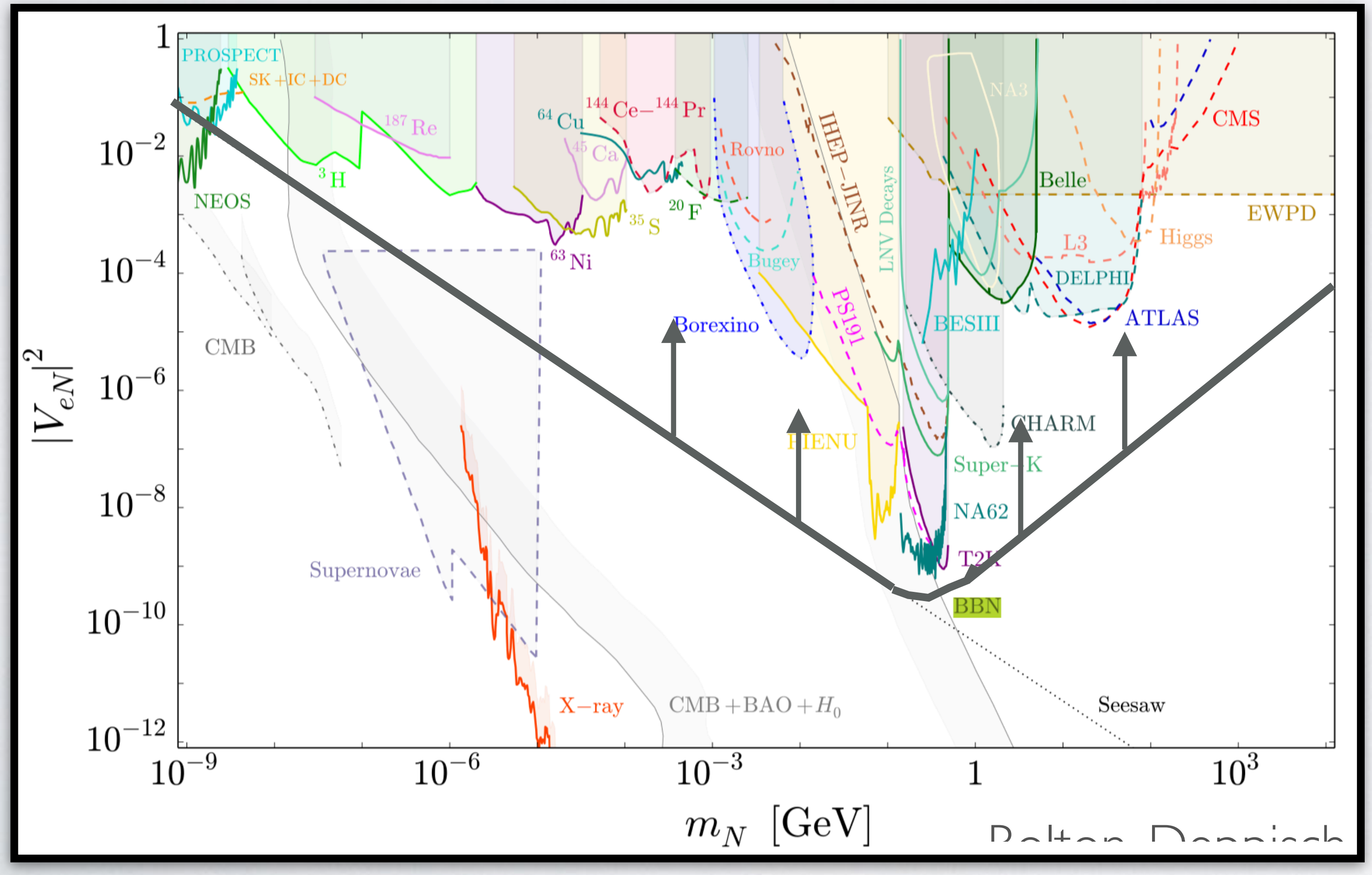
- Consider **minimal 3+2 extension** (lightest active neutrino is massless)

$$m_4 = \bar{M} - \Delta M/2\,, \qquad m_5 = \bar{M} + \Delta M/2\,, \qquad \mu = \frac{\Delta M}{\bar{M}}$$

- For small mass splittings, the heavy neutrino pair can form a **pseudo-Dirac neutrino**

- 0vbb amplitude proportional to $$\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{M(\bar{M})}{M(0)}\right] + f(\bar{M})\,\mu\,U_e^2 + \mathcal{O}(\mu^2)$$

- Bounds can be moved up for small and/or degenerate masses.

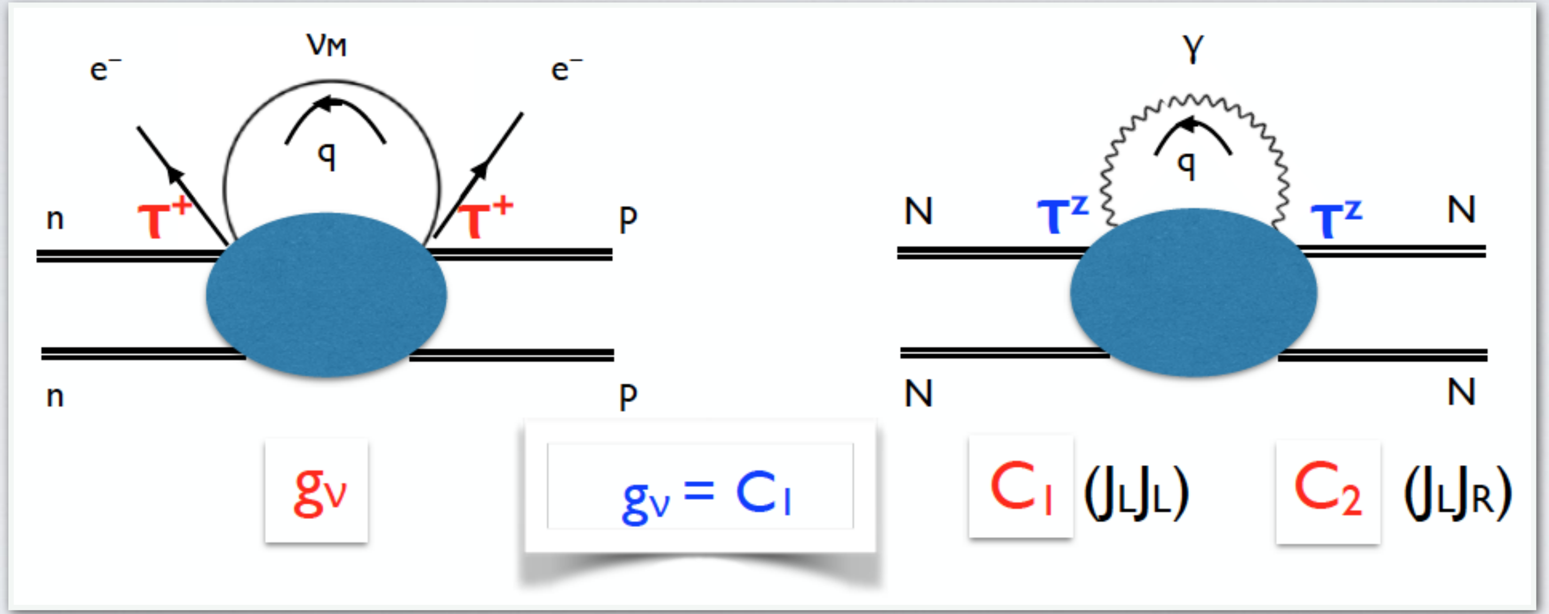


- **0vbb becomes weak for (pseudo-)Dirac sterile neutrinos**

- **Need an independent handle on the mass splitting**

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions
- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **$g_\nu \sim C_1$** only

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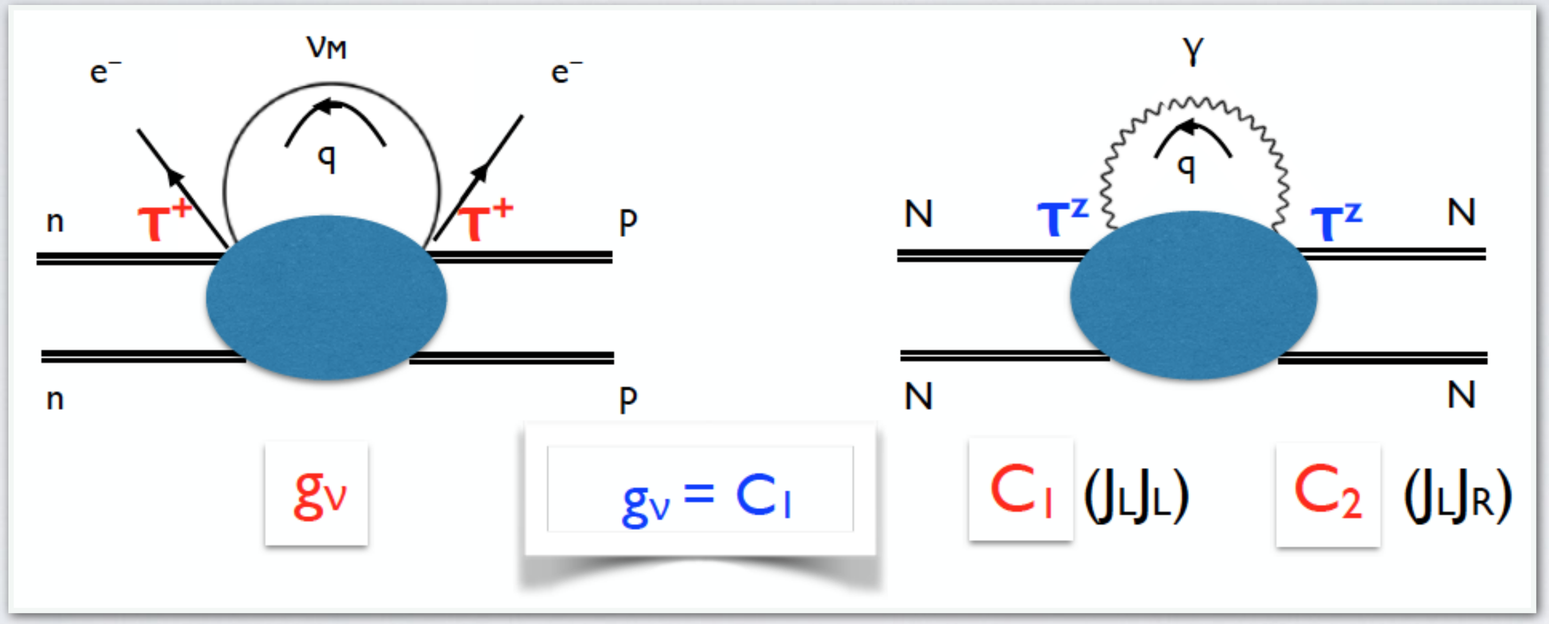

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- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **g_ν~C_1** only

- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer '21

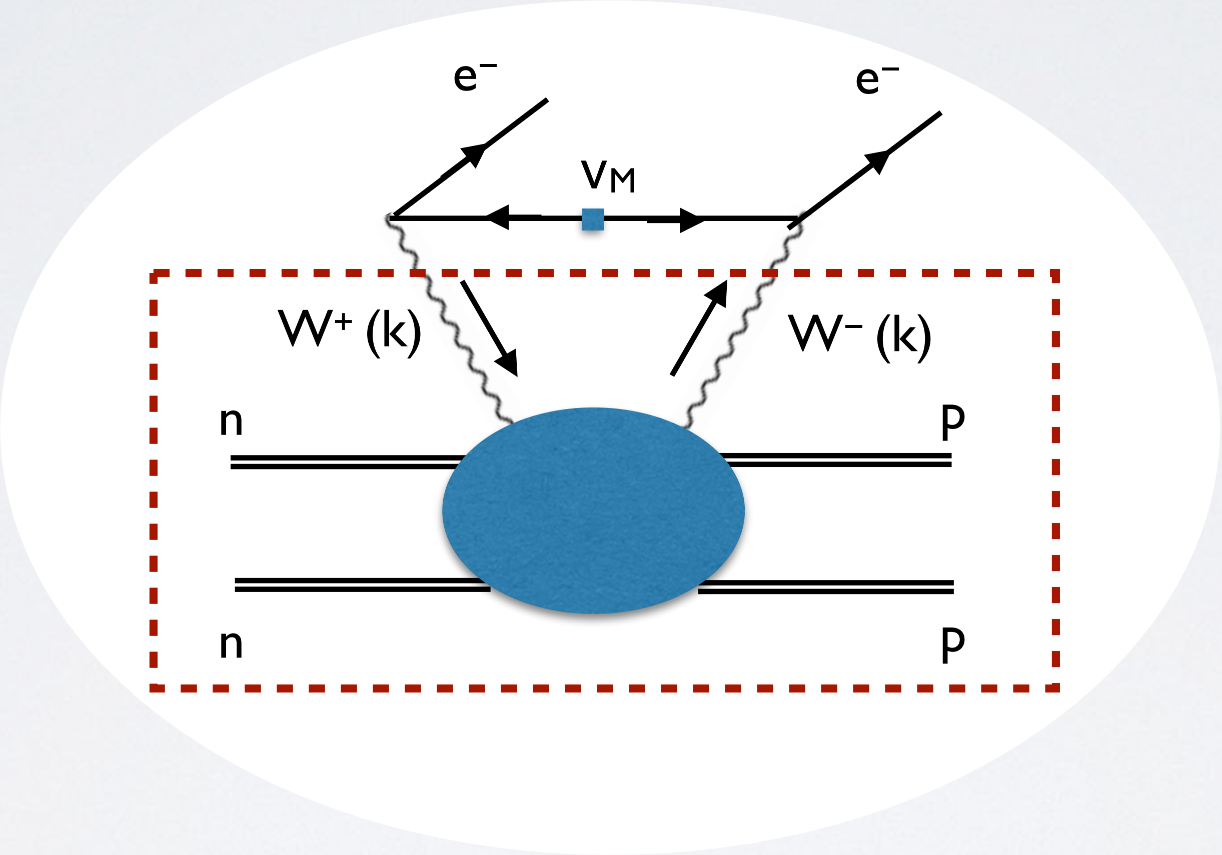
- **We originally assumed g_ν~(C_1+C_2)/2, what happens to neutrinoless double beta decay ?**

An analytic approach

- The nn → pp + ee amplitude can be represented as an integral expression

$$A_\nu \sim G_F^2 \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2} \int d^4x e^{ik\cdot x} \langle pp \,|\, T\{J_W^\mu(x) J_W^\nu(0)\} \,|\, nn \rangle$$

J_W^μ = weak current (V-A)



- Can represent the `red box' in regions of the virtual neutrino momentum k

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti JHEP '22 PRL '21

An analytic approach

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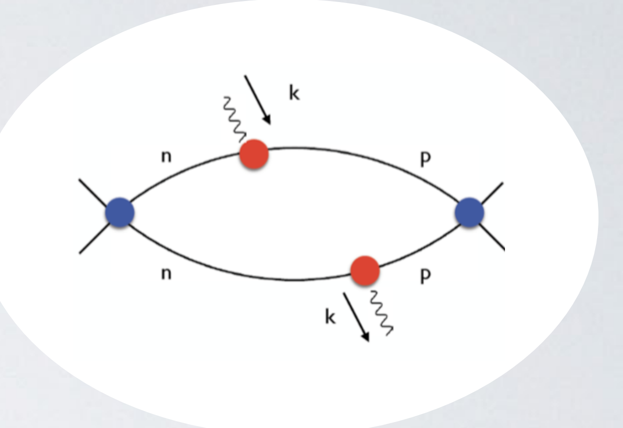
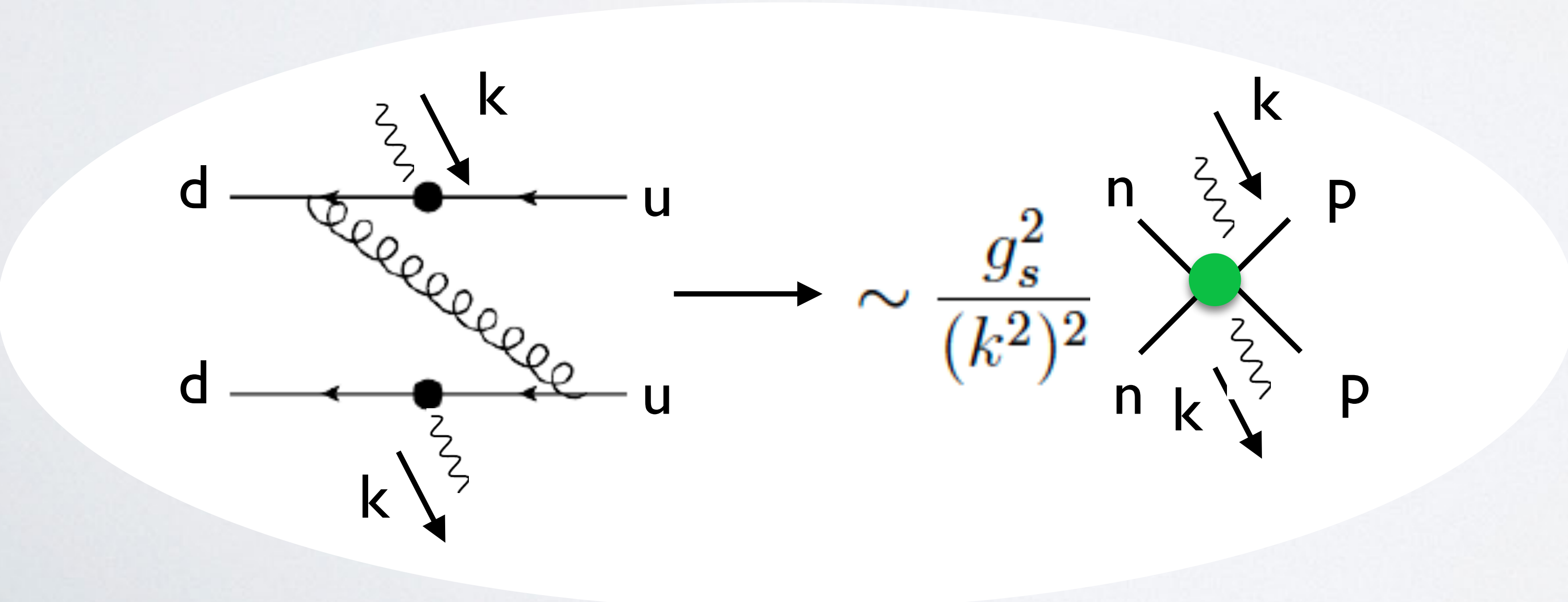


- At small virtual momentum: NLO chiral EFT
- Intermediate momentum: (**model-dependent**) resonance contributions to nucleon form factors and to NN scattering
- Large momentum: Perturbative QCD + Operator Product Expansion



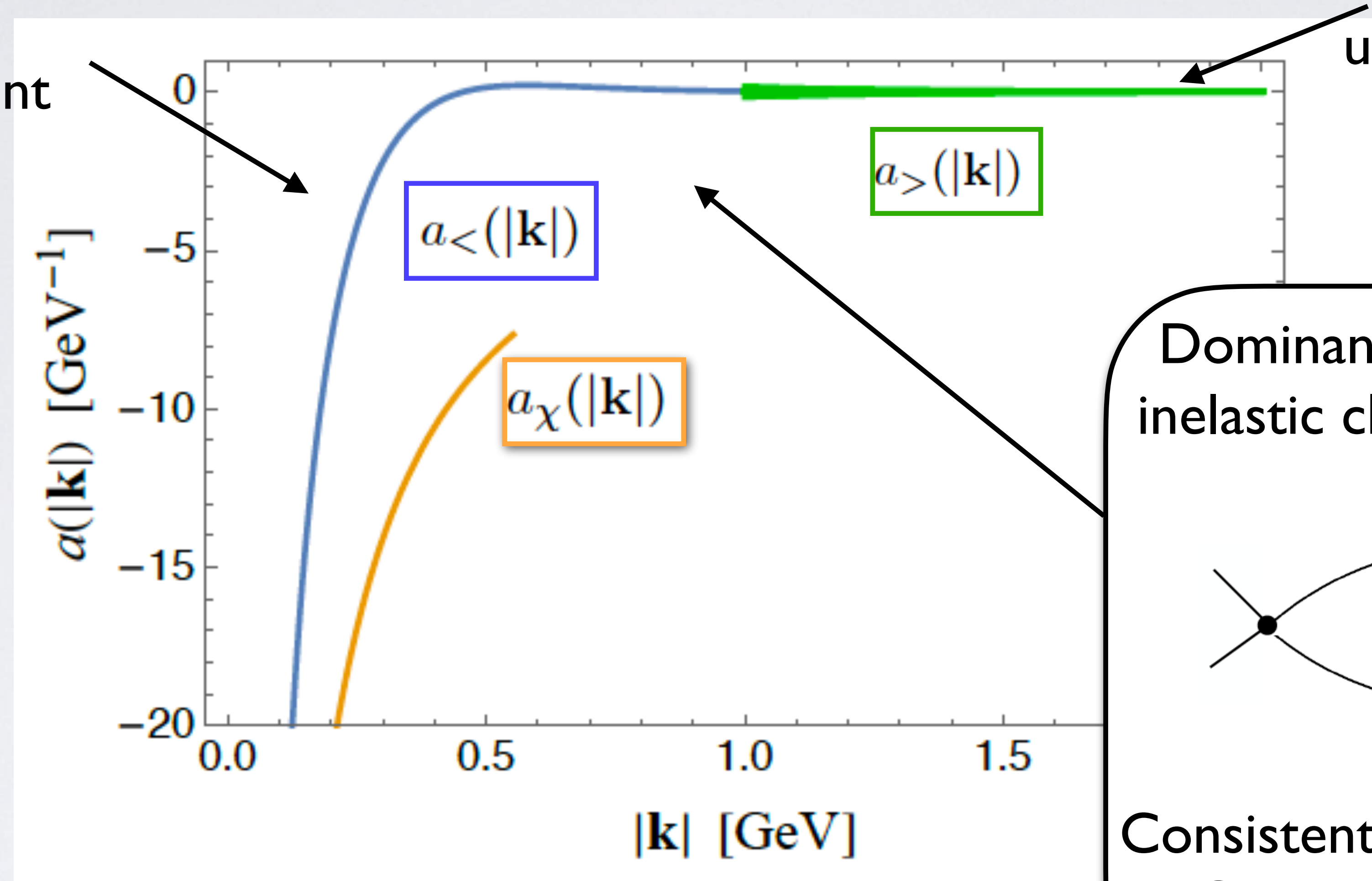
Small dependence on local 4-quark matrix elements

Determining the contact term

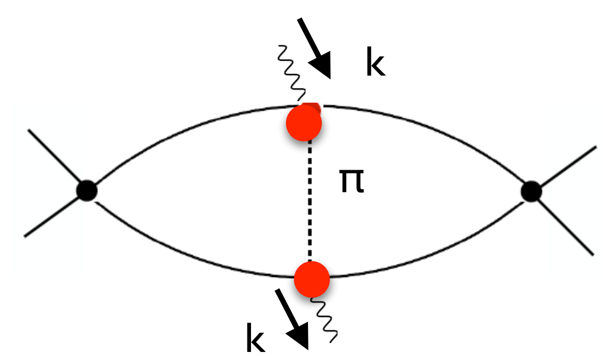
$$A_\nu \sim \int_0^\Lambda dk\, a_<(k) + \int_\Lambda^\infty dk\, a_>(k)$$

Steep falloff controlled by the $^1S_0$ effective range: model-independent

Small uncertainty due to unknown local operator matrix element



Dominant uncertainty from inelastic channels (NNπ , …):



Consistent with <30% effect in Cottingham approach to π,N EM mass splittings

- Matching:

$$2\tilde{C}_1(\mu_\chi) = \frac{1+2g_A^2}{2} - \int_0^{\mu_\chi} d|\mathbf{k}|\; a_\chi(|\mathbf{k}|) + \int_0^{\Lambda} d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^{\infty} d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$

- Inelastic channels studied by Graham van Goffrier (UCL PhD thesis '24) and found to be small

The total amplitude

- The result is an expression for **total nn →pp + ee amplitude**

$$|A_\nu(|\mathbf{p}|, |\mathbf{p}'|)| = -\,0.019(1)\,\mathrm{MeV}^{-2}$$

$|\mathbf{p}| = 25\,\mathrm{MeV}$

$|\mathbf{p}'| = 30\,\mathrm{MeV}$

- Example: in dimensional regularization in MS-bar scheme

$$g_\nu^{NN}(\mu = m_\pi) = (1.3 \pm 0.1 \pm 0.2 \pm 0.5)$$

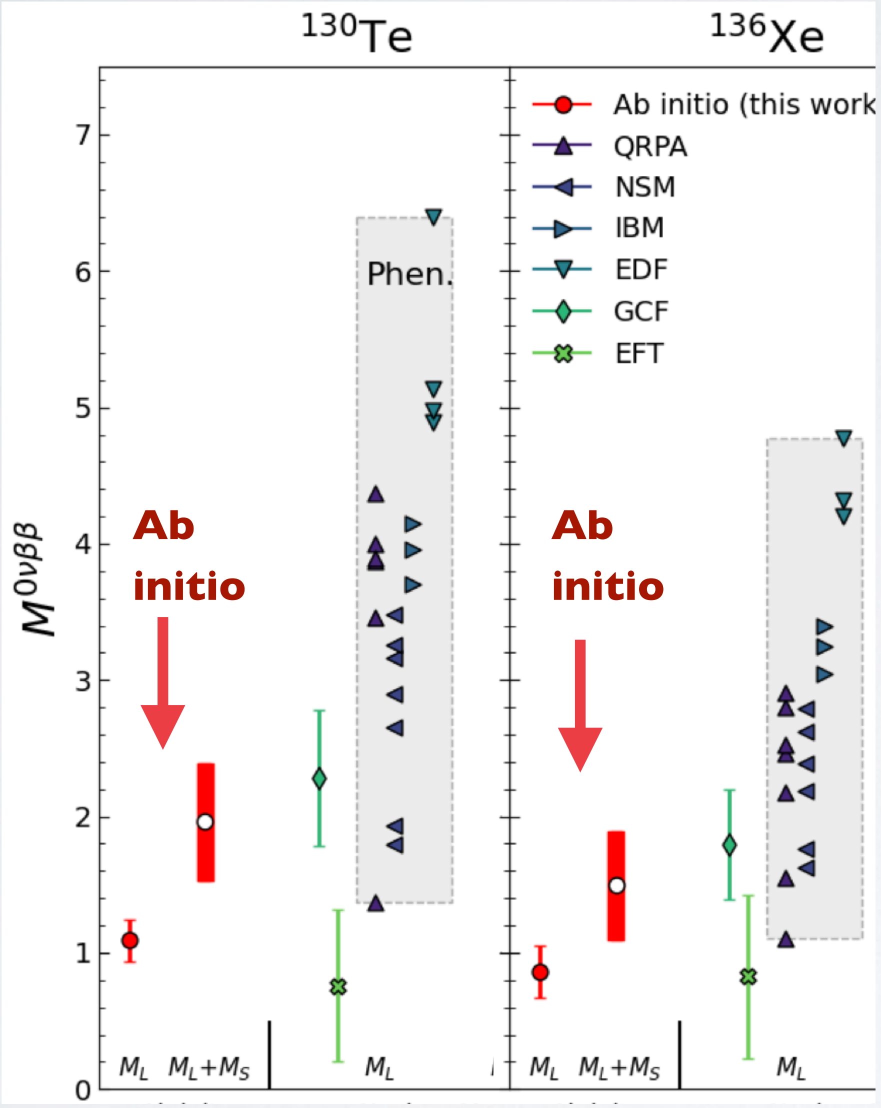
- Matching to 'fake-data' possible for **any scheme** suitable for nuclear calculations
- Now used to include the contact term into ab initio 0vbb calculations
- Same strategy was used to 'predict' EM corrections to nucleon-nucleon scattering

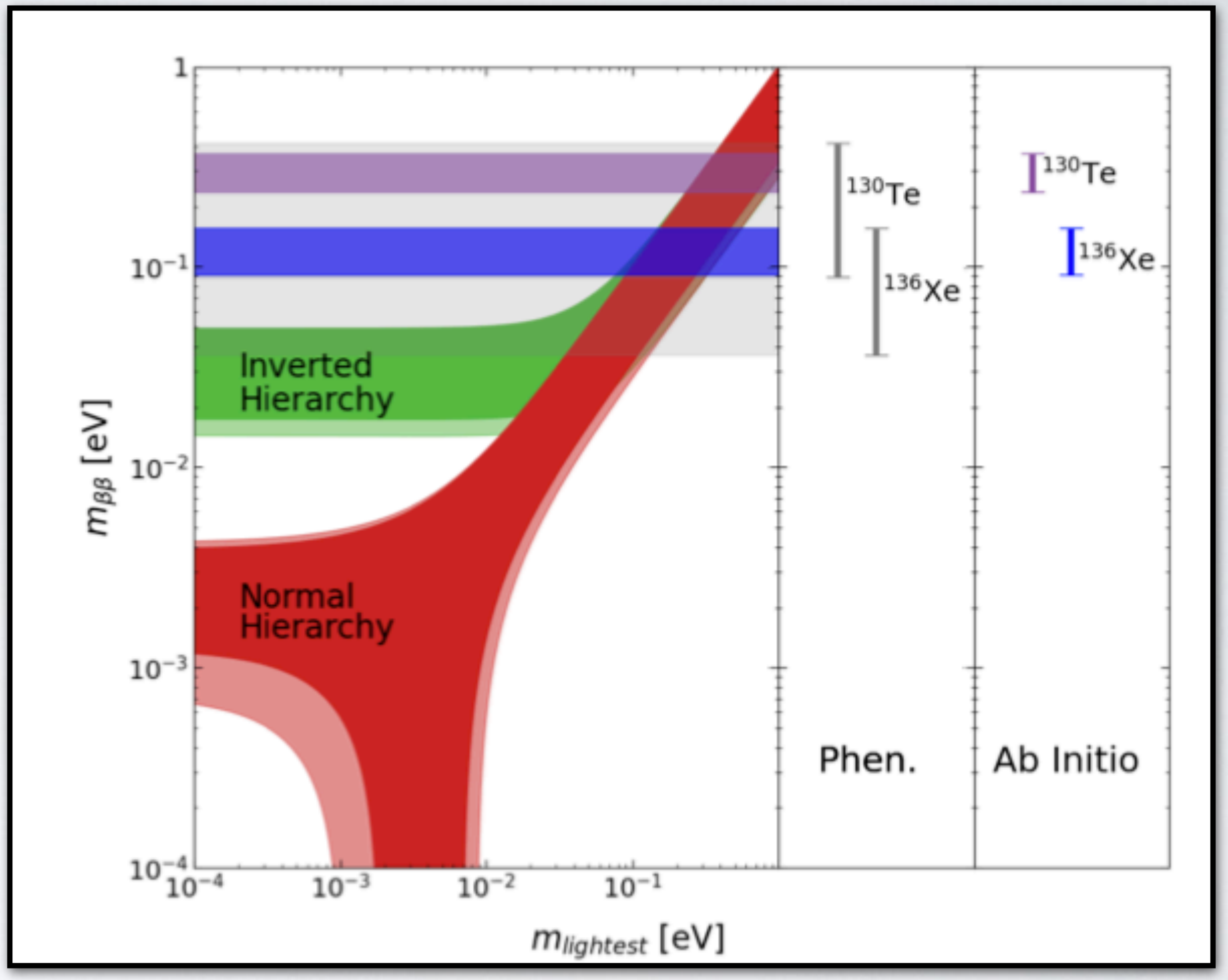
$$a_{CIB} = \frac{a_{nn} + a_{pp} - 2a_{np}}{2} = (14 \pm 5)\,\mathrm{fm} \qquad a_{CIB}^{\mathrm{data}} = (10.4 \pm 0.2)\,\mathrm{fm}$$

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti JHEP '22 PRL '21

Impact on realistic nuclei

- Some results from last year (2307.15156 Belley et al) using **VS-IMSRG**
- See also: Belley et al PRL '24 for detailed 76Ge analysis





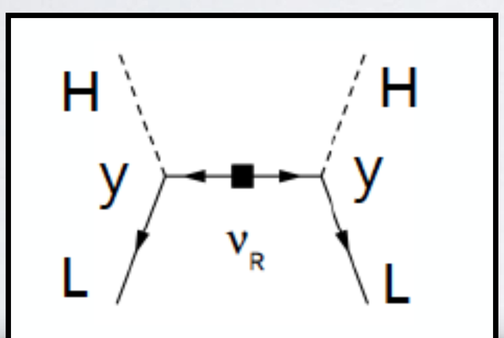
- Ab initio calculations find small long-distance NMEs compared to other methods
- **Partially compensated by new short-distance interaction (50-100% effect)**
- Just using various ab initio methods leads to significantly smaller uncertainty bands
- Question: how to compare ab initio to phenomenological interactions including short-distance ?

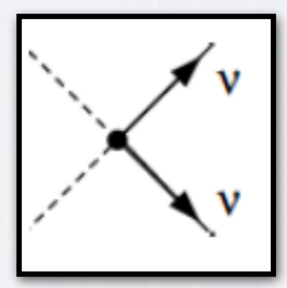
Heavy-weight neutrinos

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

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

Described by Weinberg operators





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

Feather-weight sterile neutrinos

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

eV — keV — MeV — GeV — TeV — ..... — 10¹⁵ GeV → M_R ?

What about here ?

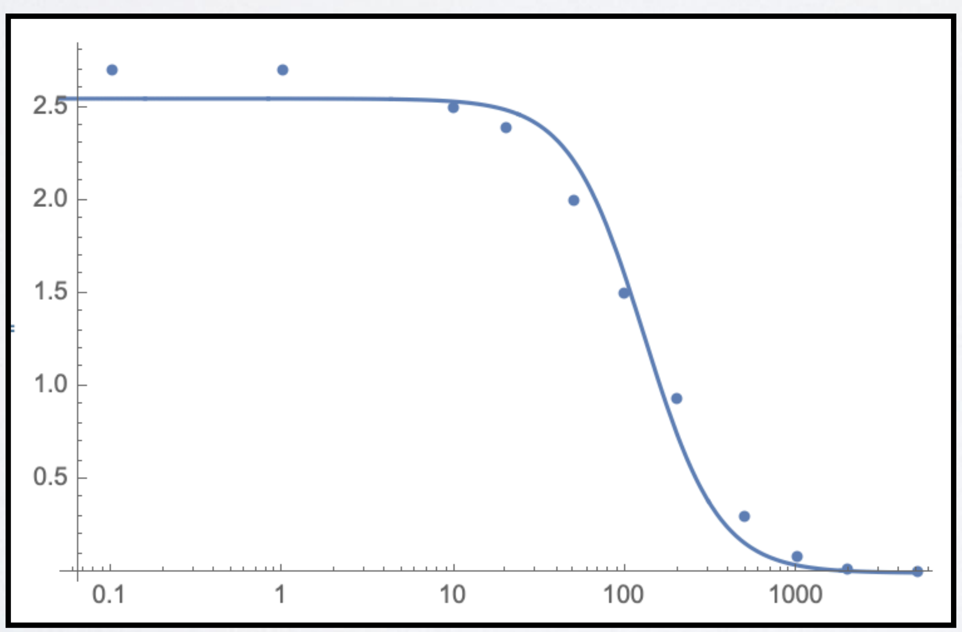
- For masses below a GeV, the 0vbb matrix elements become mass dependent

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

- In principle this looks easy enough

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

$M(m_4)$



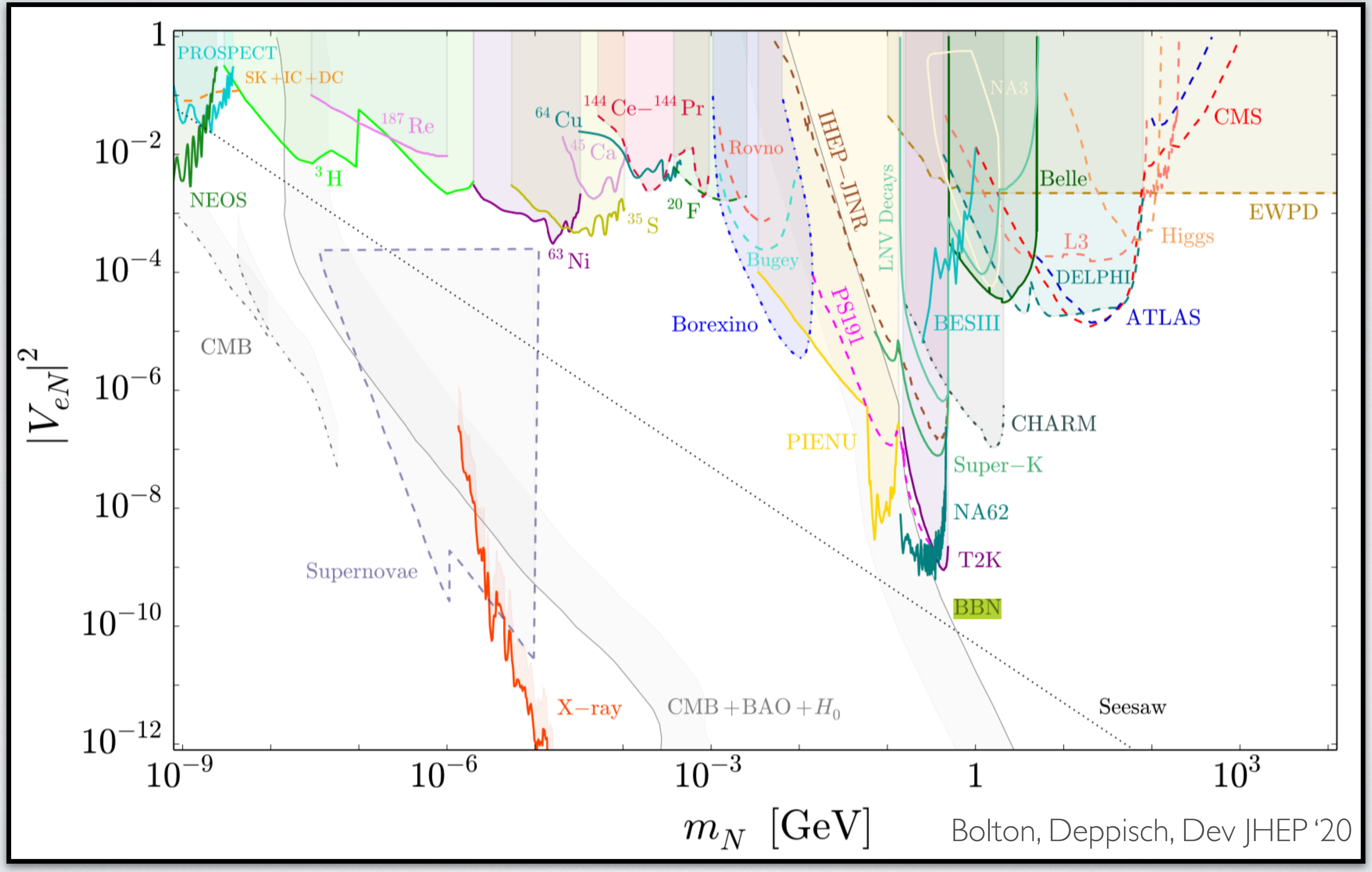
m_4(MeV)

Shell model Xe (Menendez)

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

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

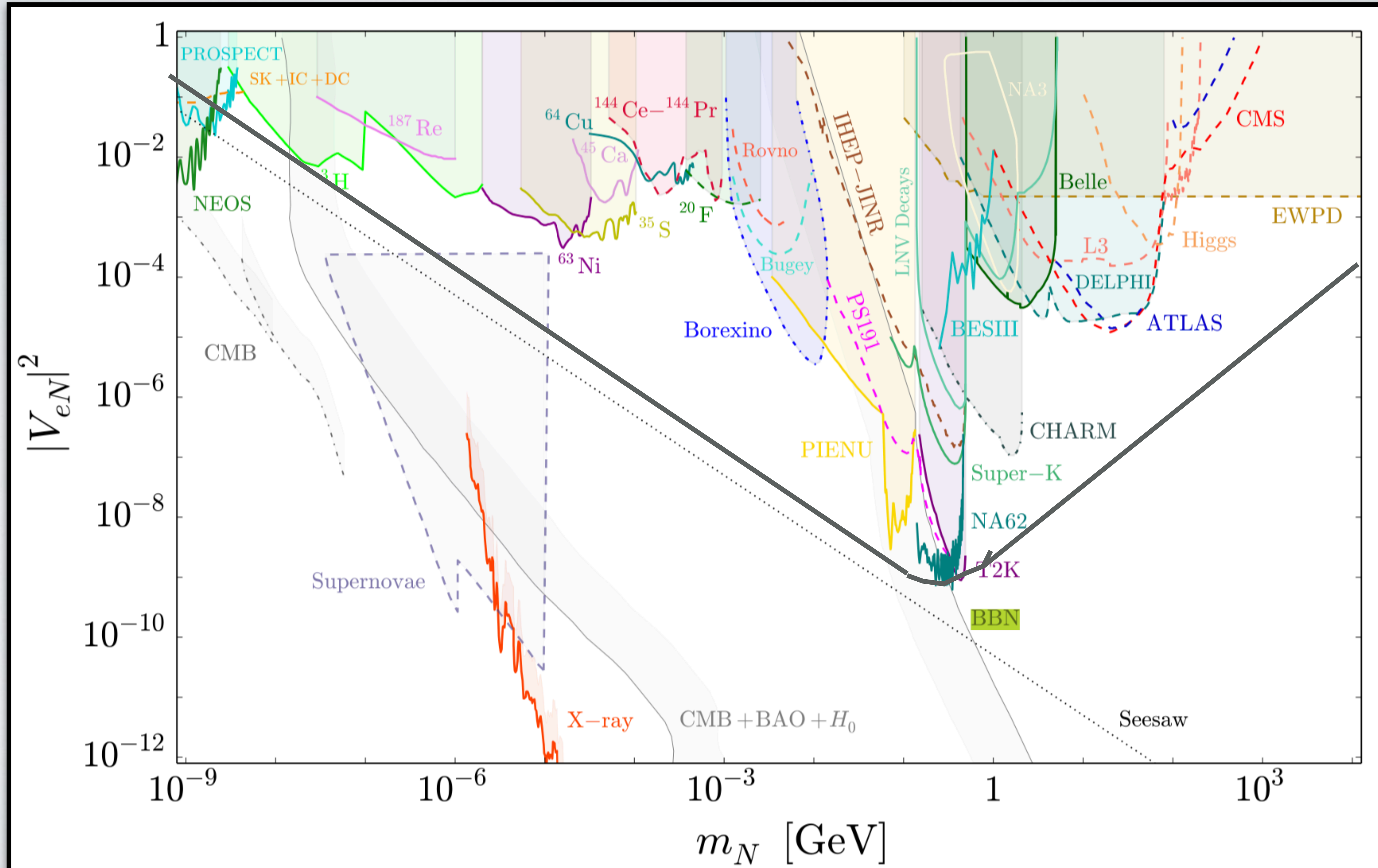
Feather-weight sterile neutrinos



Bolton, Deppisch, Dev JHEP '20

Feather-weight sterile neutrinos

- S**aturate** 0vbb lifetime with m4 contribution $$A_\nu \sim U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2}$$



This is perhaps not fair

- Consider **minimal 3+2 extension** (lightest active neutrino is massless)

$$m_4 = \bar{M} - \Delta M/2\,, \qquad m_5 = \bar{M} + \Delta M/2\,, \qquad \mu = \frac{\Delta M}{\bar{M}}$$

- For small mass splittings, the heavy neutrino pair can form a **pseudo-Dirac neutrino**

- 0vbb amplitude proportional to $$\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{M(\bar{M})}{M(0)}\right] + f(\bar{M})\,\mu\,U_e^2 + \mathcal{O}(\mu^2)$$

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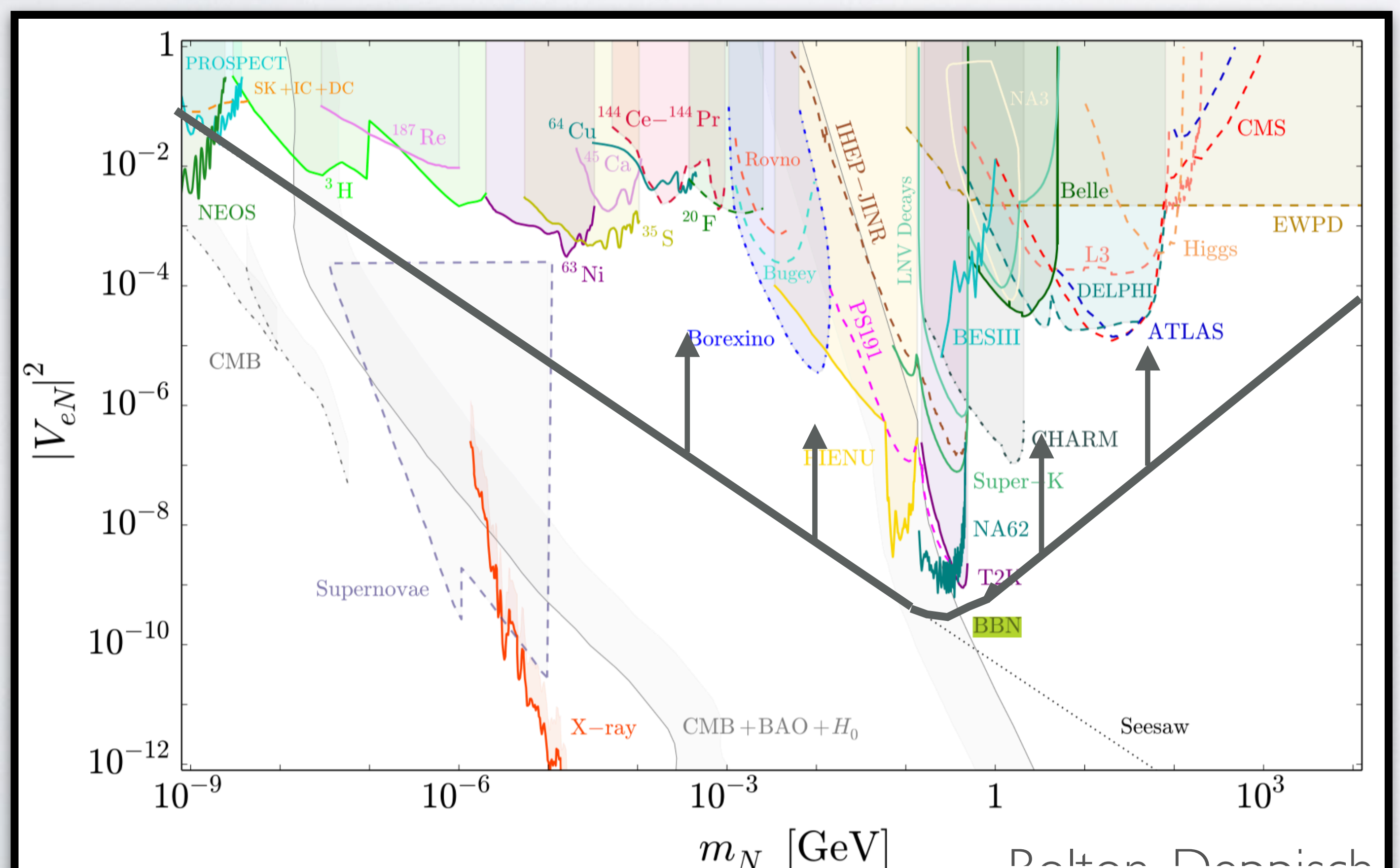


- **0vbb becomes weak for (pseudo-)Dirac sterile neutrinos**

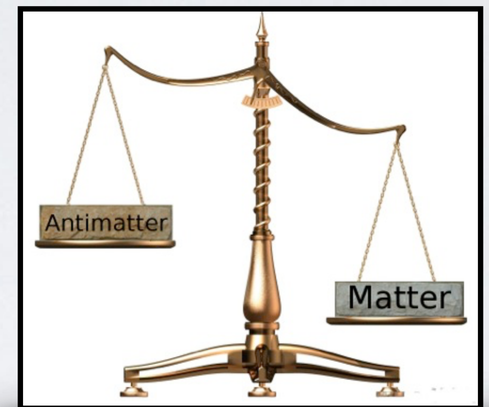
- **Need an independent handle on the mass splitting**

Low-scale leptogenesis

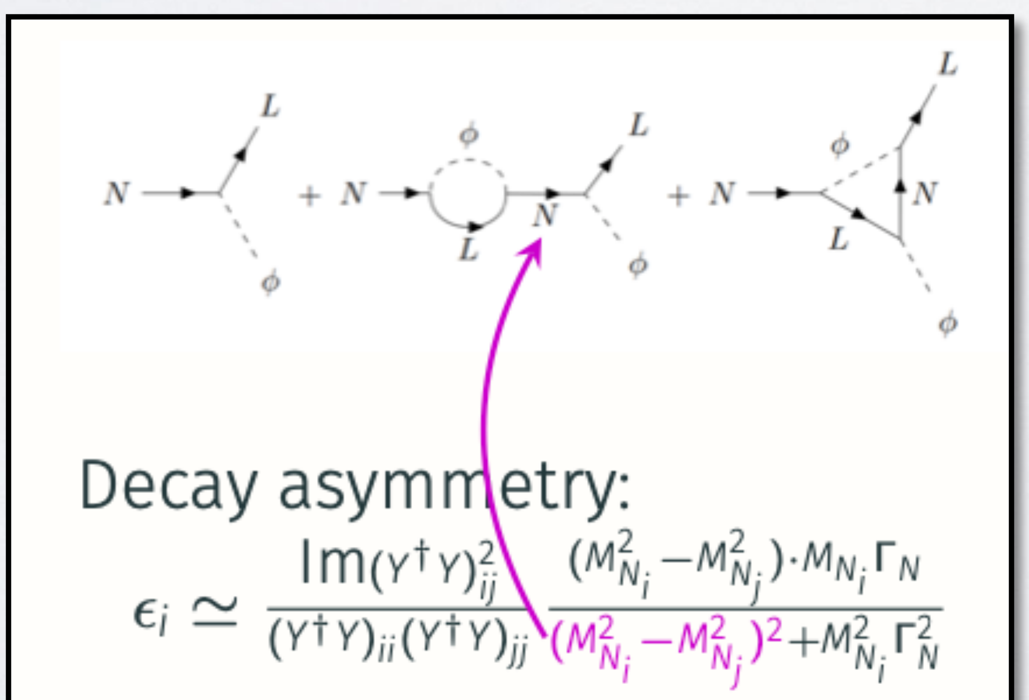
Arxiv:2407.10560

- Low-scale leptogenesis requires a small mass splitting as well !
- We can do leptogenesis at the same time in the **minimal 3+2 extension**

13.7 billion year



- Production of asymmetries enhanced by small mass splittings



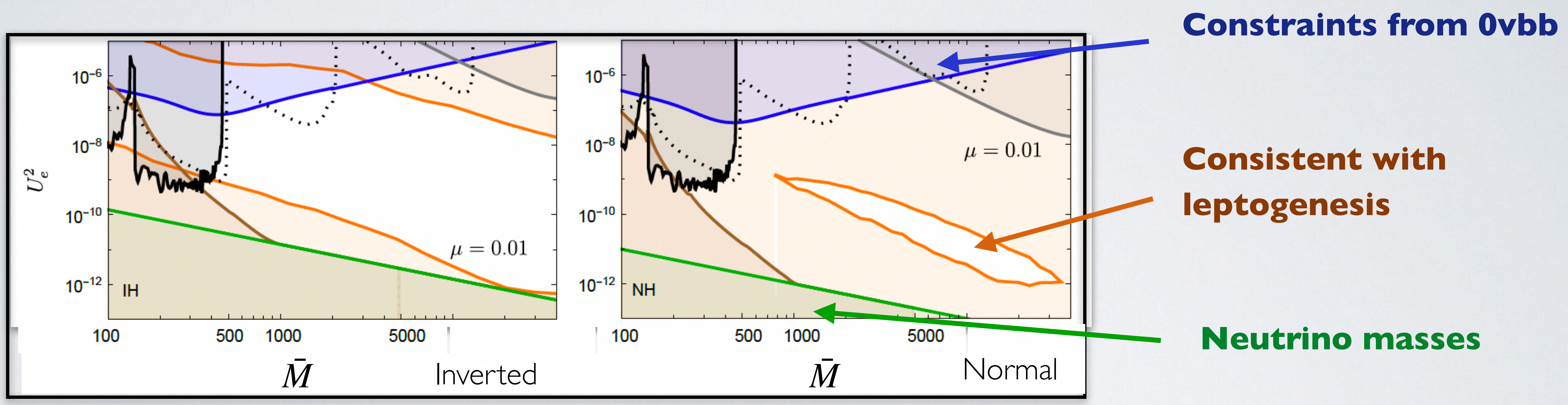
Akhmedov/Rubakov/Smirnov '98
Pilaftsis/Underwood '03
Asaka/Shaposhnikov '05

Low-scale leptogenesis

Leptogenesis contours calculated by Drewes/Georis/Klaric

Arxiv:2407.10560

- Simplest solution to neutrino masses + matter/antimatter asymmetry
- Scans give contours like this (fixed mass splitting at 1%)



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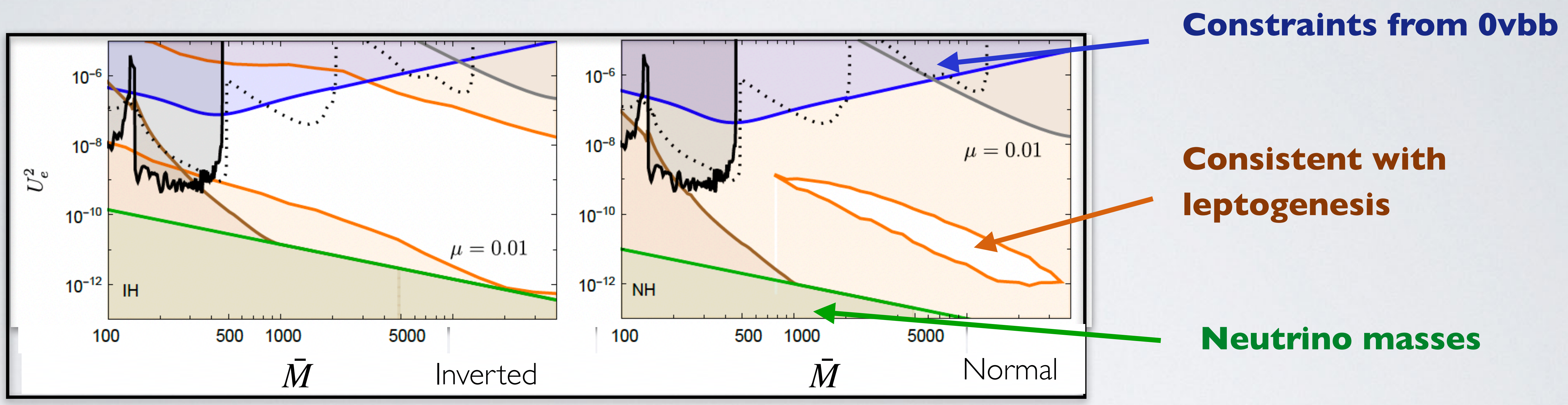

- For inverted hierarchy, 0vbb is ruling out part of the space

$$\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{M(\bar{M})}{M(0)}\right] + f(\bar{M})\,\mu\,U_e^2$$

- In inverted hierarchy, next-gen should see something unless we have a **cancellation !**

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Arxiv:2407.10560

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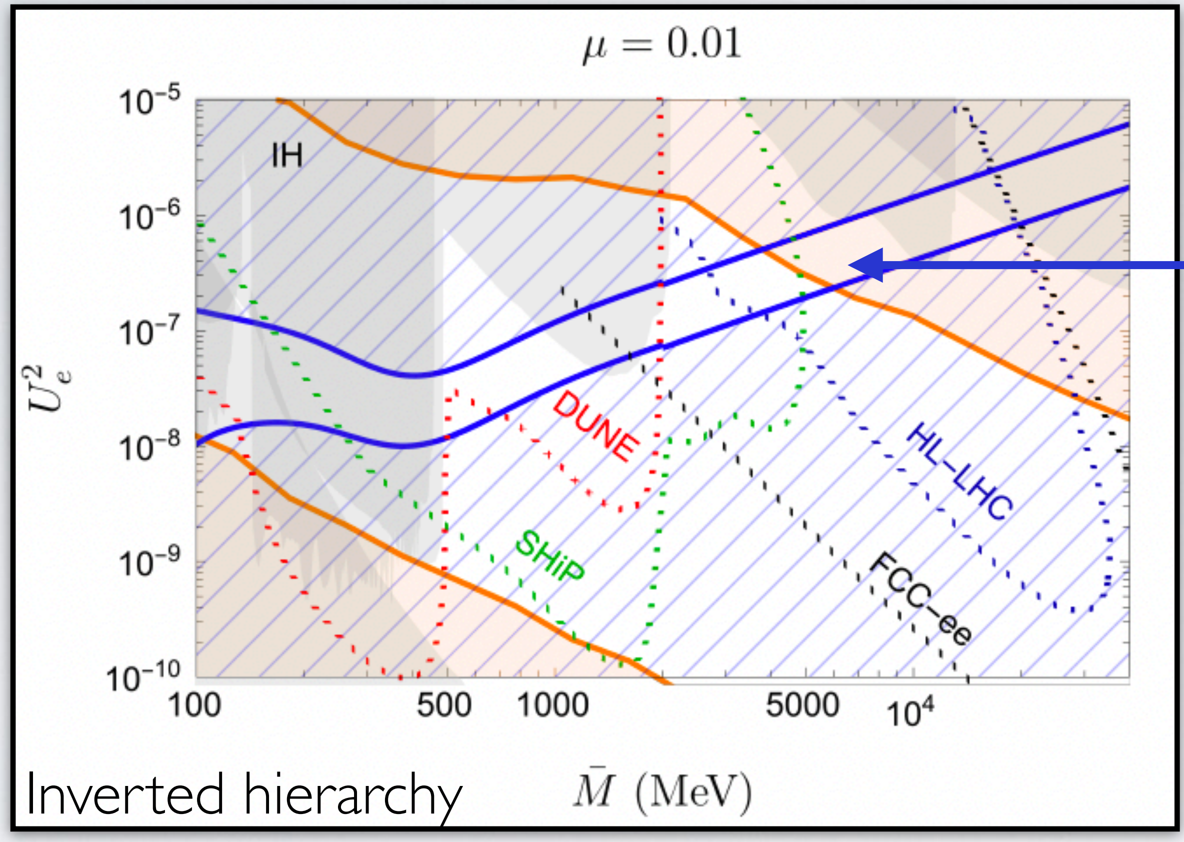


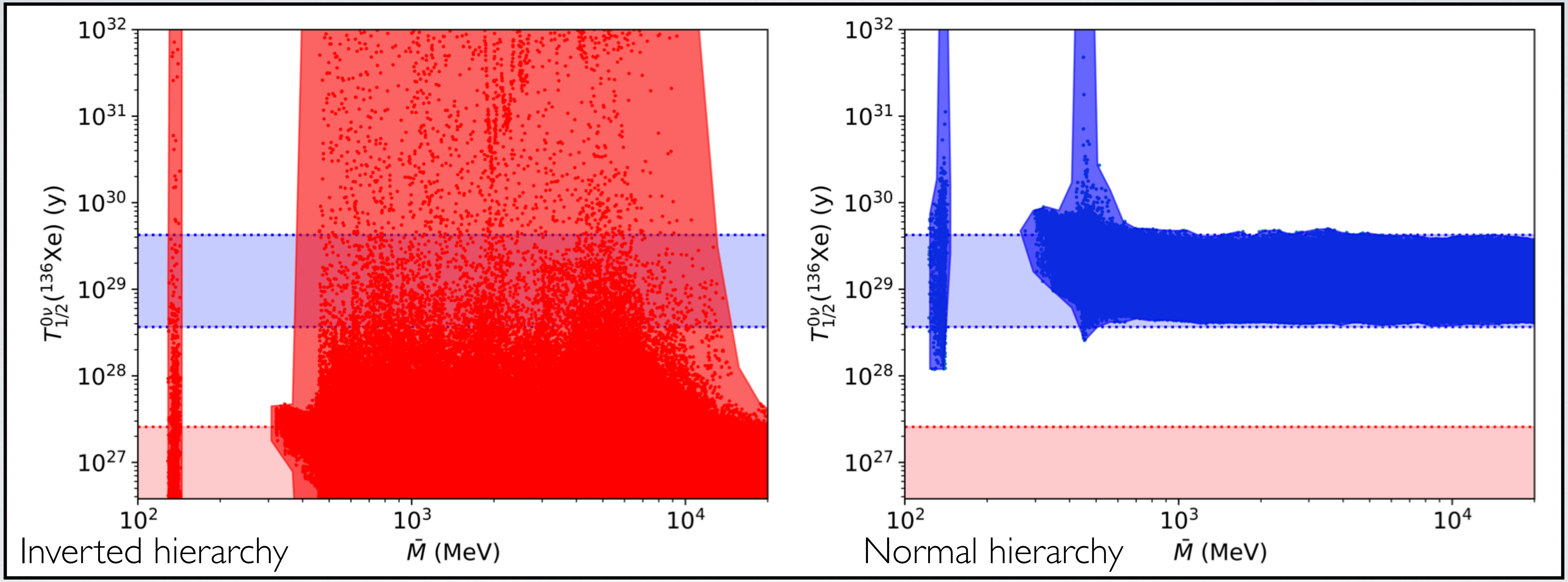
Inverted hierarchy

Consistent with no signal in next-gen 0vbb

- Inverted hierarchy,: can rule out 3+2 leptogenesis if no signal in next-gen 0vbb (100x better)
- If we do see a signal —> Nobel prize, neutrinos are Majorana, but….. **not clear if light sterile neutrinos were involved**
- Normal hierarchy: similar to IH but requires 10x better experiments then IH.
- Analysis much harder for 3+3 (see e.g. Chrzaszcz, Weniger et al' 19) more parameters !

Is the signal 'outside' the band

- If we do see a 0vbb signal, Question: is it different from the 'standard mechanism'



- **Unfortunately:** within 3+2 leptogenesis it is hard to **enhance** 0vbb rates in normal hierarchy
- **Key lessons: we should all hope we live in the Inverted Hierarchy**