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Low energy probes of physics beyond the Standard Model (2)

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Office of Science

UNIVERSITY of WASHINGTON

Flow of the lectures

- The quest for new physics at the low-energy frontier: overview of *questions* and *probes*
- How does the precision / intensity frontier work?
  - Basics & example from history: the making of the Standard Model
  - ~~The Standard Model and its symmetries~~
  - BSM effective field theory (EFT) framework
- "Zoom in" on selected low-energy probes: illustrate methods and impact
  - Search for symmetry violation
    - Neutrino mass and symmetries: Lepton Number ~~and Lepton Flavor~~ Violation
    - CP-violation and permanent Electric Dipole Moments
  - Precision tests
    - Weak charged current (β decays), neutral current (parity-violating e-scattering), muon g-2

Lecture 1

Lecture 2

Lecture 3

The Standard Model and its symmetries

SM(EFT): building blocks

- Gauge group: G= $SU(3)_c \times SU(2)_W \times U(1)_Y$
- Building blocks: fields and their "charges" (transformation properties under G)

	$SU(3)_c \times SU(2)_W \times U(1)_Y$ representation: (dim[$SU(3)_c$], dim[$SU(2)_W$], Y)	$SU(2)_W$ transformation
$l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	(1,2,-1/2)	$l \to V_{SU(2)}\, l$
$e = e_R$	(1,1,-1)	
$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$	(3,2,1/6)	$q \to V_{SU(2)}\, q$
$u^i = u^i_R$	(3,1,2/3)	
$d^i = d^i_R$	(3,1,-1/3)	
$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$	(1,2,1/2)	$\varphi \to V_{SU(2)}\, \varphi$

$Q = T_3 + Y$

		$SU(3)_c \times SU(2)_W \times U(1)_Y$ representation
gluons:	G^A_μ, $A = 1 \cdots 8$, $G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu + g_s f_{ABC} G^B_\mu G^C_\nu$	(8,1,0)
W bosons:	W^I_μ, $I = 1 \cdots 3$, $W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g \epsilon_{IJK} W^J_\mu W^K_\nu$	(1,3,0)
B boson:	B_μ, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$.	(1,1,0)

Gauge transformation:

$$W^I_{\mu\nu}\frac{\sigma^I}{2} \longrightarrow V(x)\left[W^I_{\mu\nu}\frac{\sigma^I}{2}\right]V^\dagger(x)$$

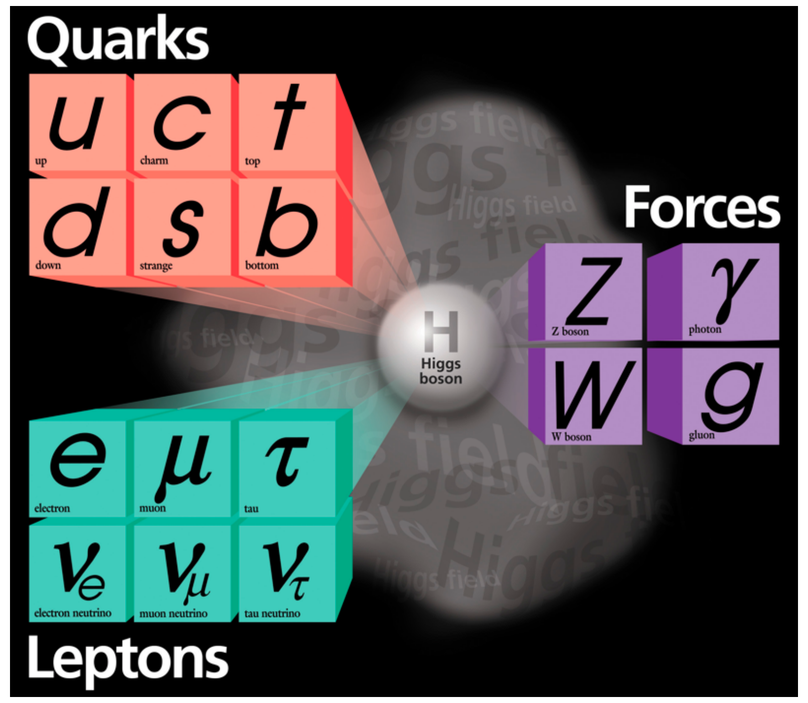
$$V(x) = e^{ig\beta_a(x)\frac{\sigma_a}{2}}$$

- Recipe to build the SM Lagrangian: write down all Lorentz and gauge invariant operators of dimension ≤ 4
- SMEFT: go beyond mass dimension 4

The SM Lagrangian: dim=4

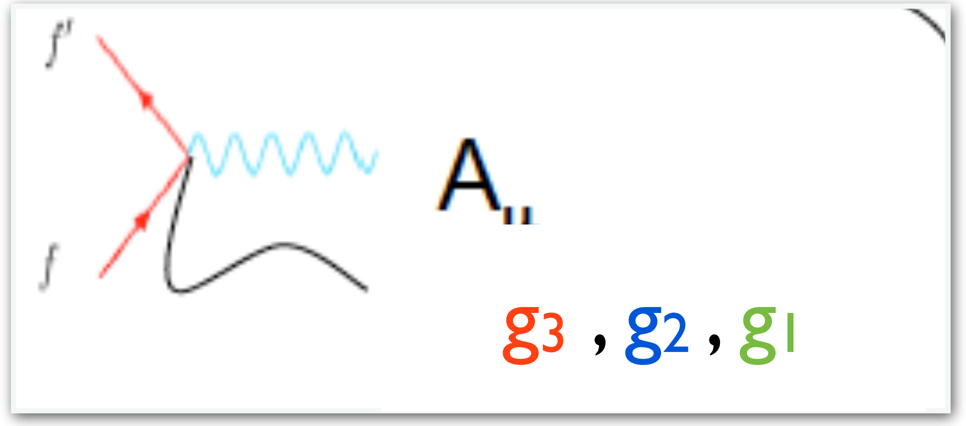
$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - i g_s \frac{\lambda^A}{2} G^A_\mu - i g \frac{\sigma^a}{2} W^a_\mu - i g' Y B_\mu$$



$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \sum_{i=1,2,3} \left(i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$



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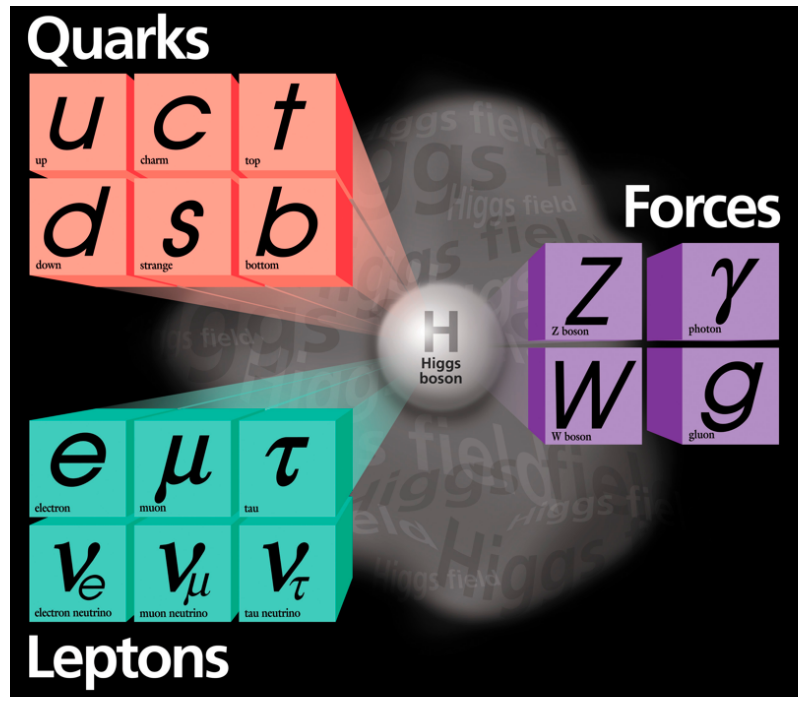

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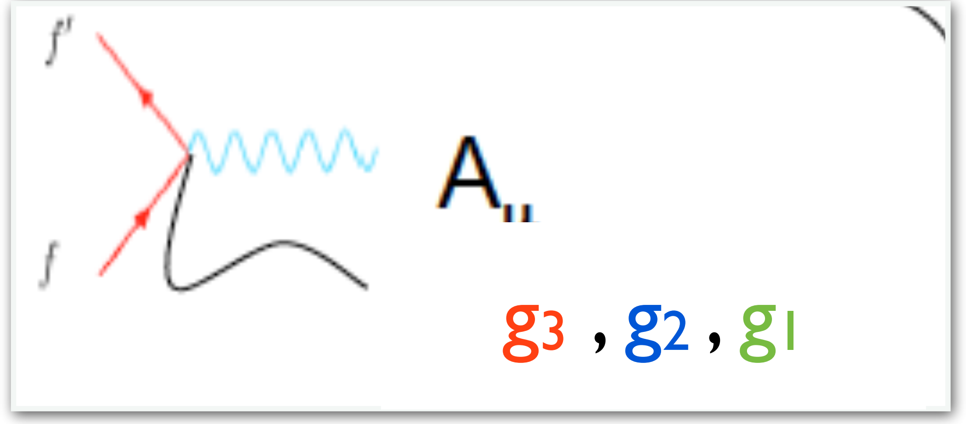
U(3) [3 families!] for each fermionic multiplet, e. g.

$q_i \rightarrow M_{ij} q_j$, $M \in U(3)$



- This Lagrangian has a large flavor symmetry group: $U(3)^5$. Nothing yet distinguishes the three families!

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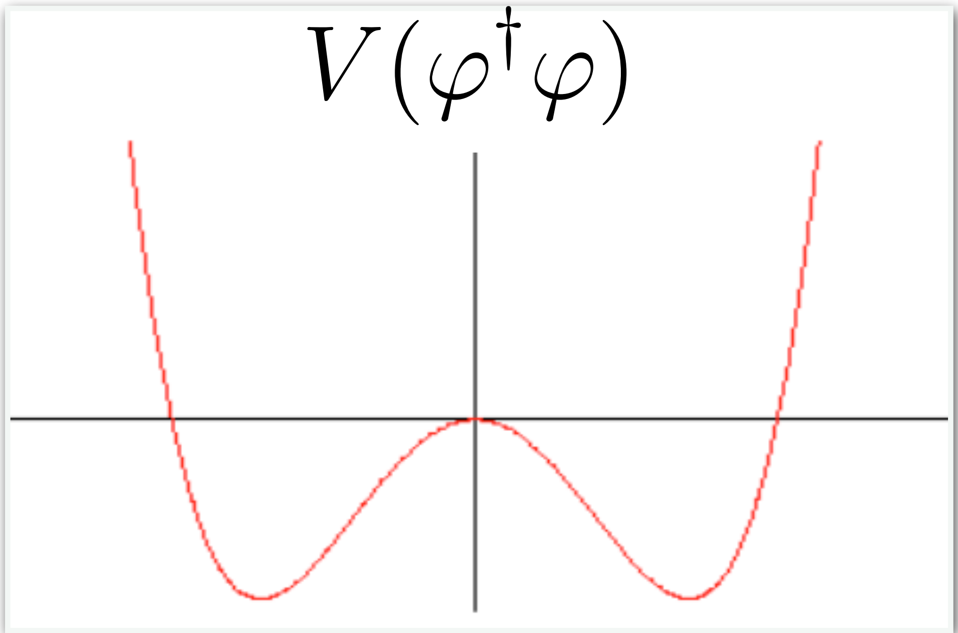
$$\mathcal{L}_{\text{Higgs}} = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \lambda(\varphi^\dagger\varphi - v^2)^2$$



EWSB →

$$\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle\tilde{\varphi}\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\,\varphi^*$$

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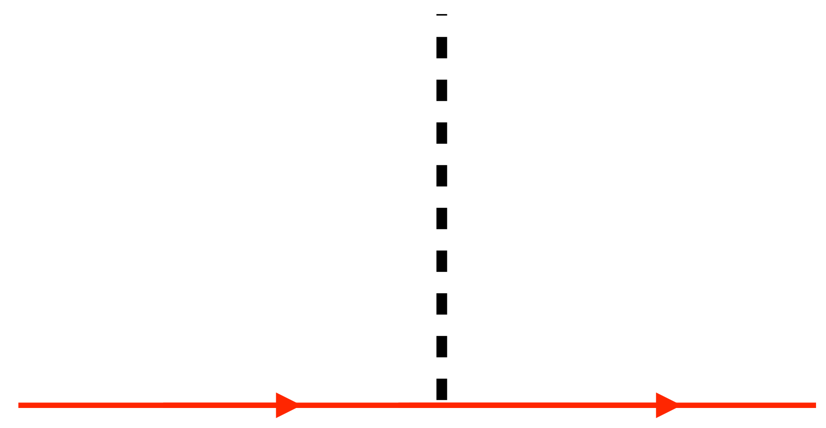

$$\mathcal{L}_{\text{Yukawa}} = \bar{\ell}\, Y_e\, e \varphi \; + \; \bar{q}\, Y_d\, d \varphi \; + \; \bar{q}\, Y_u\, u \tilde{\varphi} \; + \; \text{h.c.}$$

- $Y_{e,u,d}$ (complex) matrices are the only couplings that distinguish the three families

Standard Model symmetries (1)

- Gauge symmetry: color is manifest, SU(2)xU(1) is hidden (Higgs mechanism)

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  - $U(3)^5$ explicitly broken only by Yukawa couplings*
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  - Anomaly: only B-L is conserved

* Approximate surviving global symmetries: chiral $SU(n)_L x SU(n)_R$ (n=2,3) for light quarks ($m_q << \Lambda_{QCD}$), …

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See backup slides

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  - CP (and T) violated by CKM and QCD theta term: specific pattern of CPV in flavor transitions and EDMs

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See lecture 3 (and backup slides)

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Standard Model symmetries (2)

- Global symmetries such as B and $L_{\alpha=e,\mu,\tau}$ are *not an input* in the construction of the model, rather an *outcome* that depends on the field content and the fact that we included only operators up to dimension 4

- Weinberg called these "accidental symmetries"

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Accidental symmetries and symmetries broken in a very specific way in the SM (flavor, CP) offer great opportunity to probe physics beyond the SM

The Standard Model EFT (SMEFT)

Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} \; + \; \frac{C^{(5)}}{\Lambda} \, O^{(5)} \; + \sum_i \, \frac{C_i^{(6)}}{\Lambda^2} \, O_i^{(6)} \; + \; \ldots$$

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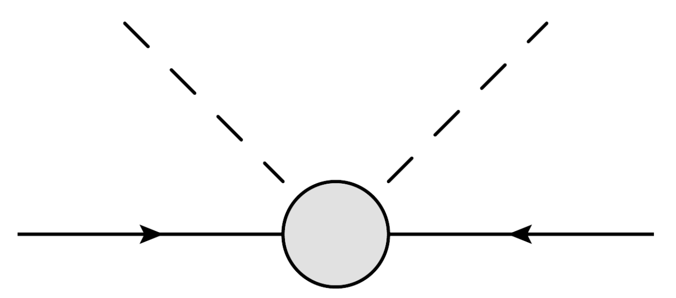
- Dim 5: only one operator

Weinberg 1979

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \ \varphi^T \epsilon \ell$$

$$C = i\gamma_2\gamma_0$$
$$\epsilon = i\sigma_2$$



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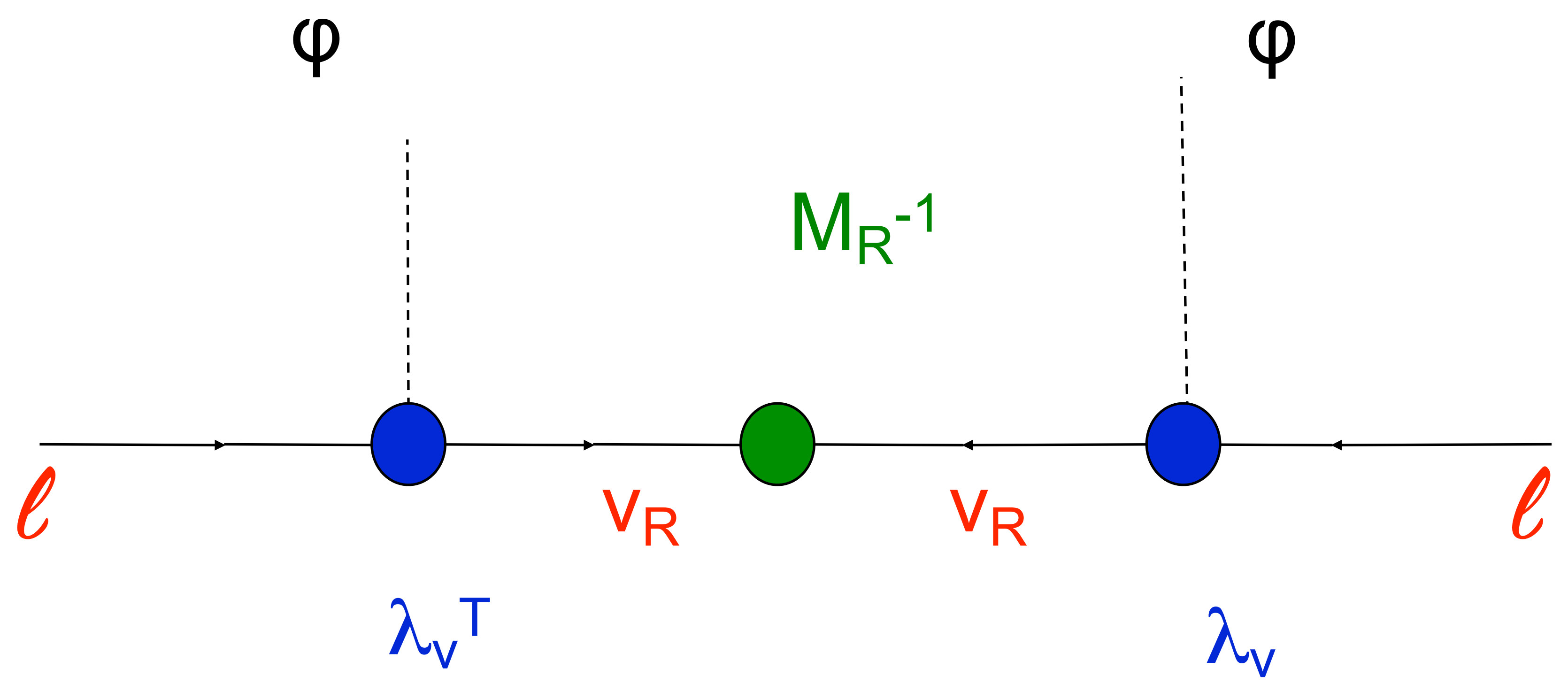
- Violates total lepton number by two units $\quad \ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$

- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\rm dim=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

- "See-saw": $\quad m_\nu \sim 1\,\text{eV} \;\to\; \Lambda \sim 10^{13}\,\text{GeV}$

- Example: explicit realization of dimension-5 operator in models with heavy R-handed Majorana neutrinos



Integrate out heavy ν_R

$g_{\alpha\beta} \sim (\lambda_\nu^T M_R^{-1} \lambda_\nu)_{\alpha\beta}$

$$\mathcal{L}_5 = g_{\alpha\beta}\, \ell_\alpha^T C \epsilon \varphi\, \varphi^T \epsilon \ell_\beta$$

Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

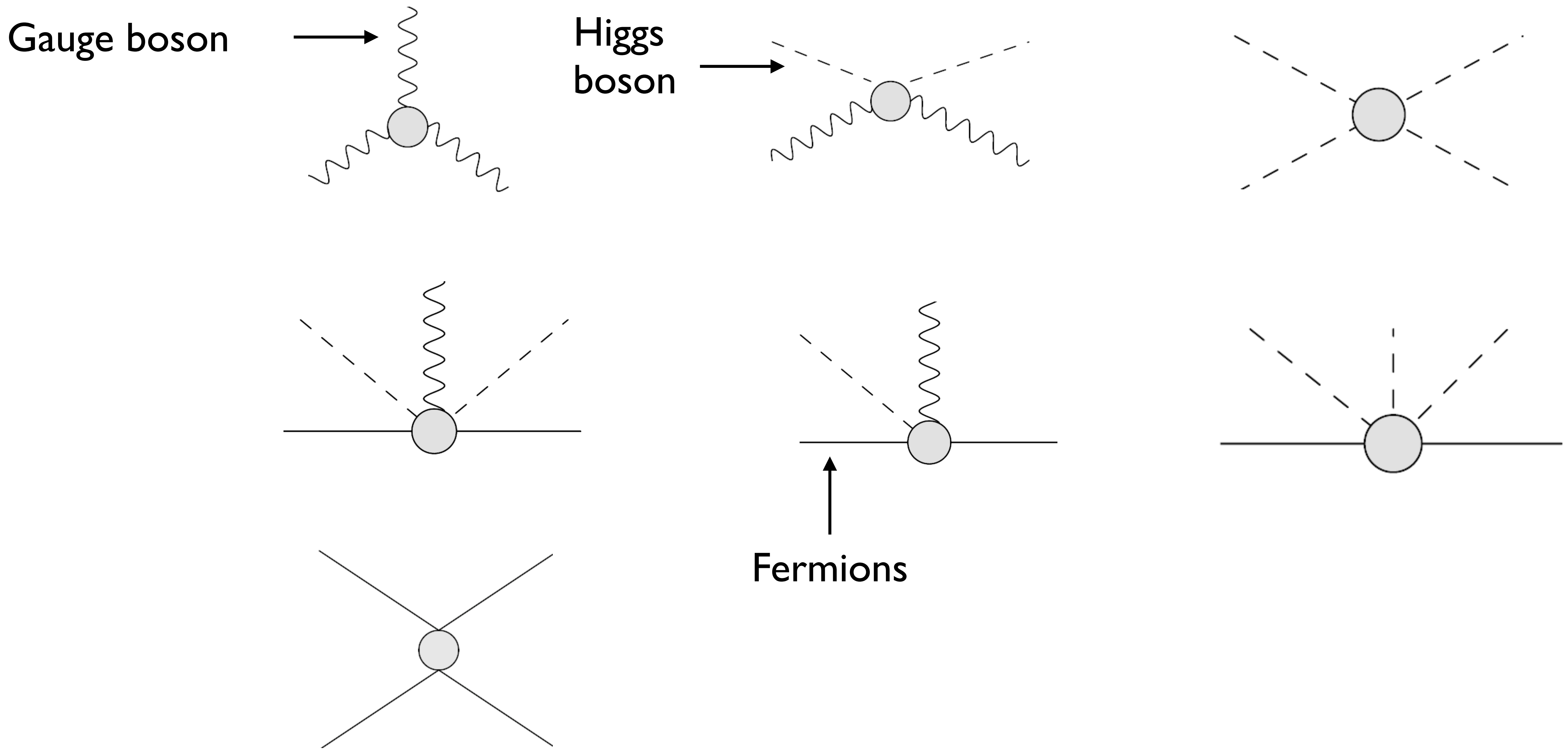
- Dim 6: affect *many* processes (59 structures not including flavor → 2499 if one includes family indices)

Alonso, Jenkins, Manohar, Trott 2013

No fermions

Two fermions

Four fermions



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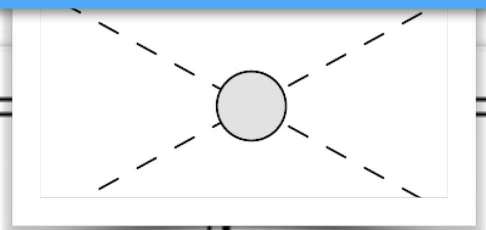
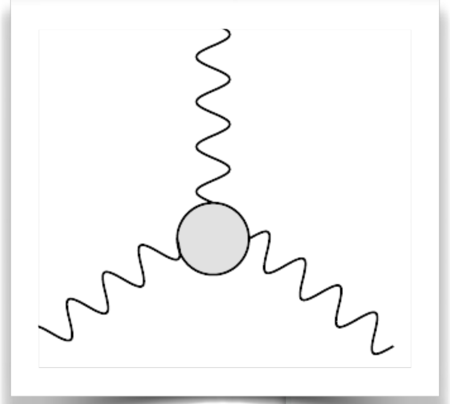
Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010)

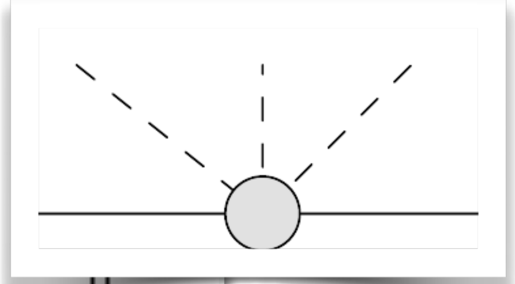
- Dim 6: affect *many* processes
    - B violation (ΔB=ΔL=1)
    - Gauge and Higgs boson couplings [LHC as a precision frontier tool!]
    - CPV, LFV, qFCNC, ...
    - Corrections to g-2, Charged Currents, Neutral Currents, …
- EFT beyond tree-level: one-loop *running of effective couplings* is known

Alonso, Jenkins, Manohar, Trott 2013

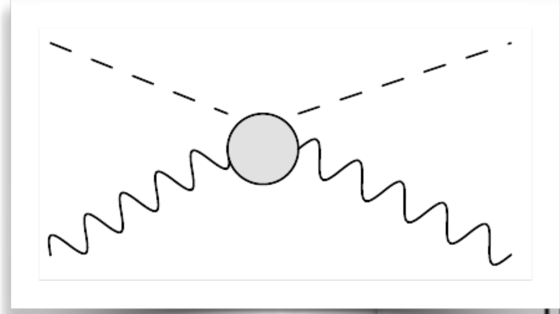
Full dim-6 operator basis (1)

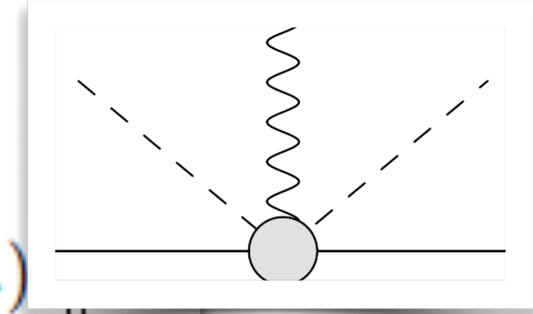




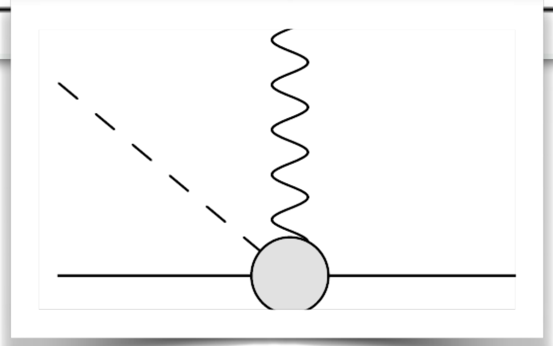


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$





$$\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$



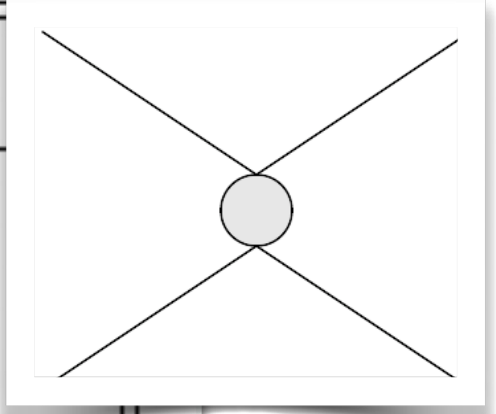
$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010) 1008.4884

Full dim-6 operator basis (2)

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

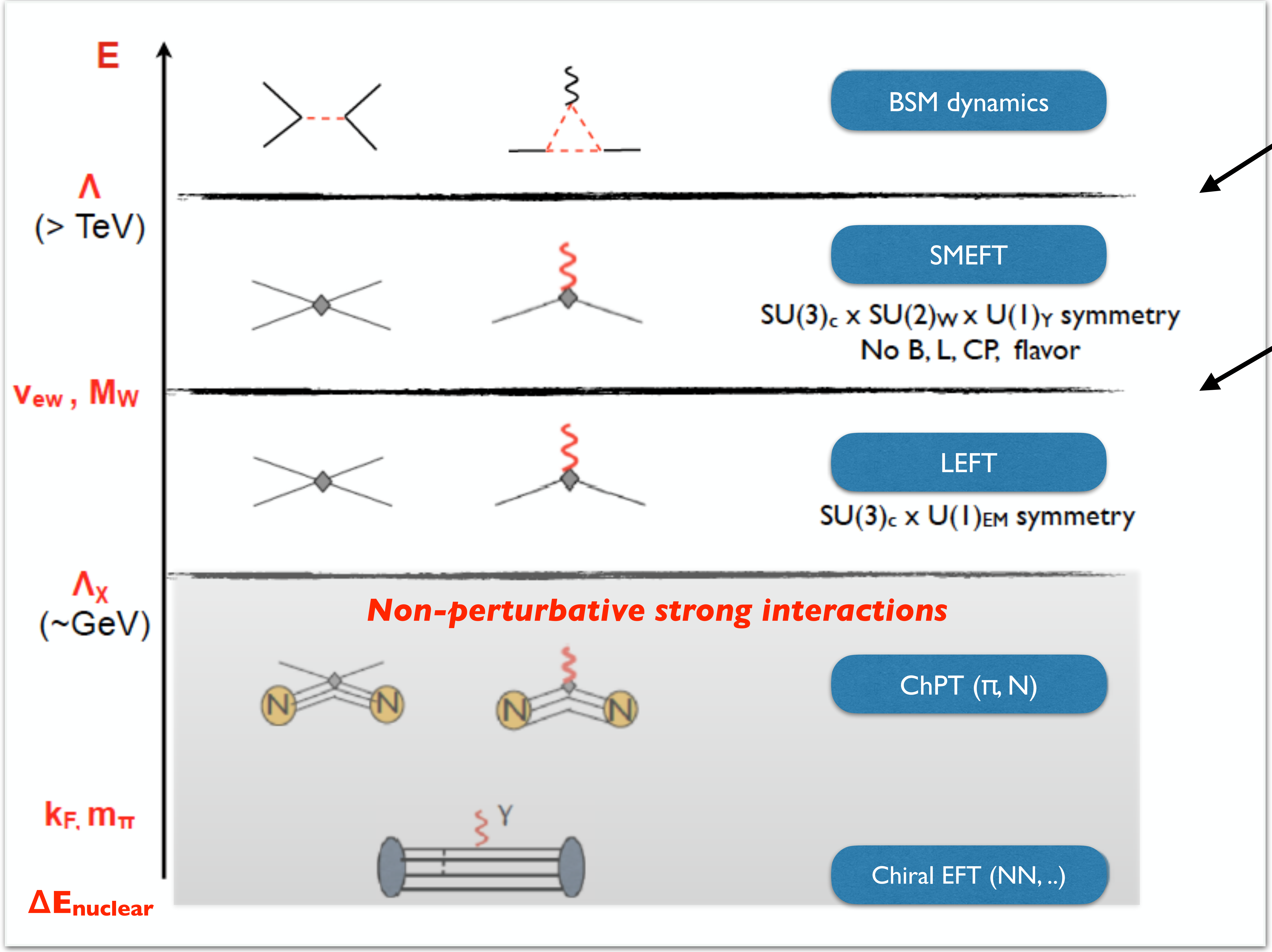


Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010) 1008.4884

What scales are we probing?

To connect UV physics to low-energy processes, use ladder of EFTs

- Use appropriate degrees of freedom in each range of energies
- Write down all interactions consistent with the given symmetries
- At each threshold, need appropriate perturbative and non-perturbative matching conditions: $A_{hi} = A_{low}$
- Expand amplitudes to a given order in m_{low}/m_{hi}



Matching with BSM theory

Perturbative matching within SM

Hadronic matrix elements

Nuclear matrix elements

What scales are we probing?

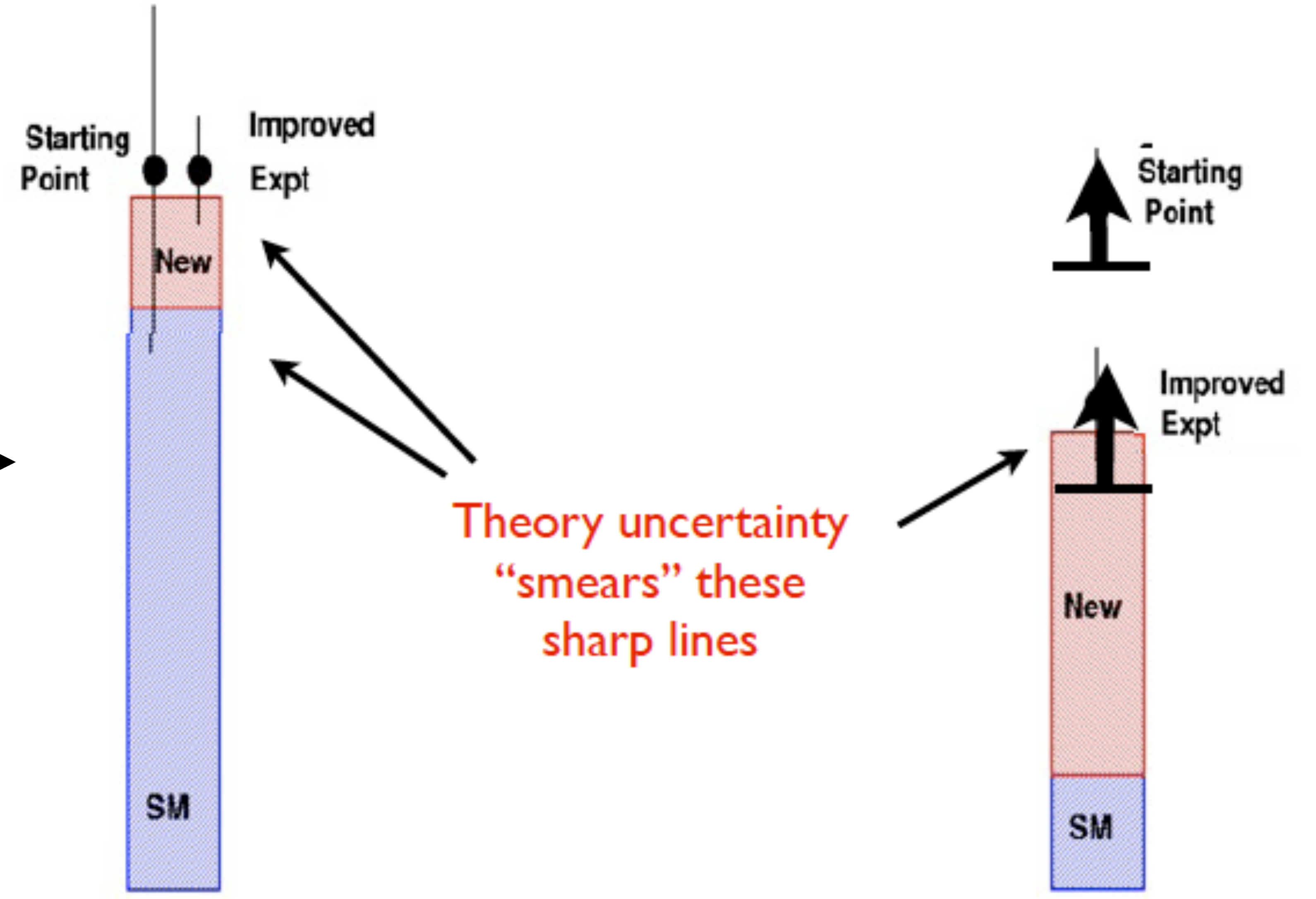
- Effective scale probed by an experiment can be obtained through this equation:

Contribution to observable 'O' induced by SMEFT operators →

$$\delta O_{\rm BSM}(\Lambda) \lesssim (O_{\rm exp} - O_{\rm SM})$$

(for any observable O, $\delta O_{\rm BSM} \sim (v/\Lambda)^n \quad n=2,4,..$)

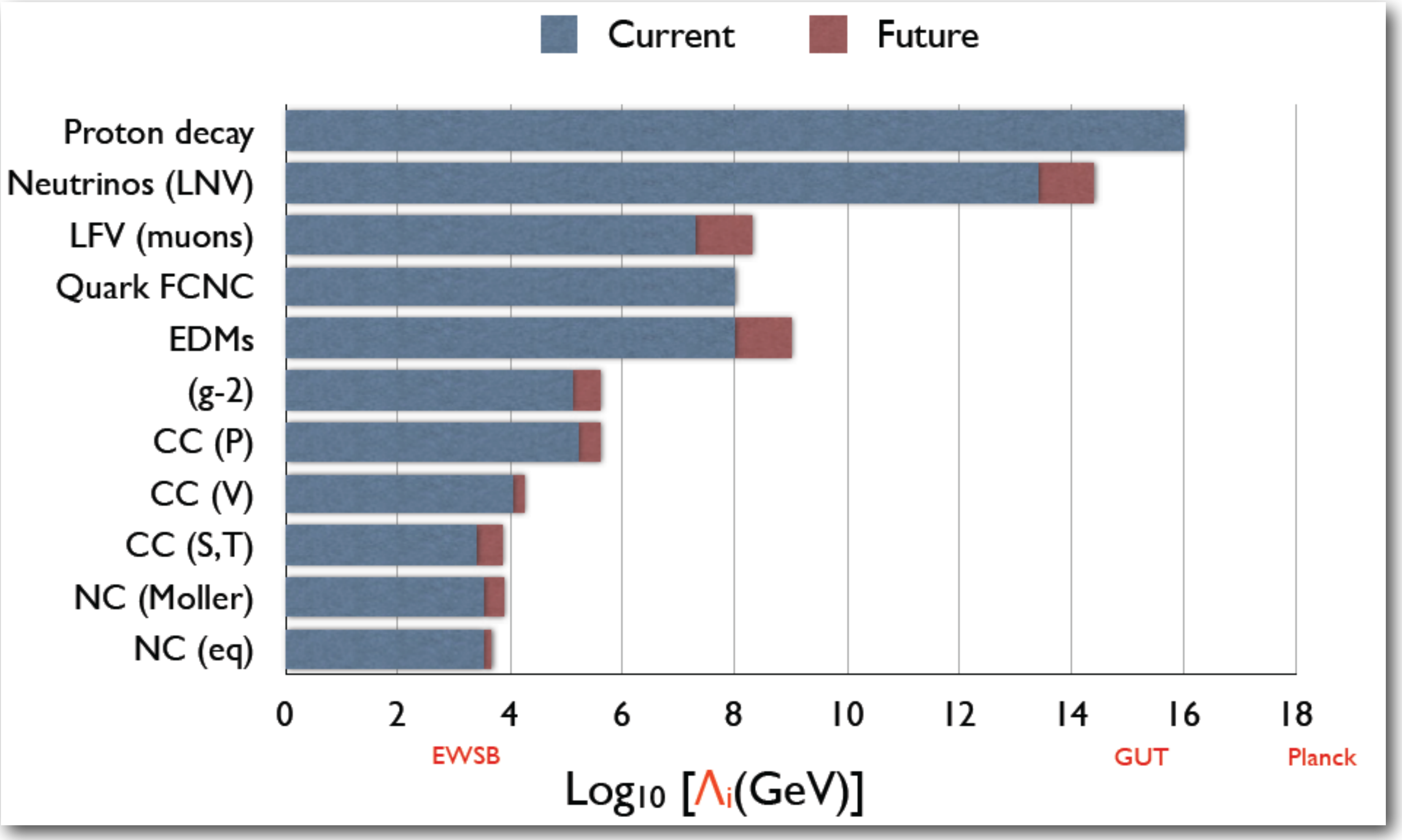
Precision tests: need high-precision theory and experiment →



← Rare / forbidden processes. Sensitive experiments & theory to gauge the 'reach'

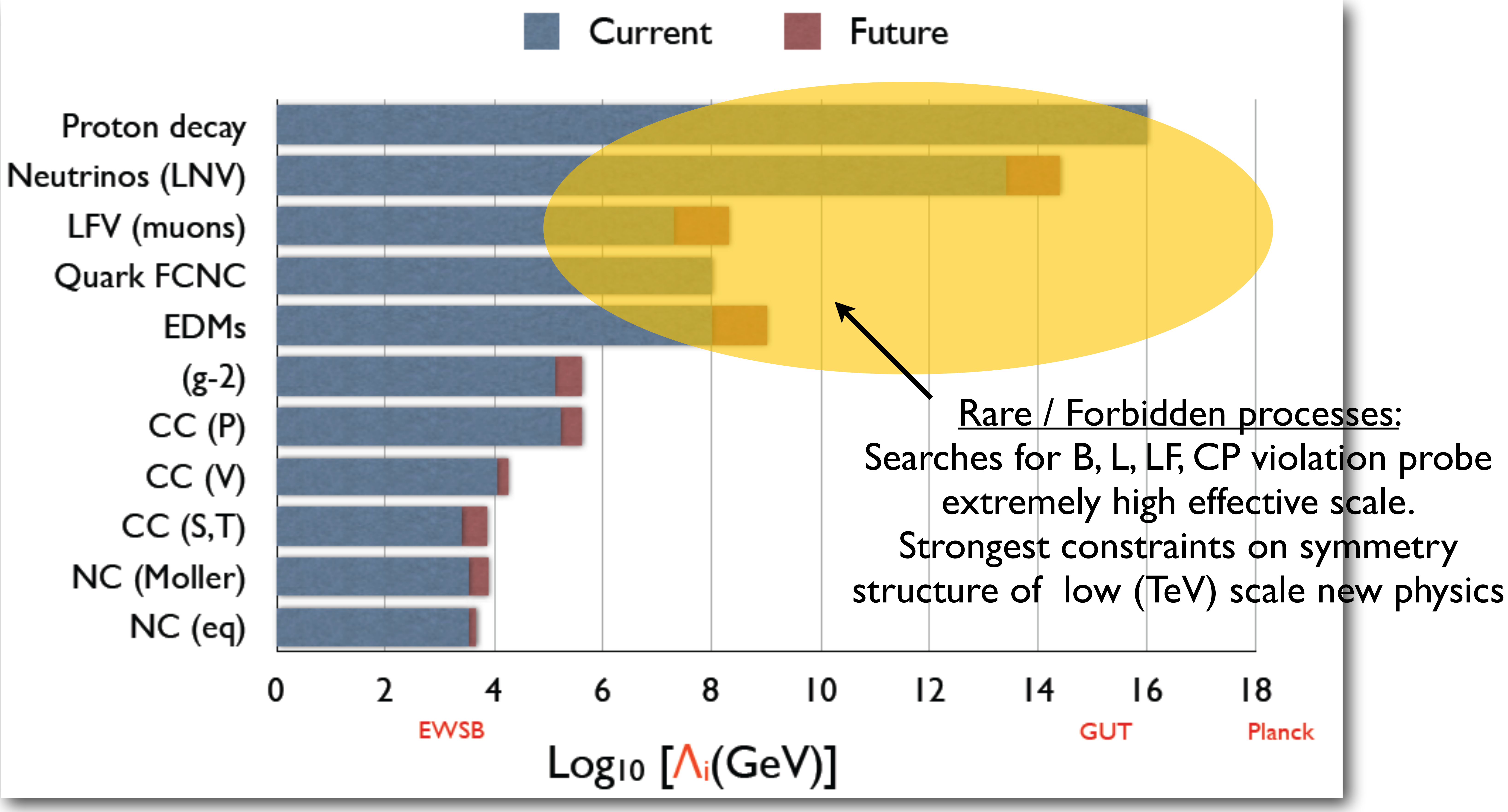
Figure copyright: David Mack

What scales are we probing?



Λ ~ *maximal* scale probed by a given measurement, obtained by assuming O(1) couplings (for all probes) and one-loop factor for g-2, EDMs, LFV, FCNC

What scales are we probing?



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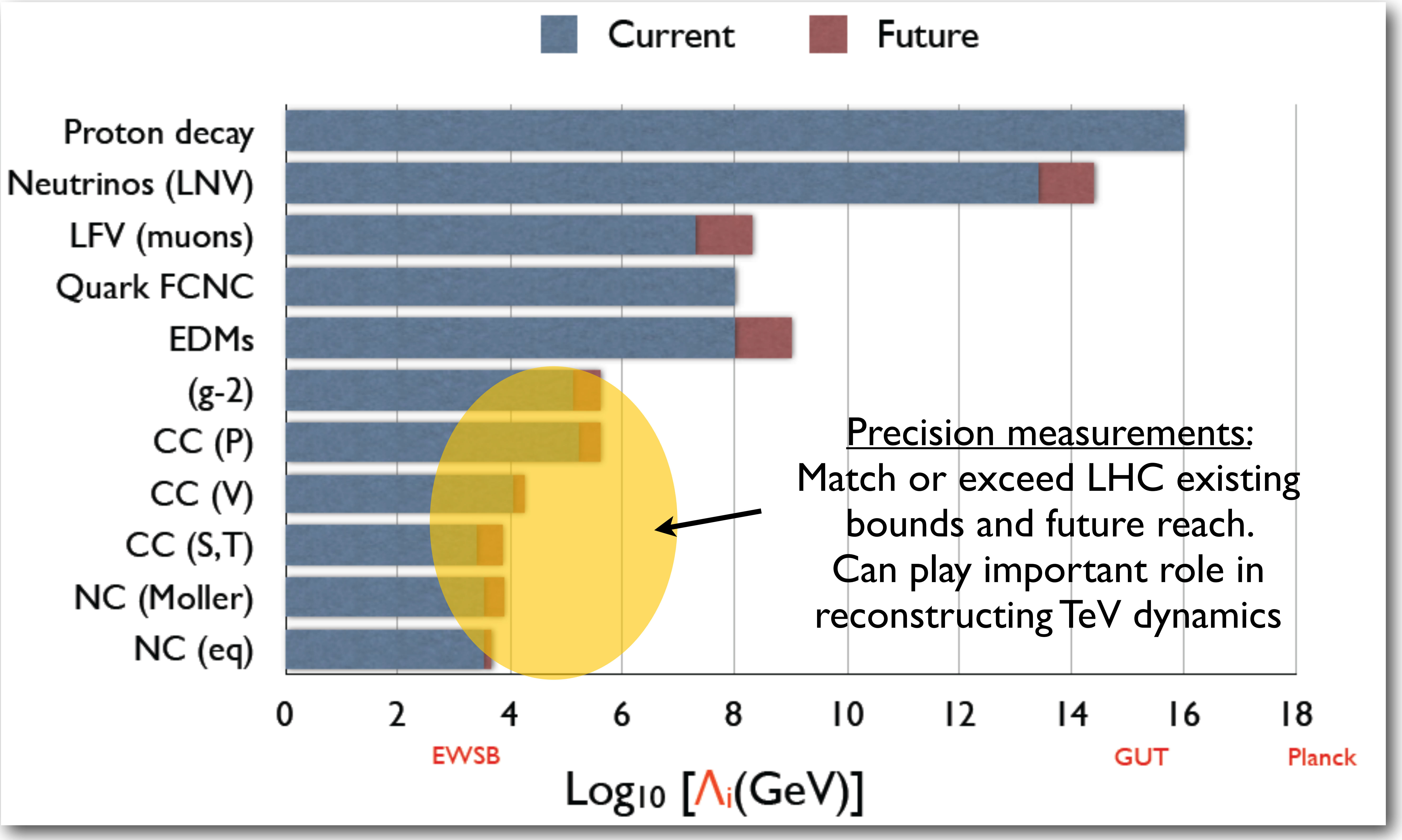
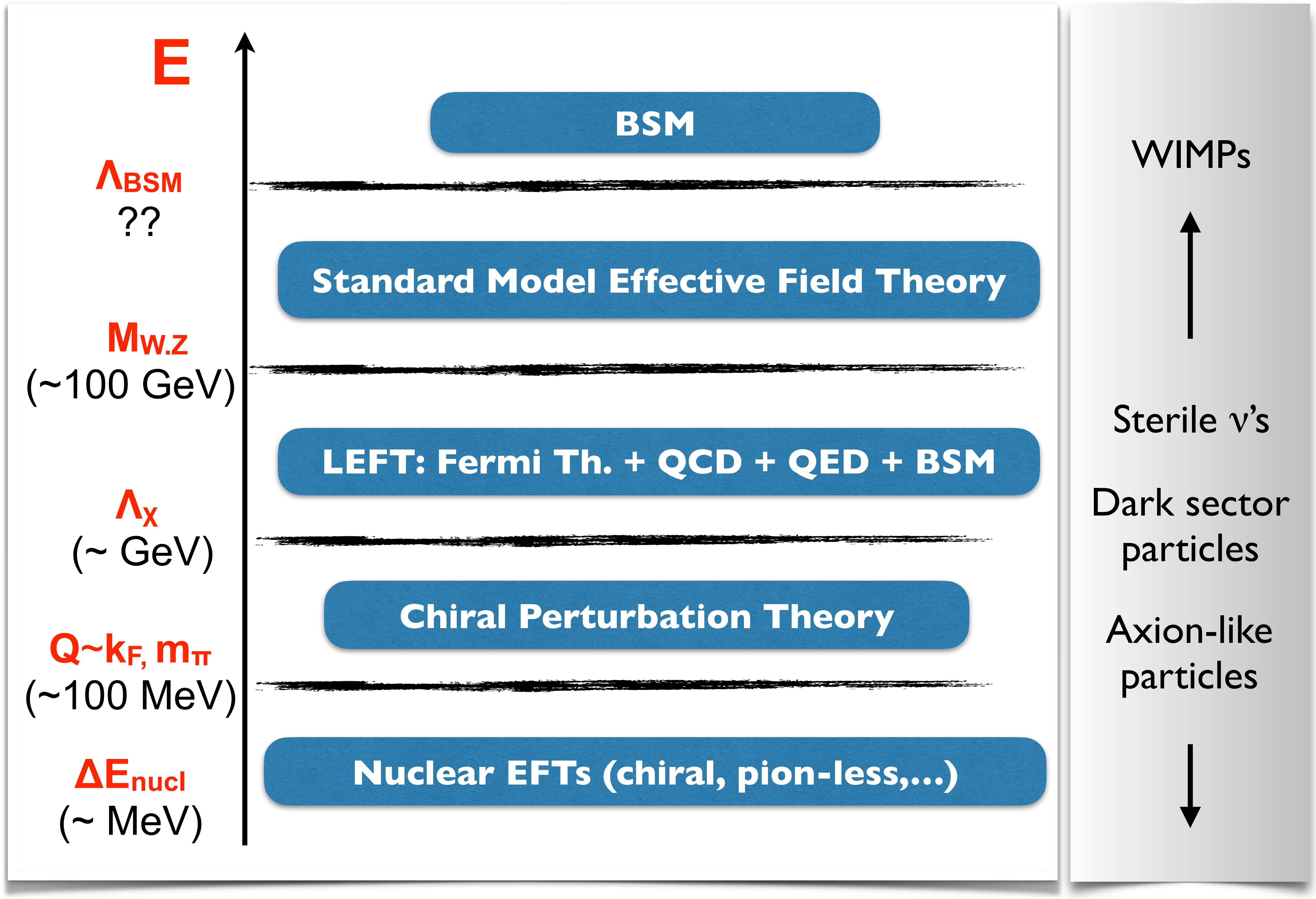
What scales are we probing?



Λ ~ *maximal* scale probed by a given measurement, obtained by assuming O(1) couplings (for all probes) and one-loop factor for g-2, EDMs, LFV, FCNC

Adding new light degrees of freedom

- New light degrees of freedom can be added to the EFT — just need to know their gauge ‘charges’

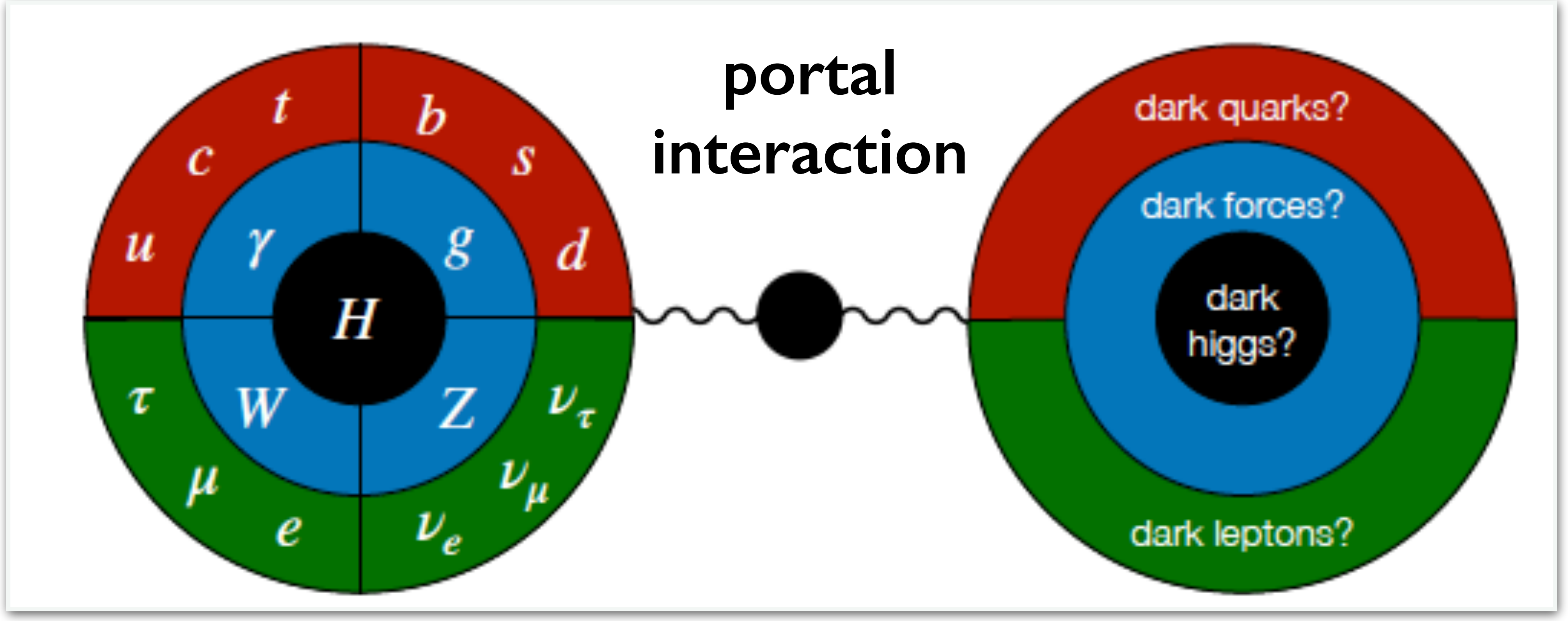


Example:

νSMEFT: SMEFT + ν_R

Light, weakly coupled new physics: portals

"Portals": dominant interactions through which the SM and dark sector couple
($\leftrightarrow$ lowest dimensional SM singlet operators)



Credit: Stefania Gori

$$\mathcal{L} \sim \quad O_{\rm portals} + O\left(\frac{1}{\Lambda}\right)$$

$$O_{\rm Vector} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$$

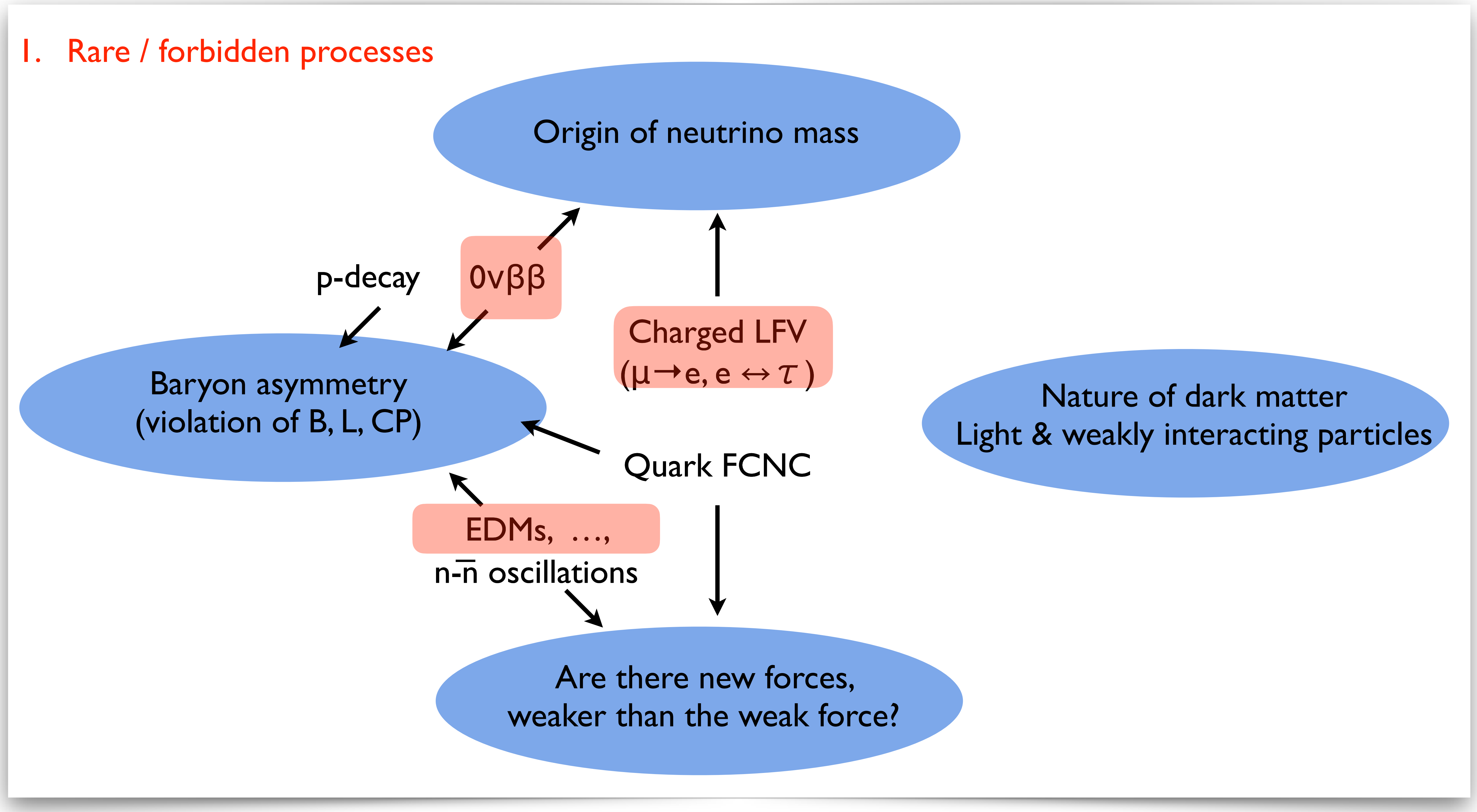
$$O_{\rm Neutrino} = -Y_N^{ij} \bar{L}_i H N_j$$

$$O_{\rm Higgs} = -H^\dagger H \left(A\,S + \lambda\,S^2\right)$$

Leading axion interactions appear at O(1/Λ):

$$aF\tilde{F}/f_a \;, aG\tilde{G}/f_a \;, \bar{\psi}\gamma^\mu\gamma_5\psi\,\partial_\mu a/f_a$$

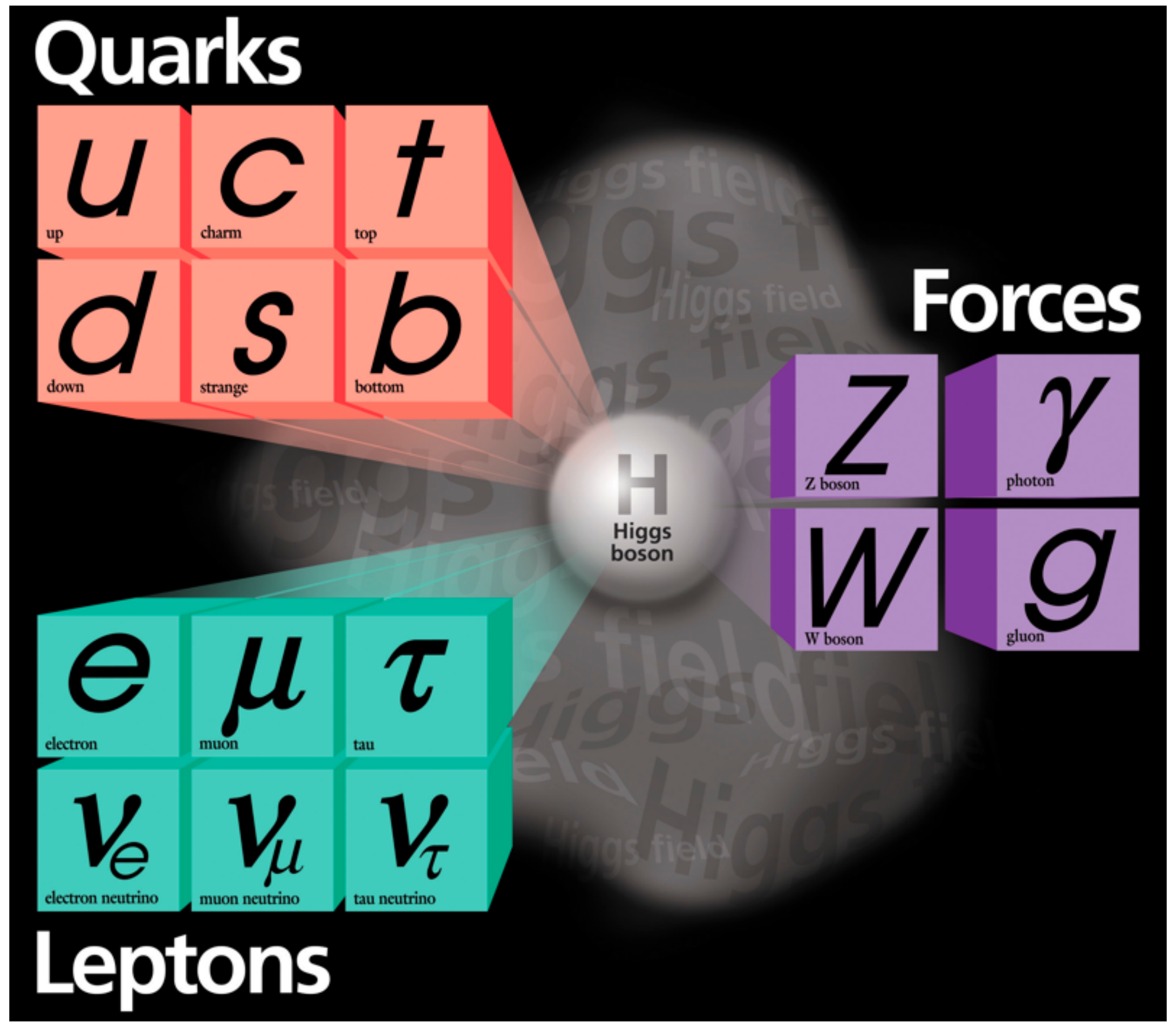
Rare / forbidden processes & symmetry violations



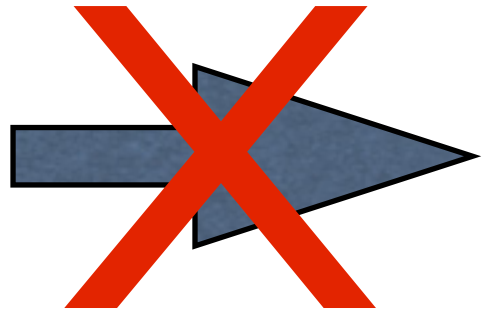
Start by taking a glimpse into the ν world

Neutrinos and the quest for new physics

The Standard Model encodes our knowledge of nature's building blocks and interactions (up to gravity)



Credit: Fermilab



Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

No Neutrino Mass, no Matter (Baryon Asymmetry), no Dark Matter, no Dark Energy

Need new physics

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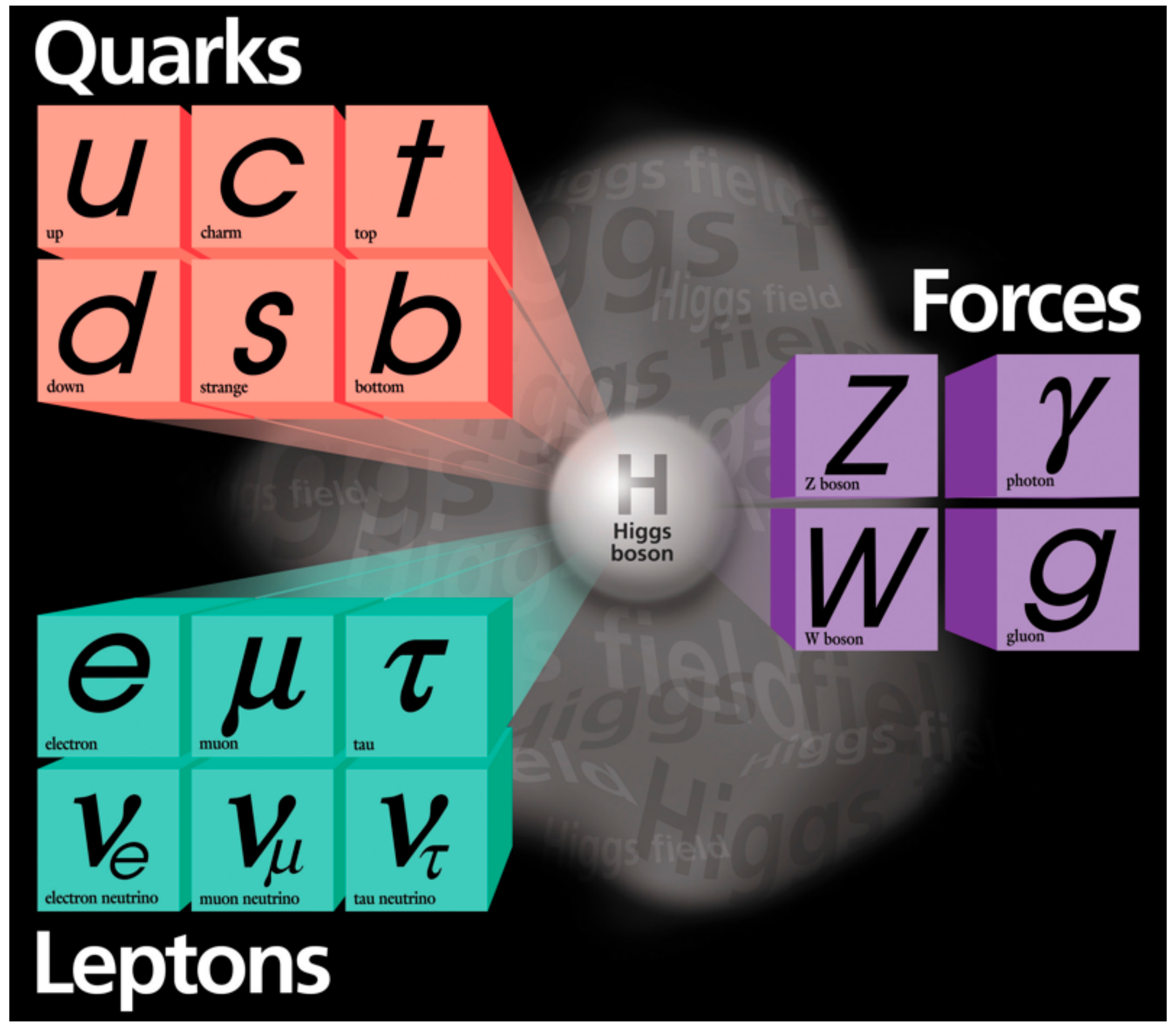

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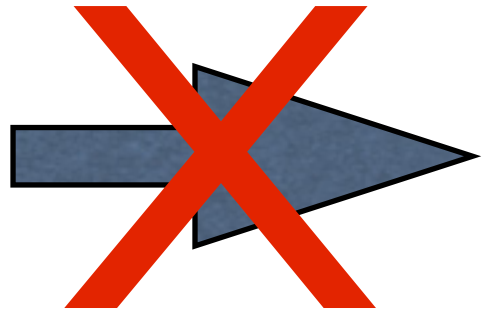


Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

No Neutrino Mass, no Matter (Baryon Asymmetry), no Dark Matter, no Dark Energy

Need ν physics?

Understanding the elusive neutrino can shed light on other mysteries

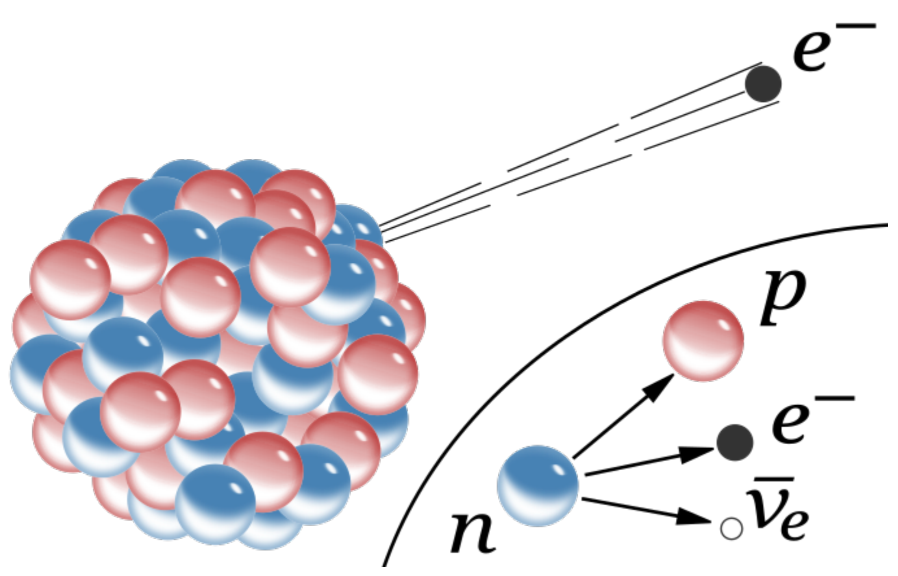
A glimpse into the ν world

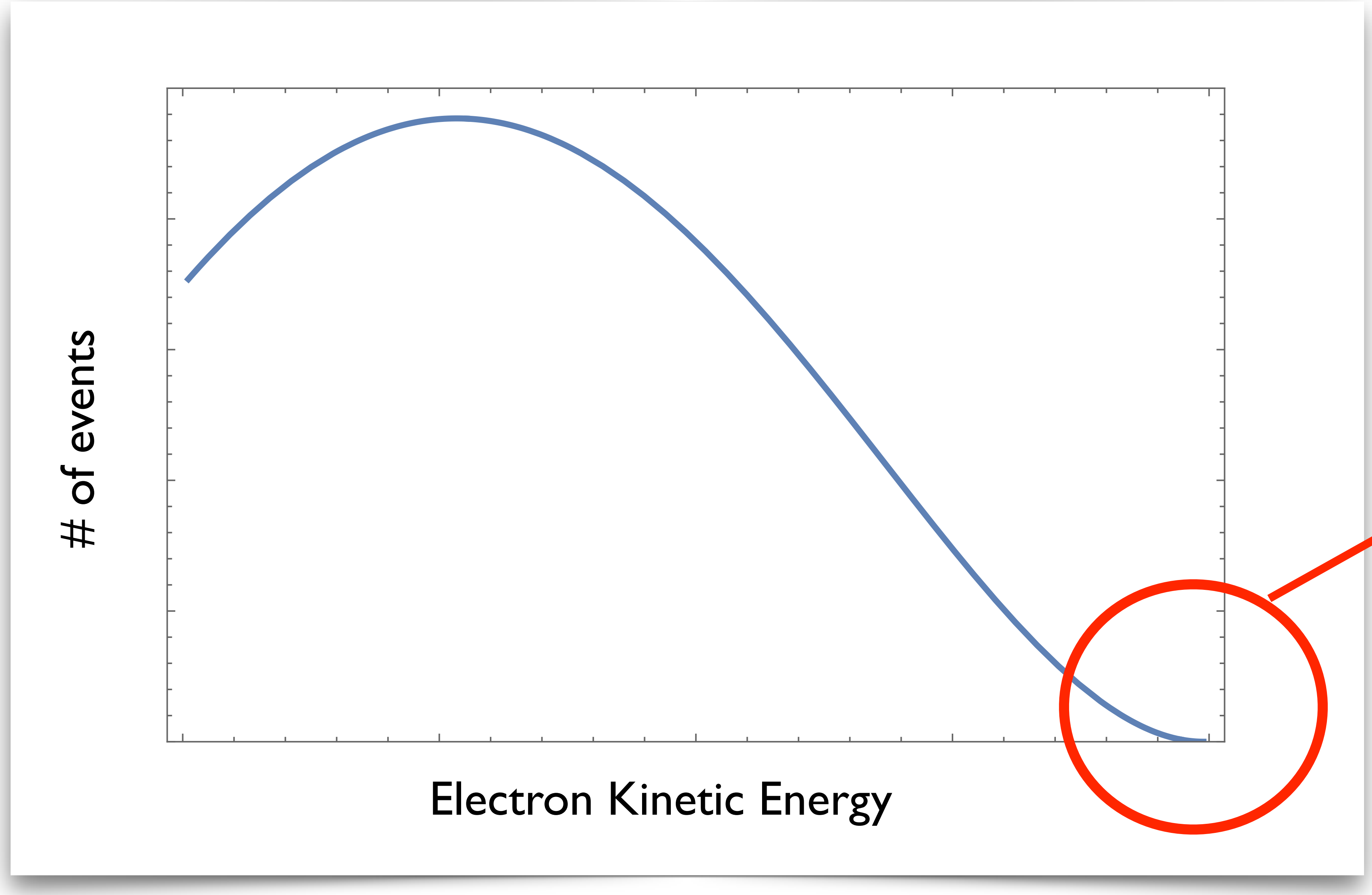
- Neutrino basics
- Neutrino mass and symmetry
- Lepton Number Violation and $0\nu\beta\beta$ decay

Neutrino basics

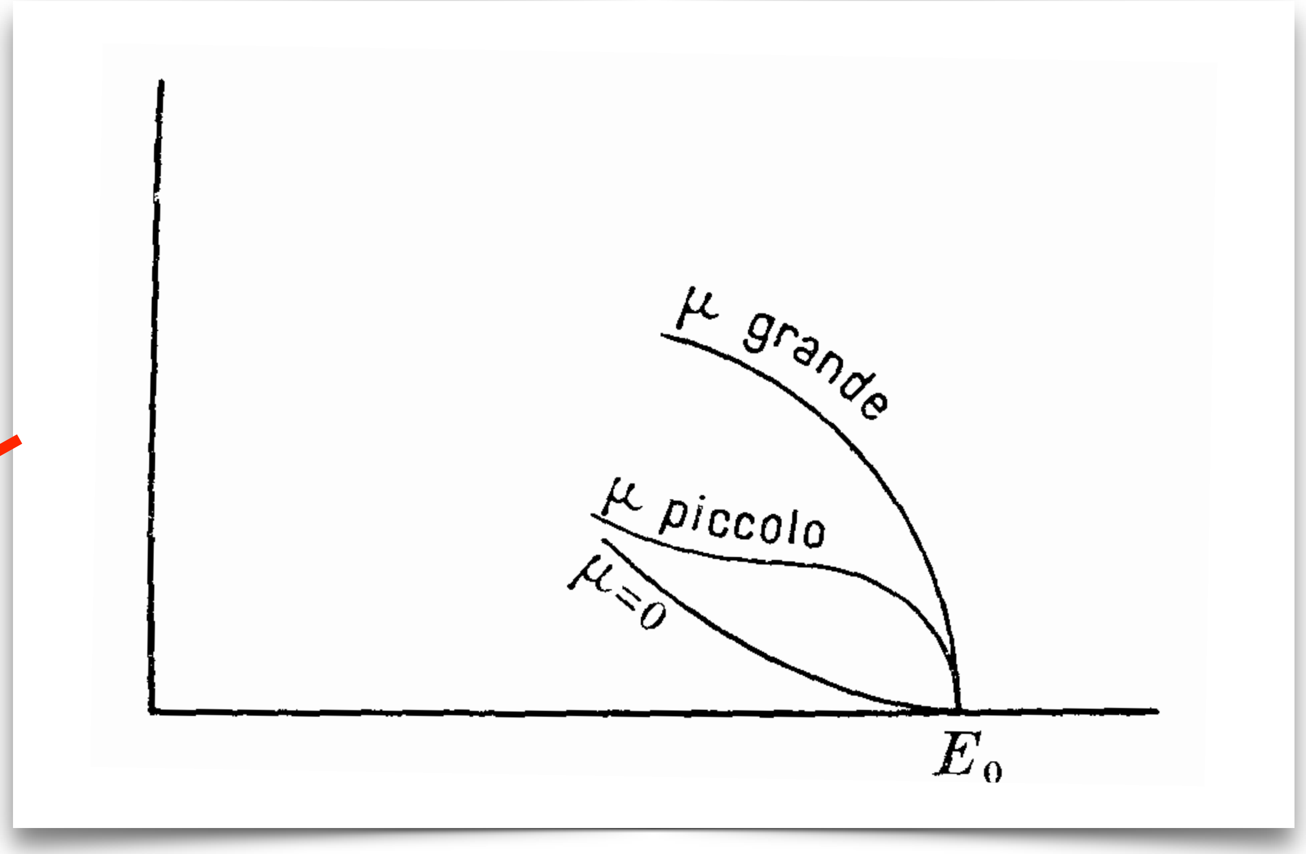
Elusive particles

- Pauli (1930): neutrinos enter the scene as 'ghost particles' needed to save energy conservation in β decays





Fermi 1934

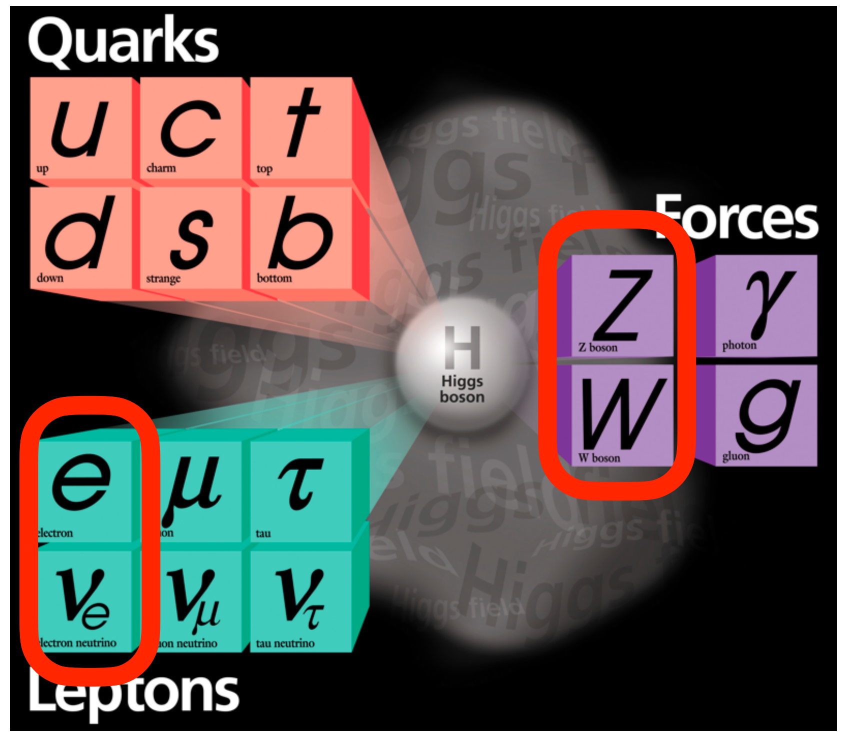


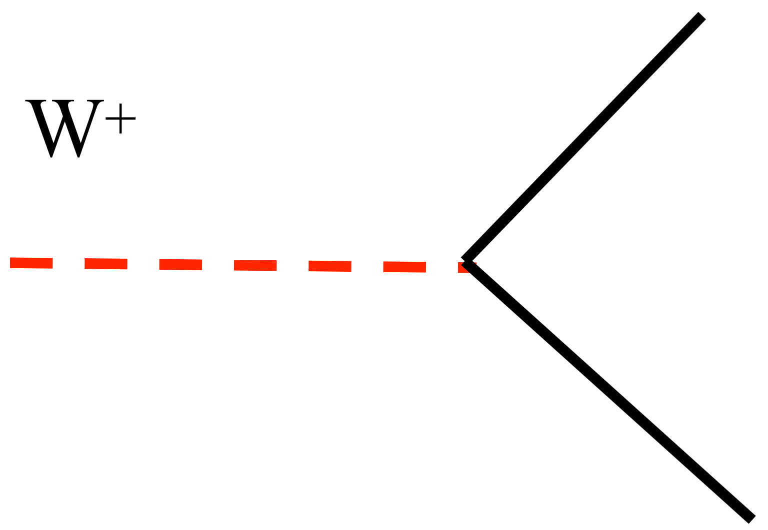
Fermi (1934) developed the theory of weak interactions and computed the β spectrum, concluding that
"The neutrino mass is zero or, in any case, small in comparison to the electron mass"

- It took decades to achieve direct detection (Cowan & Raines 1956) and almost a century to show they have (tiny) masses!

Basic neutrino properties

- Interact through gravity and the weak force (weak isospin doublet with charged leptons)





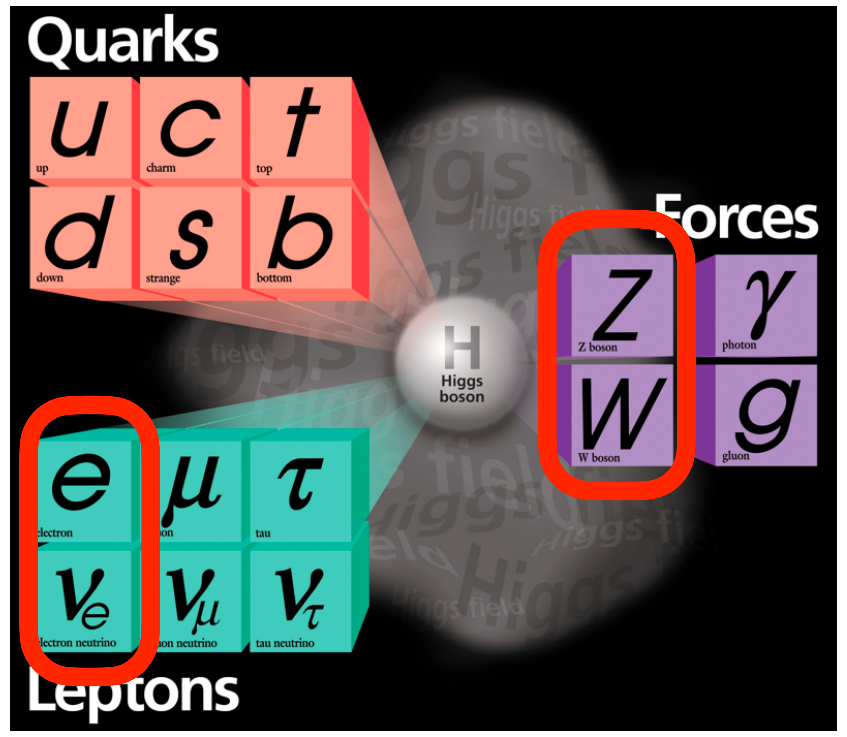
Smallness of low-energy cross sections

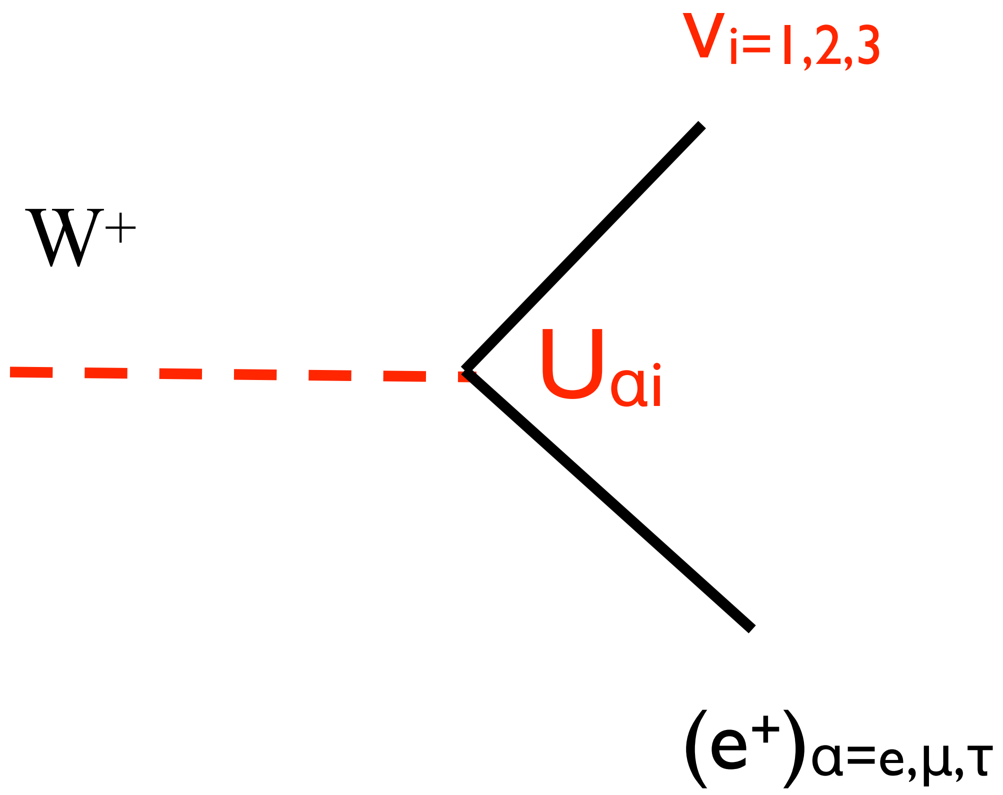
$$\sigma \sim G^2_{\rm Fermi}\, E^2_{CM}$$

$$G_{\rm Fermi} \sim \frac{g^2}{M_W^2} \sim \frac{1}{(250\,{\rm GeV})^2}$$

Basic neutrino properties

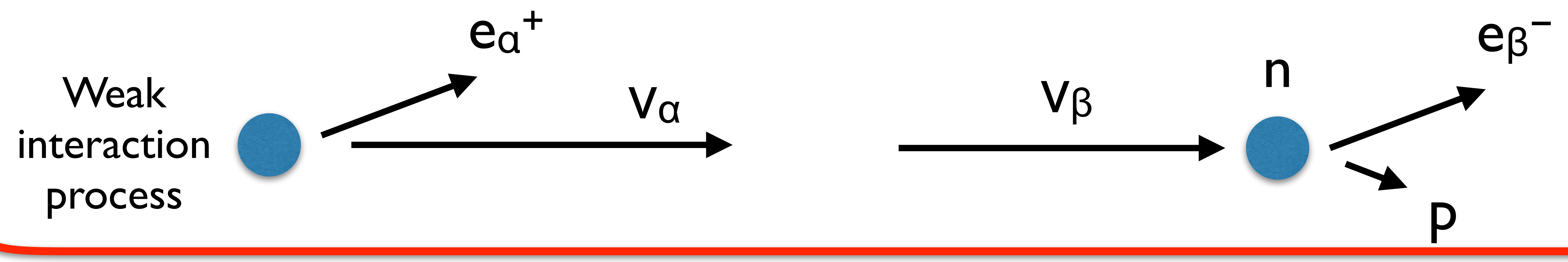
- Interact through gravity and the weak force (weak isospin doublet with charged leptons)
- *Massive* neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor





$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Neutrino (ν_α): emitted with e_α^+, when interacts with matter can produce e_β^-



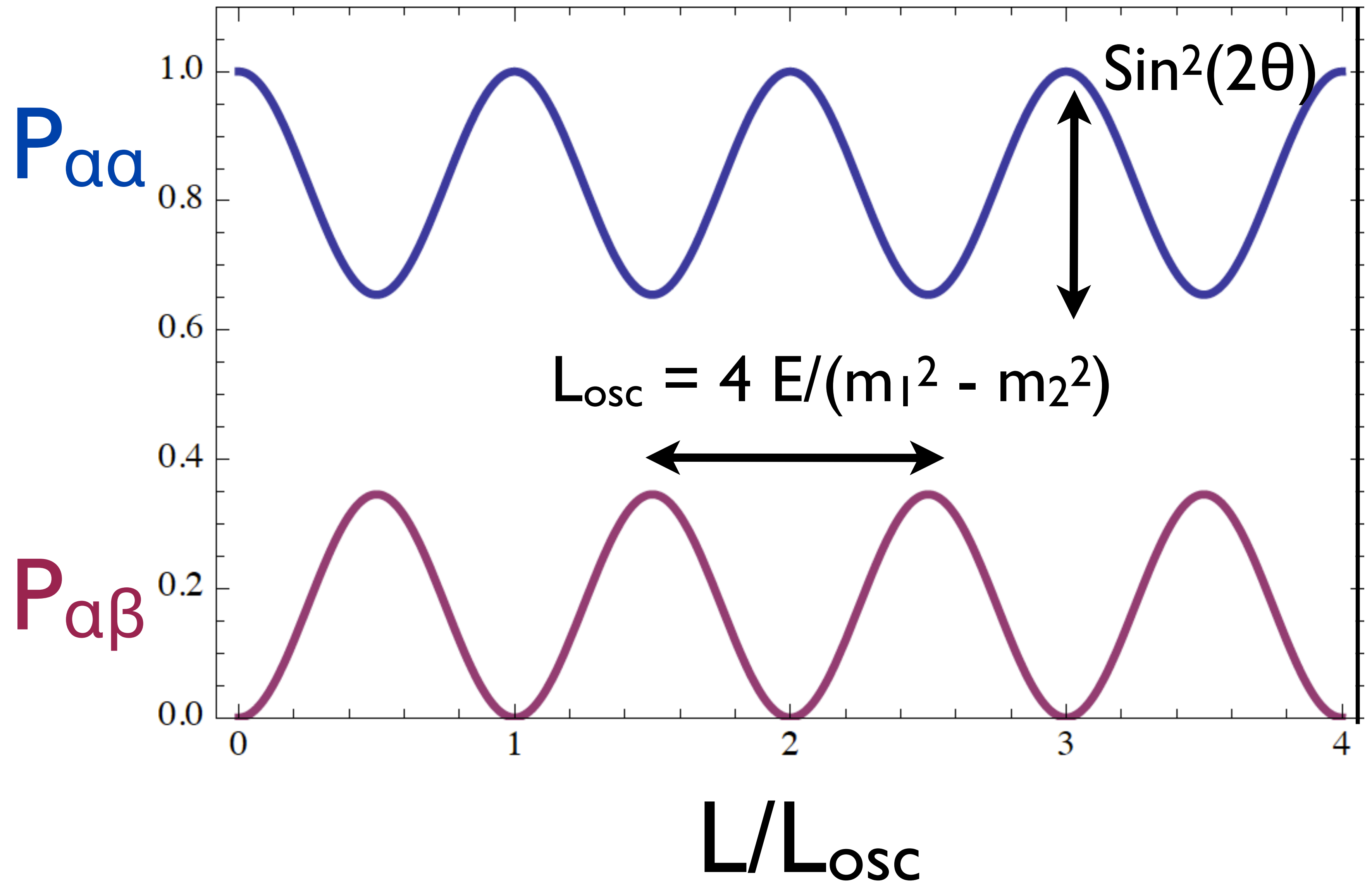
$\alpha, \beta = e, \mu, \tau$

Basic neutrino properties

- Interact through gravity and the weak force

- *Massive* neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

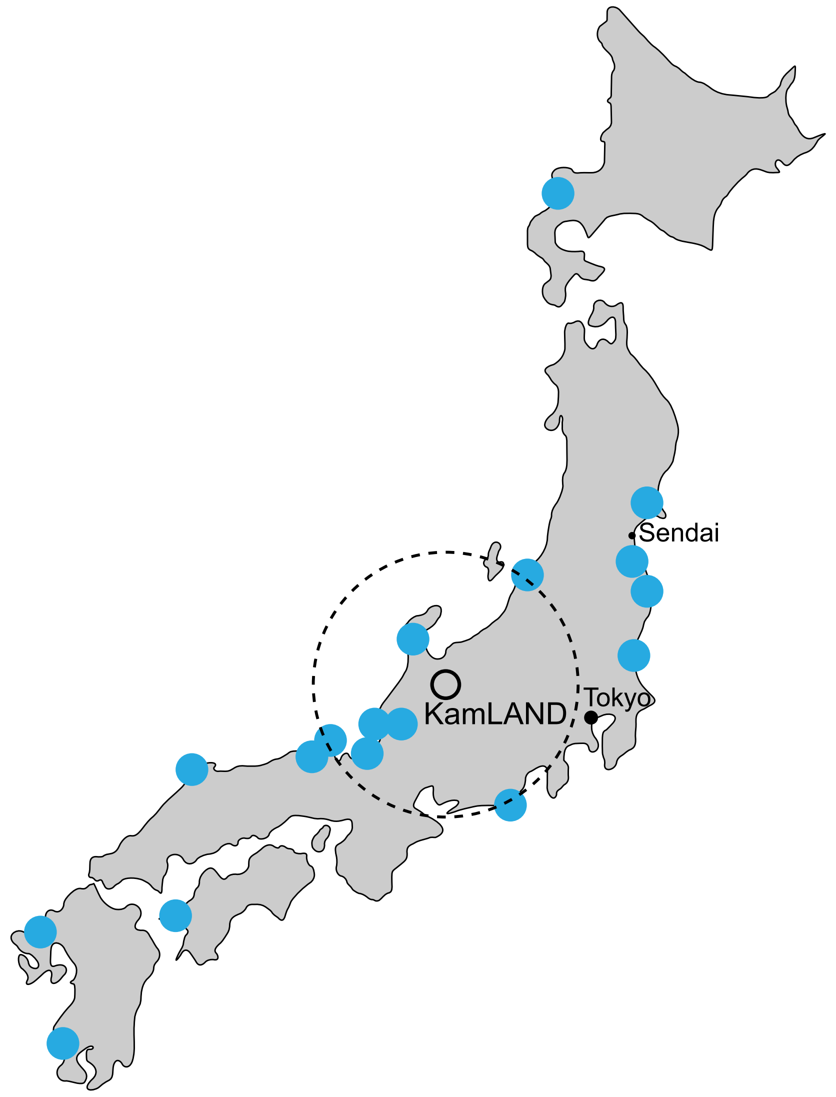


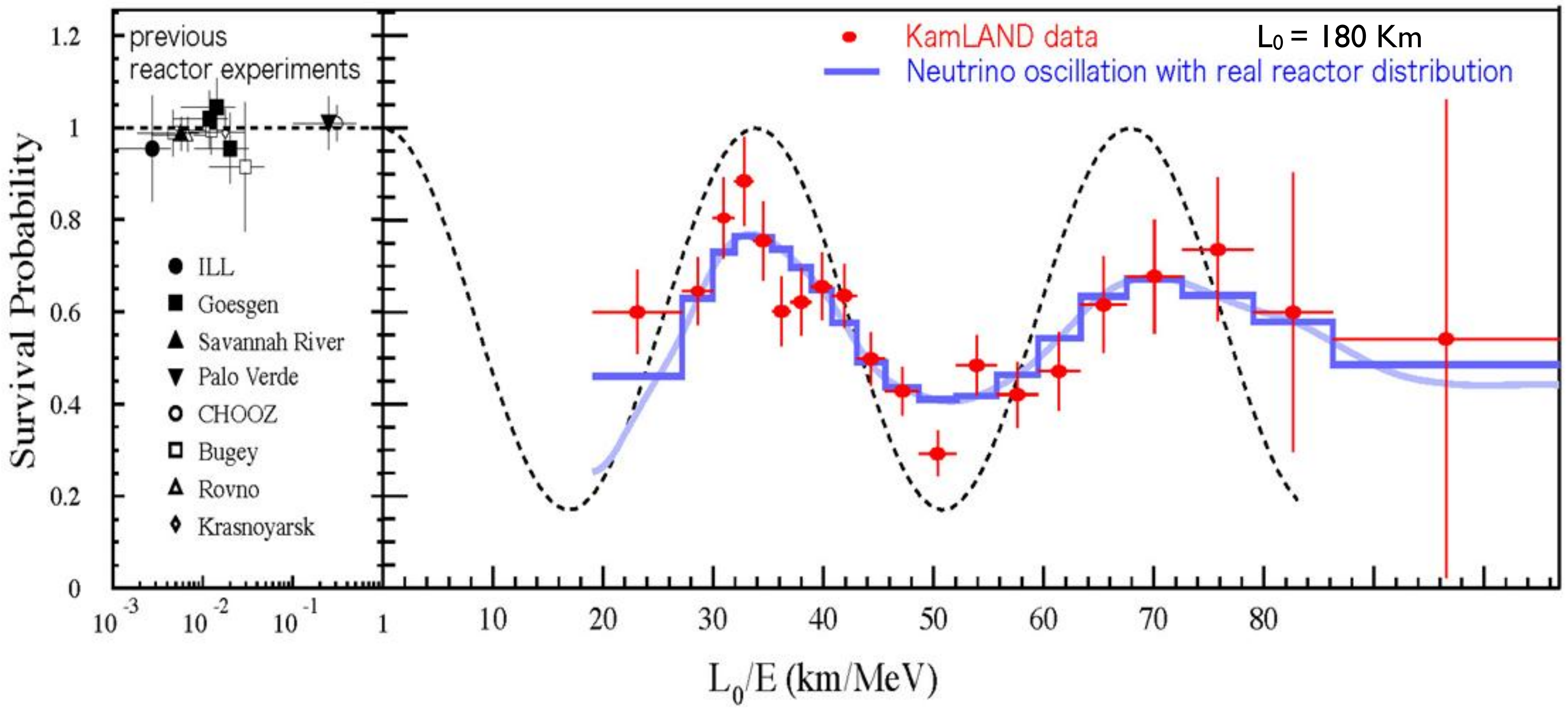
$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Basic neutrino properties

- Interact through gravity and the weak force

- *Massive* neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor

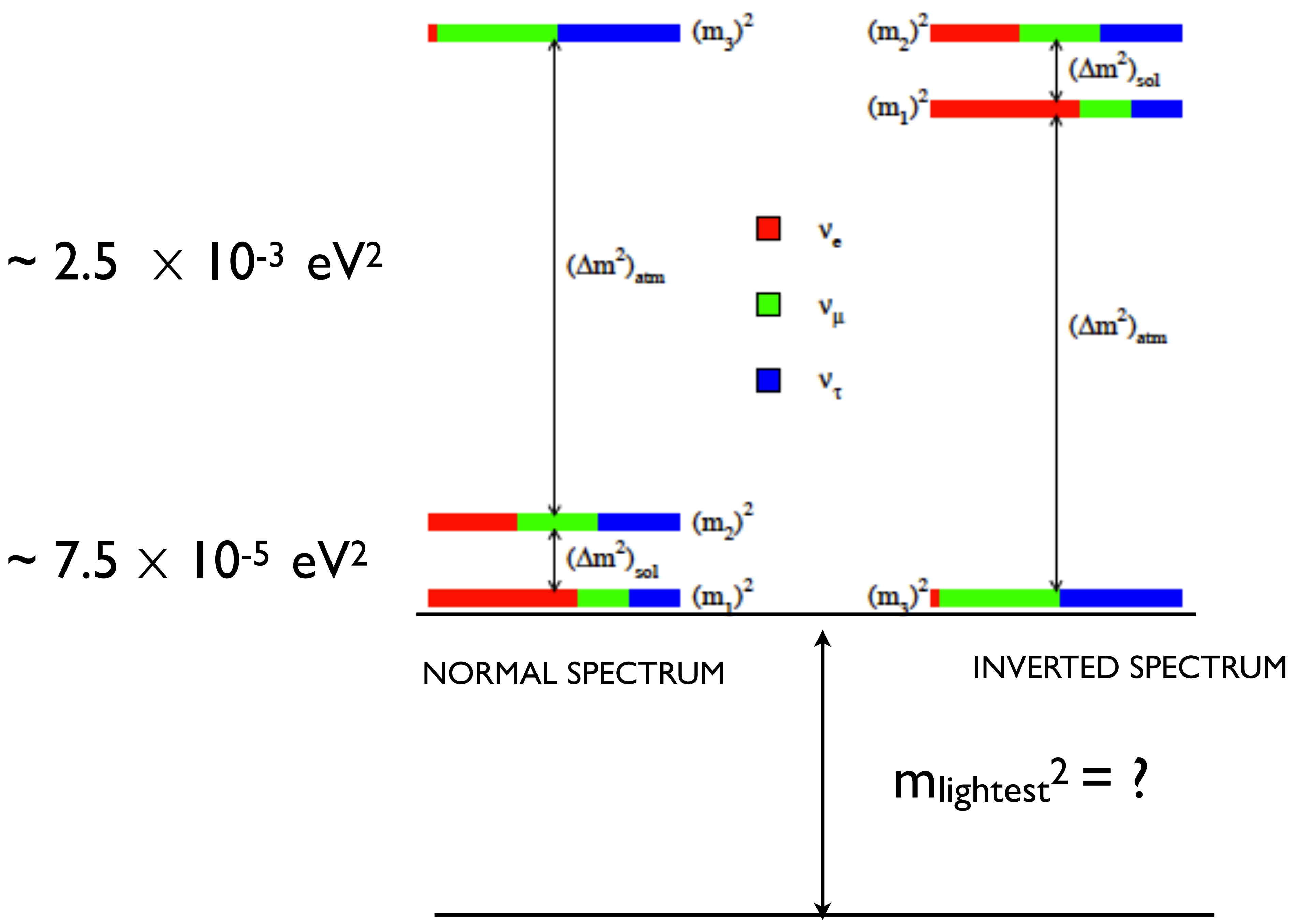




Basic neutrino properties

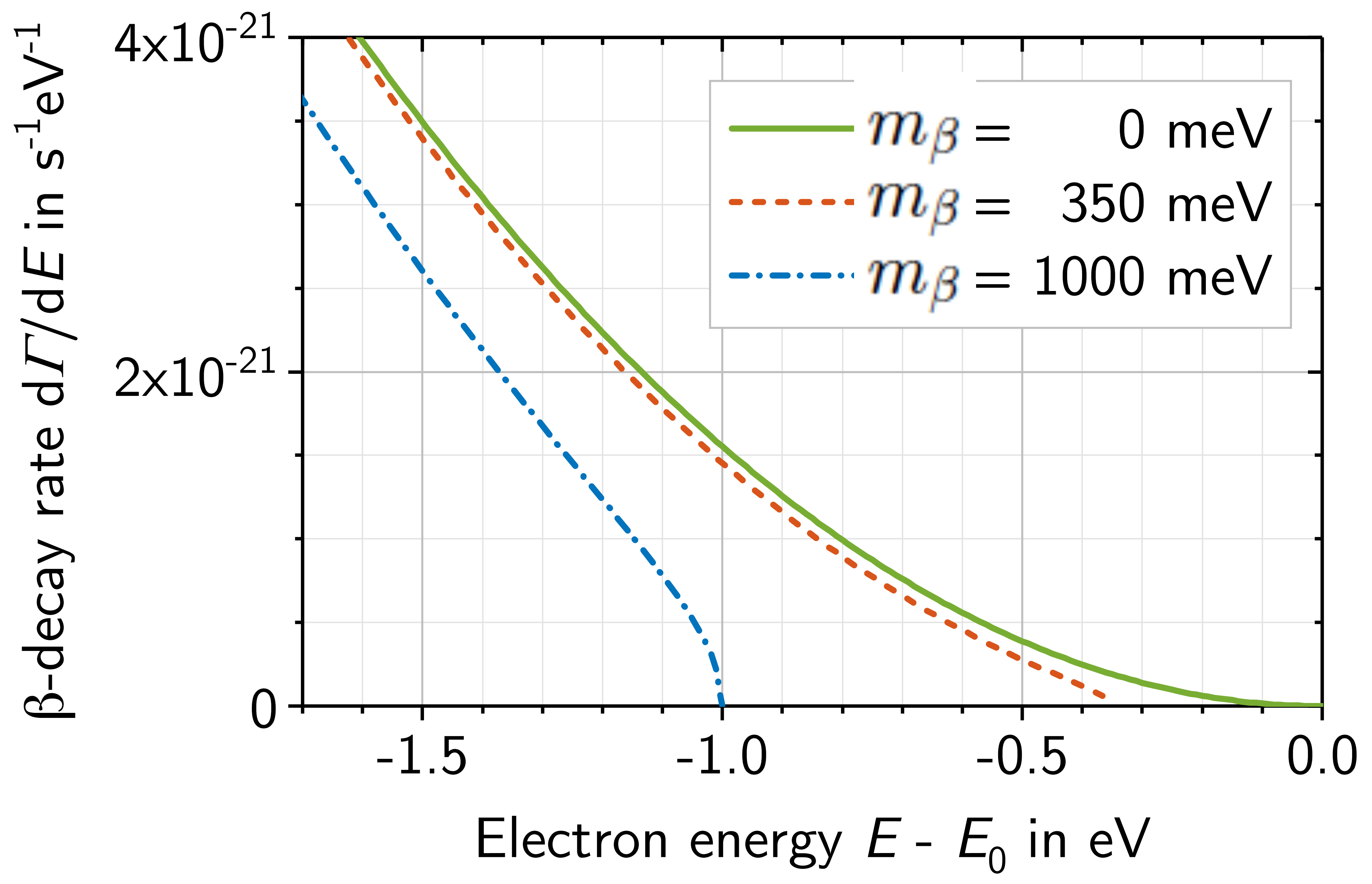
- Interact through gravity and the weak force

- *Massive* neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor



Oscillation data teach us about mass differences and cannot yet determine the spectrum ordering

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

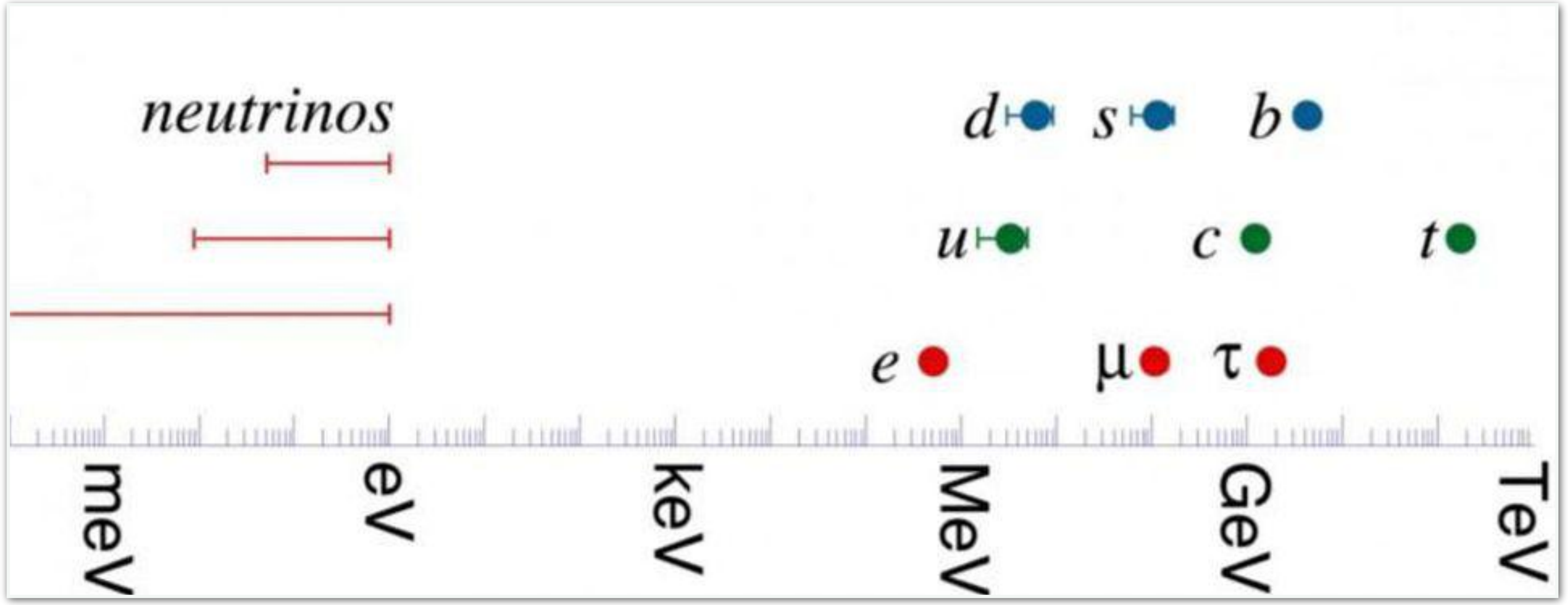


Absolute scale through electron spectrum in Tritium β decay.
KATRIN: m_β < 450 meV (90%CL) → 300 meV
Future: Project-8 aims to reach 40 meV

Basic neutrino properties

- Interact through gravity and the weak force
- *Massive* neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor
- Neutrino masses are tiny compared to other fermion's masses

H. Murayama



So what's the big deal?

Neutrino mass = new physics

The Standard Model

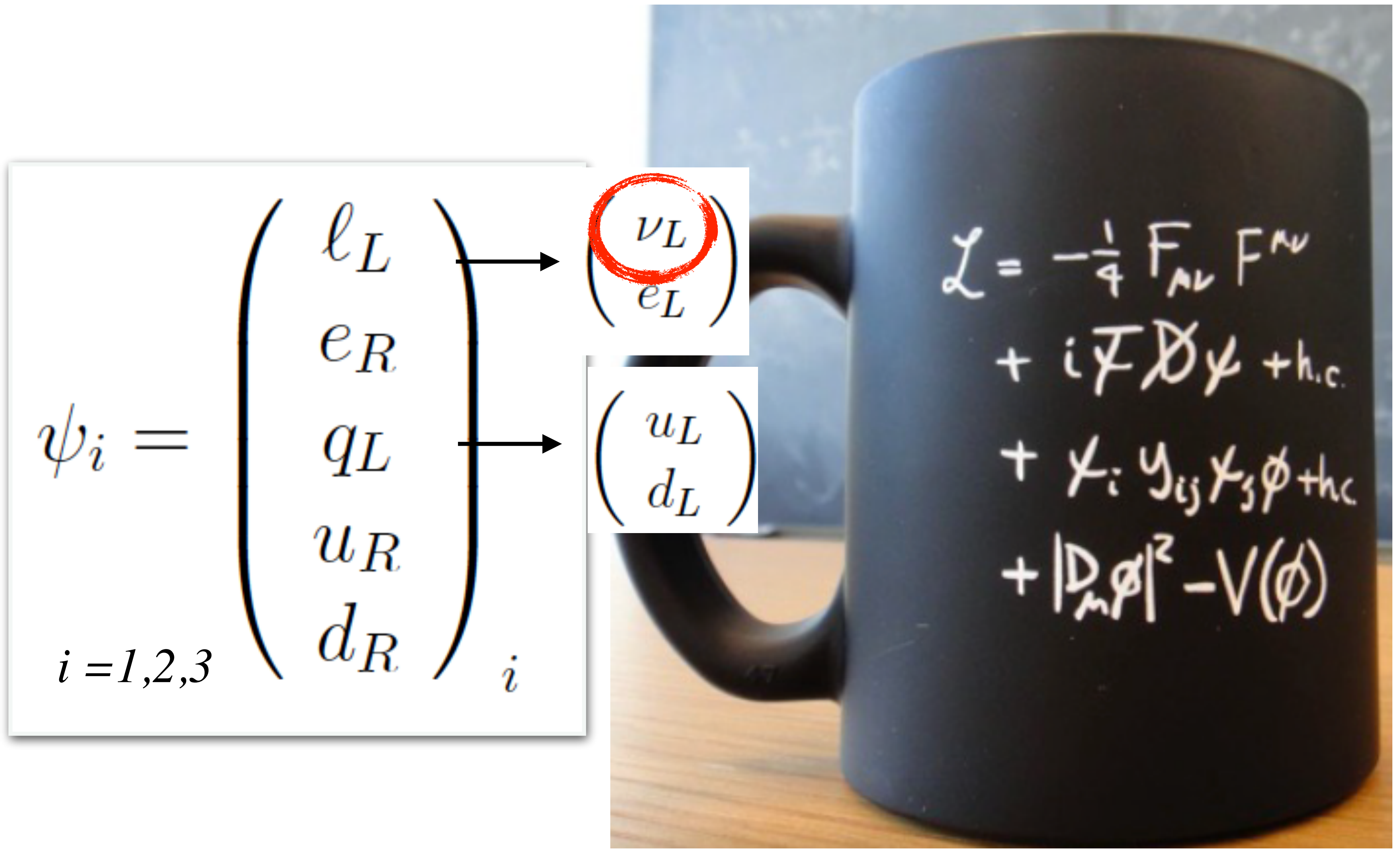


Image credit: CERN

No neutrino mass

Symmetry considerations provide guidance on how to introduce neutrino mass

Neutrino mass and symmetries

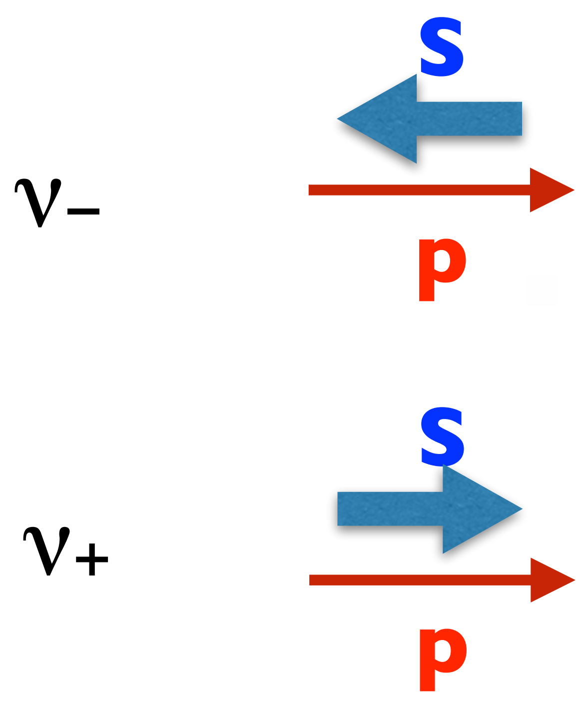
→

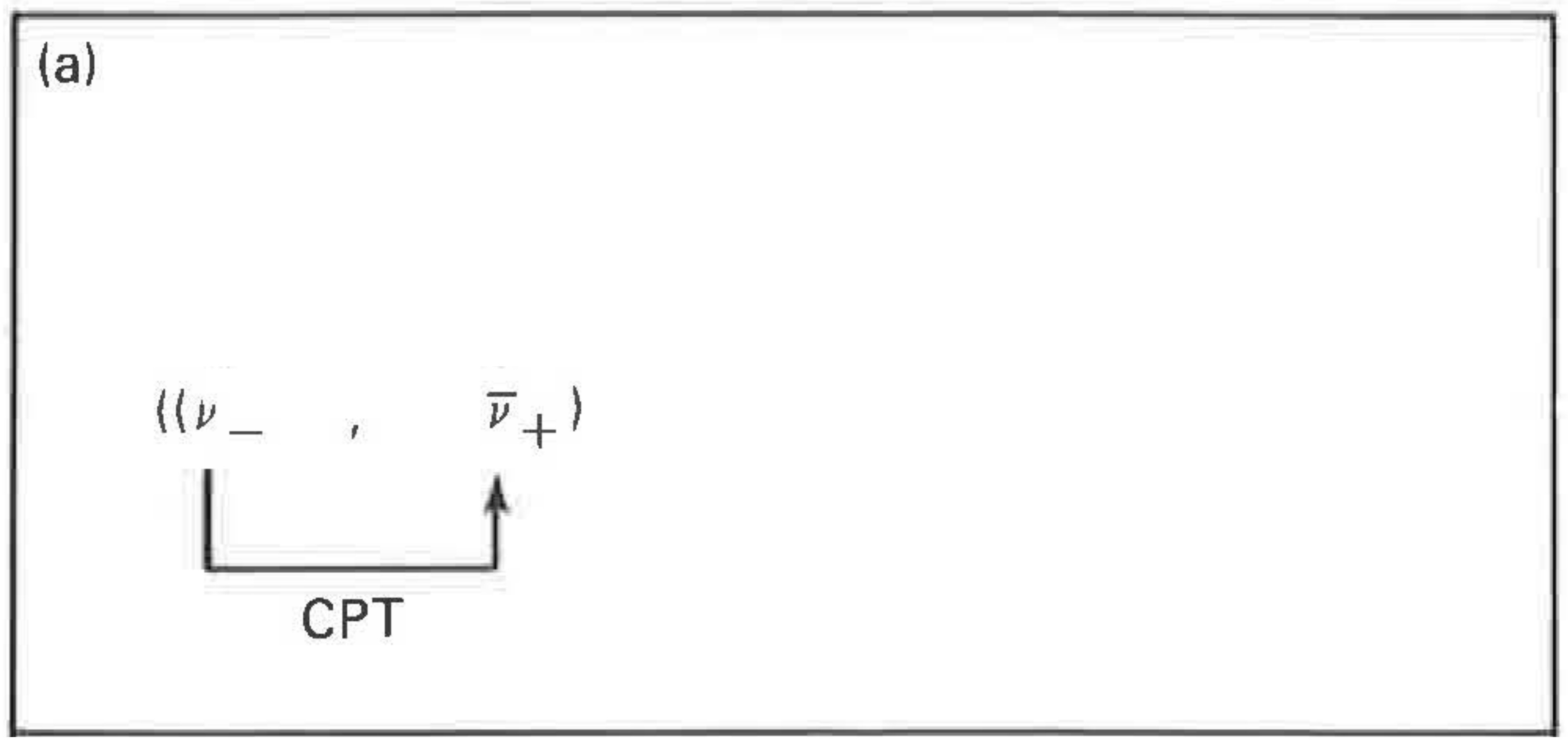
significance of $0\nu\beta\beta$ decay

Neutrino mass and symmetries

Lorentz & CPT invariance ⇒ two options for massive neutrinos

B. Kayser 1984

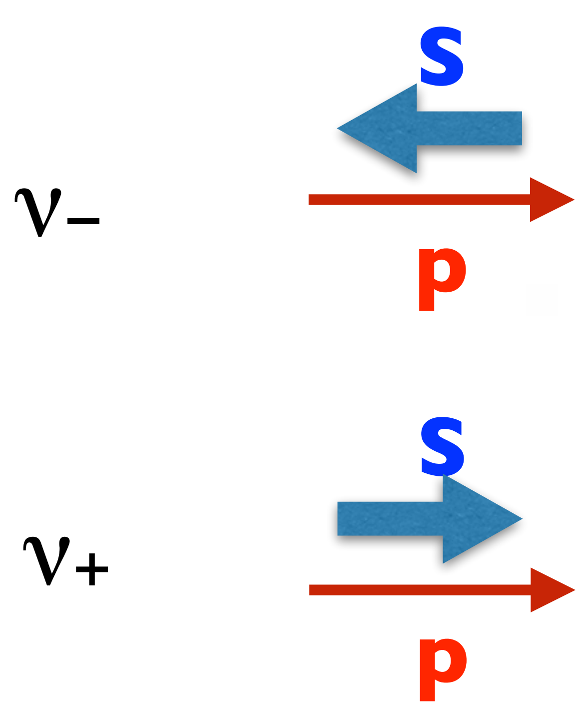


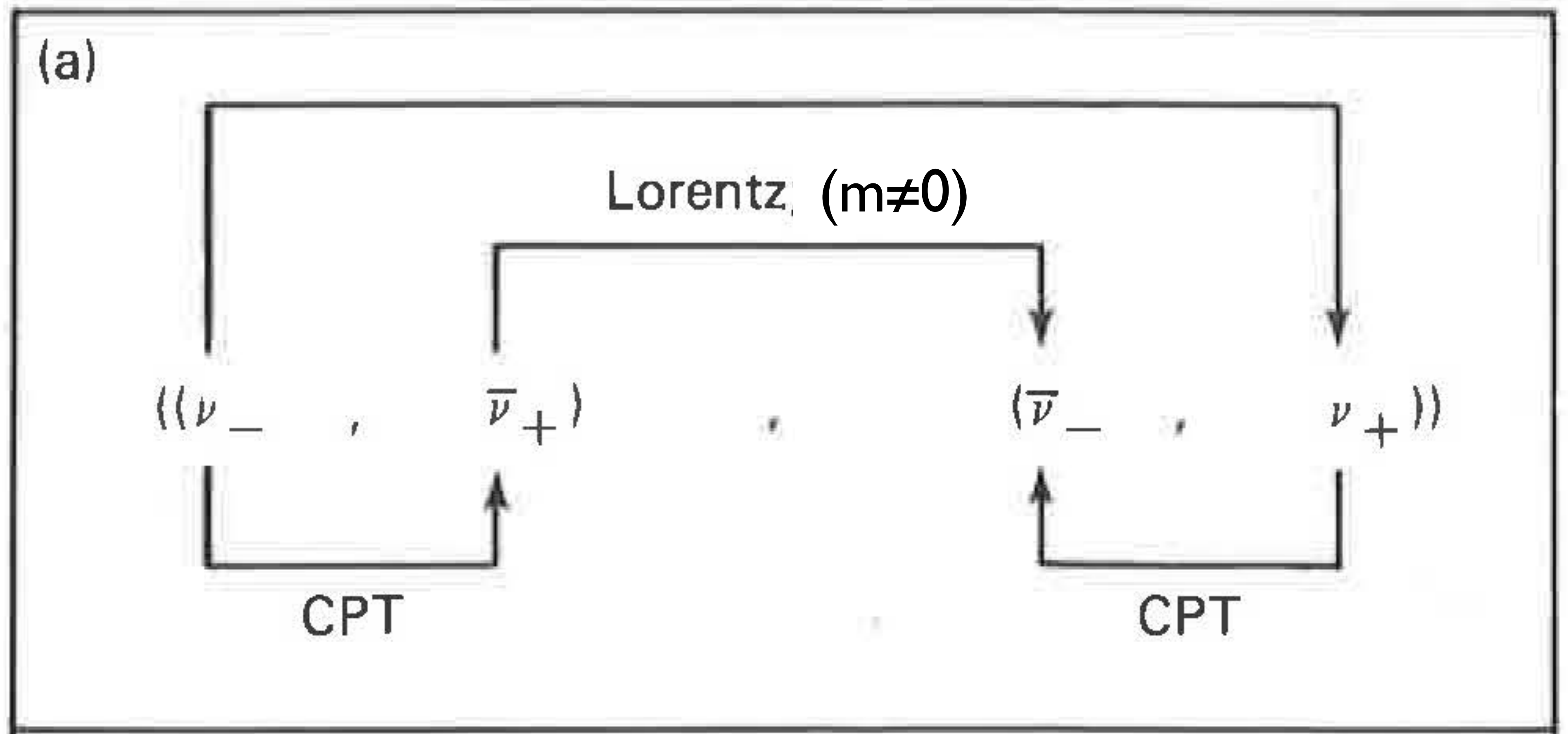


Neutrino mass and symmetries

Lorentz & CPT invariance ⇒ two options for massive neutrinos

B. Kayser 1984

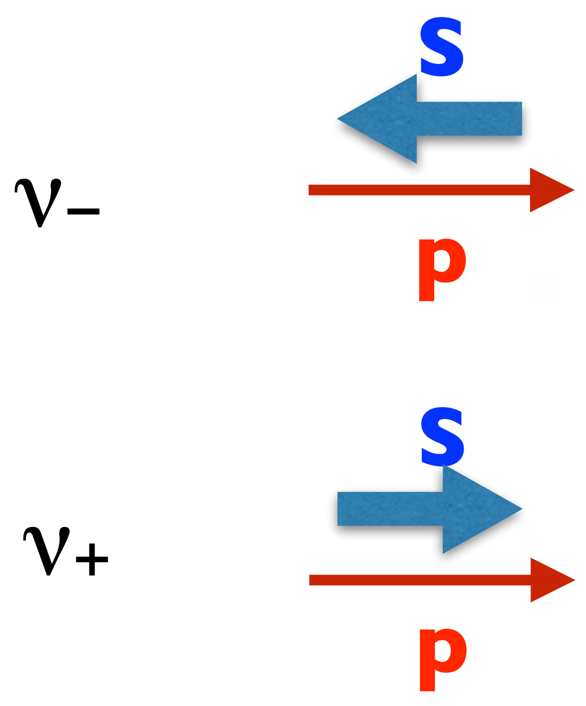




Dirac:
4 states

Neutrino mass and symmetries

Lorentz & CPT invariance ⇒ two options for massive neutrinos



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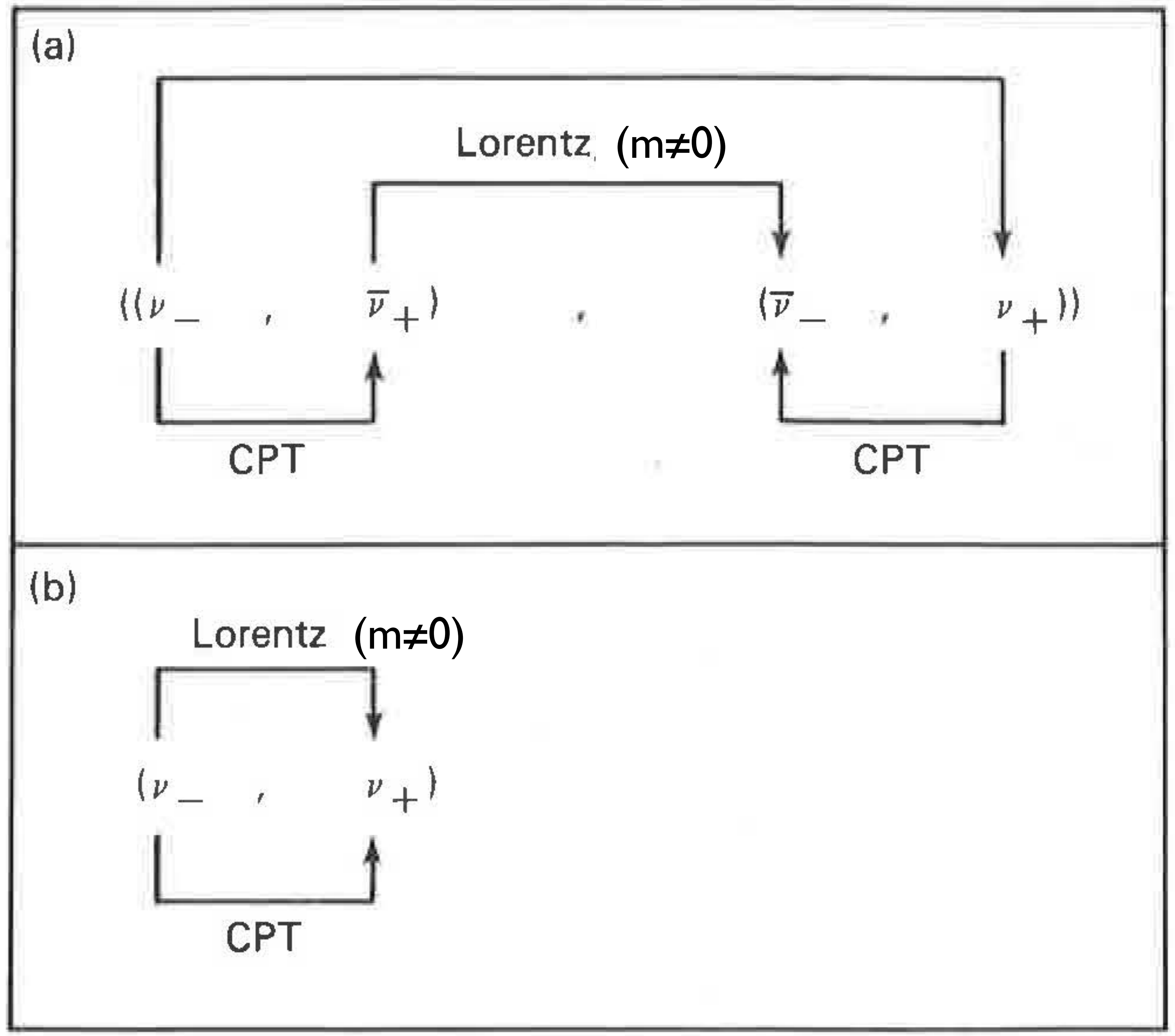


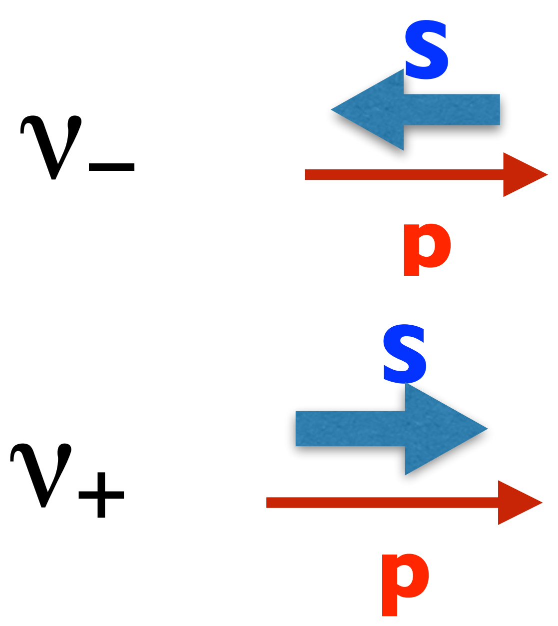
Dirac:
4 states

Majorana:
2 states ($\bar{\nu}_+ = \nu_+$)

Only possible if there is no internal quantum number (such as L) that flips sign under "C"

Neutrino mass and symmetries

Lorentz & CPT invariance $\Rightarrow$ two options for massive neutrinos



Dirac

Majorana

4 states:

$\nu_- \ \bar{\nu}_+ \qquad \nu_+ \ \bar{\nu}_-$

Participate in weak interactions

'Inert' as m $\rightarrow$ 0

2 states: $\nu_- \ \nu_+$

Neutrino = antineutrino

$$\mathcal{L}_D \sim \bar{\nu}_R \, M_D \, \nu_L$$

Conserves $L = L_e + L_\mu + L_\tau$

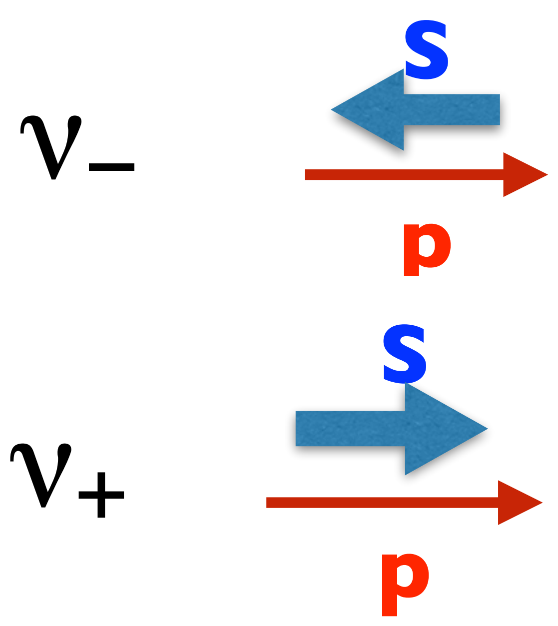
$$\mathcal{L}_M \sim \nu_L^T \, C M_M \, \nu_L$$

Violates L ($\Delta L = 2$)

Importantly, the two options are distinguished by the behavior under the global symmetry associated with lepton number (L)

Neutrino mass and symmetries

Lorentz & CPT invariance ⇒ two options for massive neutrinos




Dirac


Majorana

4 states:

$\nu_- \ \bar{\nu}_+ \qquad \nu_+ \ \bar{\nu}_-$

Participate in weak interactions

'Inert' as m → 0

2 states: $\nu_- \ \nu_+$

Neutrino = antineutrino

$$\mathcal{L}_D \sim \bar{\nu}_R M_D \nu_L$$

Conserves $L = L_e + L_\mu + L_\tau$

Not invariant under $SU(2)_W \times U(1)_Y$

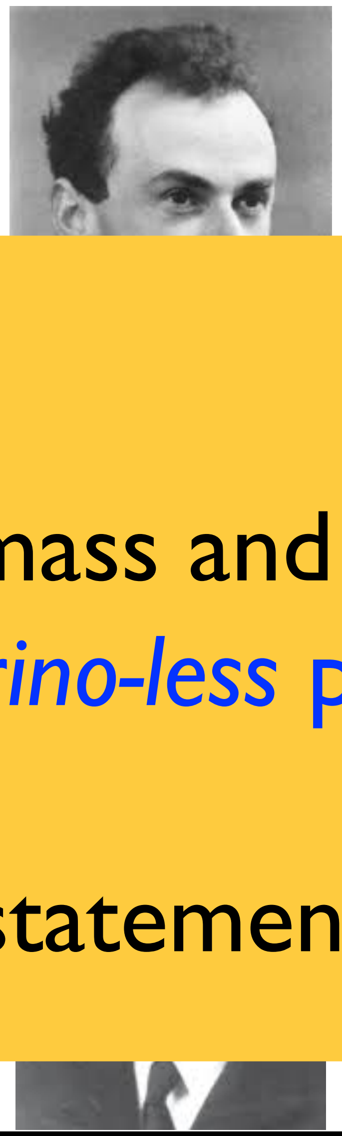
$$\mathcal{L}_M \sim \nu_L^T C M_M \nu_L$$

Violates L ($\Delta L = 2$)

Both require extending the SM

Neutrino mass and symmetries

Lorentz & CPT invariance ⇒ two options for massive neutrinos



Majorana

4 states:

Which option is realized in nature?

- Smallness of ν mass and V-A structure of the weak interactions ((m_ν/E) helicity suppression) imply that ΔL=2 *neutrino-less* processes like 0νββ decay are the best way to address this question

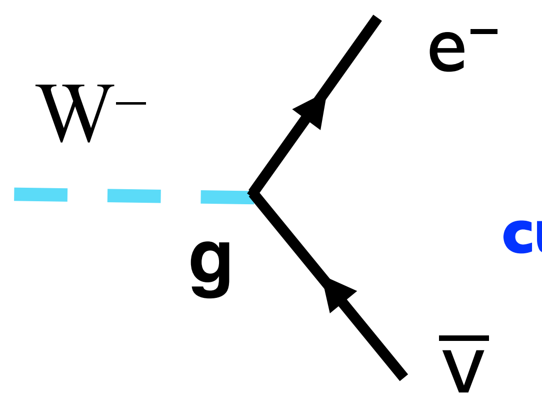
- To explain this statement, need a little more detail on the way neutrinos interact

Neutrino = antineutrino

Violates L (ΔL=2)

Both require extending the SM

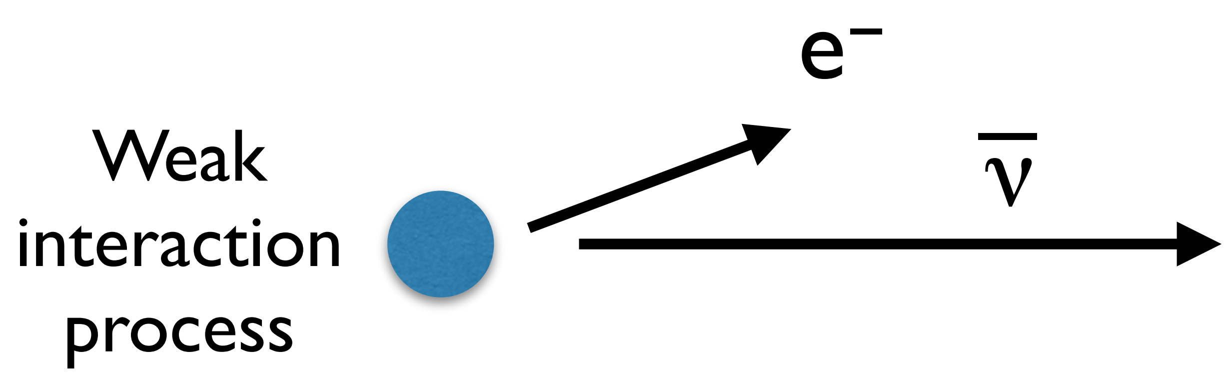
Massive ν's and weak interactions

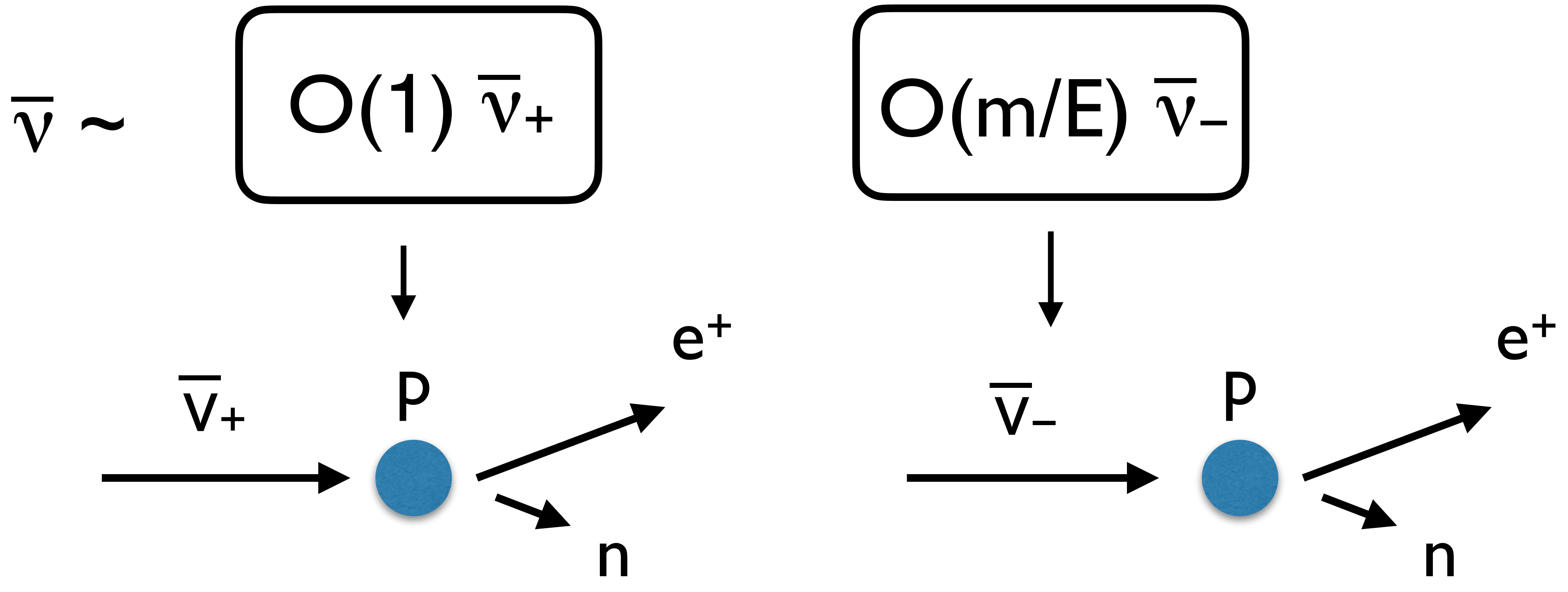


V-A current

Effect of V-A chiral structure on Dirac neutrinos

'Anti-neutrino' ($\bar{\nu}$): emitted with e^-

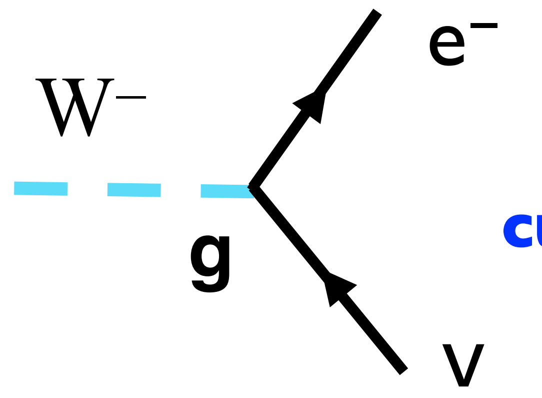




There is another m/E suppression in the vertex

Always behaves as an 'antimatter particle' (produces e^+)

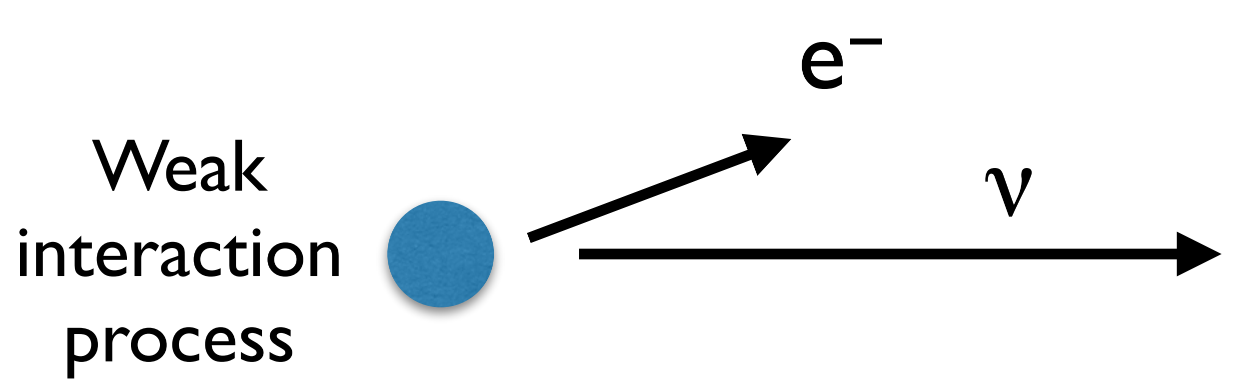
Massive ν's and weak interactions

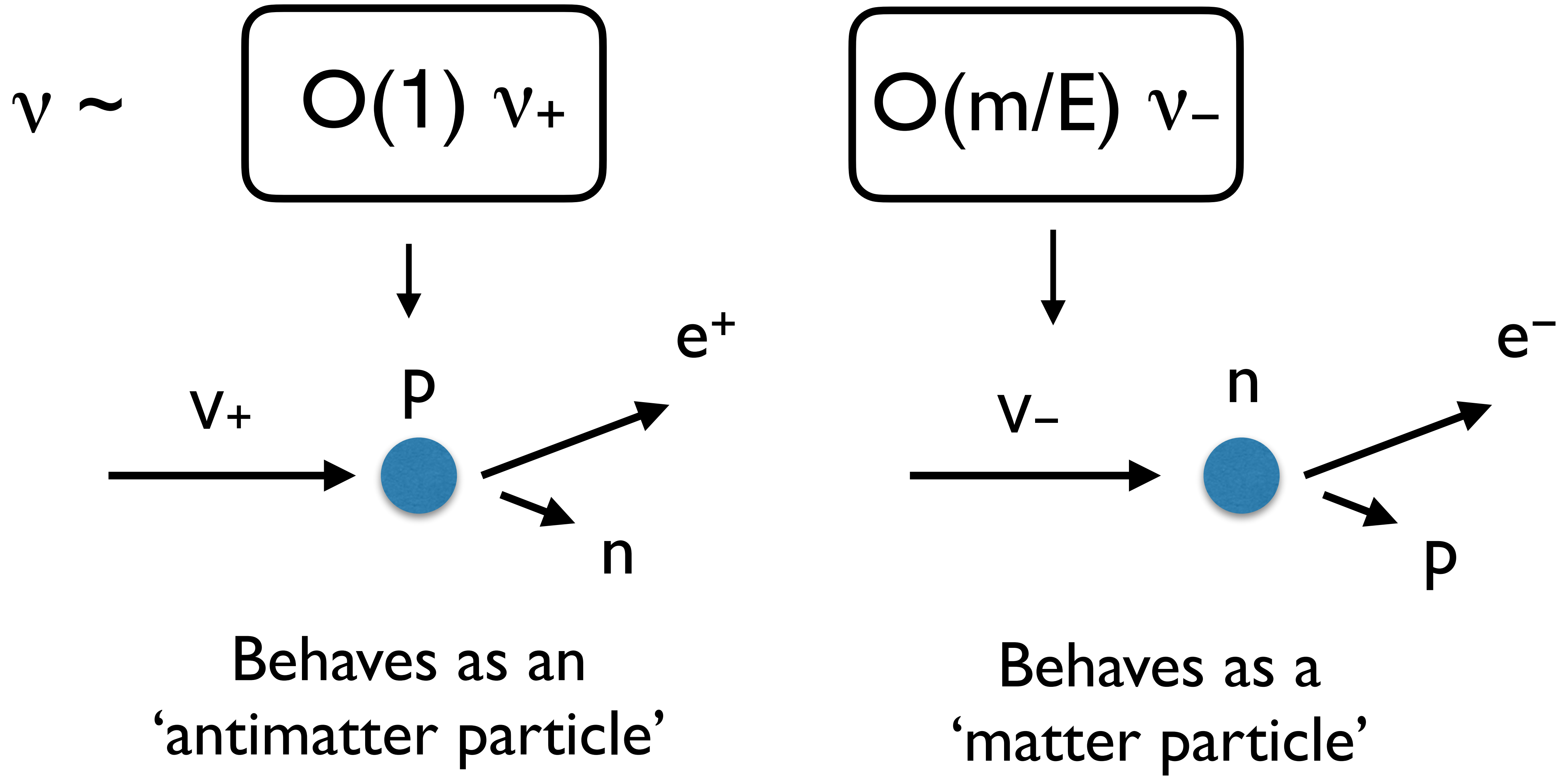


V-A current

Effect of V-A chiral structure on Majorana neutrinos

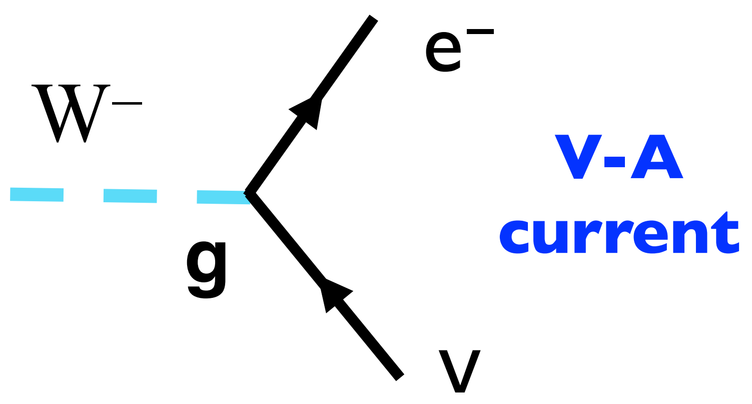
'Anti-neutrino' (ν): emitted with e⁻





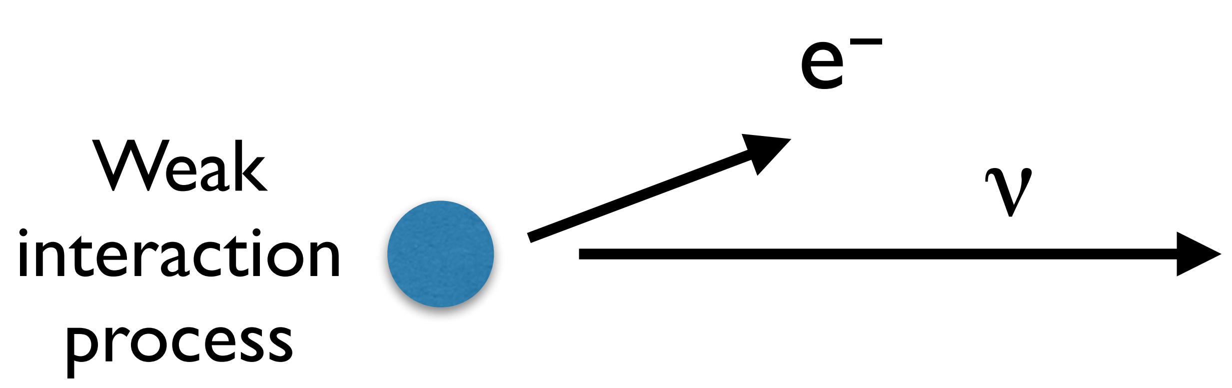
There is no additional m/E suppression in the weak vertex

Massive ν's and weak interactions

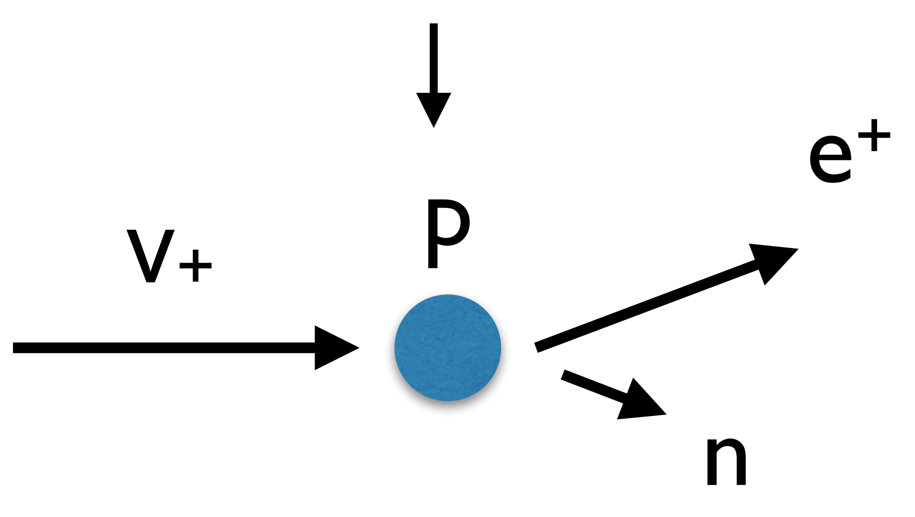


Effect of V-A chiral structure on Majorana neutrinos

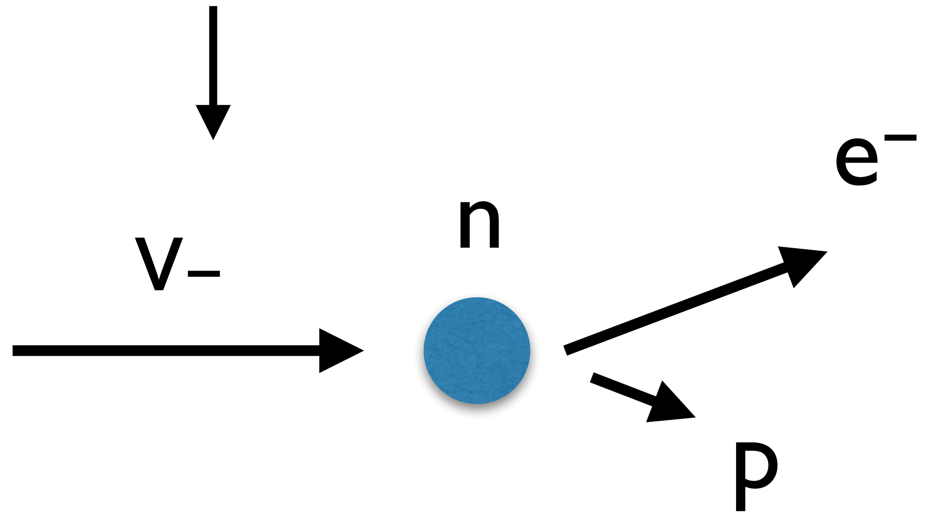
'Anti-neutrino' ($\bar{\nu}$): emitted with e^-



$\nu \sim$ O(1) ν_+ + O(m/E) ν_-



Behaves as an 'antimatter particle'

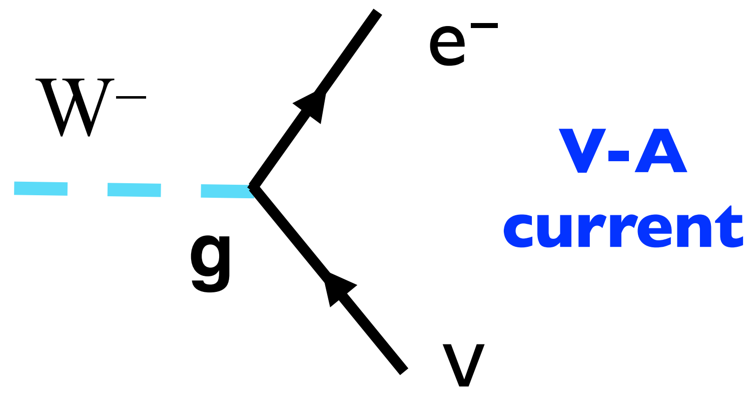


Behaves as a 'matter particle'

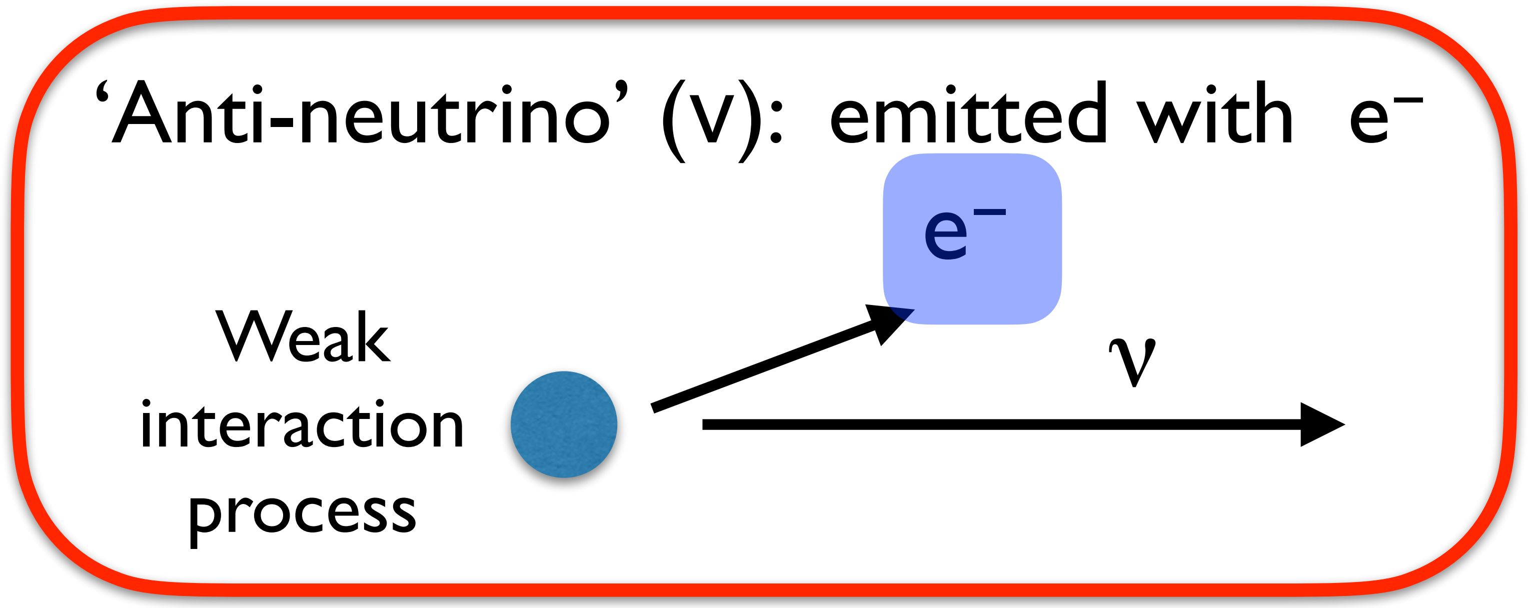
There is no additional m/E suppression in the weak vertex

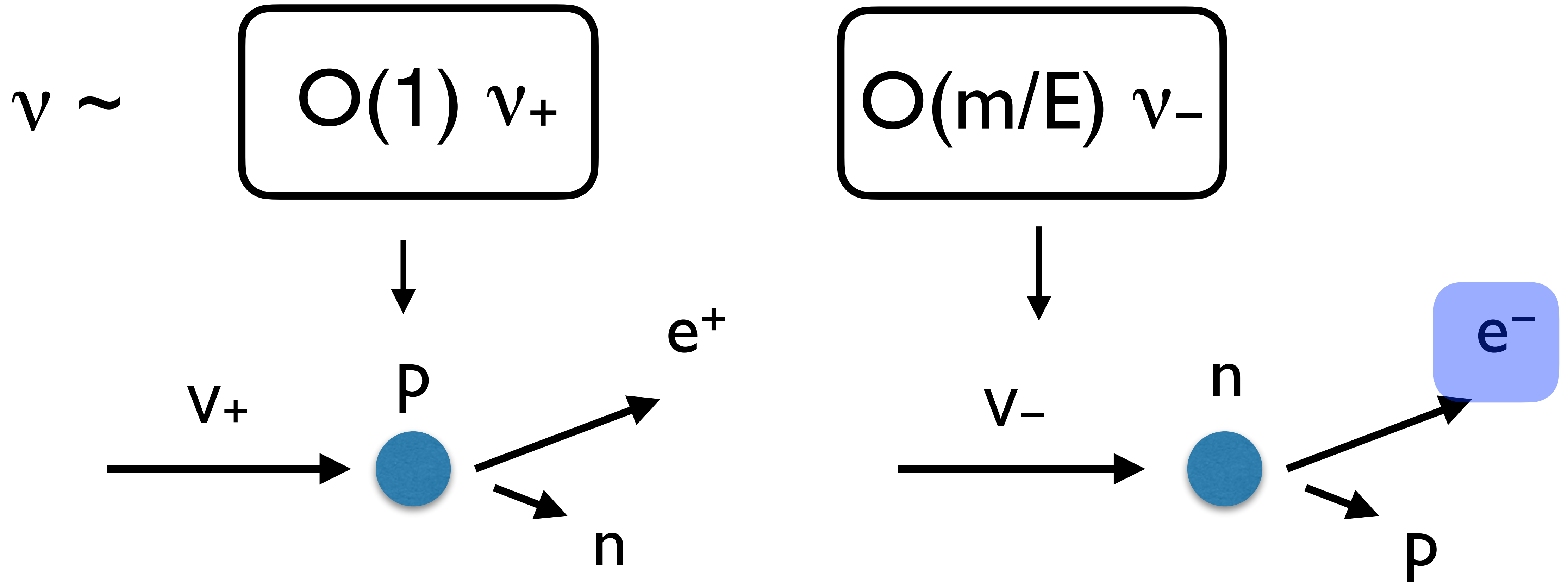
For m ≠ 0 the distinction between Dirac and Majorana matters.
The Majorana option blurs the notion of matter and antimatter!

Massive ν's and weak interactions



Effect of V-A chiral structure on Majorana neutrinos





Behaves as an 'antimatter particle'

Behaves as a 'matter particle'

There is no additional m/E suppression in the weak vertex

To detect the Majorana signature ($2e^-$ in final state, $\Delta L=2$) need to overcome the m/E factor

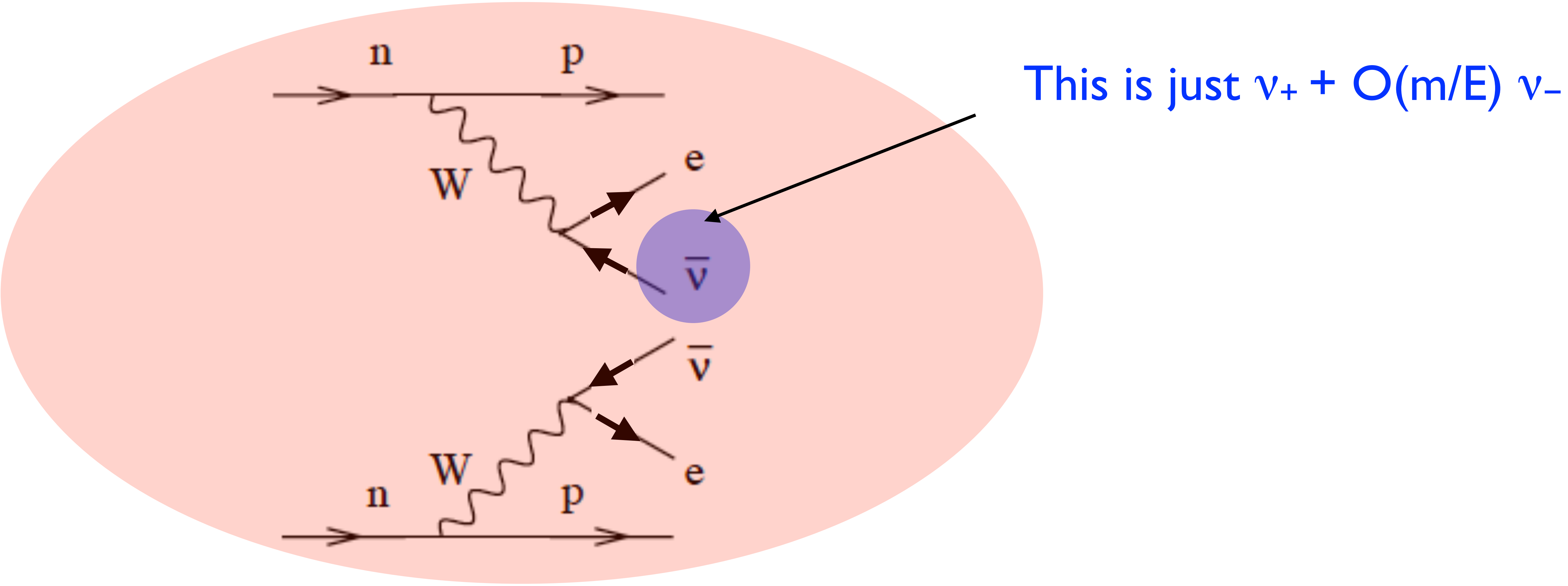
→ Non-relativistic neutrinos

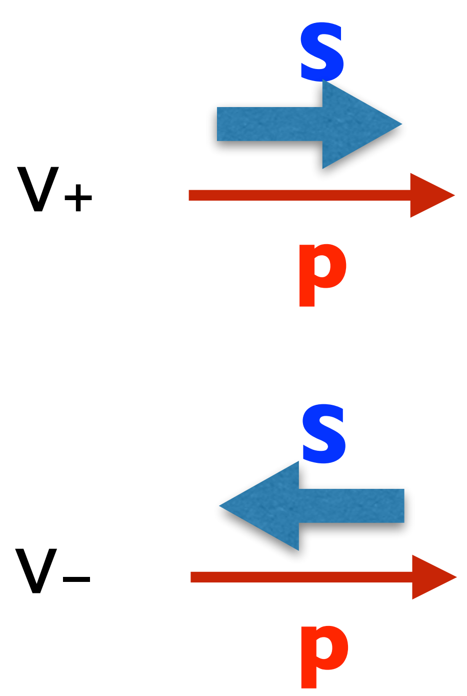
→ Avogadro's number: double beta decay!

0νββ decay is the arbiter

- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ

W. H. Furry, 1939





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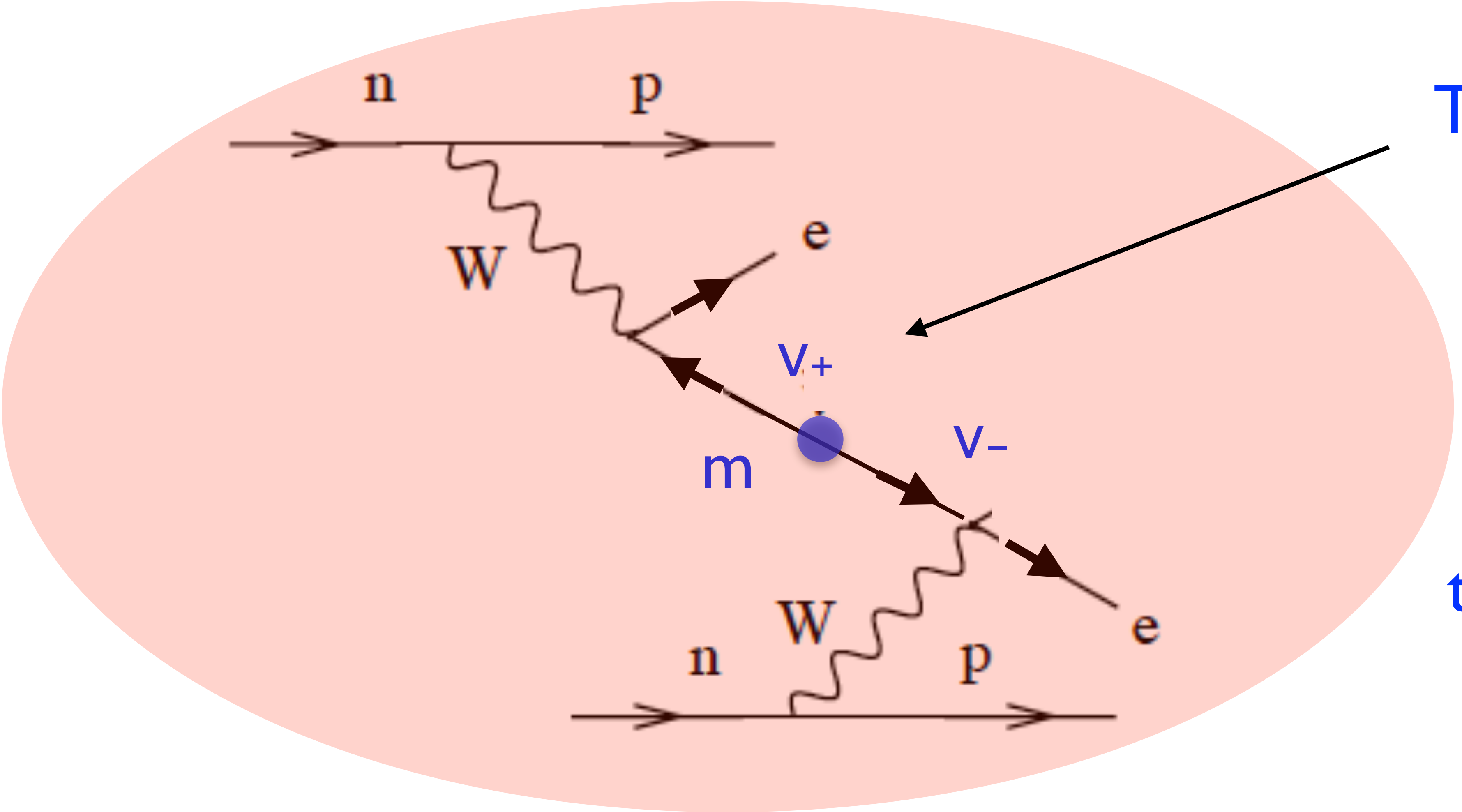
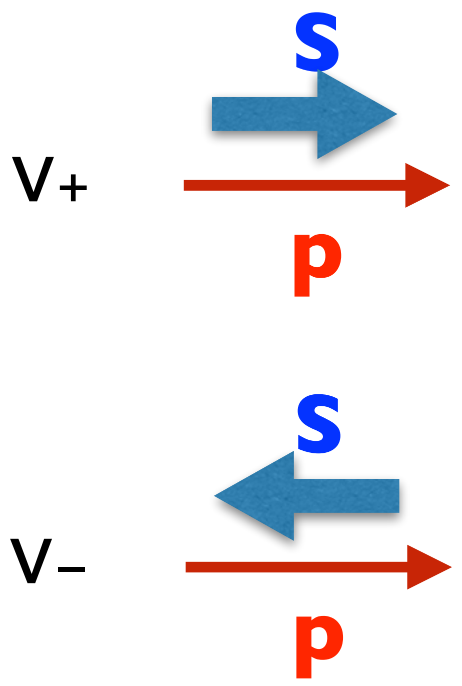


This is just $\nu_+ + O(m/E)\,\nu_-$

ν_- converts into e^- in the second interaction



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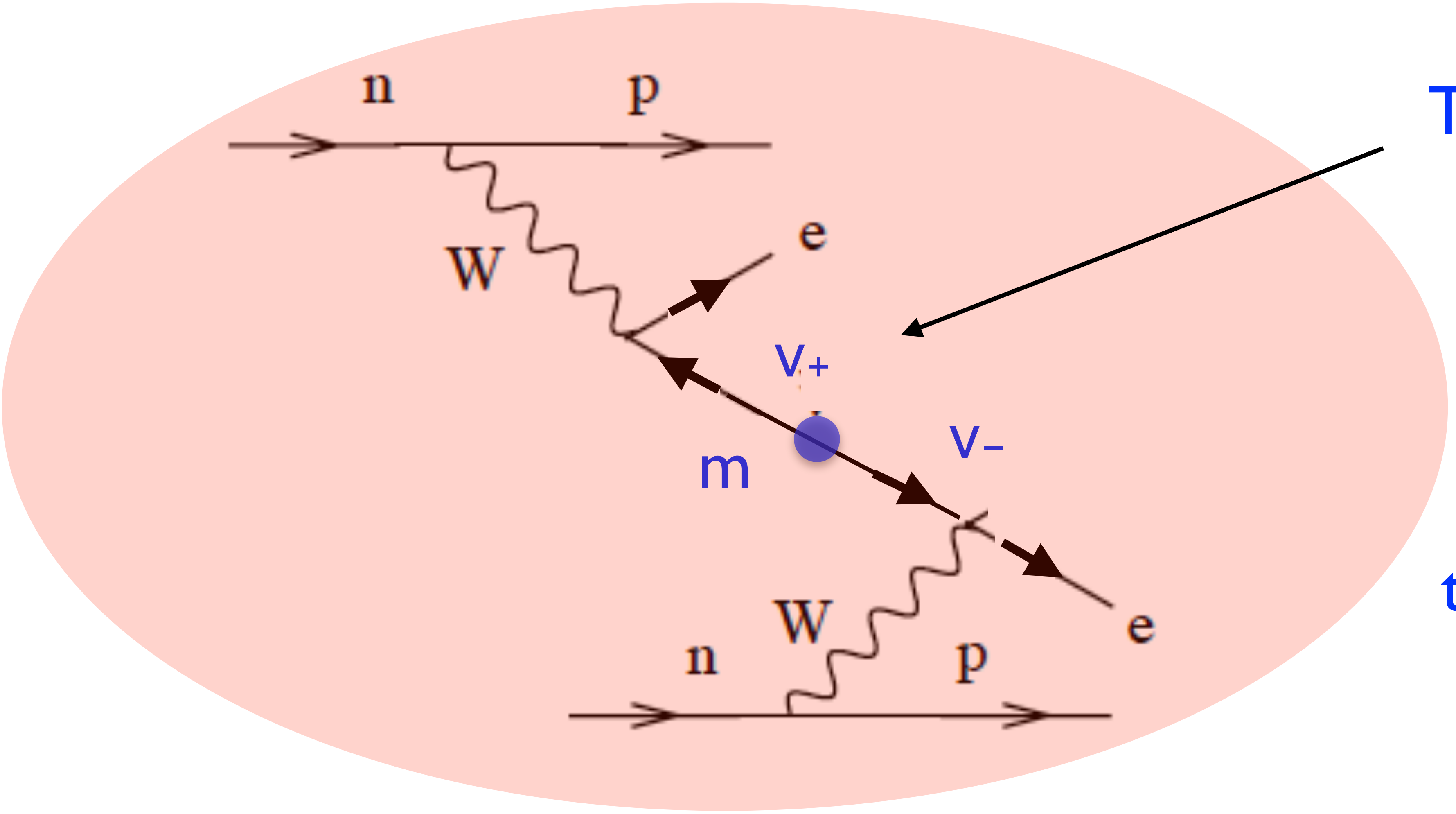

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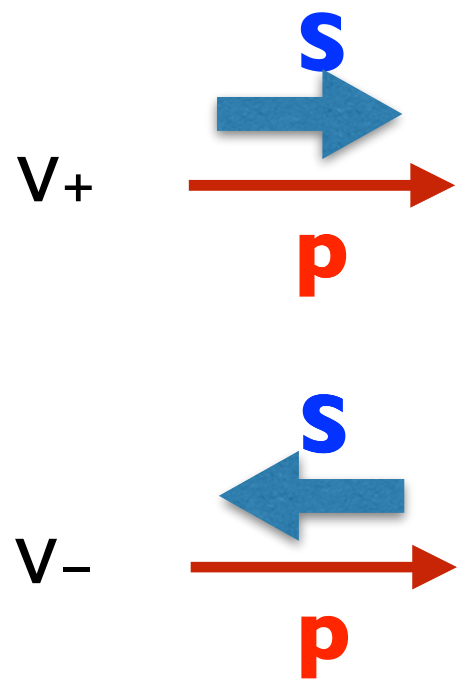
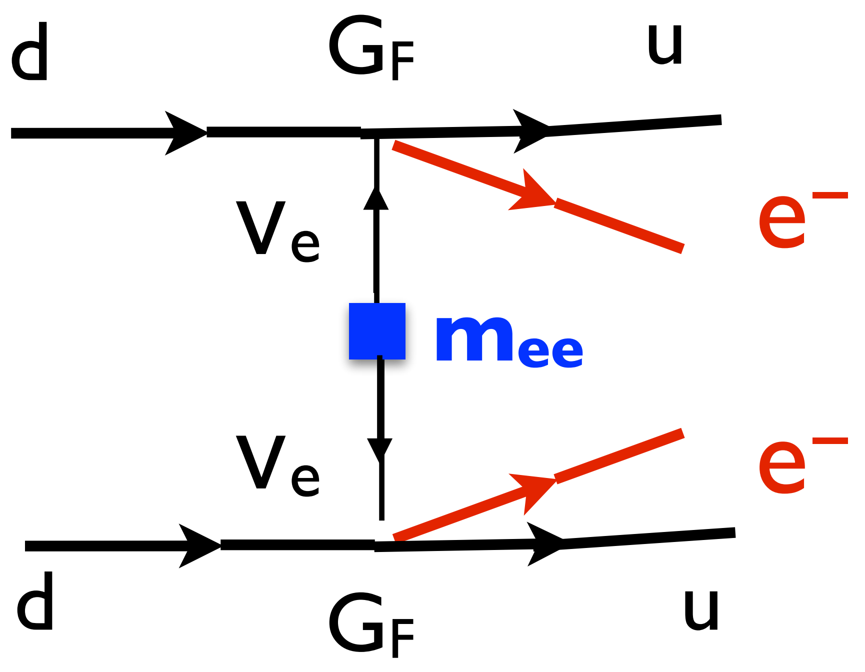
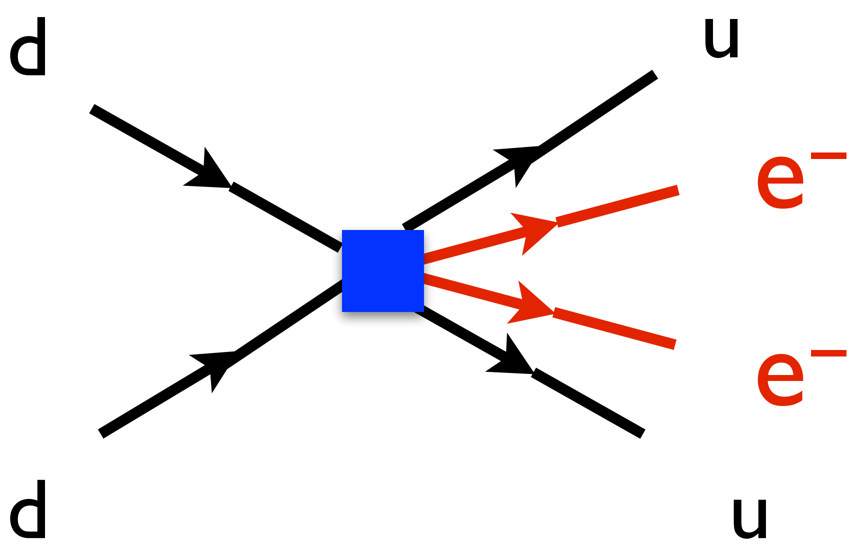


- Key point: in 0νββ Lepton Number changes by two units. Exchange of light ν_M is just one possible mechanism



but also

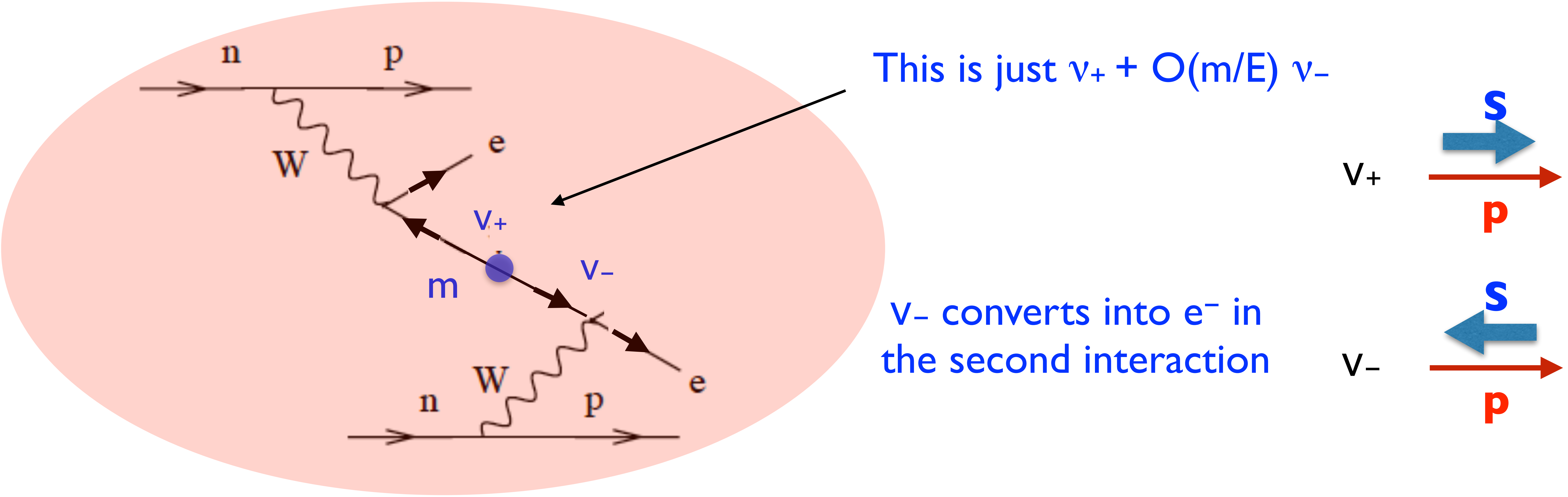


Exchange of heavier neutrinos or other Majorana particles. At low-energy induce six-fermion operator $\sim 1/\Lambda^5$

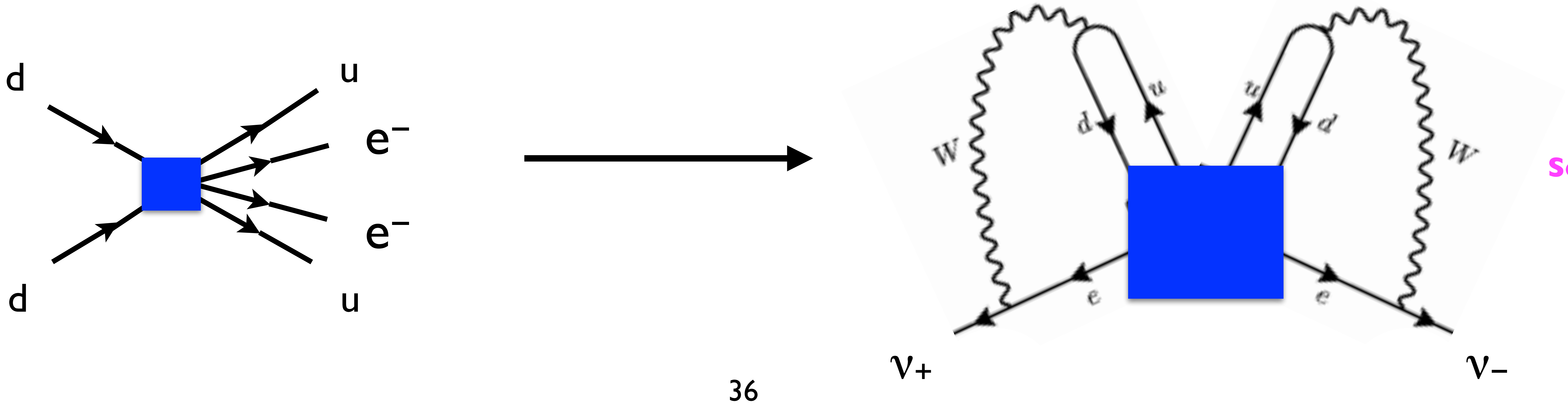
0νββ decay is the arbiter

- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ

W. H. Furry, 1939



- If 0νββ decay happens, through *quantum mechanical fluctuations a* ν_+ *can convert into* ν_- ⇒ hallmark of Majorana ν!

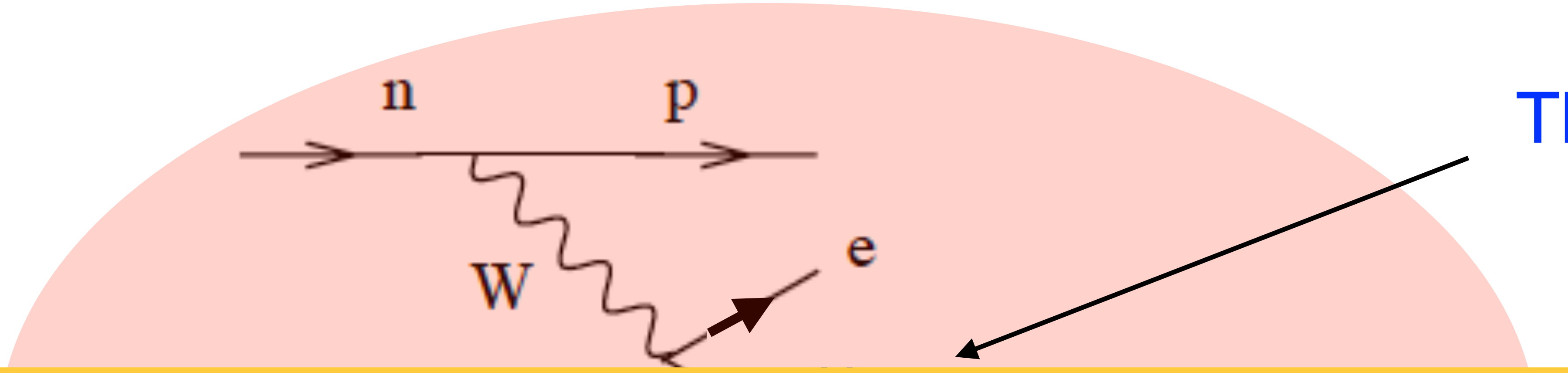


Schechter-Valle 1982

0νββ decay is the arbiter

- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ

W. H.



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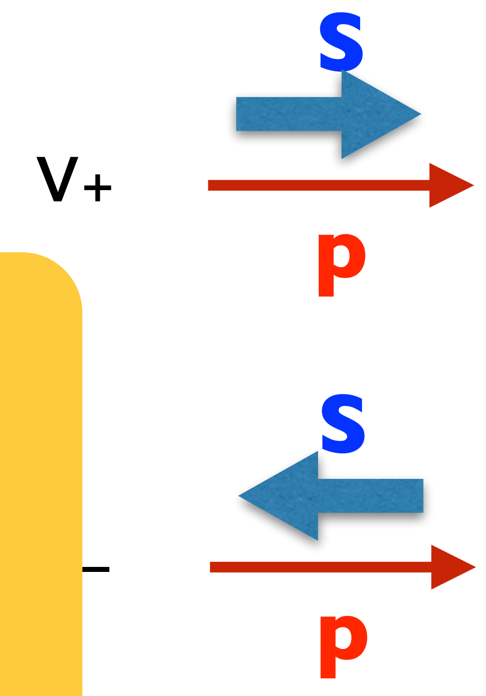
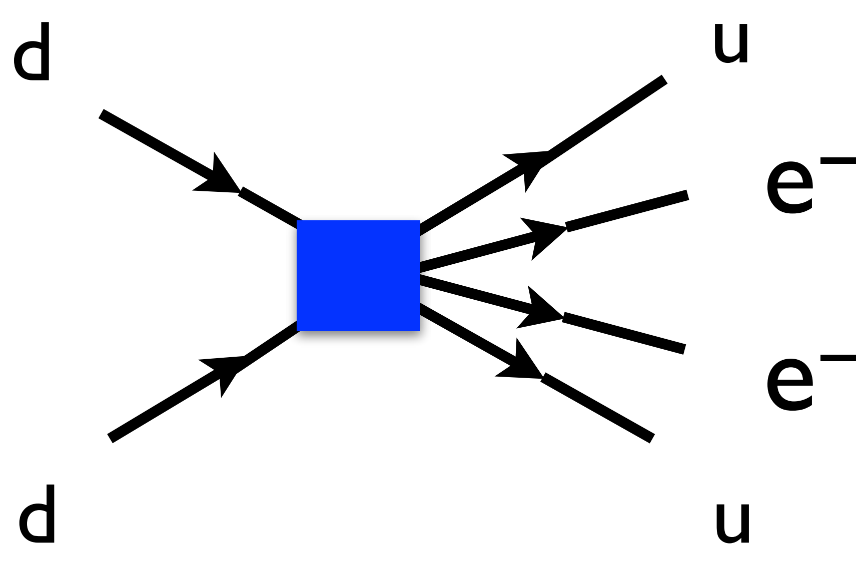
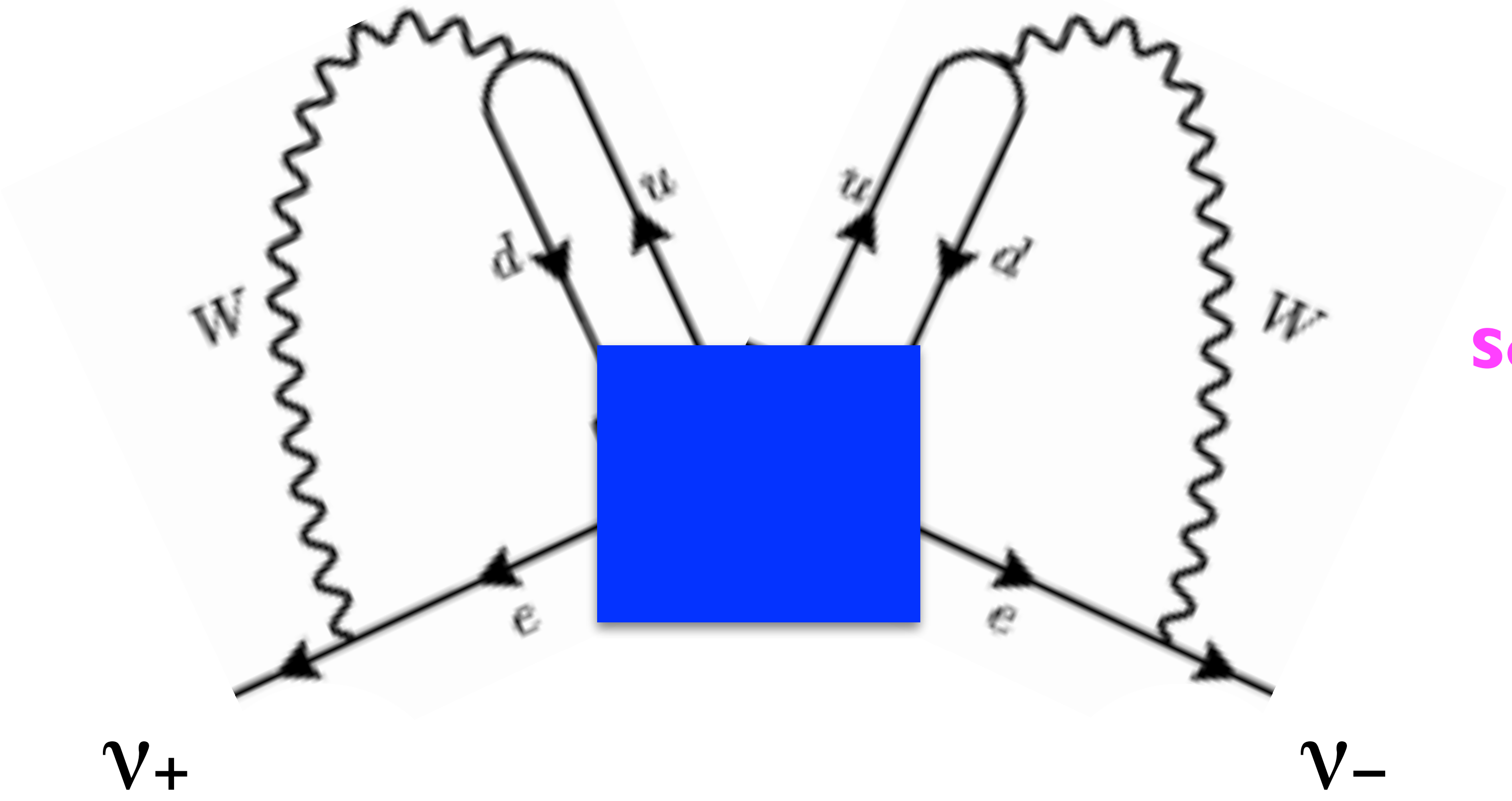


It's a two-way arrow:

Neutrino is a Majorana fermion $\Longleftrightarrow$ 0νββ decay happens at some rate

- If 0νββ decay happens, through *quantum mechanical fluctuations a* ν_+ *can convert into* ν_- ⇒ hallmark of Majorana ν!





Schechter-Valle 1982

0vββ decay and the baryon asymmetry

Recall Sakharov's conditions

#1. B (or L) violation: processes that "create matter"

A → B

#2. "Asymmetrically"

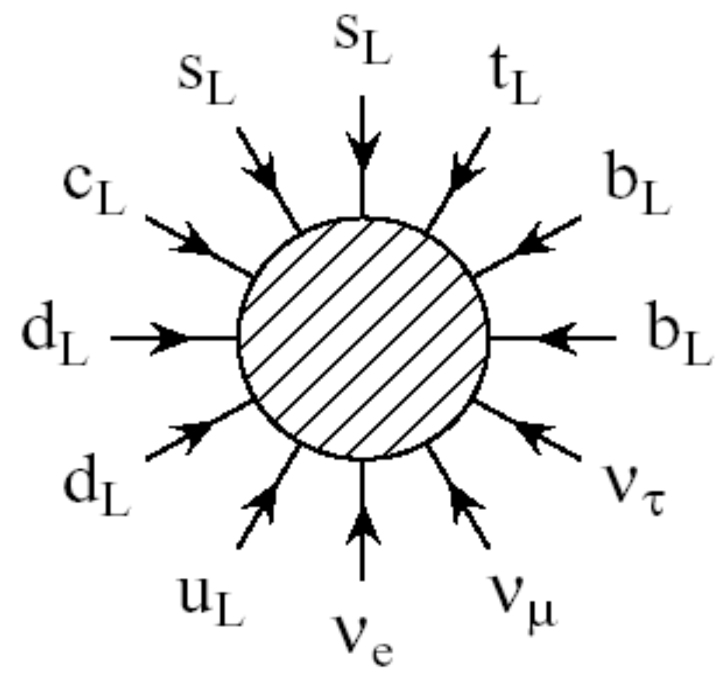
A → B ≠ $\bar{A}$ → $\bar{B}$

#3. "Irreversibly"

A → B ≠ B → A

- 0vββ addresses the first condition: ΔL=2

Electroweak anomalous processes (fast at high T)
convert L into B (ΔL= ΔB = 3)
Only B-L is exactly conserved in the SM

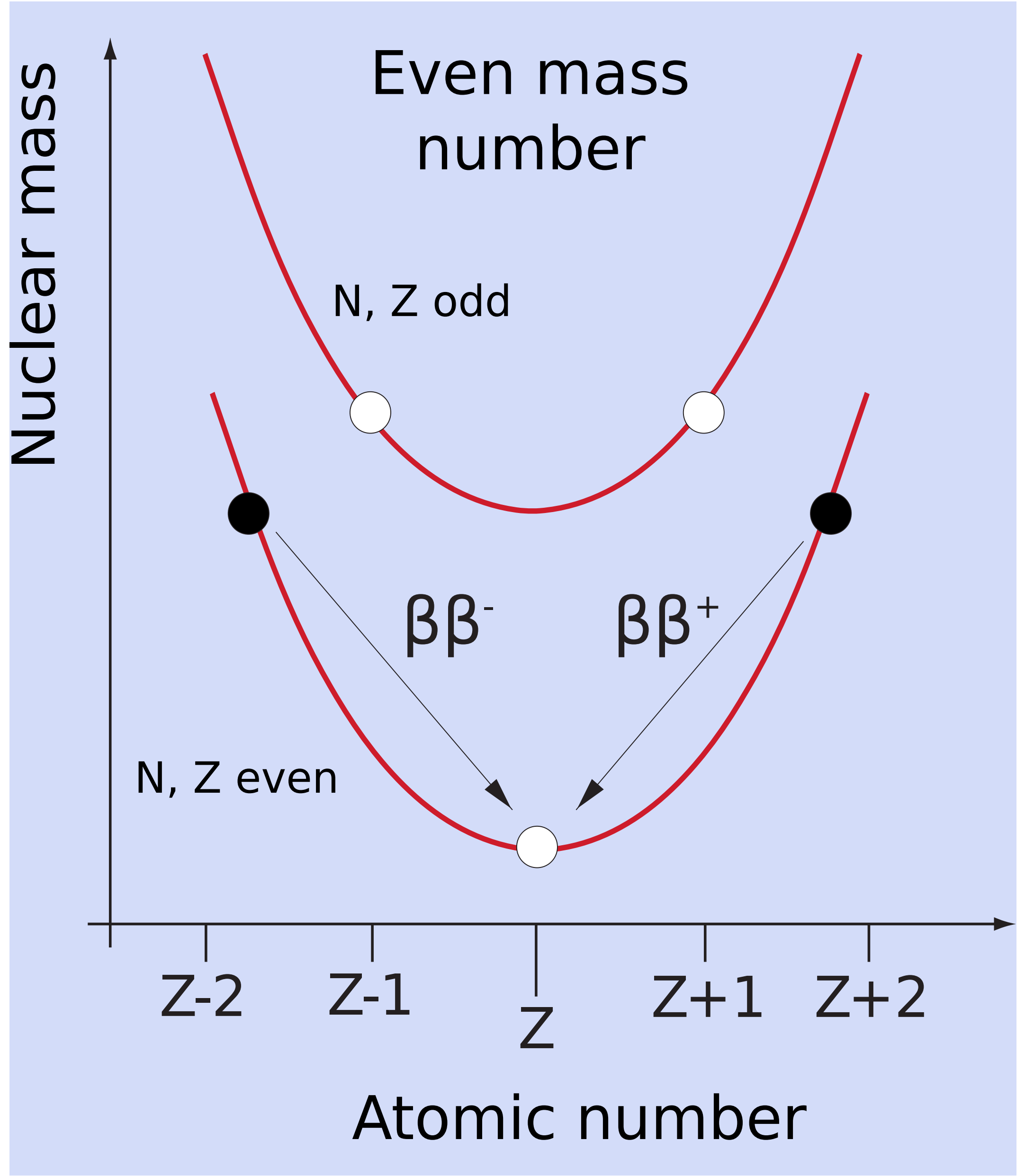


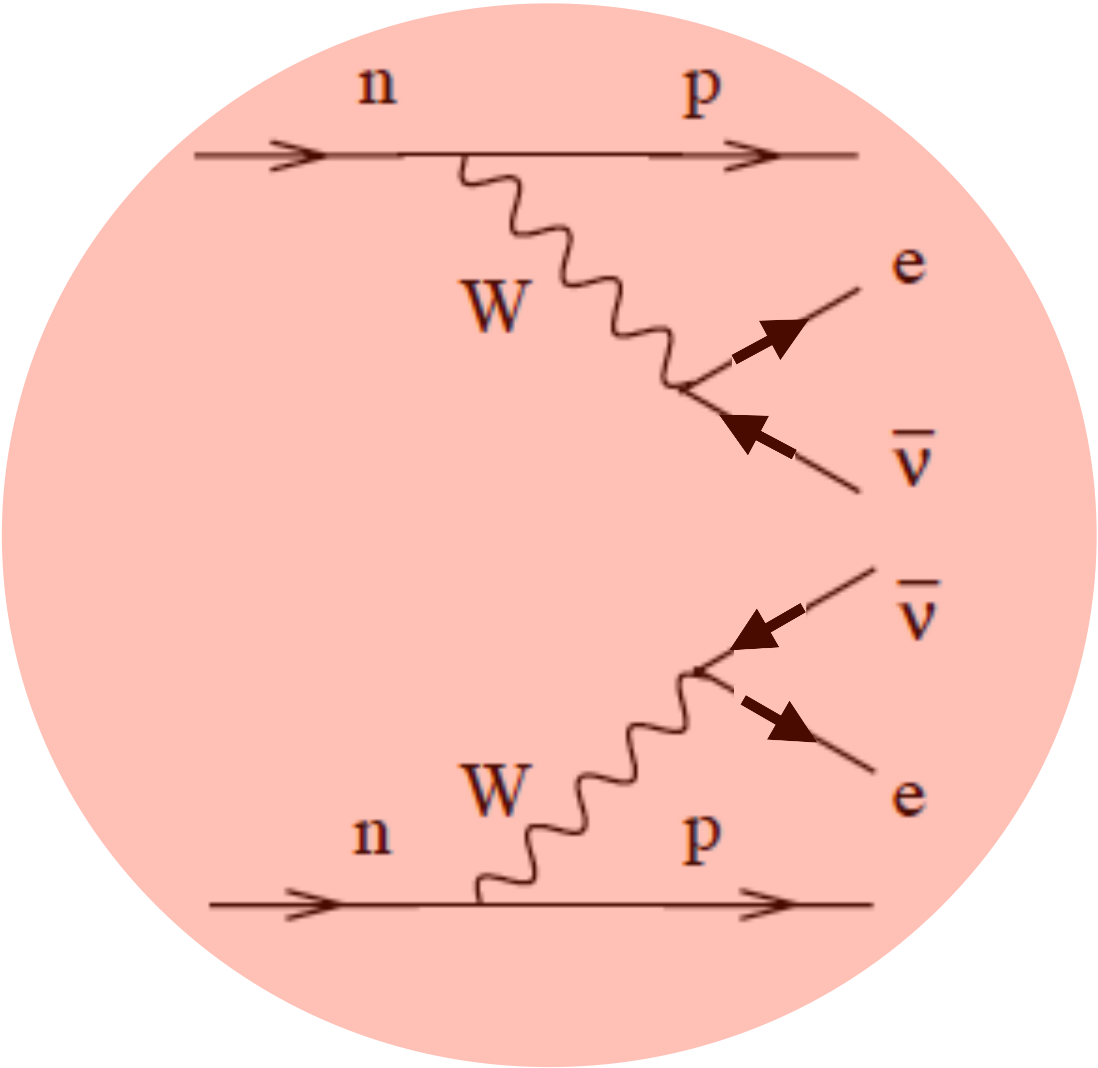
- Explicit models of Majorana neutrino mass satisfy the other two conditions → baryogengesis via leptogenesis

Fukugita-Yanagida 1987

Searching for 0νββ decay

- For certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), single β decay is energetically forbidden → ββ decay
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years

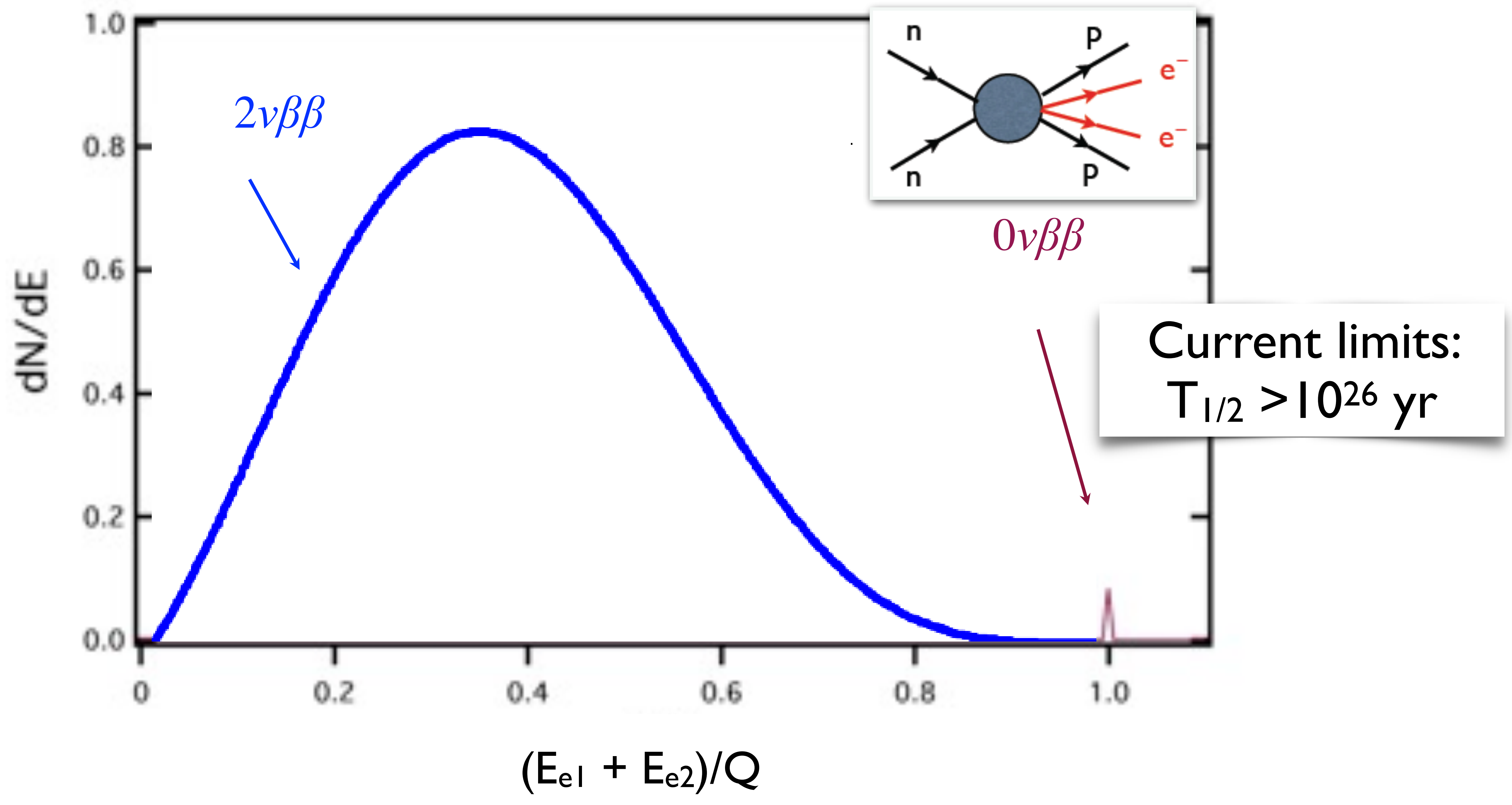


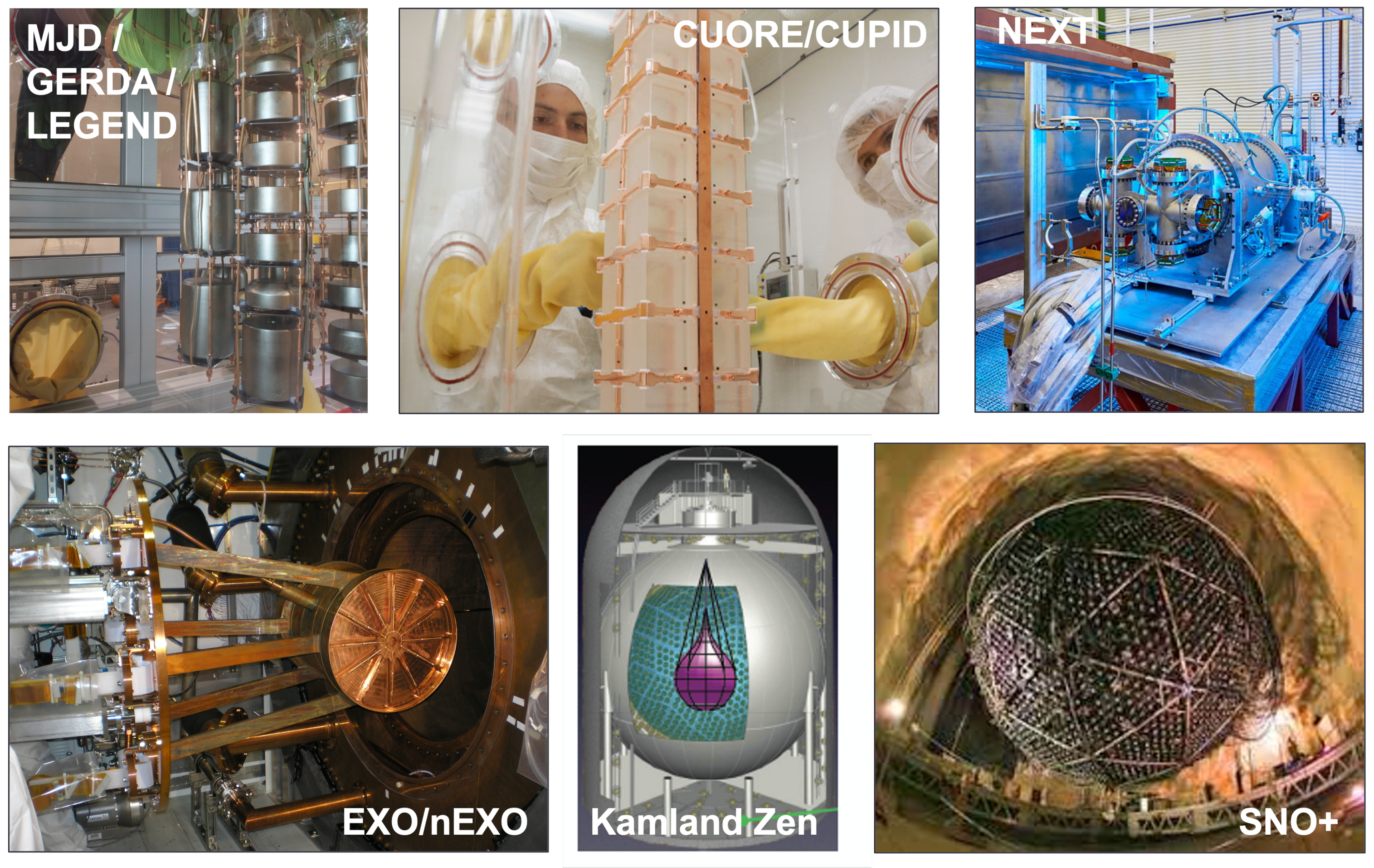


M. Goppert Mayer, 1935

Searching for 0νββ decay

- For certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), single β decay is energetically forbidden → ββ decay
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years
- Several "ton-scale" experiments with different isotopes and technologies are searching for 0νββ, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr, which is ~10^{18} times the age of the universe!

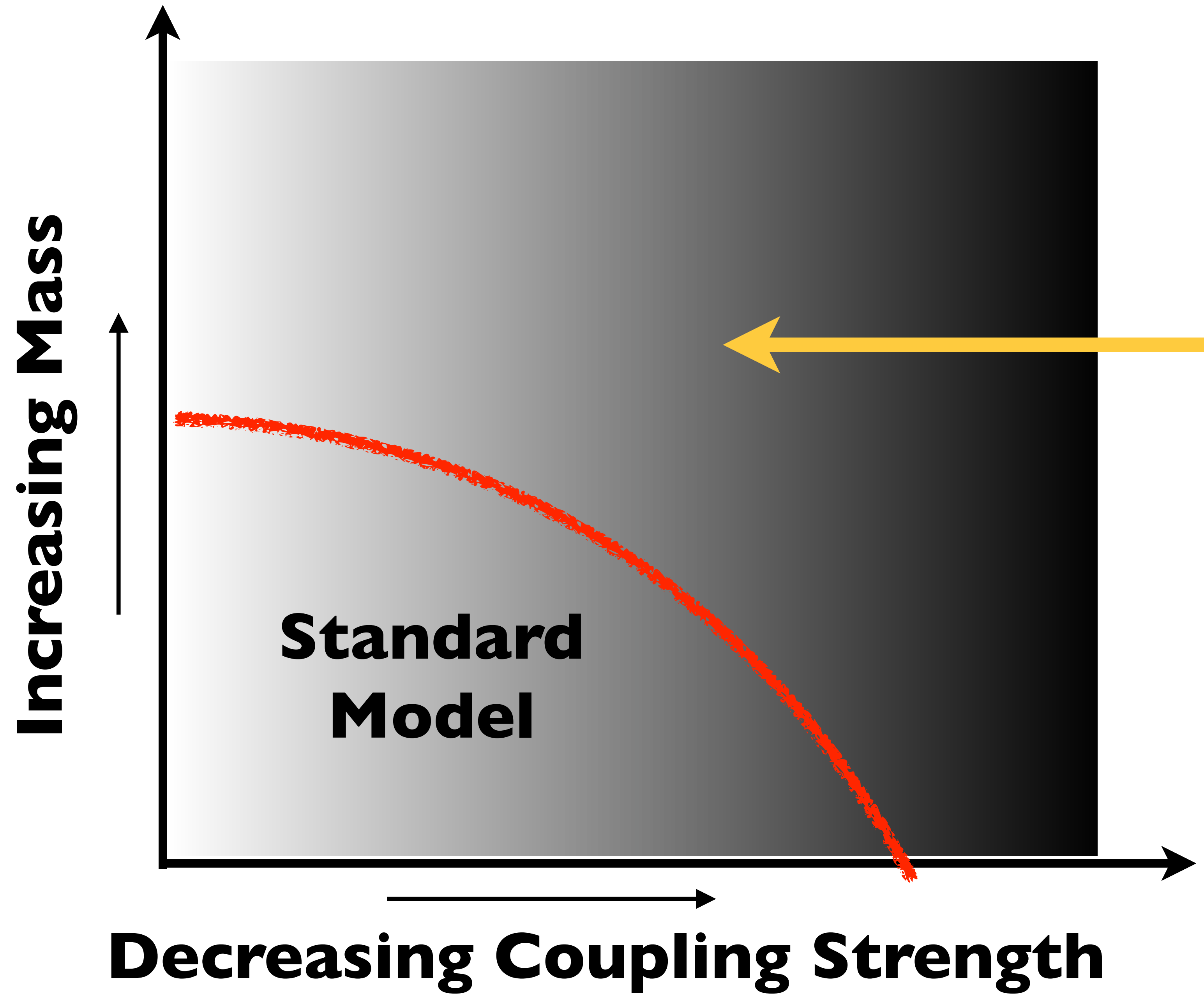




Discovery potential of 0νββ decay at the ‘ton scale’

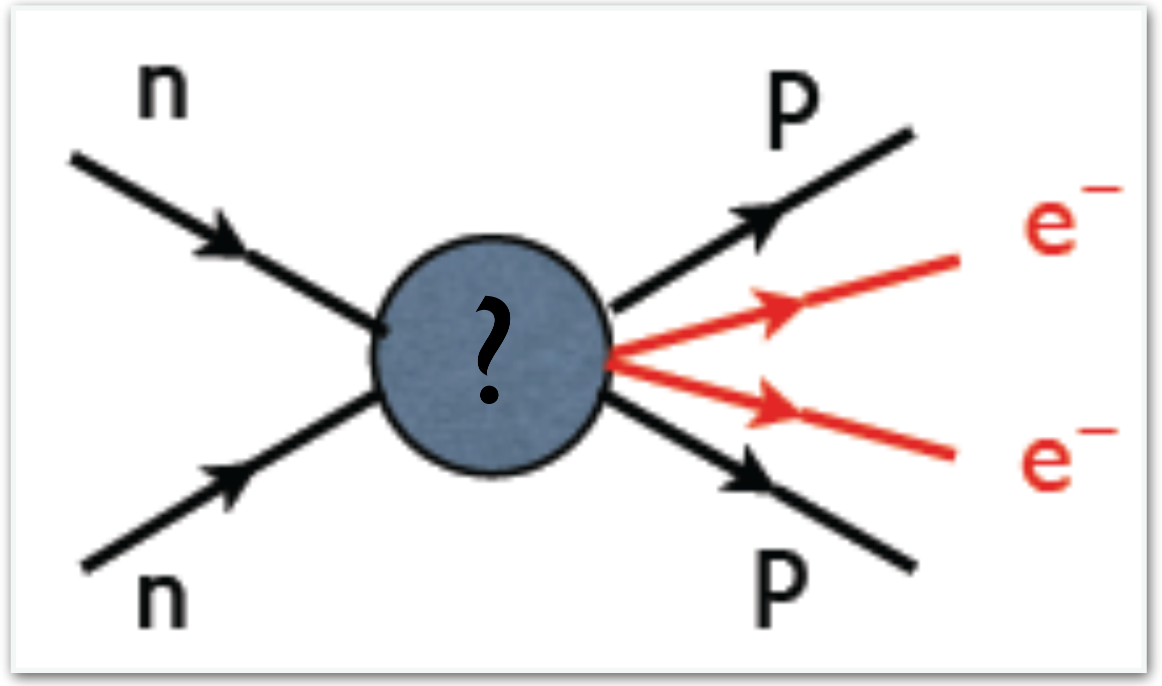
0νββ decay physics reach

0νββ searches @ $T_{1/2} \sim 10^{27\text{-}28}$ yr can discover LNV arising from a broad variety of mechanisms



Somewhere out here there must be new physics responsible for neutrino masses

If the neutrino mass is of Majorana type, most of this uncharted territory can be explored only by 0νββ decay



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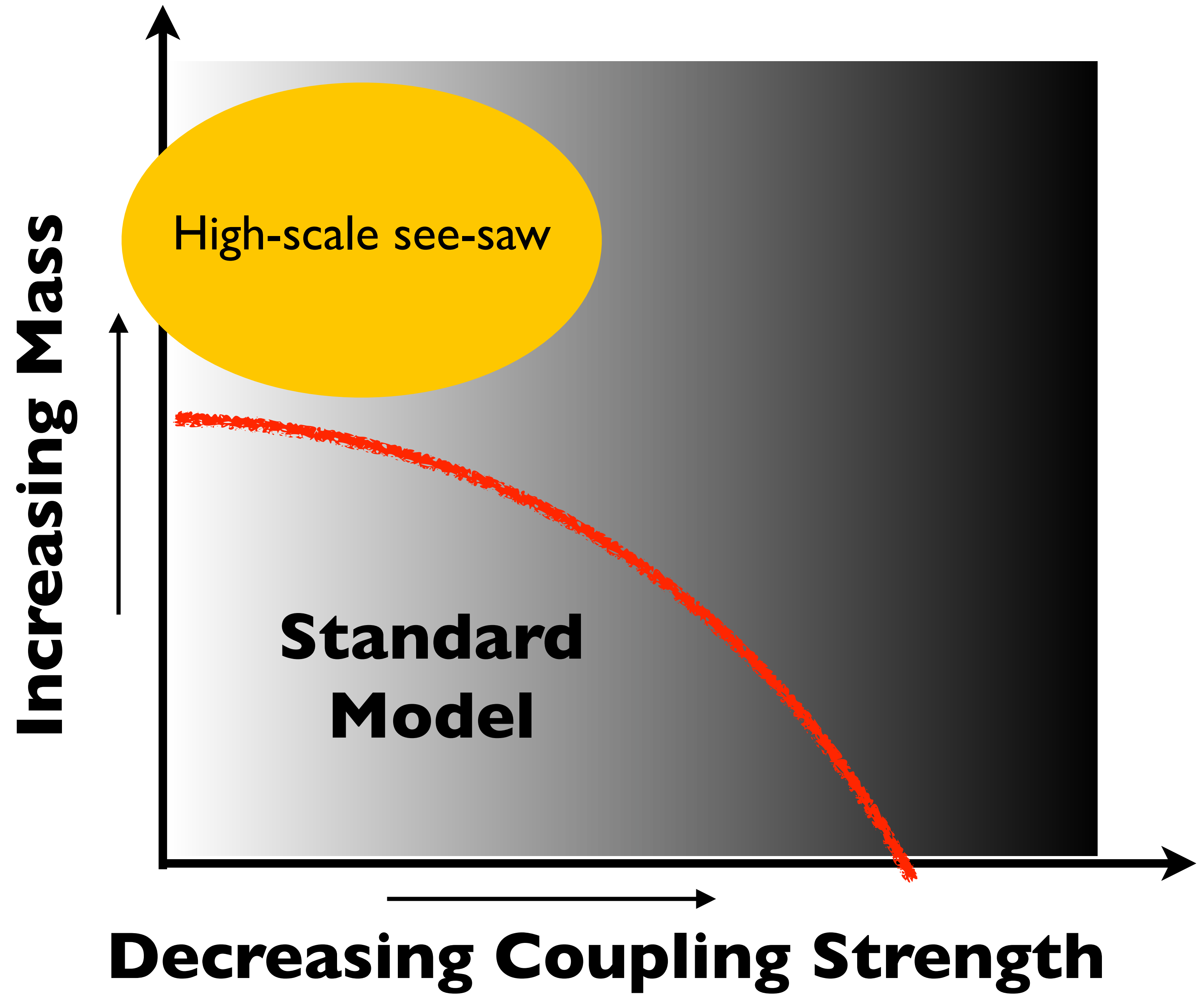
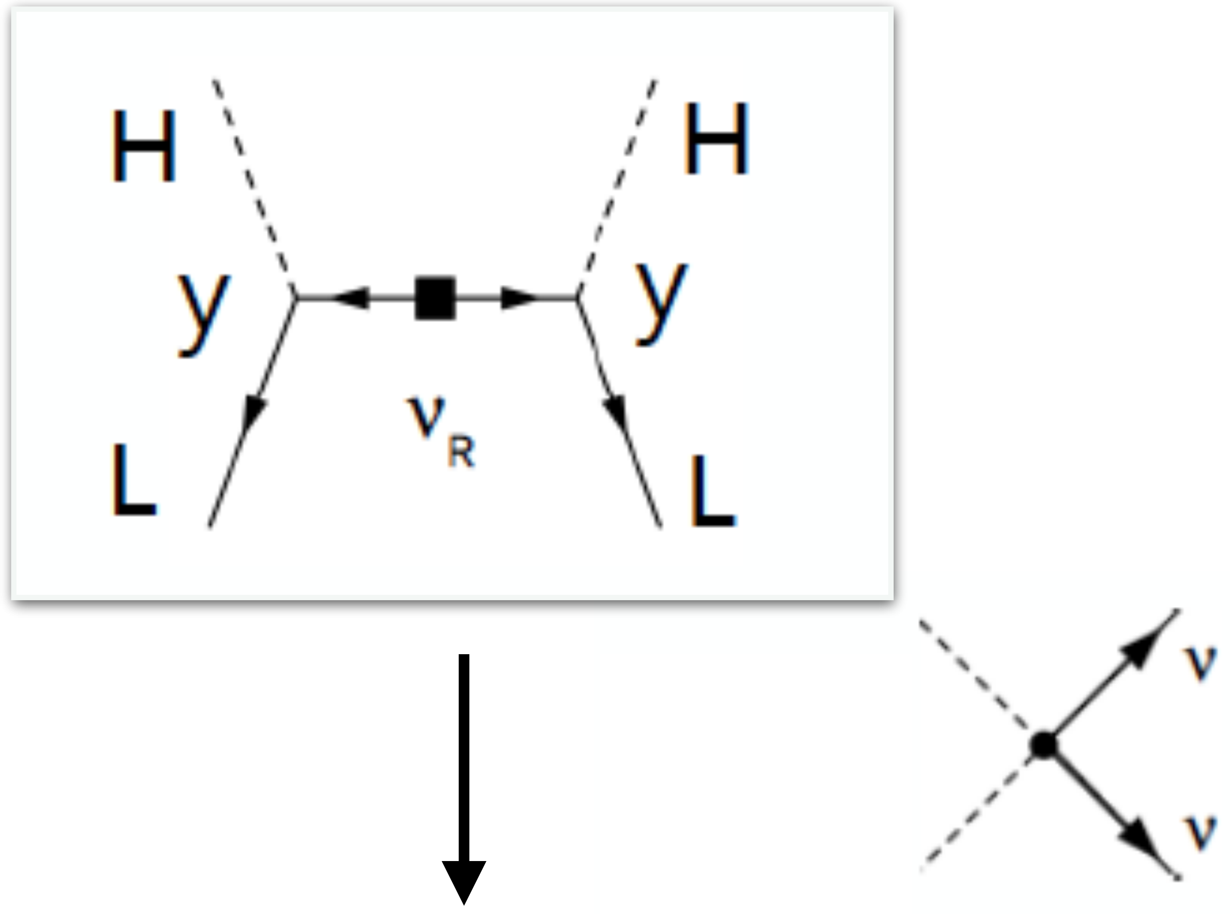
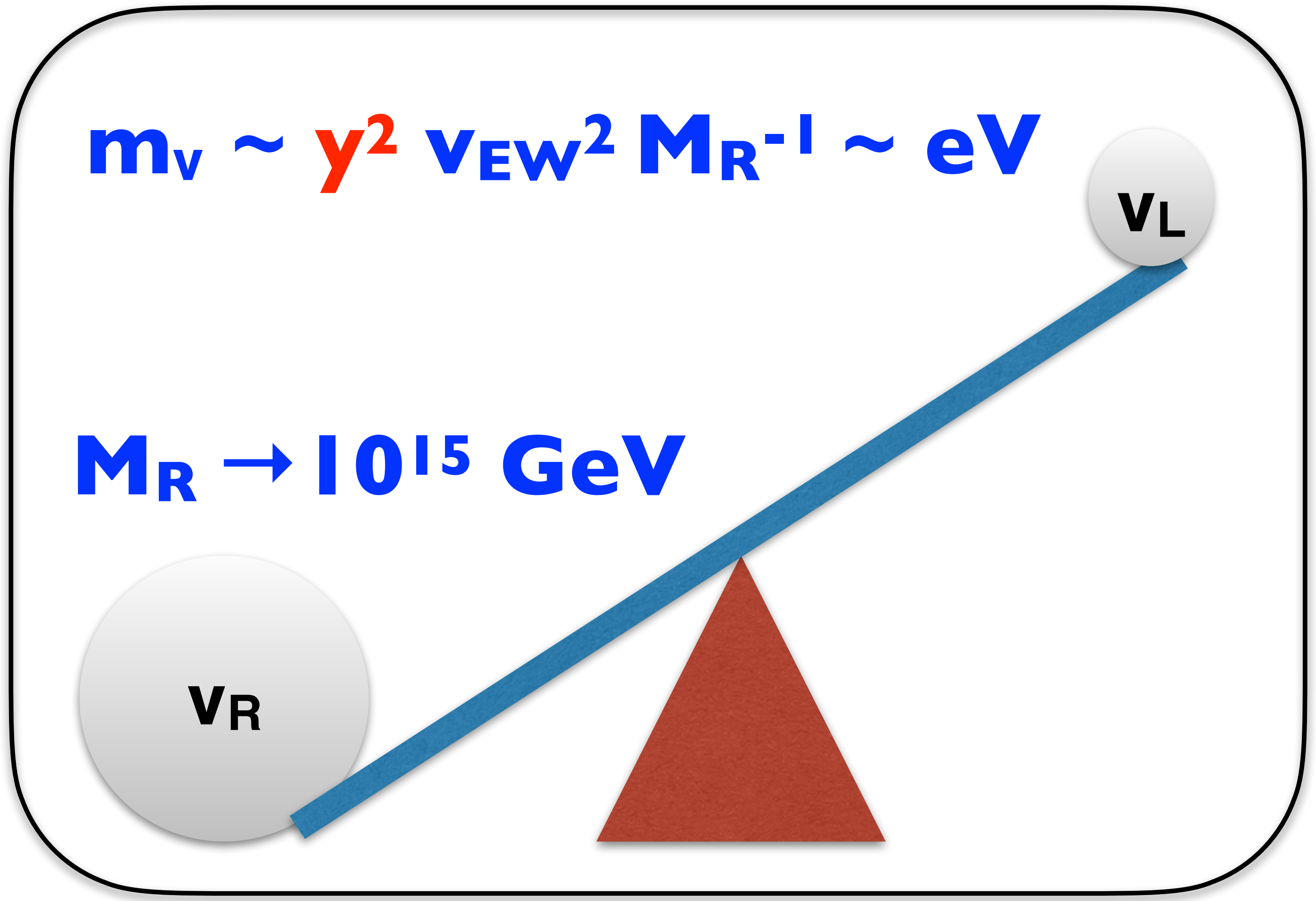


Minkowski 1977
Gell-Mann, Ramond, Slansky 1979



dim5 operator:
Majorana Mass
for light ν's



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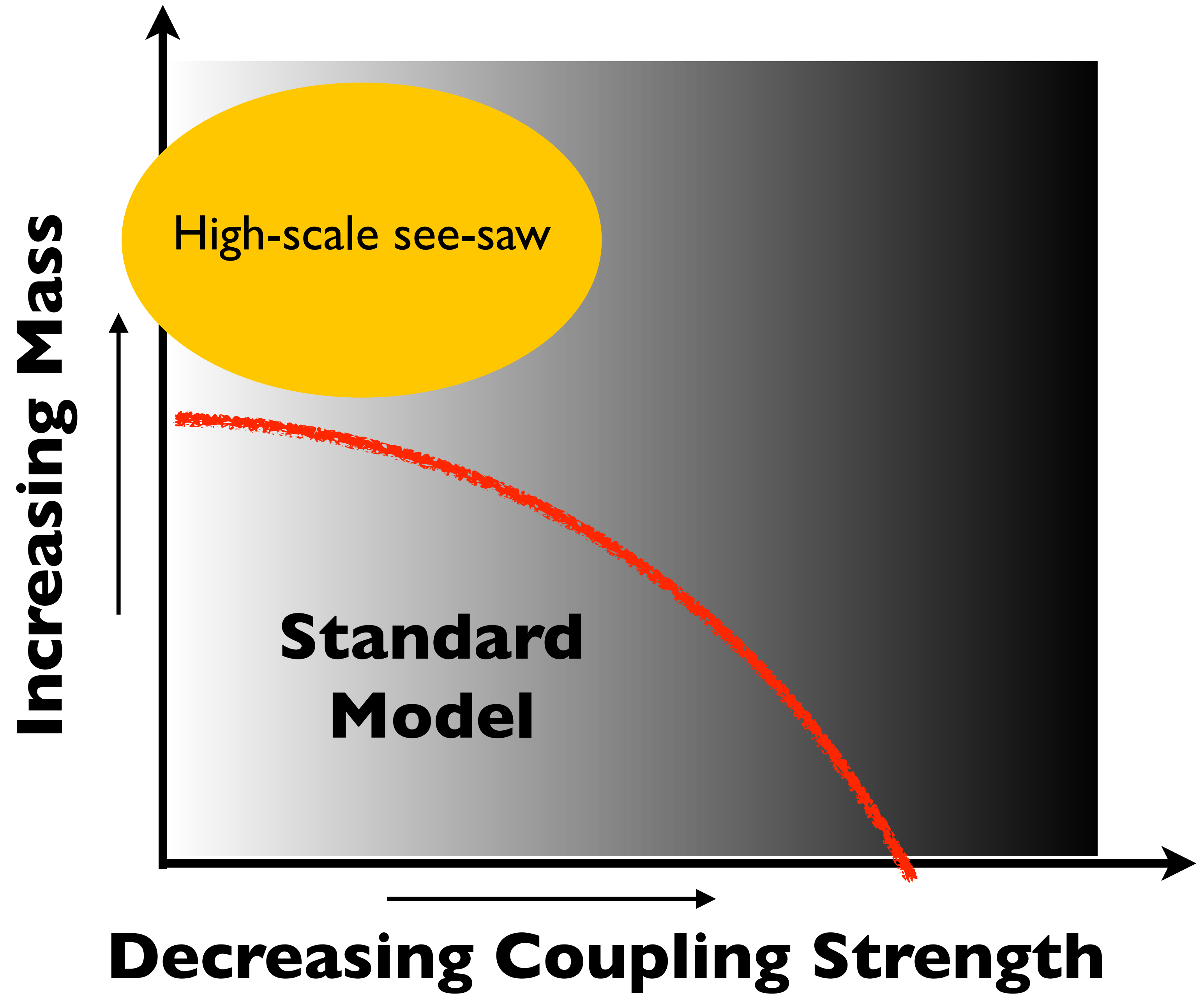

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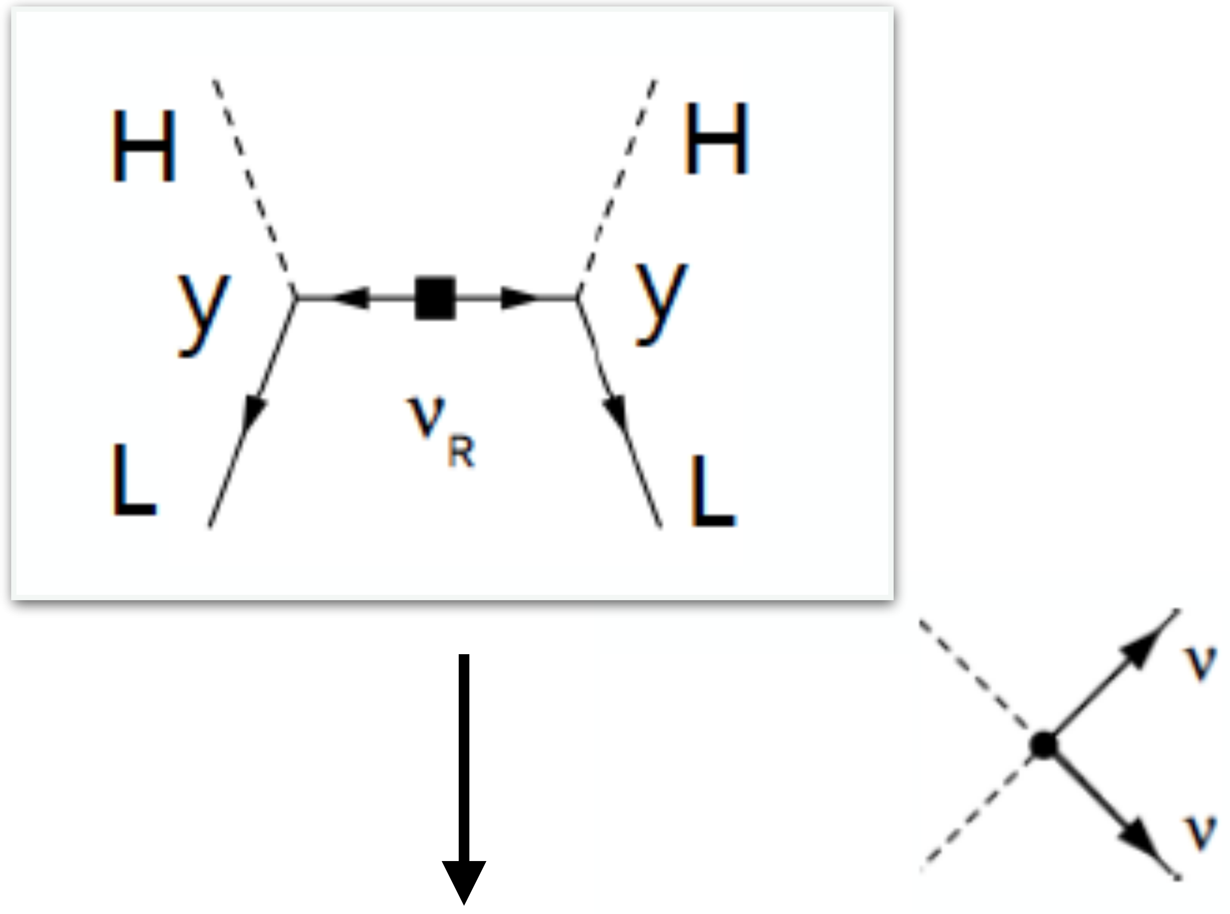
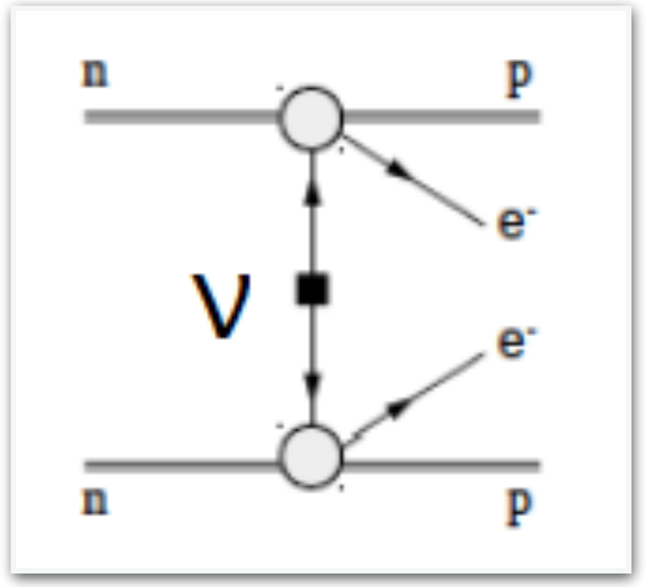


dim5 operator: Majorana Mass for light ν's



Only low-E remnant of LNV is the neutrino mass — Furry's mechanism

0νββ decay physics reach

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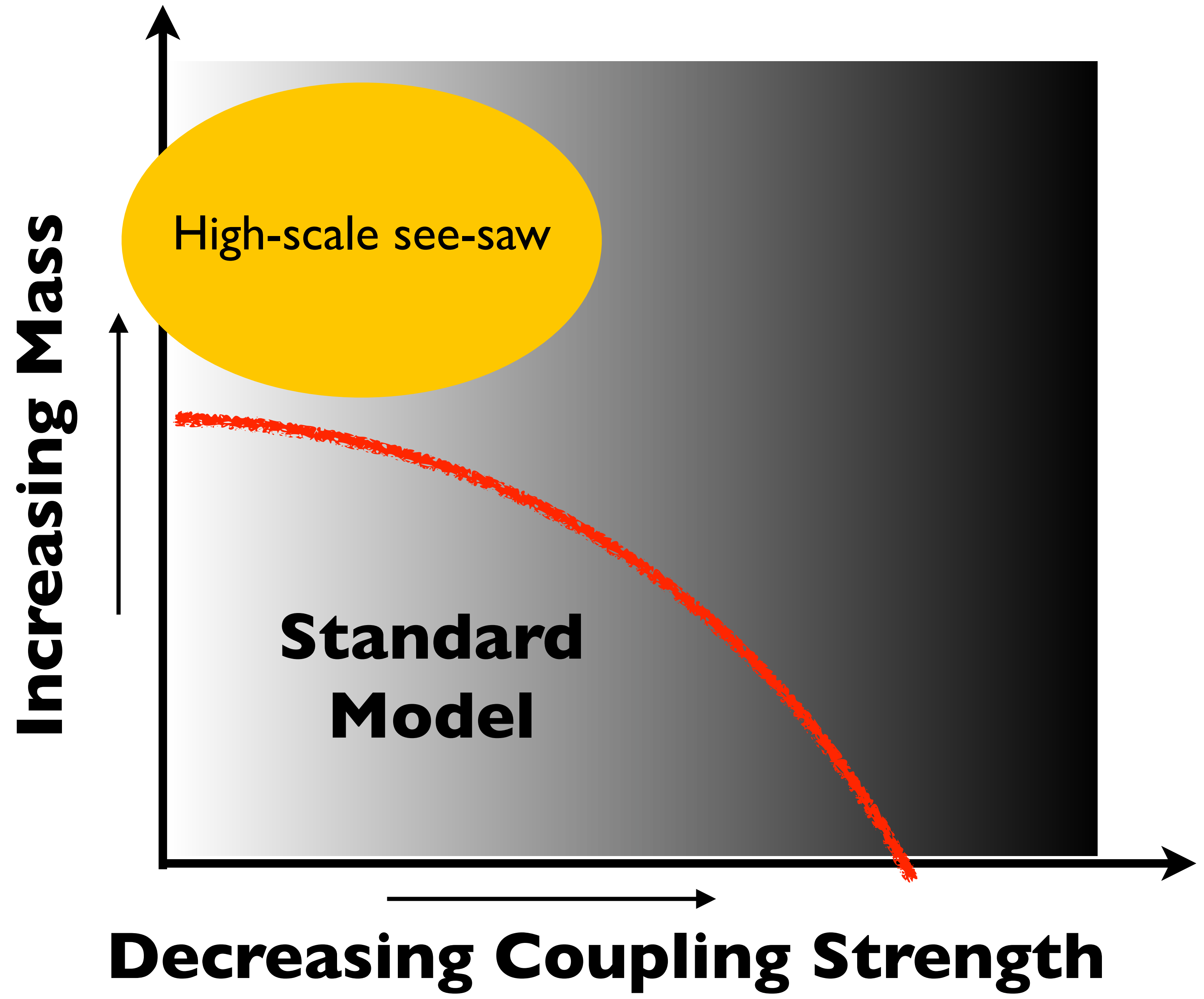
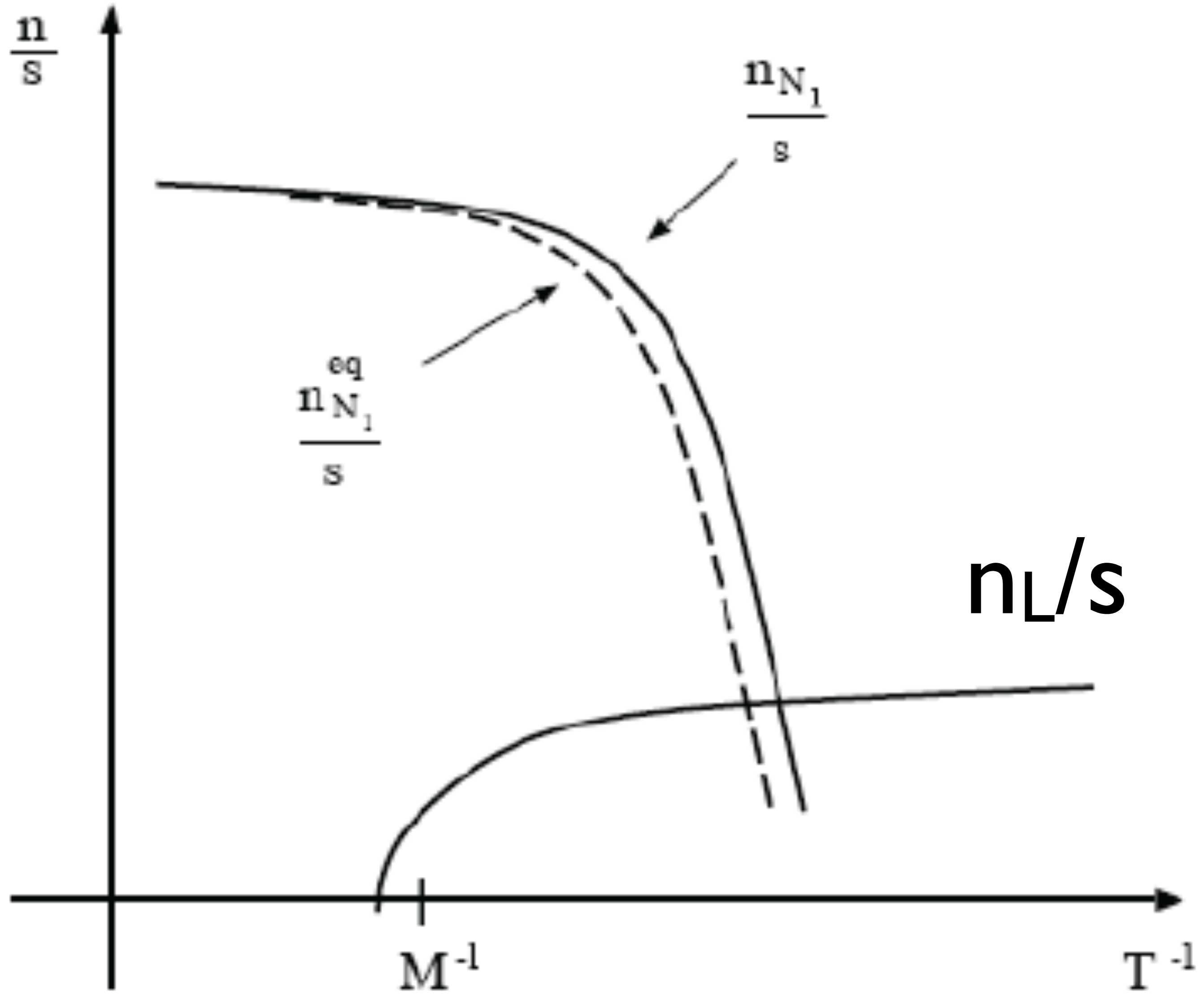


Baryogengesis via Leptogenesis

1) CP- and L- violating out-of-equilibrium decays of heavy $\nu_{Ri} \Rightarrow n_L$

$$\Gamma(\nu_R \to H^* \ell) \neq \Gamma(\nu_R \to H \bar{\ell})$$



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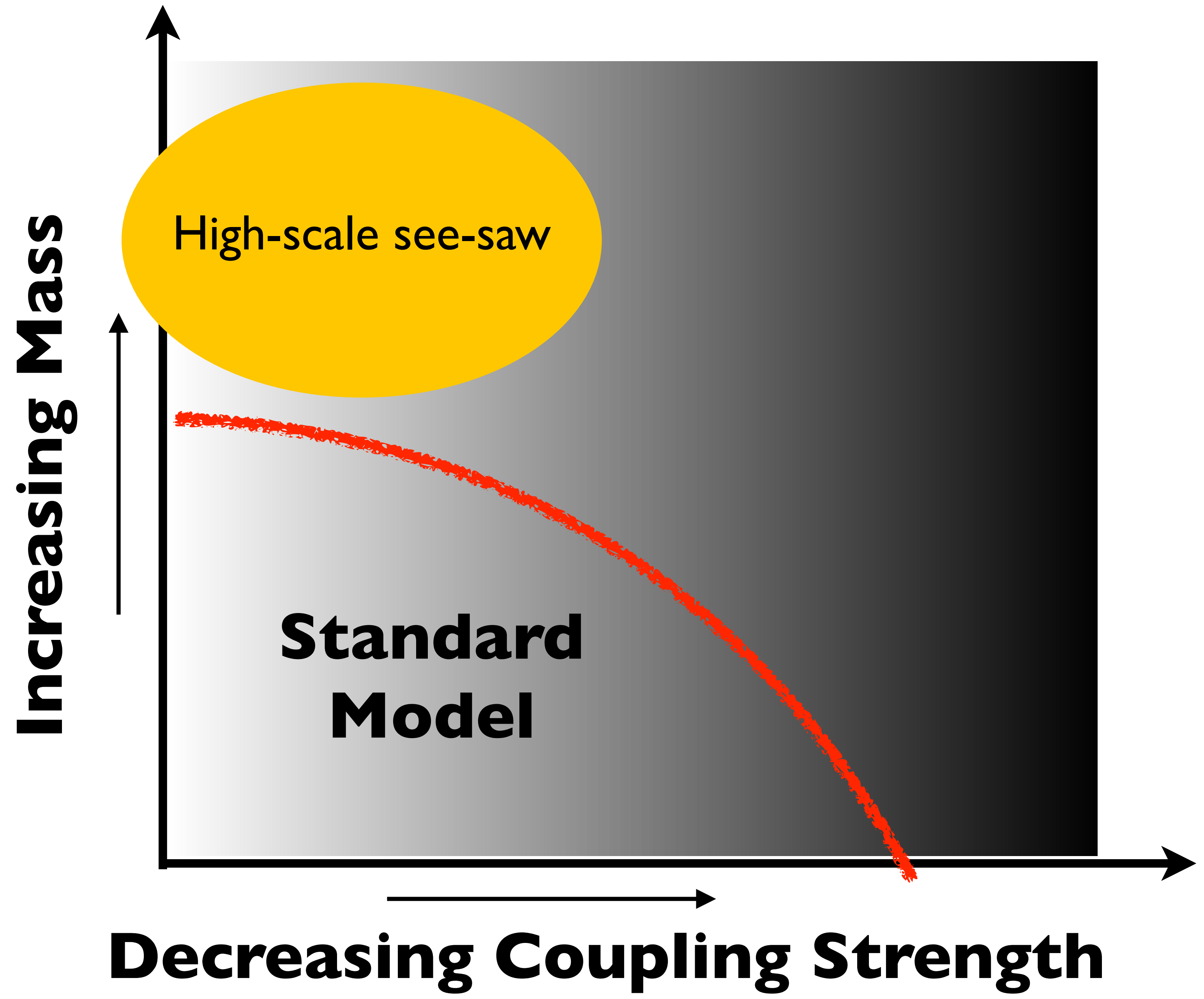

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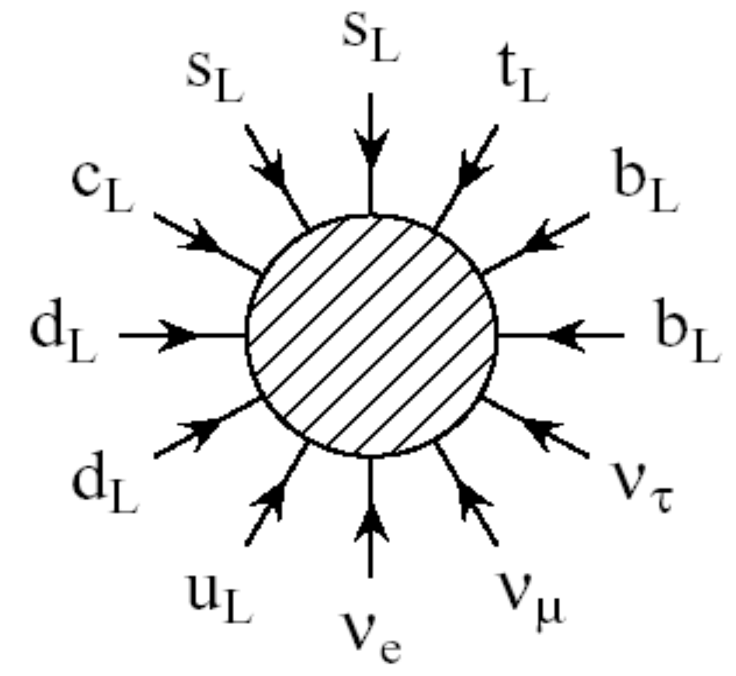
$$\Gamma(\nu_R \to H^* \ell) \neq \Gamma(\nu_R \to H \bar{\ell})$$

2) EW sphalerons ⇒ n_B = # n_L



Fukugita-Yanagida 1987

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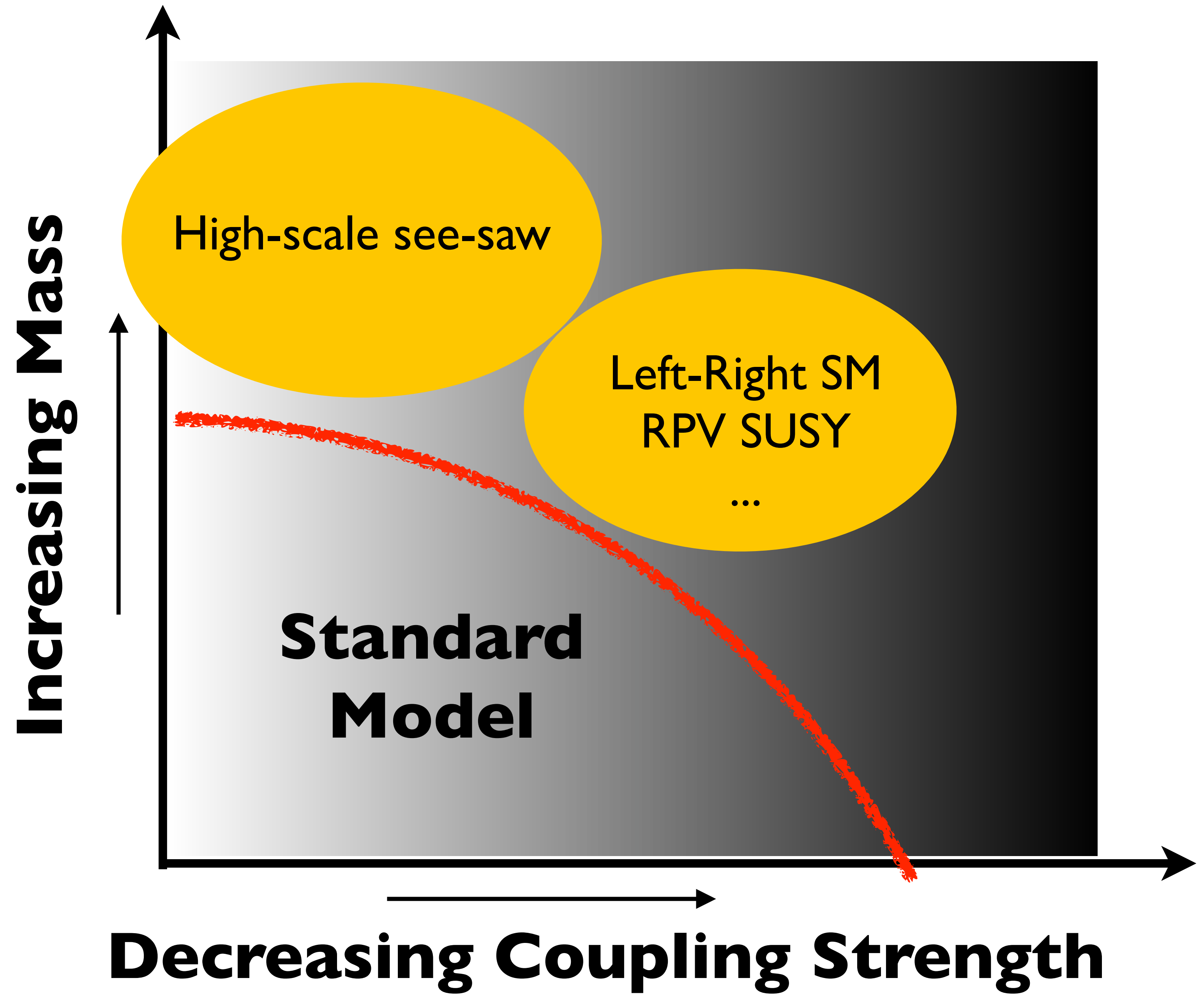
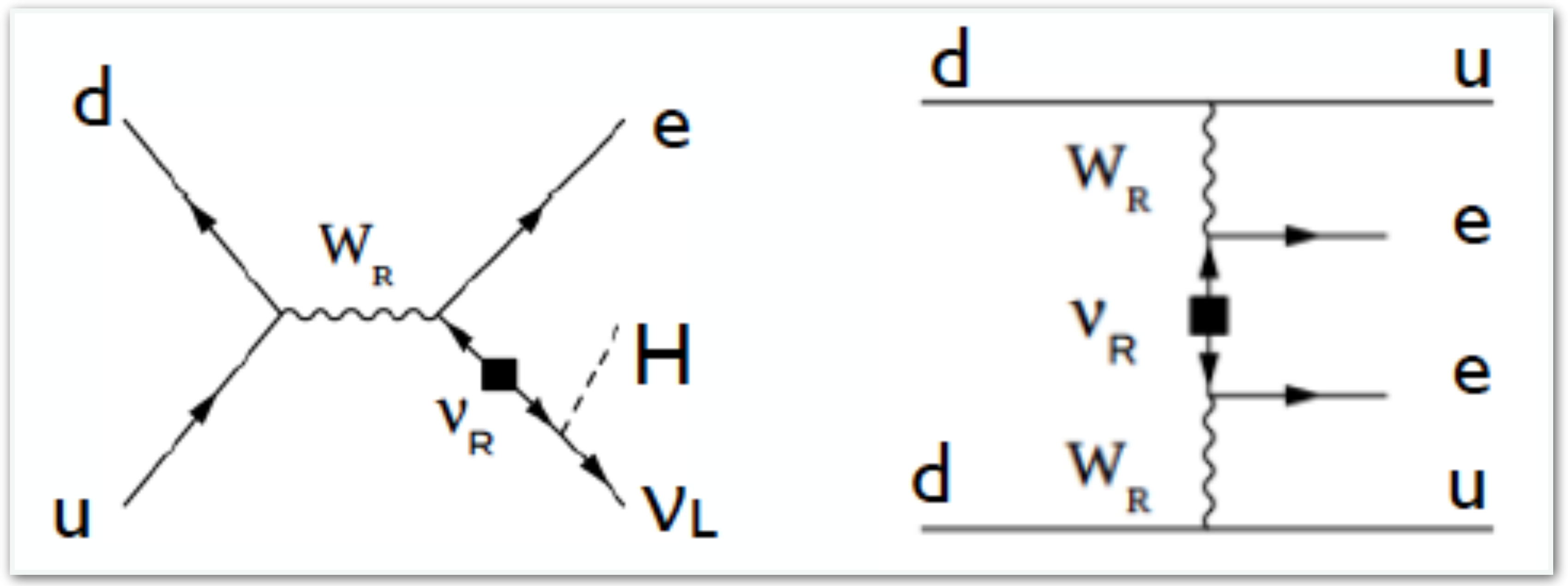
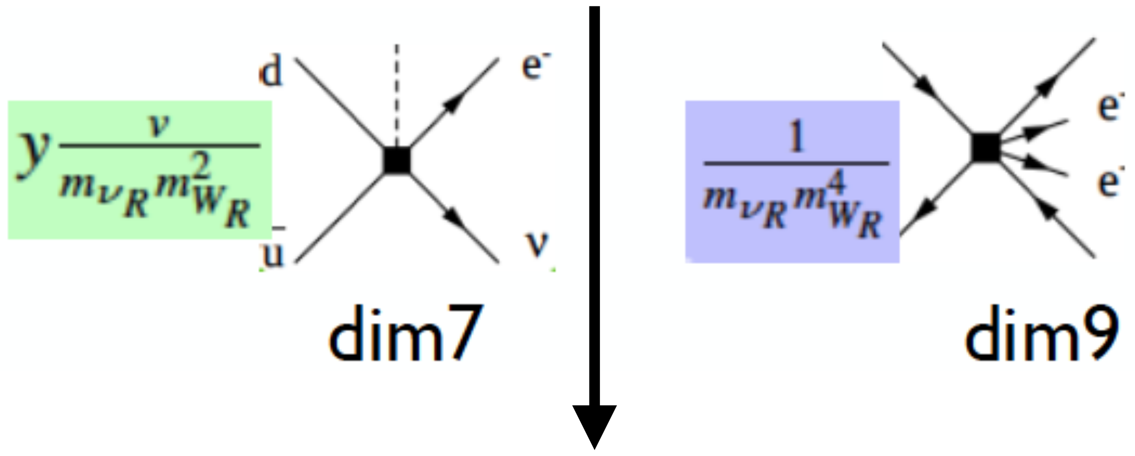
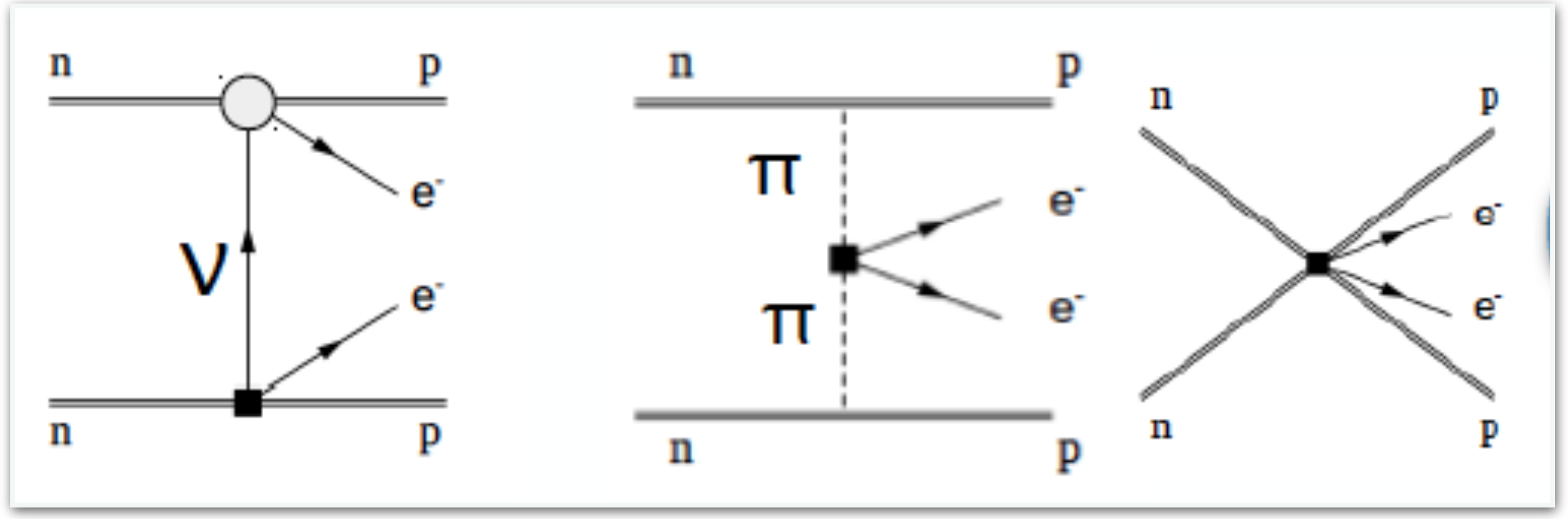


These contributions can compete if scale is not too high (10-100 TeV) and lead to new mechanisms at the nuclear scale

Mohapatra-Senjanovic 1980
...







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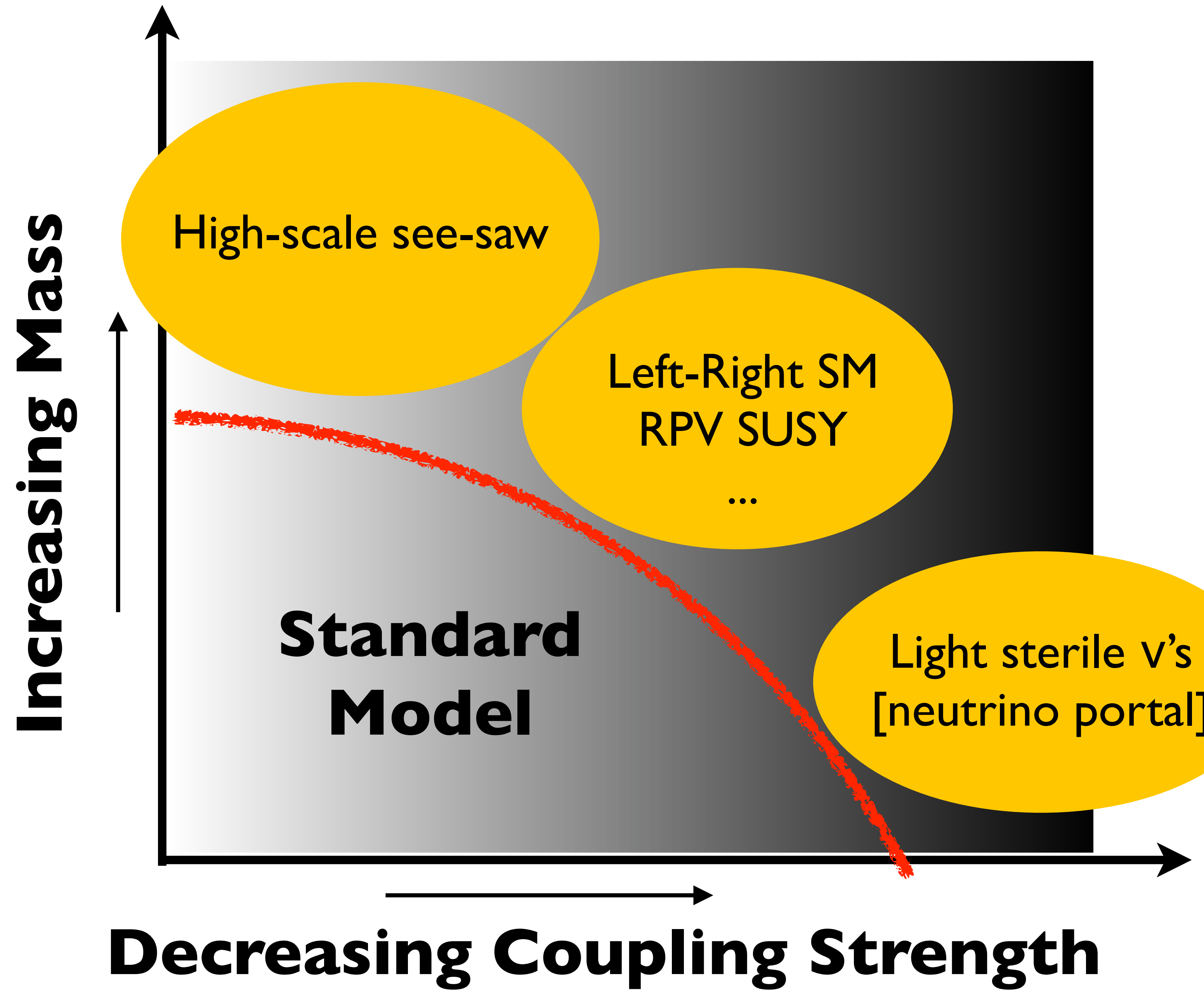
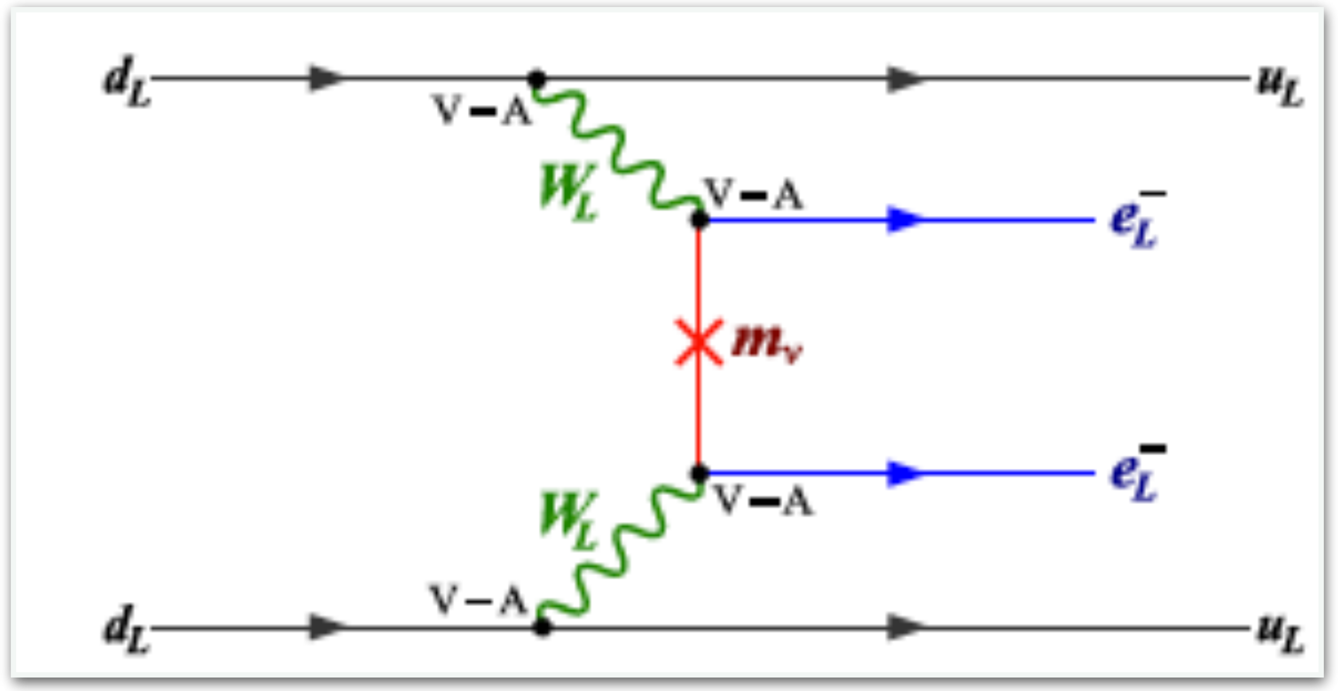
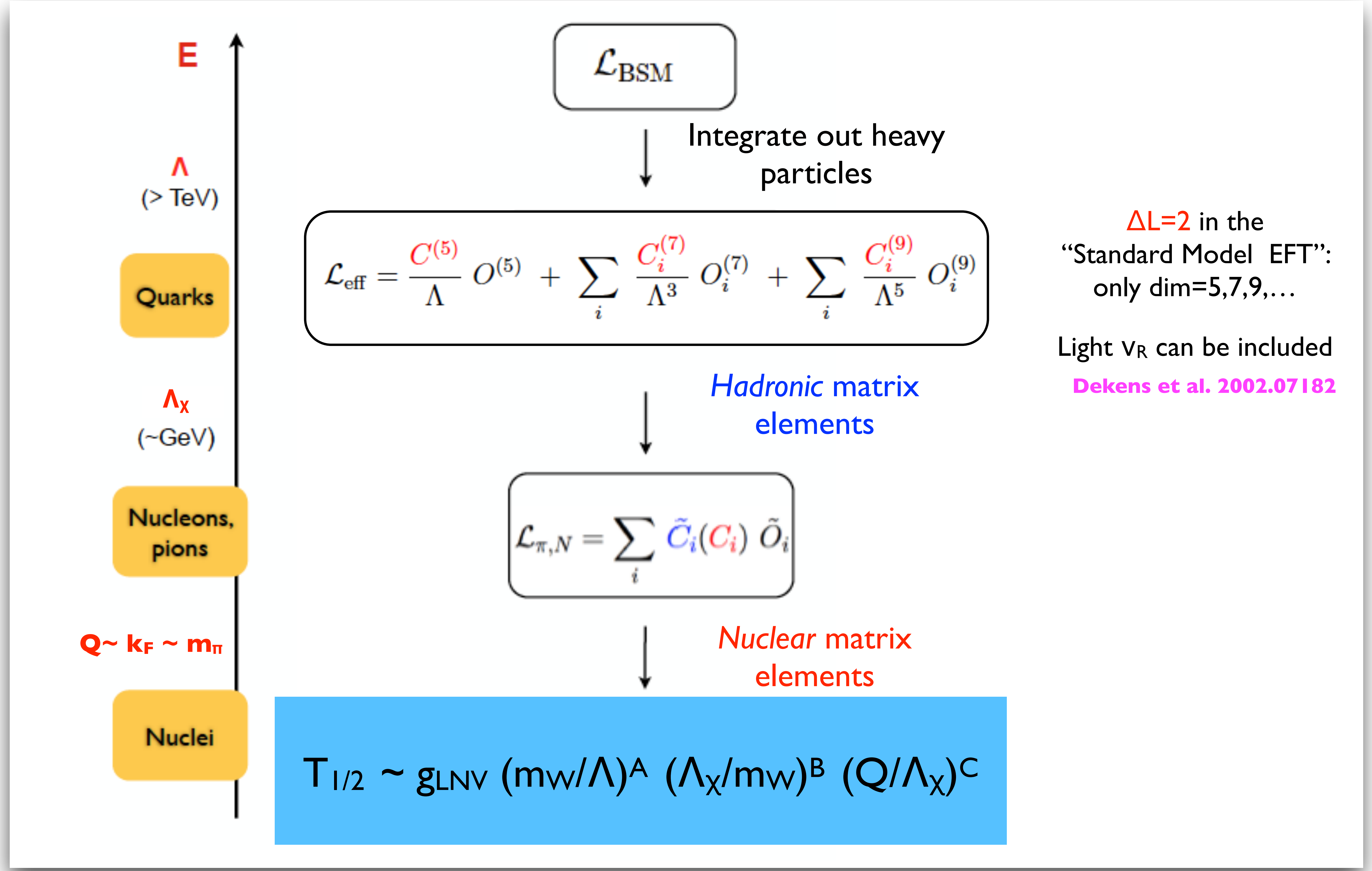




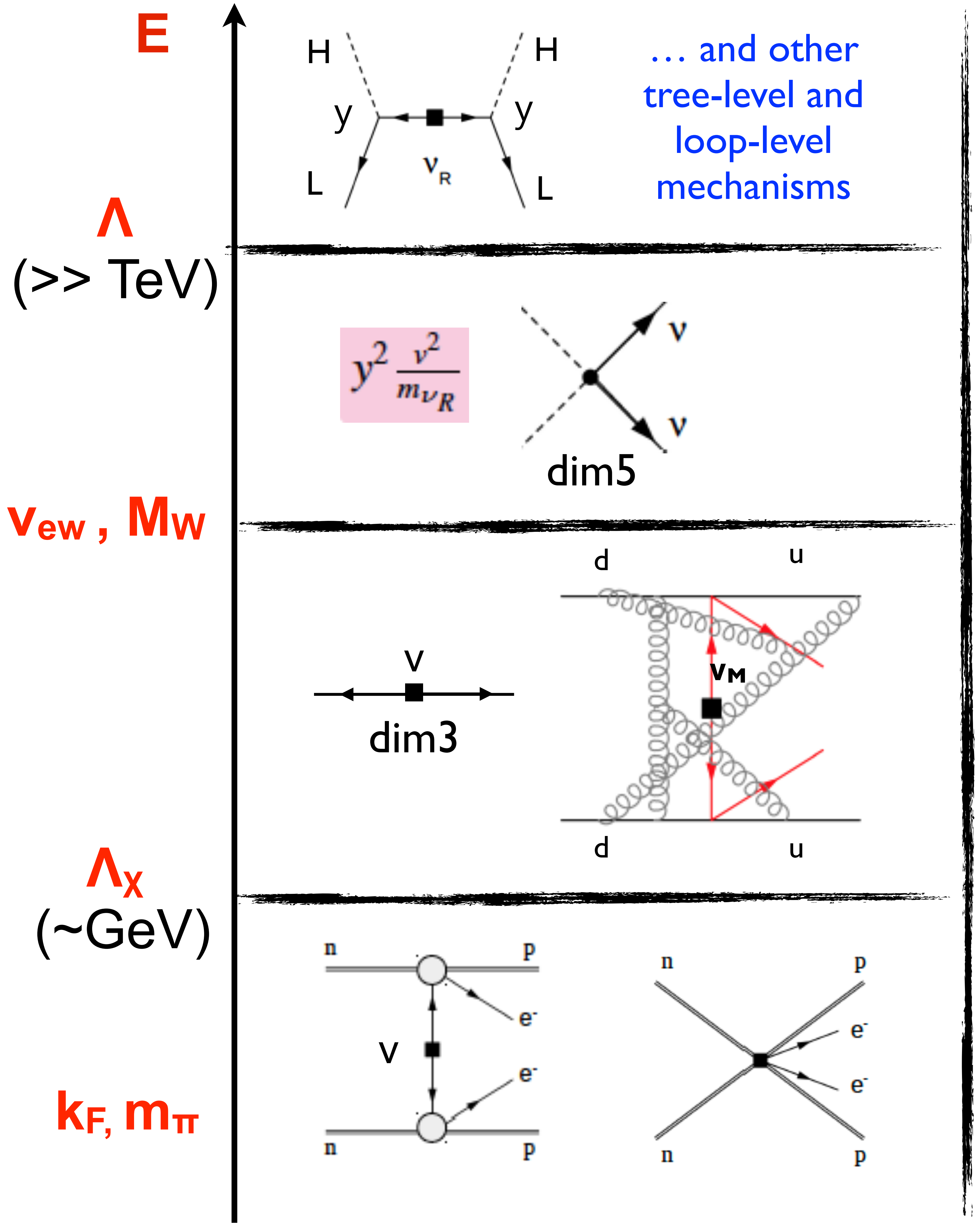
‘End-to-end’ EFT for LNV

Connecting sources of LNV to nuclei is a multi-scale problem. Best tackled through a tower of EFTs coupled to lattice QCD and ab-initio nuclear many-body calculations to achieve controlled uncertainty



White papers 2203. 21169 & 2207.01085 and refs therein

High scale LNV



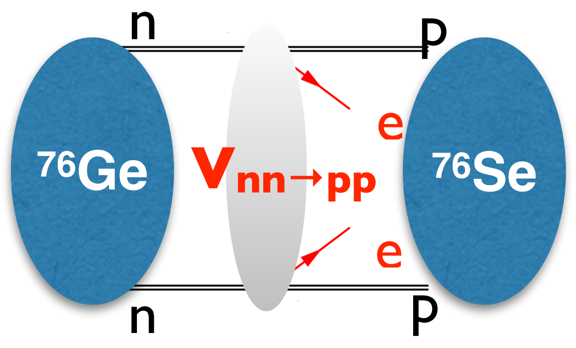
- LNV originates at very high scale ($\Lambda >> v$) → dominant low-energy remnant is Weinberg's dim-5 operator:

$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L_\alpha^T C \epsilon H \, H^T \epsilon L_{\alpha'}$$

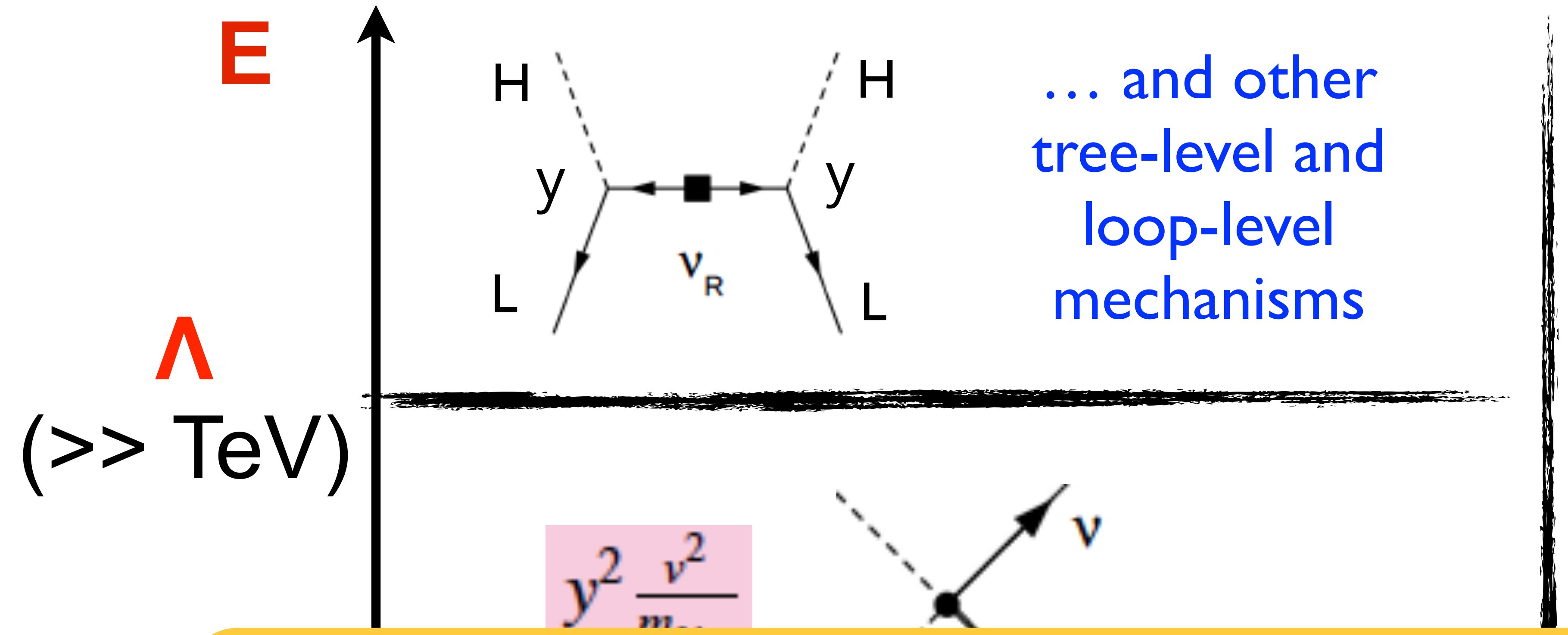
- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee} \, v^2/\Lambda$)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}} V_{ud} \, \bar{u}_L \gamma^\mu d_L \, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + {\rm H.c.}$$

- 0νββ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$



High scale LNV



- LNV originates at very high scale (Λ >> v) → dominant low-energy remnant is Weinberg's dim-5 operator:

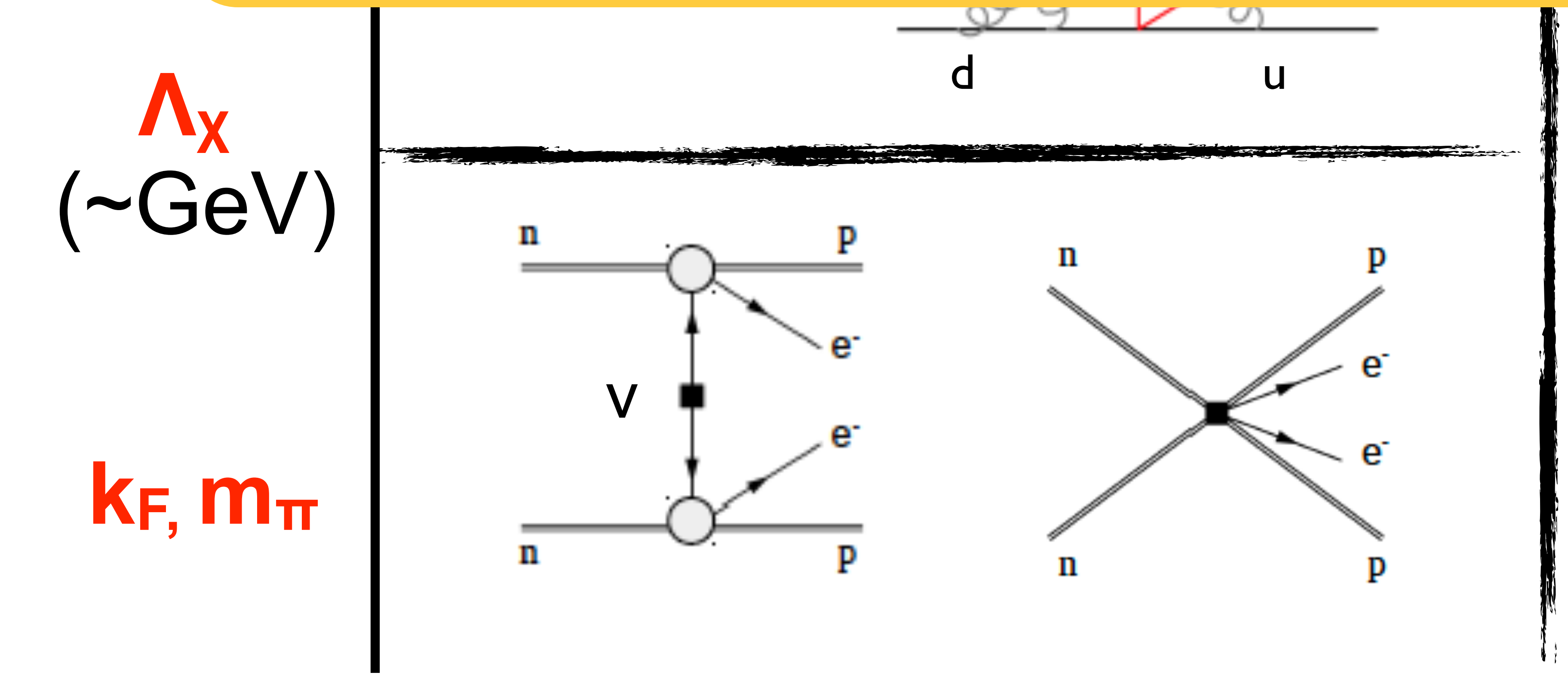
$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L^T_\alpha C\epsilon H \, H^T \epsilon L_{\alpha'}$$

We have already discovered other effects of this dim-5 operator!

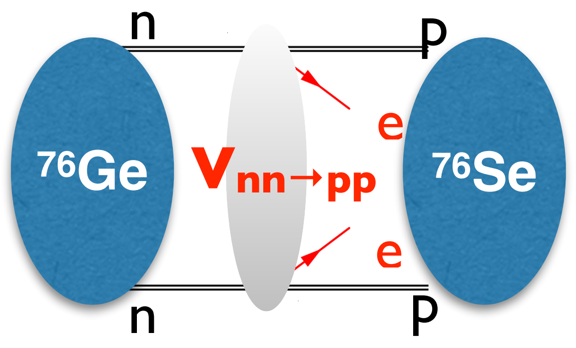
⇒

Half-life is related to neutrino mass:

concrete discovery targets & falsifiable correlations with other probes of m_ν



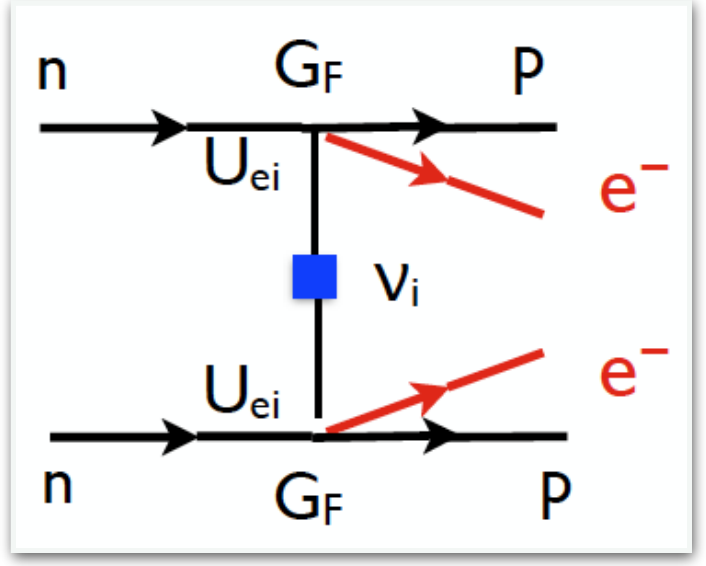
- 0νββ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$



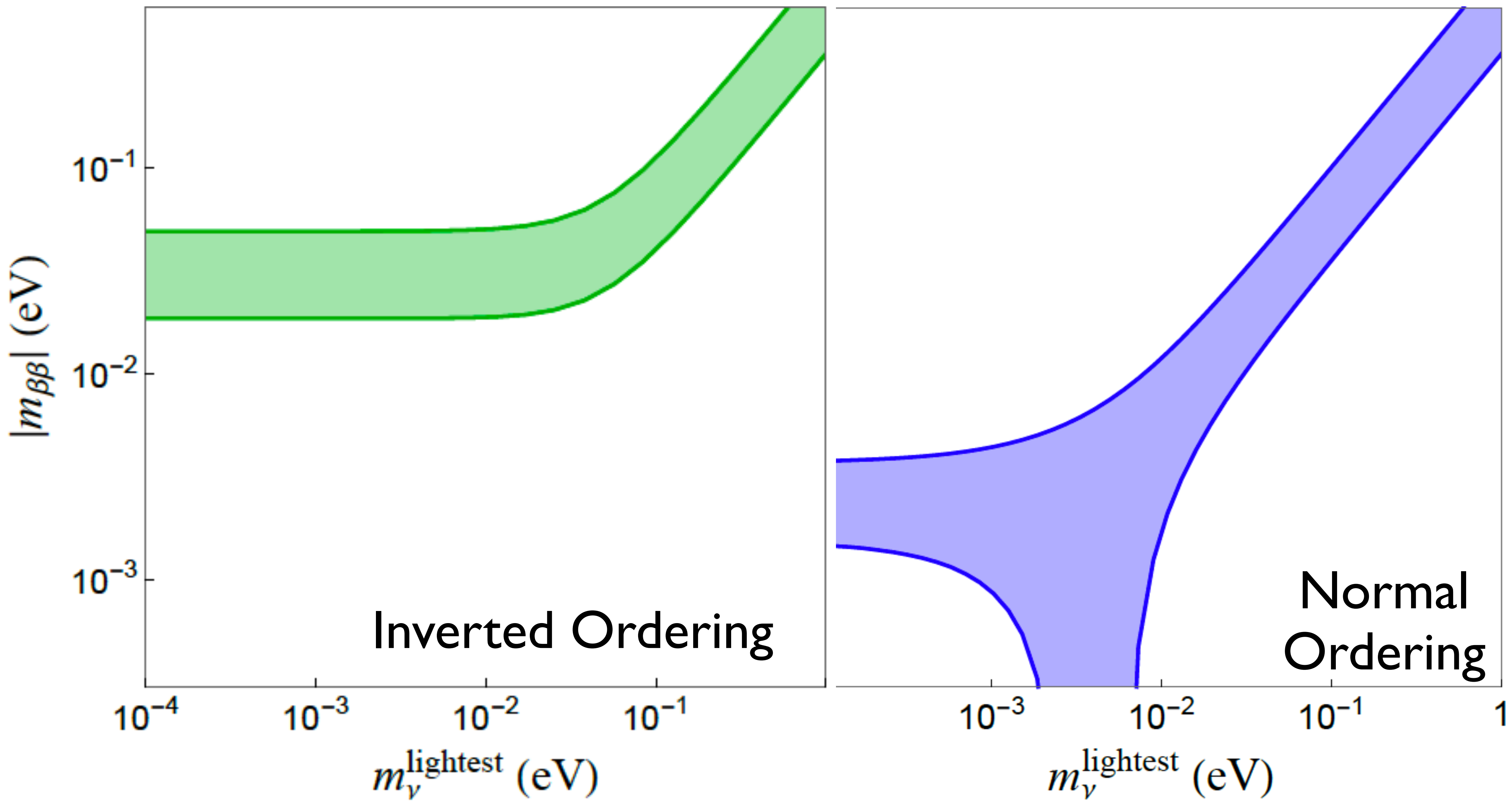
Discovery potential / target

- Within the high-scale seesaw, $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



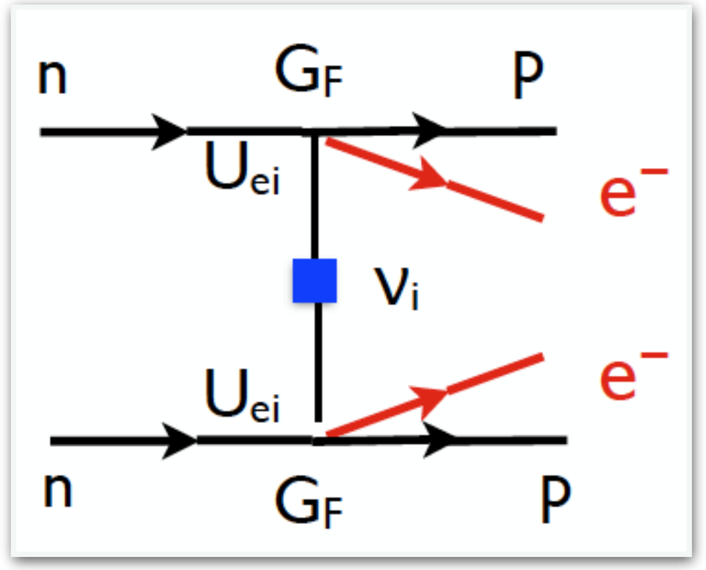
Bands: unknown Majorana phases

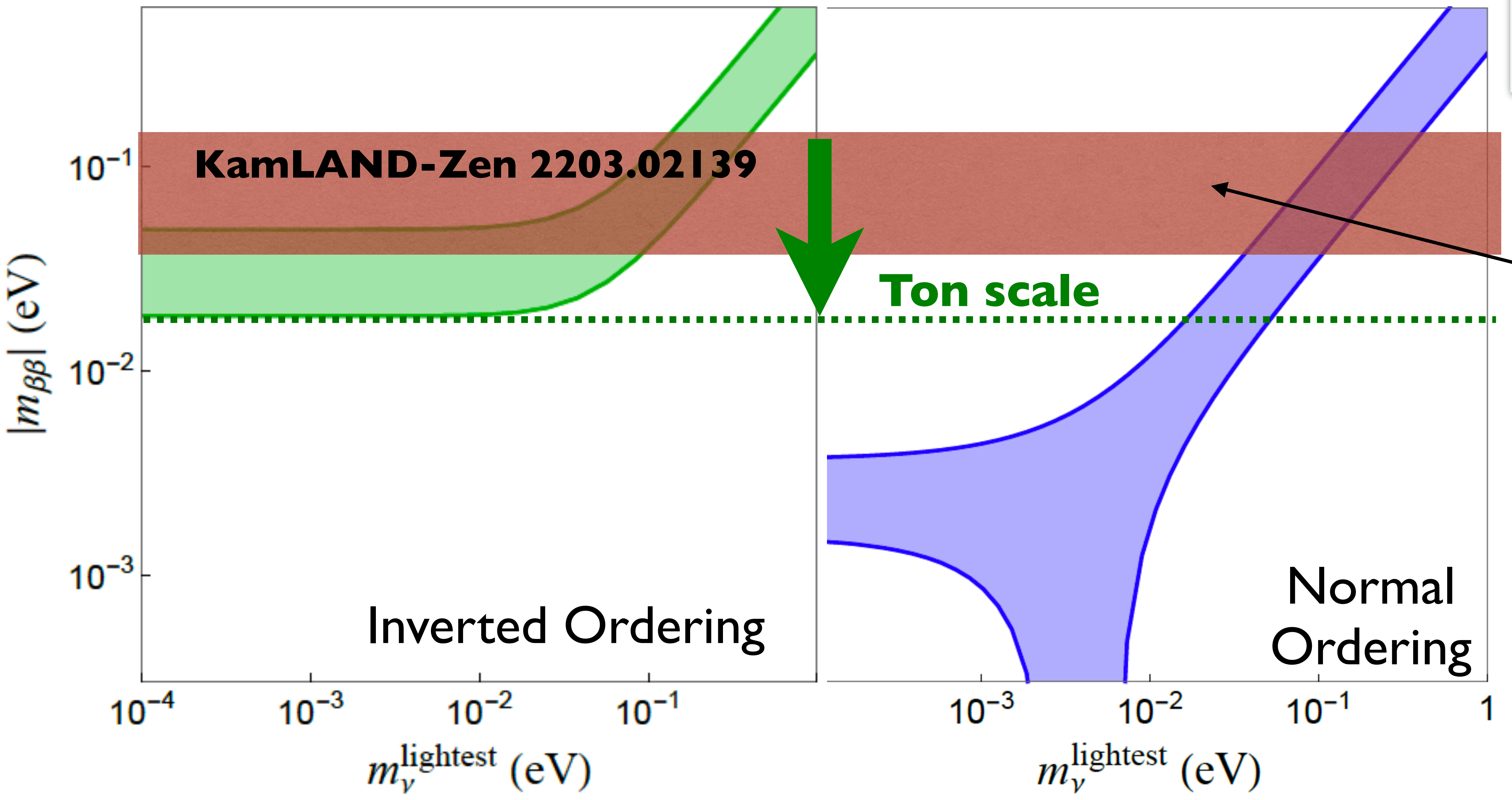


Discovery potential / target

- Within the high-scale seesaw, $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$





Bands: unknown Majorana phases

Assume range for nuclear matrix elements from different nuclear calculations

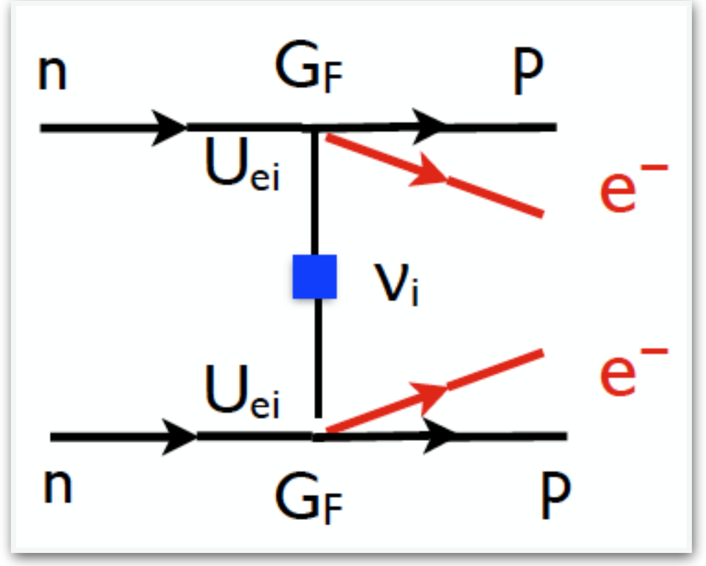
Assuming current range for matrix elements,

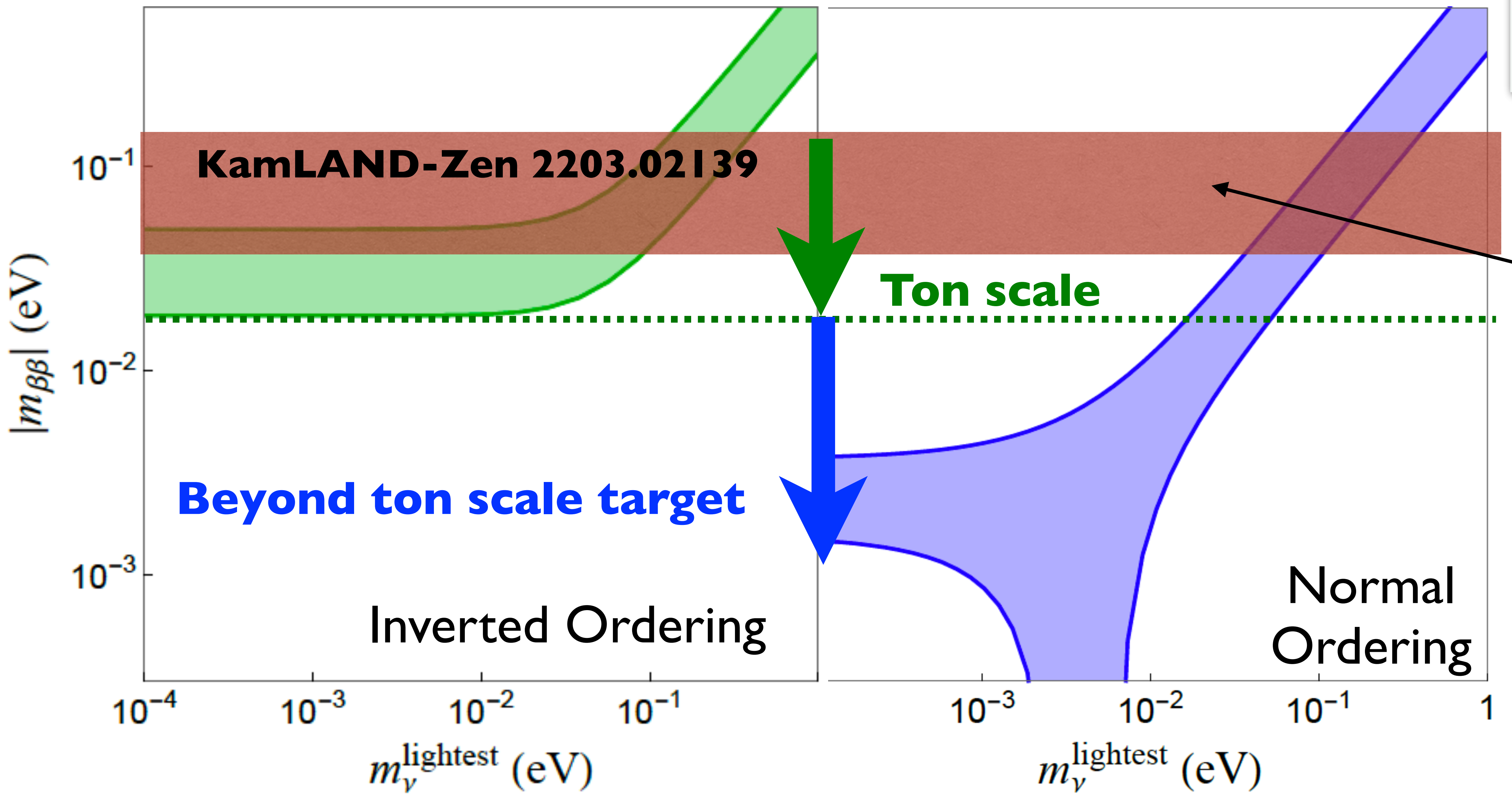
discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

Discovery potential / target

- Within the high-scale seesaw, $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$





Bands: unknown Majorana phases

Assume range for nuclear matrix elements from different nuclear calculations

Natural (but challenging!) beyond ton-scale target is $m_{\beta\beta} \sim$ meV

Falsifiable correlations

Future data coupled with improved theory can challenge the high-scale paradigm and reveal new sources of LNV or physics beyond "ΛCDM + m_ν"

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2\, m_i\right|$$

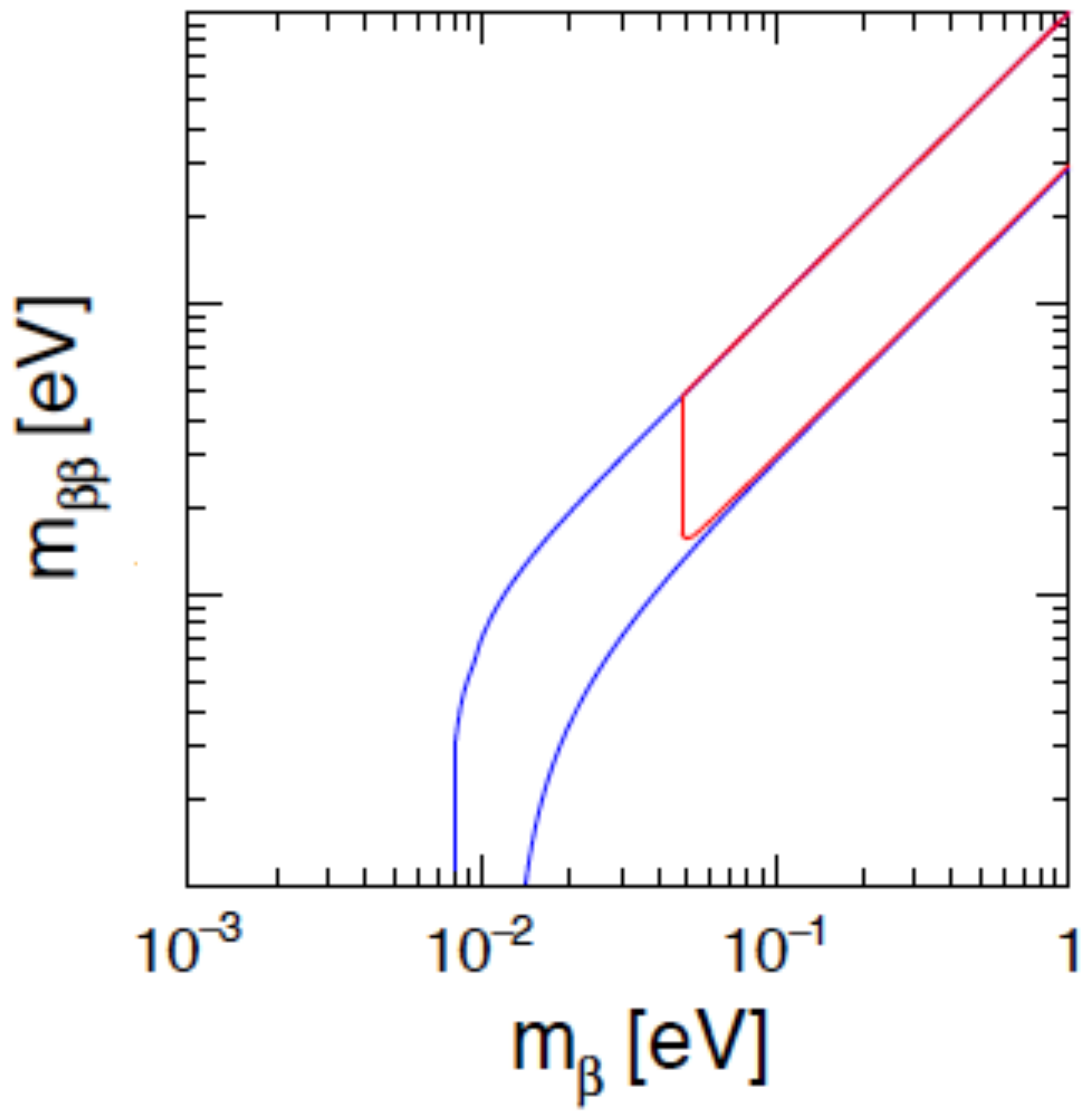
$0\nu\beta\beta$ decay

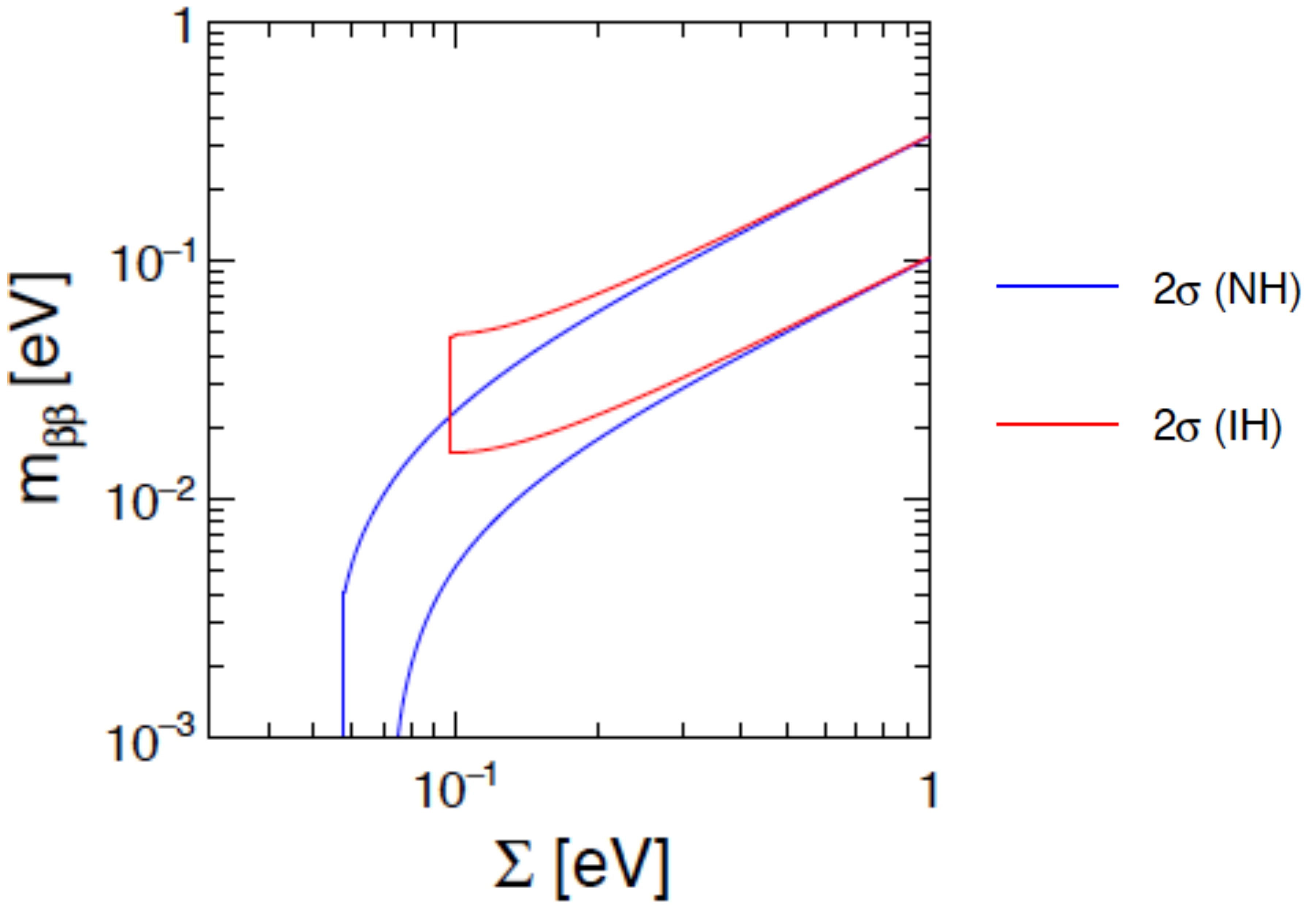
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





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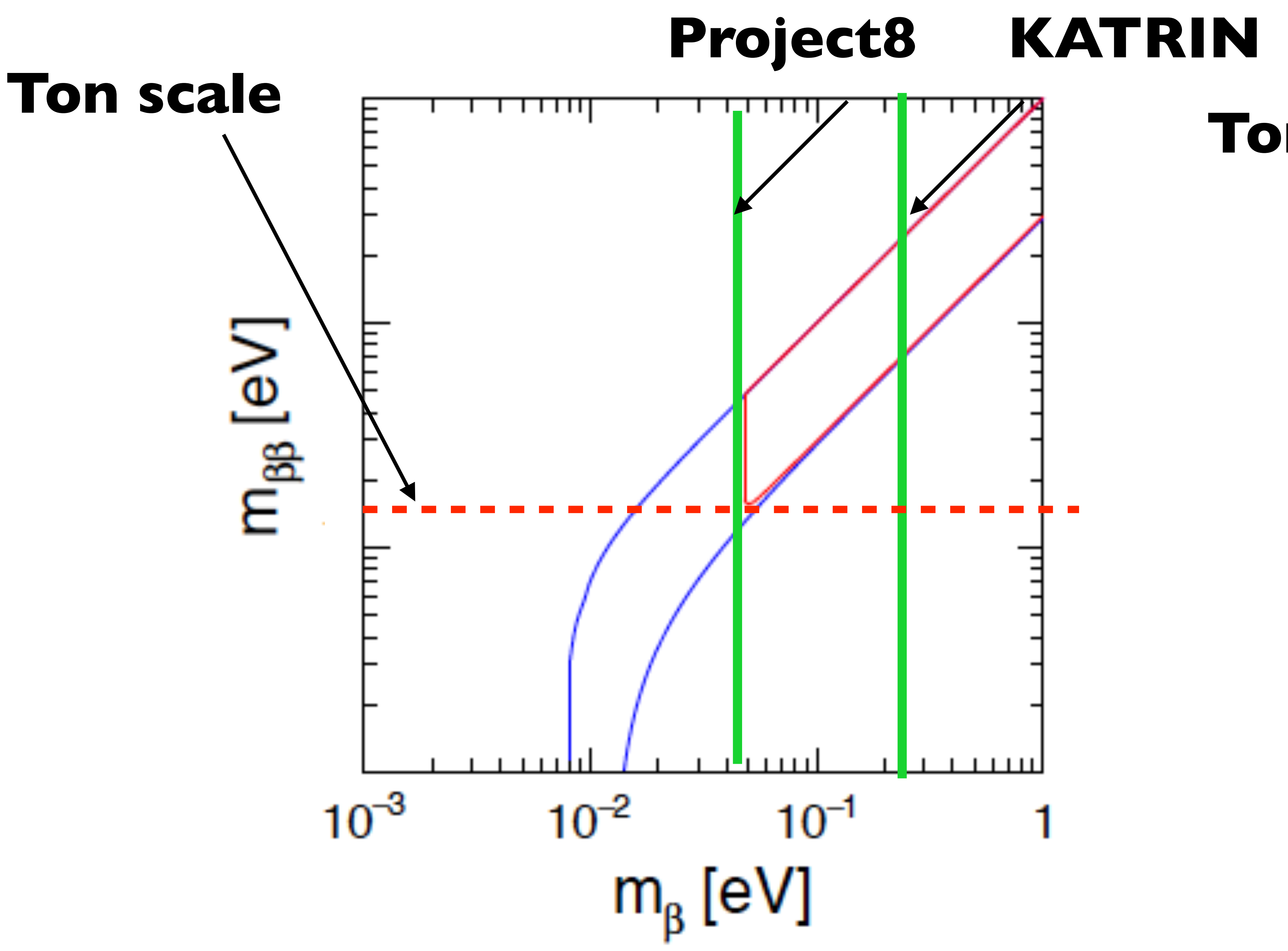

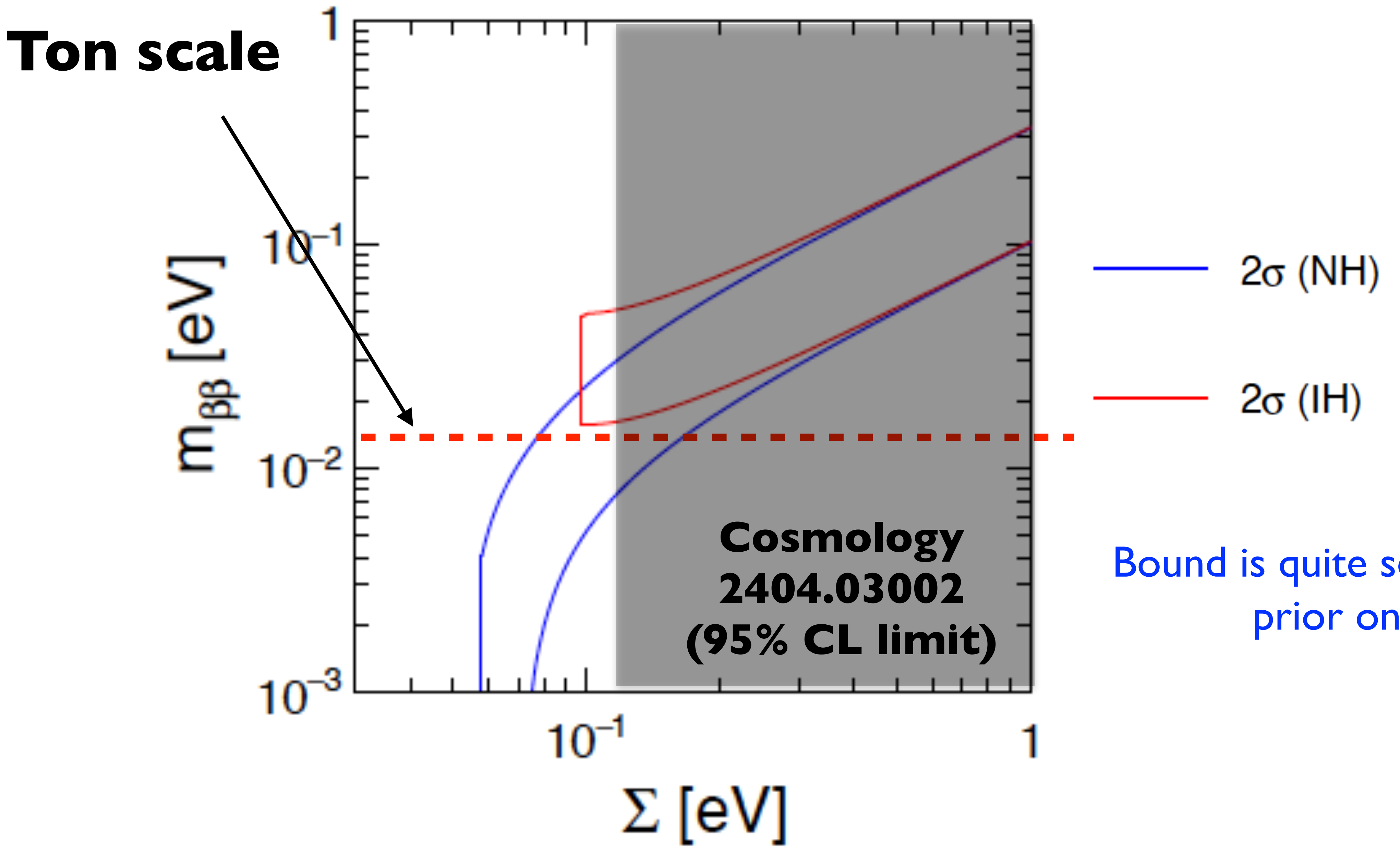

Bound is quite sensitive to prior on Σ

Falsifiable correlations

Future data coupled with improved theory can challenge the high-scale paradigm and reveal new sources of LNV or physics beyond "ΛCDM + m_ν"

$$m_{\beta\beta} = \left| \sum U_{ei}^2 \, m_i \right|$$

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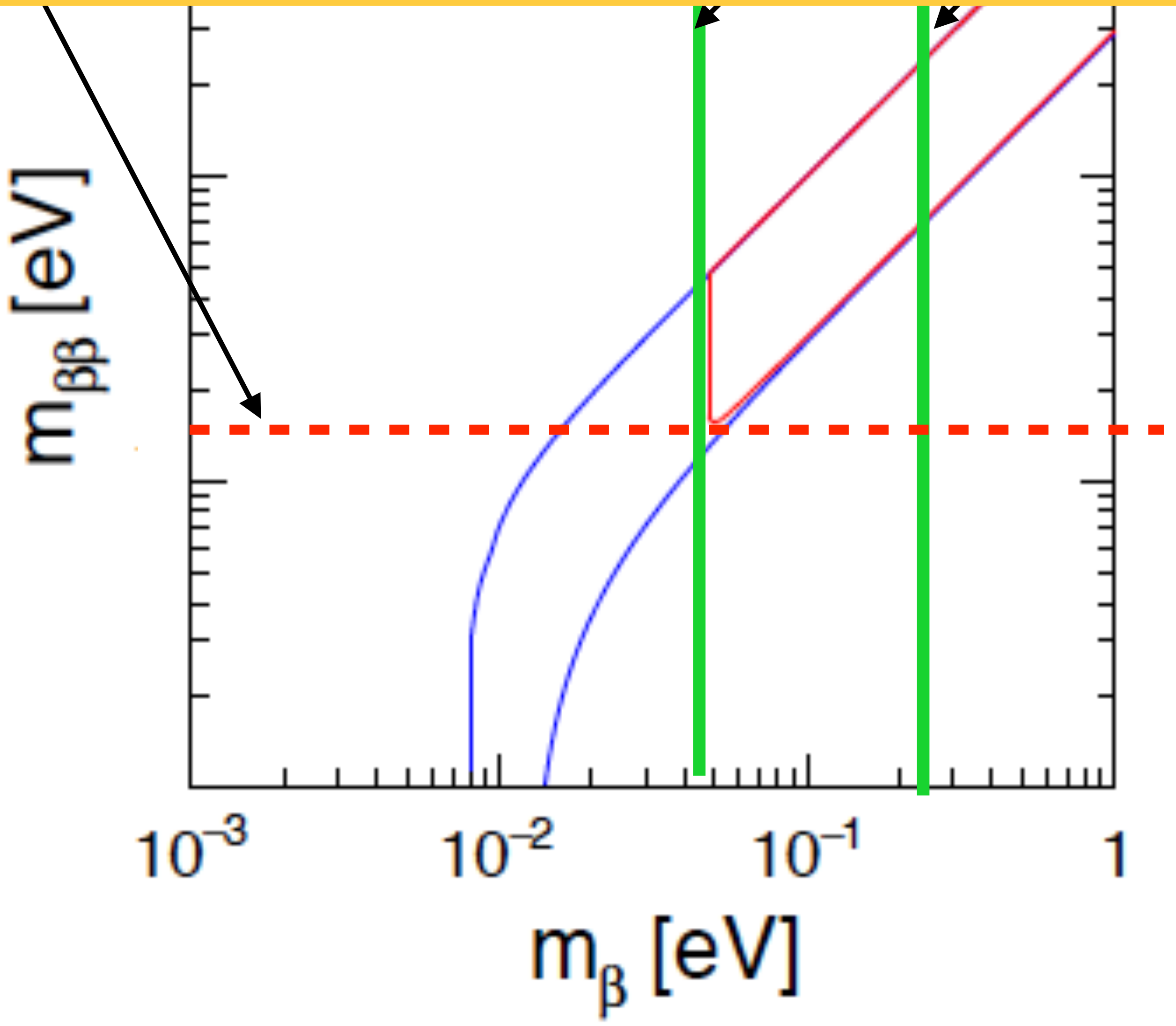
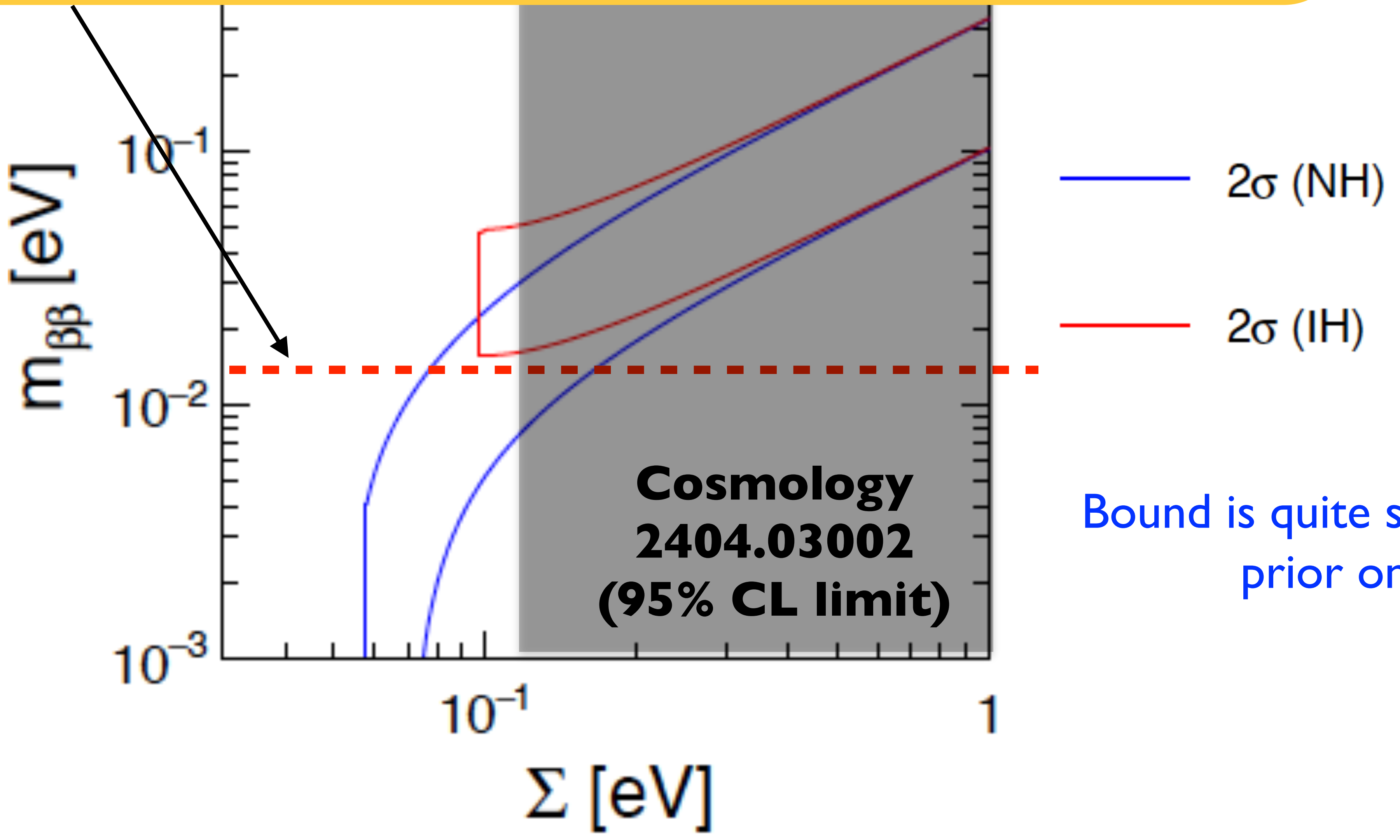
$$\Sigma = \sum m_i$$

These important *quantitative* connections require knowing nuclear matrix elements and their uncertainties!





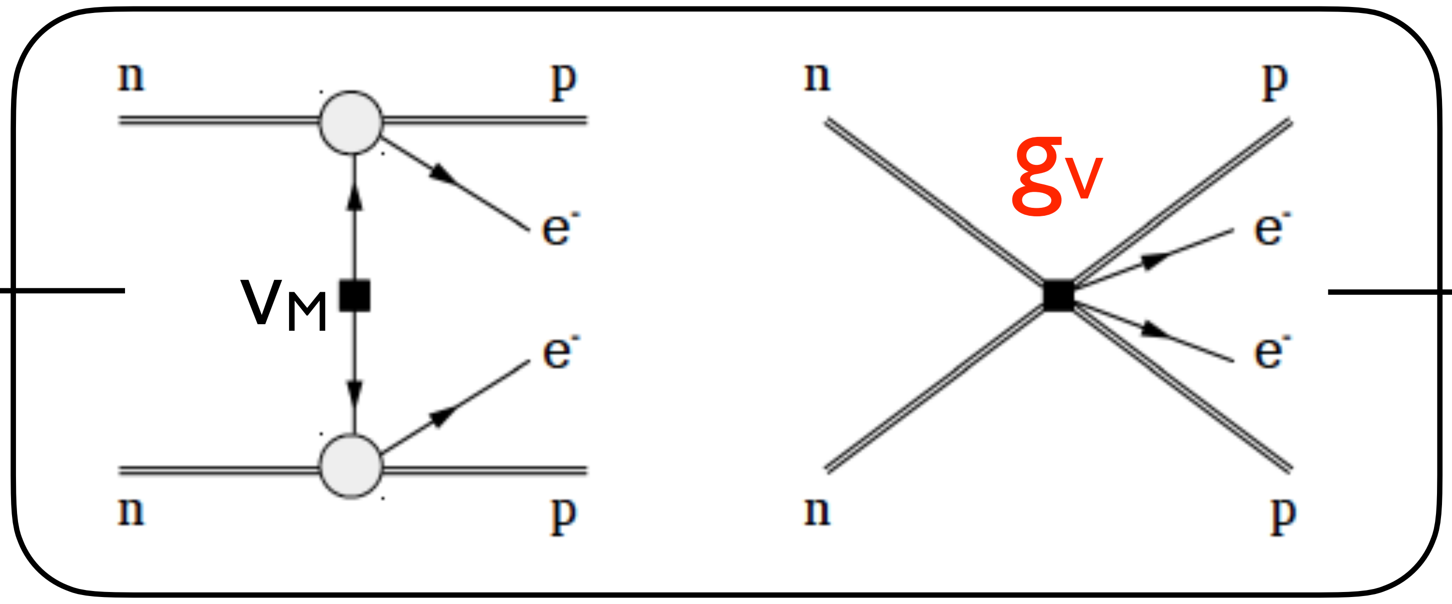
Bound is quite sensitive to prior on Σ

Key new insight from EFT

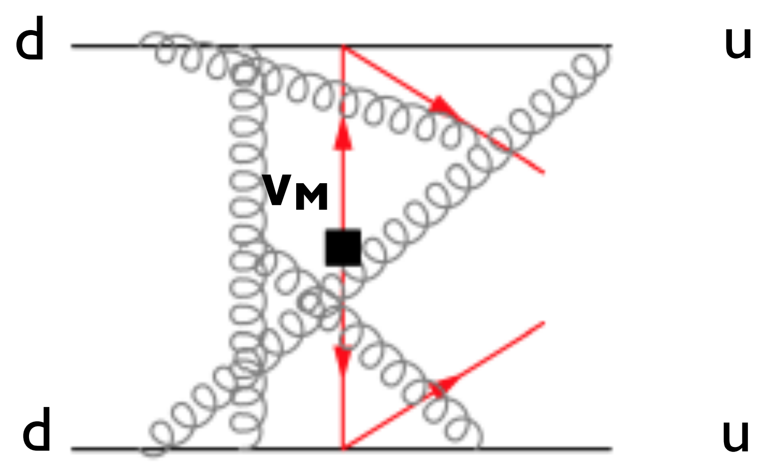
VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- To leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV), the nn → pp transition operator has *two contributions:*

'Usual' ν_M exchange $\sim 1/k_F^2 \sim 1/Q^2$
Coulomb-like long-range potential



'New': short-range potential with coupling $g_V \sim 1/Q^2$



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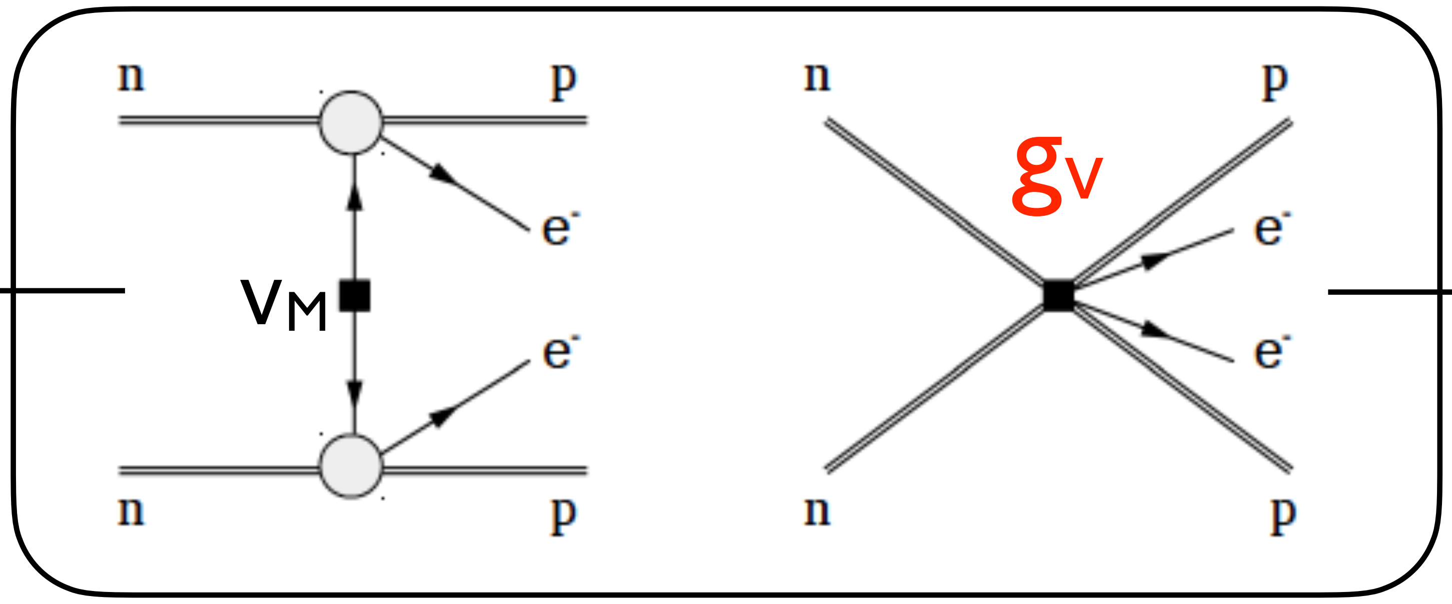

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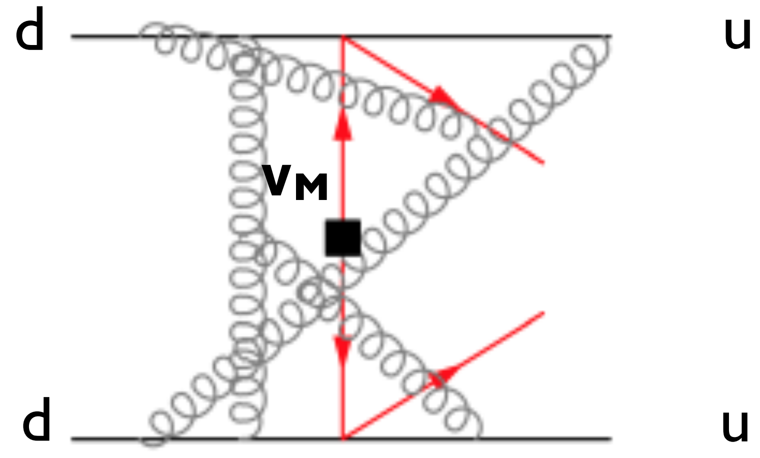
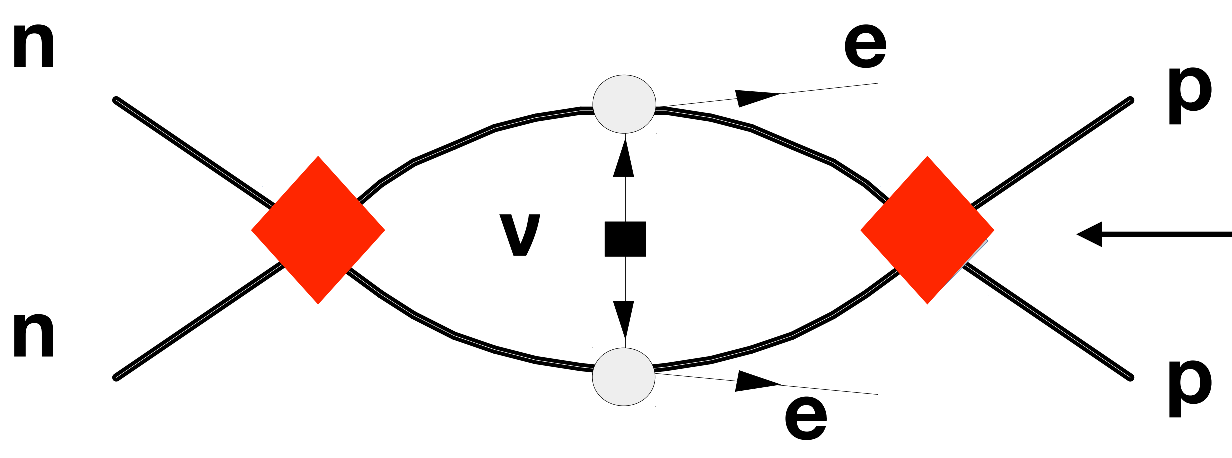


- LO scaling is required by renormalization group running induced by short-range nuclear interaction in $^1S_0$ channel



$C \sim 4\pi/(m_p Q)$ to account for large scattering length

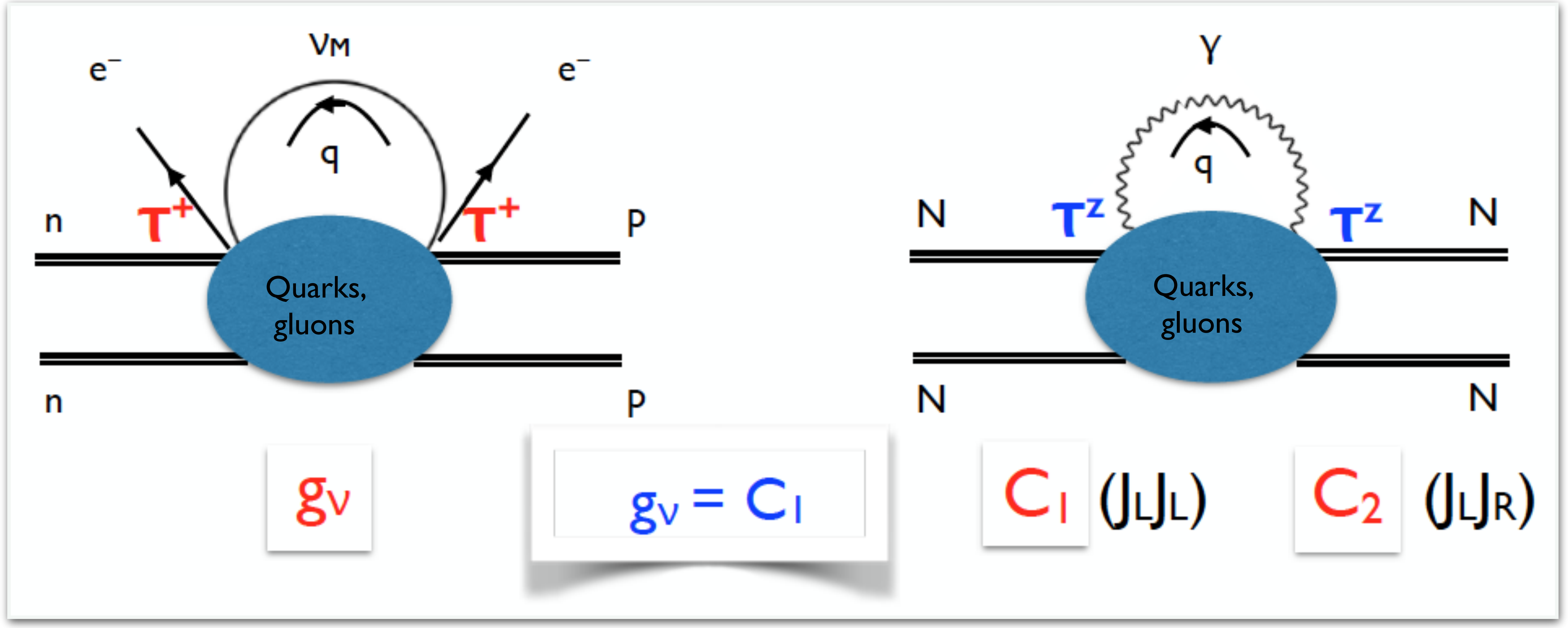
Estimating the contact term

- Isospin symmetry relates g_V to one of two I=2 e.m. couplings (hard γ's versus hard ν's)

  VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Large-N_C arguments point to $g_V \sim (C_1 + C_2)/2$

  Richardson, Shindler, Pastore, Springer, 2102.02814



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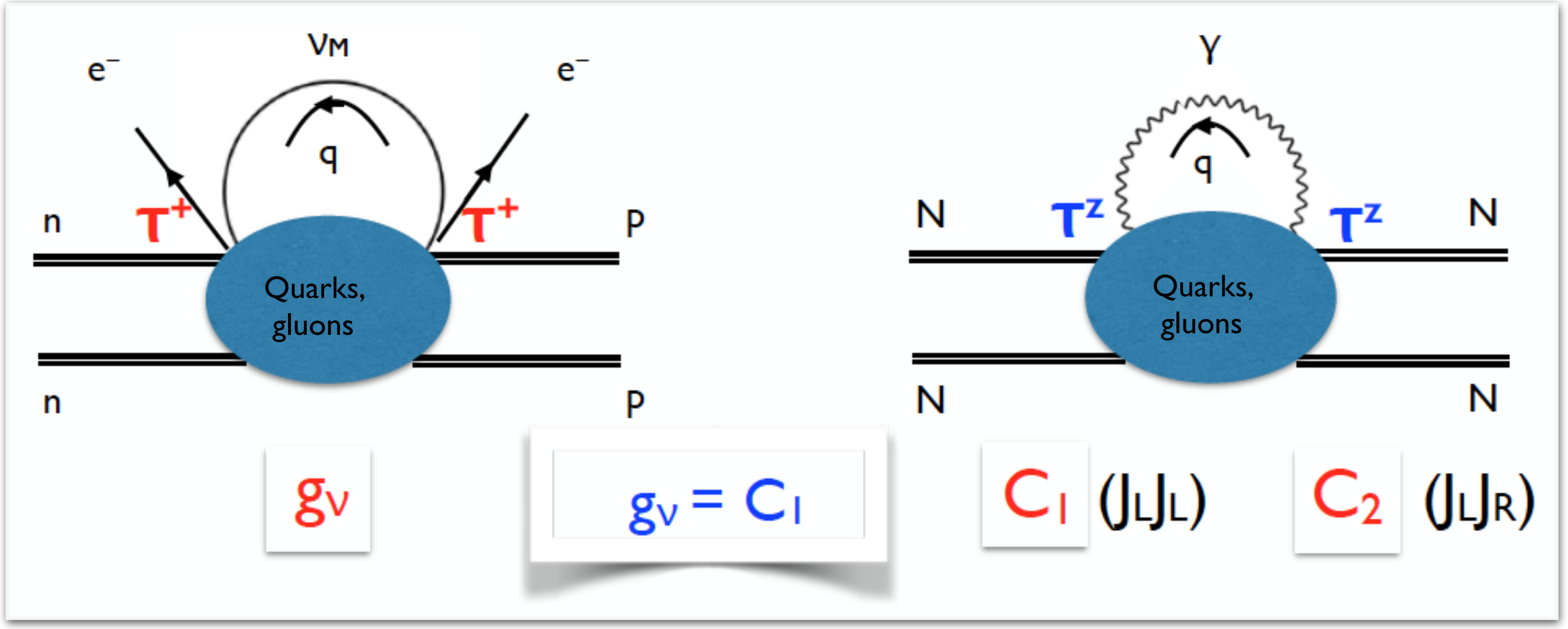
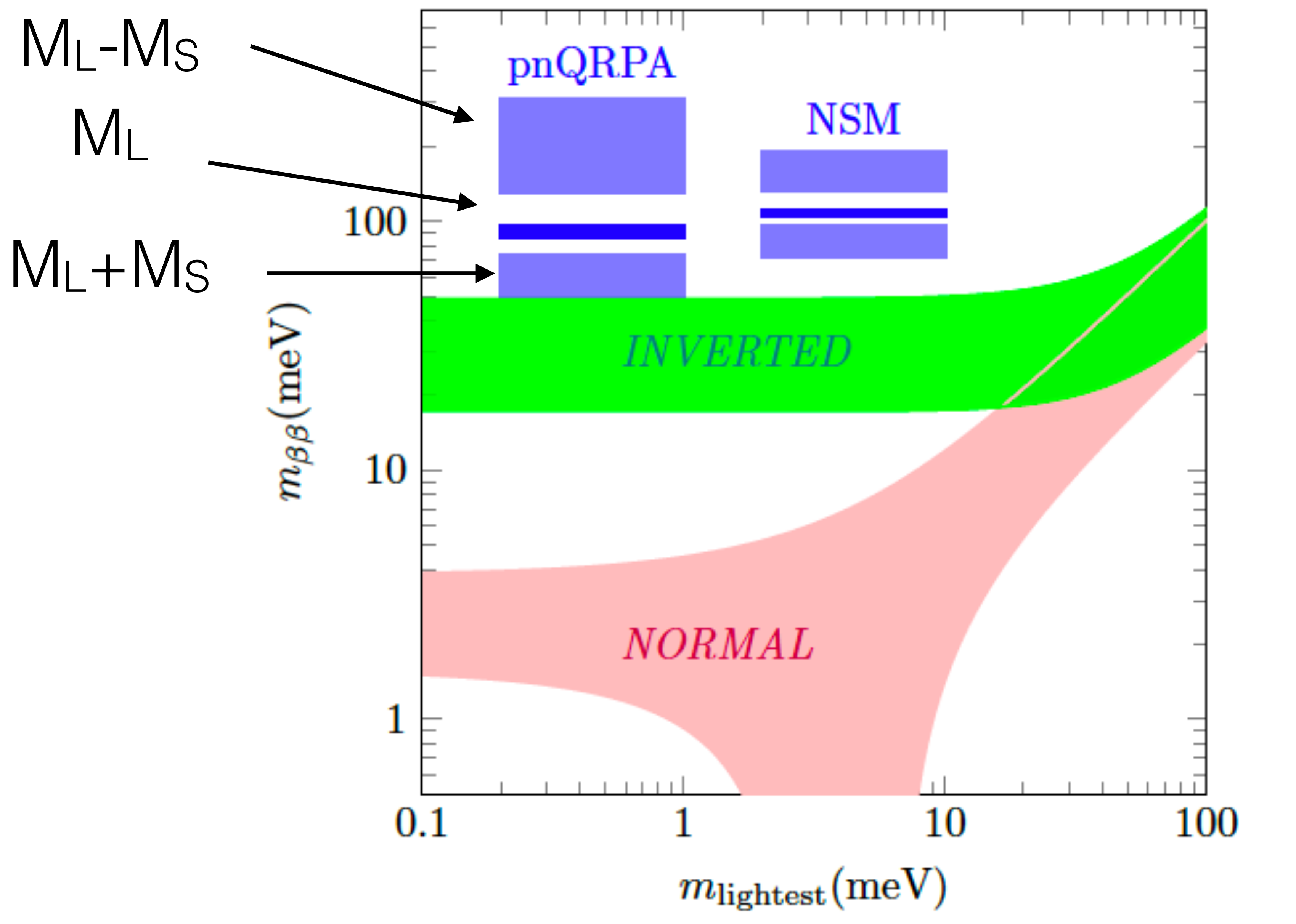


Jokiniemi-Soriano-Menendez, 2107.13354



Assuming $g_V \sim (C_1+C_2)/2$ + nuclear models → O(1) impact on m.e. and $m_{\beta\beta}$ extraction

Estimating the contact term

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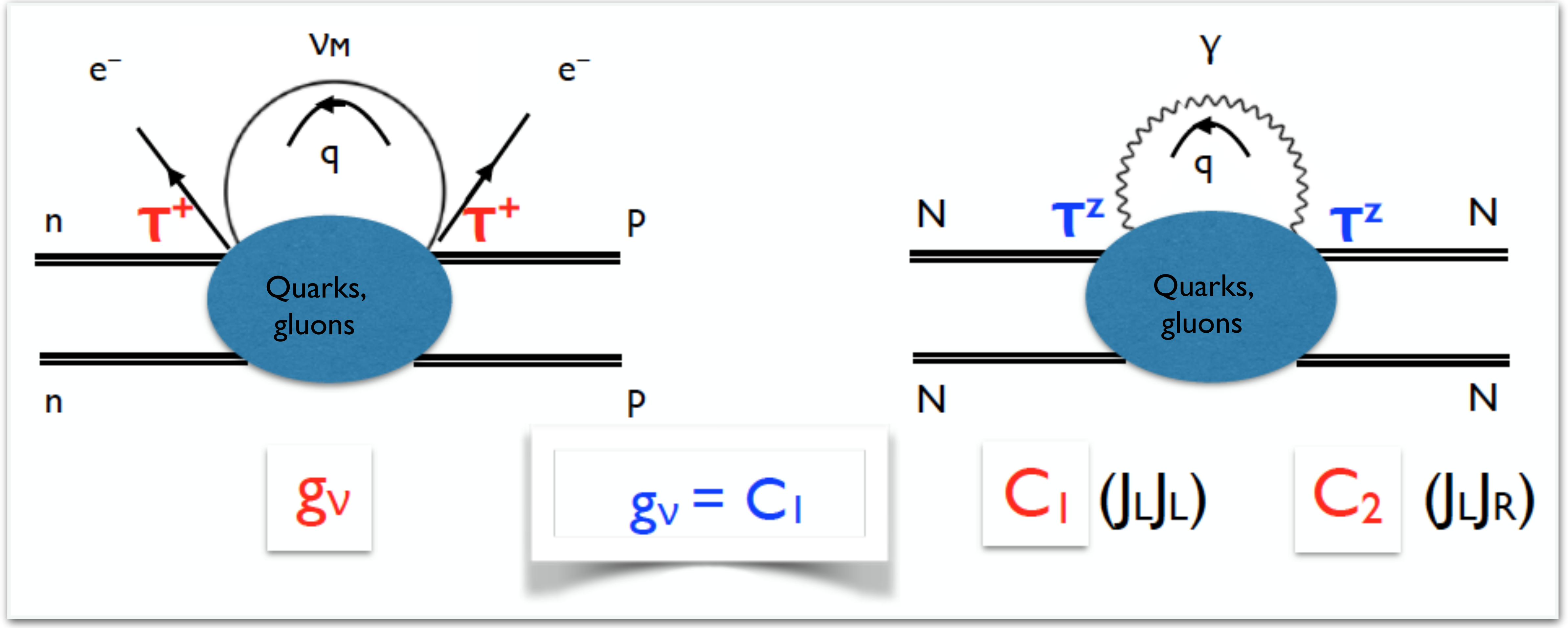
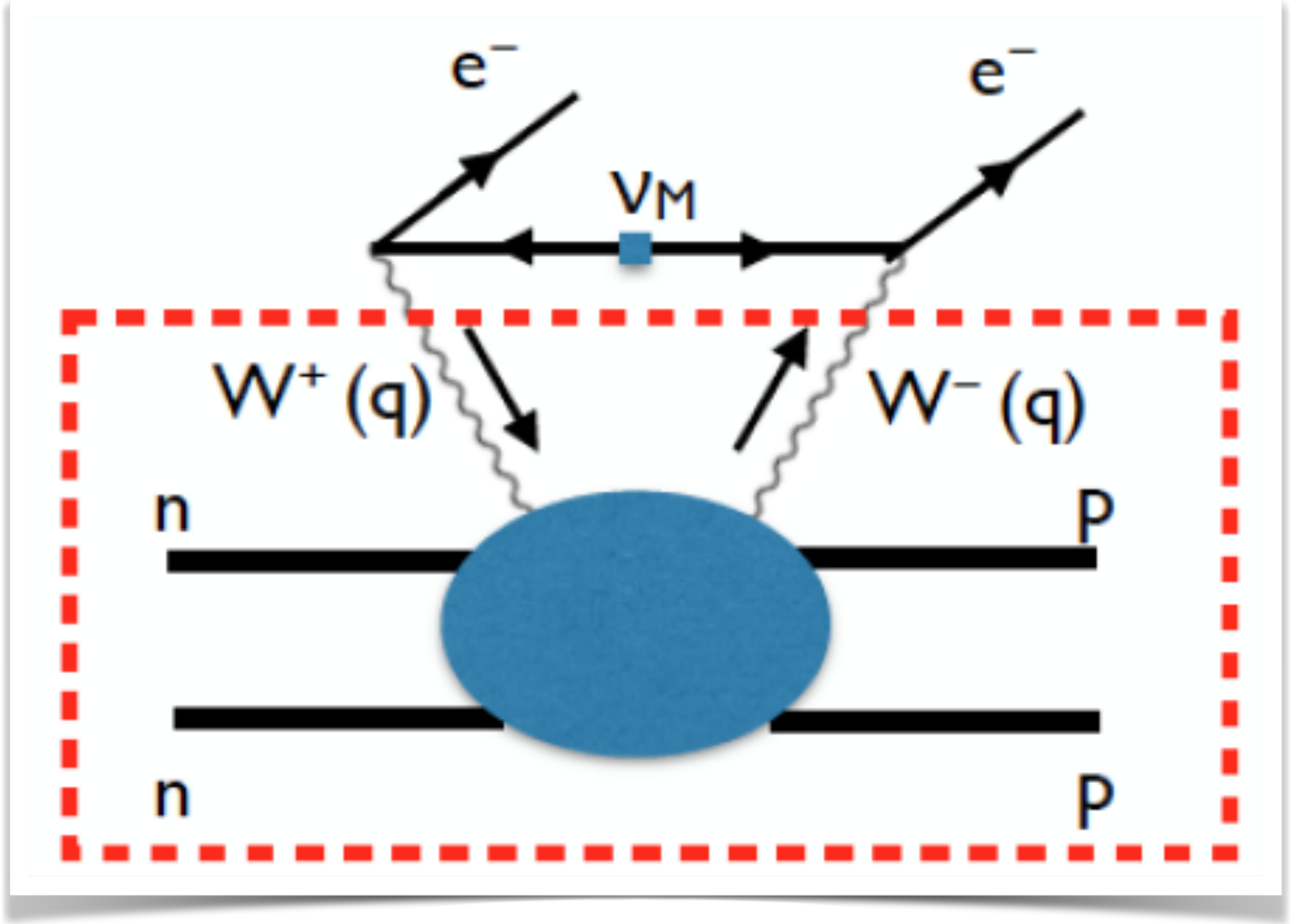
- Lattice QCD — gearing up

  Tuo et al. 1909.13525; Detmold, Murphy 2004.07404 Davoudi, Kadam, 2012.02083

- Dispersive approach — first complete estimate, with some model dependence

  VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371





Impact of the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Determined g_V with ~30% uncertainty (validated with ΔI=2 NN electromagnetic coupling)

↓

We provided 'synthetic data' for the nn→pp amplitude to be used to fit g_V in nuclear calculations

↓

Contact term fit to synthetic data and used in ab-initio calculations for

^{48}Ca [1], ^{130}Te [2], ^{136}Xe, [2], ^{76}Ge [3]

[2] Wirth, Yao, Hergert, 2105.05415 [3] Belley et al, 2307.15156 [4] Belley et al, 2308.15634

Enhances matrix elements by ~40% [Ca, Ge] and >50% [Te, Xe] —

good news for phenomenology, while we wait for Lattice QCD results

Progress in controlling all uncertainties

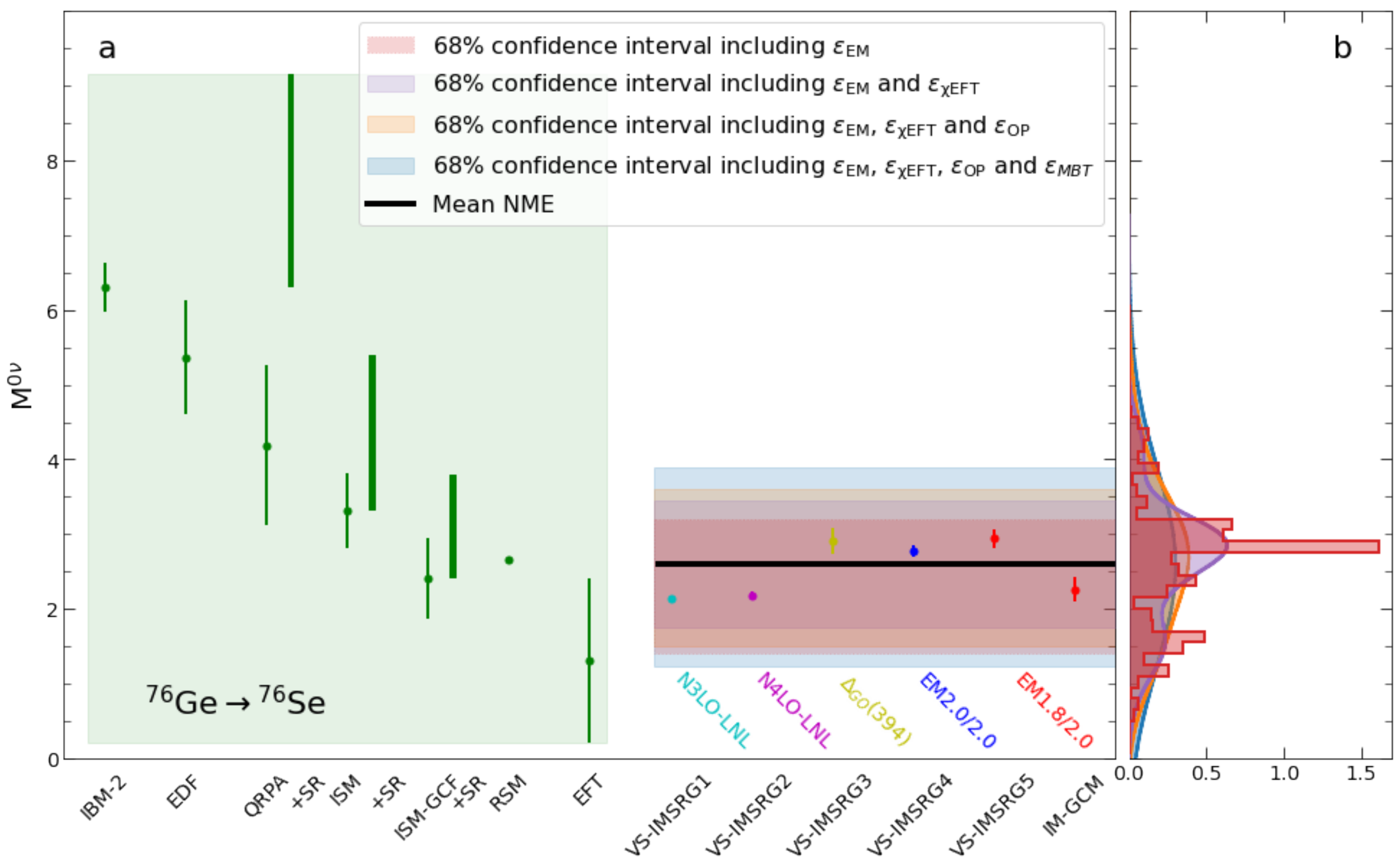
- Several first-principles many-body methods are used for the calculation of matrix elements

- Sources of quantifiable uncertainty:
    - EFT for nuclear force (effective couplings, convergence, …)
    - Transition operator (contact term, …)
    - Truncations in many-body methods

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

- Overall uncertainty still sizable but improvable

Belley et al, 2308.15634 and references therein



Various nuclear models

'Ab initio' methods using different chiral interactions

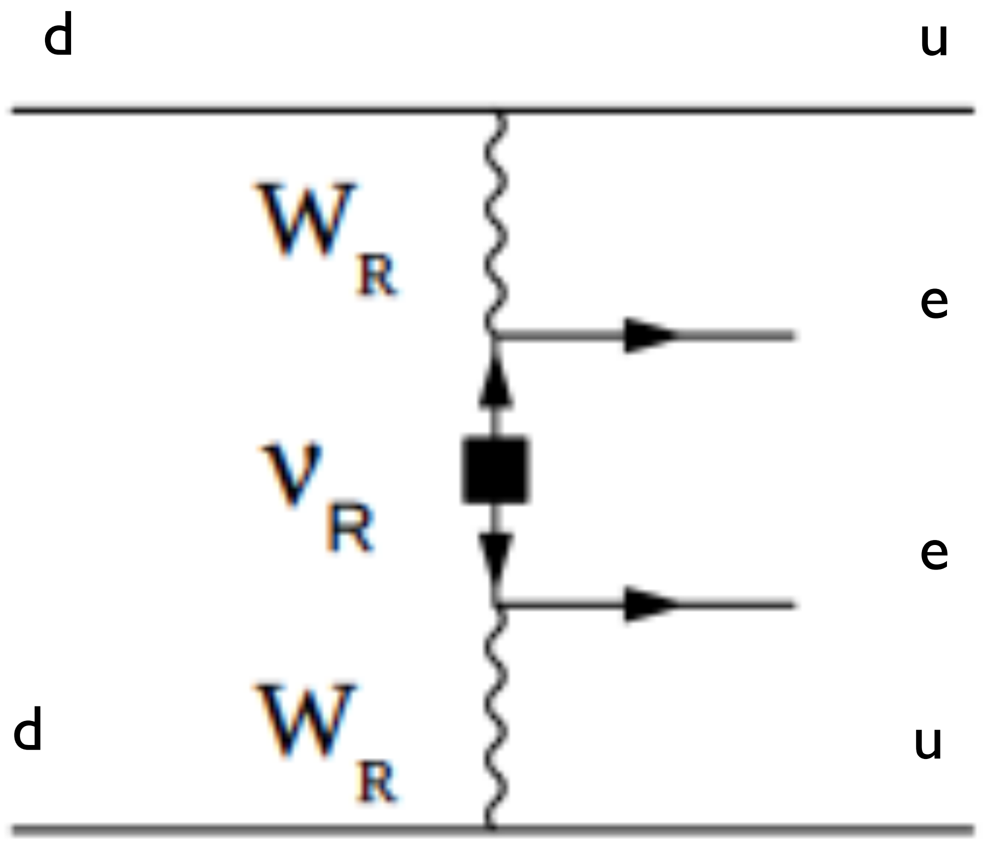
LNV @ multi-TeV-scale: key features

- Observable contributions to 0νββ *not directly related to the exchange of light neutrinos:*

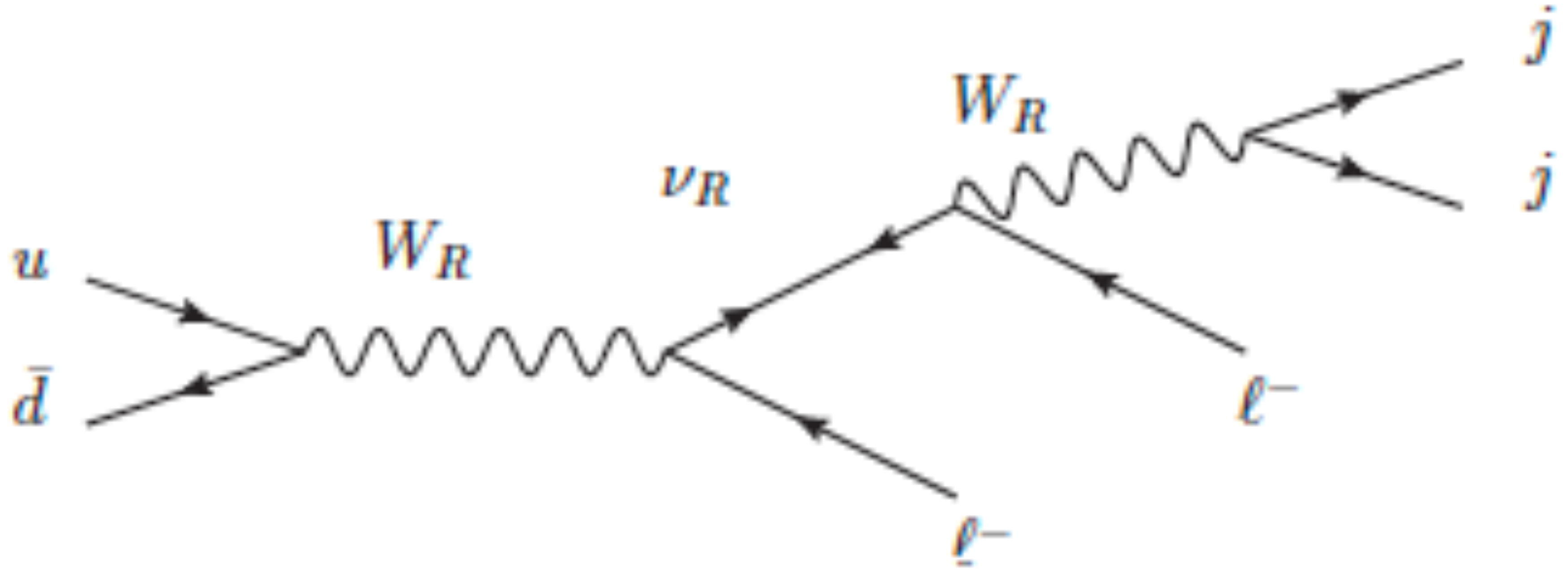
$m_{\beta\beta} G_F^2/Q^2 \sim 1/\Lambda^5$

if $m_{\beta\beta} \sim 0.1$ eV and Λ~TeV

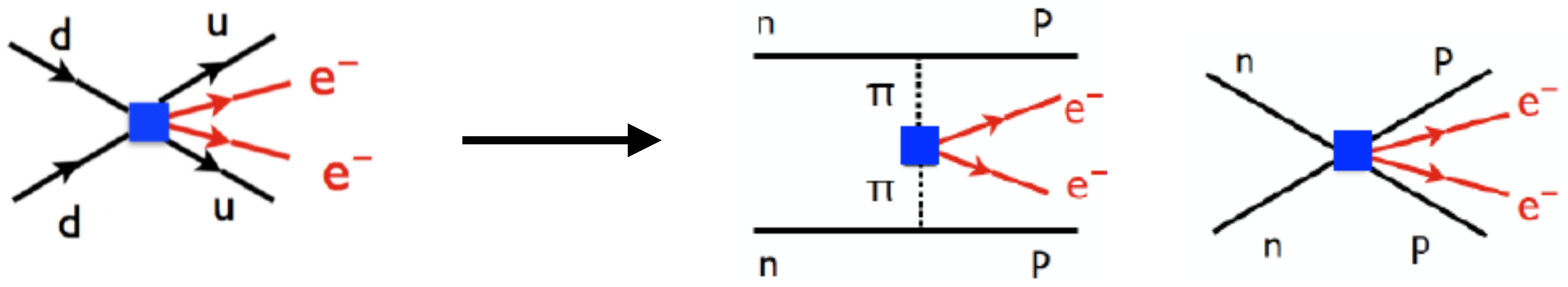
(For example $\Lambda \sim M_{\nu R} \sim M_{WR}$)



- Possible correlated signal at LHC: $pp \rightarrow ee\, jj$



- Hadronic scale: new pion-range and short-range transition operators



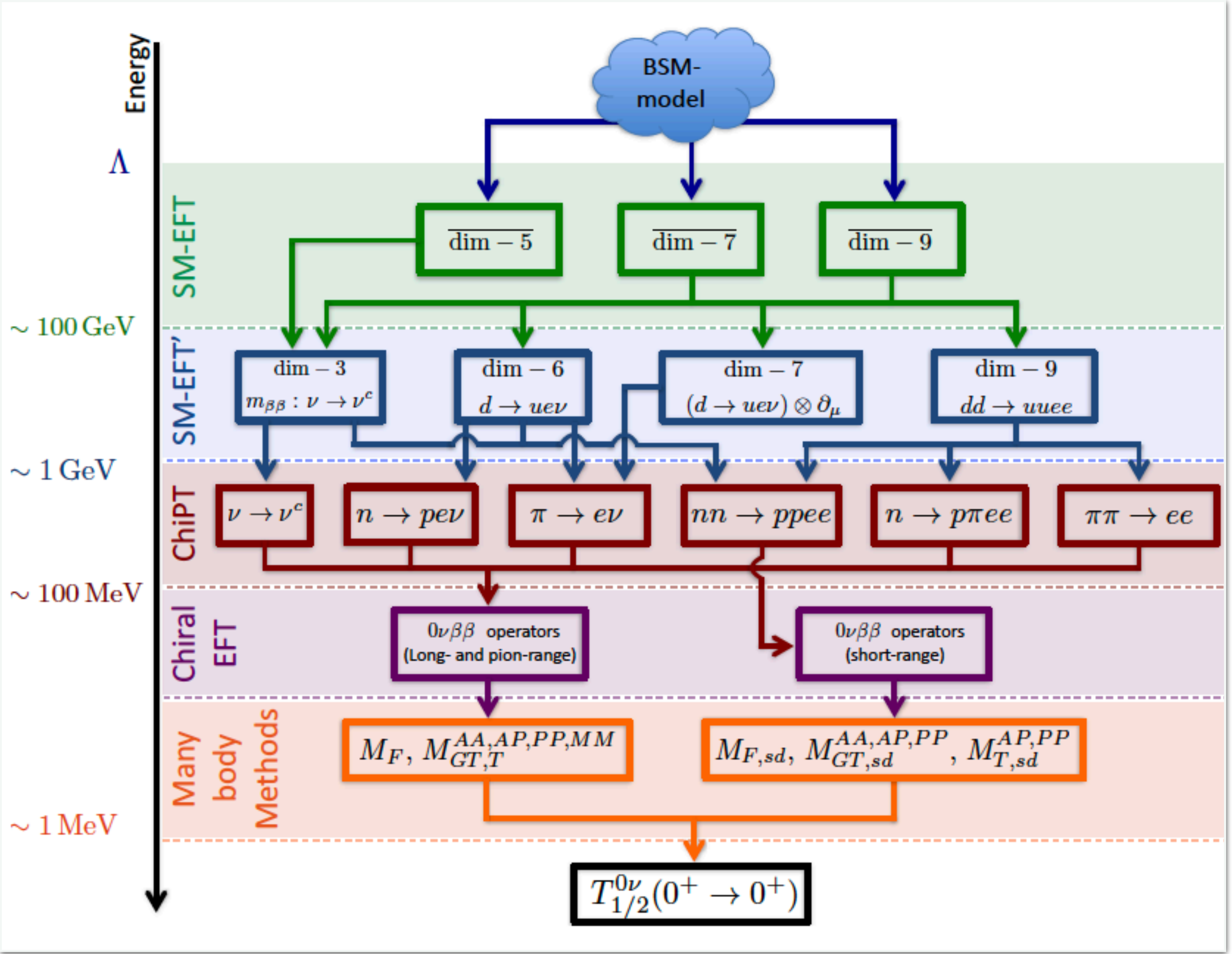
EFT-based master formula for half-life

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

- Put everything together: master formula for half-life
- Framework to interpret 0νββ searches in terms of any high-scale model and possibly unravel the underlying mechanism in case of discovery

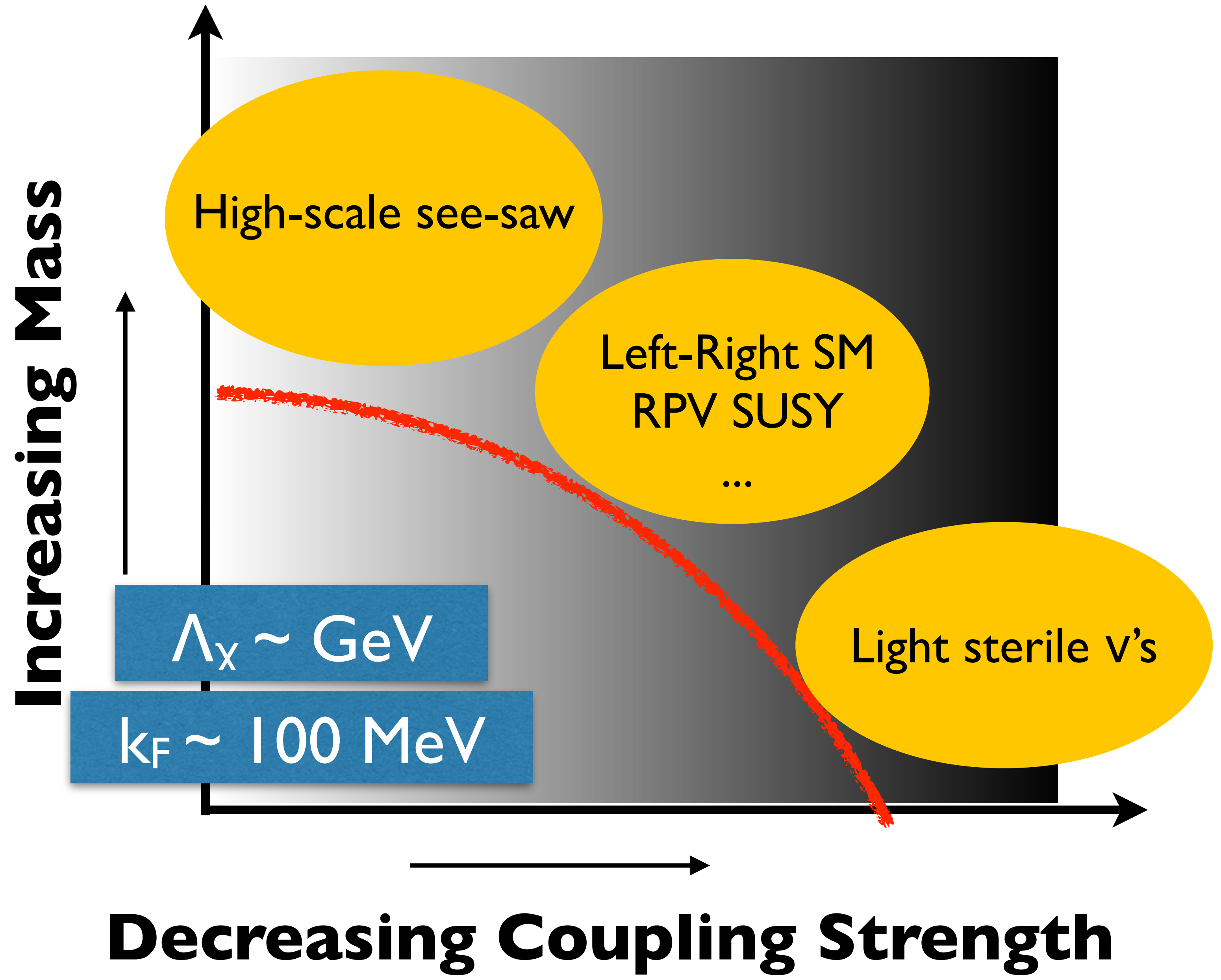
vDoBe Python tool:
Scholer-deVries-Graf, 2304.05415

- Progress at every step of the ladder, and lot more to do: EFT to higher orders, matching to Lattice QCD, order-by-order chiral EFT



Outlook on LNV

- Observation of $0\nu\beta\beta$ would address big questions:
  - Reveal Majorana nature of the neutrino
  - Establish key ingredient for baryogengesis via leptogenesis
  - Probe the absolute mass of neutrinos (in high-scale seesaw scenario)



- Significant discovery potential in ton-scale experiments — we simply don't know the origin of m_ν and the scale Λ associated with LNV

- EFT approach relates $0\nu\beta\beta$ to underlying LNV dynamics & organizes contributions to nuclear matrix elements. Key to interpret a positive or null signal

Improving the theory uncertainty is challenging, but there are exciting prospects thanks to advances in EFT, lattice QCD, and nuclear structure

Backup

Anomalous symmetry breaking

- Action is invariant, but path-integral measure is not!

$$\int [d\psi][d\bar{\psi}]\ e^{iS[\psi,\bar{\psi}]}$$

$$\psi \to \psi' \qquad \bar{\psi} \to \bar{\psi}'$$

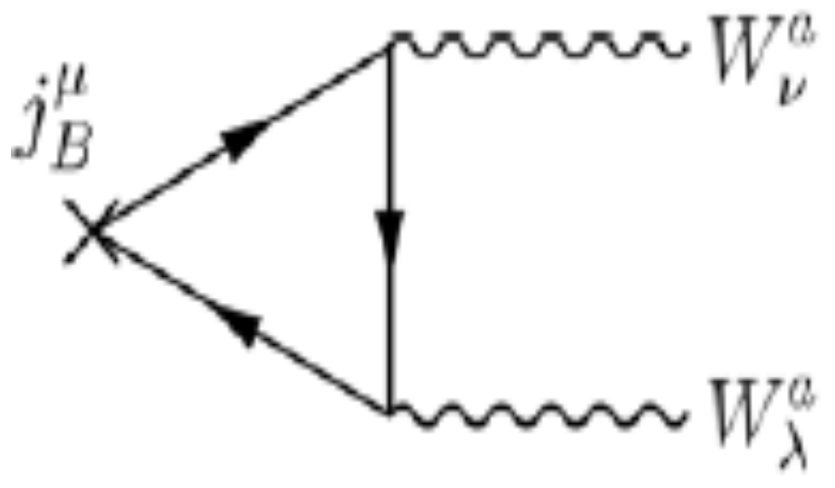
$$S[\psi,\bar{\psi}] = S[\psi',\bar{\psi}']$$

$$\int [d\psi][d\bar{\psi}] = \int [d\psi'][d\bar{\psi}']\,\mathcal{J} \qquad \mathcal{J} \neq 1$$

- Important examples: trace (scale invariance) and chiral anomalies

- Baryon (B) and Lepton (L) number are anomalous in the SM

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right)$$



- Only B-L is conserved; B+L is violated (large rates at high temperature)

Implications of symmetry

- If a state is realized in nature, its "transformed" is also possible
- Time evolution and transformation commute: for a given initial state, transformed of the evolved = evolved of the transformed

- In Quantum Mechanics
  - Symmetries represented by (anti)-unitary operators U_S (Wigner)

$$|\langle a | U_S^\dagger U_S | b \rangle|^2 = |\langle a | b \rangle|^2$$

  - U_S commutes with Hamiltonian $[U_S, H] = 0$

  - Classification of the states of the system, selection rules, …**

Implications of symmetry

- If a state is realized in nature, its "transformed" is also possible
- Time evolution and transformation commute: for a given initial state, transformed of the evolved = evolved of the transformed

- Continuous symmetries imply conservation laws

Symmetry	Conservation law
Time translation	Energy
Space translation	Momentum
Rotation	Angular momentum
U(1) phase	Electric charge
…	…

$$\psi(x) \rightarrow e^{i\epsilon}\,\psi(x)$$

Emmy Noether

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Symmetry	Conservation law
Time translation	Energy
Space translation	Momentum
Rotation	Angular momentum
U(1) phase	#particles - #anti-particles
...	...

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Implications of symmetry

- If a state is realized in nature, its "transformed" is also possible
- Time evolution and transformation commute: for a given initial state, transformed of the evolved = evolved of the transformed

- Continuous symmetries imply conservation laws

$$\begin{aligned} x^\mu &\to x^\mu + \delta x^\mu \\ \phi(x) &\to \phi(x) + \delta\phi(x) \end{aligned}$$

$$\begin{aligned} \delta x^\mu &= \epsilon^a A_a^\mu \\ \delta\phi(x) &= \epsilon^a (M_a \phi - A_a^\mu \partial_\mu \phi) \end{aligned}$$

$$\partial_\mu J_a^\mu = 0$$

$$\frac{d}{dt}\int d^3x J_a^0(x) = 0$$

$$J_a^\mu = -\frac{\delta \mathcal{L}}{\delta(\partial_\mu \phi_i(x))}\frac{\delta \phi_i}{\delta \epsilon^a} - \mathcal{L}\frac{\delta x^\mu}{\delta \epsilon^a}$$

Emmy Noether

Aside: CP violation in the SM

$$\mathcal{L}_4^{CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \left(\frac{g_2}{2\sqrt{2}}W_\mu^+\ \bar{u}_i\gamma^\mu(1-\gamma_5)V_{ij}d_j + \text{h.c.}\right)$$

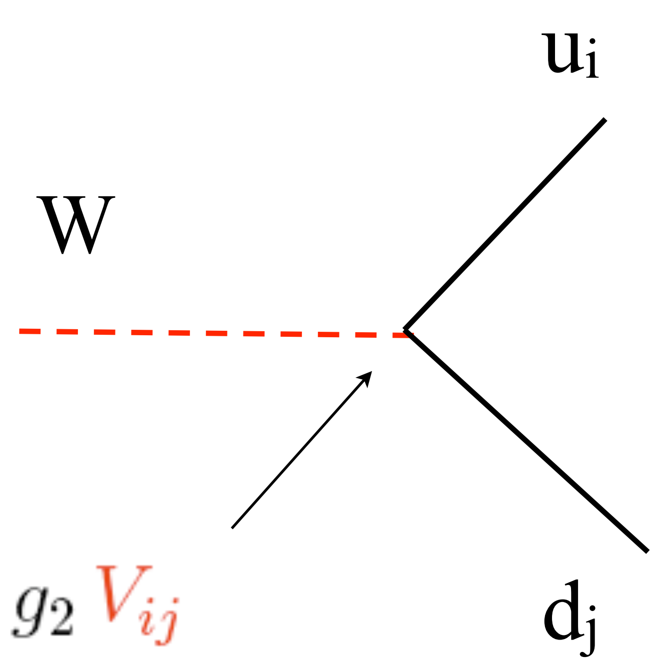
$$\bar{\theta} = \theta - \text{ArgDet}(\mathcal{M}_q)$$

'QCD theta term'

~ $B_c \cdot E_c$

$$V_{\rm CKM} = V_{u_L}V_{d_L}^\dagger$$

Physically observable mismatch in the transformation of u_L and d_L needed to diagonalize quark masses



$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maksawa (CKM) matrix

- CKM matrix is unitary:
  - 9 real parameters, but redefinition of quark phases reduces physical parameters to 4: 3 mixing angles and 1 phase

$$V_{ij} \;\rightarrow\; V_{ij}\; e^{i((\phi_d)_j-(\phi_u)_i)}$$

5 independent parameters (phase differences)

- Irreducible phase implies CP violation:

$$g_2 V_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L \;+\; g_2 V^*_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L$$

$\downarrow$ CP transformation

$$g_2 V_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L \;+\; g_2 V^*_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L$$