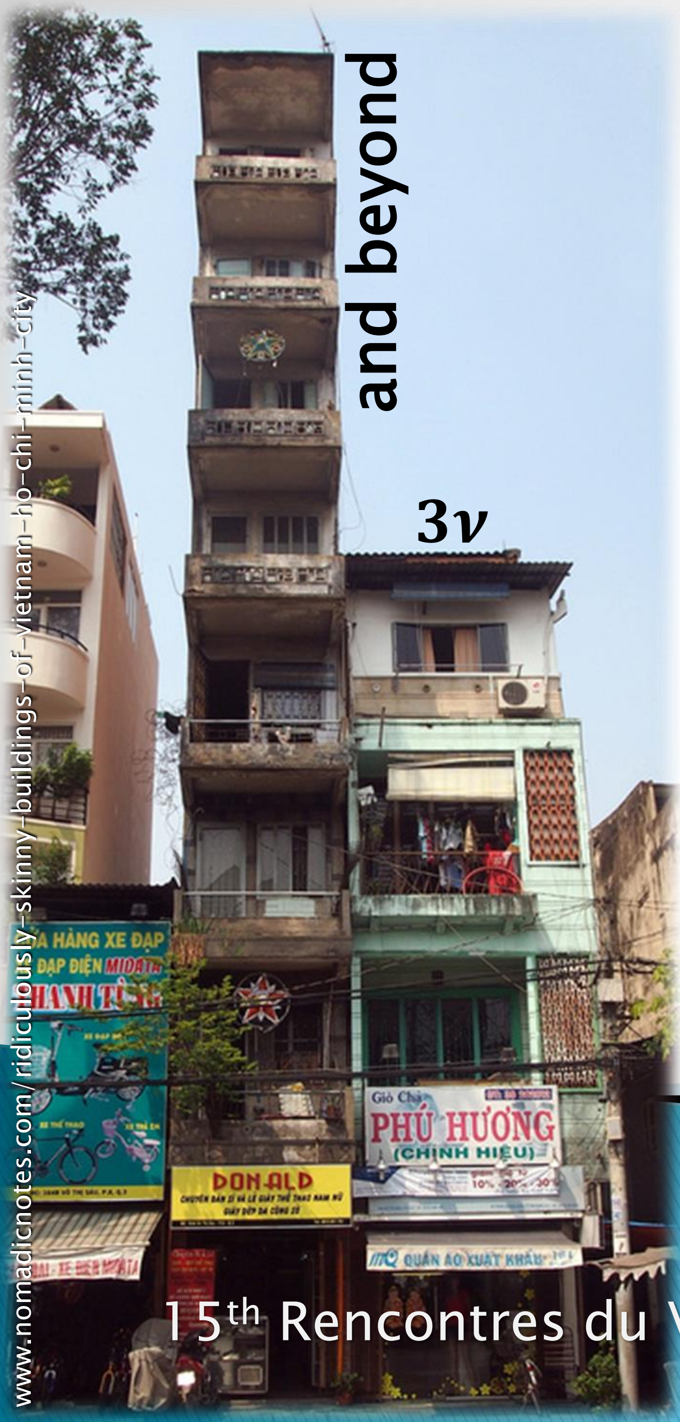
UCL
University College London



www.nomadicnotes.com/ridiculously-skinny-buildings-of-vietnam-ho-chi-minh-city

Double Beta Decay and Neutrino Mass Models

Frank Deppisch
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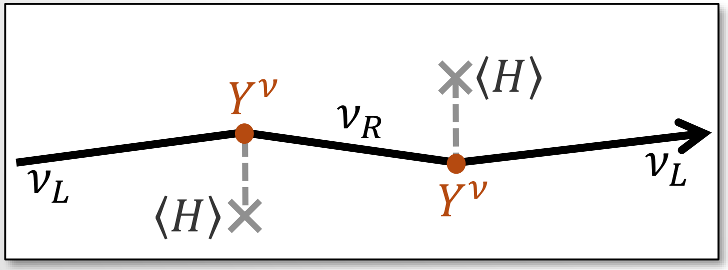
University College London

15th Rencontres du Vietnam | ICISE Quy Nhon | 4-10/8/2019

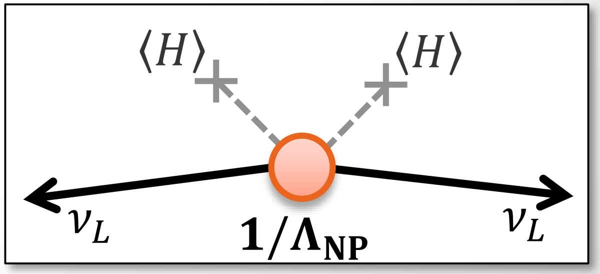
Dirac vs Majorana

- 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

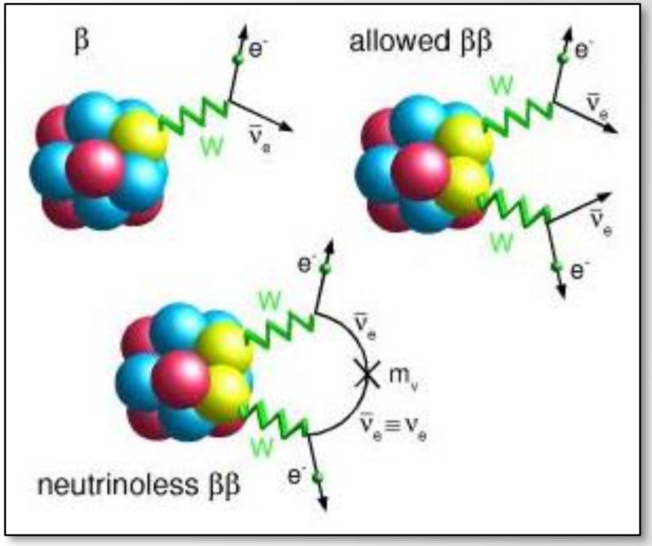


Beta Decays and ν Mass

- Single beta decay

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

  - 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

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

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

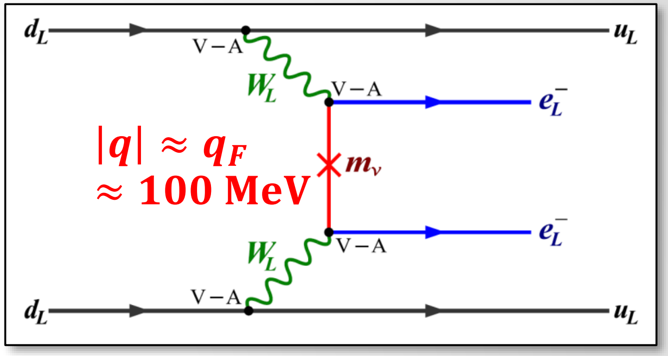
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

  - Violation of lepton number
  - Mediated by Majorana neutrinos

Three Active Neutrinos

- Half-life

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

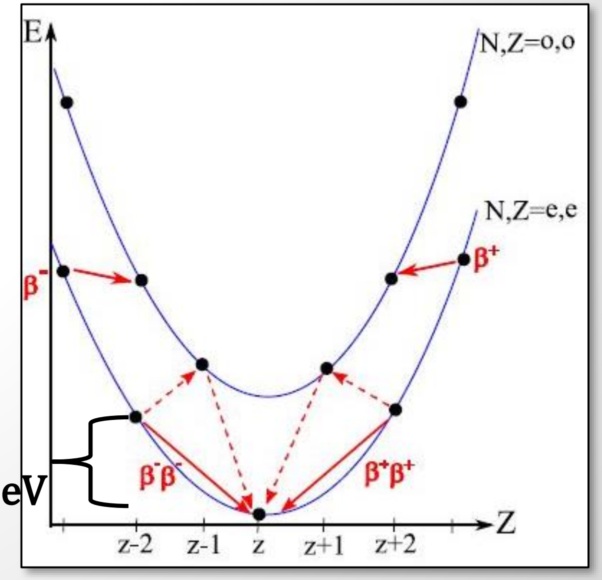


$|q| \approx q_F$
$\approx$ **100 MeV**

- 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 $M^{0\nu} \approx 1$



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

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

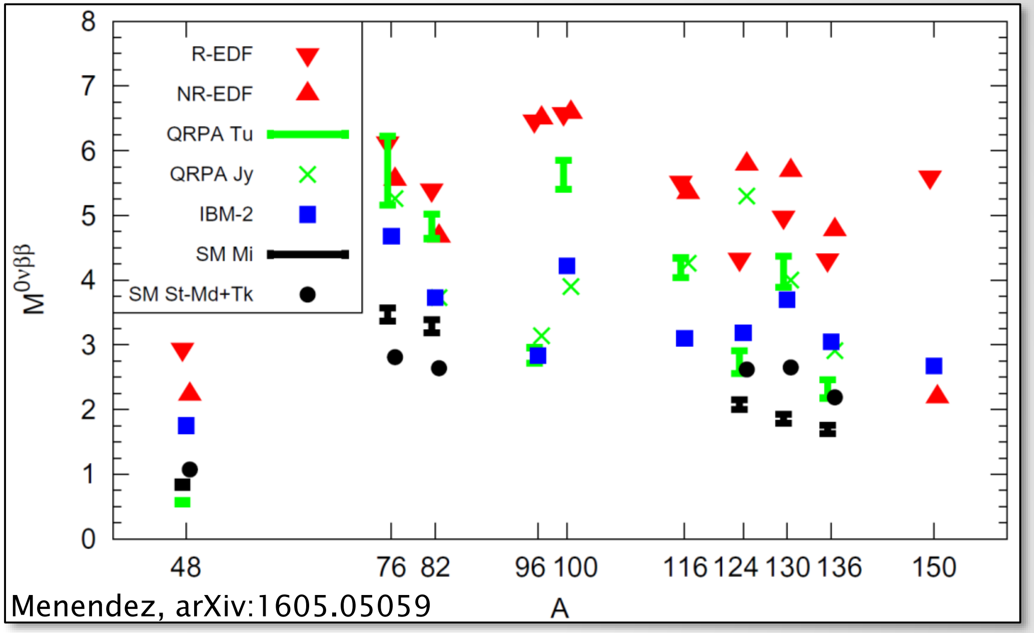
$\boldsymbol{Q + 2m_e}$
$\approx$ **3–5 MeV**

Nuclear Matrix Elements

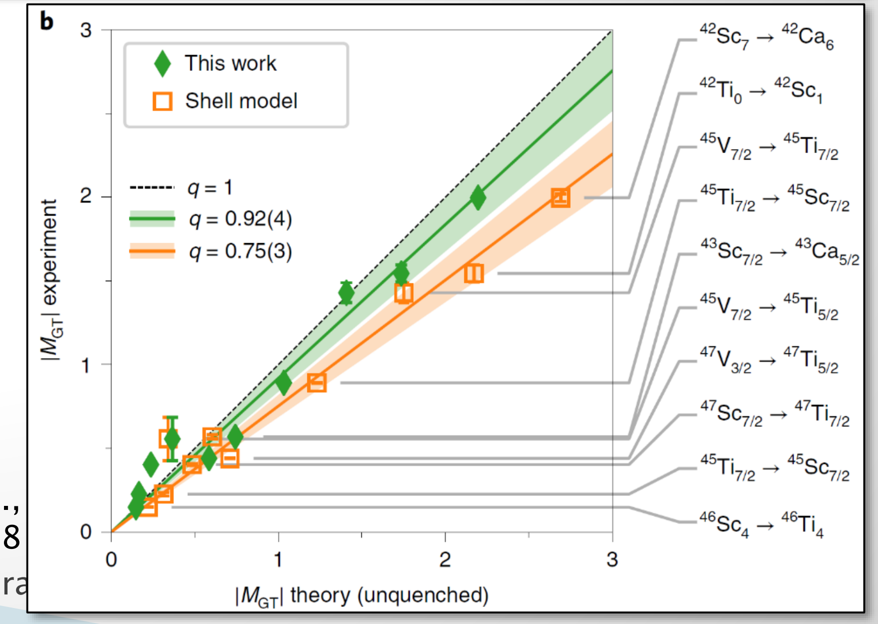
- Nuclear Matrix Element

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

  - 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



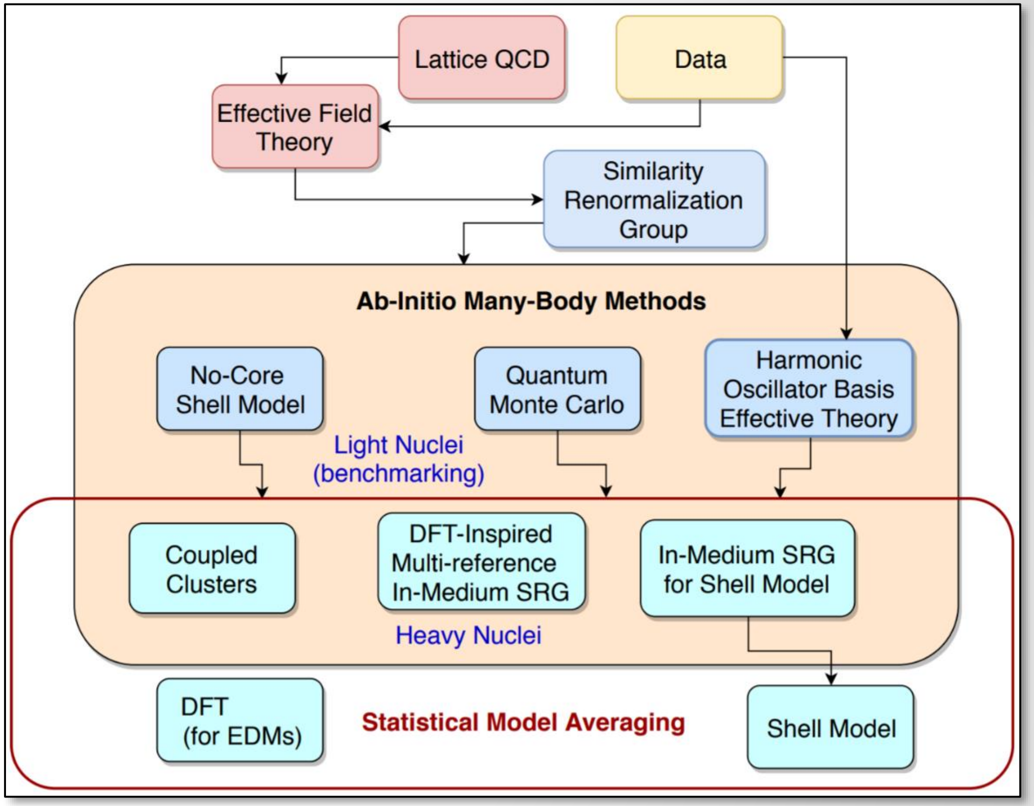
Gysbers et al.,
Nature Physics 15 (2019) 428

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 χEFT, No-core shell model)
    - Experiment (Muon capture, Charge exchange reactions @ NUMEN)



Lattice QCD

Data

Effective Field Theory

Similarity Renormalization Group

Ab-Initio Many-Body Methods

No-Core Shell Model

Quantum Monte Carlo

Harmonic Oscillator Basis Effective Theory

Light Nuclei (benchmarking)

Coupled Clusters

DFT-Inspired Multi-reference In-Medium SRG

In-Medium SRG for Shell Model

Heavy Nuclei

DFT (for EDMs)

Statistical Model Averaging

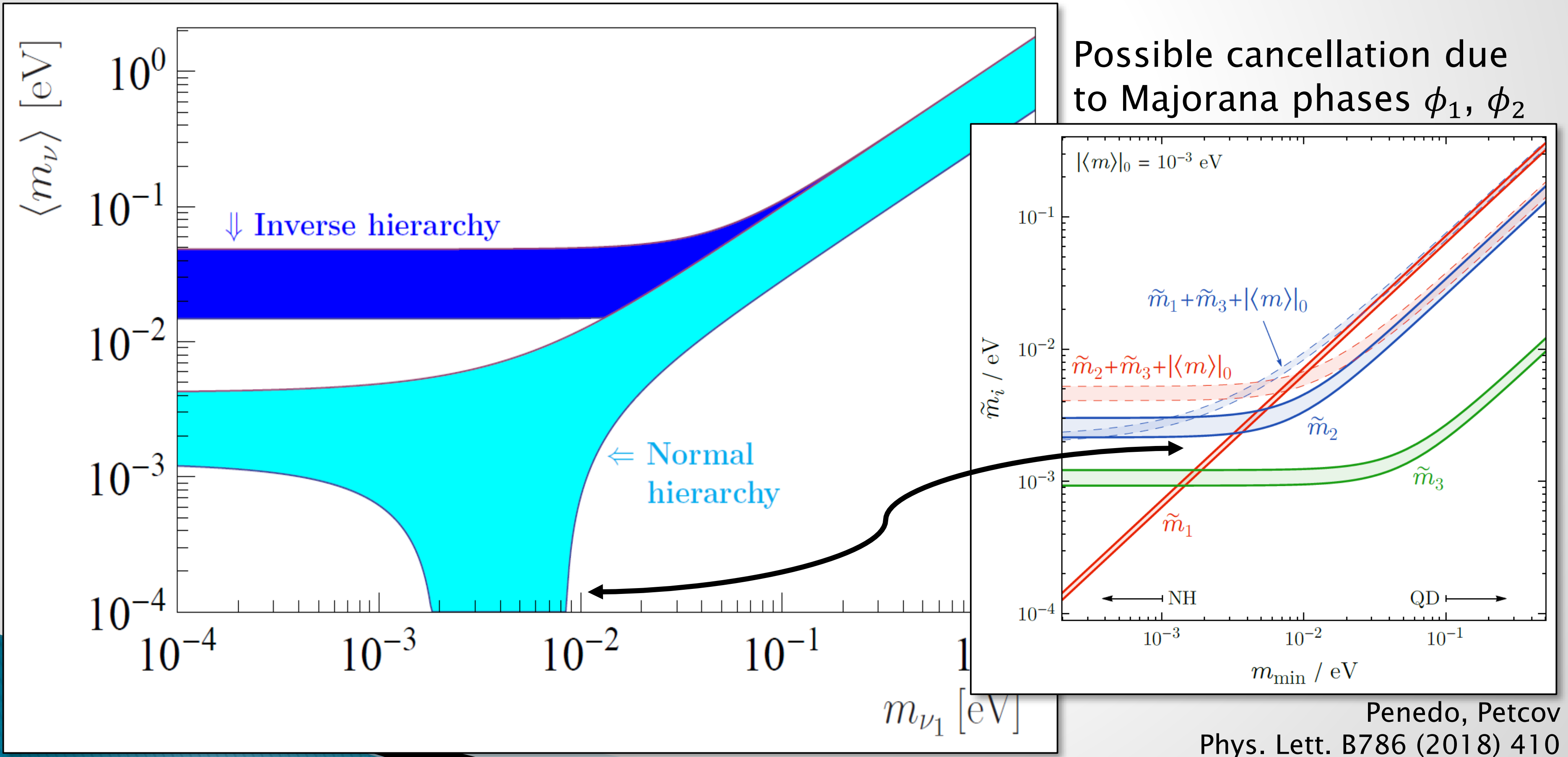
Shell Model

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

Three Active Neutrinos

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

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

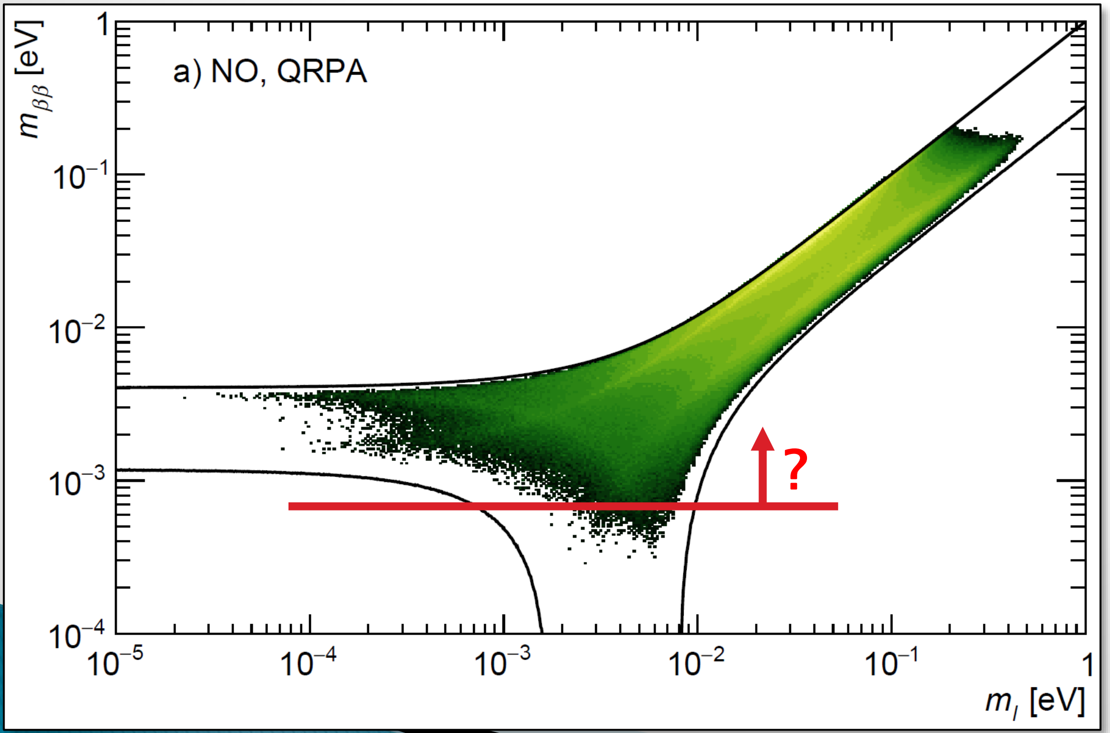


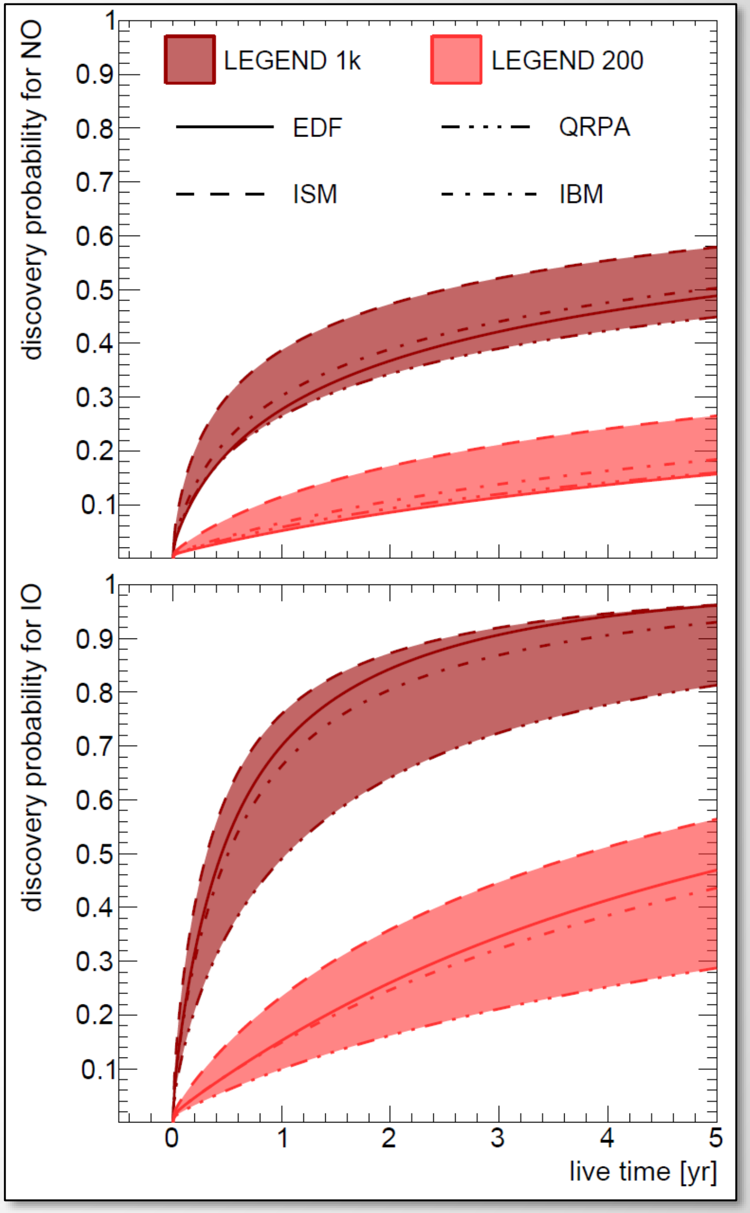
Possible cancellation due to Majorana phases ϕ_1, ϕ_2

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

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

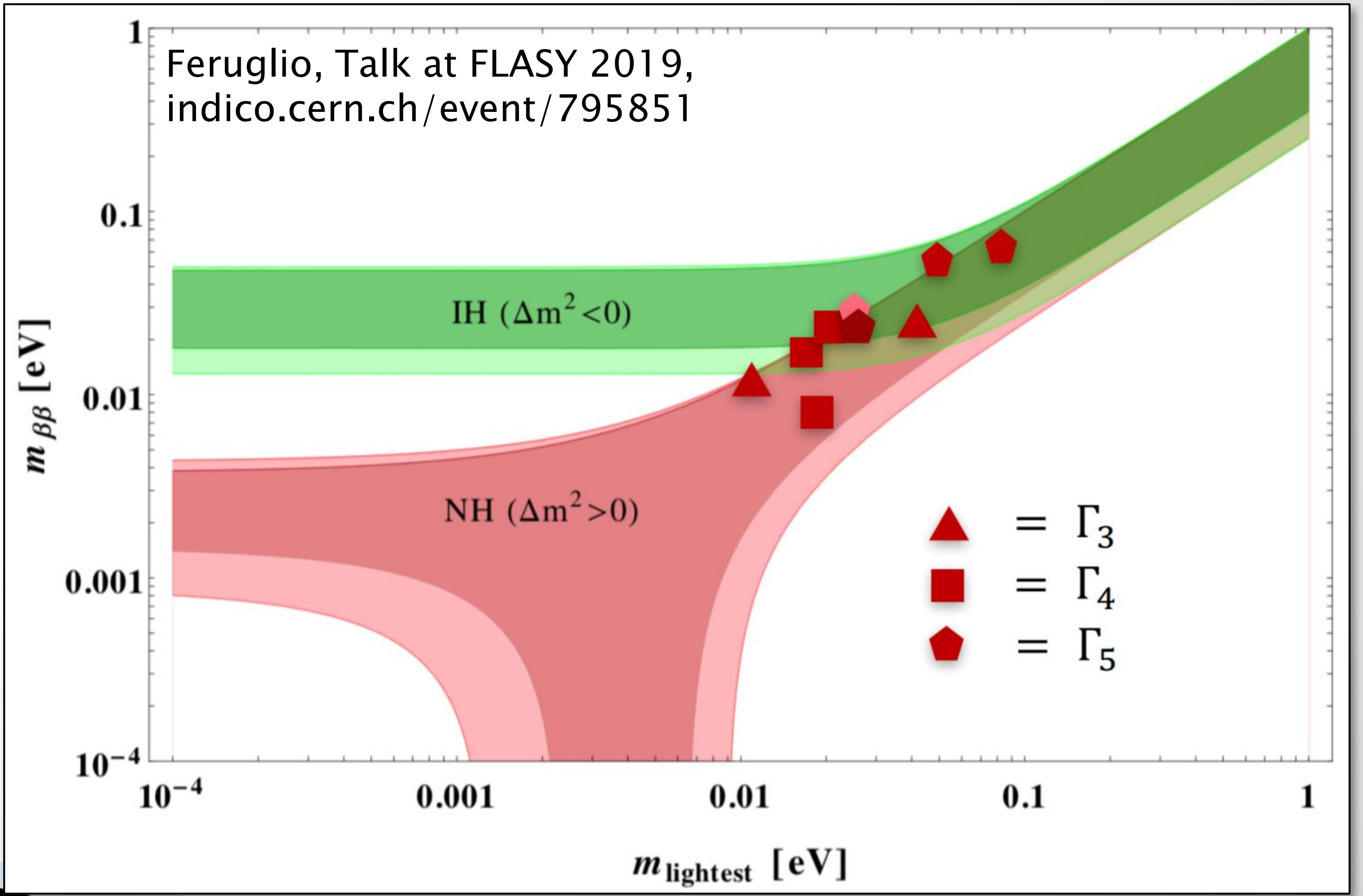
- From volume-effect on accidental cancellation in $m_{\beta\beta}$
  - Bayesian analysis with flat priors on Majorana phases
    Agostini, Benato, Detwiler
    Phys. Rev. D 96 (2017) 053001





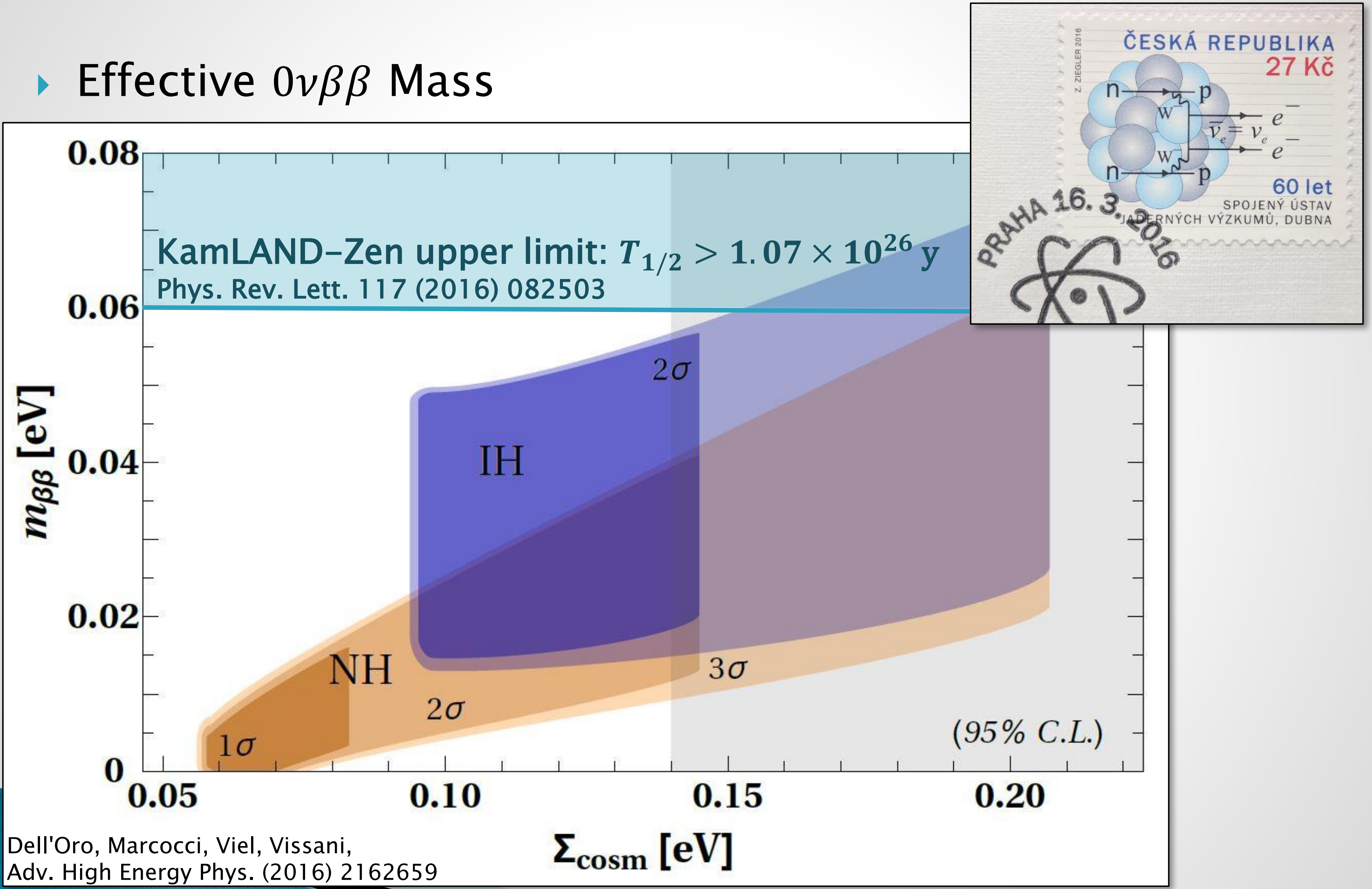
Lower Limit on $m_{\beta\beta}$?

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


Feruglio, Talk at FLASY 2019, indico.cern.ch/event/795851

Experimental Sensitivity

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



KamLAND–Zen upper limit: $T_{1/2} > 1.07 \times 10^{26}$ y
Phys. Rev. Lett. 117 (2016) 082503

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

Experimental Sensitivity

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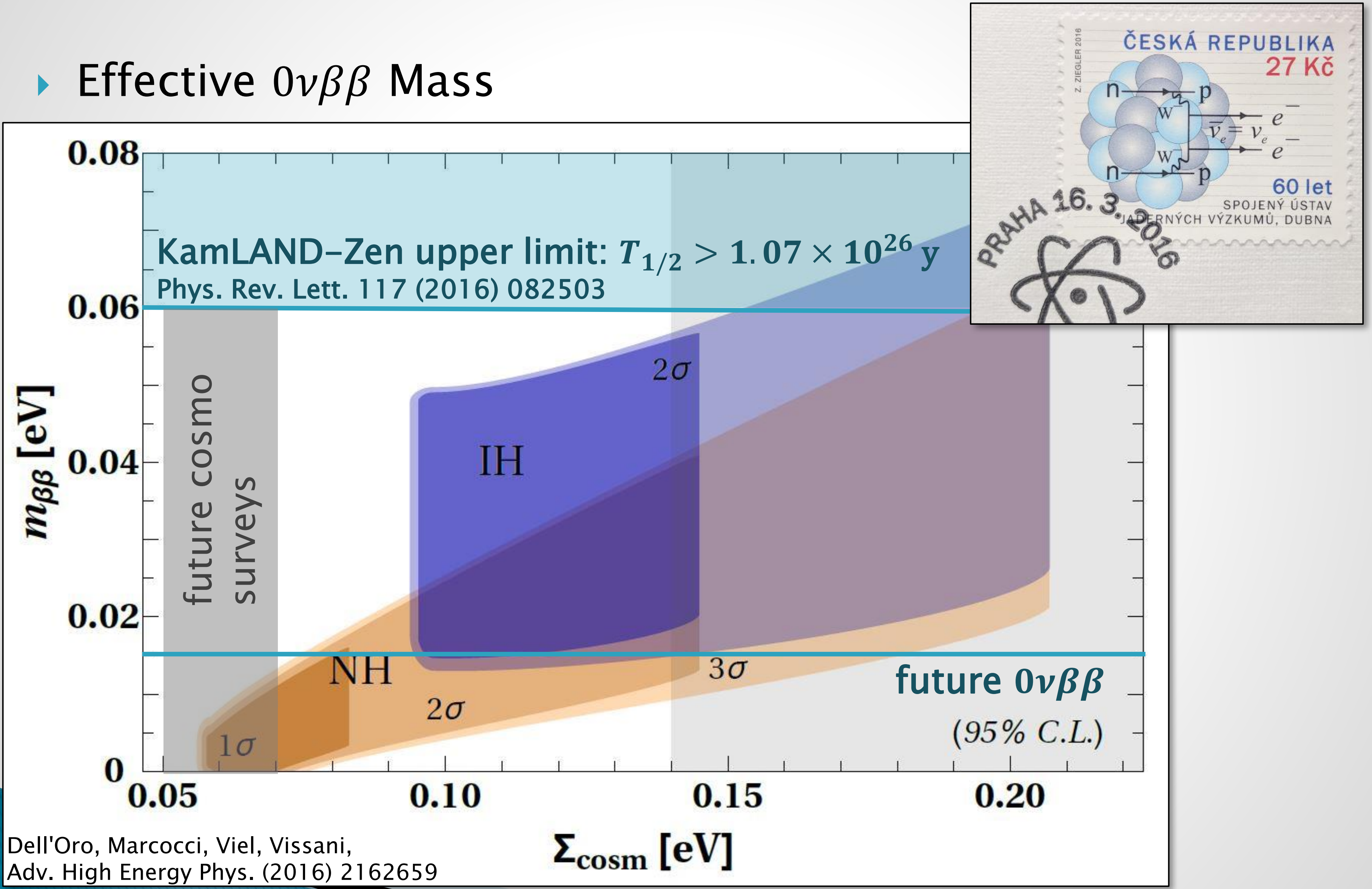


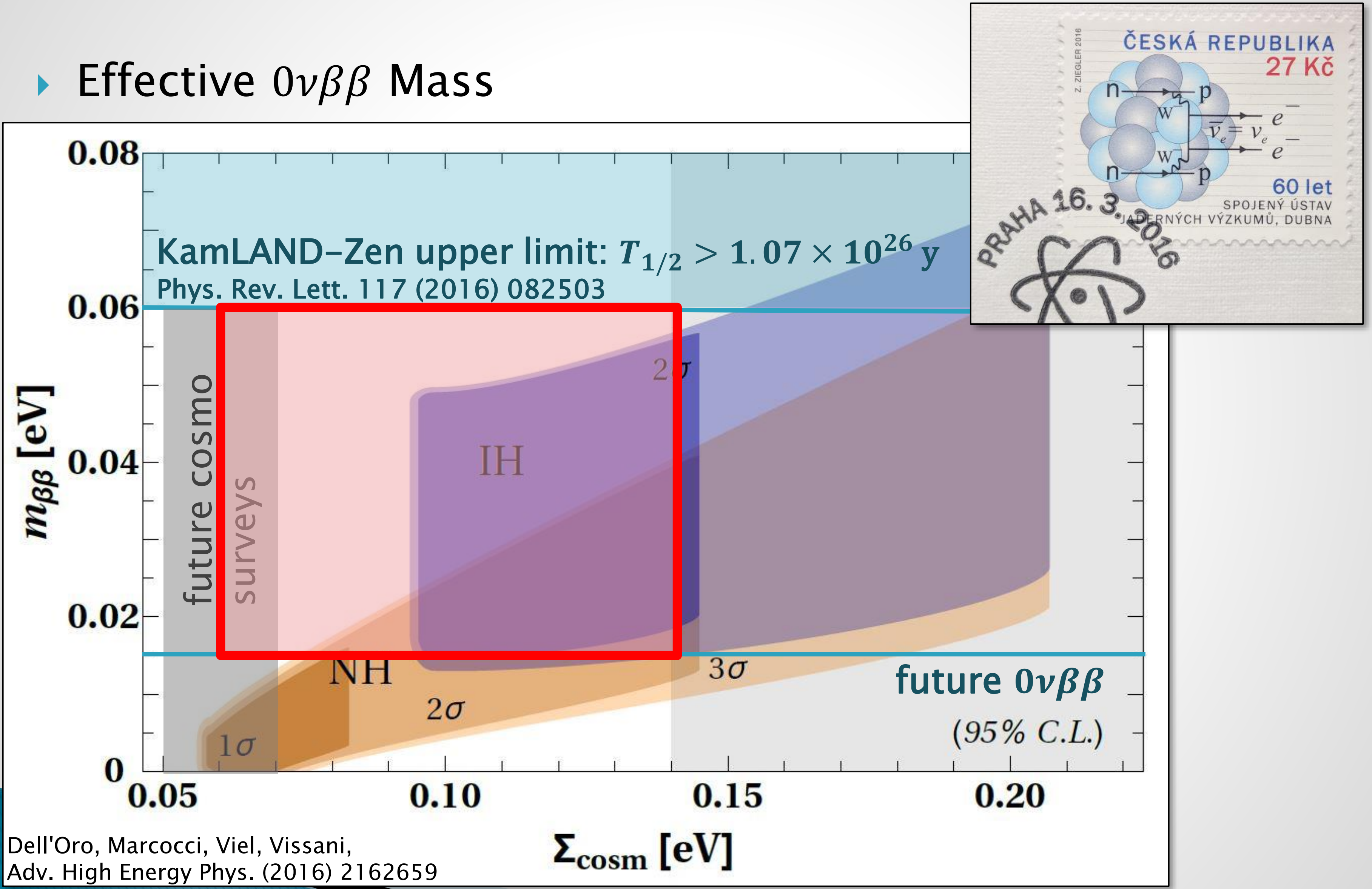
KamLAND–Zen upper limit: $T_{1/2} > 1.07 \times 10^{26}$ y
Phys. Rev. Lett. 117 (2016) 082503

future $0\nu\beta\beta$
(95% C.L.)

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

Experimental Sensitivity

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



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Dell'Oro, Marcocci, Viel, Vissani,
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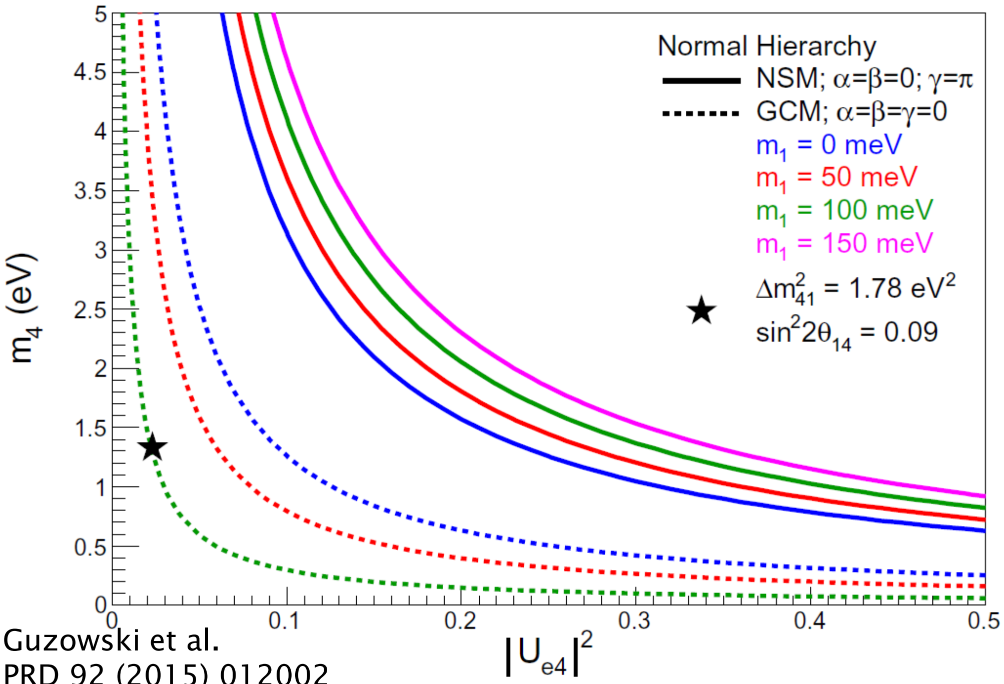
Light Sterile Neutrinos

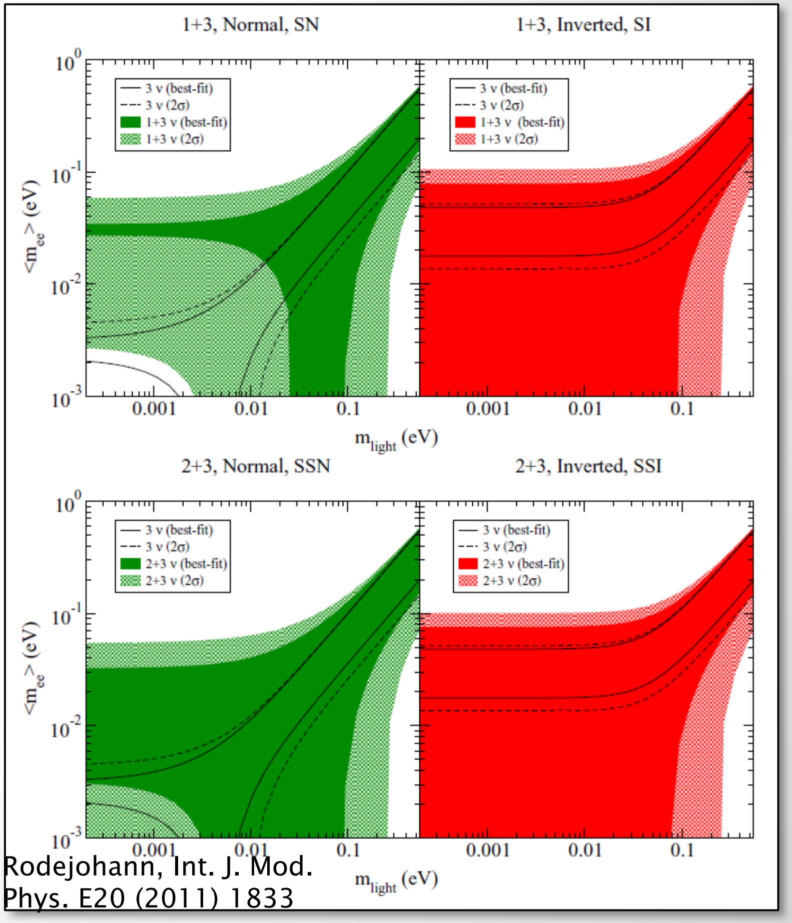
- with masses smaller than $\approx 100\,\mathrm{MeV}$

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- Dependence on new mass, mixing, phase



Guzowski et al.
PRD 92 (2015) 012002



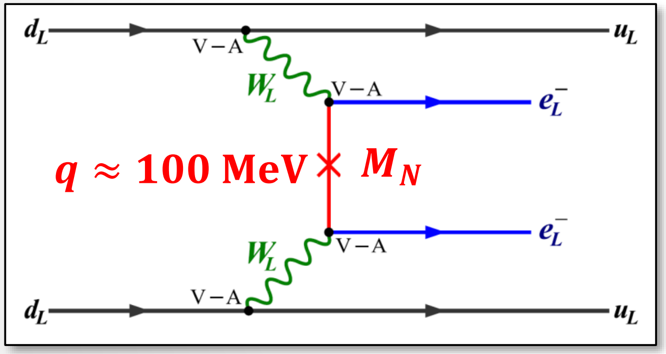
Rodejohann, Int. J. Mod. Phys. E20 (2011) 1833

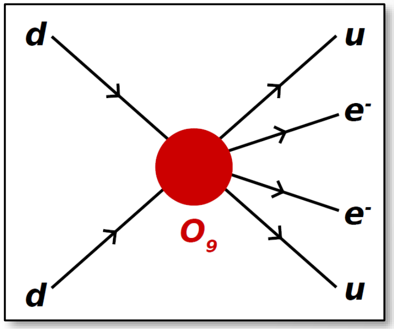
Heavy Sterile Neutrinos

- with masses larger than ≈ 100 MeV

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

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

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

'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 ≈ 100 MeV

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

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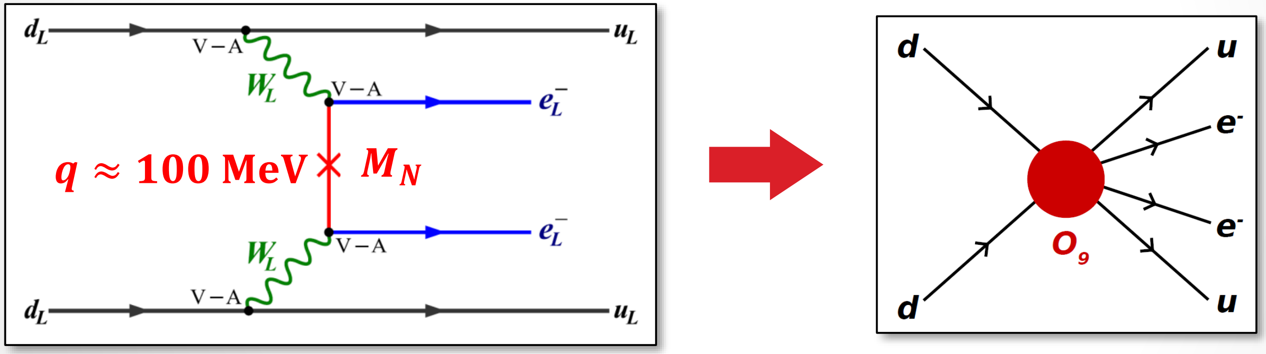


- Light neutrino mass via seesaw

$$\mathrm{diag}(m_\nu, M_N, M_N+\Delta M_N) = U\cdot\begin{array}{c} \\ \left(\begin{array}{ccc}\nu & N_1 & N_2\\ \end{array}\right.\end{array}$$

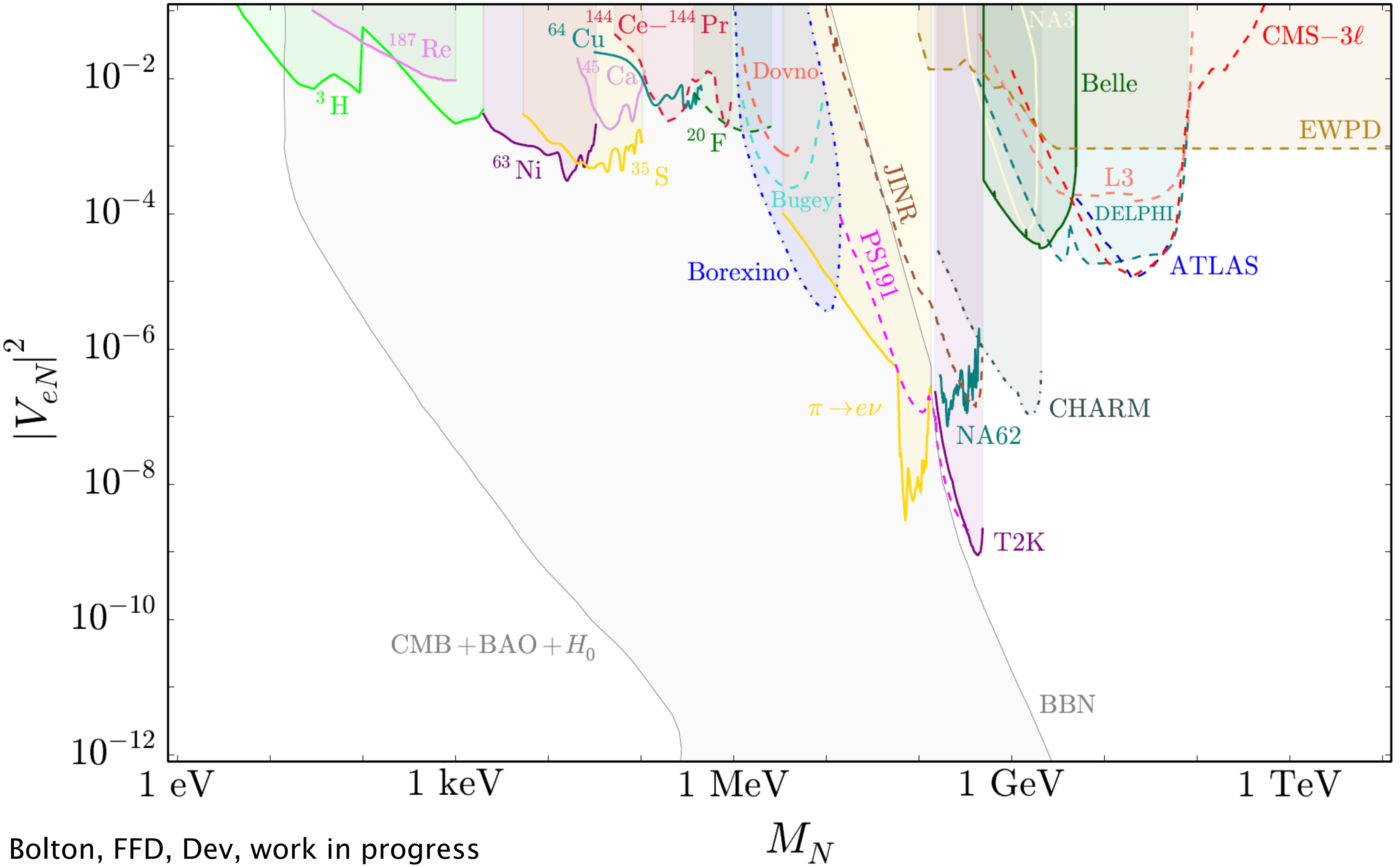
$$\begin{array}{cccc} & \nu & N_1 & N_2 \\ \mathrm{diag}(m_\nu, M_N, M_N+\Delta M_N) = U\cdot & \left(0\right. & m_D & \left.0\right) \\ & m_D & \mu_R & M \\ & \left(0\right. & M & \left.\mu_S\right)\cdot U^T \end{array}$$

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

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

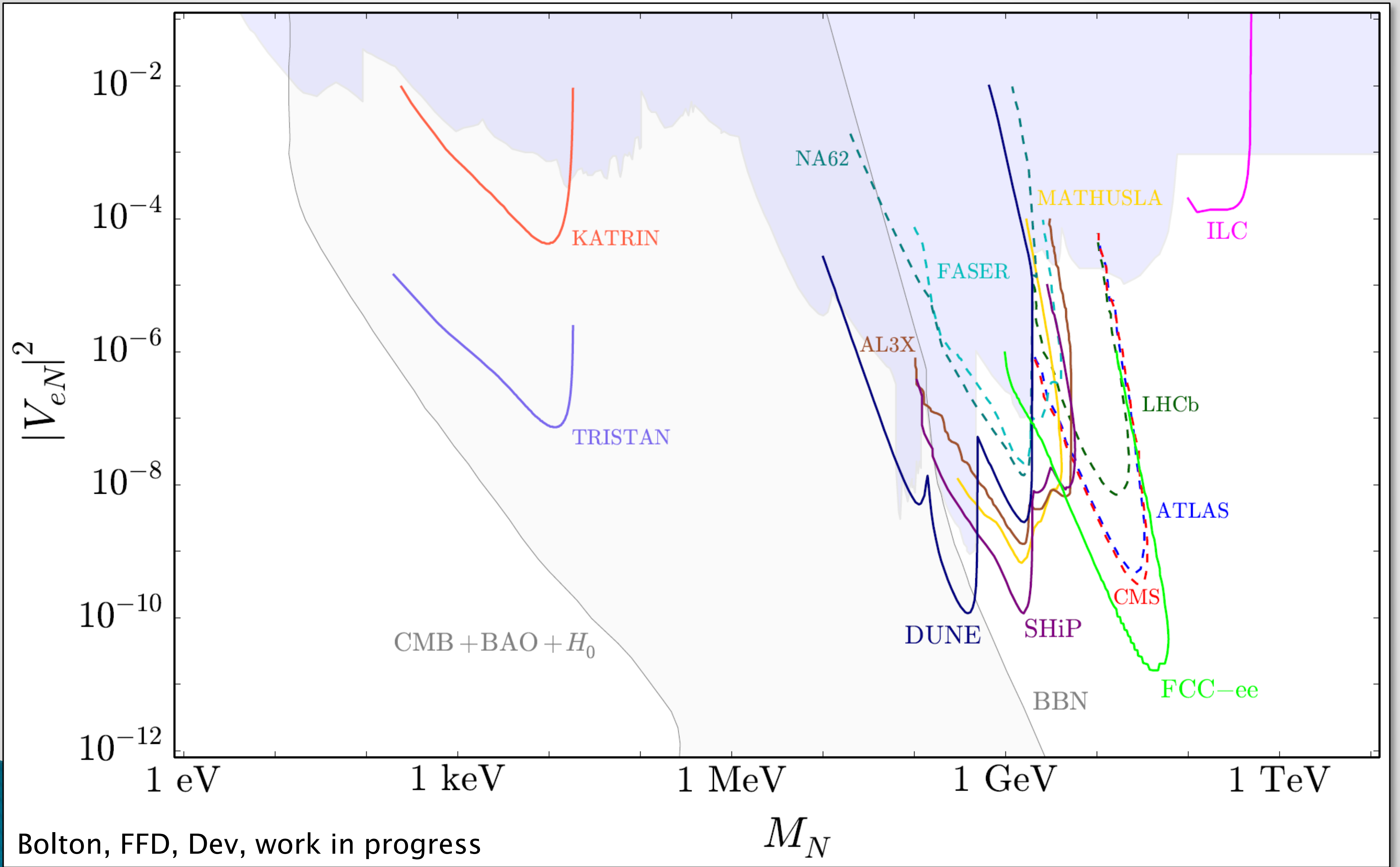
Quasi-Dirac N
Approximate L conservation

Heavy Sterile Neutrinos



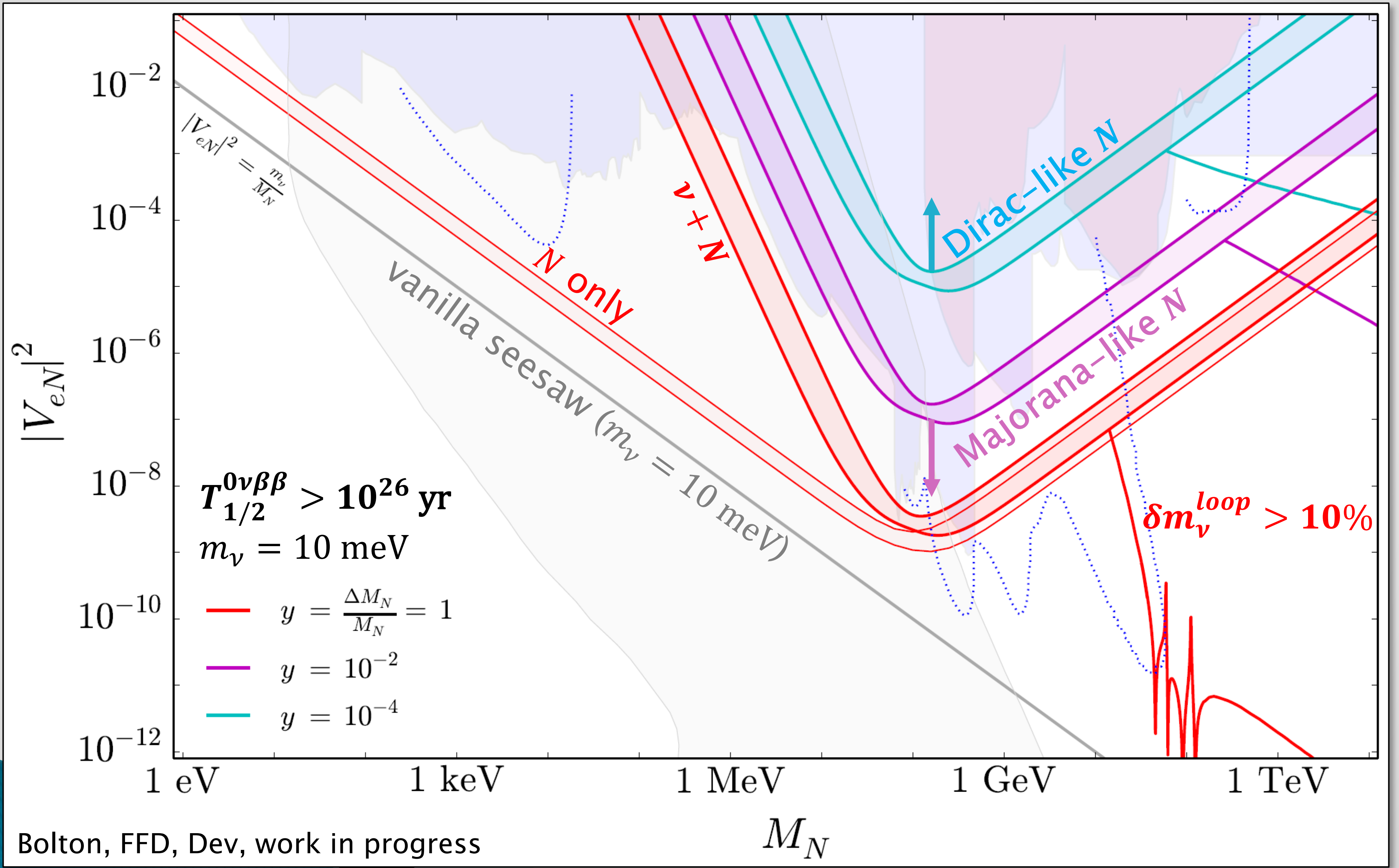
Bolton, FFD, Dev, work in progress

Heavy Sterile Neutrinos



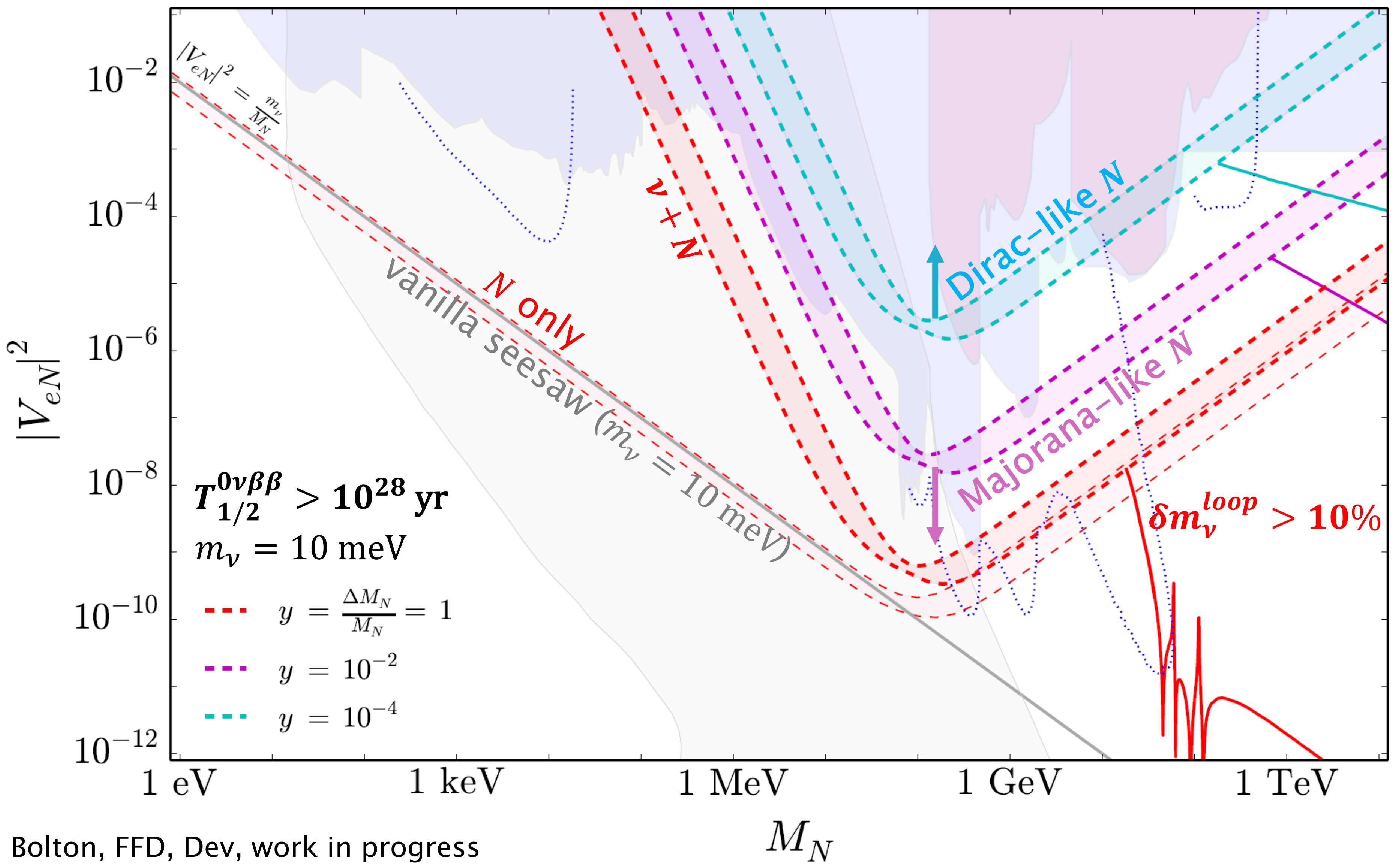
Bolton, FFD, Dev, work in progress

Heavy Sterile Neutrinos



Bolton, FFD, Dev, work in progress

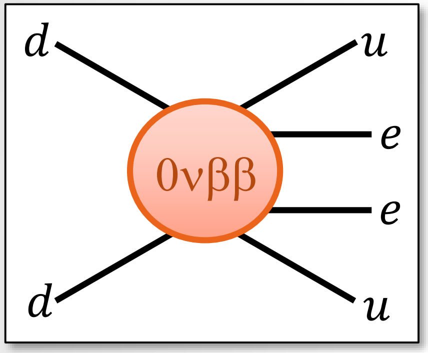
Heavy Sterile Neutrinos



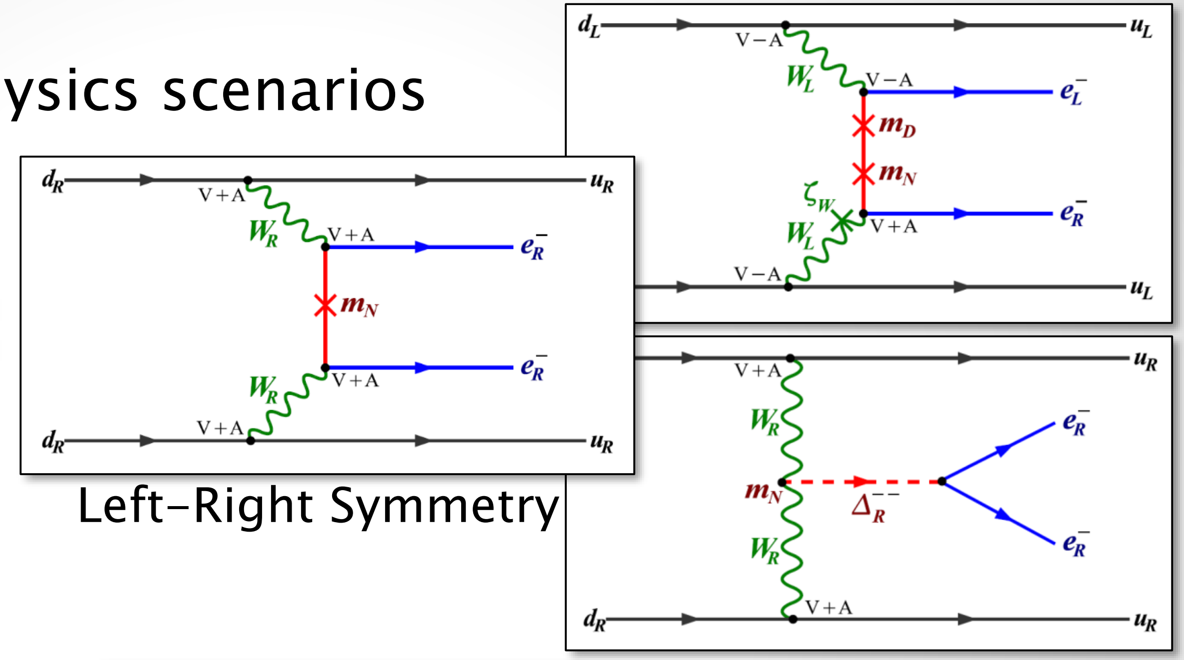
Bolton, FFD, Dev, work in progress

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

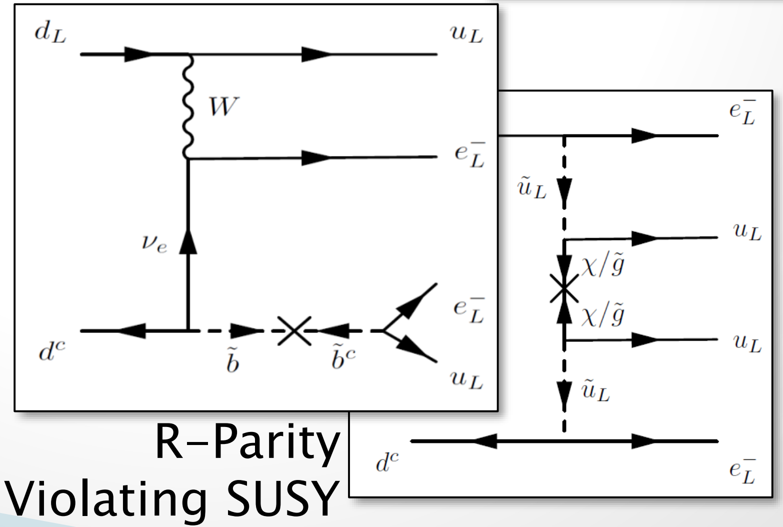
- Plethora of New Physics scenarios



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



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

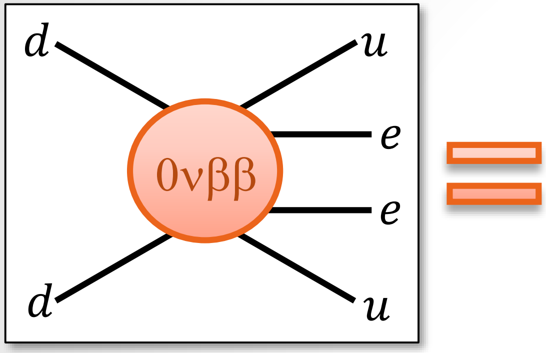
Majorons

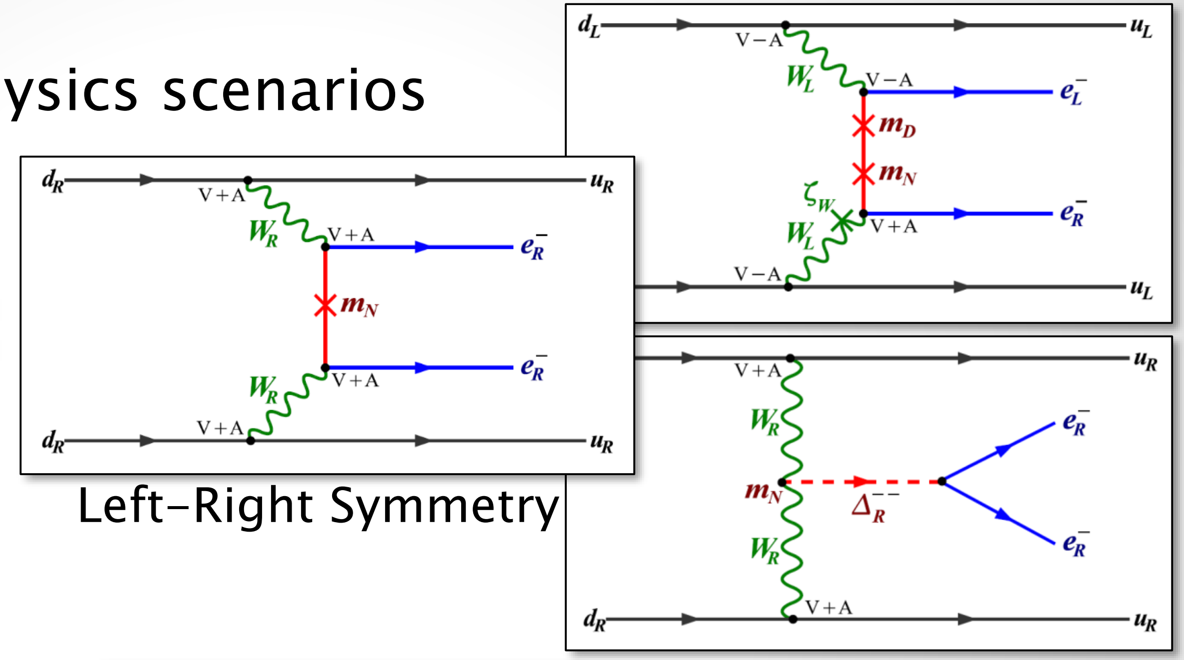
Leptoquarks

…

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

- Plethora of New Physics scenarios

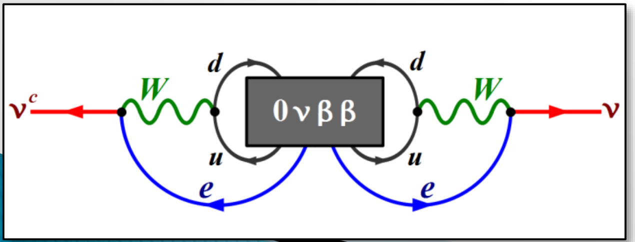


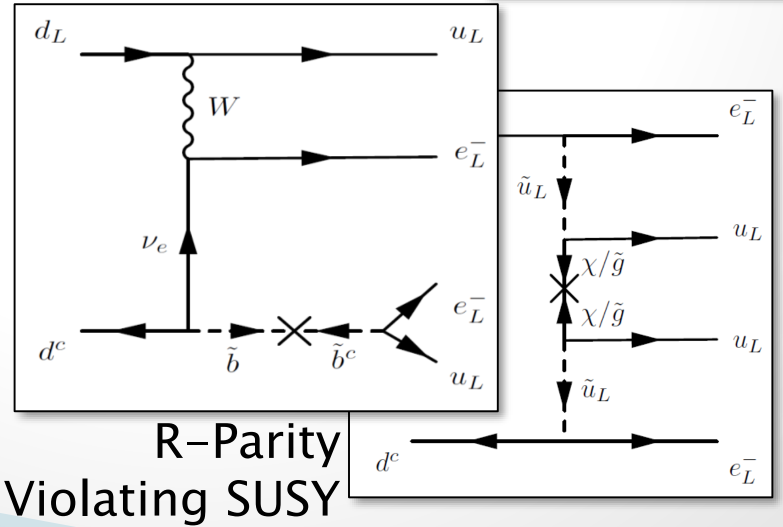


Left-Right Symmetry

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

- Neutrinos still Majorana
  Schechter, Valle
  Phys. Rev. D25 (1982) 2951





R-Parity Violating SUSY

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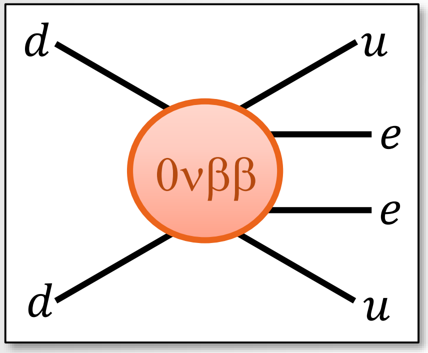
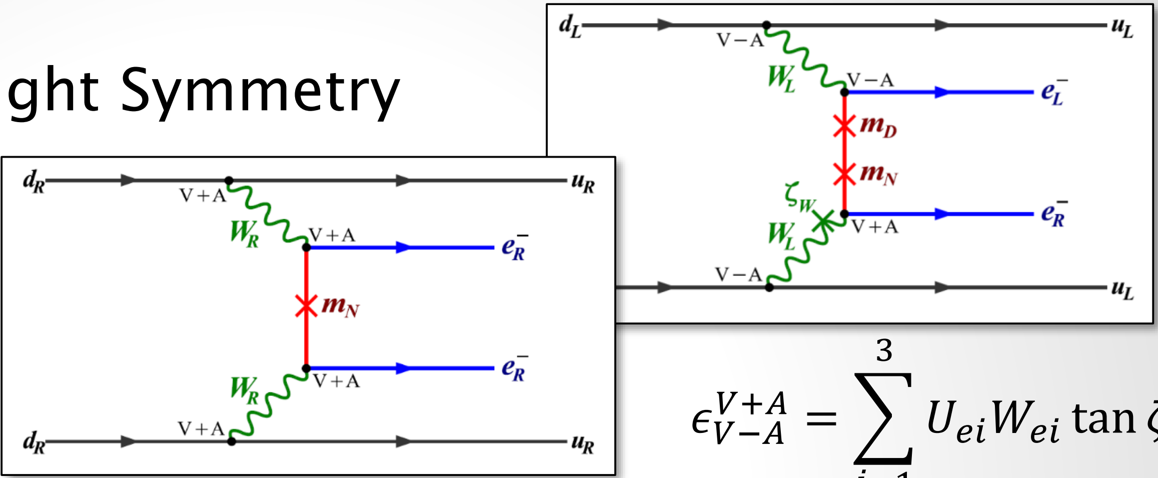
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry



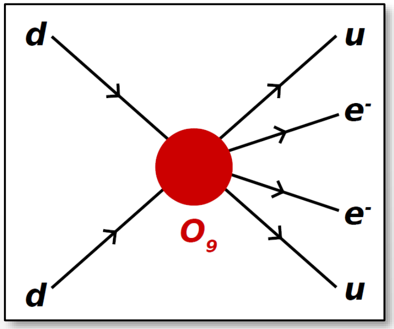


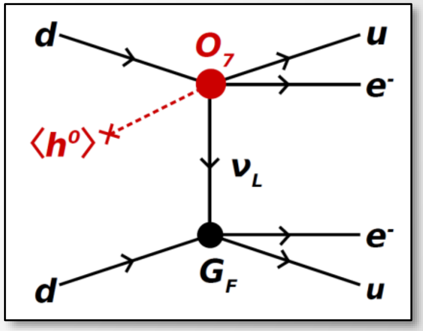
$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \text{TeV})^5}$$

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

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

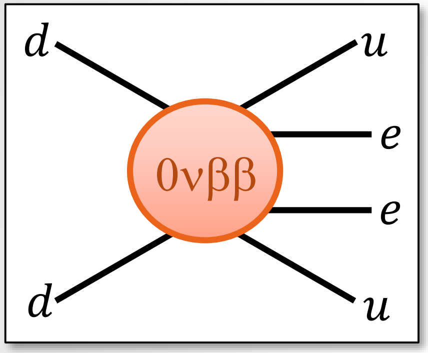
- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators





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

- Examples in Left-Right Symmetry



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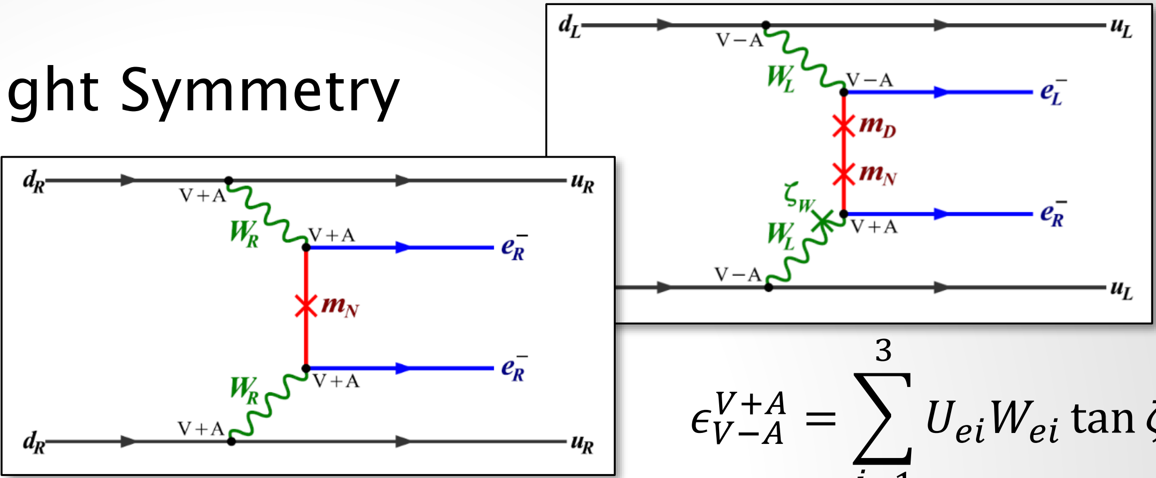
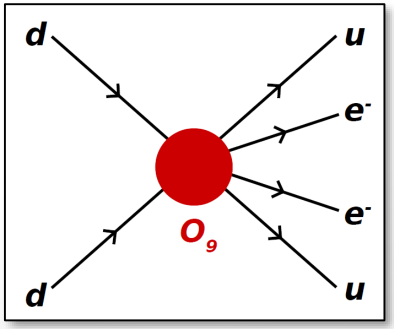


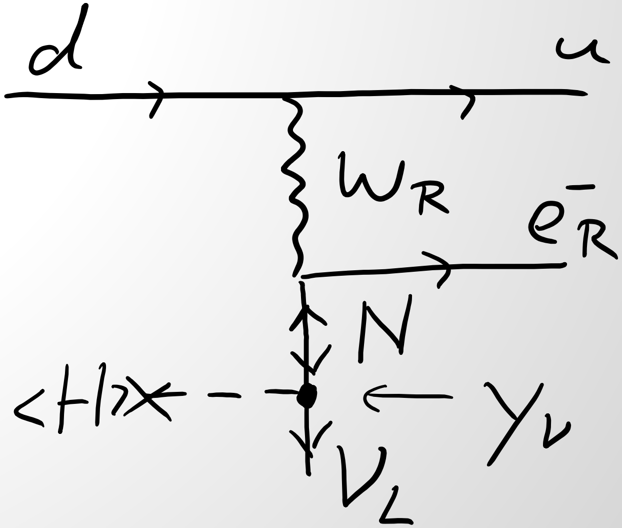
$$\boxed{T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2}$$

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

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

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

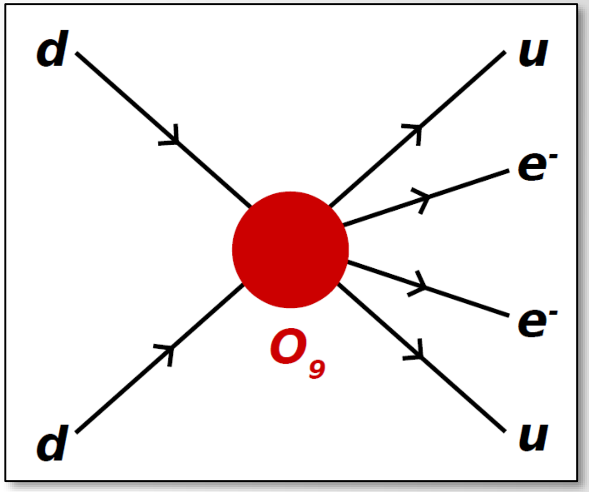




Short–Range Mechanisms

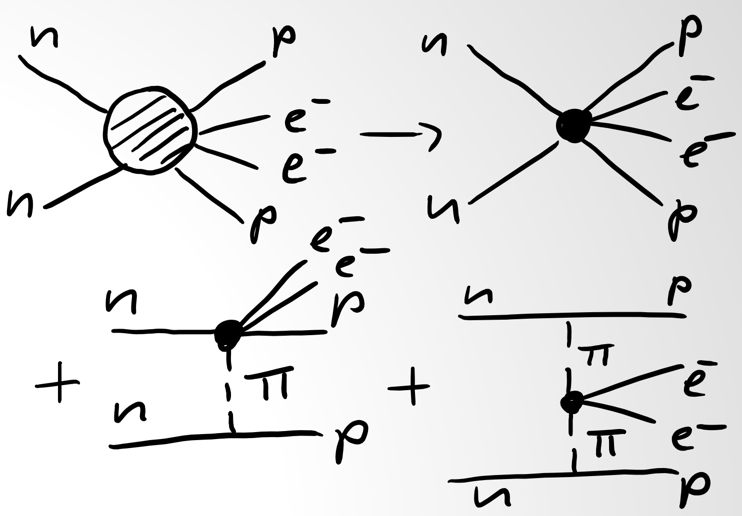
- Evaluation of limits on short–range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators
    (Paes et al. '01)

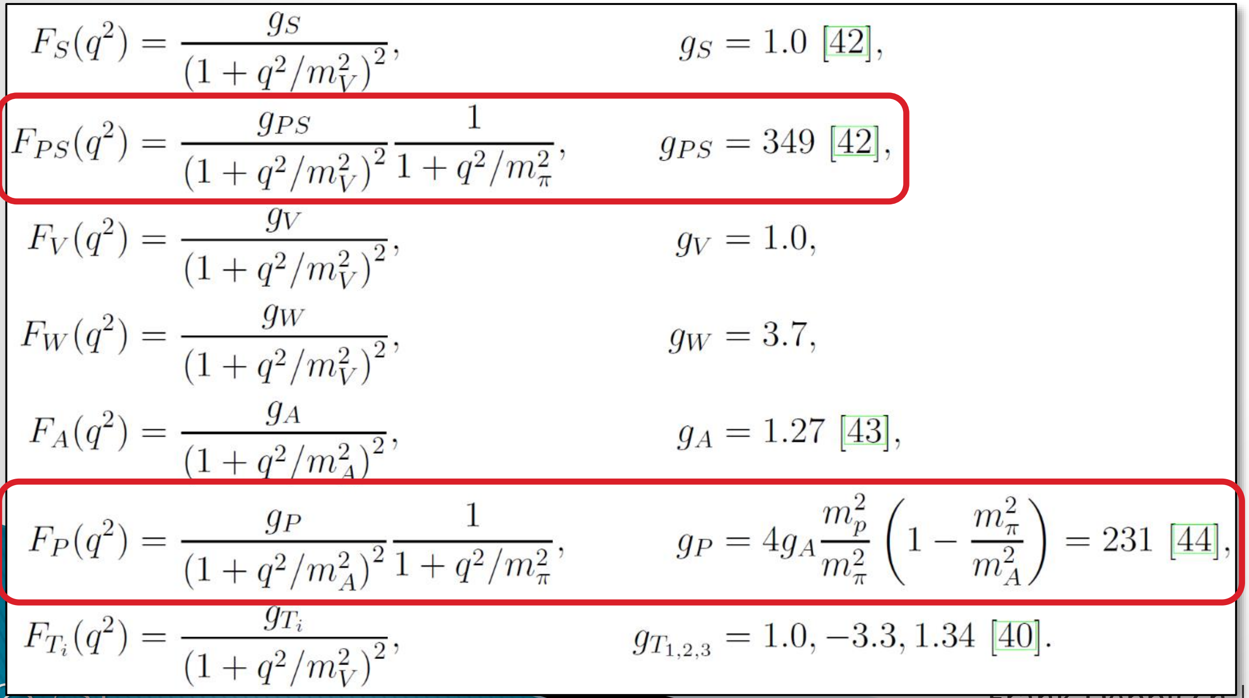
$$L = \frac{G_F^2}{2m_p}(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\nu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu})$$



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)
  - Nucleon currents
  - Nucleon form factors





$$F_S(q^2) = \frac{g_S}{(1+q^2/m_V^2)^2}, \qquad g_S = 1.0\ [42],$$

$$F_{PS}(q^2) = \frac{g_{PS}}{(1+q^2/m_V^2)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_{PS} = 349\ [42],$$

$$F_V(q^2) = \frac{g_V}{(1+q^2/m_V^2)^2}, \qquad g_V = 1.0,$$

$$F_W(q^2) = \frac{g_W}{(1+q^2/m_V^2)^2}, \qquad g_W = 3.7,$$

$$F_A(q^2) = \frac{g_A}{(1+q^2/m_A^2)^2}, \qquad g_A = 1.27\ [43],$$

$$F_P(q^2) = \frac{g_P}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_P = 4g_A\frac{m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right) = 231\ [44],$$

$$F_{T_i}(q^2) = \frac{g_{T_i}}{(1+q^2/m_V^2)^2}, \qquad g_{T_{1,2,3}} = 1.0, -3.3, 1.34\ [40].$$

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)

Interference with $m_{\beta\beta}$

Same lepton current

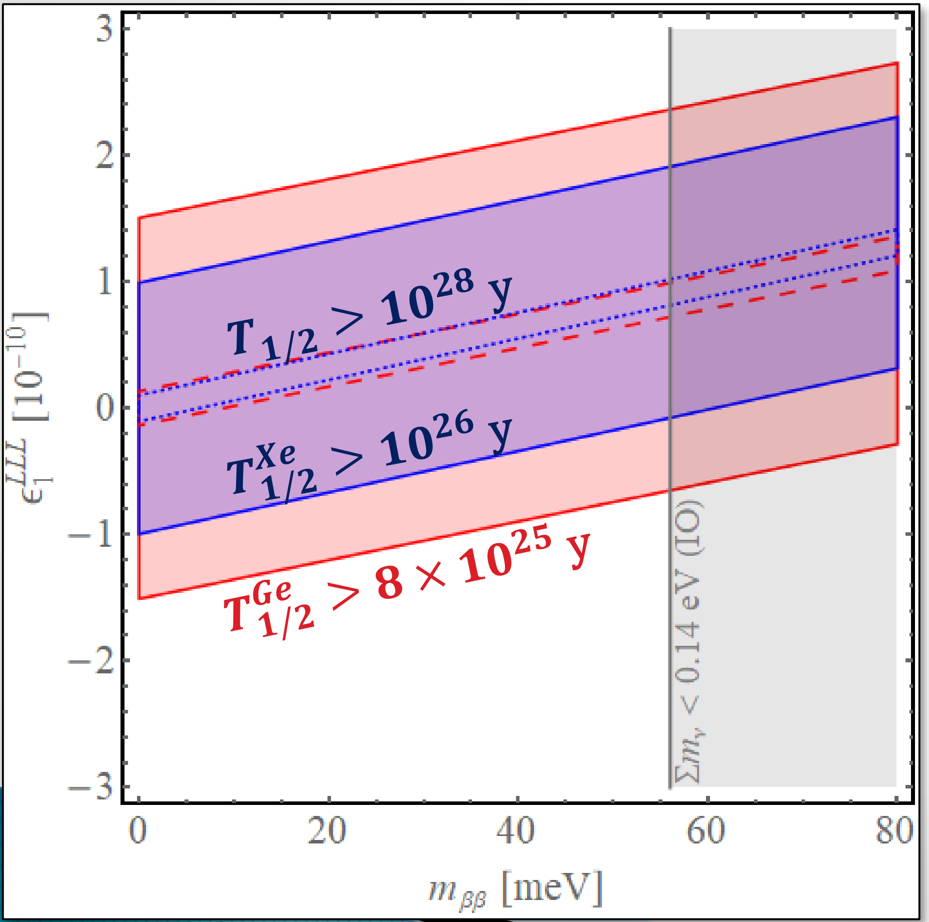
$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{\beta\beta}}{m_e} \mathcal{M}_\nu + \epsilon \mathcal{M}_\epsilon \right|^2$$

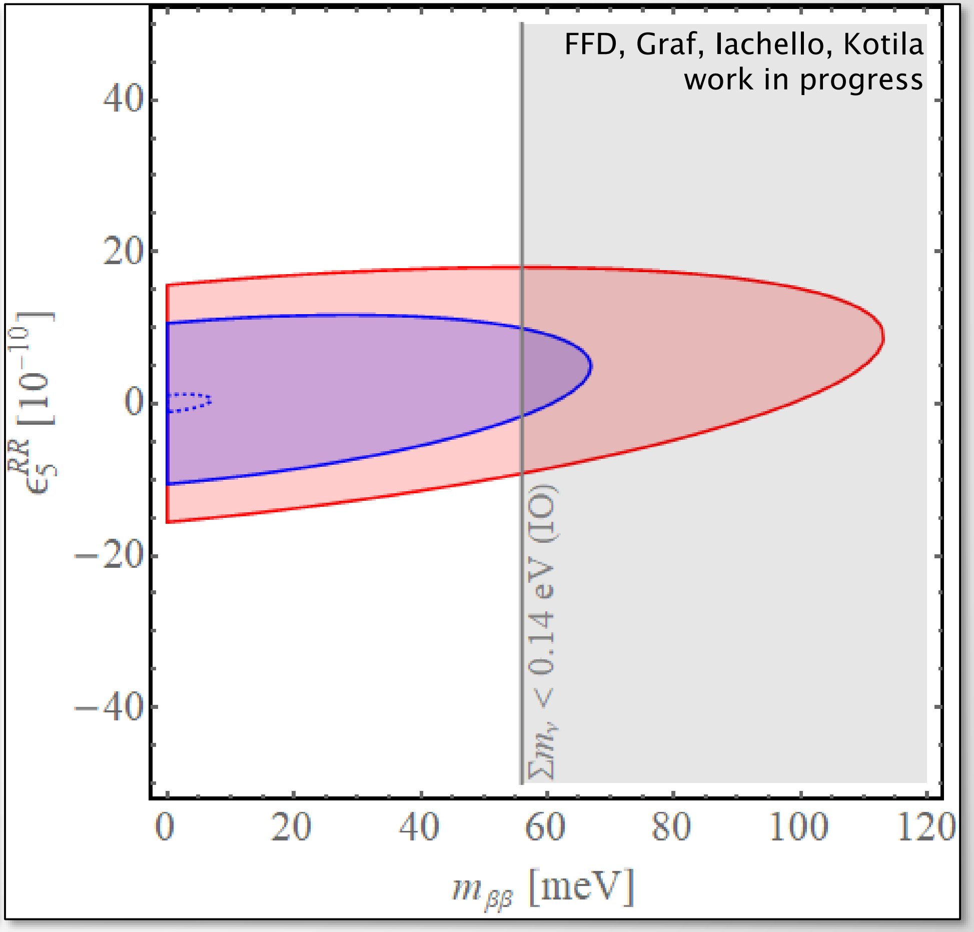
e.g. heavy neutrino exchange

Mitra, Pascoli, Wong, Phys. Rev. D 90 (2014) 093005

Different currents

$$T_{1/2}^{-1} = \frac{|m_{\beta\beta}|^2}{m_e^2} |\mathcal{M}_\nu|^2 G_\nu + |\epsilon|^2 |\mathcal{M}_\epsilon|^2 G_\epsilon + 2Re\left[\frac{m_{\beta\beta}}{m_e} \epsilon^* \mathcal{M}_\nu \mathcal{M}_\epsilon^*\right] G_{\nu\epsilon}$$





FFD, Graf, Iachello, Kotila
work in progress

Interference with $m_{\beta\beta}$

University College London

Same lepton current

$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{\beta\beta}}{m_e}\mathcal{M}_\nu + \epsilon \mathcal{M}_\epsilon \right|^2$$

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Mitra, Pascoli, Wong, Phys. Rev. D 90 (2014) 093005

Different currents

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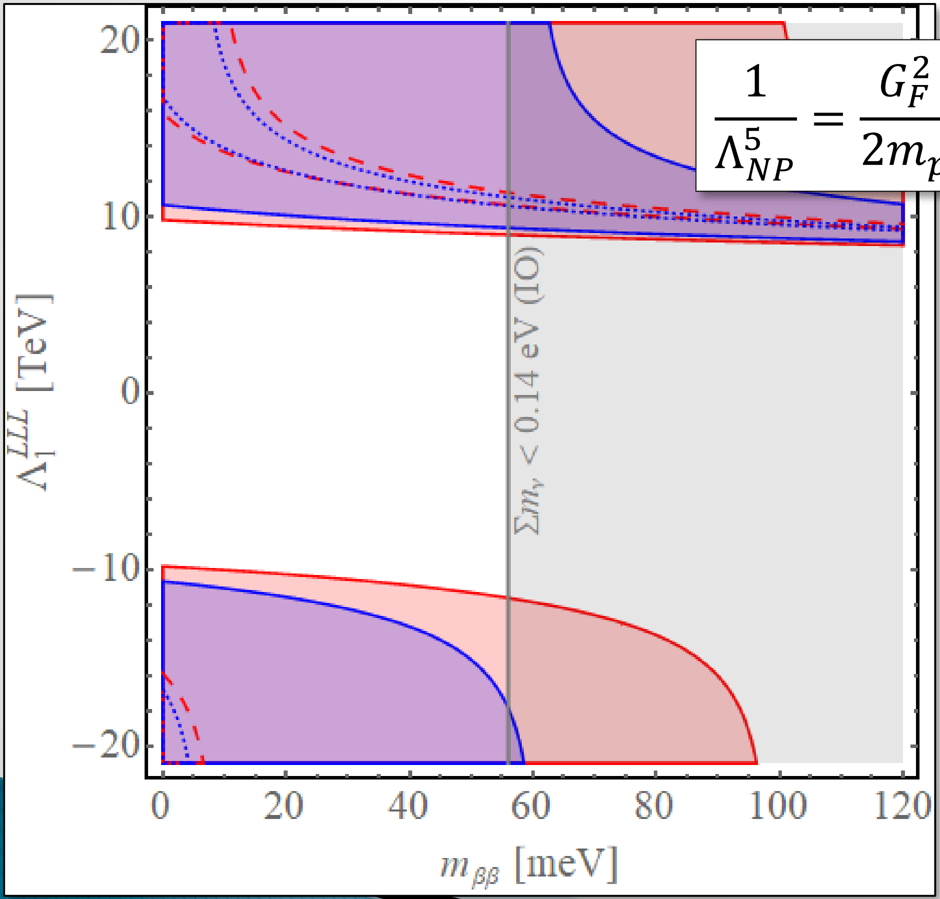
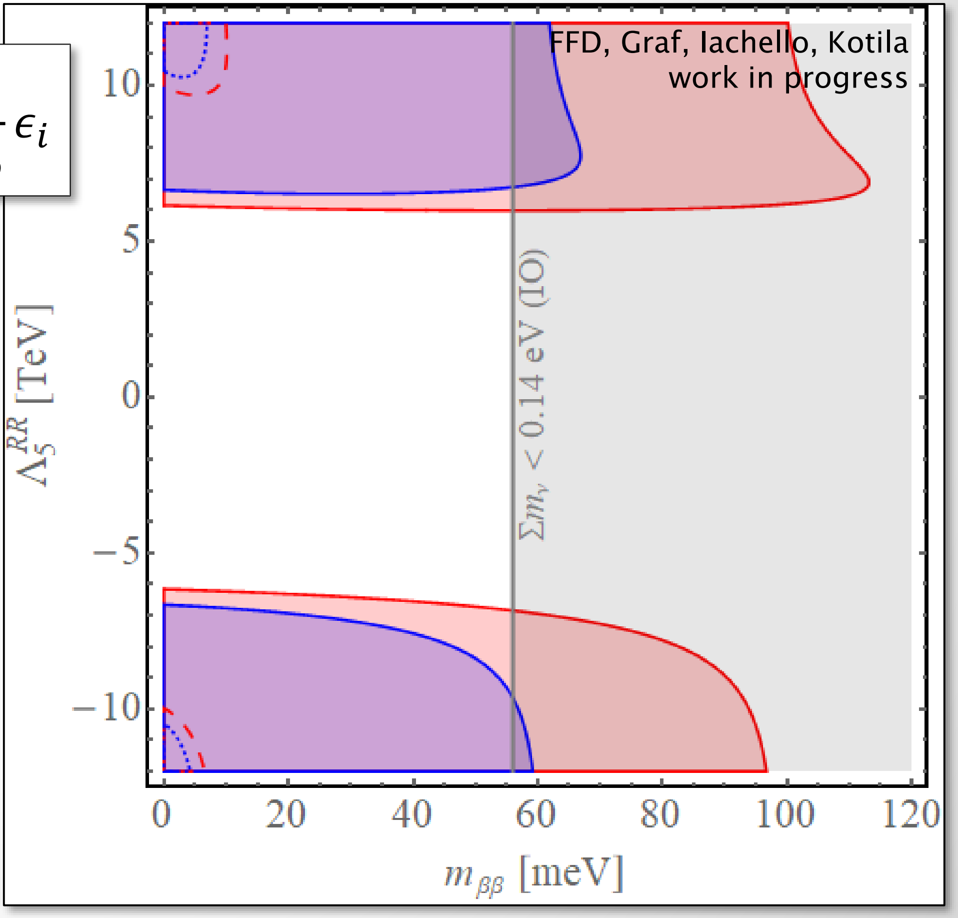


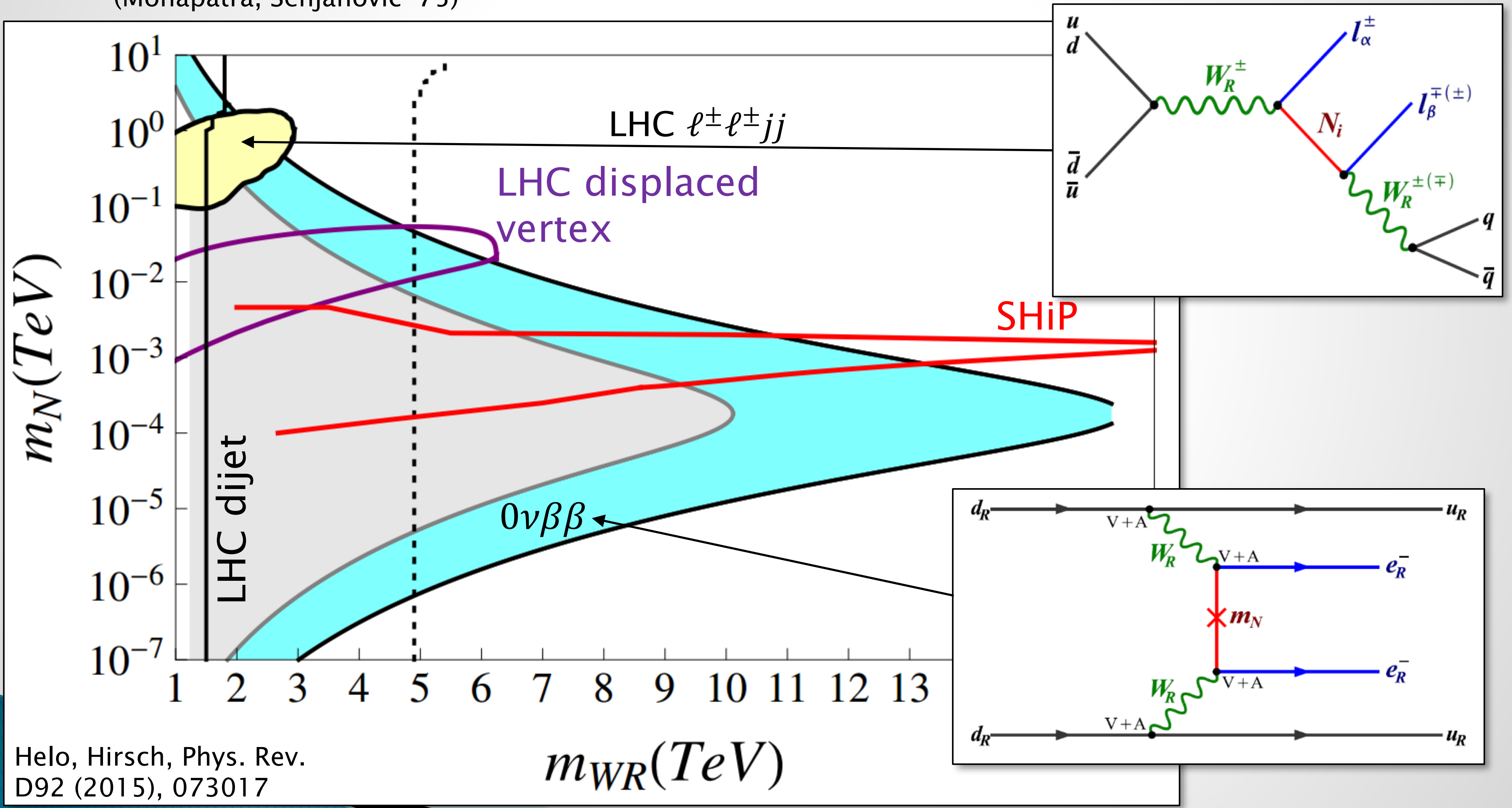
$$\frac{1}{\Lambda_{NP}^5} = \frac{G_F^2}{2m_p}\epsilon_i$$



FFD, Graf, Iachello, Kotila work in progress

Left–Right Symmetry

- $SU(3)_C \times SU(2)_L \times \boldsymbol{SU(2)_R \times U(1)_{B-L}} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$
  (Mohapatra, Senjanovic ‘75)



Helo, Hirsch, Phys. Rev. D92 (2015), 073017

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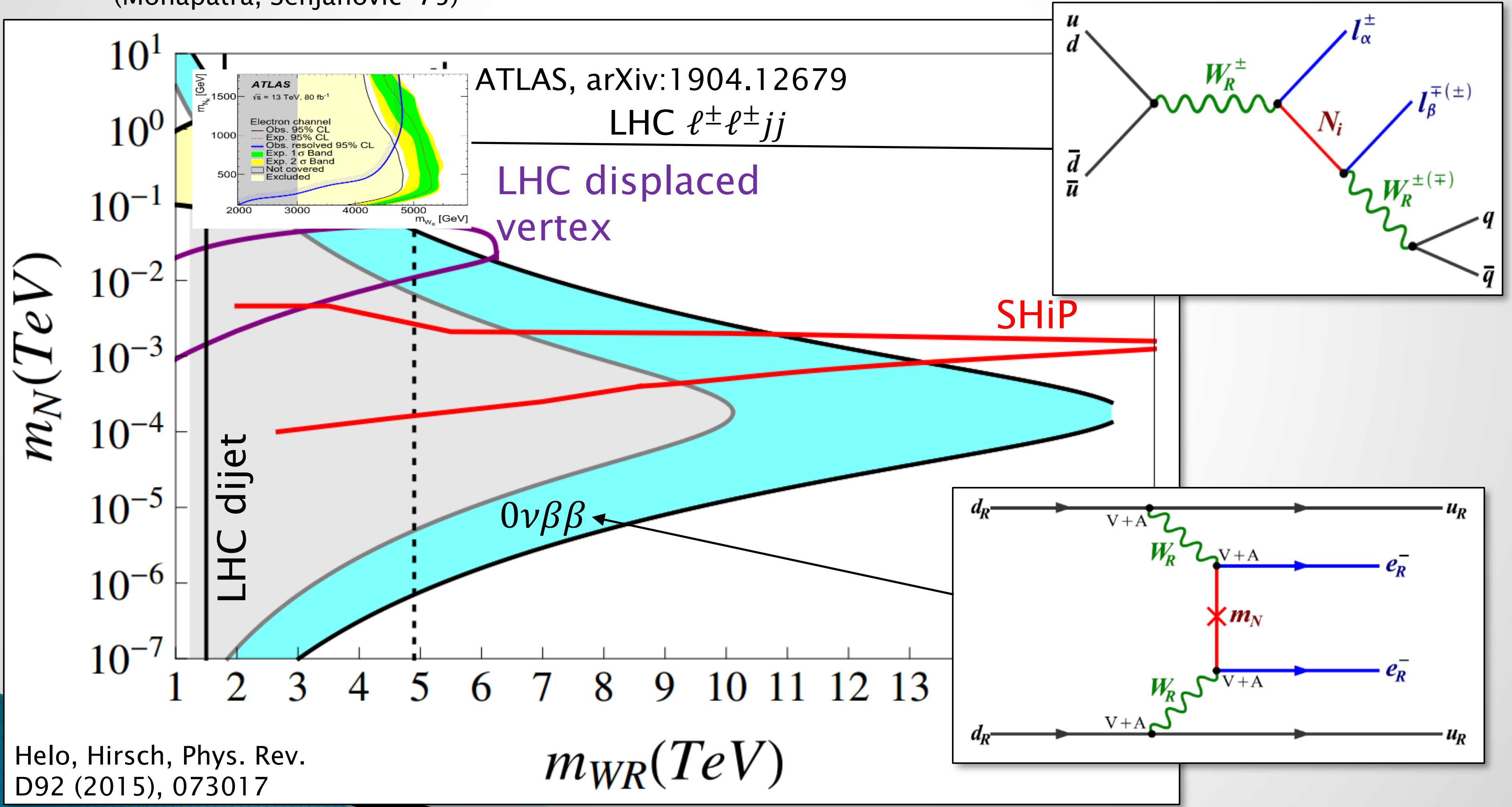
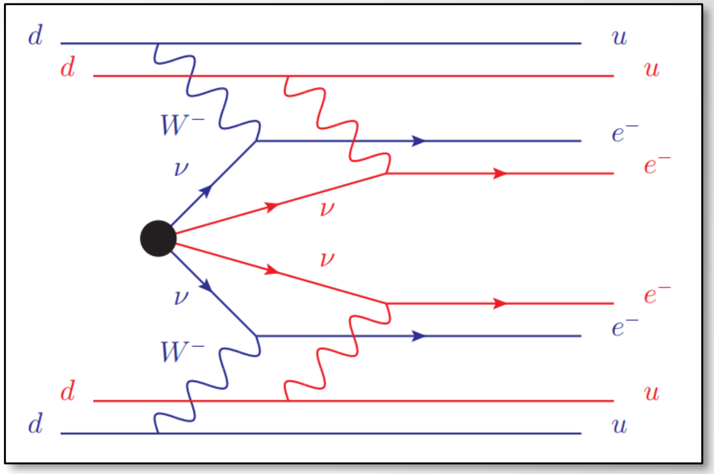
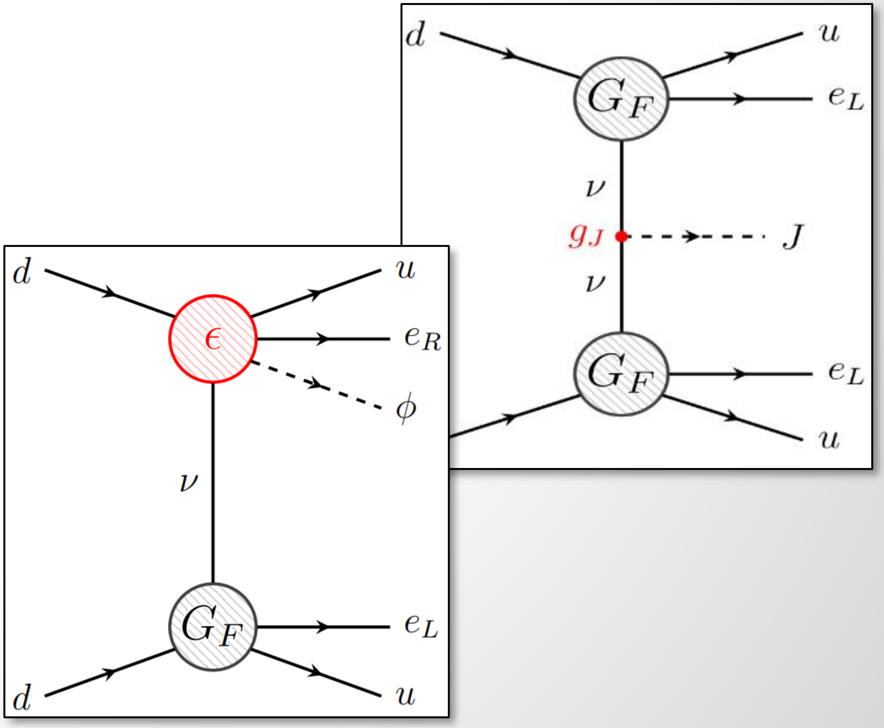


Helo, Hirsch, Phys. Rev. D92 (2015), 073017

$0\nu\beta\beta$ Exotica

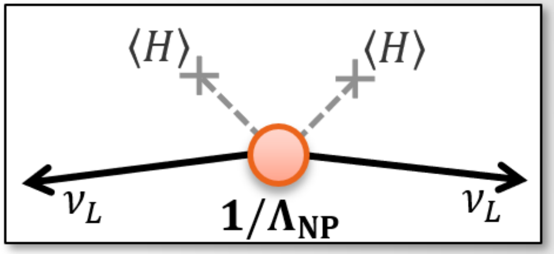
- Quadruple beta decay
  Heeck, Rodejohann, EP Lett. 103 (2013) 32001
  - $\Delta L = 4$ and Dirac neutrinos
- Emission of one or more neutral bosons
  - Majoron model of neutrino mass generation
  - From RH effective current e.g. in Left-Right symmetric model with Dirac neutrinos
    Cepedello, FFD, González, Hati, Hirsch, Phys. Rev. Lett. 122 (2019) 181801





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
  - Important to look for alternative scenarios
    - Missing energy → lepton number conserved?
    - Neutrino mass may be associated with exotic light particles



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

- **Importance of probing LNV around the TeV scale**
  - Can we rule out mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe
    (FFD, Harz, Hirsch, Phys. Rev. Lett. 112 (2014) 221601;
    FFD, Harz, Hirsch, Huang, Päs, Phys. Rev. D 92 (2015) 036005)