# Theoretical Review of Neutrinoless Double Beta Decay


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IRN Neutrino Meeting | 10-11/06/2021

# Overview

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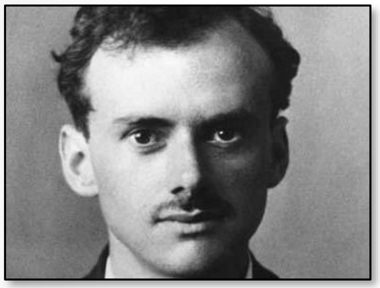
- Dirac vs Majorana Neutrinos and Lepton Number
- Beta Decay Processes and Nuclear Matrix Elements
- Light Neutrino Exchange in $0\nu\beta\beta$
- Heavy Sterile Neutrinos and Exotic Contributions
- Connection to Baryogenesis
- New Physics in $2\nu\beta\beta$

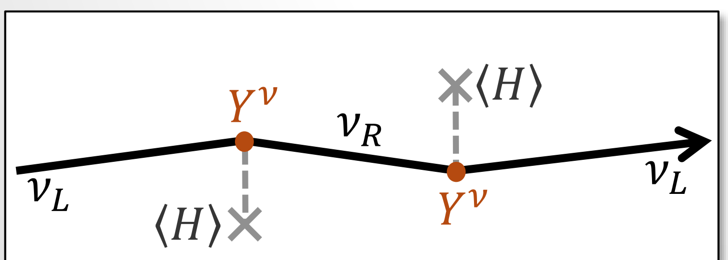
# Dirac vs Majorana

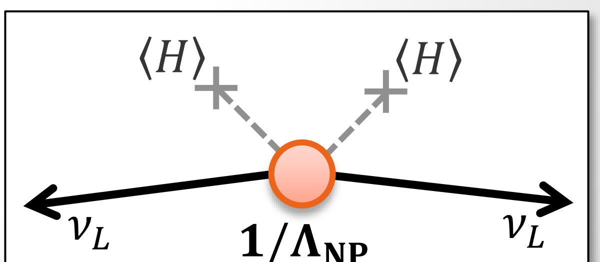
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass



Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation



# Dirac vs Majorana

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- Origin of neutrino masses beyond the Standard Model
- Crucial role of total lepton number $L$ symmetry
  - Arises accidentally as global $U(1)_L$ in SM from particle content and gauge symmetry
  - Already broken non-perturbatively with $B - L$ remaining conserved
  - Global symmetries expected to be broken gravitational effects? Naïve expectation:

$$\boxed{m_\nu \approx \frac{v^2}{M_{\mathrm{Planck}}} \approx 10^{-5}\ \mathrm{eV}}$$

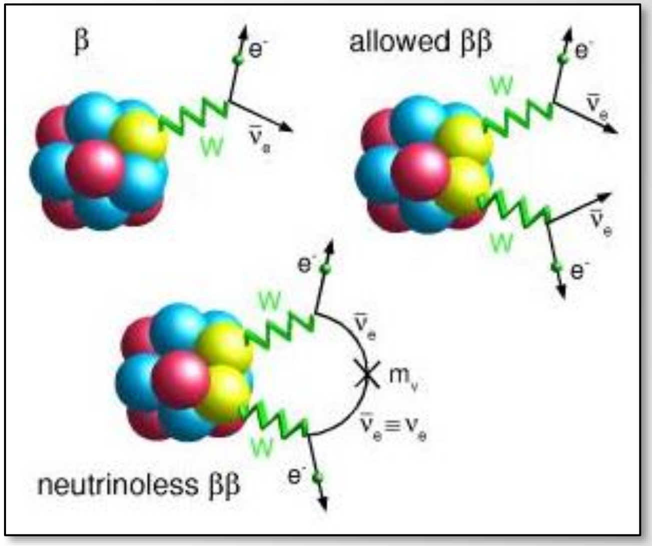
  - Too small to explain oscillations but too large as subdominant splitting

# Beta Decays and $\nu$ Mass

- Single beta decay

$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$

  - Tritium decay, KATRIN: $\boldsymbol{m_\beta \approx 0.2}$ **eV**
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $\boldsymbol{m_\beta \approx 0.05}$ **eV**
  - HOLMES: $e^-$ capture in $^{163}\mathrm{Ho}$: $\boldsymbol{m_\beta \approx 0.1}$ **eV?**




- Allowed double beta ($2\nu\beta\beta$) decay

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

- Neutrinoless double beta ($0\nu\beta\beta$) decay

$$(A,Z) \to (A,Z+2) + 2e^-$$

  - Violation of lepton number
  - Mediated by Majorana neutrinos

# Neutrinoless Double Beta Decay

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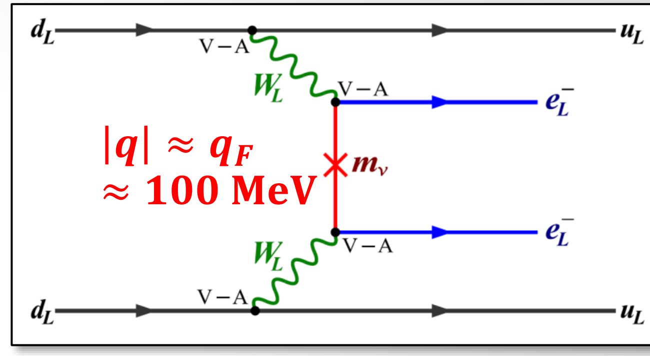
- Half-life

$$\boxed{T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2}$$

- Particle Physics



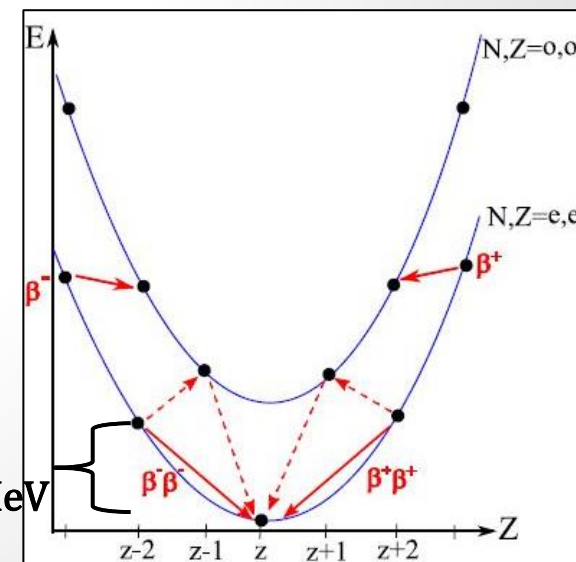

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\cancel{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\boxed{\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}} \rightarrow \boldsymbol{m_{\beta\beta}}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$

$$\boxed{T_{1/2}^{-1} \propto |m_{\beta\beta}|^2 q_F^2 G_F^4 Q^5}$$

$$\boxed{\frac{10^{25}\,\mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2}$$

$\boldsymbol{Q + 2m_e}$
$\boldsymbol{\approx 3\text{–}5\ \mathrm{MeV}}$



# Nuclear Matrix Elements

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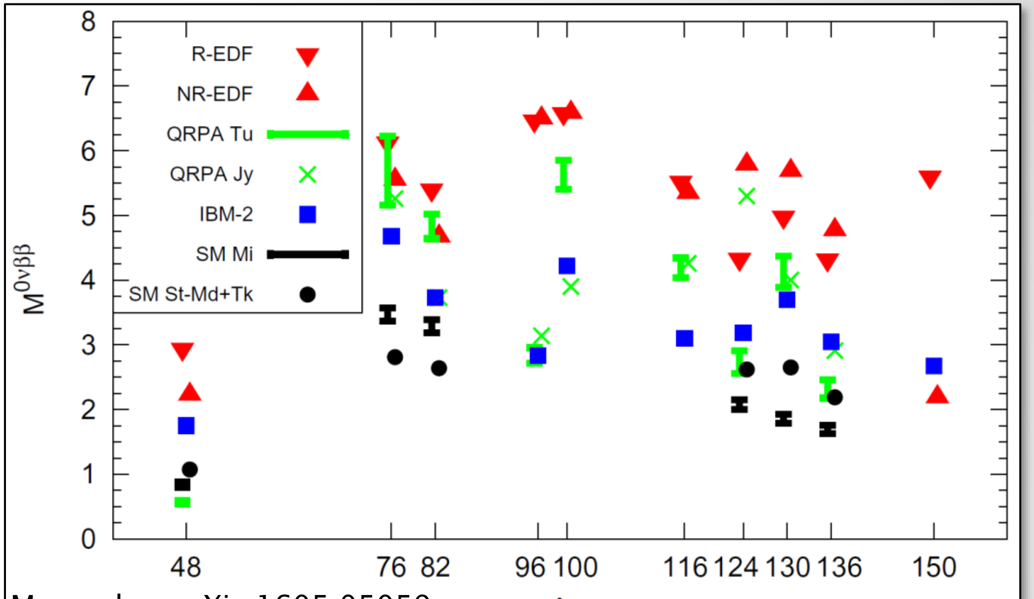
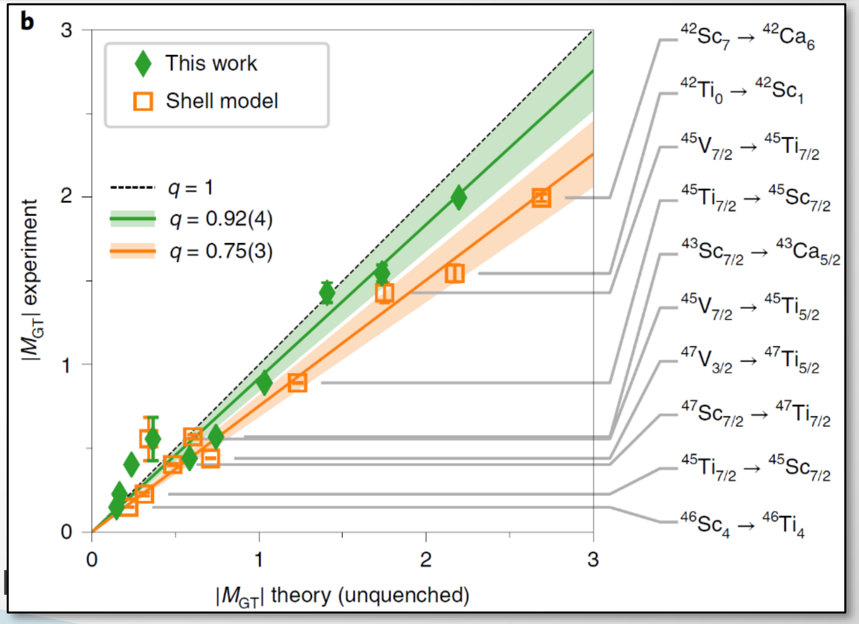
- Nuclear Matrix Element

$$M^{0\nu} = g_A^2 \left( M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)$$

  - Factor 2 – 3 uncertainty between nuclear models
  - "Quenching" of axial nucleon coupling $g_A$?
    - Restricted model space
    - Missing effect of two-body currents




Menendez, arXiv:1605.05059




Gysbers et al., Nature Physics 15 (2019) 428

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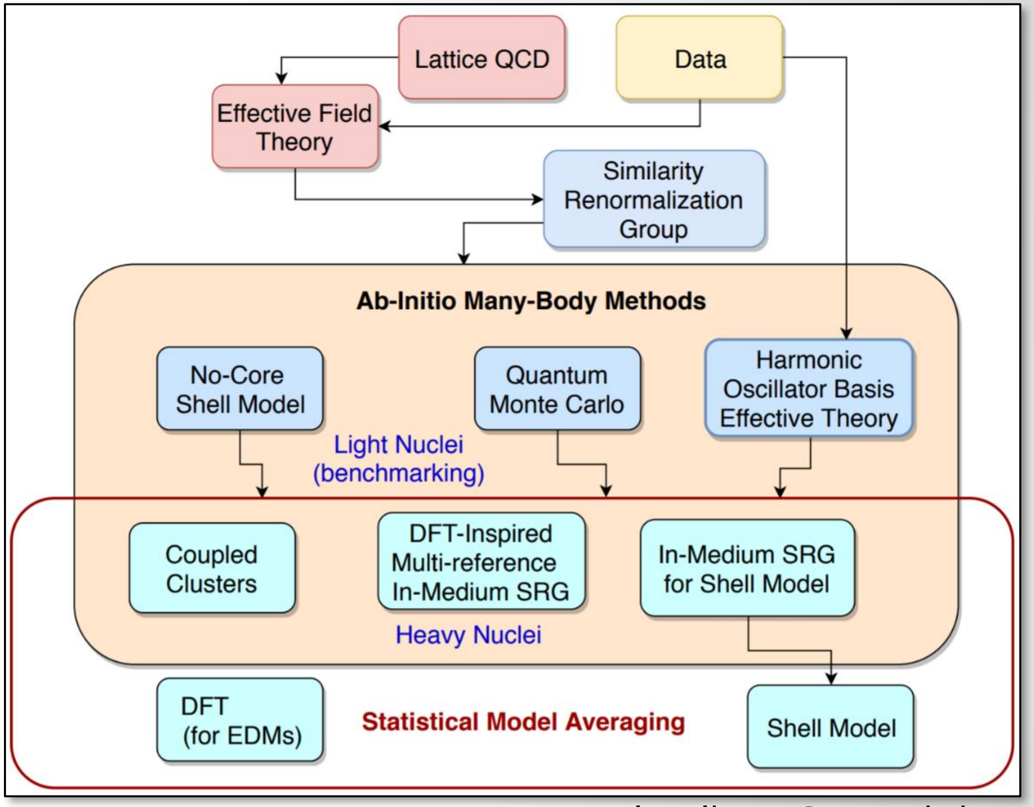
# Nuclear Matrix Elements

- Nuclear Matrix Element

$$\boxed{M^{0\nu} = g_A^2\left(M_{GT} - \frac{g_V^2}{g_A^2}M_F + M_T\right)}$$

  - Factor 2 – 3 uncertainty between nuclear models
  - "Quenching" of axial nucleon coupling $g_A$?
    - Restricted model space
    - Missing effect of two–body currents
  - Dedicated effort to reduce uncertainty
    - Theory (Ab initio interactions in $\chi$EFT, No–core shell model)
    - Experiment (Muon capture, Charge exchange reactions @ NUMEN)




J. Engel, Talk at ECT* Workshop "Progress and Challenges in $0\nu\beta\beta$"
indico.ectstar.eu/event/33/timetable/#20190715

# Three Active Neutrinos

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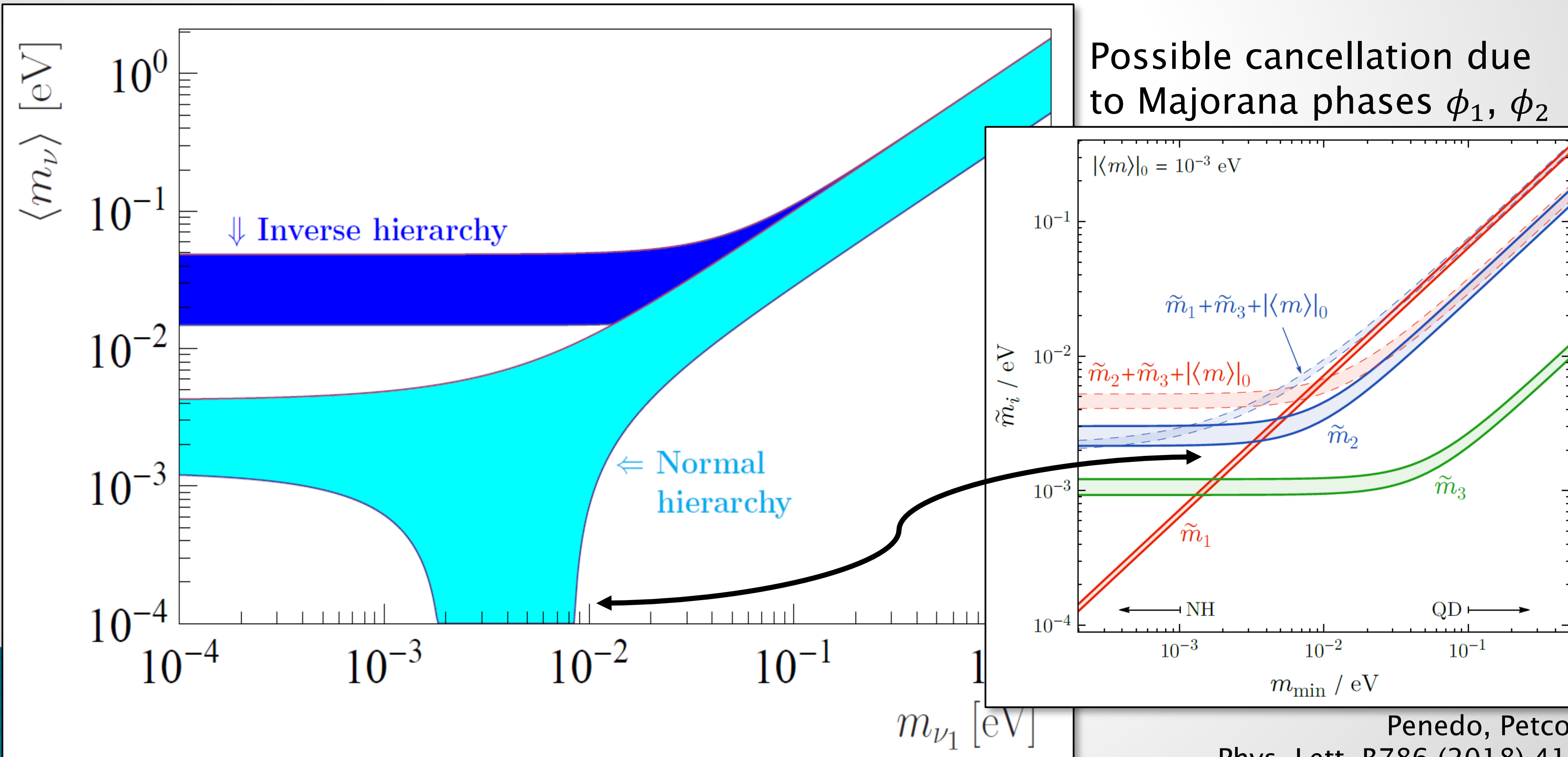
- Effective $0\nu\beta\beta$ Mass

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}| \underbrace{\approx}_{\text{degenerate \& } \theta_{13} \approx 0} m_\nu \sqrt{1 - \sin^2(2\theta_{12}) \sin^2(\phi_{12}/2)}$$

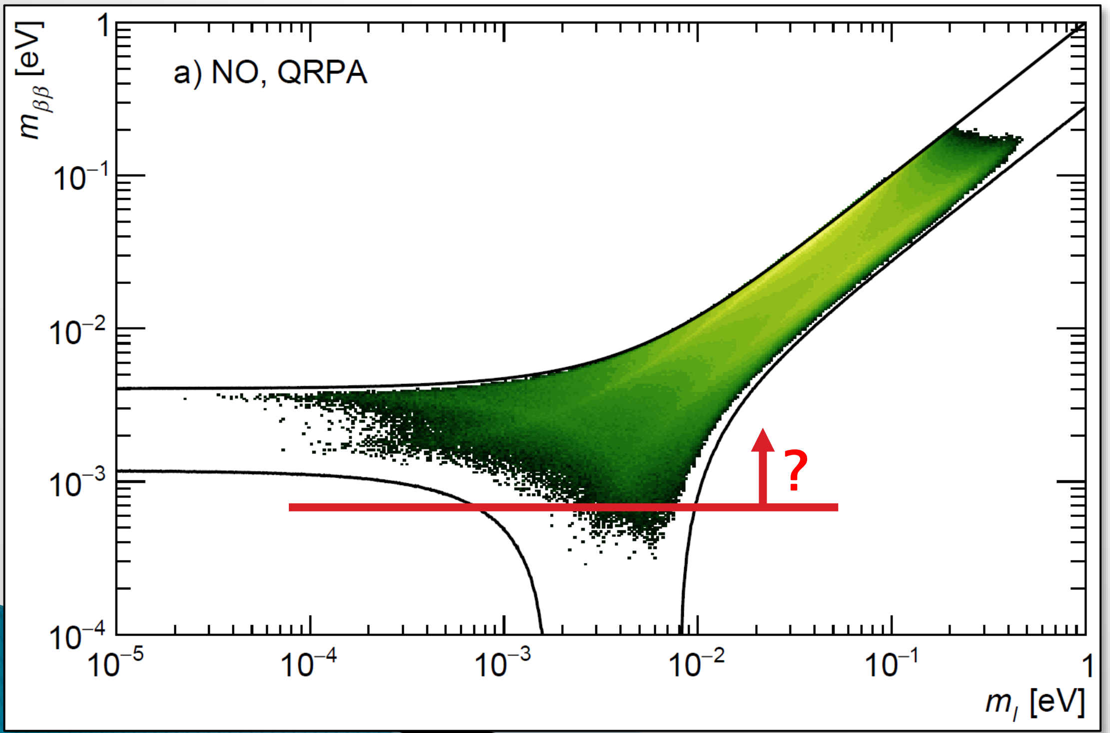
Possible cancellation due to Majorana phases $\phi_1$, $\phi_2$

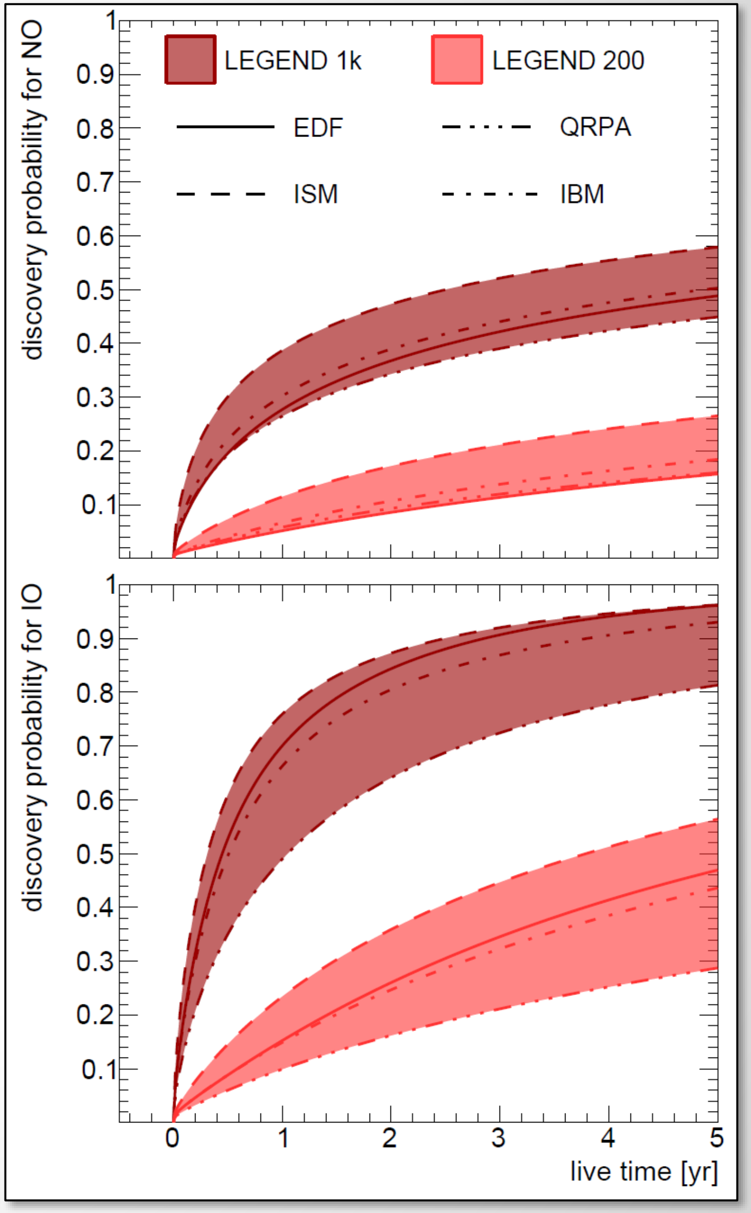



Penedo, Petcov
Phys. Lett. B786 (2018) 410

# Lower Limit on $m_{\beta\beta}$?

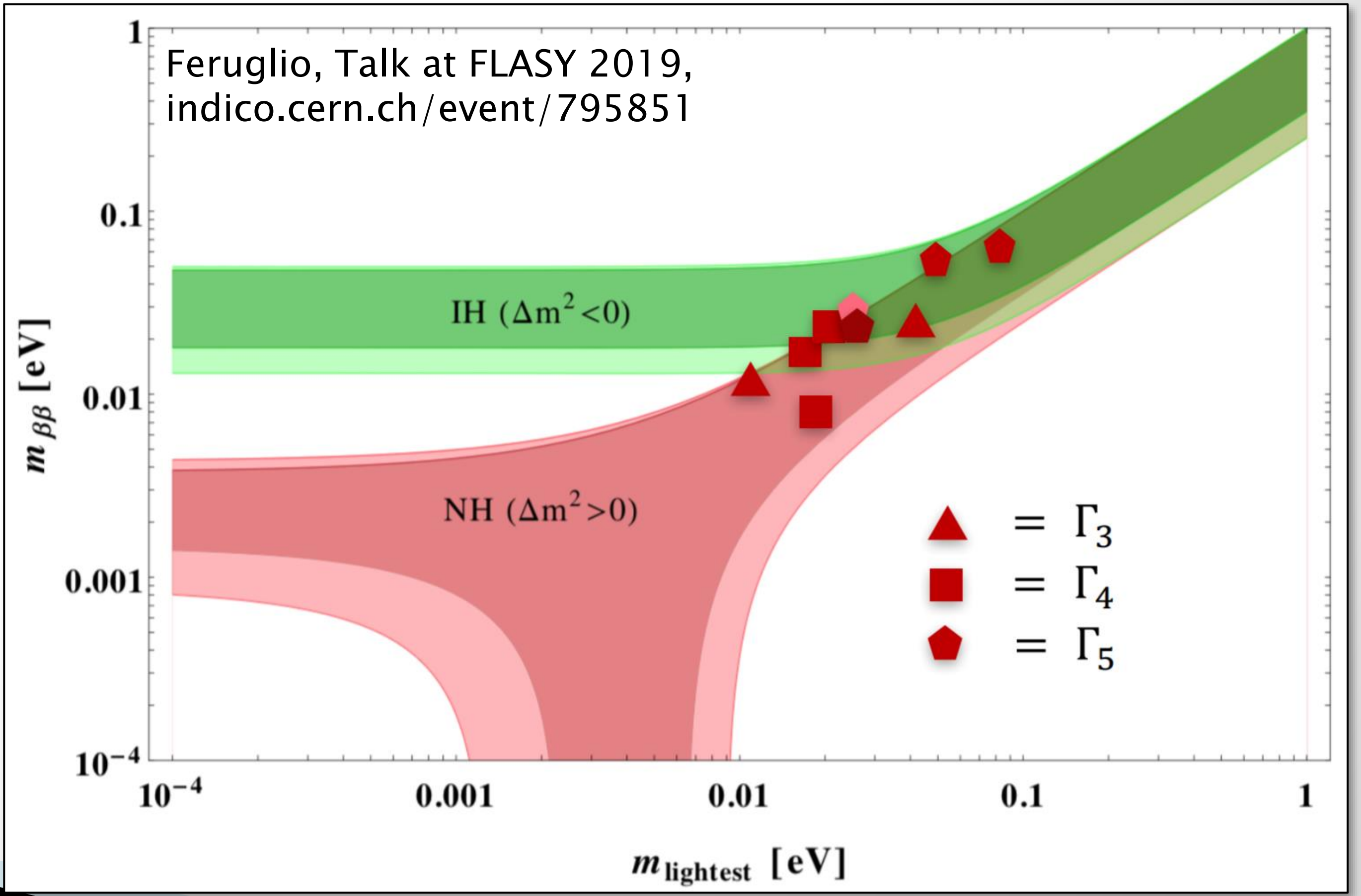
- From volume-effect on accidental cancellation in $m_{\beta\beta}$
  - Bayesian analysis with flat priors on Majorana phases
    Agostini, Benato, Detwiler
    Phys. Rev. D 96 (2017) 053001



# Lower Limit on $m_{\beta\beta}$?

- From flavour and generalized CP symmetries
  - Example: Majorana masses, mixing and phases predicted from 'Modular Invariance' (Feruglio, arxiv:1706.08749)
  - Preference for solutions with NO and large $m_{\beta\beta}$



# Experimental Sensitivity

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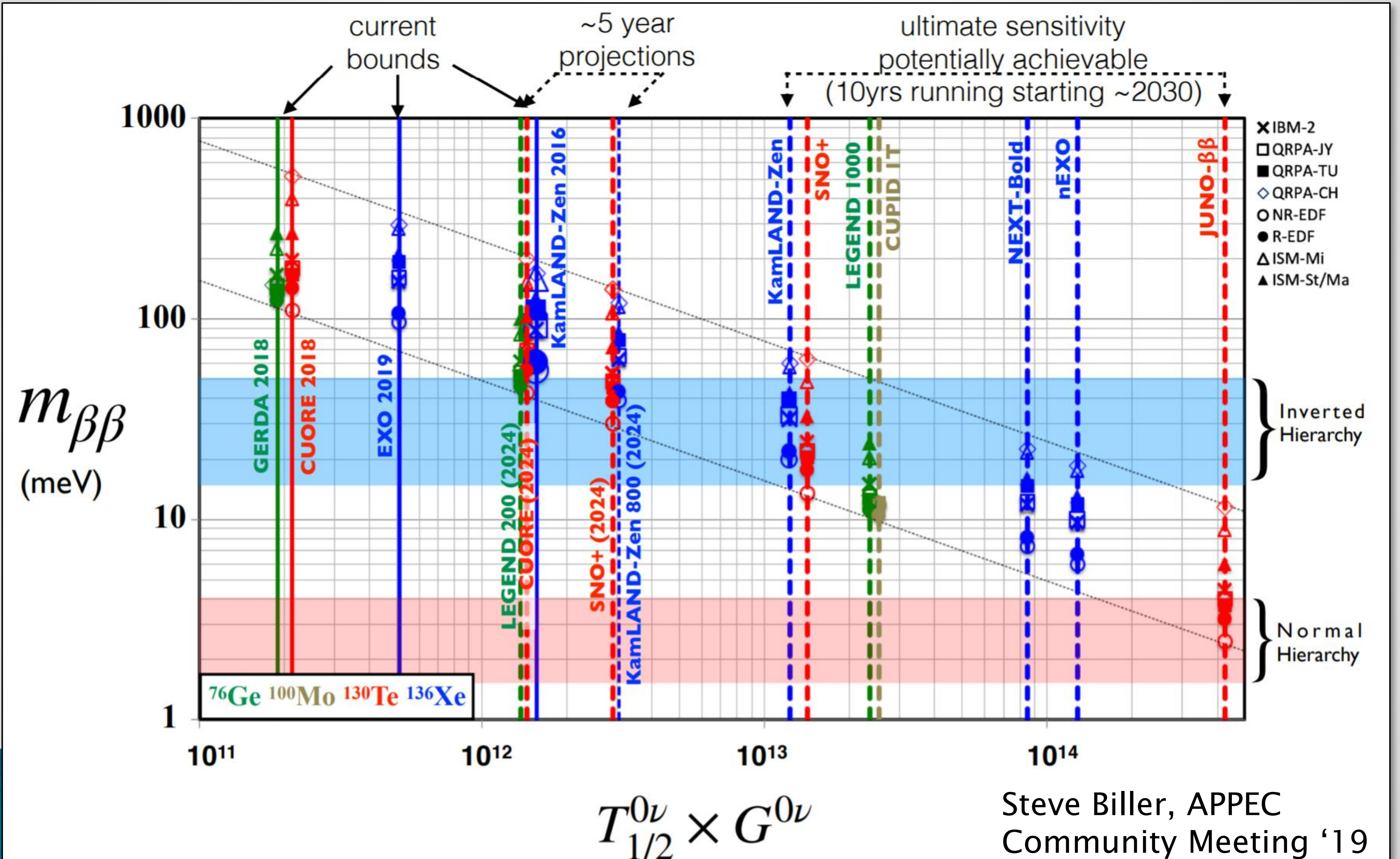


Steve Biller, APPEC Community Meeting '19

# Three Active Neutrinos

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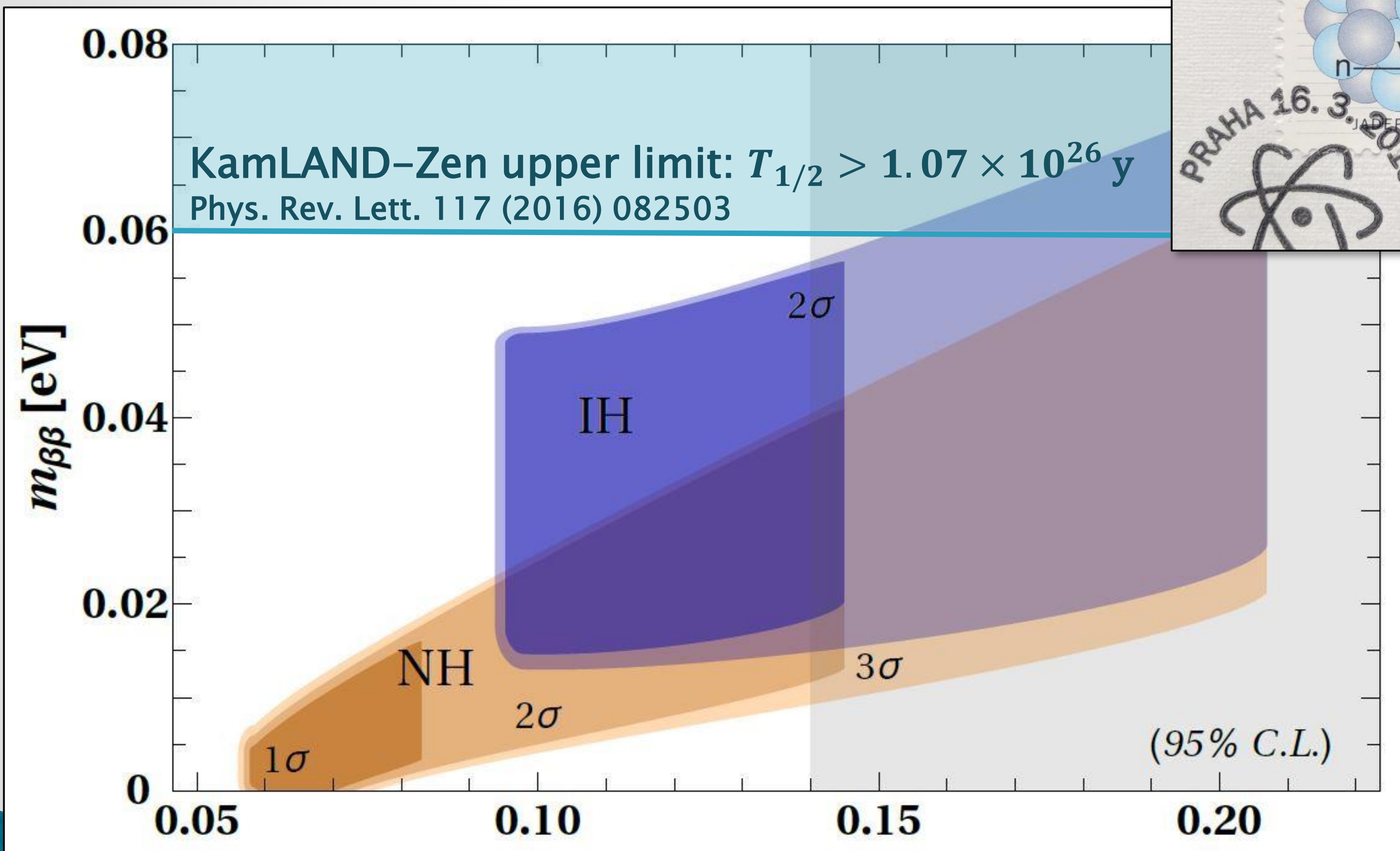
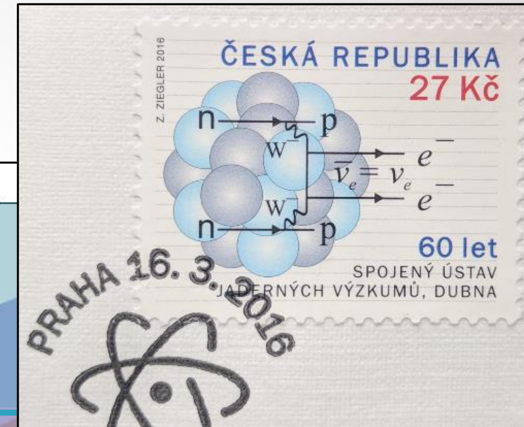
- Effective $0\nu\beta\beta$ Mass




Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659



# Three Active Neutrinos

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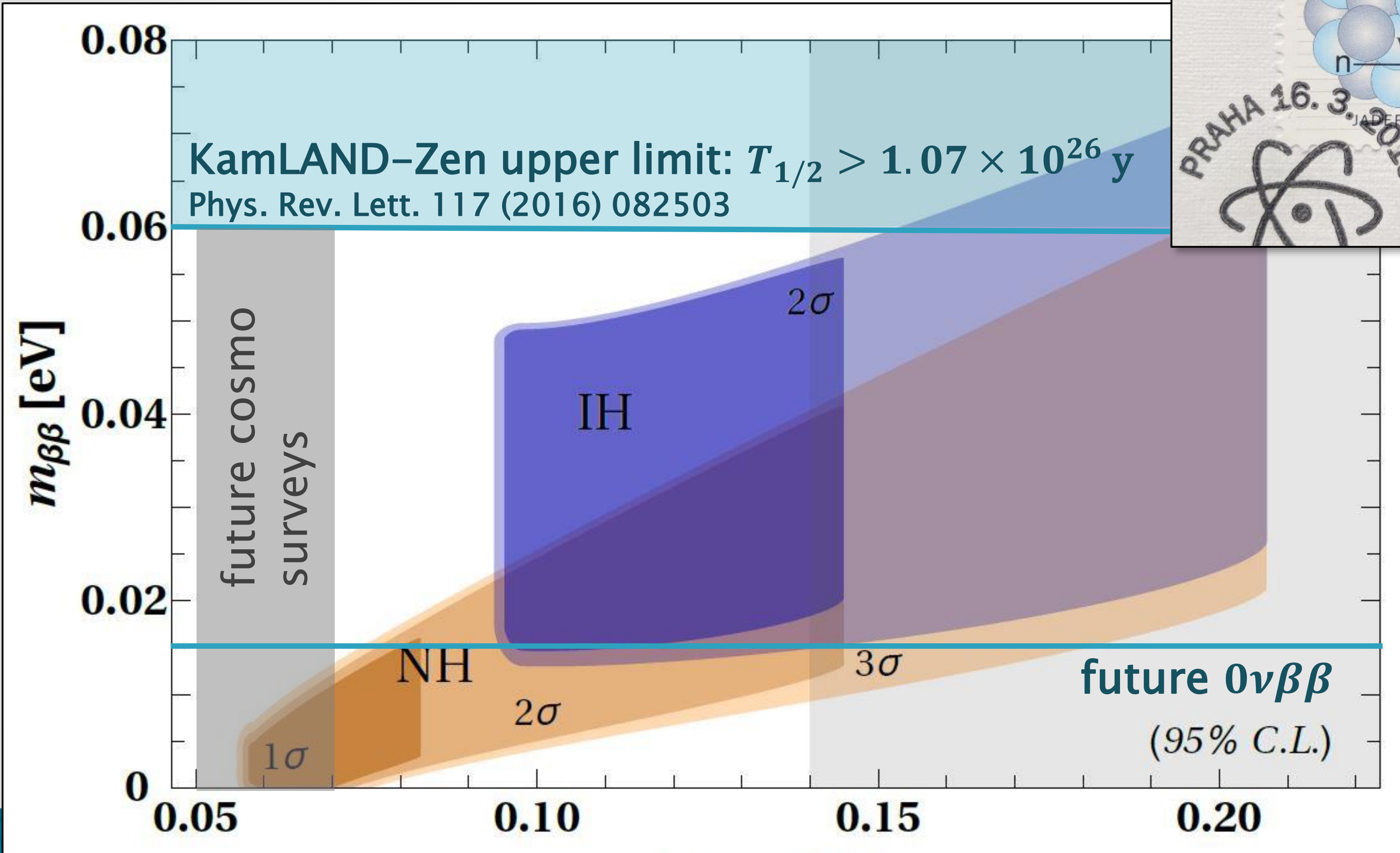
- Effective $0\nu\beta\beta$ Mass



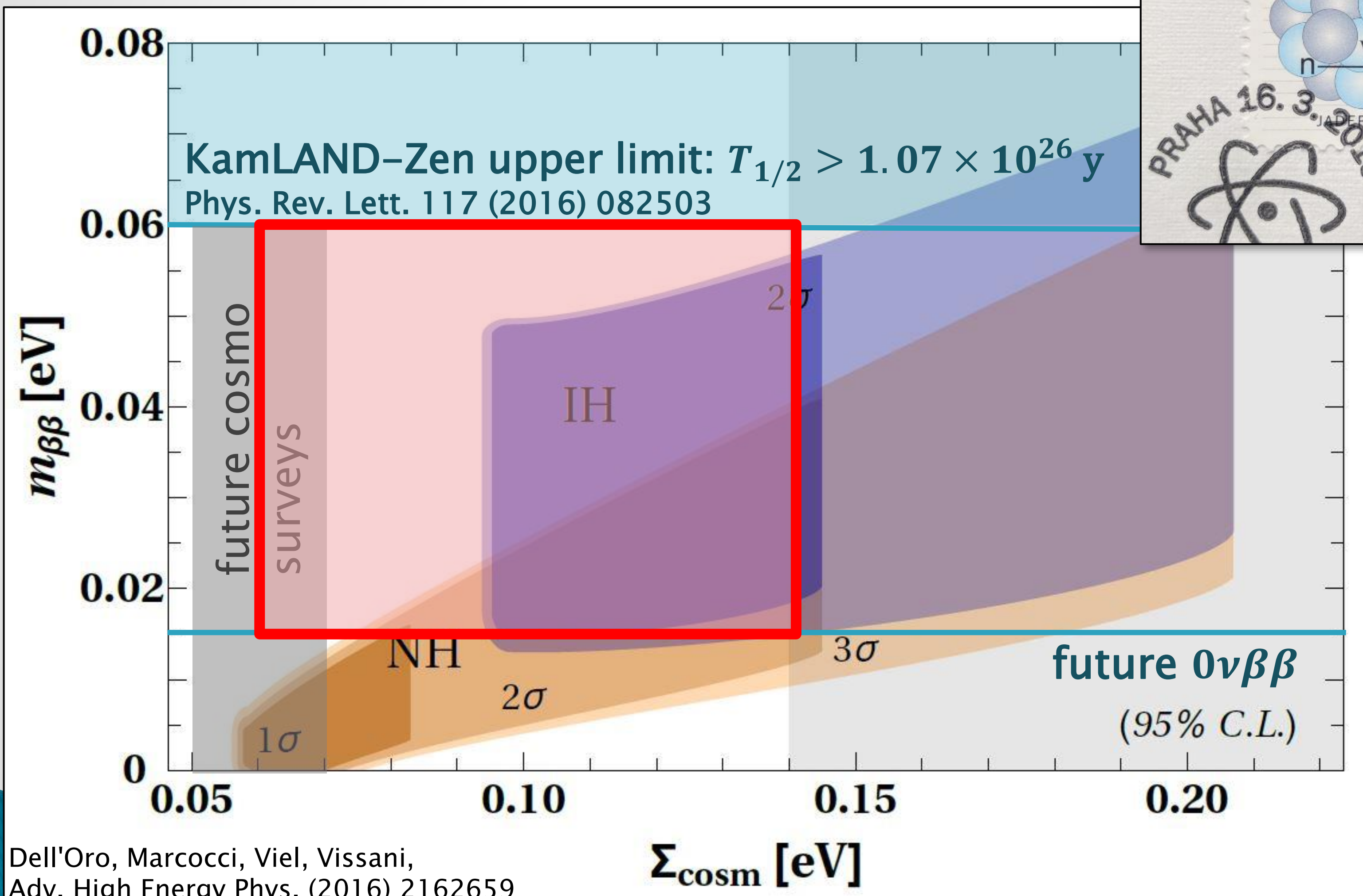


Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

# Three Active Neutrinos



- Effective $0\nu\beta\beta$ Mass




Dell'Oro, Marcocci, Viel, Vissani,
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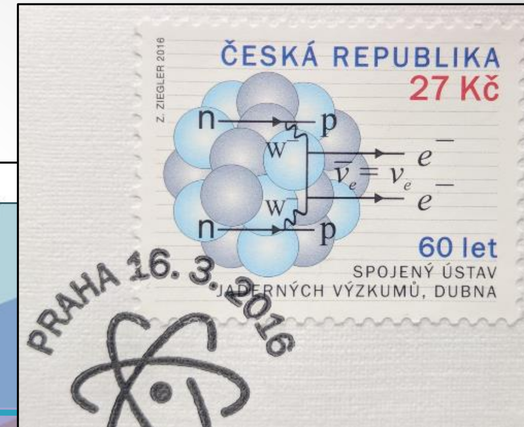
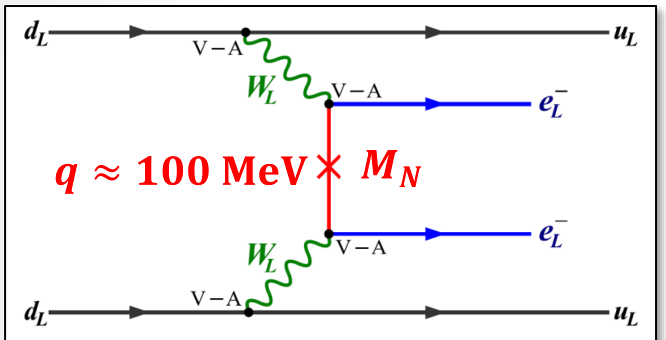


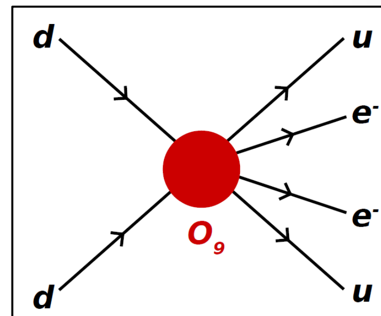
# Heavy Sterile Neutrinos

- with masses larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q}+M_{N_i}}{q^2-M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}}} \to \left\langle \frac{1}{M_N}\right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale




- Light neutrino mass via seesaw

$$\mathrm{diag}(m_\nu, M_N, M_N+\Delta M_N) = U\cdot \begin{array}{c} \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot U^T$$

'Vanilla' seesaw $\mu_R \gg m_D$

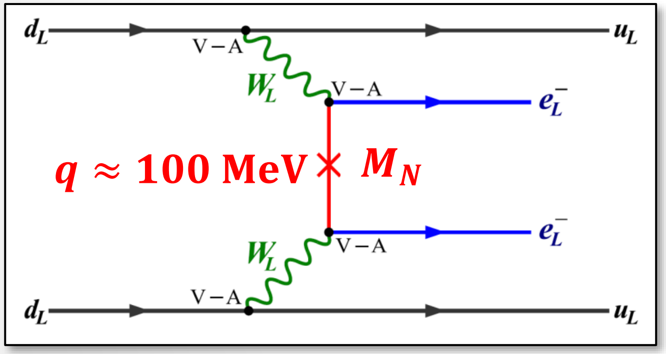
$$\frac{m_\nu}{0.1\text{ eV}} = \frac{V_{eN}^2}{10^{-12}}\frac{M_N}{100\text{ GeV}}$$

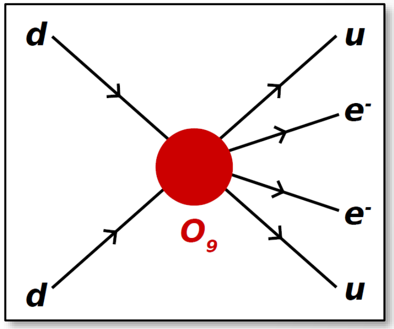
# Heavy Sterile Neutrinos

- with masses larger than $\approx 100$ MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\cancel{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}}} \rightarrow \left\langle\frac{1}{M_N}\right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale




- Light neutrino mass via seesaw

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{array}{c} \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot V^T$$

Inverse seesaw

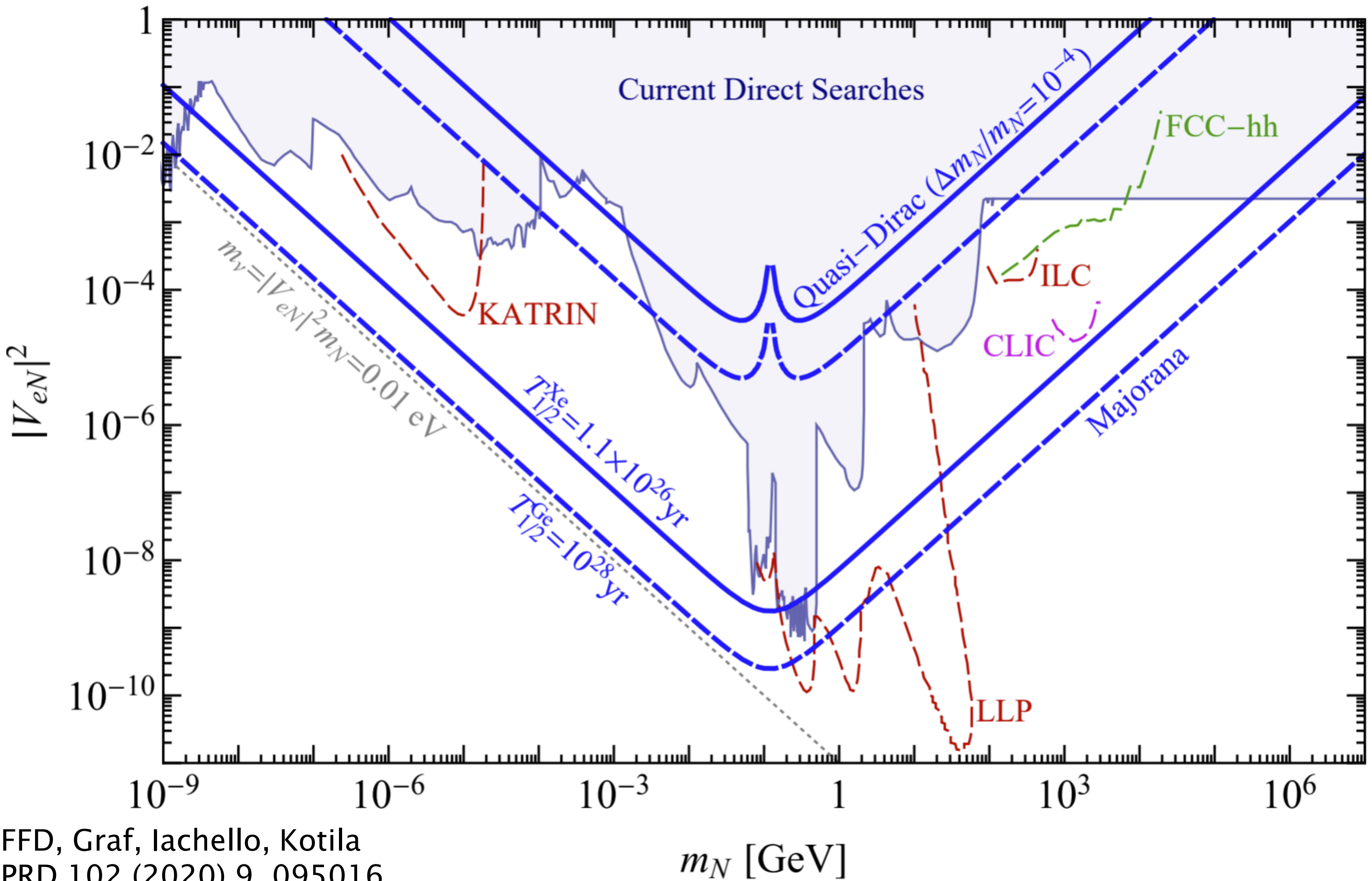
$M \gg \mu_S, \mu_R, m_D$

$$\boxed{\frac{m_\nu}{0.1\ \mathrm{eV}} = \frac{V_{eN}^2}{10^{-4}}\frac{\mu_S}{\mathrm{keV}}}$$

Quasi-Dirac $N$

Approximate $L$ conservation

# Heavy Sterile Neutrinos




FFD, Graf, Iachello, Kotila
PRD 102 (2020) 9, 095016

# New Physics and $0\nu\beta\beta$

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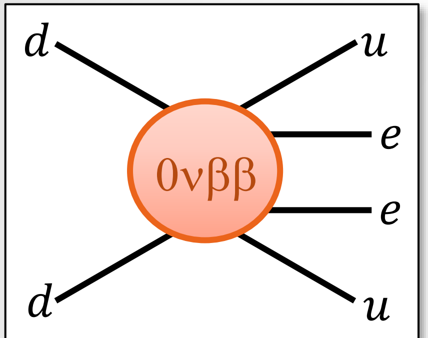
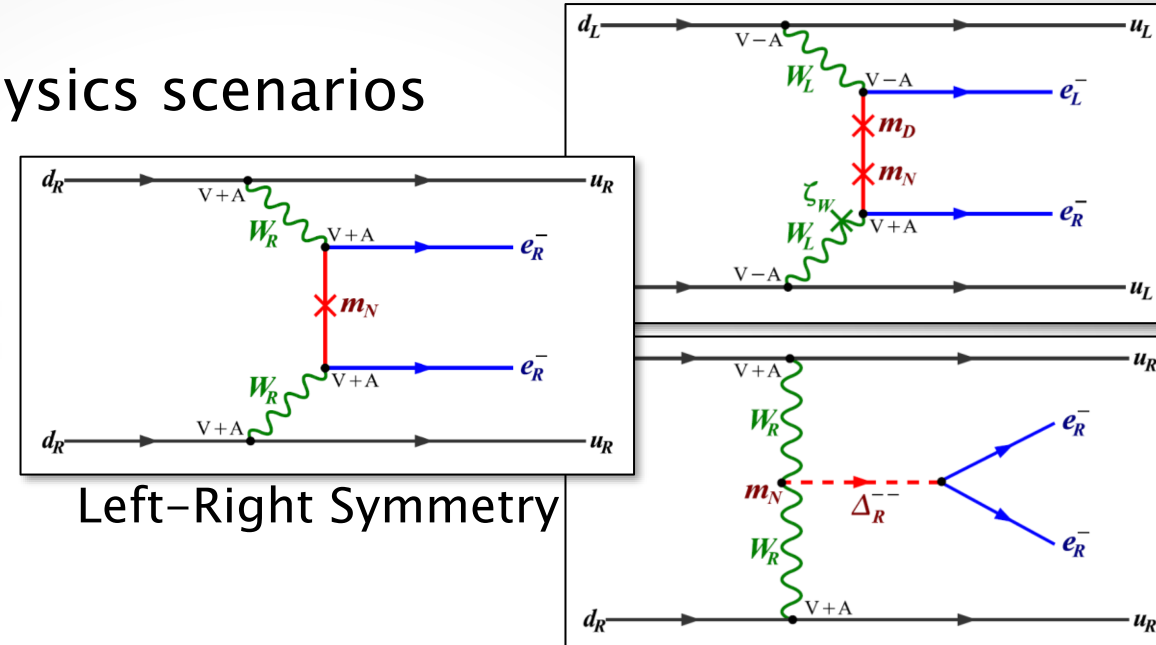
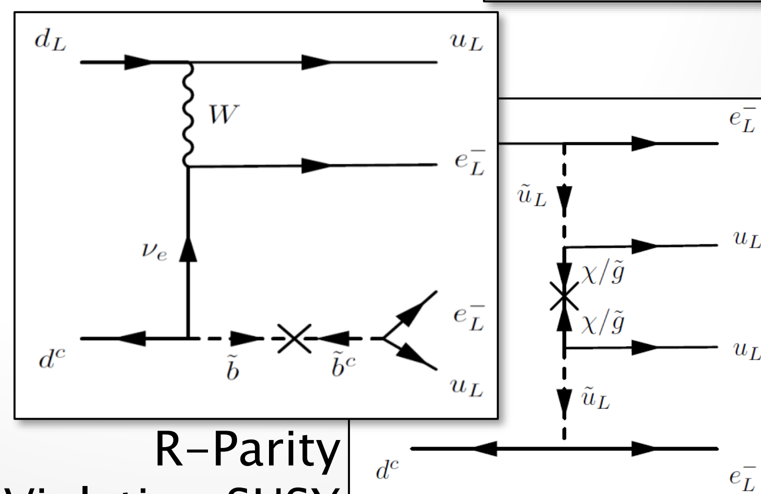
- Plethora of New Physics scenarios




$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$




Left-Right Symmetry




R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

…

# New Physics and $0\nu\beta\beta$

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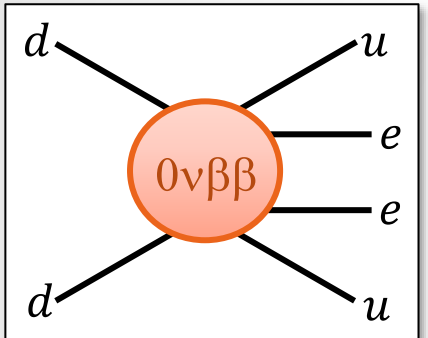
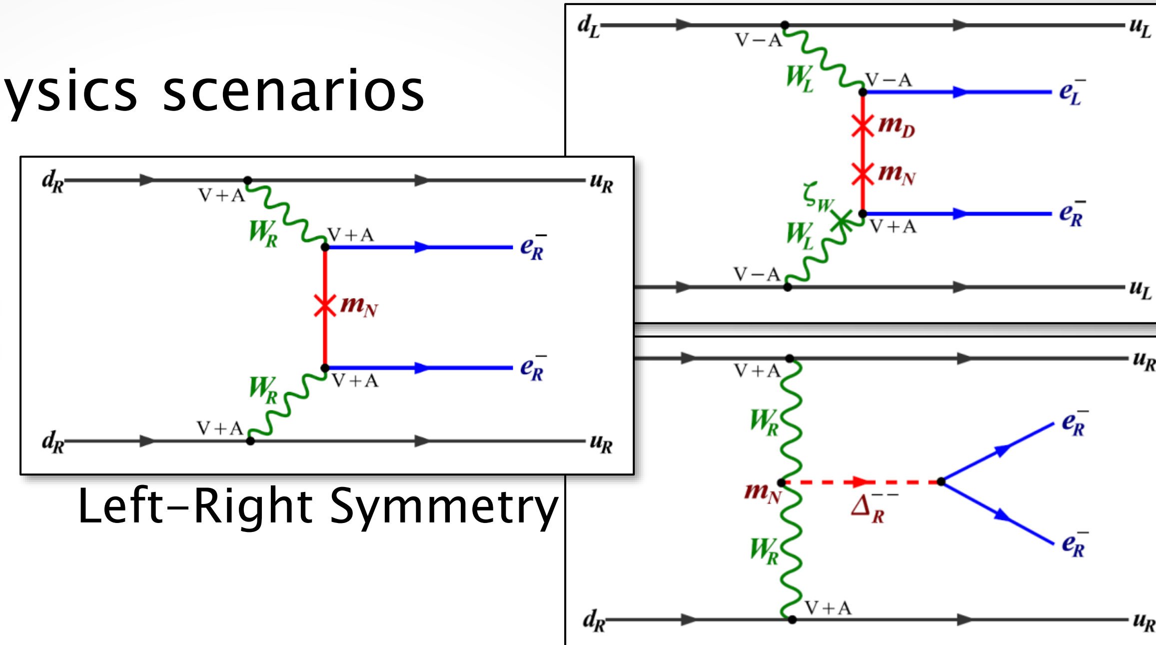
- Plethora of New Physics scenarios



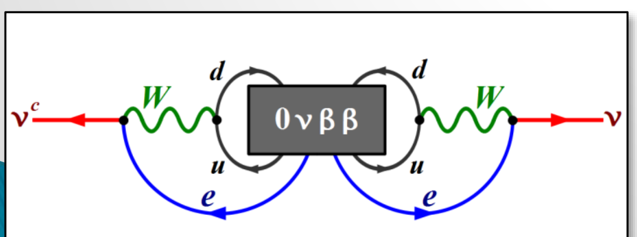

$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

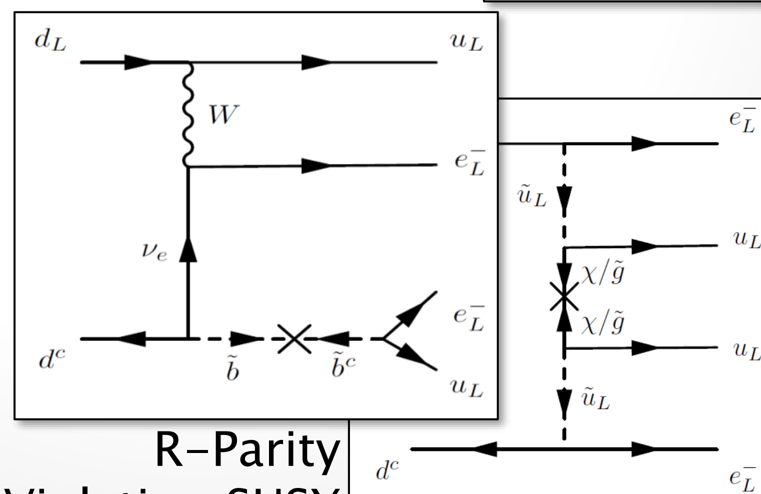



Left-Right Symmetry

- Neutrinos still Majorana

Schechter, Valle
Phys. Rev. D25 (1982) 2951




R-Parity Violating SUSY

Extra Dimensions

Majorons

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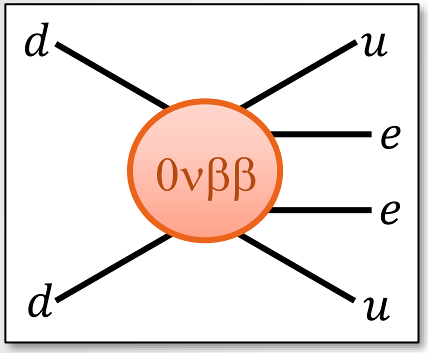
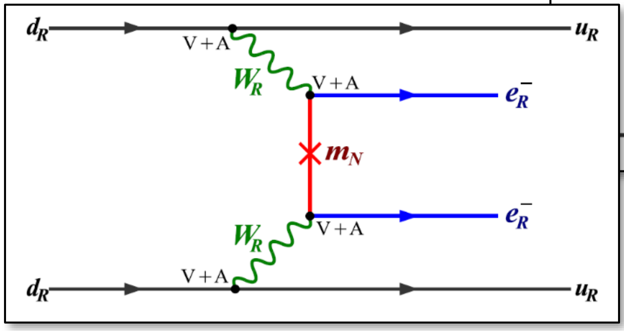
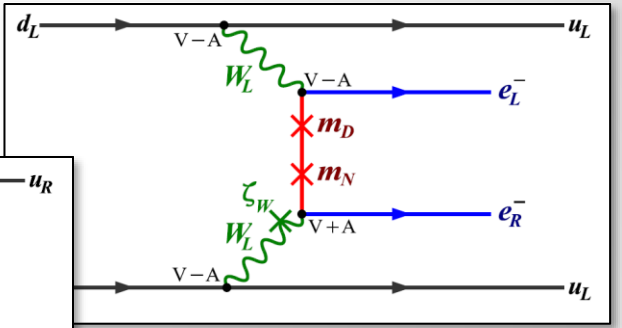
...

# New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry



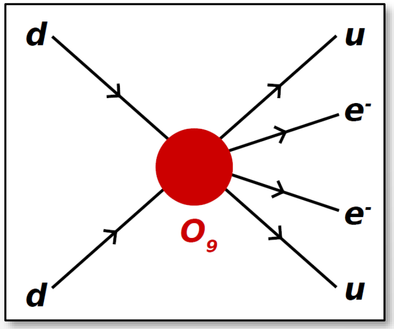



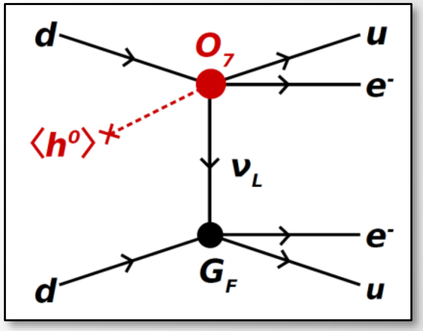

$$\boxed{T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2}$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\text{ TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\text{ TeV})^3}$$

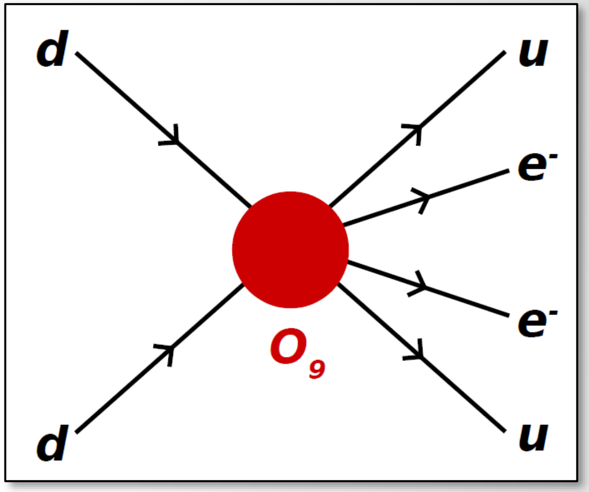
- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators



# Short-Range Mechanisms

- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators (Paes et al. '01)




$$L = \frac{G_F^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\nu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right)$$

# Short-Range Mechanisms

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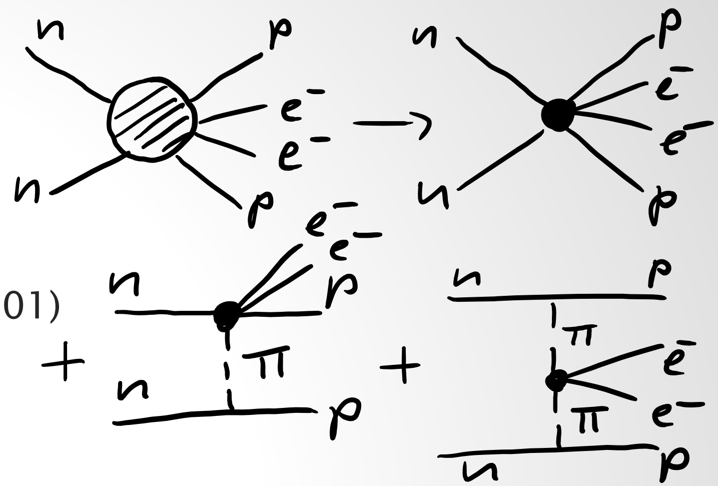
- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators (Paes et al. '01)
  - NMEs from IBM-2 with $g_A = 1.0$ and short-range correlations in Argonne parametrization




$$
\begin{aligned}
F_S(q^2) &= \frac{g_S}{(1+q^2/m_V^2)^2}, & g_S &= 1.0\ [42],\\
F_{PS}(q^2) &= \frac{g_{PS}}{(1+q^2/m_V^2)^2}\frac{1}{1+q^2/m_\pi^2}, & g_{PS} &= 349\ [42],\\
F_V(q^2) &= \frac{g_V}{(1+q^2/m_V^2)^2}, & g_V &= 1.0,\\
F_W(q^2) &= \frac{g_W}{(1+q^2/m_V^2)^2}, & g_W &= 3.7,\\
F_A(q^2) &= \frac{g_A}{(1+q^2/m_A^2)^2}, & g_A &= 1.27\ [43],\\
F_P(q^2) &= \frac{g_P}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}, & g_P &= 4g_A\frac{m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right) = 231\ [44],\\
F_{T_i}(q^2) &= \frac{g_{T_i}}{(1+q^2/m_V^2)^2}, & g_{T_{1,2,3}} &= 1.0, -3.3, 1.34\ [40].
\end{aligned}
$$

Pion-mediated contributions

- R-parity violating SUSY
  (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
- Chiral EFT with Pion operators from Lattice QCD
  (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)

# Short-Range Mechanisms

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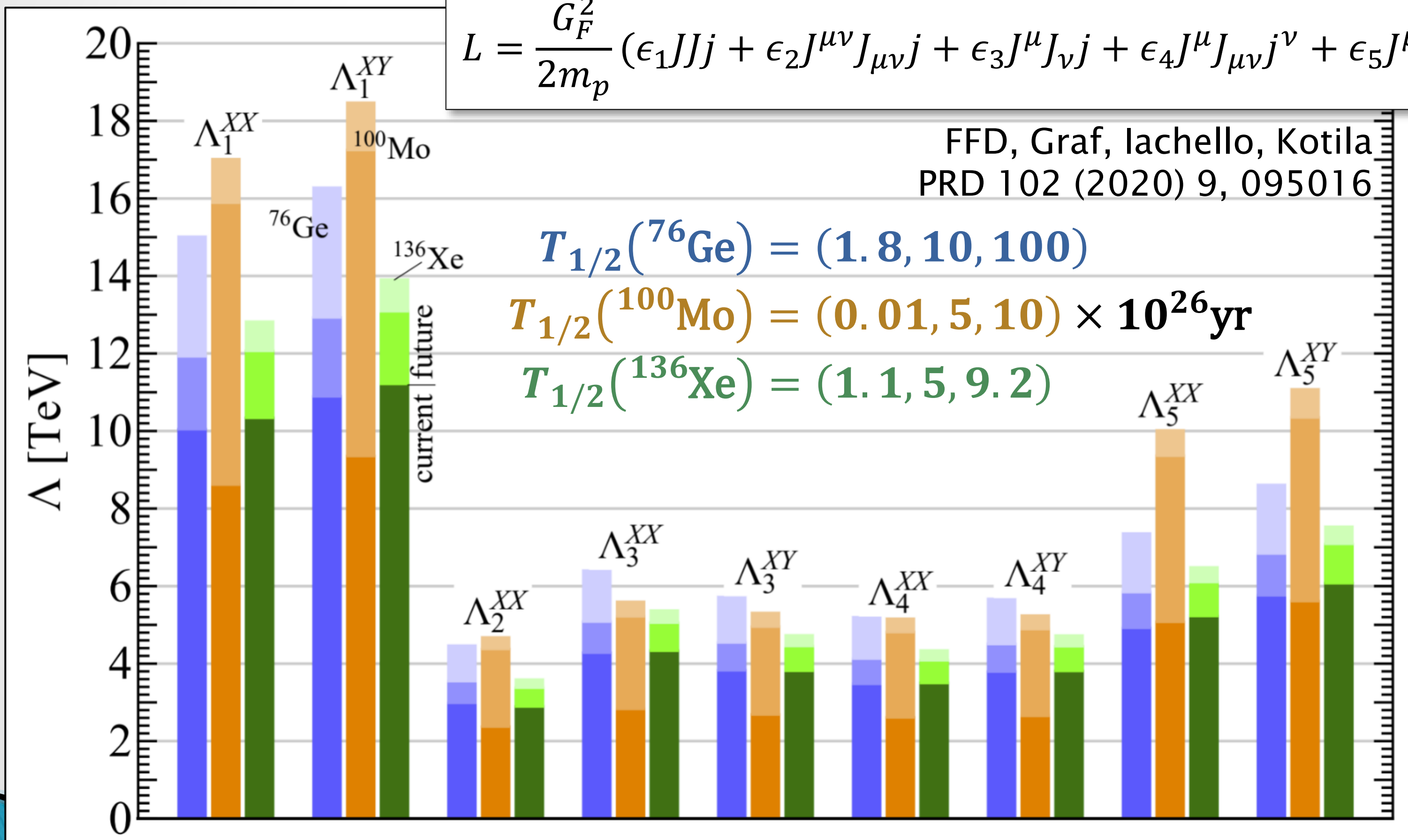
- Evaluation of limits on short-range operators

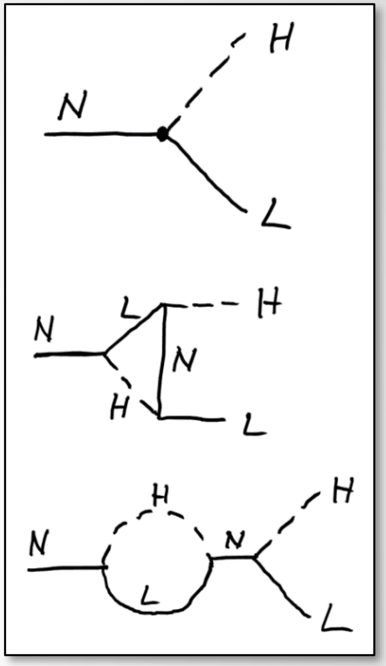
$$L = \frac{G_F^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\nu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right)$$



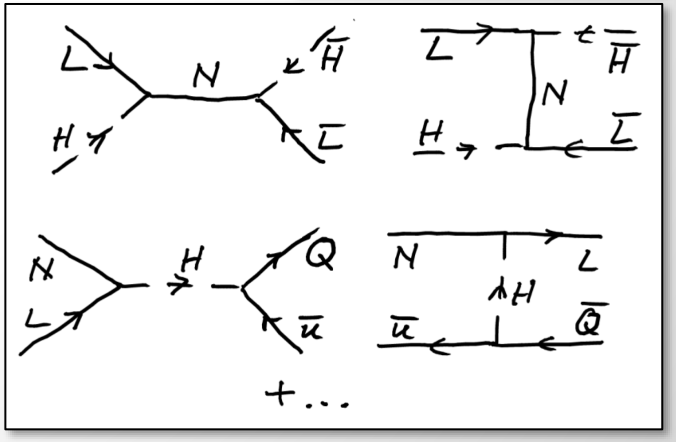
# Falsifying Baryogenesis

- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

$$\boxed{\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}}$$




- Other possible scenarios
  - For us only important: $(B - L)$ asymmetry generated above LHC scale



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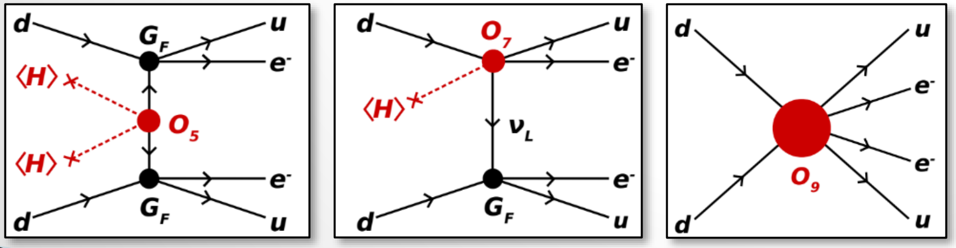
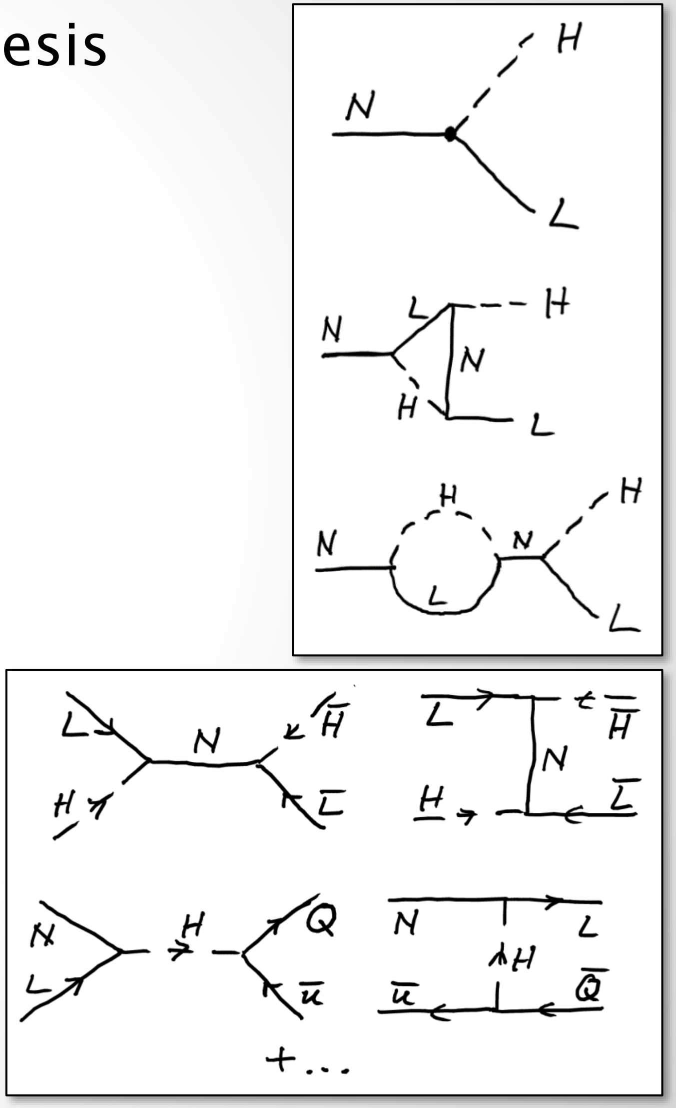
# Falsifying Baryogenesis

- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

$$\boxed{\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}}$$

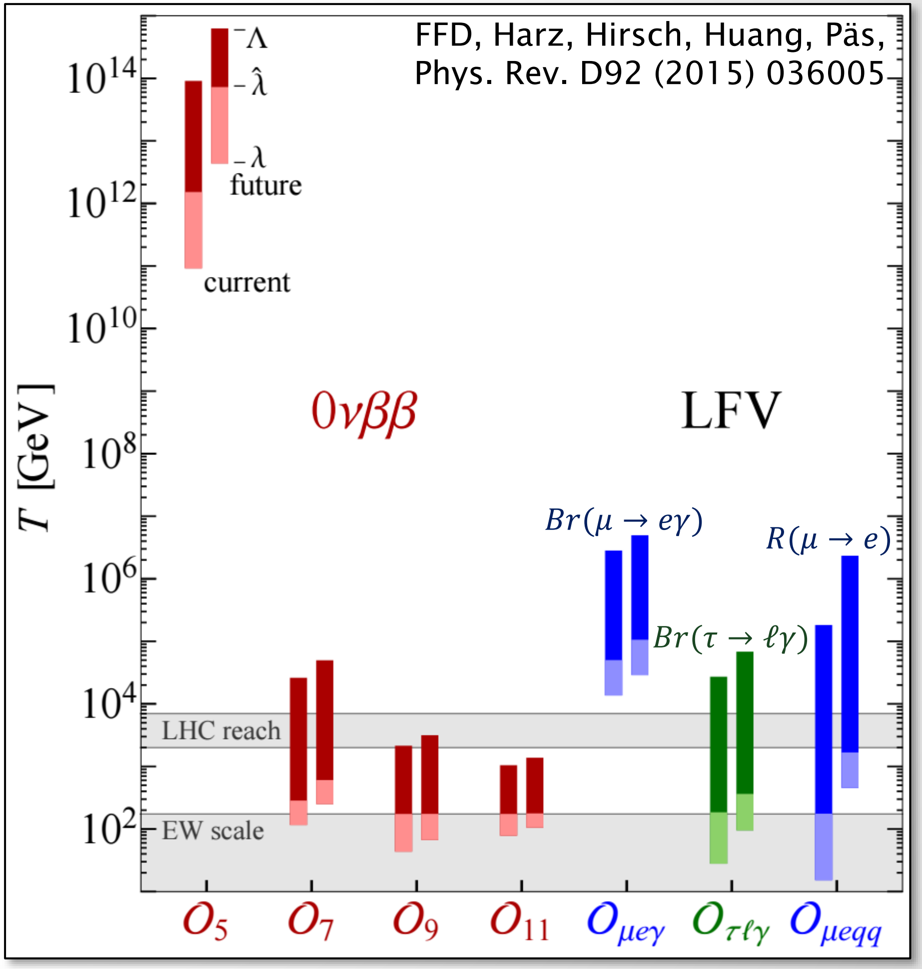
- What if we observe lepton number violating processes in $0\nu\beta\beta$?



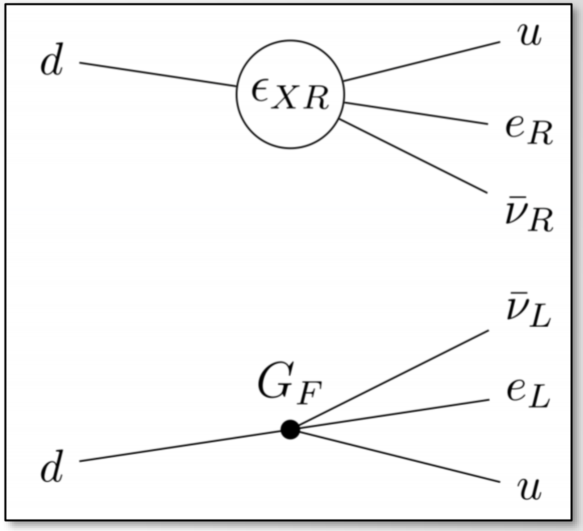
# Falsifying Baryogenesis

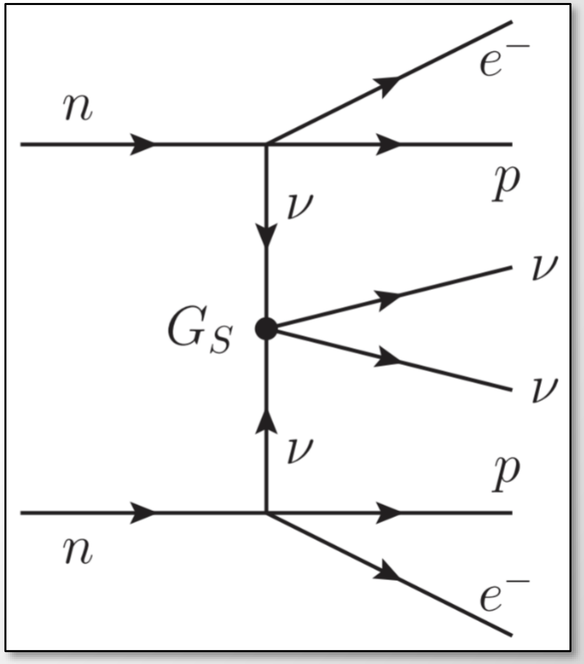
- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



# New Physics in $2\nu\beta\beta$

- Lepton-number conserving right-handed currents
(FFD, Graf, Simkovic, PRL 125 (2020) 17, 171801)
  - Estimated current limit $\epsilon_{XR} < 2.7 \times 10^{-2}$ from NEMO3 (angular correlation) competitive to other searches
- Neutrino self-interactions
(FFD, Graf, Rodejohann, Xu, PRD 102 (2020) 5, 051701)
  - Excludes regime $G_S \approx 4 \times 10^{9}\, G_F$ suggested to resolve Hubble tension
  - Excludes quadruple $0\nu4\beta$ decay



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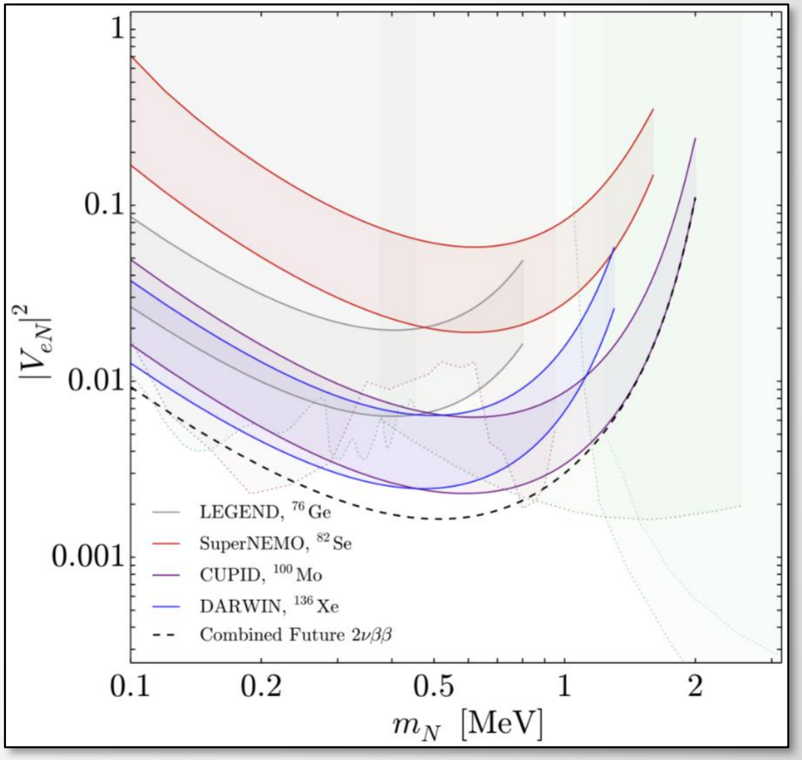
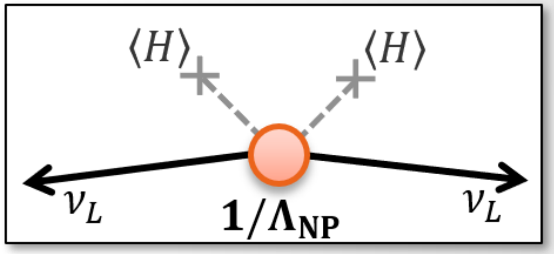
  - Excludes quadruple $0\nu4\beta$ decay
- Sterile neutrino search through energy endpoint
  (Bolton, FFD, Graf, Simkovic, arXiv:2011.13387;
  Agostini, Bossio, Ibarra, Marcano,
  arXiv:2012.09281)



# Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Standard interpretation: New Physics near GUT scale breaking lepton number
  - Direct sensitivity to LNV physics at scales $m_N \approx 1\,\mathrm{eV} - 10\,\mathrm{TeV}$
- **Many omissions**
  - Majoron and other exotic emissions
  - Angular and energy distributions
- **$2\nu\beta\beta$ is becoming sensitive to New Physics as well**
- **Importance of probing LNV around the TeV scale**
  - Can we discover mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe




$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\,\mathrm{y}} \approx \left(\frac{\Lambda_{\mathrm{NP}}}{10^{15}\,\mathrm{GeV}}\right)^2$$