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Neutrino Physics
Lecture 3

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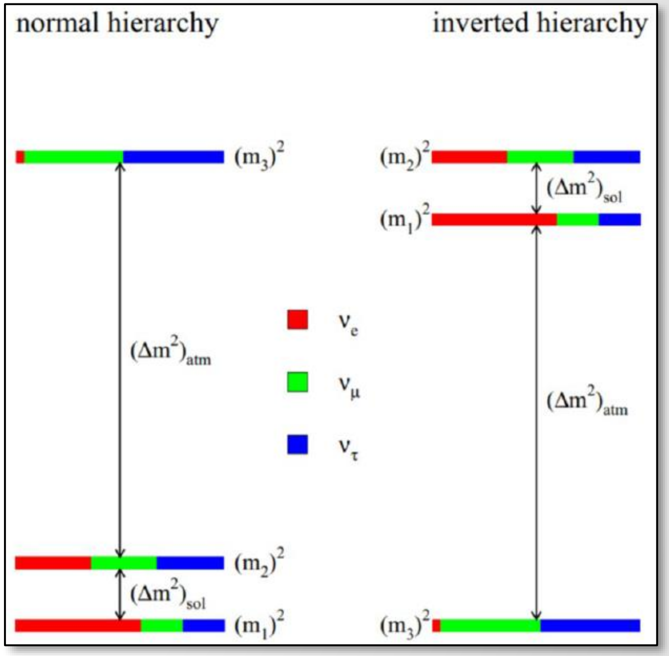
University College London

5th Chilean School of HEP | Valparaiso | 15 – 18 January 2018

Neutrino Oscillations

- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation

$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



- Era of neutrino precision physics
  - Current errors ~ 1–10%
- Experimental unknowns and anomalies
  - CP Violation? Sign of Δm_{13}? Octant of θ_{23}? Sterile Neutrinos?

Neutrino Oscillations

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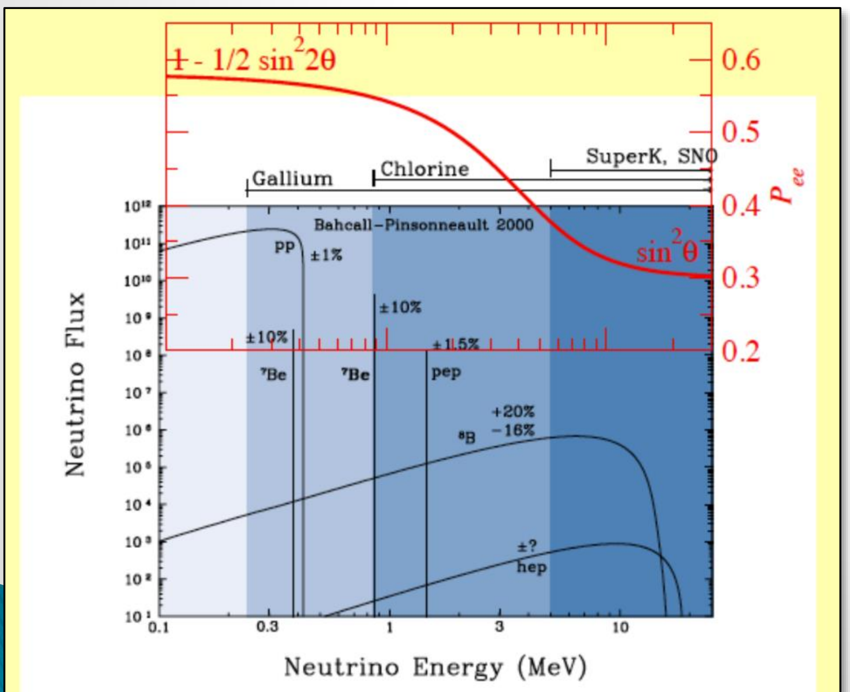
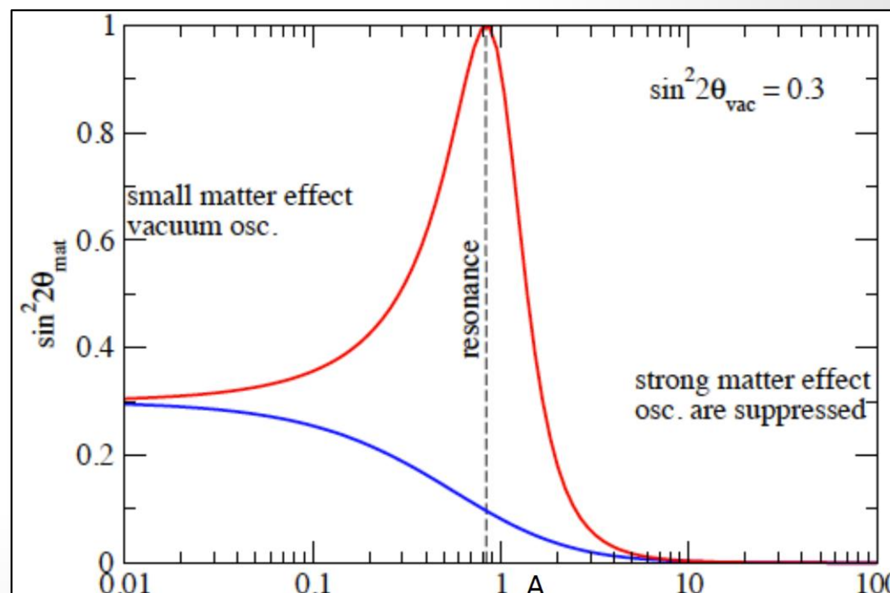
- Matter effect important in Sun
  - Resonant enhancement of mixing
  - Decoherence of oscillations
  - ν_e produced in Sun
    but $P(\nu_e \to \nu_e) \approx 0.3$ (dep. on energy).





Neutrino Oscillations

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Solar neutrinos: Oscillations or No-oscillations?

A. Yu. Smirnov

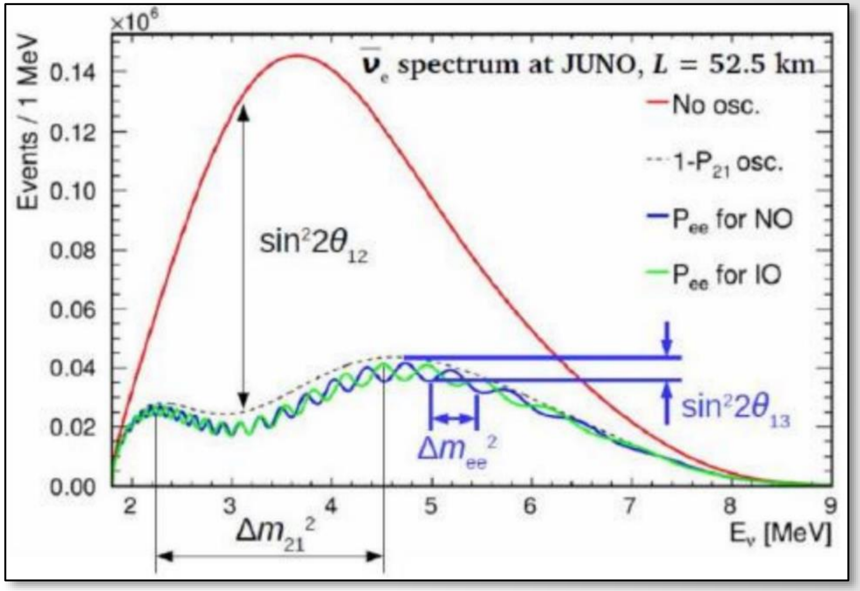
(Submitted on 8 Sep 2016 (v1), last revised 19 Sep 2017 (this version, v2))

The Nobel prize in physics 2015 has been awarded "... for the discovery of neutrino oscillations which show that neutrinos have mass". While SuperKamiokande (SK), indeed, has discovered oscillations, SNO observed effect of the adiabatic (almost non-oscillatory) flavor conversion of neutrinos in the matter of the Sun. Oscillations are irrelevant for solar neutrinos apart from small ν_e regeneration inside the Earth. Both oscillations and adiabatic conversion do not imply masses uniquely and further studies were required to show that non-zero neutrino masses are behind the SNO results. Phenomena of oscillations (phase effect) and adiabatic conversion (the MSW effect driven by the change of mixing in matter) are described in pedagogical way.

Comments: 19 pages, 12 figures, Comments and 1 figure added
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Solar and Stellar Astrophysics (astro-ph.SR); High Energy Physics - Experiment (hep-ex)
Cite as: **arXiv:1609.02386 [hep-ph]**
(or **arXiv:1609.02386v2 [hep-ph]** for this version)

Neutrino Oscillation Experiments

- Solar
  - Radiochemical: Homestake, Gallex, SAGE
    - Only rate of ν_e, no energy
  - Cherenkov radiation: (Super-)Kamiokande, SNO
    - Real-time, energy and direction, all flavours
  - Liquid scintillation: Borexino
    - Low energy threshold
  - Reactor: KamLAND
- Atmospheric ($E_\nu \approx \mathrm{GeV} - \mathrm{TeV}$)
  - Super-Kamiokande
    - Originally background to proton decay
  - Neutrino telescopes: ANTARES, IceCube
    - Originally for high energy neutrinos
- Short-baseline Reactor
  - CHOOZ, Palo Verde, Daya Bay, RENO, Double Chooz, Future: JUNO, RENO-50
    - Measurement of θ_{13}
- Long-baseline Accelerator
  - K2K, MINOS, T2K, Noνa, Future: DUNE, T2H(H)K,



Neutrino Oscillations

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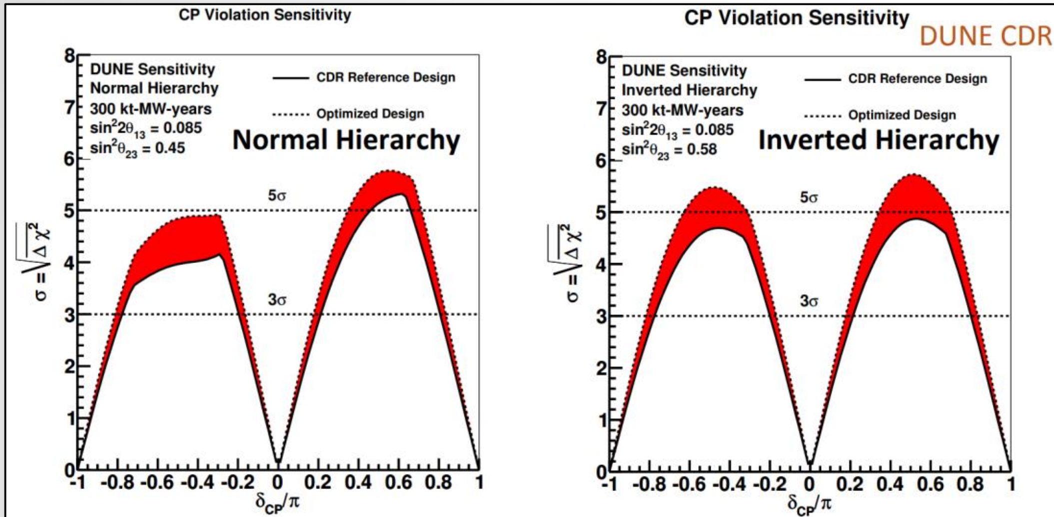
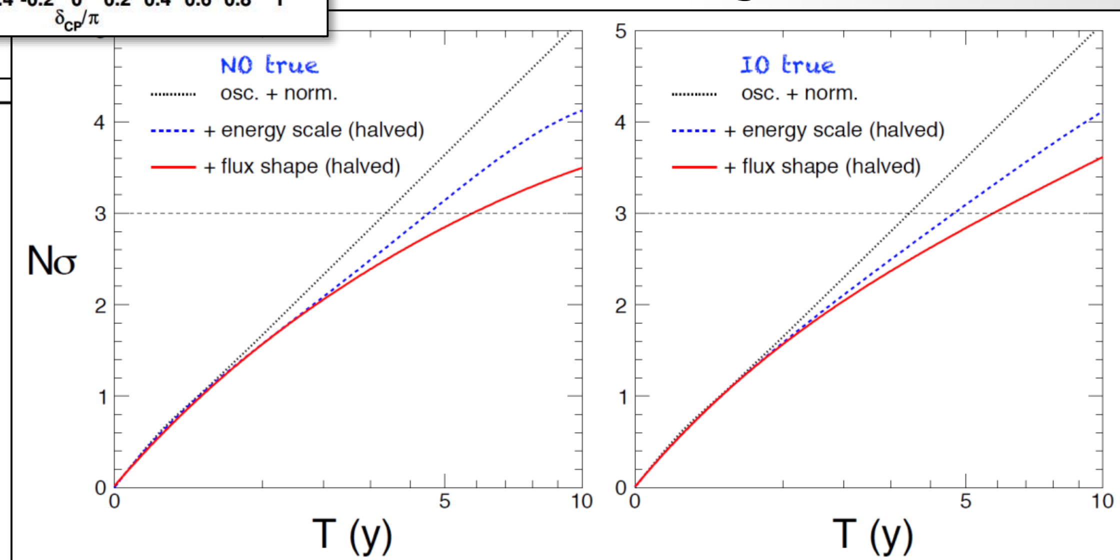
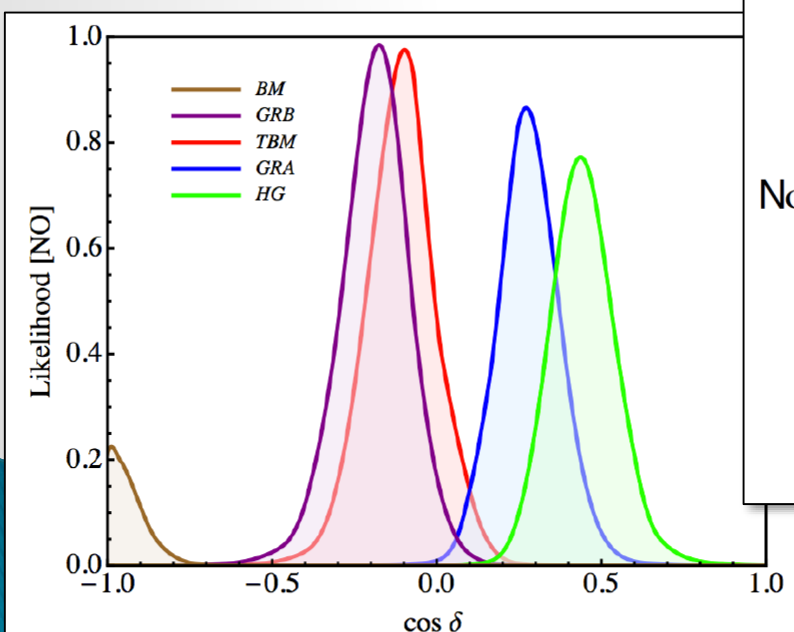


Dune sensitivity to CP violating phase

JUNO sensitivity to mass ordering (Marrone et al. '15)





Impact on flavour models (Girardi '14)

Neutrinos and the Universe

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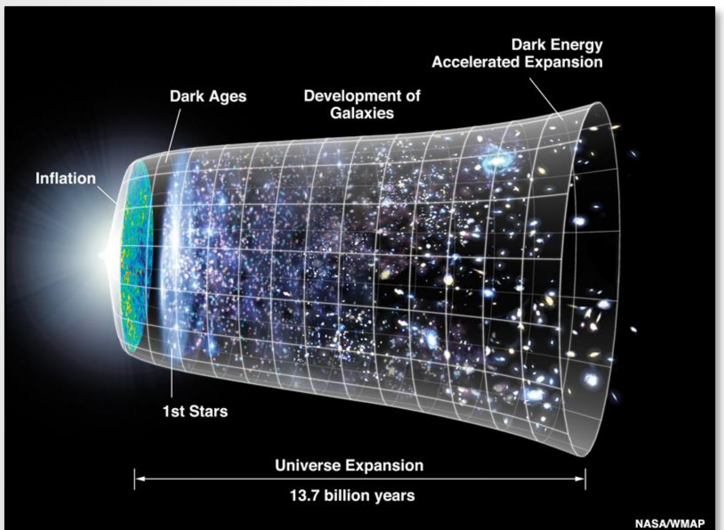
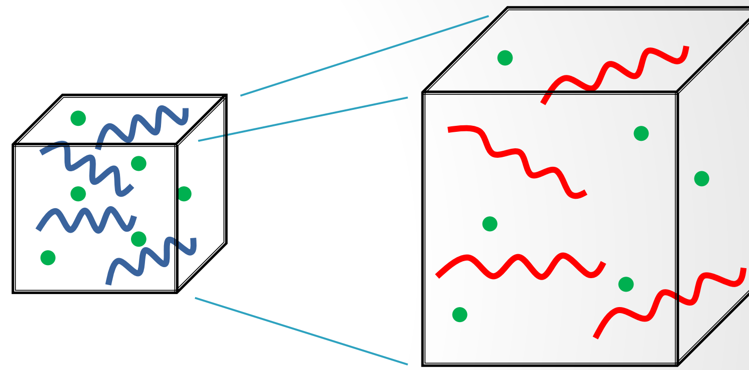
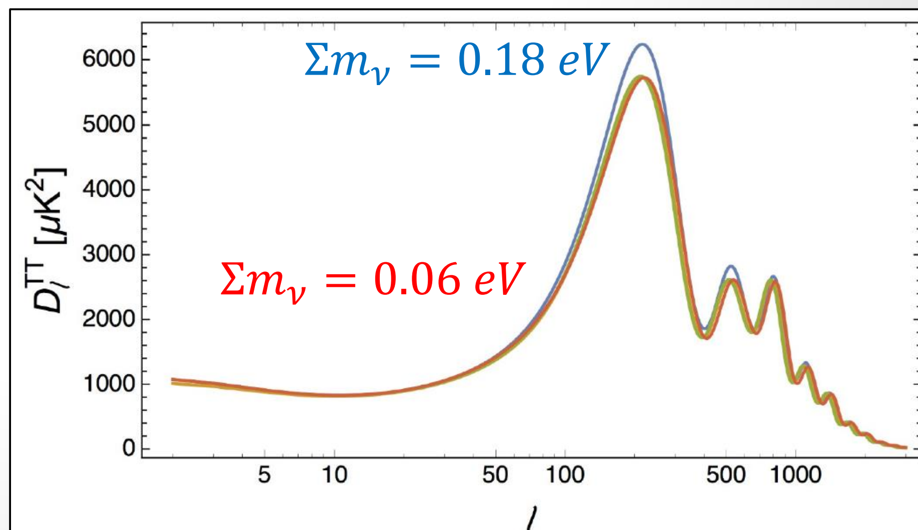
- Impact on the evolution of the Universe
  - Practically massless neutrinos act as radiation (≈photons)
  - Possibility to count the number of neutrinos

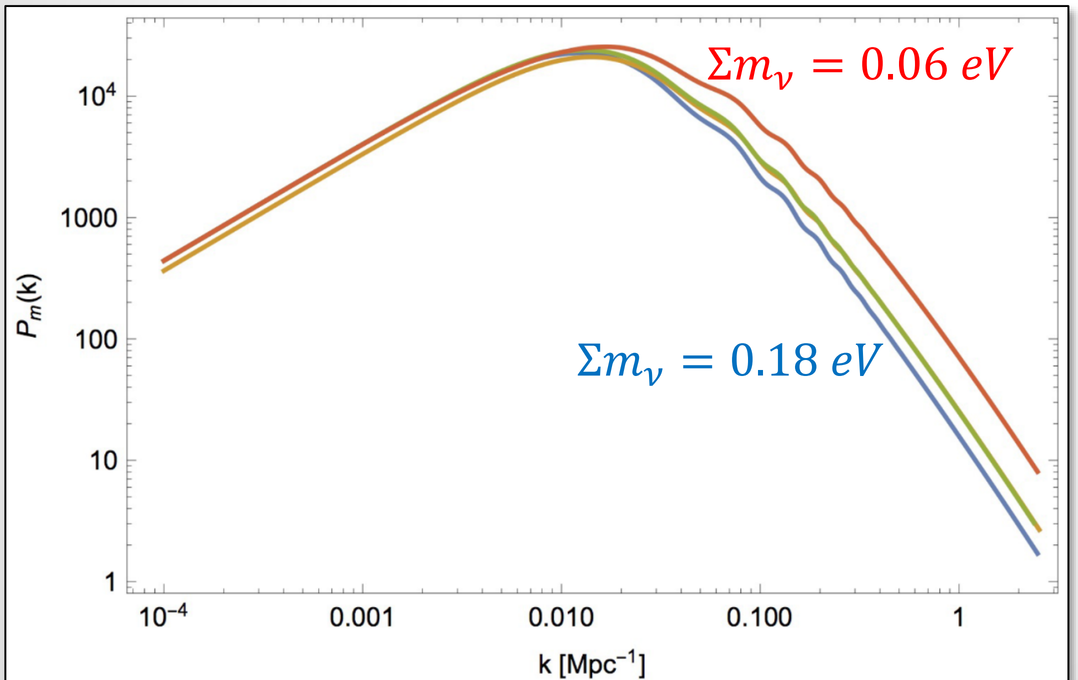


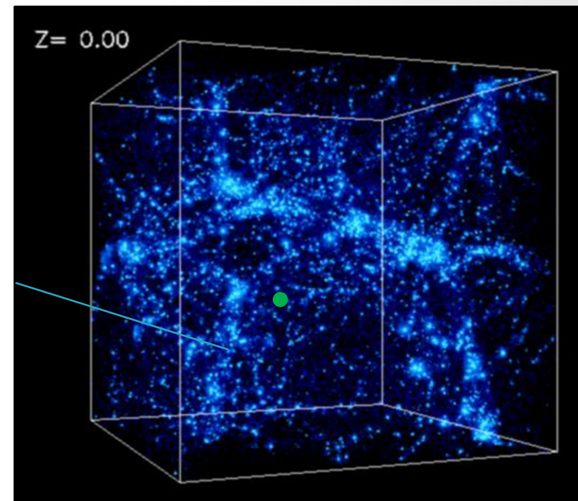




Neutrinos and the Universe

- Impact on large scale structures of the Universe
  - “Free-streaming” neutrinos wash out structures
  - Possibility to measure the sum of neutrino masses





Fermion Masses

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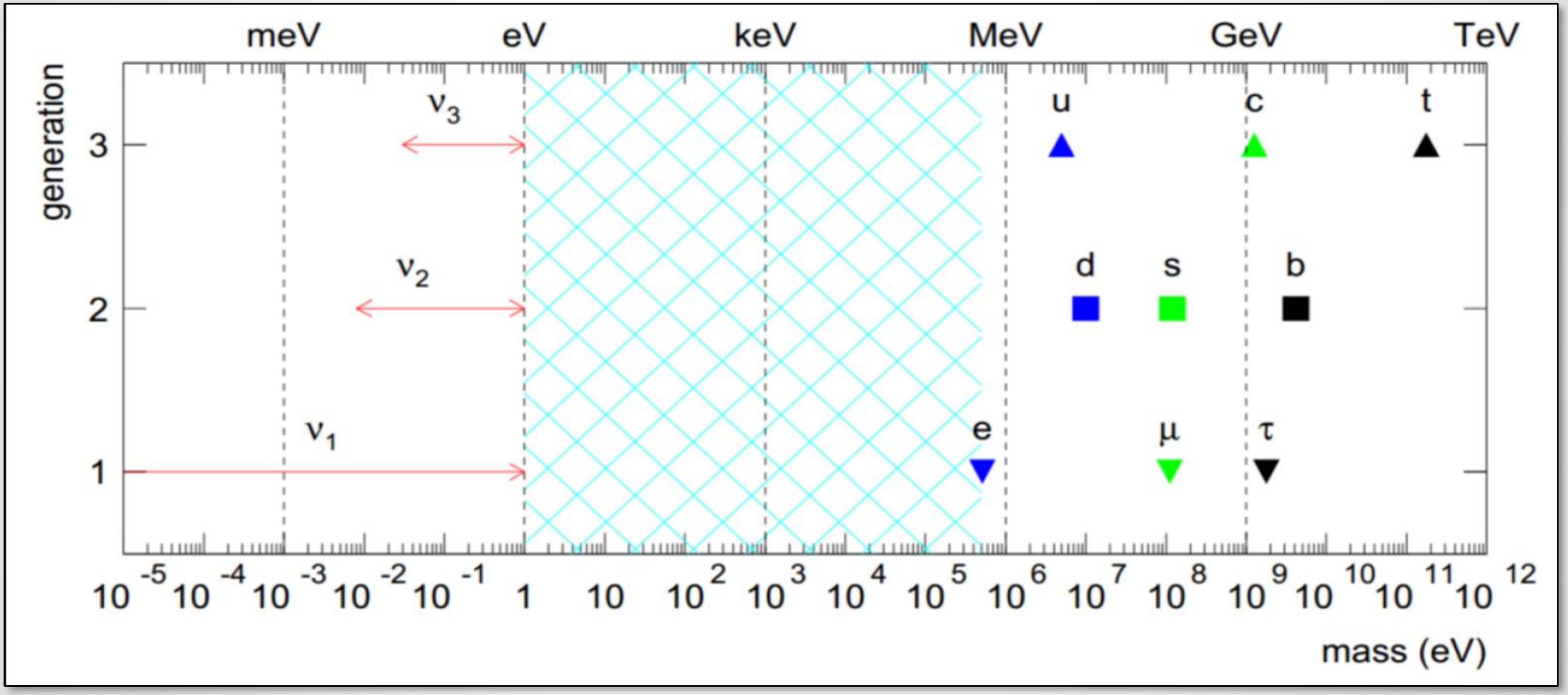

Dirac vs Majorana

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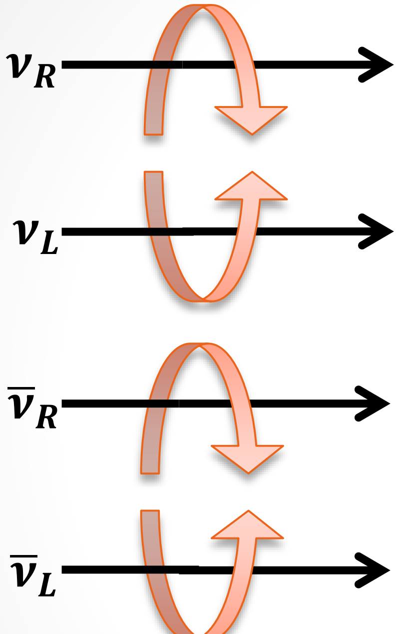
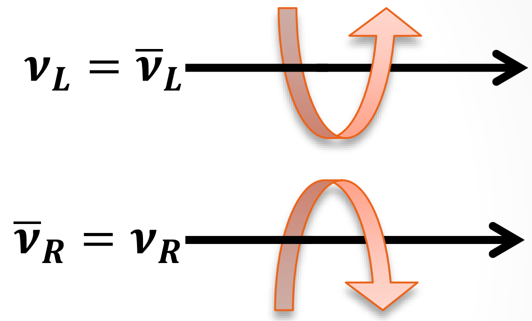
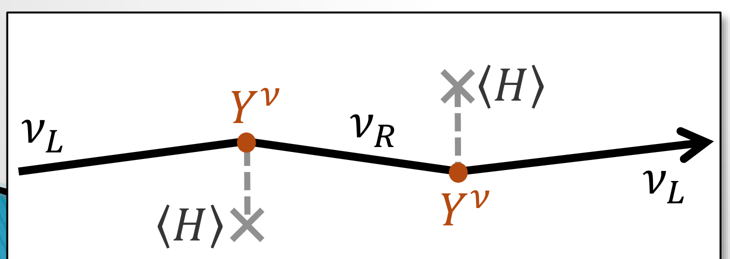
- Two possibilities to define fermion mass

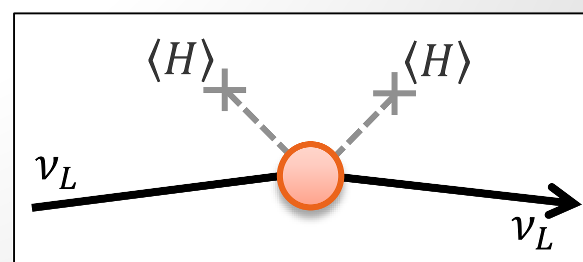




Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs



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



Lepton Flavour versus Lepton Number Violation

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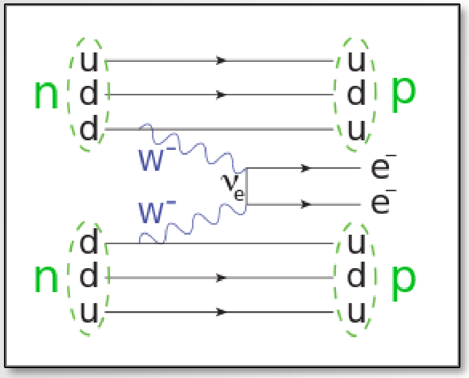
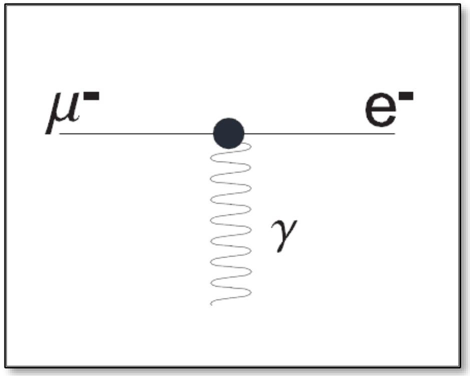
Neutrinoless double beta decay



$\Delta L_e = 2, \Delta L_\mu = 0, \Delta L = 2$

Lepton Number Violation

$\boldsymbol{\mu^- \to e^- \gamma}$



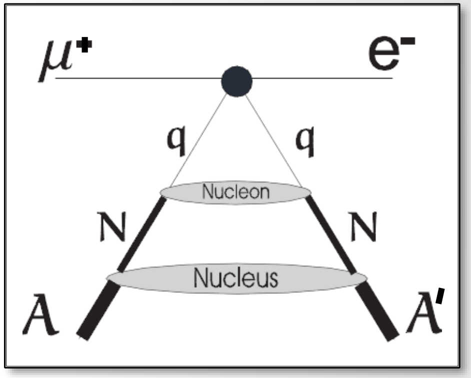
$\Delta L_e = 1, \Delta L_\mu = -1, \Delta L = 0$

Lepton Flavour Violation

nobelprize.org

Neutrino Oscillations

$\mu^+ \to e^-$ conversion in nuclei

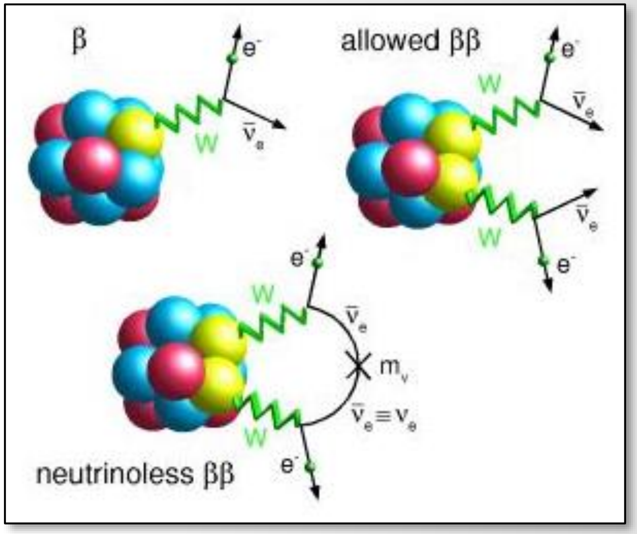


$\Delta L_e = 1, \Delta L_\mu = 1, \Delta L = 2$

Lepton Flavour Violation + Lepton Number Violation

Beta decays

- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
- 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
  - Variants
    - $0\nu\beta^+\beta^+$: $(A,Z) \rightarrow (A,Z-2) + 2e^+$
    - $0\nu\beta^+\mathrm{EC}$: $(A,Z) + e^- \rightarrow (A,Z-2) + e^+$
    - $0\nu\mathrm{ECEC}$: $(A,Z) + 2e^- \rightarrow (A,Z-2)^*$
- Majoron-assisted $0\nu\beta\beta$ decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + n\chi$$



$0\nu\beta\beta$

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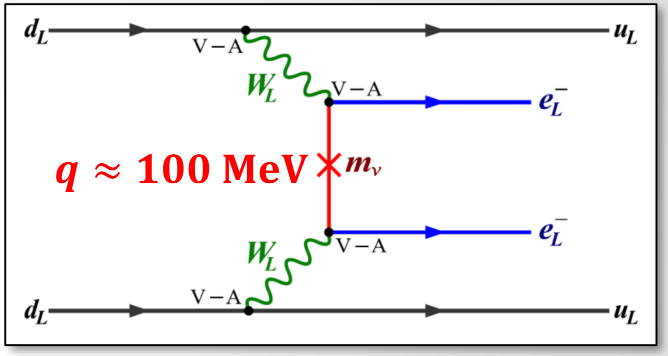
- Half-life

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



- Particle Physics

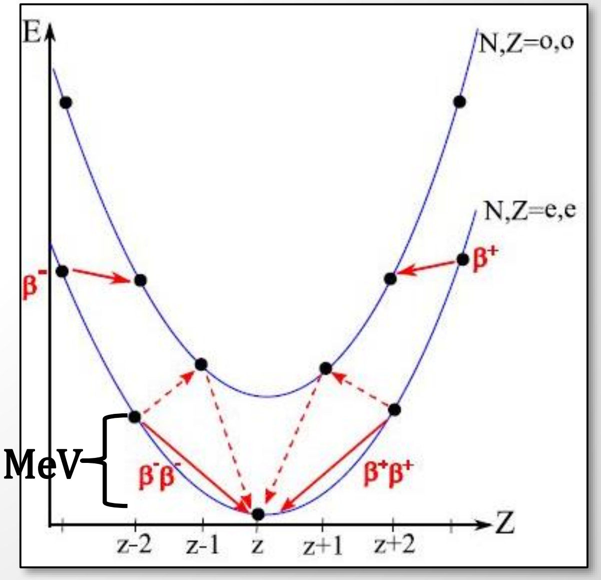
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$

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

$$\frac{10^{25}\text{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{eV}\right)^2$$

$Q \approx 2\text{–}4$ MeV



$0\nu\beta\beta$

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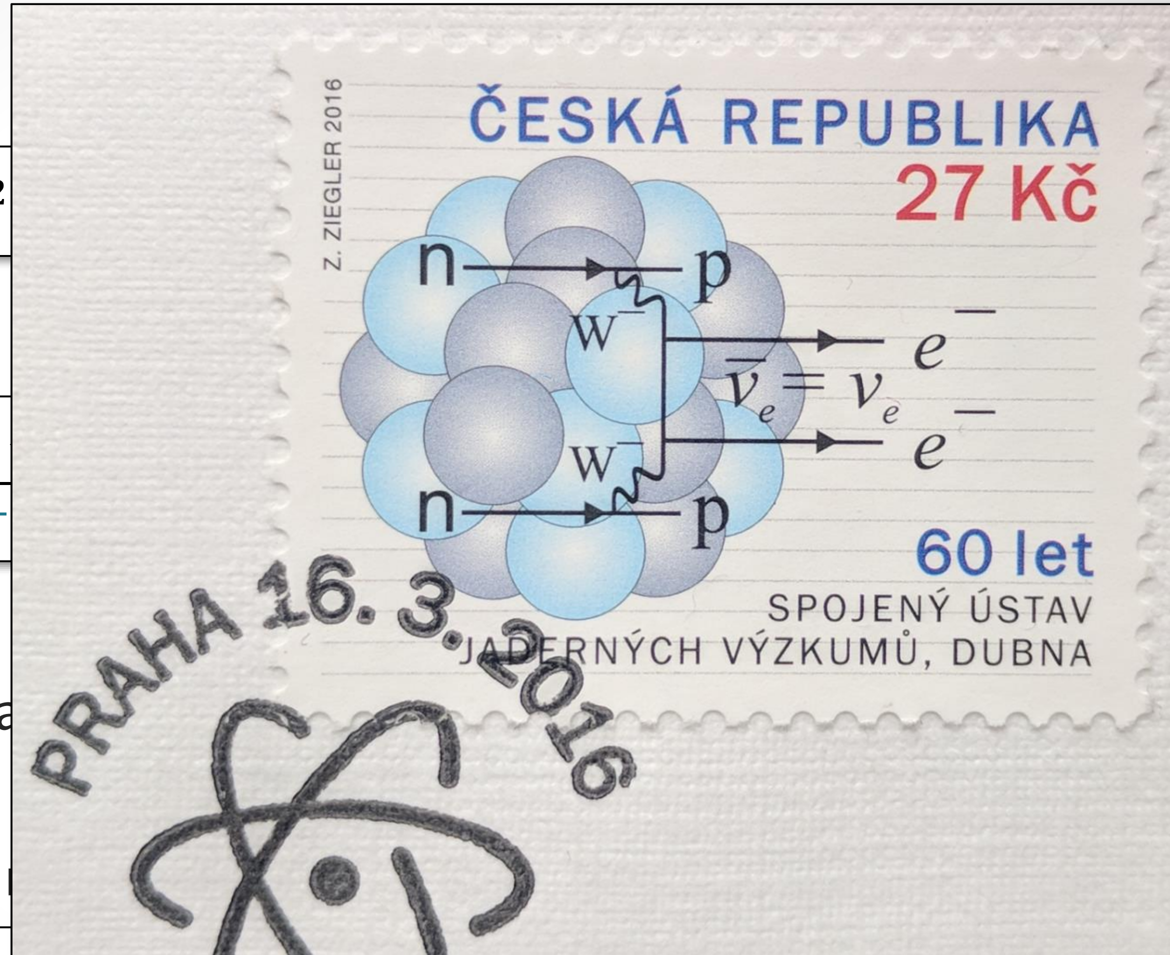
- Half-life

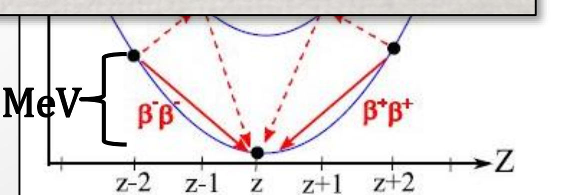
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2$$

- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + }{q^2 - }$$

- Atomic Physics
  - Leptonic phase spa
- Nuclear Physics
  - Nuclear transition





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

$$\frac{10^{25}\text{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{eV}\right)^2$$

$Q \approx 2-4$ **MeV**

$0\nu\beta\beta$ – Light Neutrinos

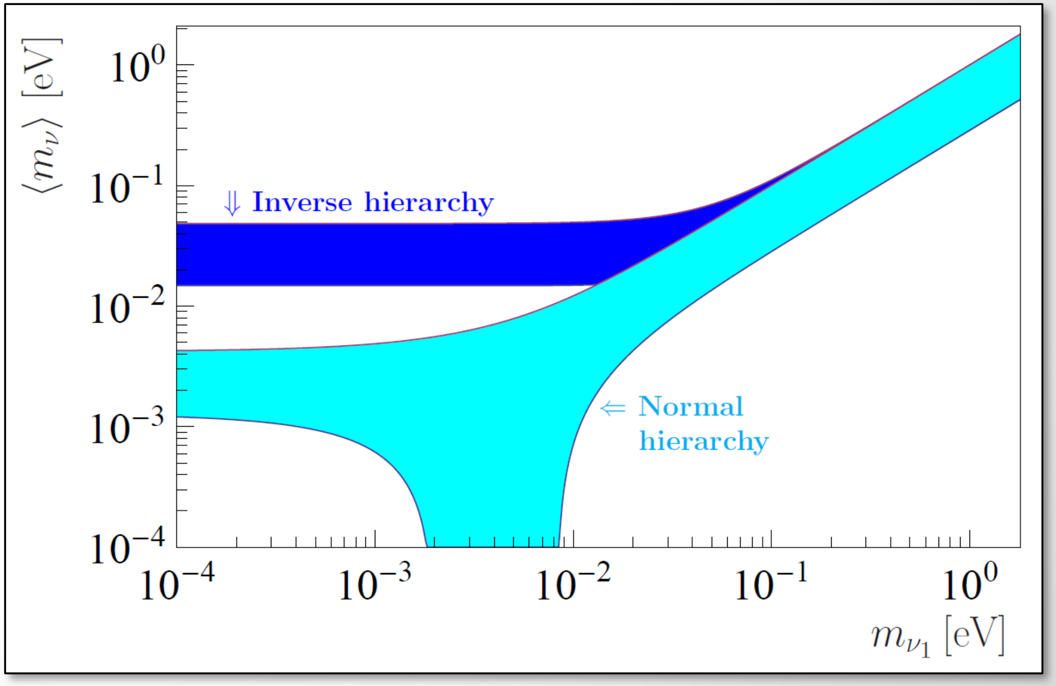
- Effective $0\nu\beta\beta$ Mass

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

- Degenerate Regime

$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases
- Accidental cancellation for NH possible



$0\nu\beta\beta$ – Light Neutrinos

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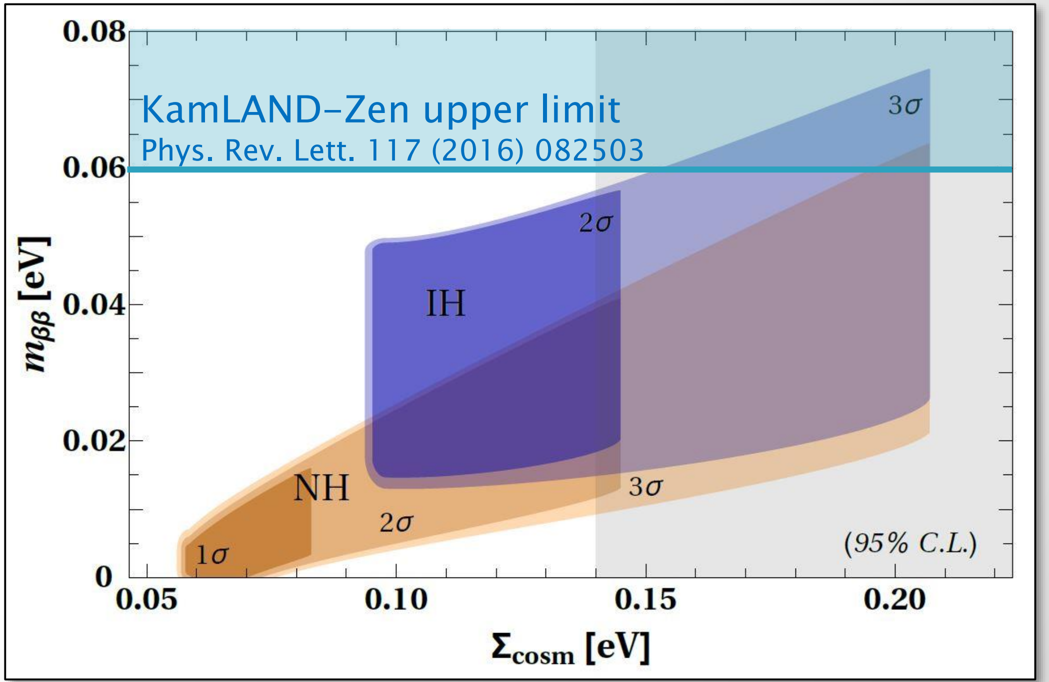

Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

$0\nu\beta\beta$ – Light Neutrinos

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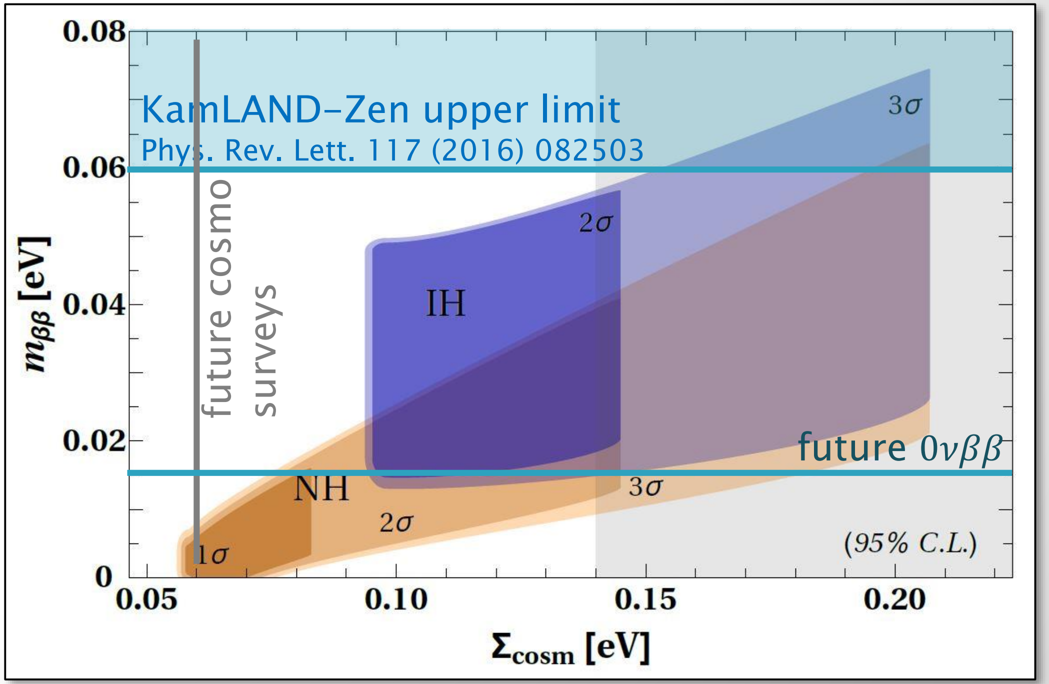

Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

$0\nu\beta\beta$ – Light Neutrinos

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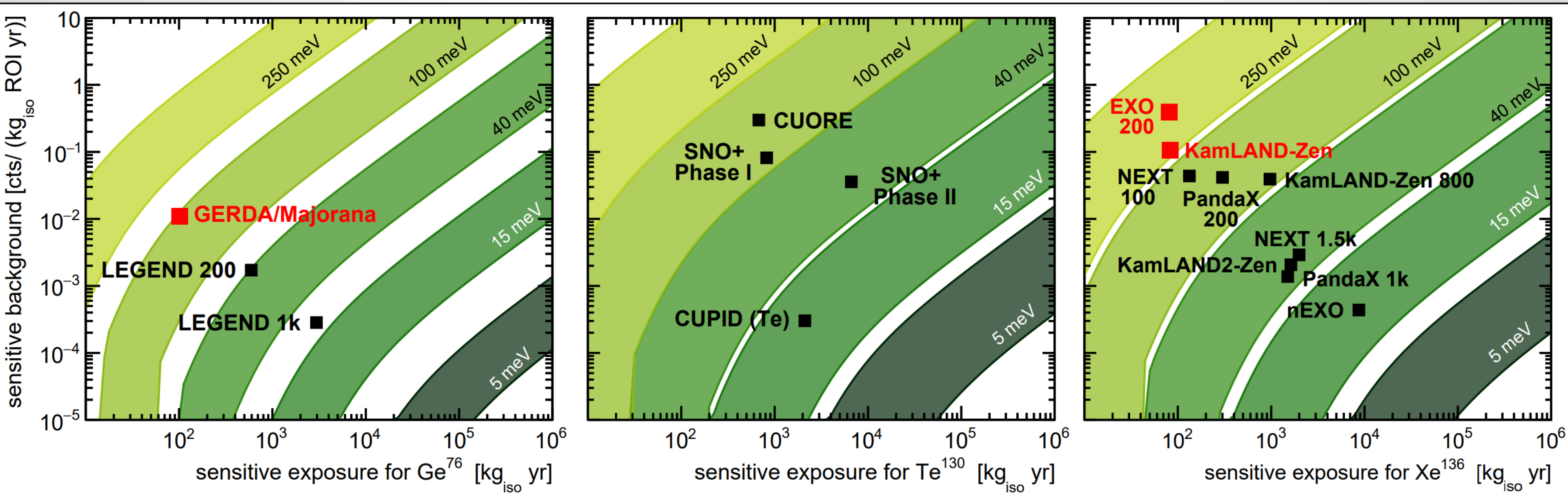
- Experimental Sensitivity



Agostini, Benato, Detwiler
arXiv:1705.02996

Nuclear Matrix Elements

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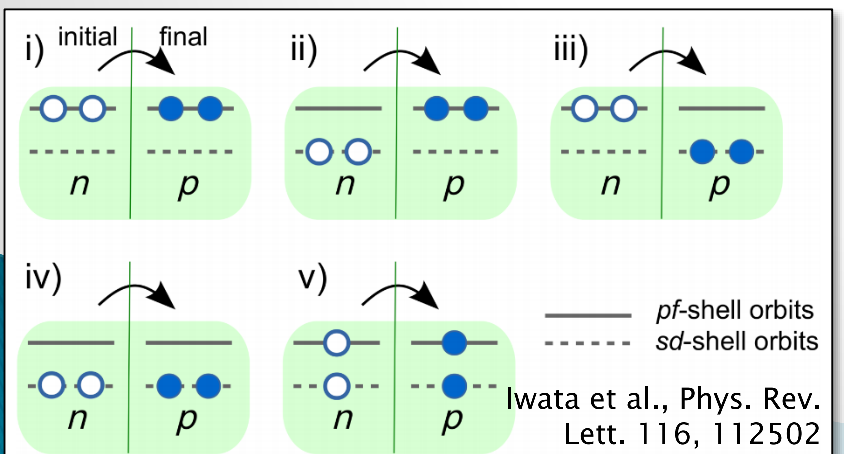
- Hadronic current

$$J^{\mu}(q) = g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5 + \frac{i g_M}{2m_N}\sigma^{\mu\nu} q_\nu - g_P \gamma^5 q^{\mu}$$

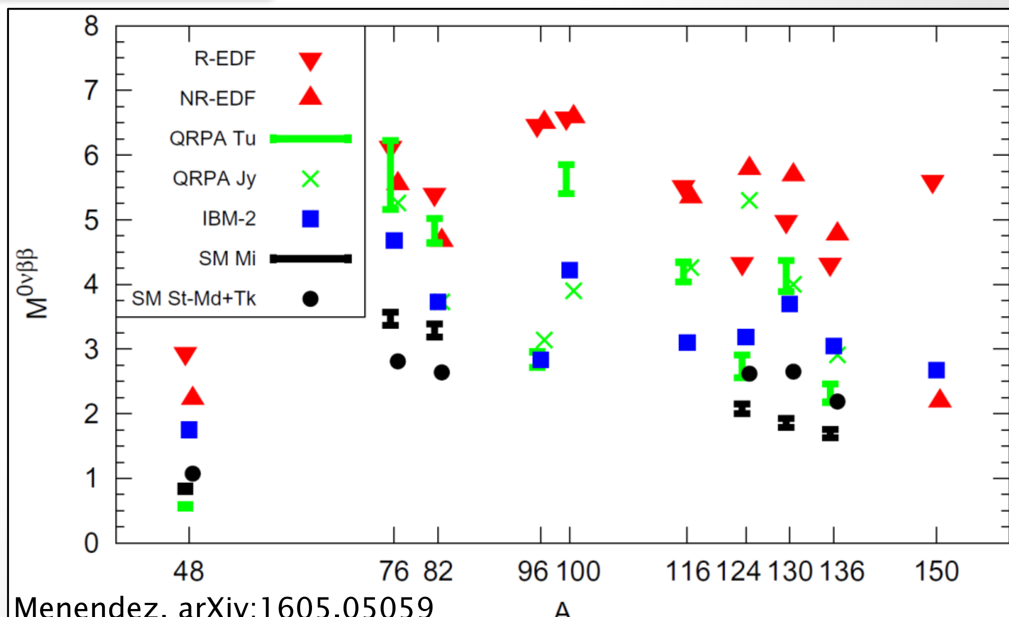
- Nuclear Matrix Element $M^{0\nu}$

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

  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models



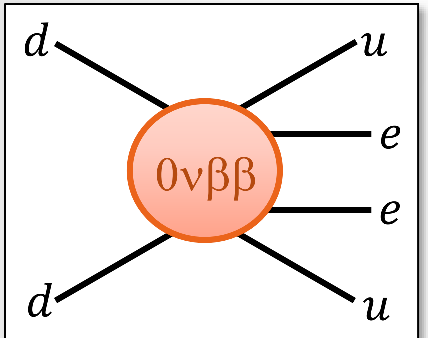
Iwata et al., Phys. Rev. Lett. 116, 112502



Menendez, arXiv:1605.05059

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

- Plethora of New Physics scenarios



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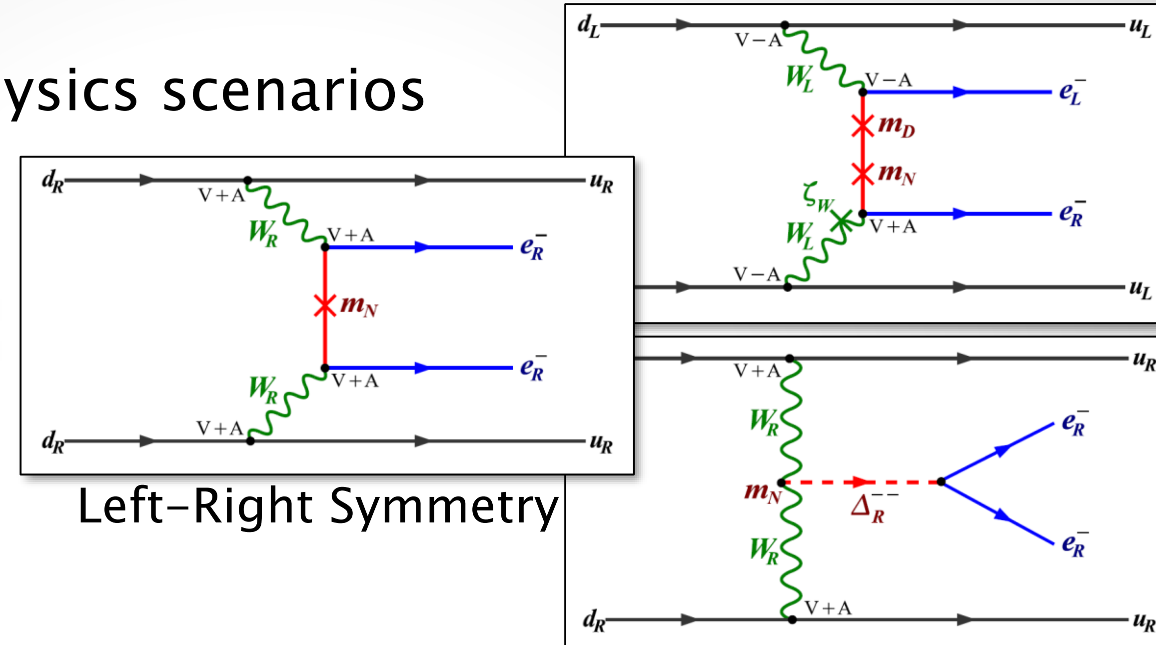
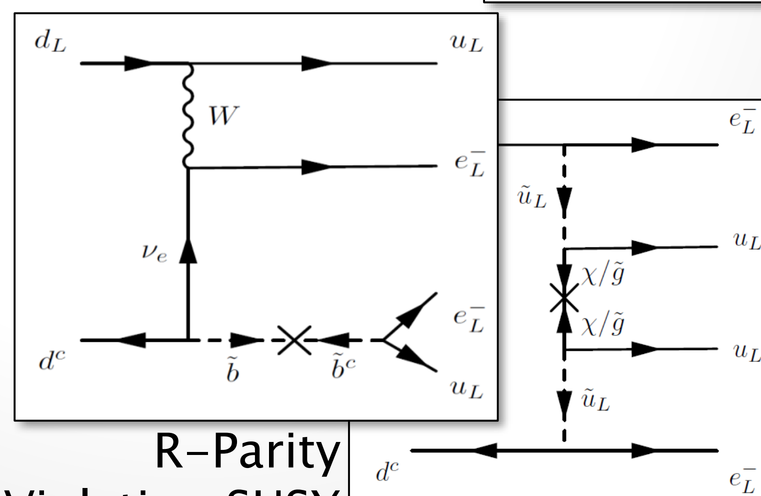


Left–Right Symmetry

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



R–Parity Violating SUSY

Extra Dimensions

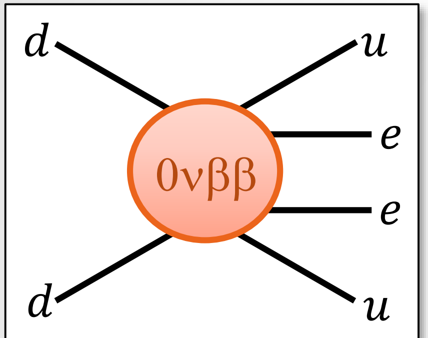
Majorons

Leptoquarks

…

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

- Plethora of New Physics scenarios



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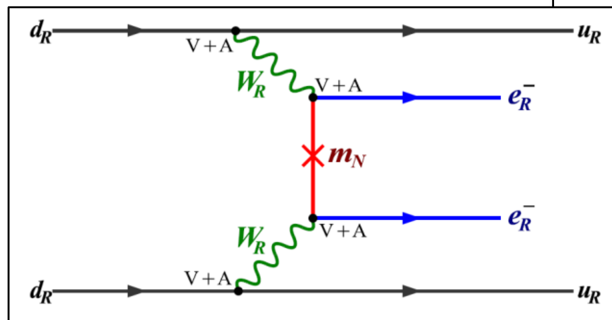
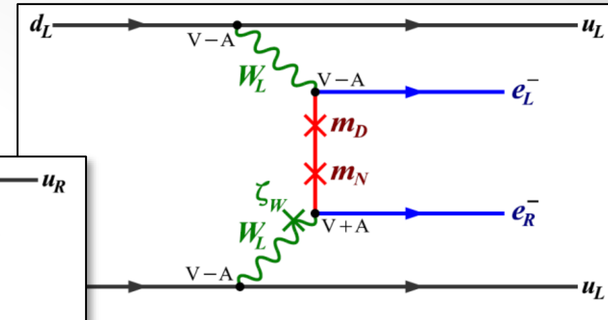
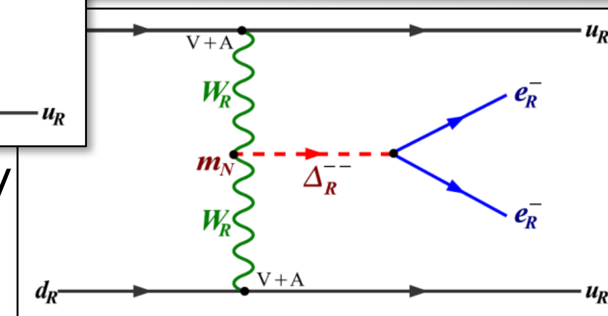


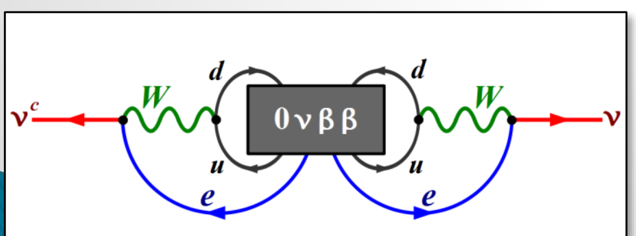


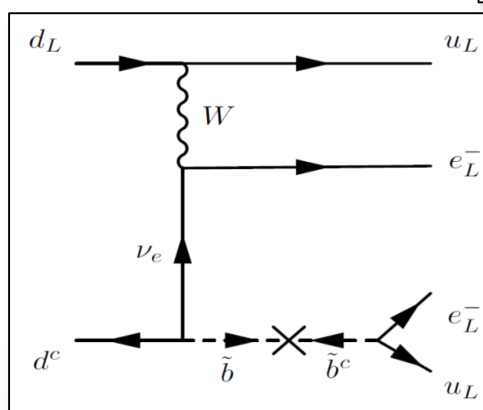


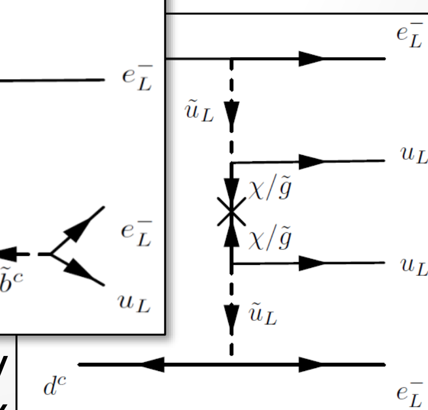
Left-Right Symmetry

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

- Neutrinos still Majorana







R-Parity Violating SUSY

Extra Dimensions

Majorons

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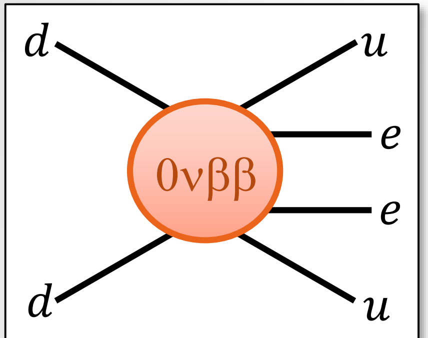
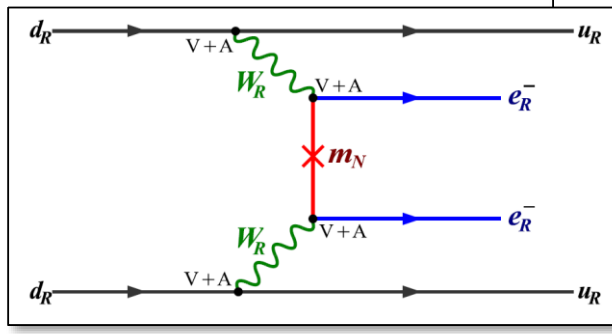
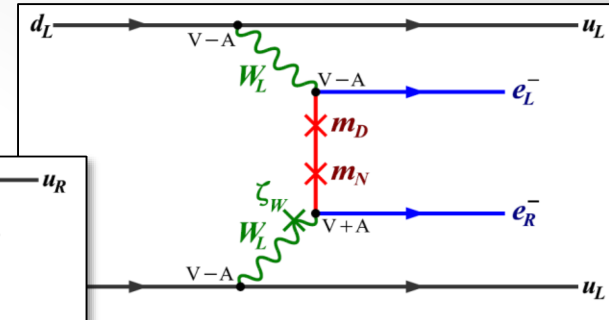
...

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

- Examples in Left-Right Symmetry







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

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

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

- $0\nu\beta\beta$ probes the TeV scale

Neutrino Mass Models

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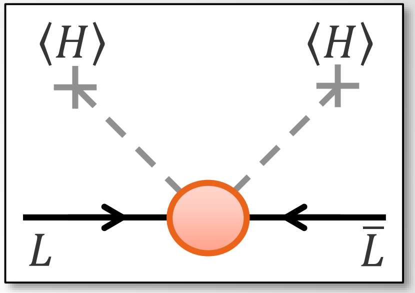
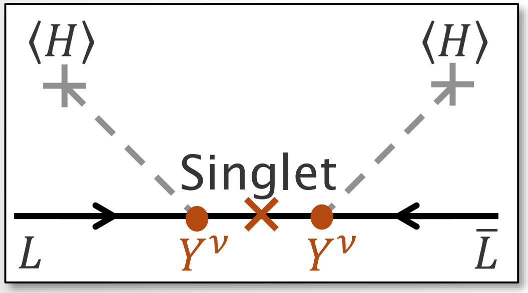
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

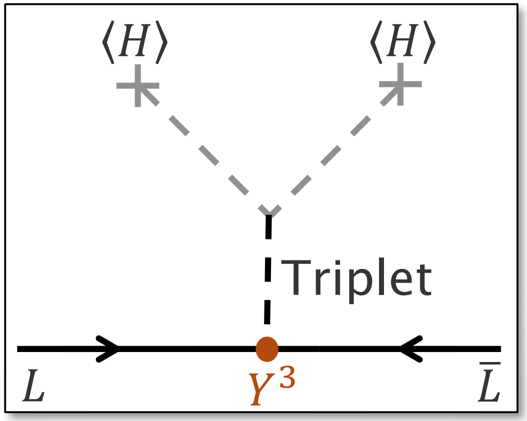


- Seesaw Mechanism

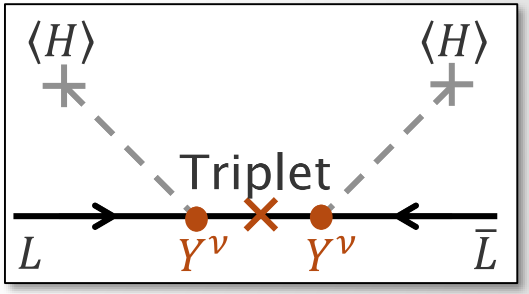
Seesaw I



Seesaw II



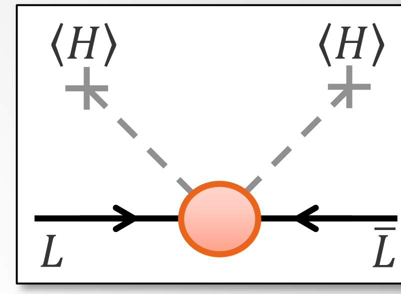
Seesaw III



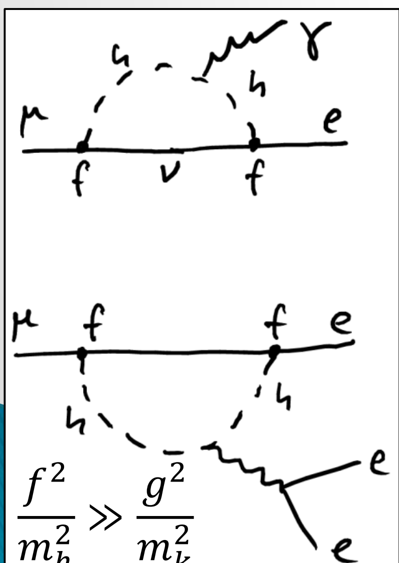
Neutrino Mass Models

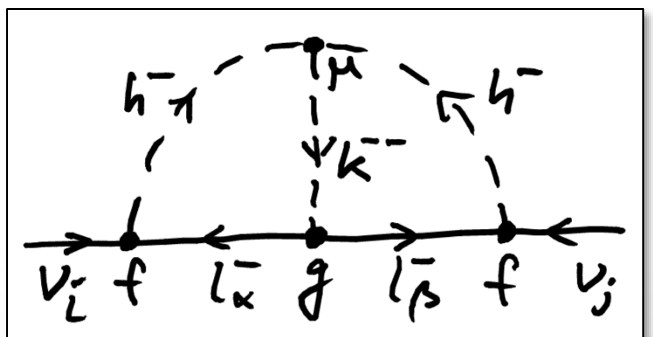
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\big(H^T \cdot L_j\big) \xrightarrow[\langle H\rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

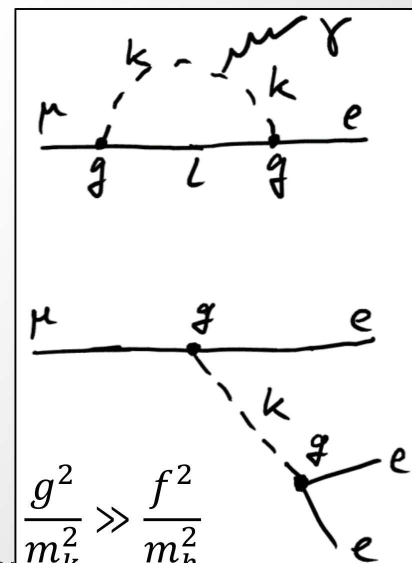


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. Babu-Zee model (Zee ’85, Babu ‘88)





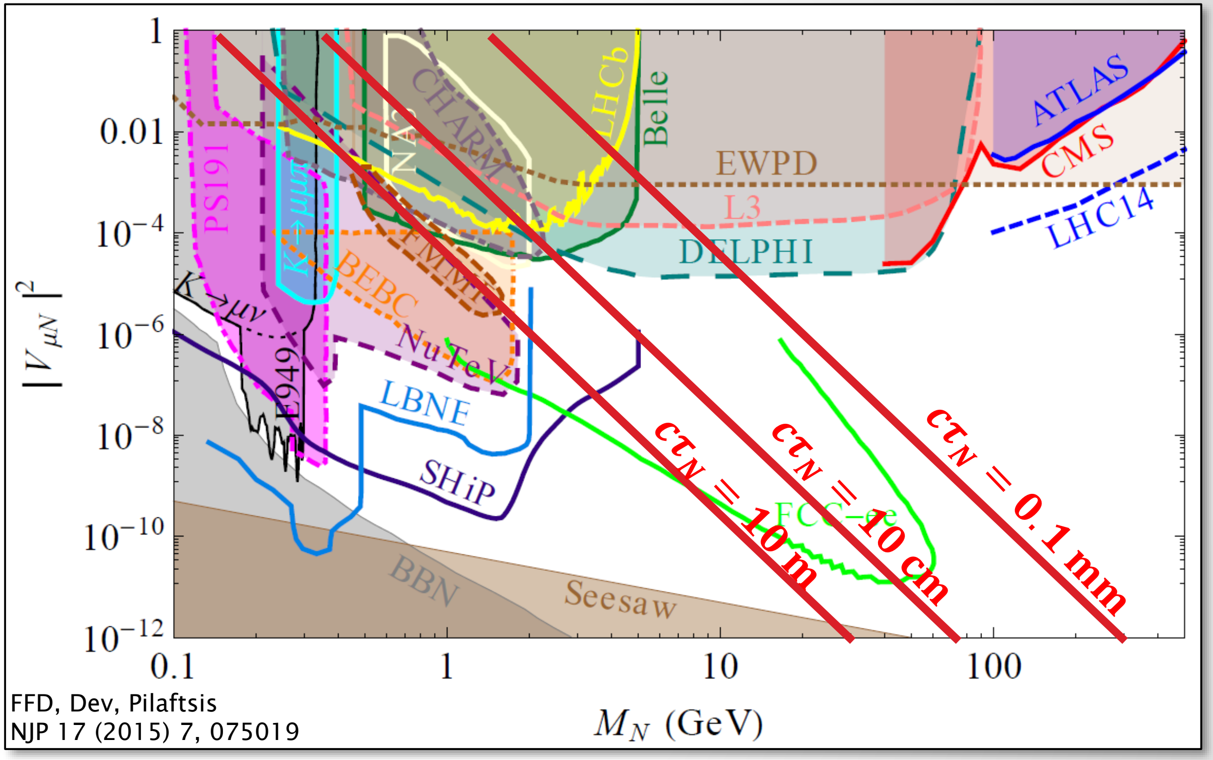
Neutrino masses suppressed at 2-loop



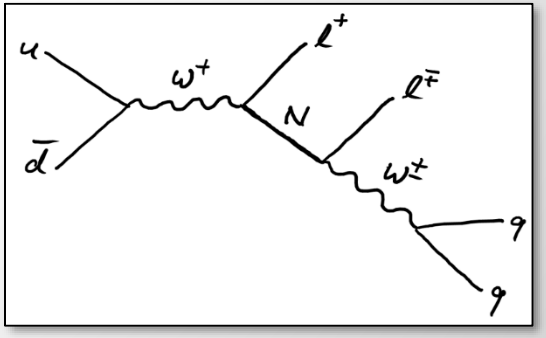
Heavy Sterile Neutrinos

University College London

- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
  - GERDA
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$
  - Belle
- Beam Dump Experiments
  - e.g. PS191, CHARM
  - LBNE
- LNV Meson Decays
  - $K \to ee\pi$
  - SHiP
- Z Decays
  - LEP: L3, Delphi
  - FCC-ee
- Electroweak Precision Tests
  - EWPD: Fit of electroweak precision observables, lepton universality observables



FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019

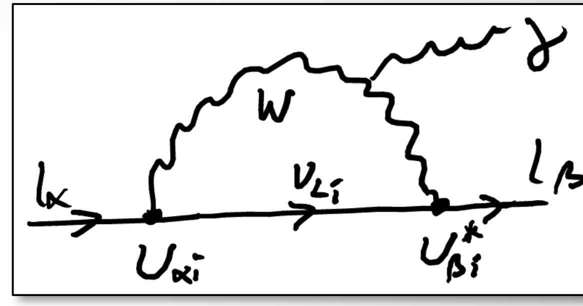


Heavy Sterile Neutrinos

University College London

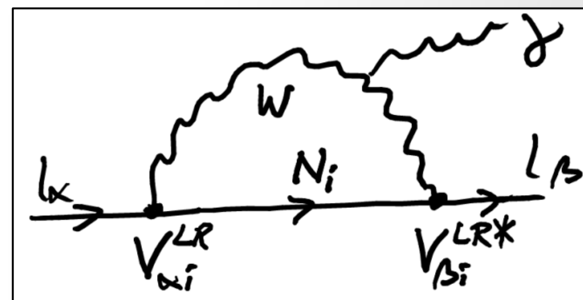
- CLFV in the Seesaw Mechanism
  - Light neutrino exchange
    - Negligible due to small neutrino masses

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 \approx 10^{-56}$$



  - Heavy neutrino exchange
    - Sizable for TeV scale heavy neutrinos and large LR mixing $V^{LR} \approx 10^{-2}$

$$Br(\mu \to e\gamma) \approx 4 \times 10^{-3}\left|\sum_i V^{LR*}_{\mu i} V^{LR}_{ei} G\left(\frac{m^2_{N_i}}{m^2_W}\right)\right|^2 \approx 10^{-11}\left(\frac{V^{LR}}{10^{-2}}\right)^4$$



$$\mathcal{U}^\nu = \begin{pmatrix} U & V^{LR} \\ (V^{LR})^\intercal & U^R \end{pmatrix}$$

Baryon Asymmetry

University College London

- The Universe is not matter–antimatter symmetric
  - CMB Anisotropy
  - Primordial Nucleosynthesis
  - No matter–antimatter annihilation
- Observed asymmetry

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

  - Very small… Universe may have begun symmetric
  - Still too large… to be compatible with the Standard Model

Baryon Asymmetry

- Dynamic generation of baryon asymmetry requires (Sakharov '66)
  - Baryon number violation
  - C and CP Violation
  - Out-of-equilibrium dynamics
- Standard Model
  - Baryon number violated at quantum level (Sphalerons)
  - C and CP violated but effect too small

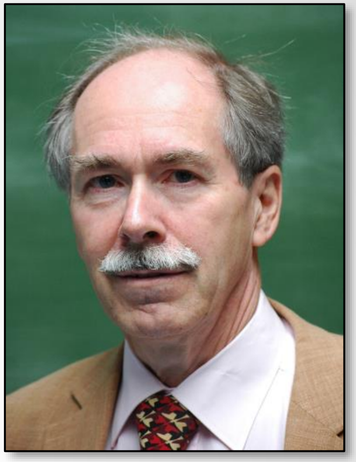
$$\frac{\mathrm{Im}\,\det(m_u m_u^+ m_d m_d^+)}{v^{12}} = J\,\frac{m_t^4 m_c^2 m_b^4 m_s^2}{v^{12}} \approx 10^{-19}$$

  - Electroweak phase transition out-of-equilibrium if first order but requires

$$m_h < 60 \ - 80\ \mathrm{GeV}$$

Sphalerons

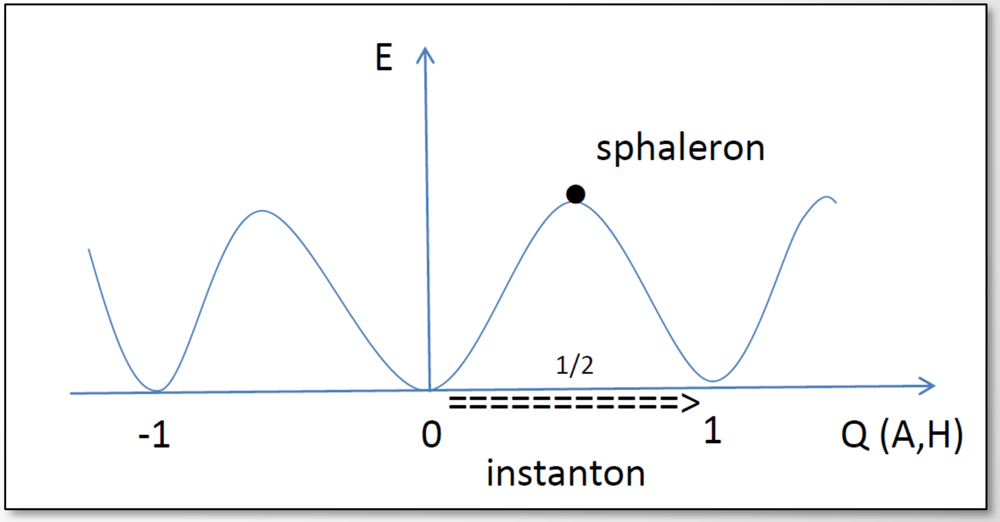
- Baryon and Lepton numbers accidental, classical symmetries in the Standard Model
- Violated at the quantum level (t' Hooft '76)



$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

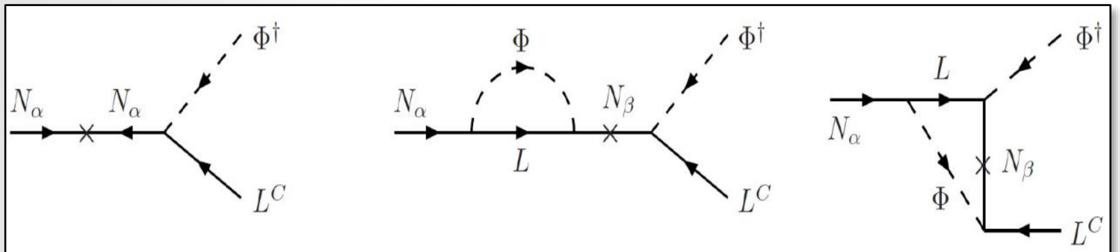
  - $B + L$ violated
  - $B - L$ remains conserved
- Sphaleron transitions in equilibrium $\frac{\Gamma_{Sph}}{H} > 1$ for

$$\Lambda_{EW} \approx 10^2 \text{GeV} < T < 10^{12}\ \text{GeV}$$



Leptogenesis

- Decays of heavy Majorana neutrinos violating L and CP (Fukugita, Yanagida '86)

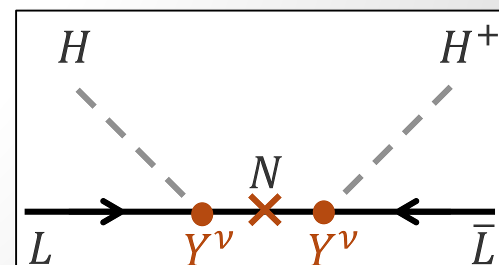


  - CP asymmetry

$$\epsilon_1 = \frac{\Gamma(N_1 \to LH^+) - \Gamma(N_1 \to \bar{L}H)}{\Gamma(N_1 \to LH^+) + \Gamma(N_1 \to \bar{L}H)} \approx \frac{3}{8\pi} \frac{\mathrm{Im}\left[(Y_\nu Y_\nu^+)_{1k}^2\right]}{(Y_\nu Y_\nu^+)_{11}} \frac{M_1}{M_k} \approx 10^{-6} \frac{M_1}{10^{10}\,\mathrm{GeV}} \frac{m_3}{0.05\,\mathrm{eV}}$$

- Competition with washout processes eradicating L asymmetry

$$m_\nu < O(0.1)\ \mathrm{eV}$$



- Conversion to baryon asymmetry via sphaleron processes

$$\eta_B \approx \eta_L$$

References

- Some plots stolen from Martin Hirsch's lectures at the 4th Chilean School of High Energy Physics (with resources from Mariam Tortola)
- For a recent status on topics discussed: https://www.frontiersin.org/research-topics/5341/, e.g.
  - Neutrino oscillations and Non-Standard Interactions
    Yasaman Farzan, Mariam Tortola, https://arxiv.org/abs/1710.09360
  - Lepton-Number Violation: Seesaw Models and Their Collider Tests
    Yi Cai, Tao Han, Tong Li, Richard Ruiz, https://arxiv.org/abs/1711.02180
  - From the trees to the forest: a review of radiative neutrino mass models, Yi Cai, Juan Herrero-García, Michael A. Schmidt, Avelino Vicente, Raymond R. Volkas, https://arxiv.org/abs/1706.08524
  - Status of neutrino properties and future prospects – Cosmological and astrophysical constraints
    Massimiliano Lattanzi, Martina Gerbino, https://arxiv.org/abs/1712.07109