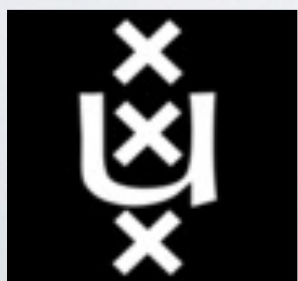
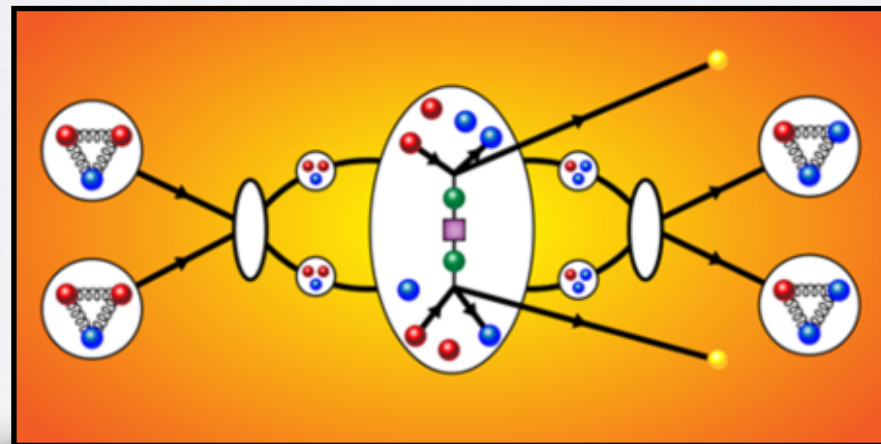


# NEUTRINOLESS DOUBLE BETA DECAY: ANNOYING NUCLEAR MATRIX ELEMENTS

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)*

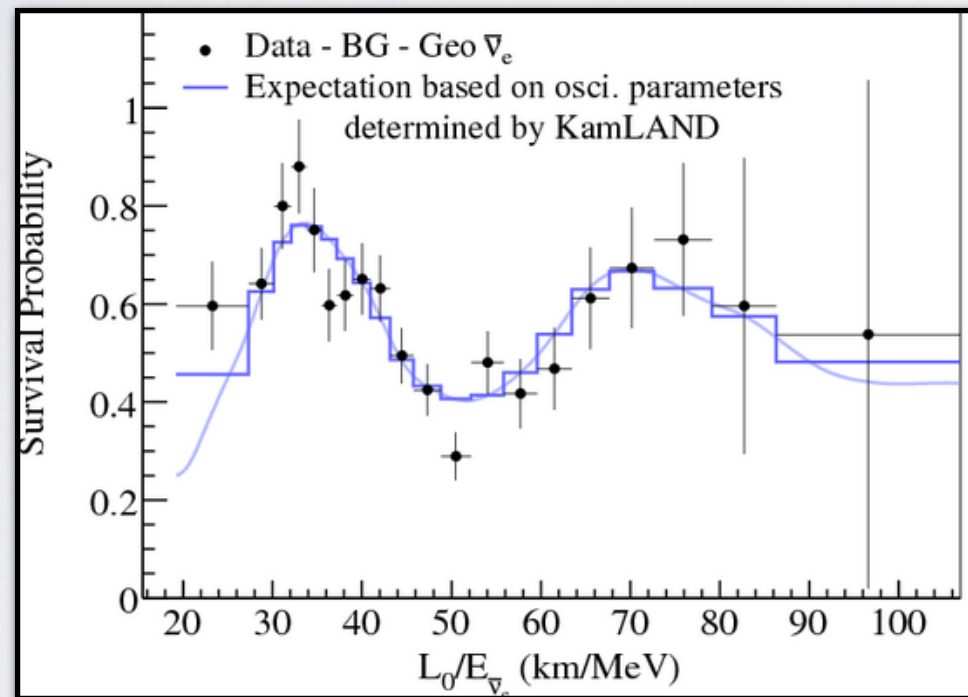
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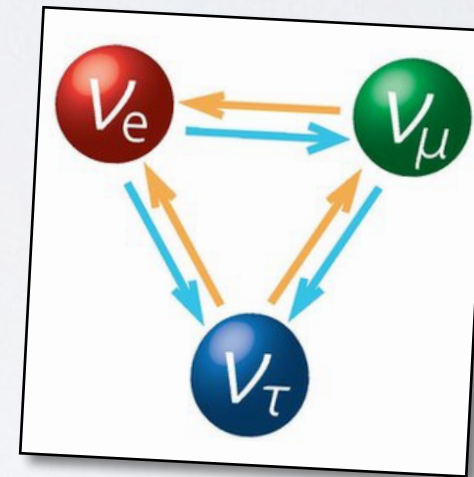
- Not crazy: from beta decay experiments

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

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

# 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  $\nu$ -nightmare scenario**



# The puzzle of the neutrino mass

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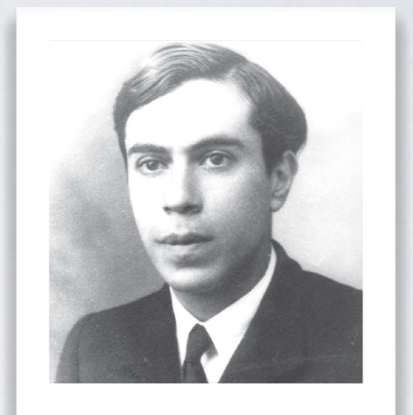
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$$\mathcal{L} = -y_\nu \bar{\nu}_L \nu_R \varphi - M_R \nu_R^T C \nu_R$$

*‘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**



**Ettore Majorana**

# The puzzle of the neutrino mass

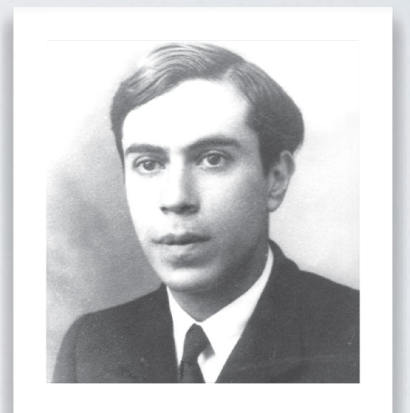
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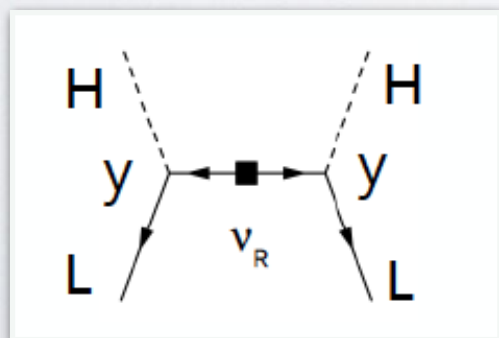
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*'Everything that is not forbidden is compulsory'*



Ettore Majorana

- This is not allowed for any Standard Model particle !
- $M_R$  not connected to electroweak scale: could be a **completely new scale**
- If  $M_R$  large compared to electroweak scale  $\rightarrow$  integrate it out



$$\mathcal{L}_5 = C_5 (L^T C \tilde{H})(\tilde{H}^T L)$$

Weinberg '79

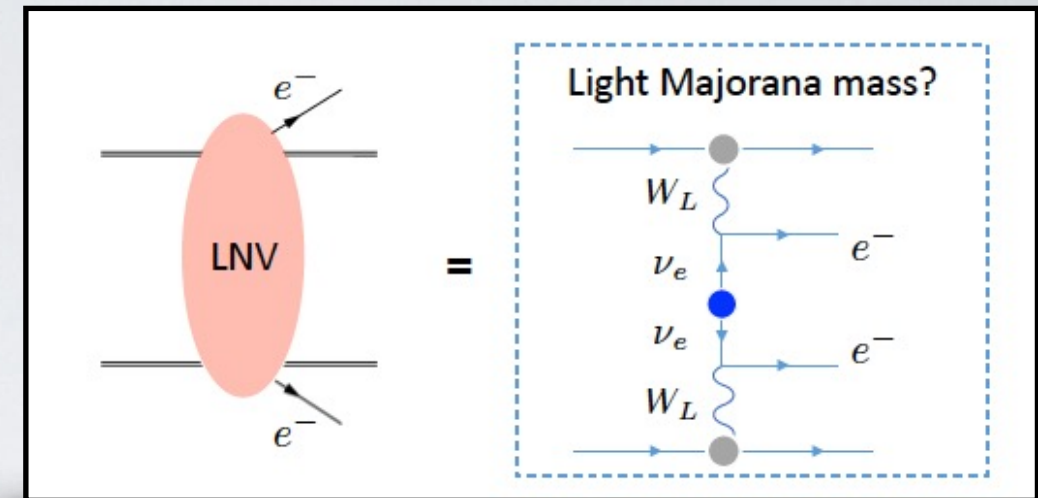
**Light neutrinos are massive and Majorana**

# Probes of lepton number violation

- Most promising way: look at 'neutrinoless' processes

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

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

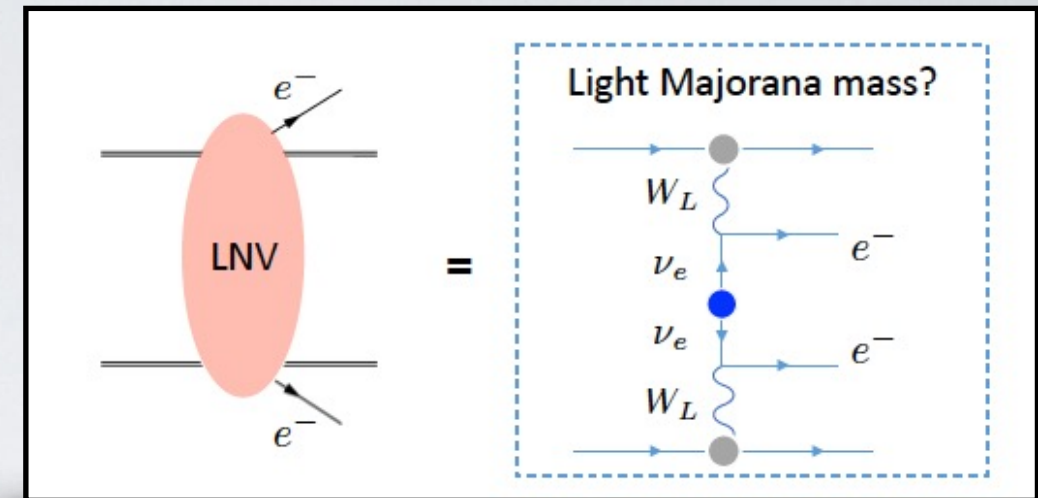
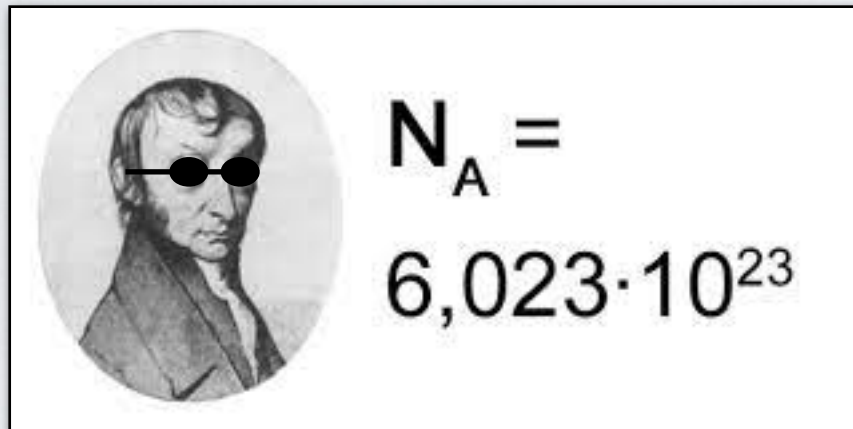


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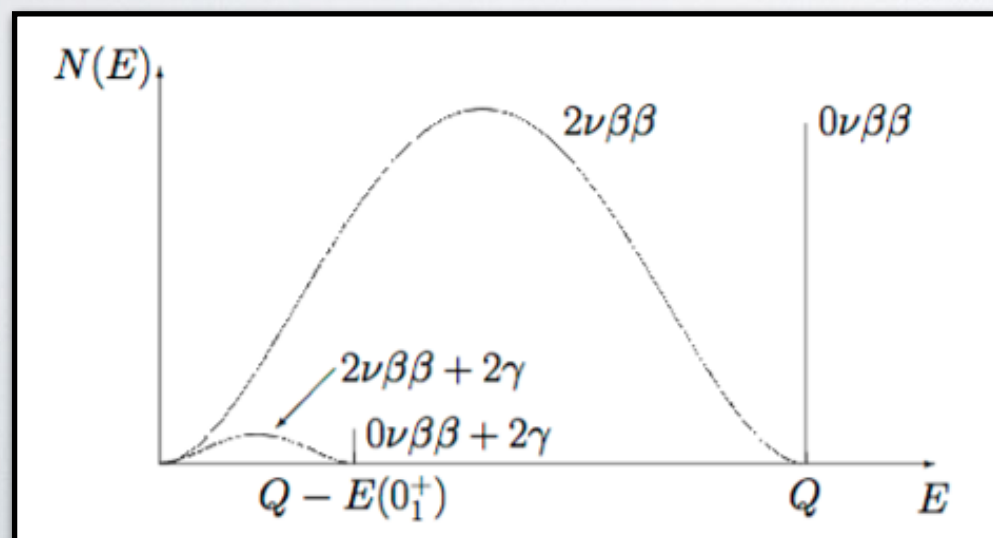
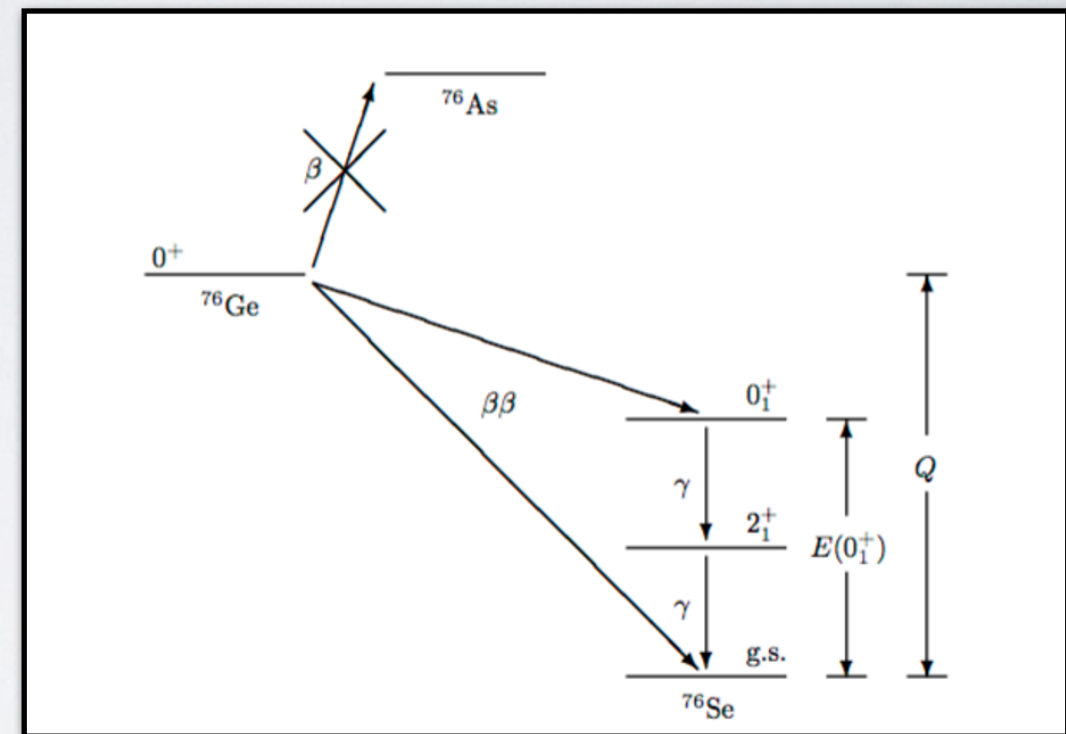
$$K^- \rightarrow \pi^+ + e^- + e^- \quad pp \rightarrow e^+ + e^+ + \text{jets}$$

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

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

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

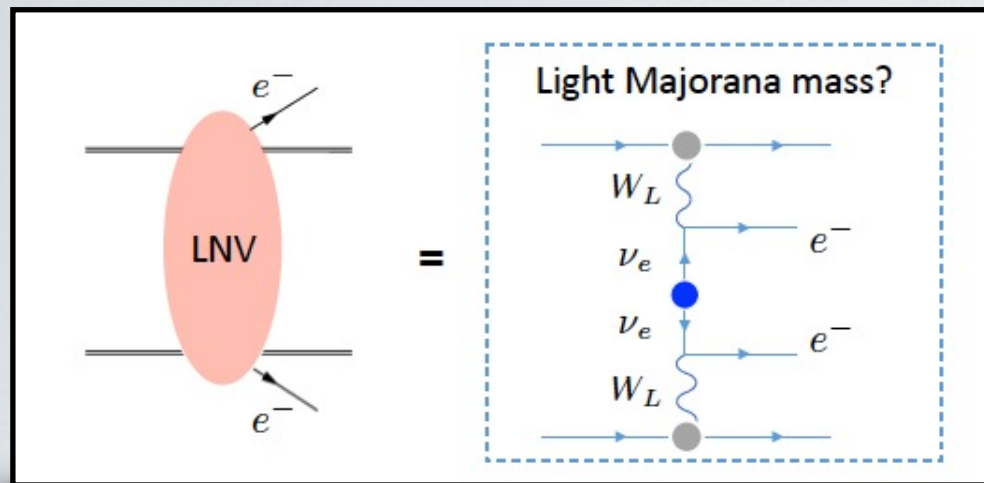
$$T_{1/2}^{2\nu} (^{76}\text{Ge} \rightarrow ^{76}\text{Se}) = (1.84^{+0.14}_{-0.10}) \times 10^{21} \text{ yr}$$



|                                     | Lifetime                      | Experiment  | Year |
|-------------------------------------|-------------------------------|-------------|------|
| $^{76}\text{Ge}$                    | $1.9 \cdot 10^{26} \text{ y}$ | LEGEND-200  | 2025 |
| $^{130}\text{Te}$                   | $3.2 \cdot 10^{25} \text{ y}$ | CUORE       | 2019 |
| <b><math>^{136}\text{Xe}</math></b> | $3.8 \cdot 10^{26} \text{ y}$ | KamLAND-Zen | 2024 |

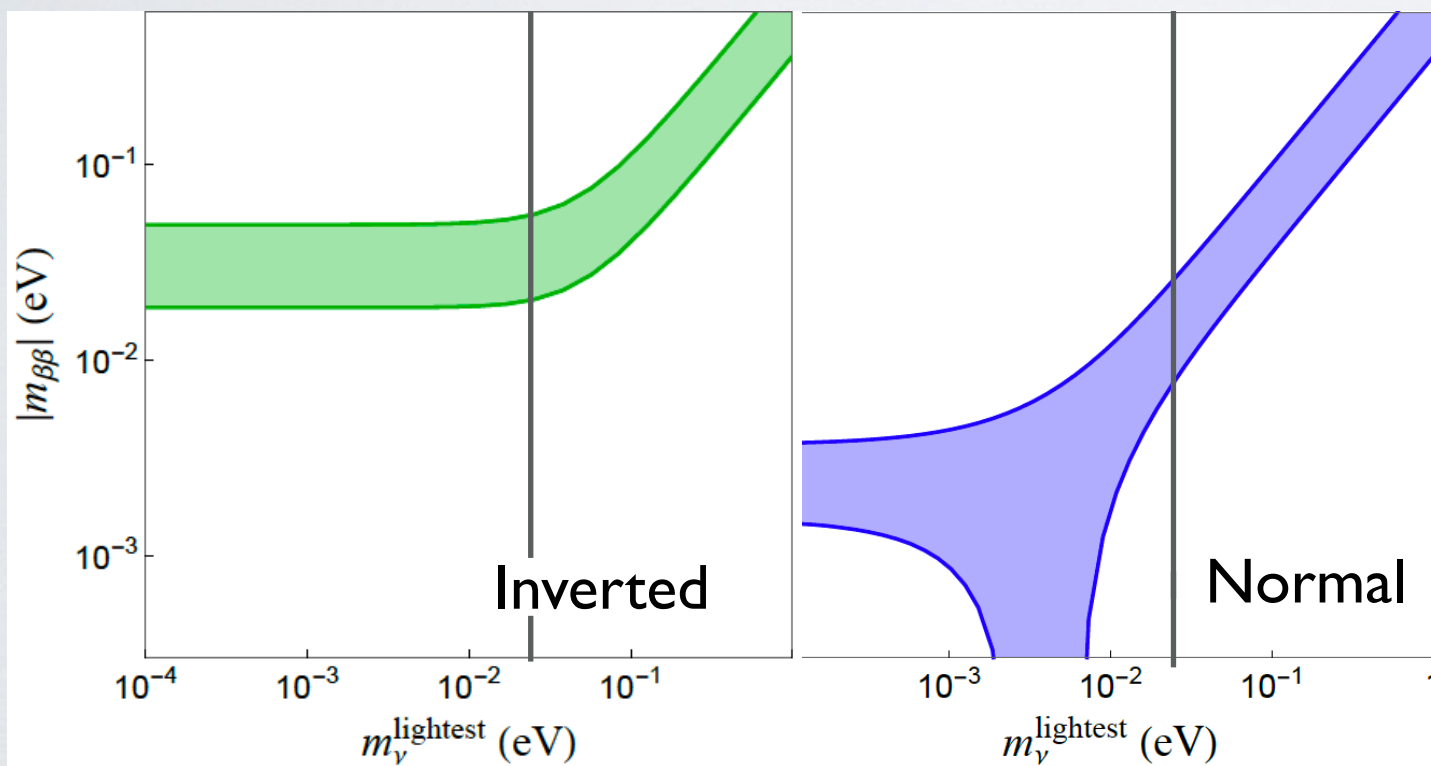
Note: age of universe  $\sim 10^{10}$  year

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



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

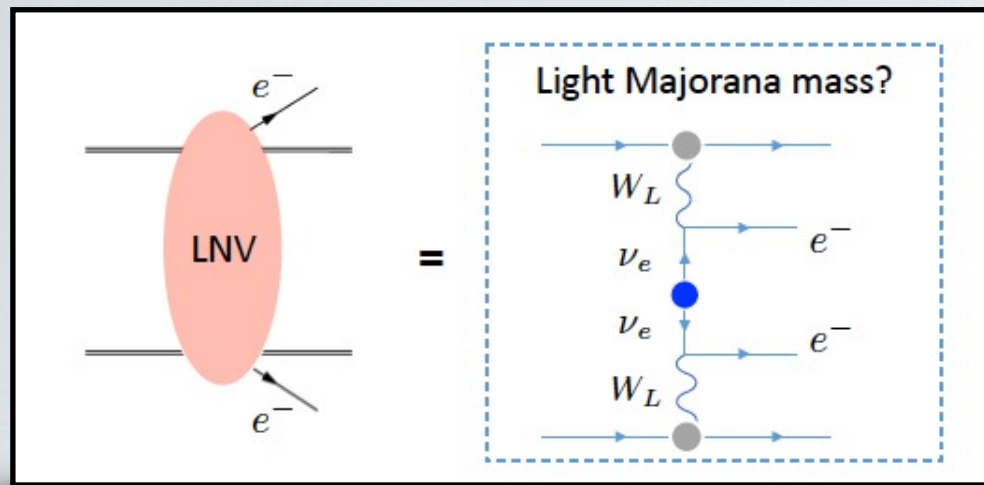
$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\lambda_1} + m_3 s_{13}^2 e^{2i(\lambda_2 - \delta_{13})} = \text{Effective neutrino mass}$$



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

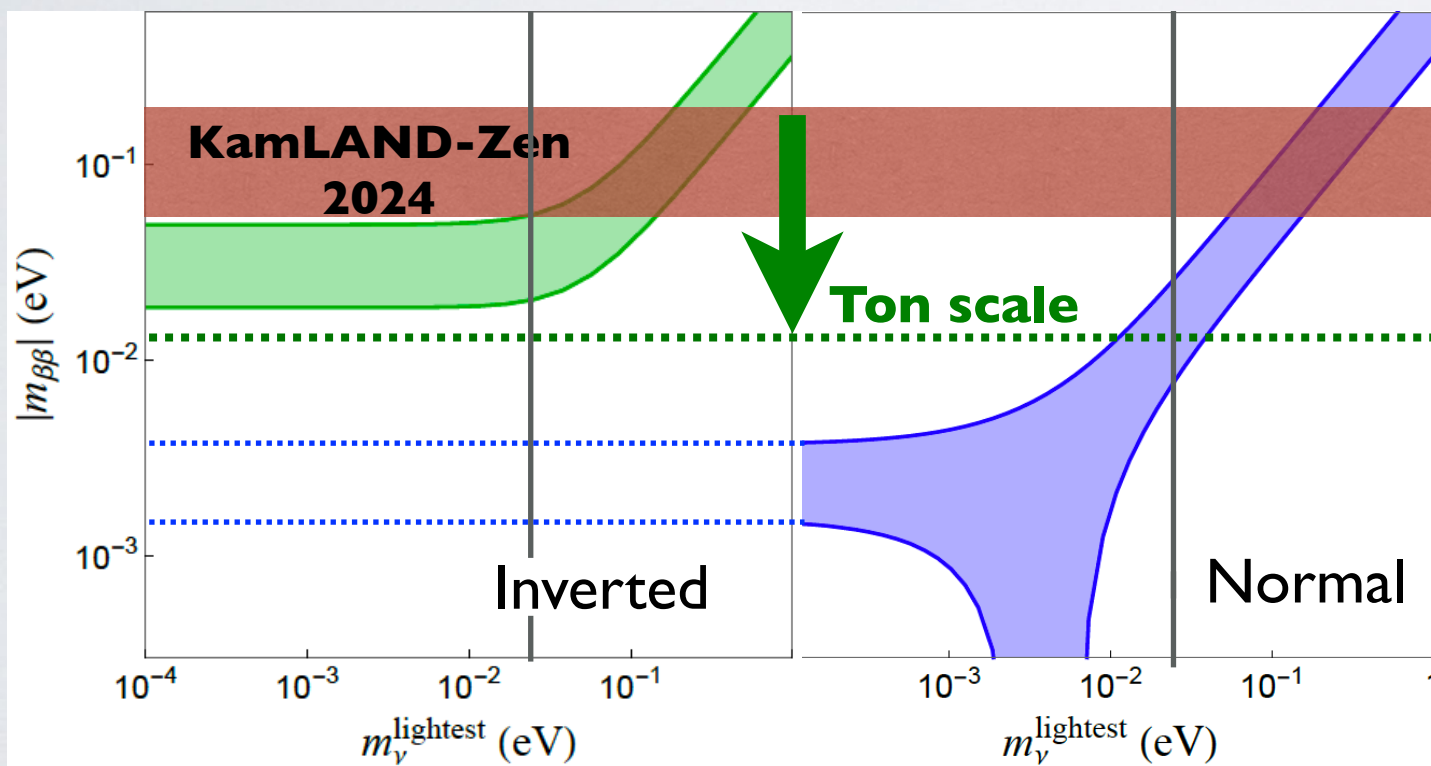
**How close are experiments ?**

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



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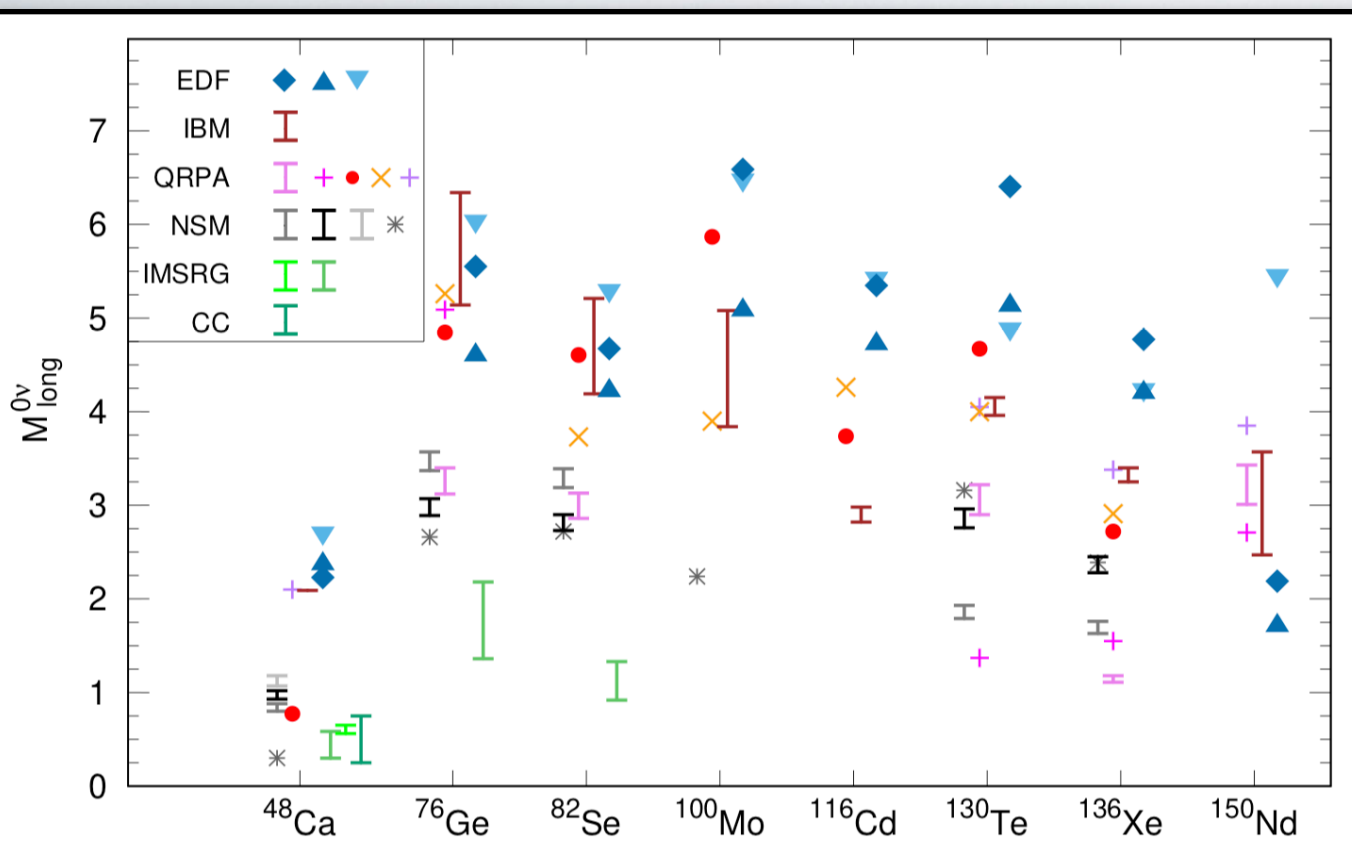


**Quite close !!**

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

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

From: Menendez et al review '22



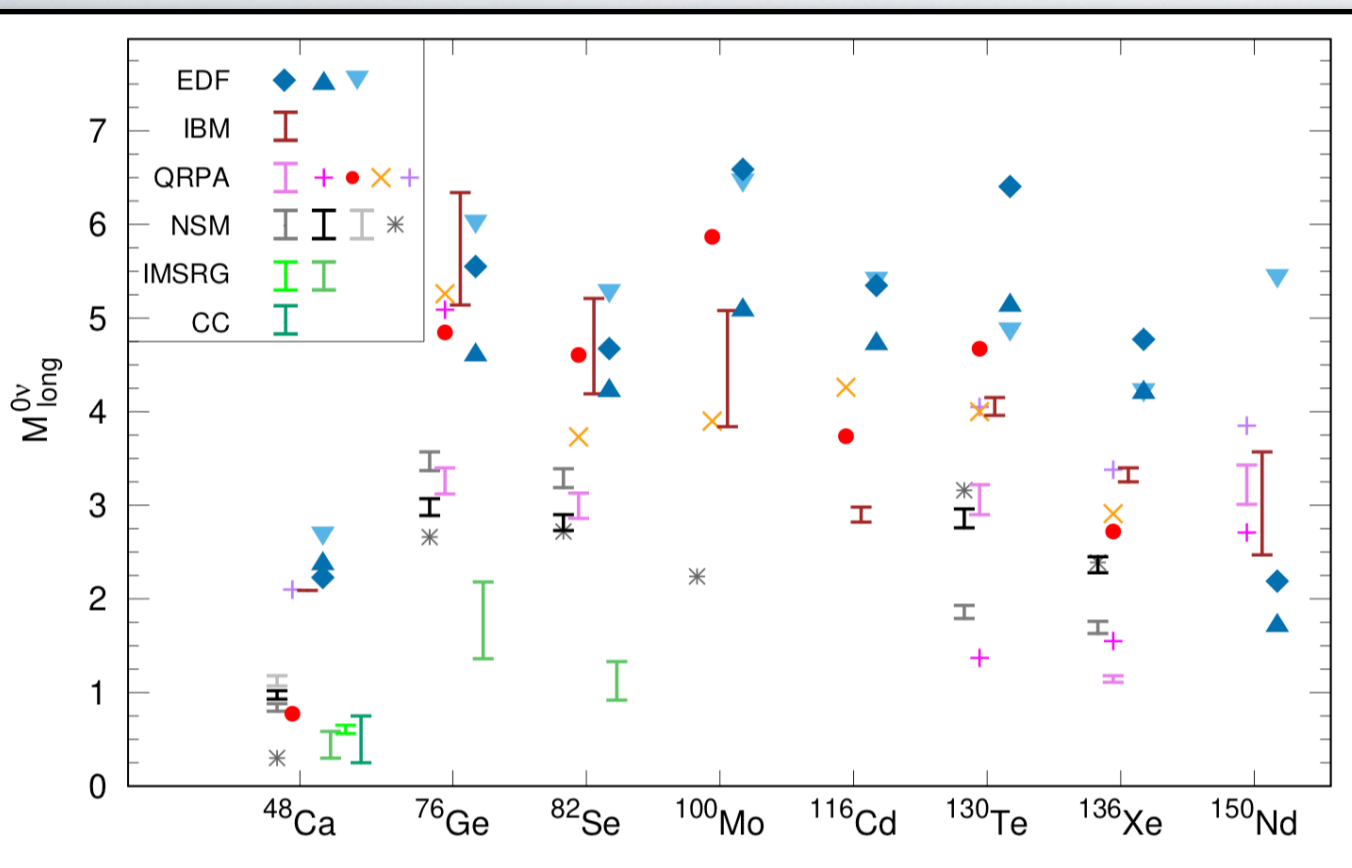
$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2$$

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

**Where is this coming from ?**

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

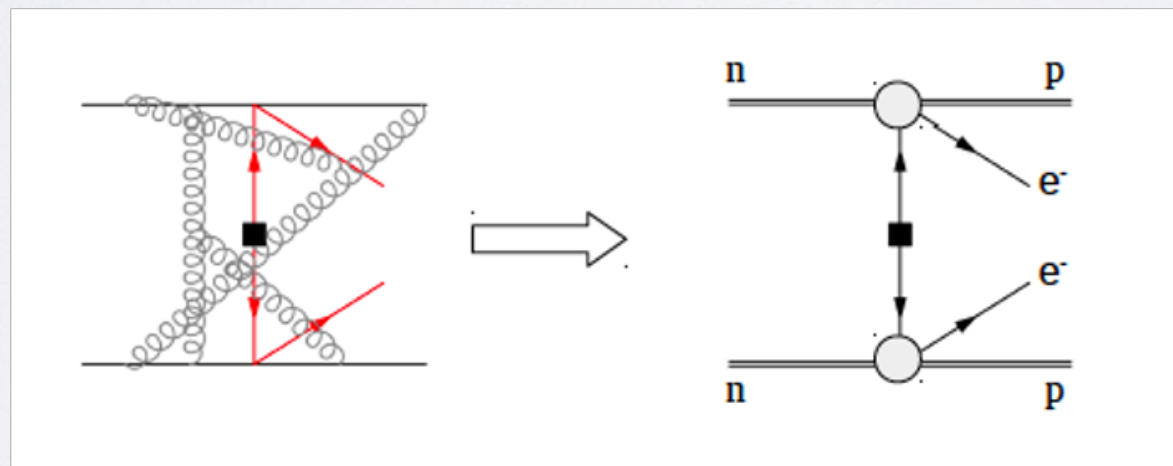
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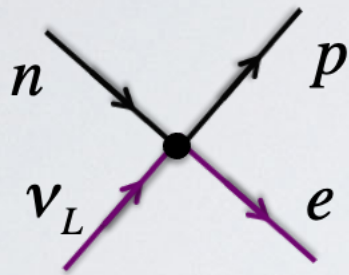
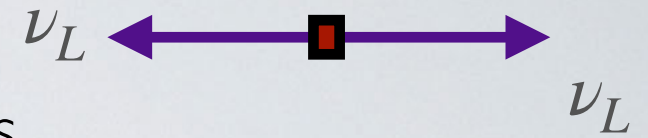
**Where is this coming from ?**



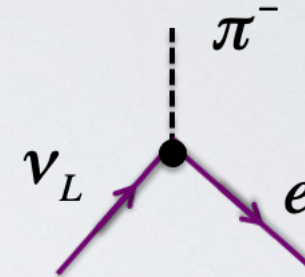
- Large nuclei —> complicated many-body nuclear matrix elements
- Neutrinoless double beta decay is intrinsically a two-nucleon process
- **Can modern methods (chiral EFT + ab initio) help ?**

# 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

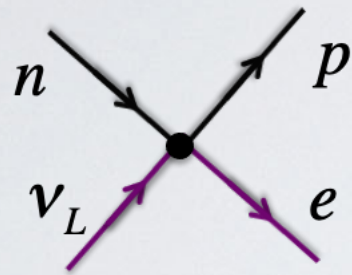
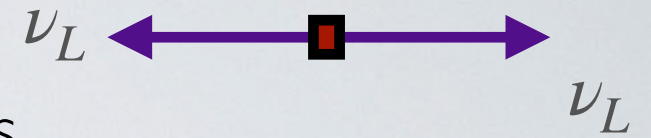


$$L_{\chi, Fermi} = G_F f_\pi \left( \partial_\mu \pi^- \bar{e}_L \gamma^\mu \nu_L \right) + G_F \bar{p} \left( \gamma^\mu - g_A \gamma^\mu \gamma^5 \right) n \bar{e}_L \gamma^\mu \nu_L + \dots$$

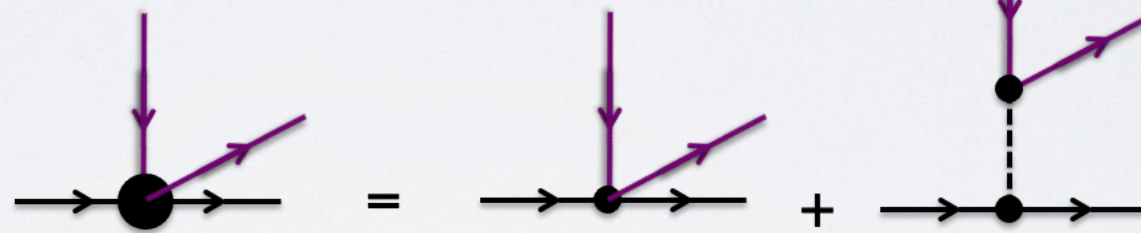
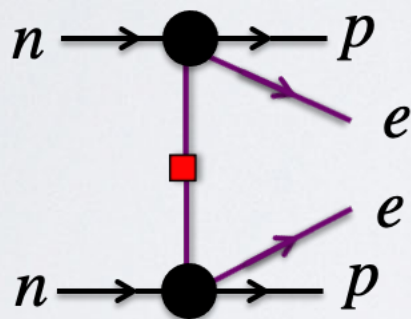
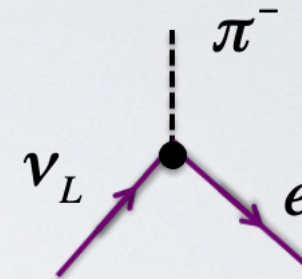


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$$L_{\chi, \text{Fermi}} = G_F f_\pi \left( \partial_\mu \pi^- \bar{e}_L \gamma^\mu \nu_L \right) + G_F \bar{p} \left( \gamma^\mu - g_A \gamma^\mu \gamma^5 \right) n \bar{e}_L \gamma^\mu \nu_L + \dots$$

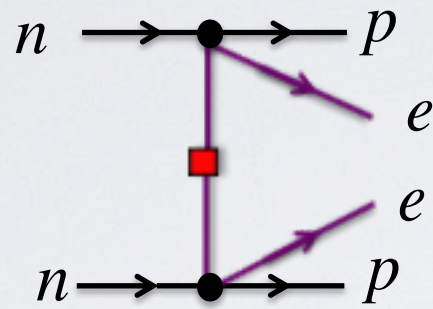


$$V_\nu(^1S_0) = (2G_F^2 m_{\beta\beta}) \tau_1^+ \tau_2^+ \frac{1}{\mathbf{q}^2} \left[ (1 + 2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)} \right] \otimes \bar{e}_L e_L^c$$

- This is the leading-order 'neutrino potential'

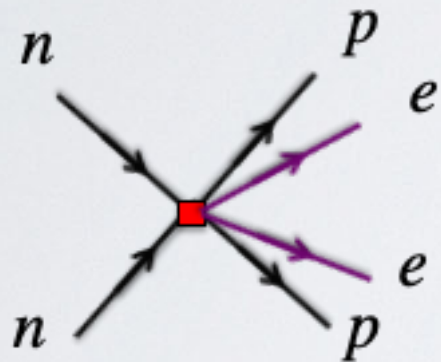
# Light Majorana neutrinos (standard mechanism)

- Leads to 'long-range'  $nn \rightarrow pp + ee$



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

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

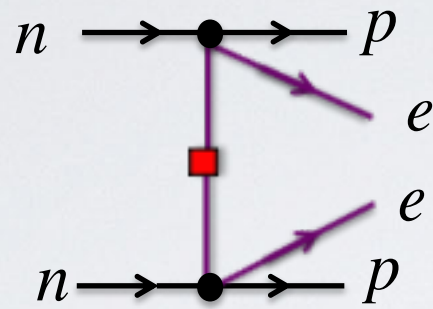


- Contributions from virtual hard neutrinos  $\mathbf{q} \sim \Lambda_\chi \sim 1 \text{ GeV}$
- Naive-dimensional analysis tells us this is NNLO

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

# Light Majorana neutrinos (standard mechanism)

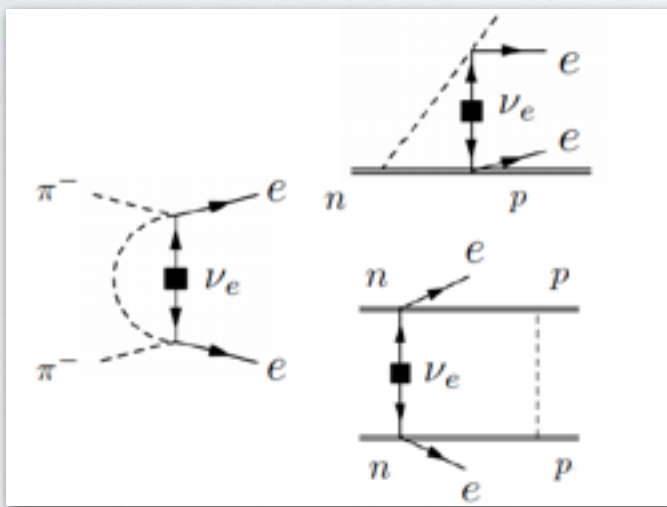
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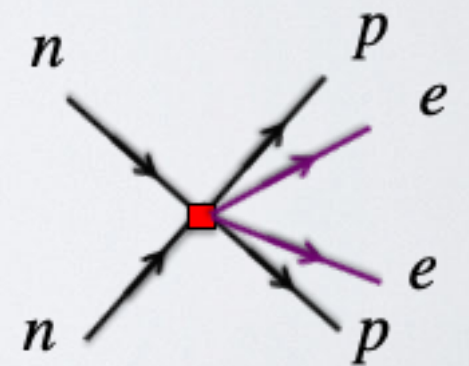
- More contributions at higher orders in chiral perturbation theory



- Loops at N<sup>2</sup>LO are divergent: come with counter terms

$$V_\nu^{\text{N}^2\text{LO}} \sim \left( V_{\text{finite}} + V_{UV} \log \frac{m_\pi^2}{\mu^2} + V_{\text{CT}} \right) \otimes \bar{e}_L e_L^c$$

- Divergences absorbed by counter terms



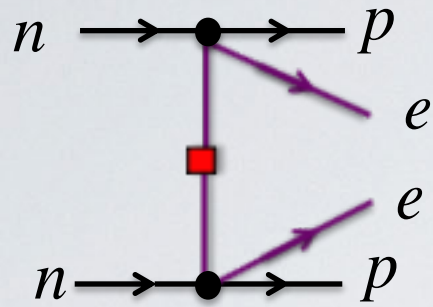
Cirigliano, Dekens, Mereghetti, Walker-Loud '17

- At higher orders also 'closure corrections' and three-body effects

e.g. Engel et al '18

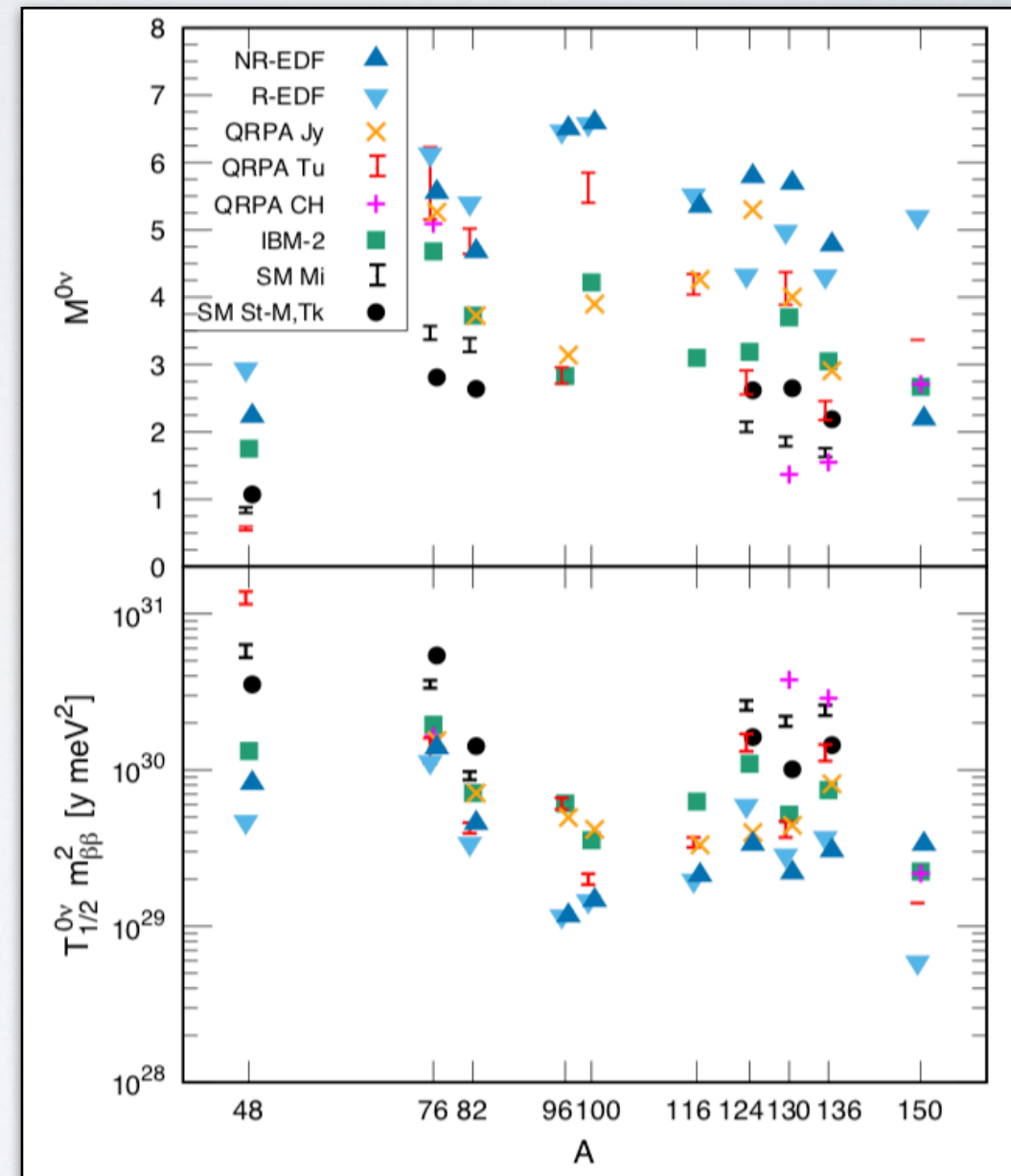
Mereg et al '18

# Leading-order transition currents



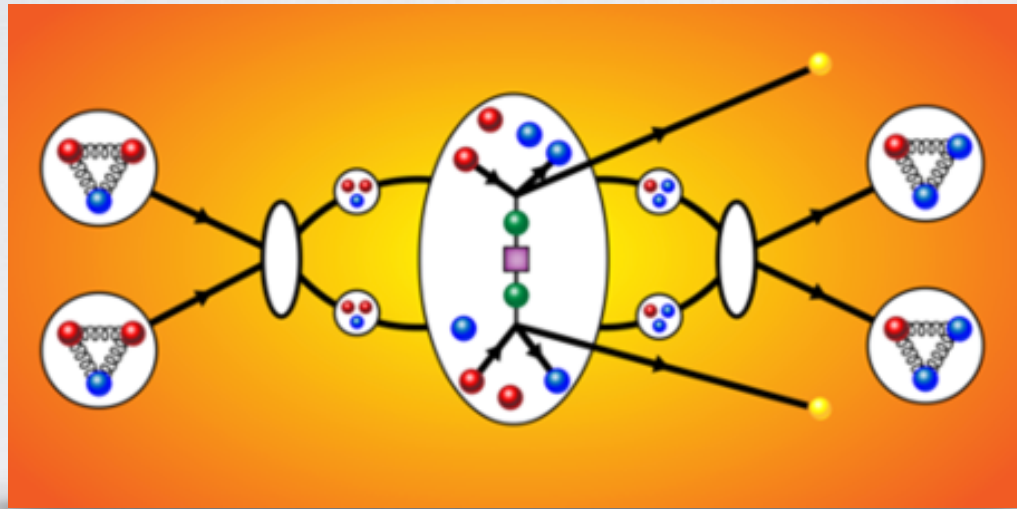
$$V_\nu = (2G_F^2 m_{\beta\beta}) \tau_1^+ \tau_2^+ \frac{1}{\mathbf{q}^2} \left[ (1 + 2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)} \right] \otimes \bar{e}_L e_L^c$$

- Leading-order  $0\nu\text{bb}$  current is very simple
- No unknown hadronic input ! Only unknown is  $m_{\beta\beta}$
- But this was already the input for calculations !
- Original idea: study simpler nuclear systems
- **Not relevant for experiments but as a theoretical laboratory**

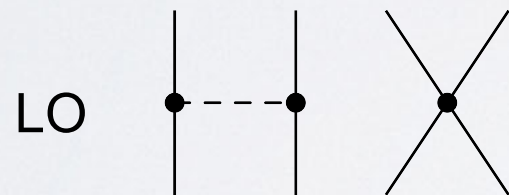


# Neutron-Neutron $\rightarrow$ Proton-Proton

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



- Derive wave functions from chiral effective field theory  $T = V + V G_0 T$



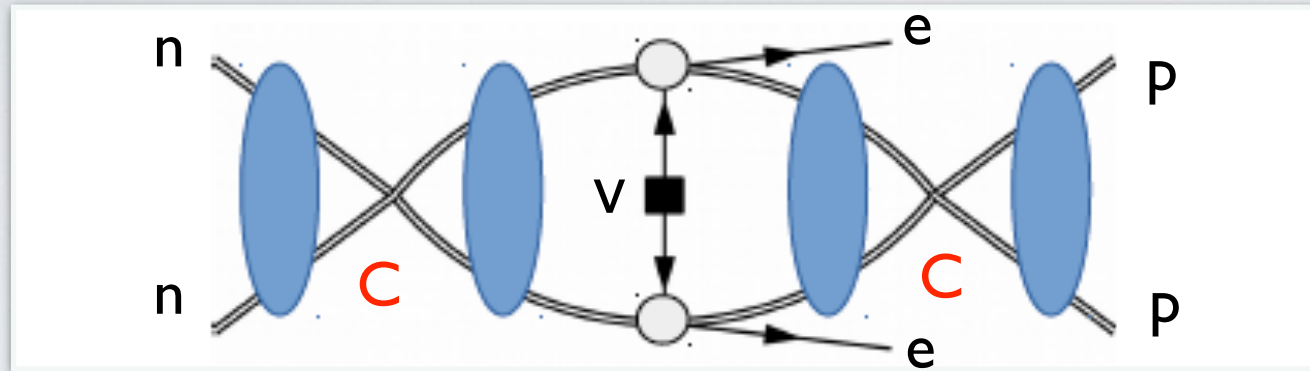
$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

Weinberg 90' 91'

- Contact term low-energy constant fitted to  $^1S_0$  scattering length

# Leading-order transition currents

- Insert long-distance neutrino exchange into scattering states

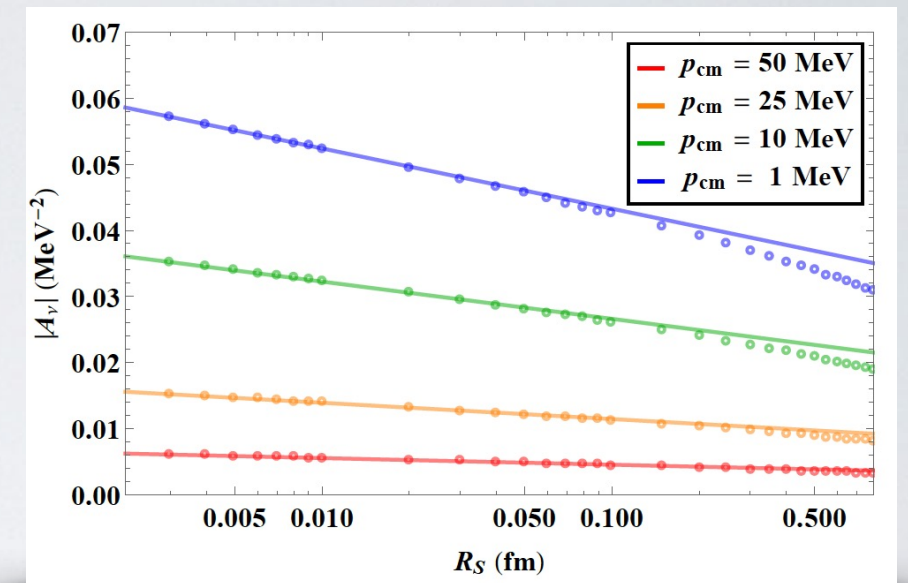


$$\sim (1 + 2g_A^2) \left( \frac{m_N C_0}{4\pi} \right)^2 \left( \frac{1}{\epsilon} + \log \frac{\mu^2}{p^2} \right)$$

## New divergences

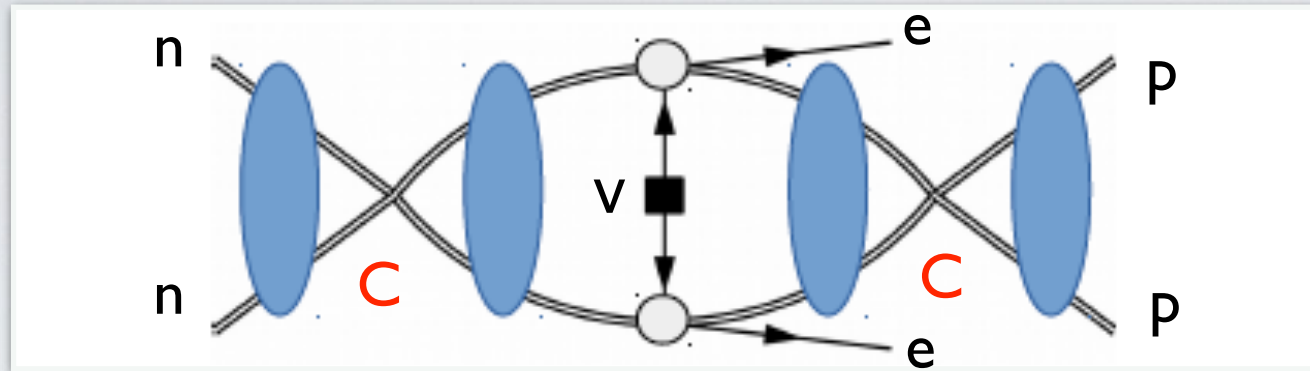
Similar to pion-mass dependence of  $C_0$  in Kaplan/Savage/Wise '98

Phillips/Valderrama PRL '14



# Leading-order transition currents

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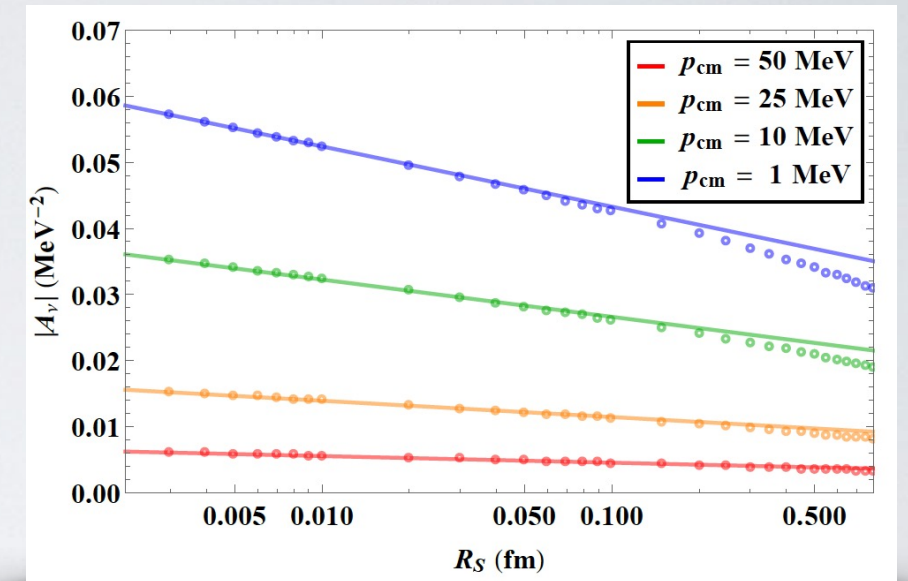


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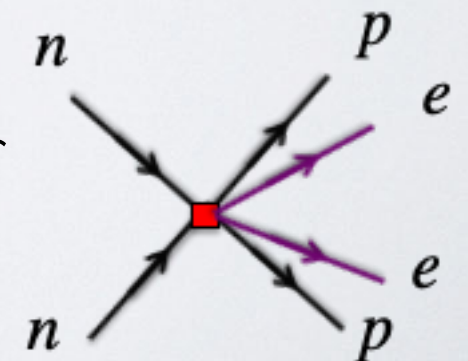
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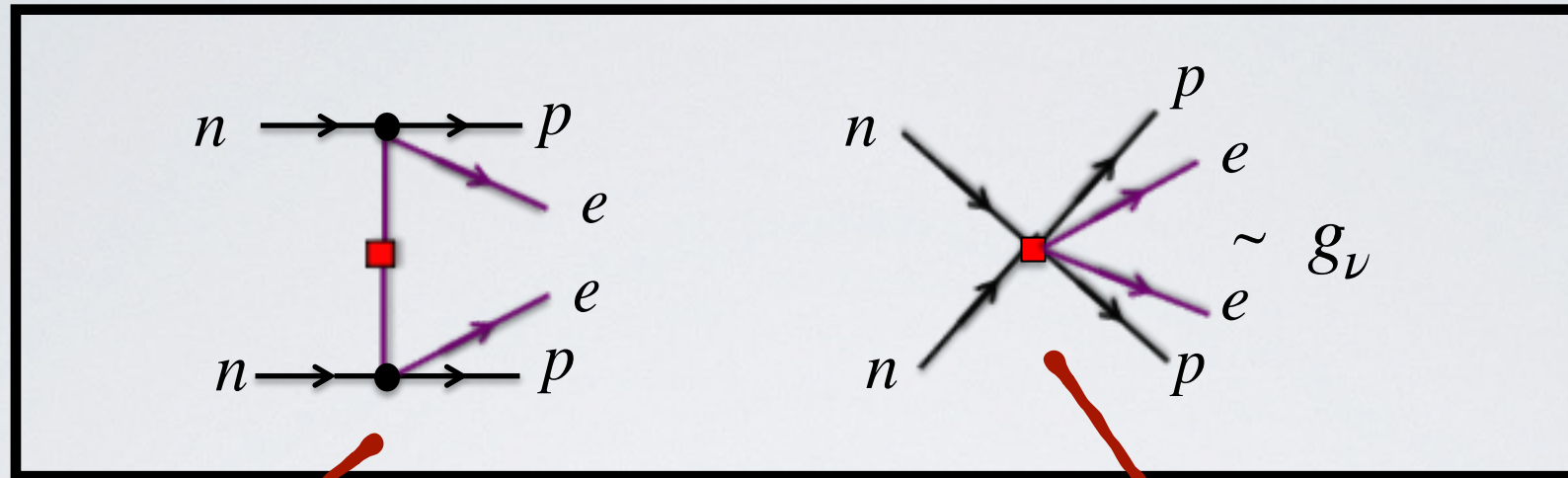


## Logarithmic regulator dependence

- Divergence indicates sensitivity to short-distance physics (hard-neutrino exchange)
- Suggest to add a counter term: a short-range  $nn \rightarrow pp + ee$  operator



# A new leading-order contribution

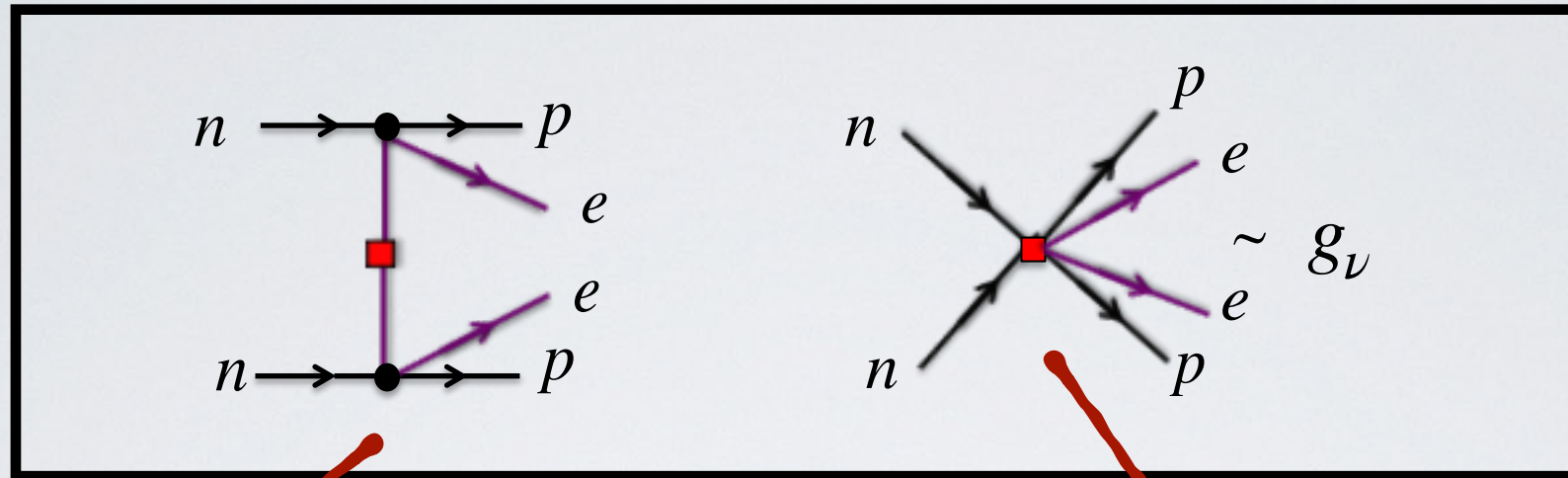


‘Long-range’ neutrino-exchange

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

- **Short-distance piece depends on QCD matrix element  $g_\nu$**

# 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 for a technical talk)

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC '19 PRL '21

Davoudi, Kadam PRL '21 Briceno et al '19 '20

Van Groffier JHEP '24

Richardson, Schindler, Pastore, Springer '21

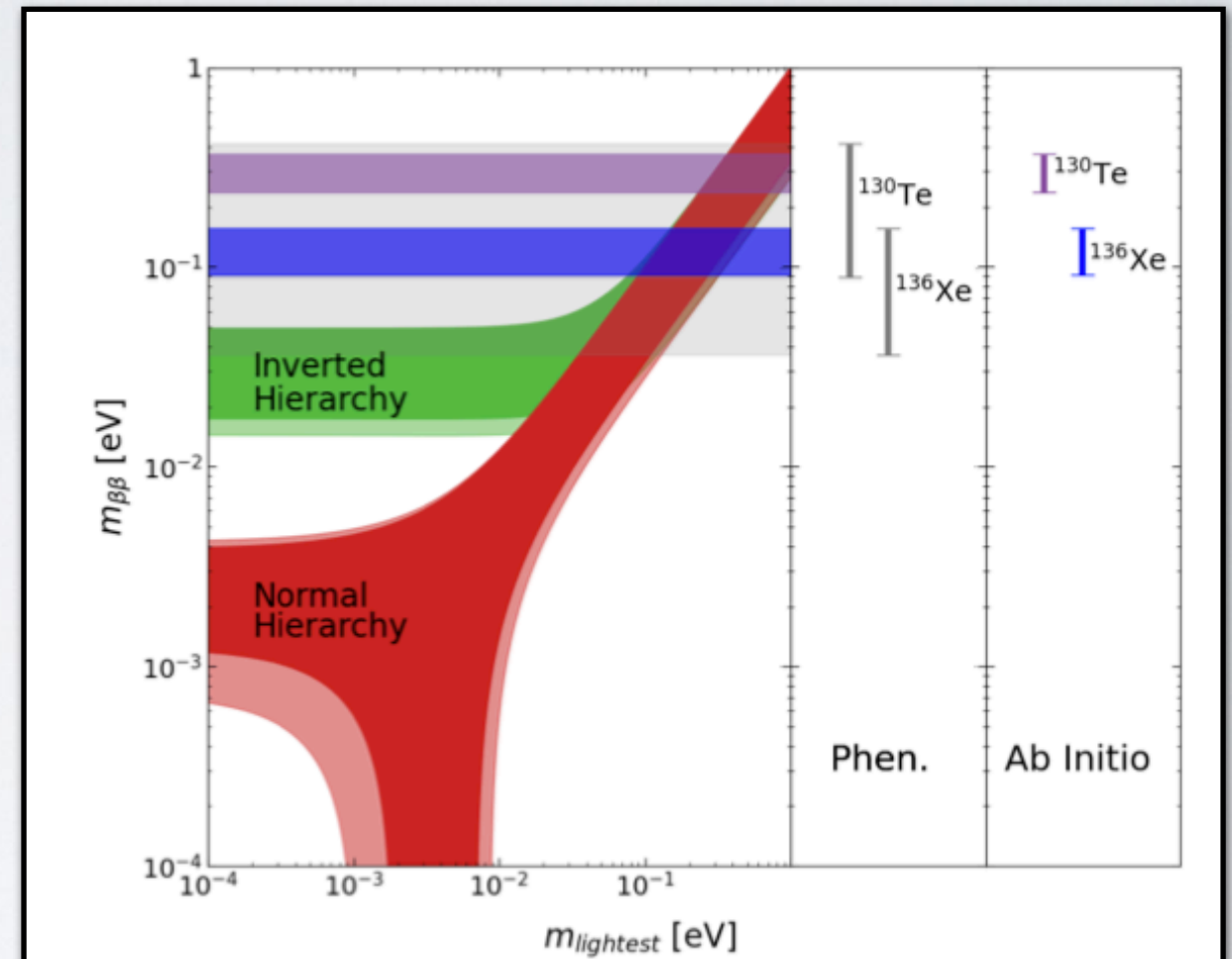
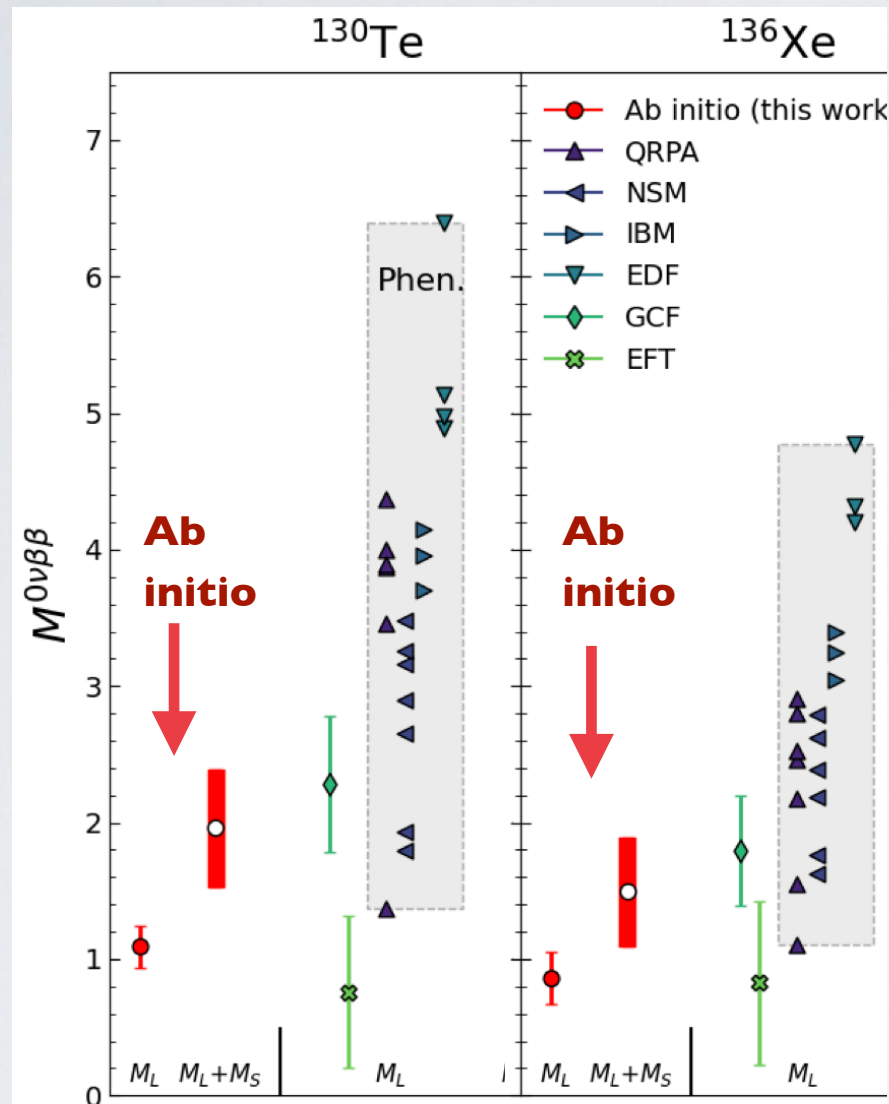
Tuo et al. '19; Detmold, Murphy '20 '22

Yang, Zhao '23 '24 PRL '25 (using relativistic NN theory)

- The modified leading order neutrino potential is **starting point for ab initio theory**

# Ab initio calculations

- Results from 2307.15156 Belley et al using **VS-IMSRG** (earlier work e.g. Yao et al 1908.05424)



- Ab initio calculations find **small long-distance NMEs** compared to other methods
- Partially compensated** by new short-distance interaction (50-100% effect)
- Better overlap with nuclear models but still big spread

# Ab initio calculations

- Belley et al: detailed analysis of uncertainties for Ge transition 'PRL '24.
- Vary regulators, chiral potentials, fitting of LECs, (next talk has more details)

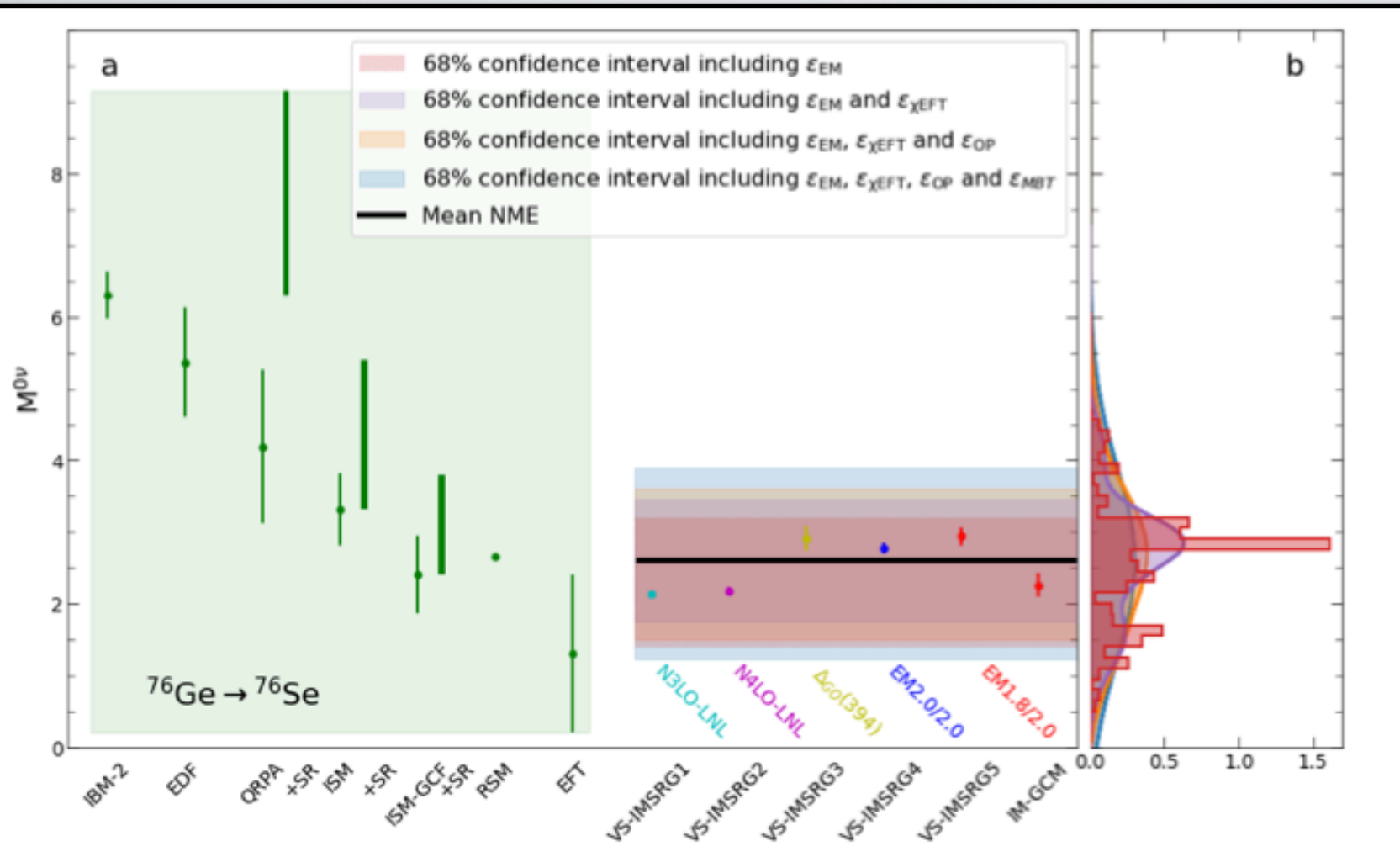


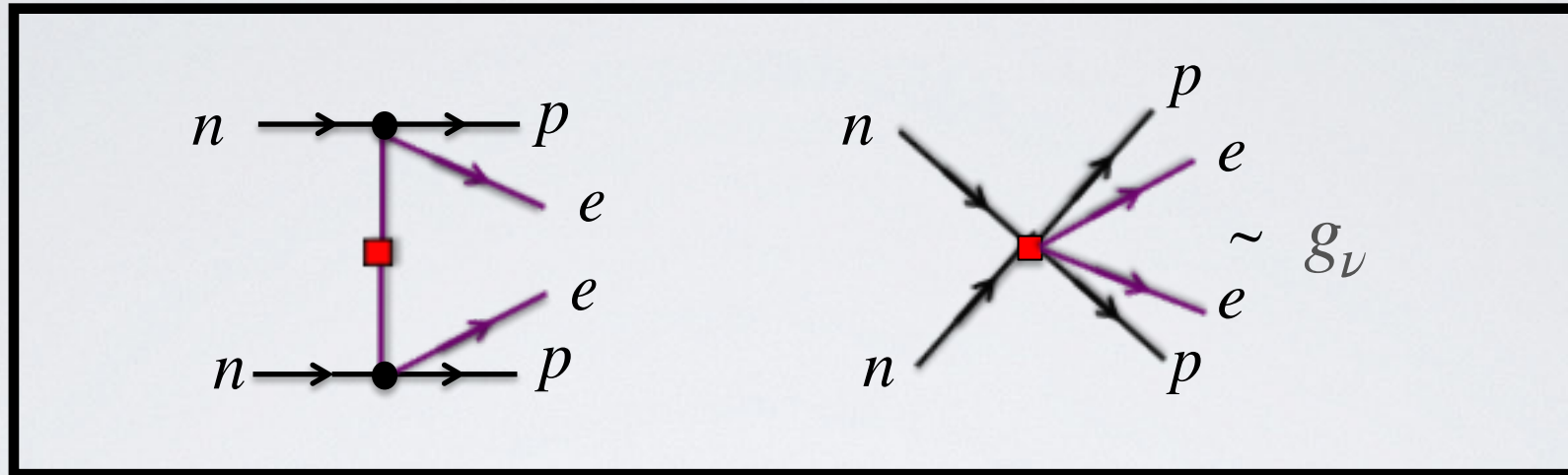
TABLE I. The recommended value for the total NME of  $0\nu\beta\beta$  decay in  $^{76}\text{Ge}$ , together with the uncertainties from different sources.

| $M^{0\nu}$             | $\epsilon_{\text{LEC}}$ | $\epsilon_{\chi\text{EFT}}$ | $\epsilon_{\text{MBT}}$ | $\epsilon_{\text{OP}}$ | $\epsilon_{\text{EM}}$ |
|------------------------|-------------------------|-----------------------------|-------------------------|------------------------|------------------------|
| $2.60^{+1.28}_{-1.36}$ | 0.75                    | 0.3                         | 0.88                    | 0.47                   | <0.06                  |

- Bayesian analysis of errors leads to  $M_{0\nu}(^{76}\text{Ge}) = 2.6^{+1.3}_{-1.4}$
- Ab initio still **smaller** than 'traditional' calculations (despite inclusion of **short-range**)
- Even with 50% uncertainties some other calculations fall outside the range
- This result was used by LEGEND-200 collaboration to limit neutrino Majorana mass (PRL '26)

# Higher-order corrections

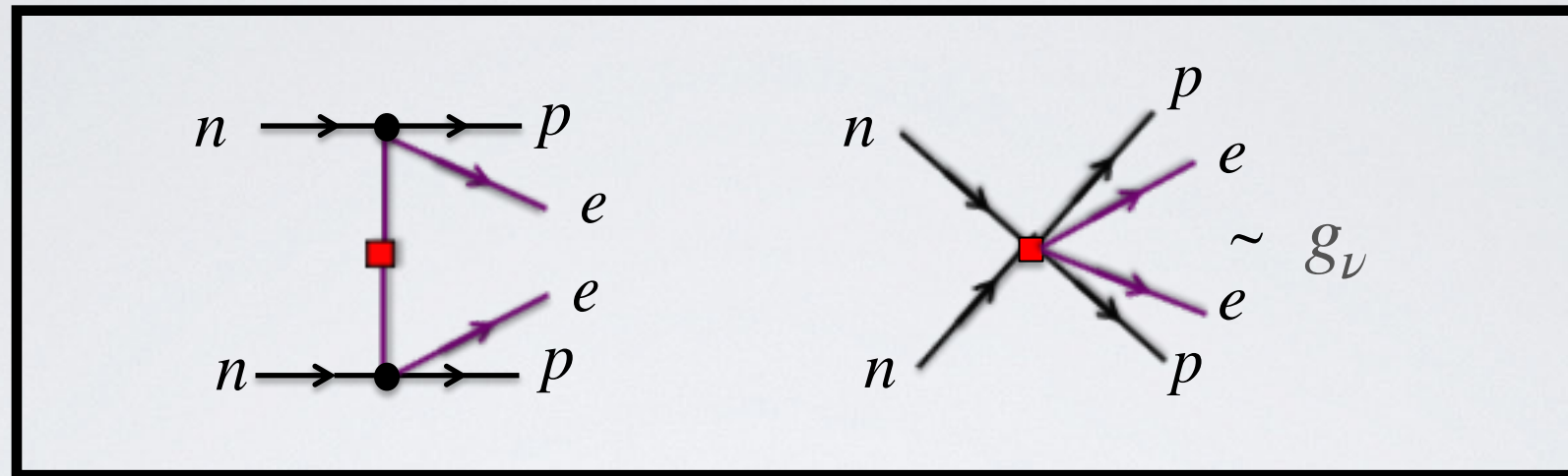
- It seems now that the leading-order 0vbb current contains 2 terms



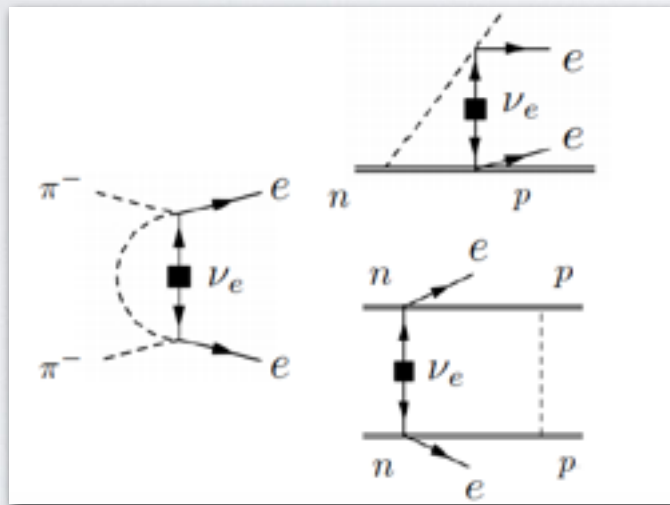
- Are there more surprises ?

# Higher-order corrections

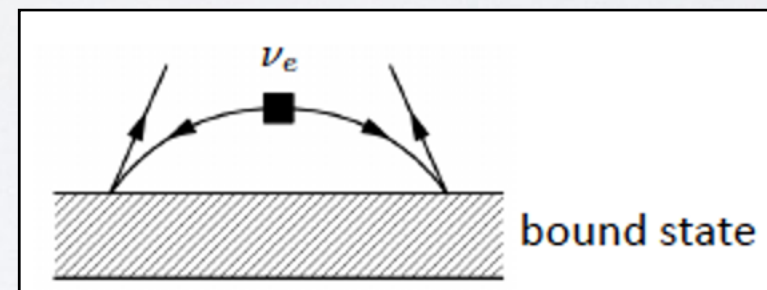
- It seems now that the leading-order 0vbb current contains 2 terms



- At NNLO we get additional contributions from loops



‘Soft’ neutrinos



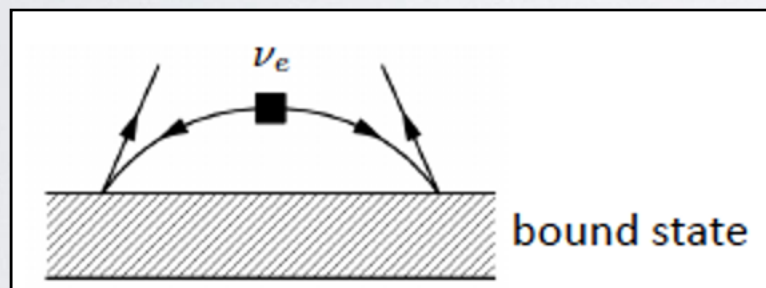
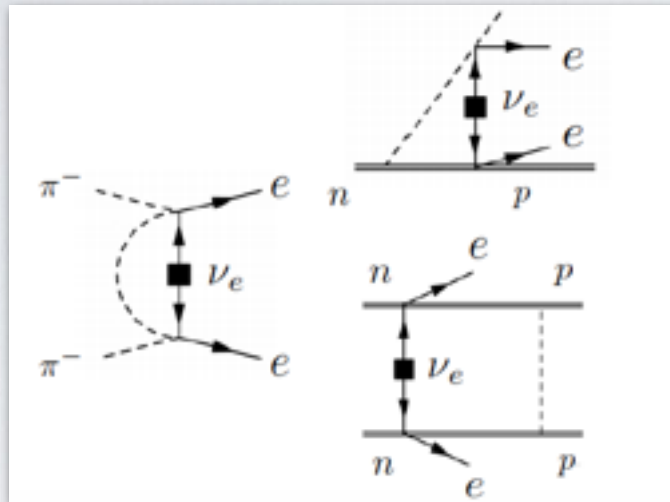
‘Ultra-soft’ neutrinos

- Ultrasoft depends on nuclear excited states

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

# Higher-order corrections in the nuclear shell model

- Soft loops (Cirigliano et al '17) and ultrasoft (Dekens et al '24) calculated in chiral EFT
- Implemented by Javier Menendez and collaborators (2408.03373) in Shell Model



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

- **Confirms that these effects are relatively small (10% corrections roughly)**
- Power counting seems to work

# Just extract the NMEs !!

- ***Considering how hard it has been to compute, can't we measure them ?***
- Find a proxy process for  $0\nu\beta\beta$  that probes the same nuclear physics

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- Find a proxy process for  $0\nu\beta\beta$  that probes the same nuclear physics

$\gamma\gamma$  decay as a probe of neutrinoless  $\beta\beta$  decay nuclear matrix elements

B. Romeo<sup>a,b,\*</sup>, J. Menéndez<sup>c</sup>, C. Peña Garay<sup>b,d</sup>

<sup>a</sup> Donostia International Physics Center, 20018 San Sebastián, Spain

<sup>b</sup> Laboratorio Subterráneo de Canfranc, 22880 Canfranc-Estación, Spain

<sup>c</sup> Department of Quantum Physics and Astrophysics and Institute of Cosmos Sciences, U

<sup>d</sup> Institute for Integrative Systems Biology (I<sup>2</sup>SysBio), Valencia, Spain

**Double Gamow-Teller Transitions and its Relation to Neutrinoless  $\beta\beta$  Decay**

**Ab initio correlations between neutrinoless and two-neutrino double-beta decays in  $^{48}\text{Ca}$**

X. Lian,<sup>1</sup> C. R. Ding,<sup>2,3</sup> C. L. Bai,<sup>1,\*</sup> and J. M. Yao<sup>2,3,4,†</sup>

<sup>1</sup>College of Physics, Sichuan University, Chengdu 610065, China

<sup>2</sup>School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, P.R. China

<sup>3</sup>Guangdong Provincial Key Laboratory of Quantum Metrology and Sensing, Sun Yat-sen University, Zhuhai 519082, P.R. China

<sup>4</sup>Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8502, Japan

[Yako](#)

**Correlation of  $0\nu\beta\beta$  decay nuclear matrix elements with nucleon-nucleon phase shifts**

A. Belley<sup>ID</sup> 1,2,3 I. Pitcher<sup>ID</sup> 2,3,4 T. Mivani<sup>ID</sup> 5,6,7,8 S. R. Stroberg<sup>ID</sup> 9 and I. D. Holt<sup>ID</sup> 2,10

**Benchmarking nuclear matrix elements of  $0\nu\beta\beta$  decay with high-energy nuclear collisions**

Yi Li,<sup>1,2</sup> Xin Zhang,<sup>3</sup> Giuliano Giacalone,<sup>4,\*</sup> and Jiangming Yao<sup>1,2,†</sup>

<sup>1</sup>School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, P.R. China

<sup>2</sup>Guangdong Provincial Key Laboratory of Quantum Metrology and Sensing, Sun Yat-Sen University, Zhuhai 519082, China

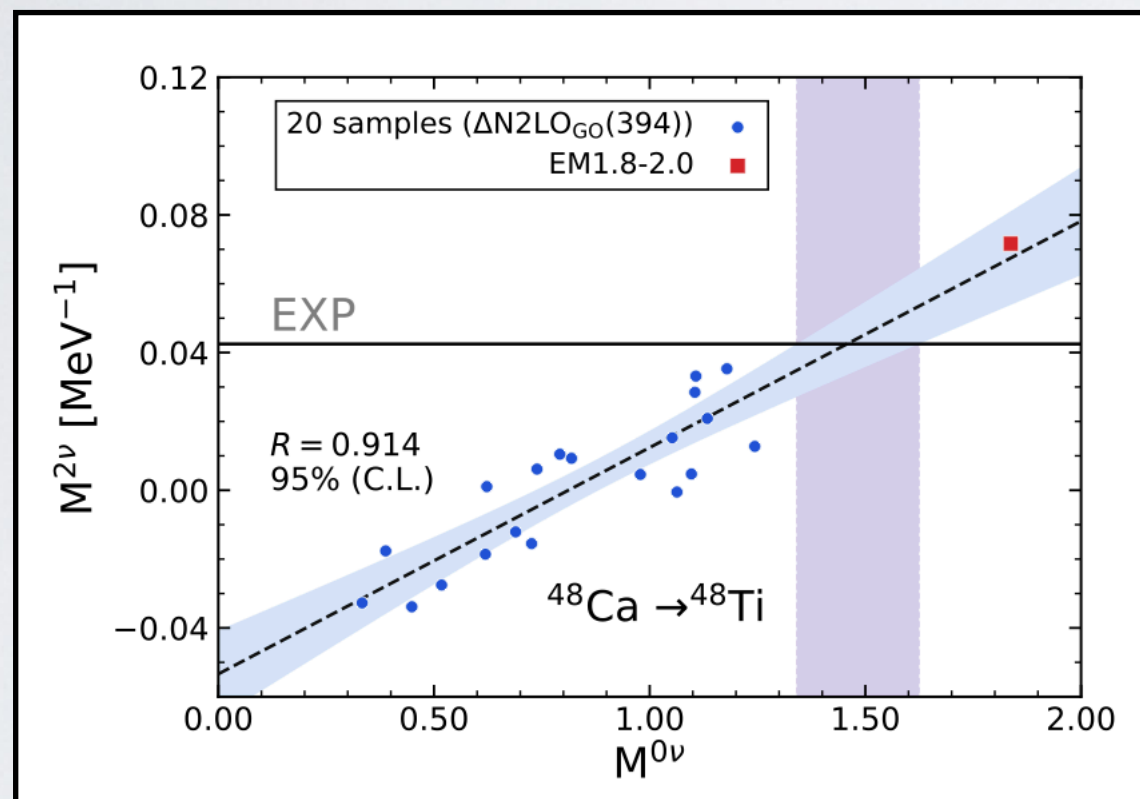
<sup>3</sup>Department of Physics, Kyoto University, Kyoto 606-8502, Japan

<sup>4</sup>Theoretical Physics Department, CERN, CH-1211 Genève 23, Switzerland

(Dated: July 9, 2025)

# Correlation between 2nubb and 0vbb

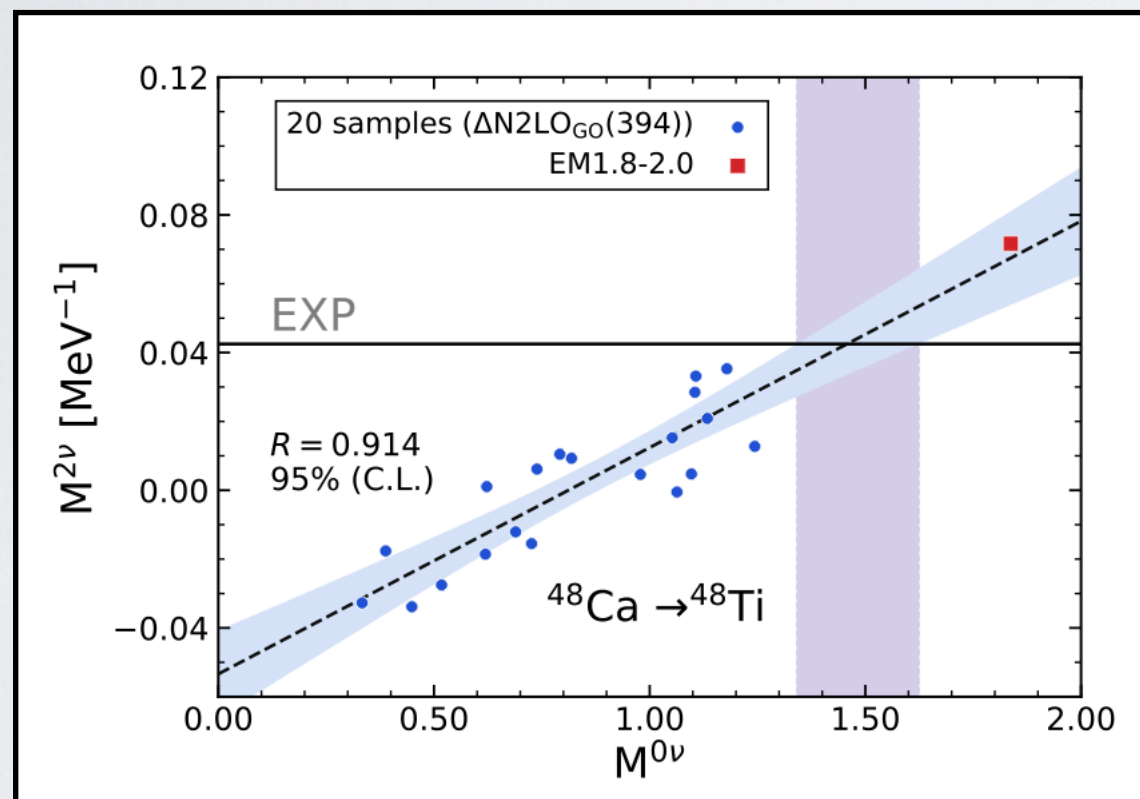
- One example: arXiv:2605.19479 (Lian, Ding, Bai, Yao)
- Sophisticated ab initio (from chiral potentials) many-body calculations of measured 2nubb rates and 0vbb rates
- Compute  $M_{2\nu}$  and  $M_{0\nu}$  from a range of potentials (different LECs/regulators etc)



- **Problem solved ?**

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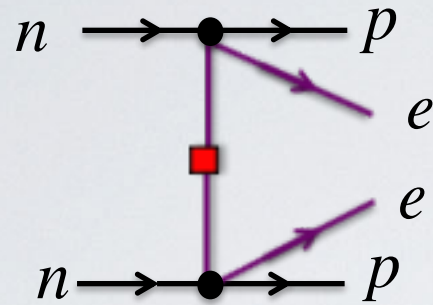


- **Problem solved ?**

- **Reasons to be prudent:**

- No error bars on theory predictions.
- None of the theory predictions agree with 2nubb data
- **No microscopic understanding of the correlation**

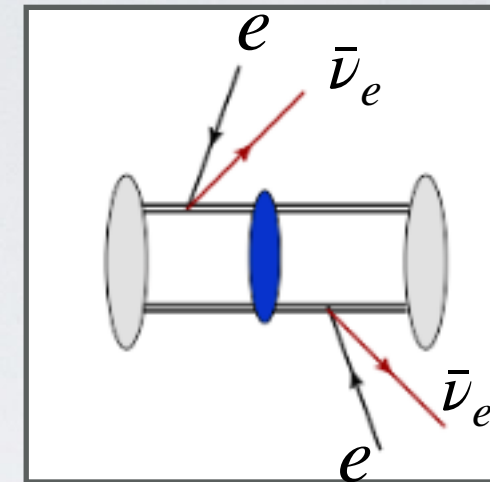
# Anatomy of 2nubb and 0vbb decays



$$T_{0\nu} \sim \langle \Psi_f | V_\nu | \Psi_i \rangle$$

0vbb is a *ground-state to ground-state* transition

EFT point of view: virtual neutrino carries momentum  $\sim$  binding momentum  $\sim$  100 MeV. It does not **`see`** the nuclear excited spectrum.



$$M_{GT}^{K,L} \sim \sum_n G_n \frac{E_n - E_i}{[E_n - E_i]^2 - E_{e,\nu}^2}$$

Combination  
of lepton  
energies

In 2vbb the intermediate nucleon pair is almost on-shell: sensitive to tower of nuclear excited states

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

**Need to compute many transitions**

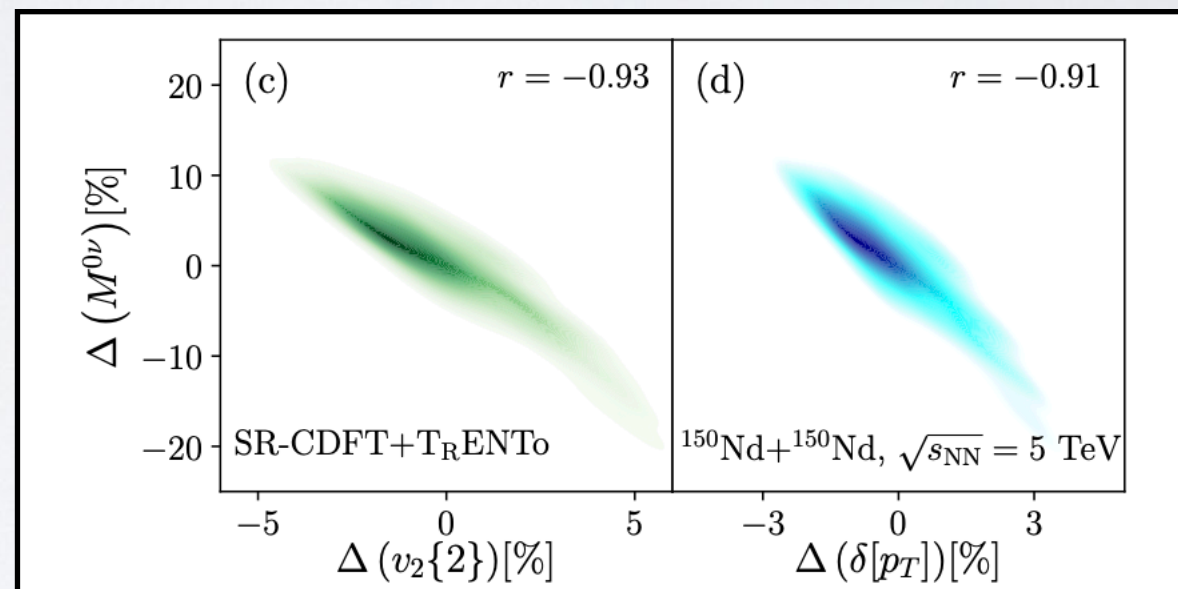
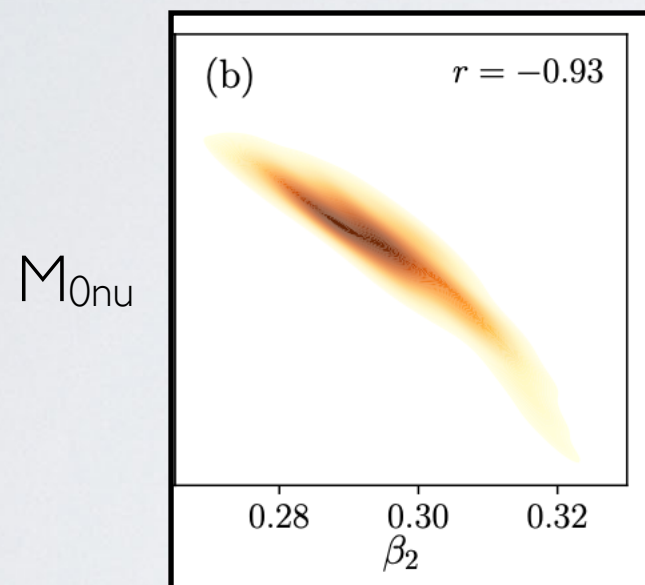
**No obvious relation between matrix elements from EFT point of view**

Requires further work to make these correlations robust

# 0vbb, shape parameters, and heavy ion collisions

- Observed correlation between 0vbb NMEs and *quadrupole deformation parameter of daughter nucleus*
- Great insight from recent years that heavy ion collisions can extract the latter
- Can they to 'measure' 0vbb nuclear matrix elements ? —> more in the next talks

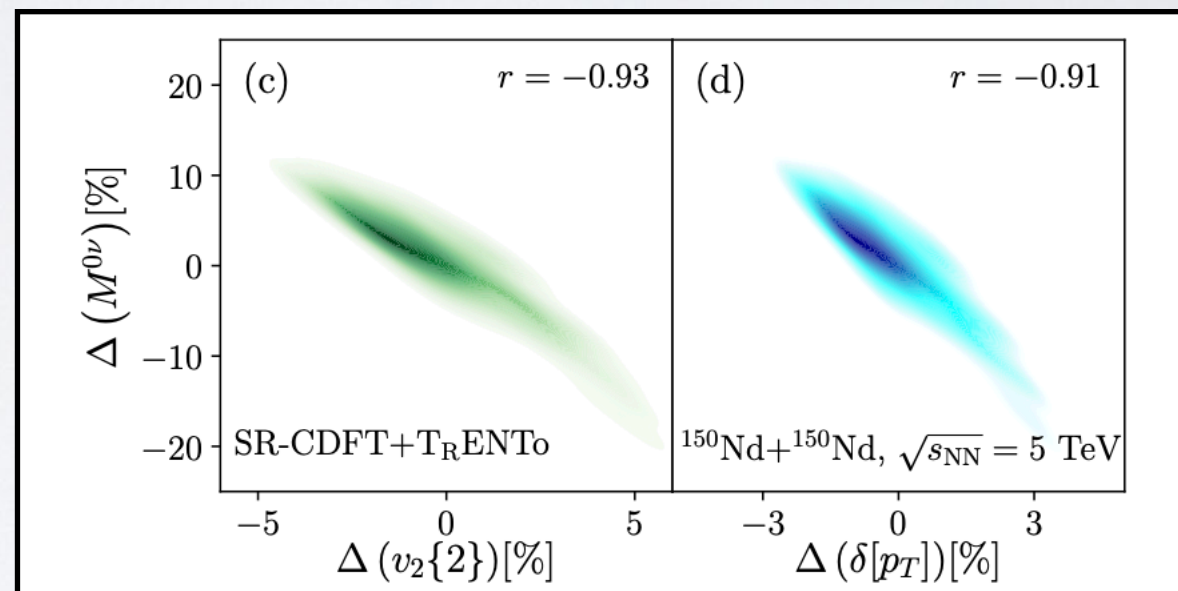
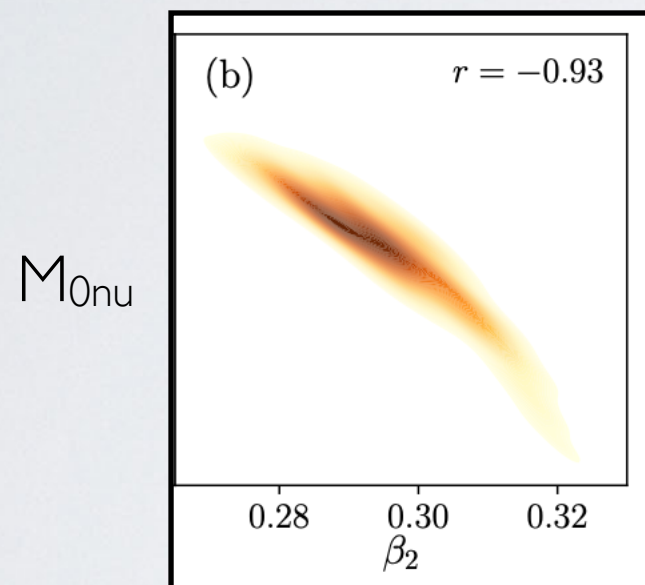
Li, Zhang, Giacalone, Yao, PRL '25



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Li, Zhang, Giacalone, Yao, PRL '25



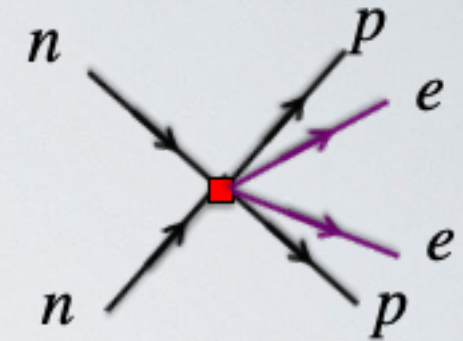
## Challenge for the future:

- **Can we develop a microscopic understanding of the correlation between total NME (long + short) and nuclear shape ?**
- **Can we make the connection to nuclear collisions robust ?**

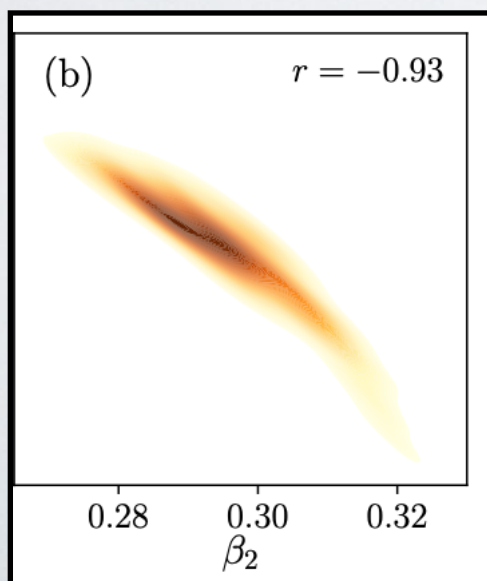
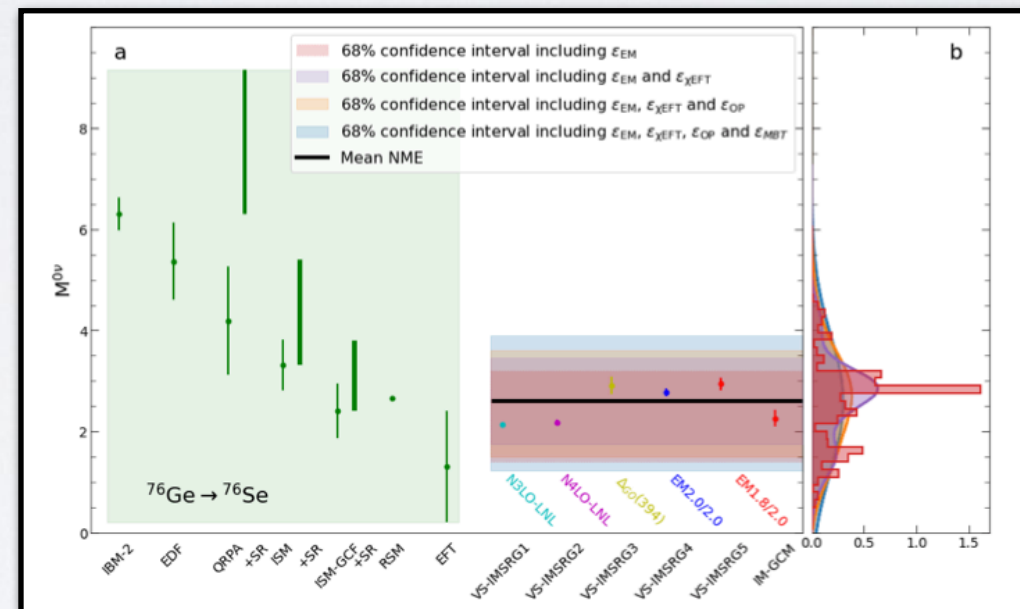
# Concluding remarks

- **Neutrinoless double beta decay best way to determine if neutrinos are Majorana states —> Big question in particle physics**

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



- Progress from EFT + ab initio nuclear structure but still large uncertainties

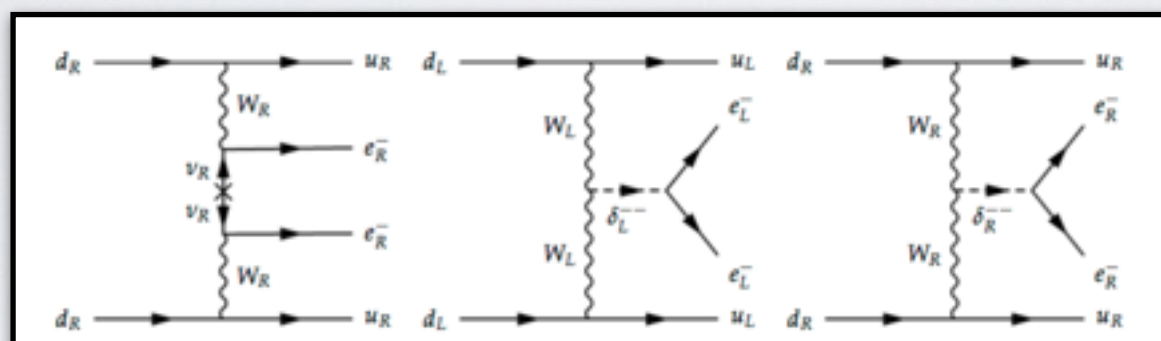


- Can heavy ion collisions provide input to reduce the uncertainties ?

# Backup

# Beyond neutrino masses

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

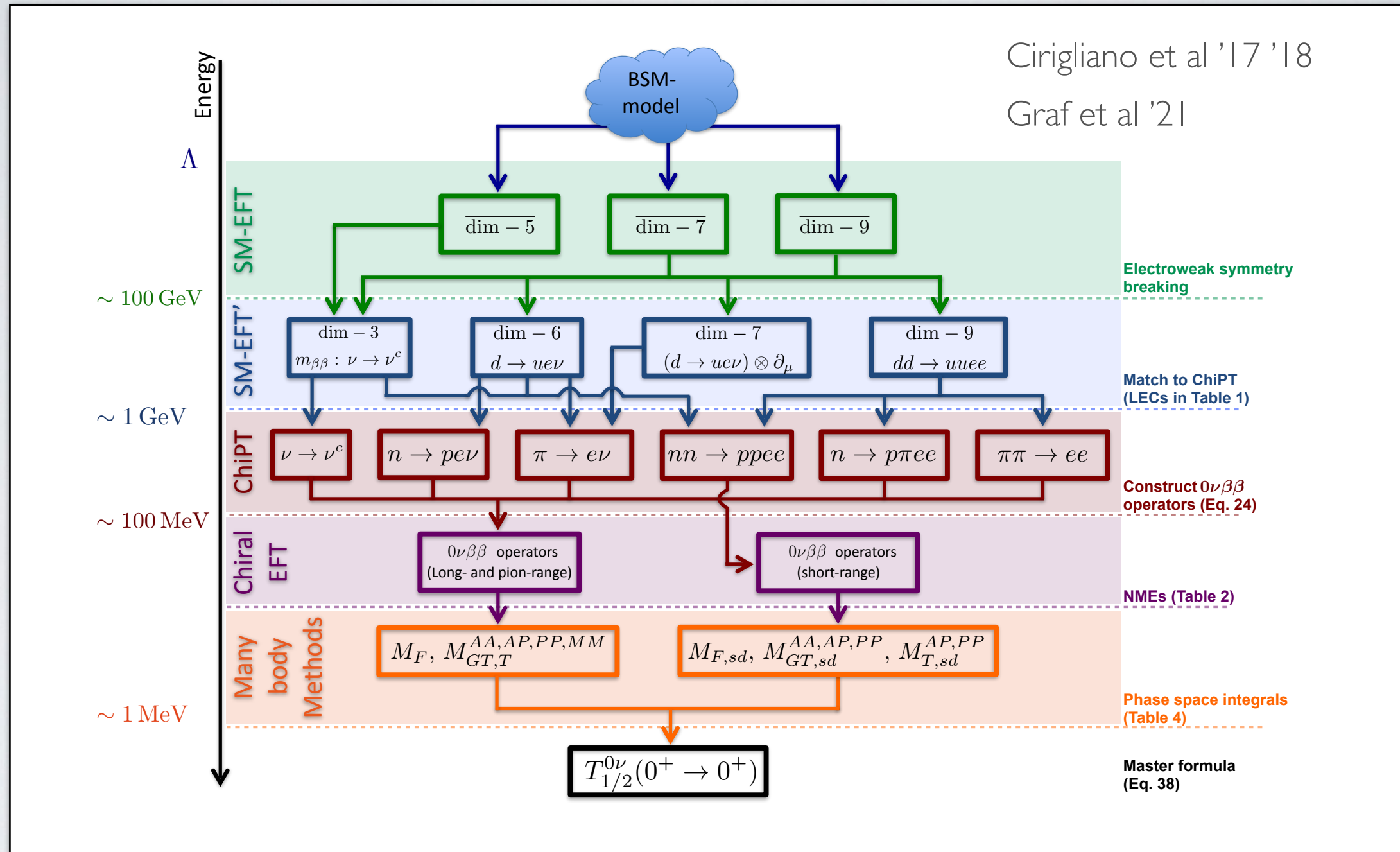


- No light neutrinos appear at all in these processes but **same observable signature**
- If scale of LNV is high they can be captured by effective field theory techniques

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

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

# Other sources of lepton-number violation



- 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/>