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Neutrinos and BSM Physics

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Fermion Masses

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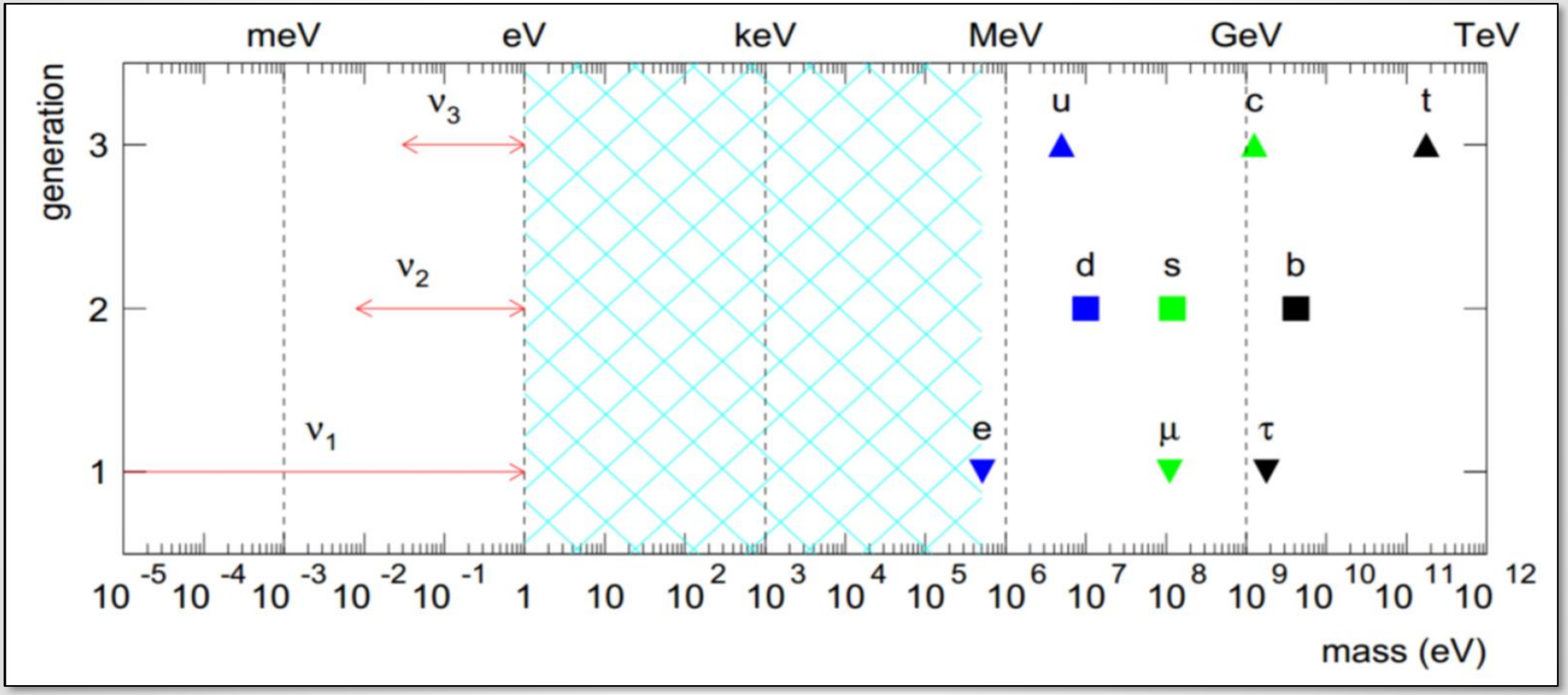
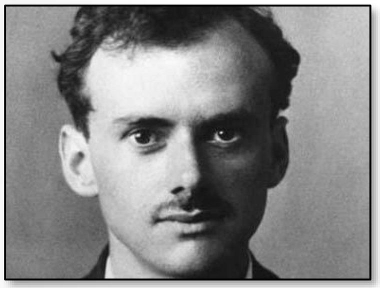


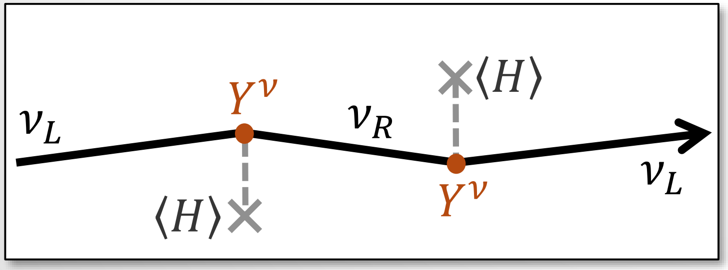
Dirac vs Majorana

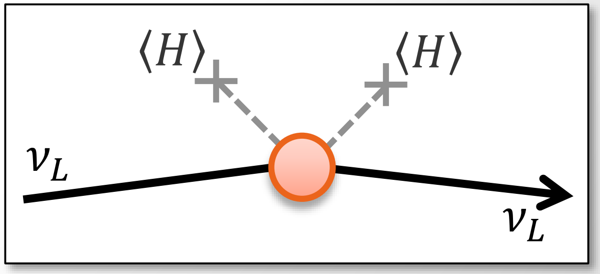
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass



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





Neutrino Oscillations

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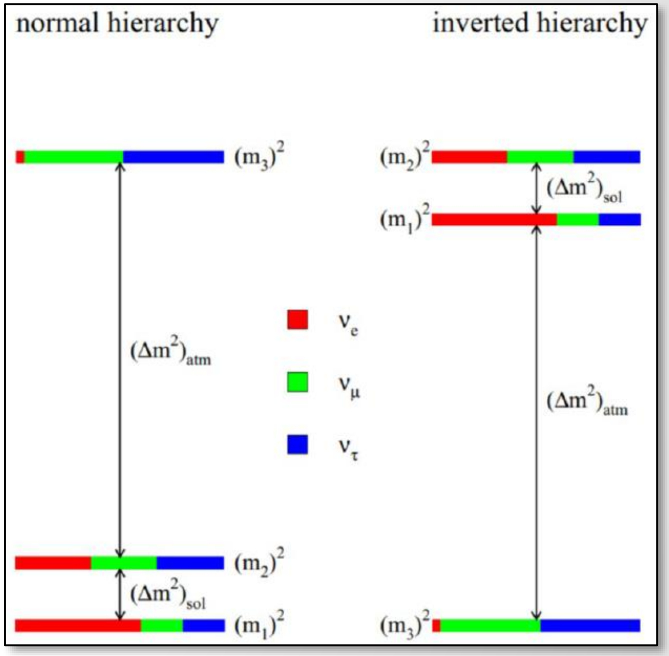
- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation

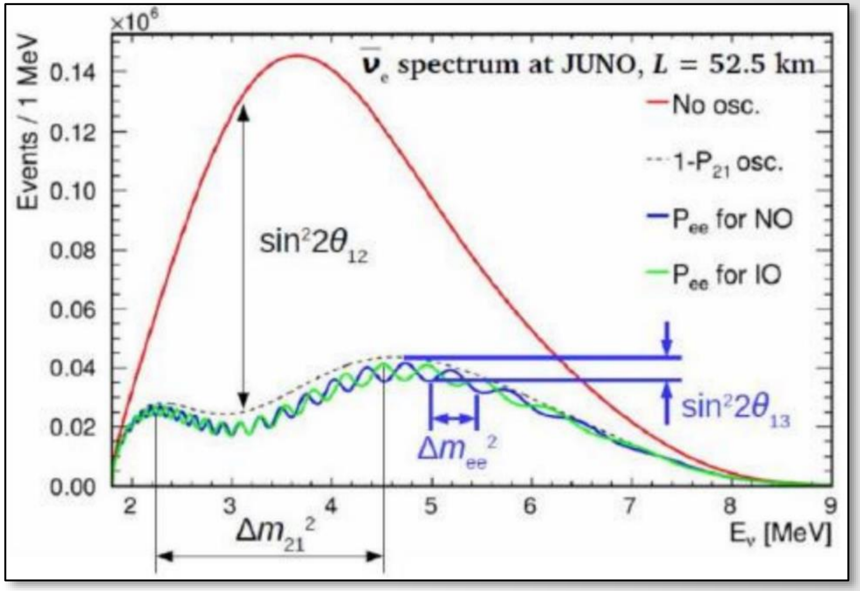
$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



- Quantum effect on macroscopic distances
  - Verified in vacuum and matter
- Era of neutrino precision physics
  - Current errors ~ 1–10%
- Experimental unknowns
  - CP Violation? Sign of Δm_{23}? Octant of θ_{23}? Sterile Neutrinos? Non-standard Interactions?

Neutrino Oscillations 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

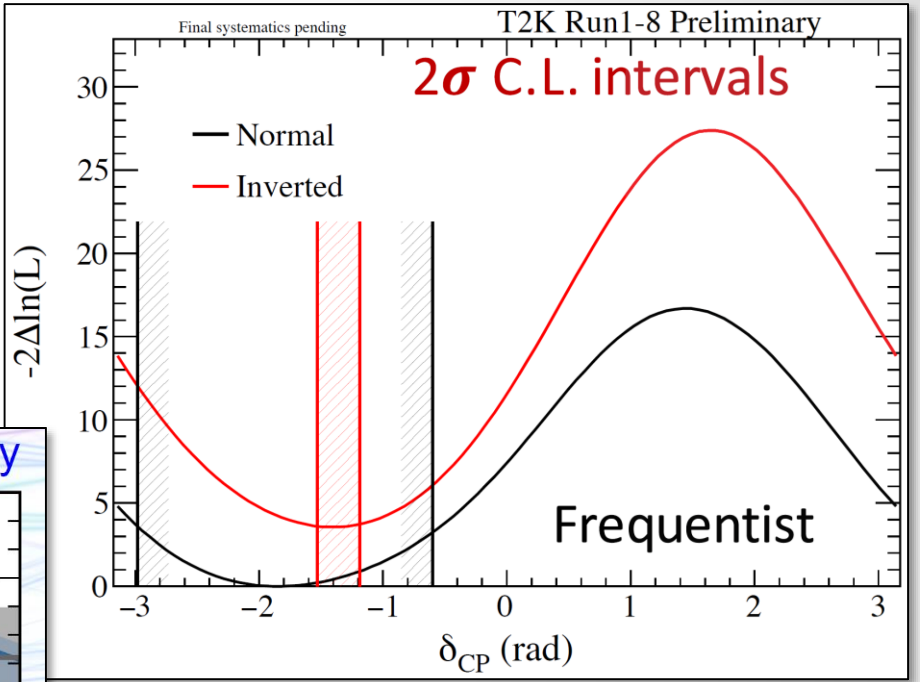


Neutrino Oscillations
CP Violation

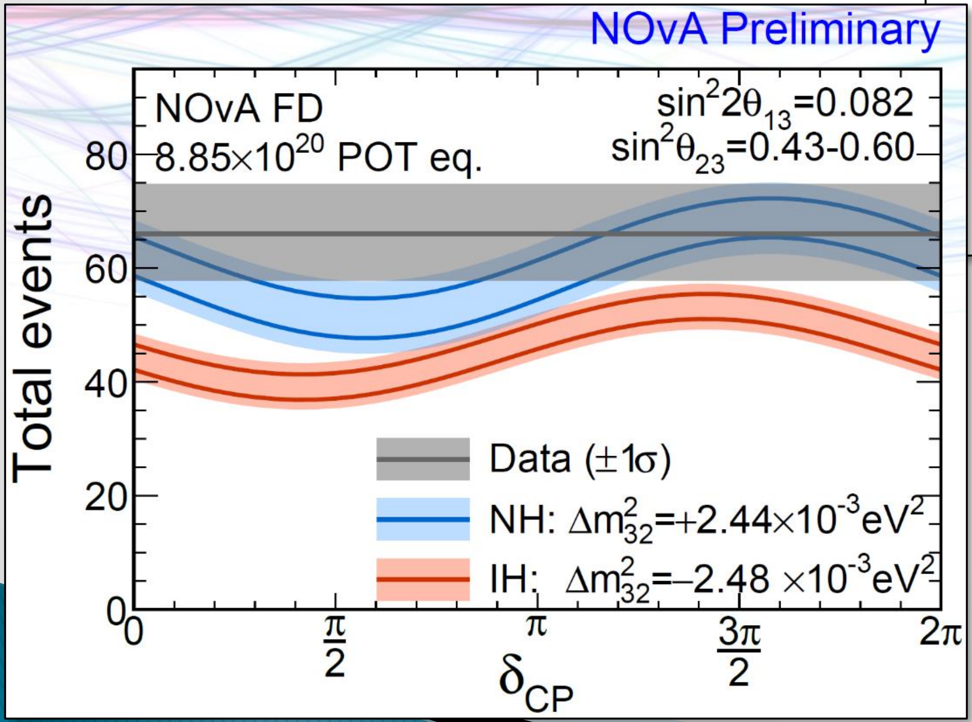
- Hint for maximal CP phase?

$$\delta_{CP} \approx \frac{3}{2}\pi?$$

- Symmetry origin?



Cao, Moriond18



Backhouse, Moriond18

Neutrino Oscillations
θ_{23} and Mass Order

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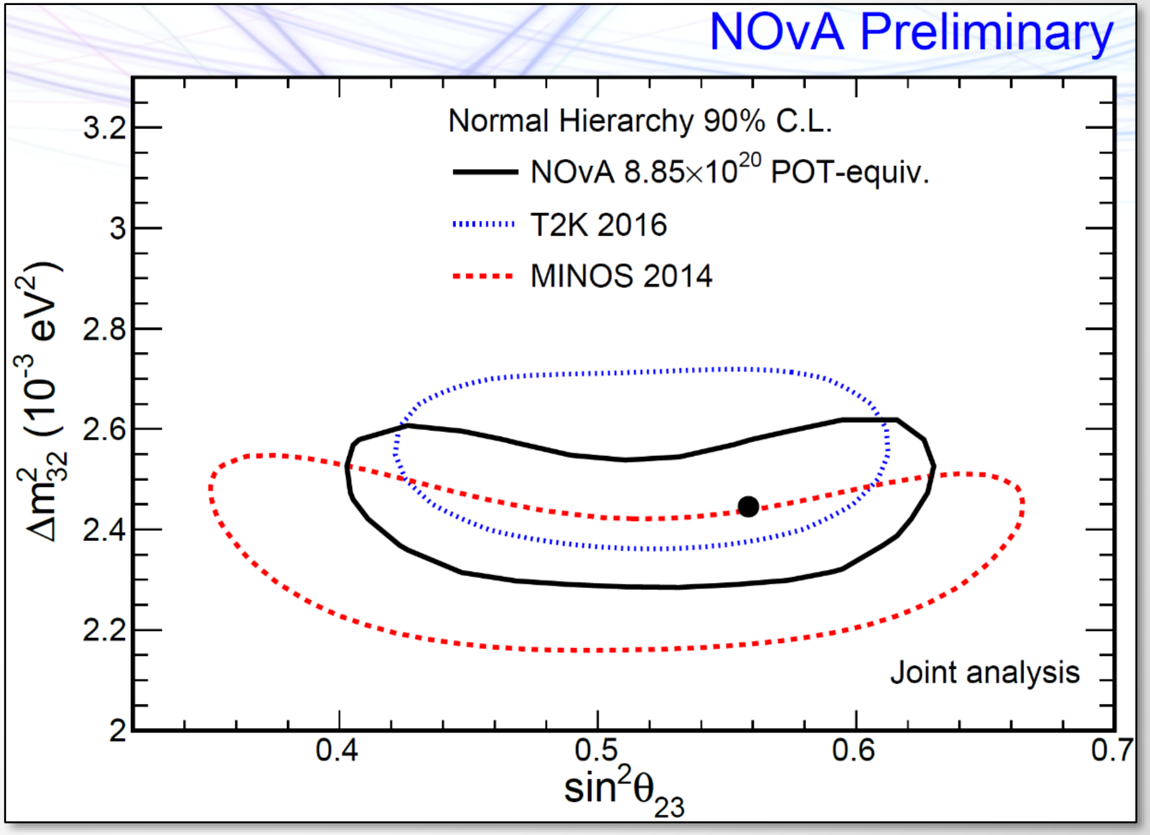
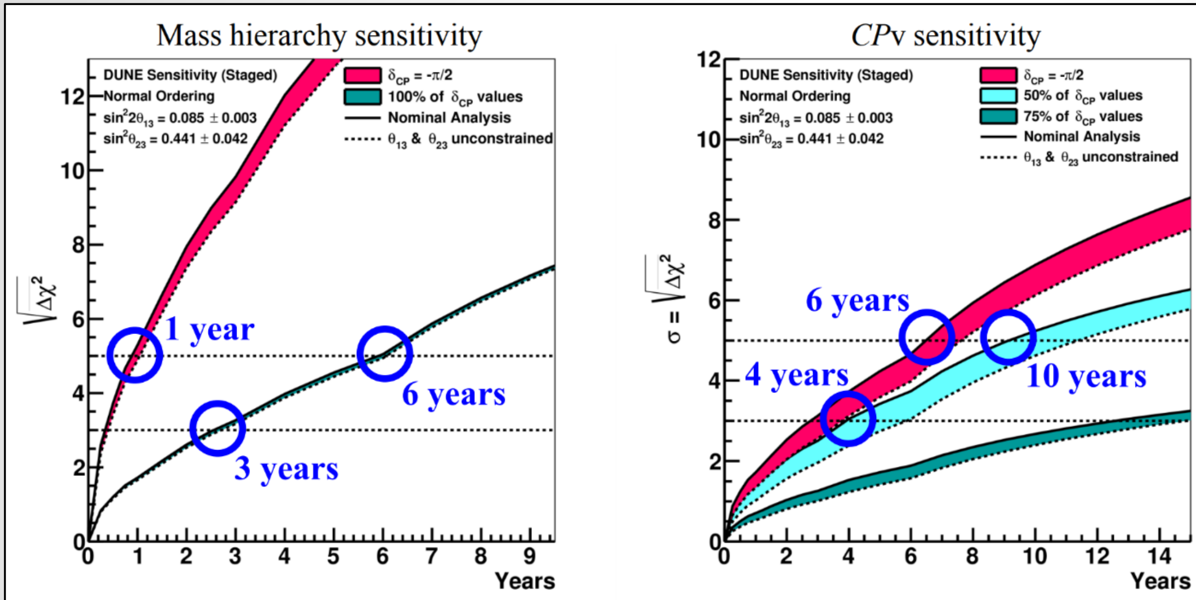
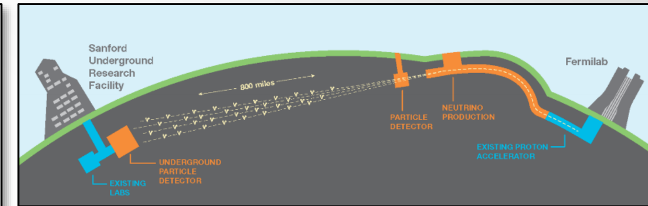
- Atmospheric Mixing Angle
  - Compatible with maximal mixing
  - Symmetry origin?
- Mass Ordering
  - Slightly larger tension for IH between T2K and NoνA

Backhouse, Moriond18

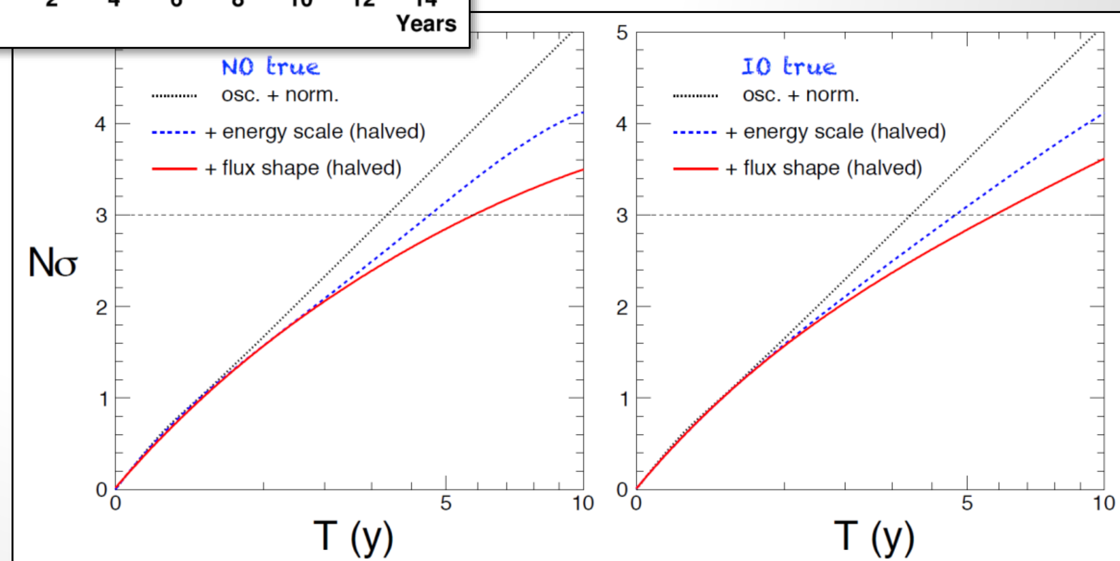


Neutrino Oscillations Future Prospects





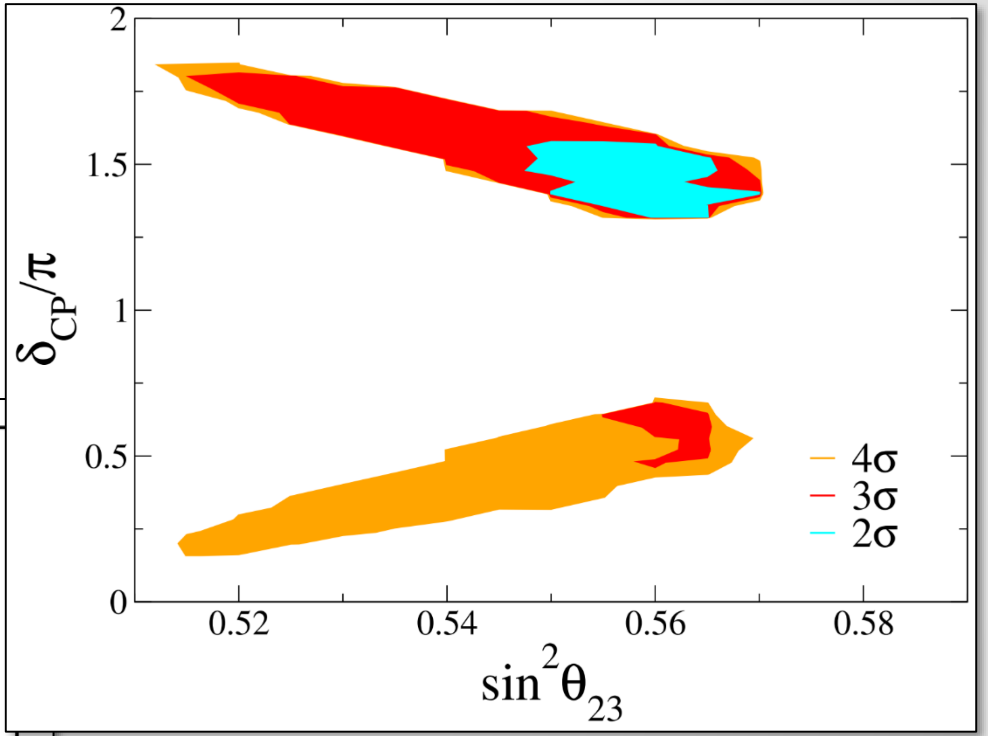
DUNE sensitivity
(Patterson, Moriond18)



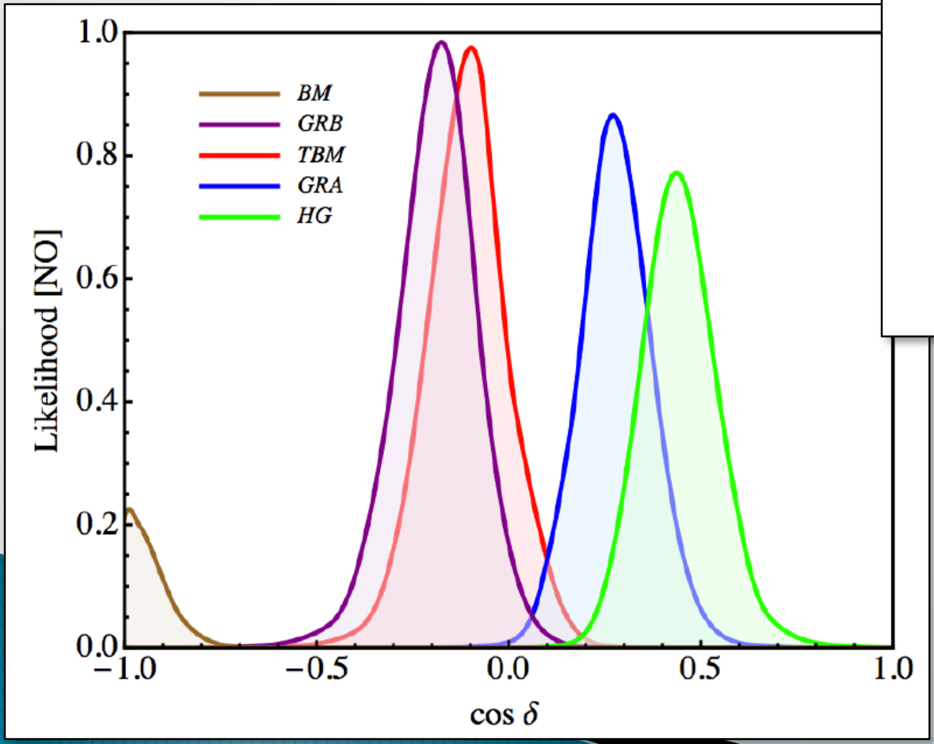
JUNO sensitivity to mass ordering (Marrone et al. '15)

Neutrino Oscillations
Flavour Symmetries

- Hints of large θ_{23} and δ_{CP}
  - interesting for flavour models…
  - of which there are a lot



Prediction in example flavour model
(Srivastava et al. '14)



Impact of measurement on flavour models (Girardi '14)

Neutrino Oscillations
New Physics in ν Physics

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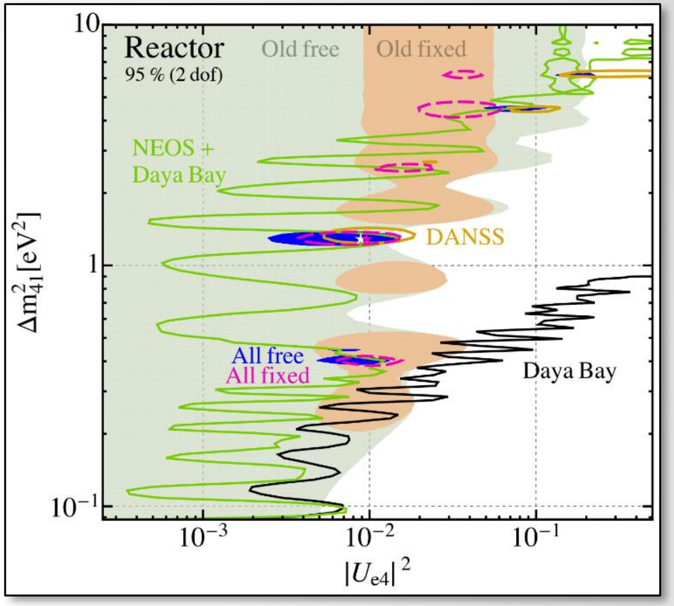
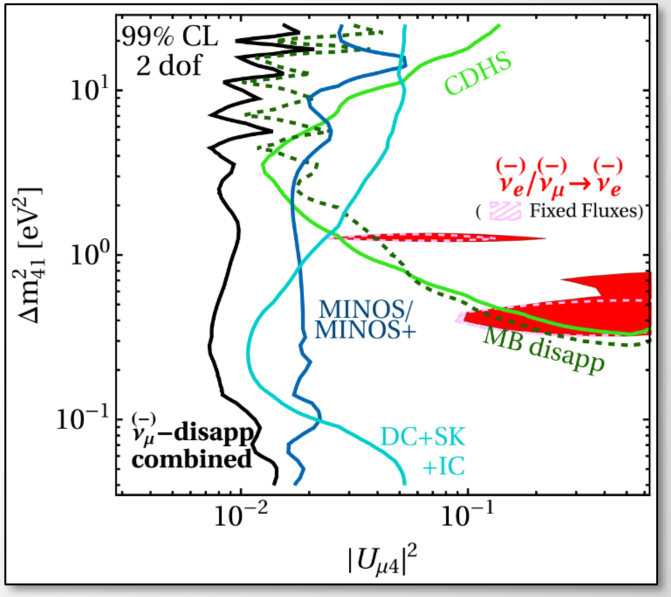
- **Sterile neutrinos**
  - ν_e app. and ν_μ app. in tension at 4.7σ
  - ν_e disapp.: sterile ν favoured at 3σ
- Non-unitarity
  - Generally expected (seesaw), albeit small
- Non-standard interactions
  - COHERENT ν-nucleus scattering
  - Can impact standard oscillations but strong bounds from ch. lepton physics (gauge invariance)
- Long-range forces
- Lorentz / CPT violation



Dentler et al. '18 (arXiv:1803.10661)



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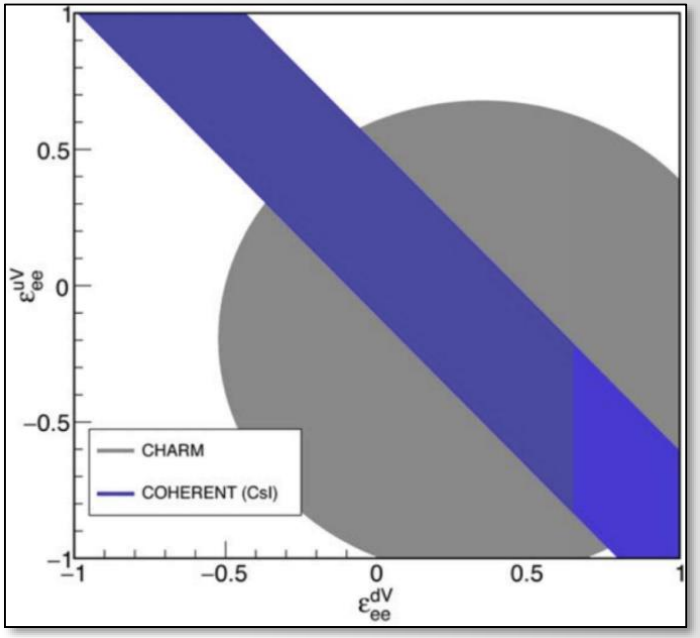

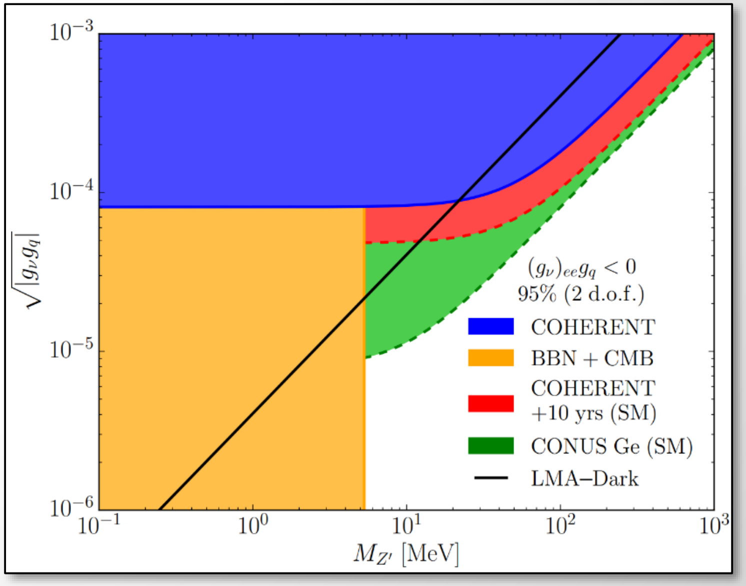

Denton, Farzan, Shoemaker '18

Absolute Neutrino Mass Cosmology

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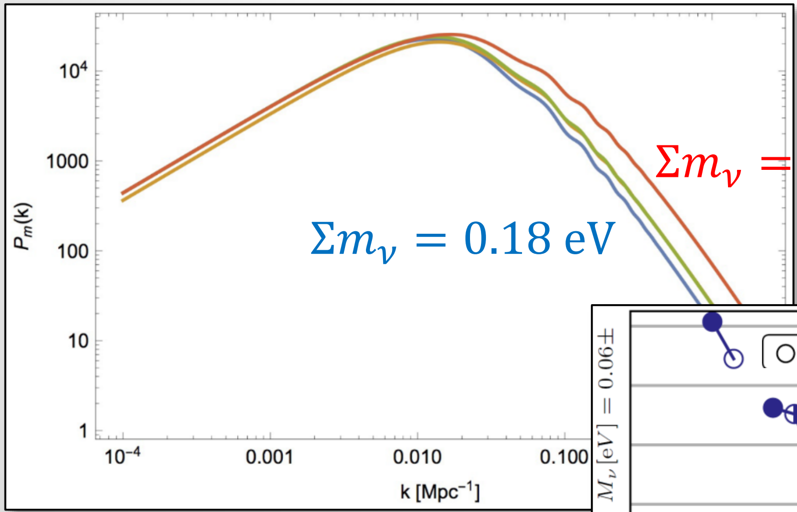
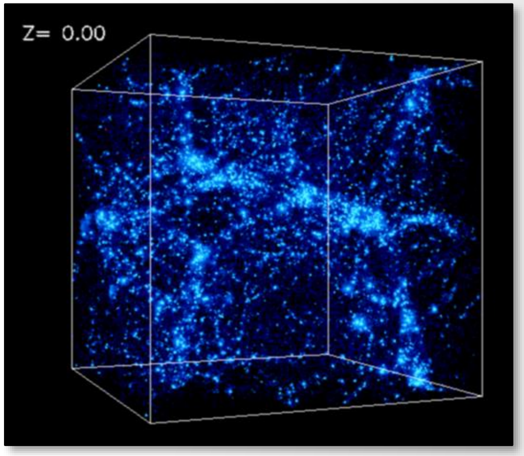
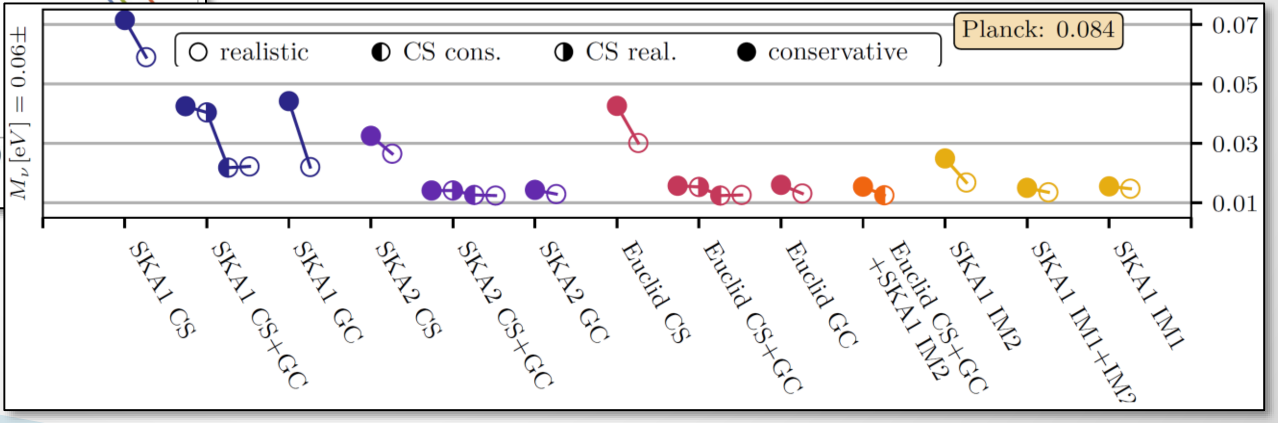
- Impact on large scale structures of the Universe
  - Light sterile neutrinos = extra DOFs of radiation
  - Sensitive to sum of neutrino masses

$$n_{eff} < 3.4, \quad \sum m_\nu < 0.15 - 0.25 \text{ eV}$$



Gerbino, Lattanzi '18





Sprenger et al. '18

Absolute Neutrino Mass
Beta Decays

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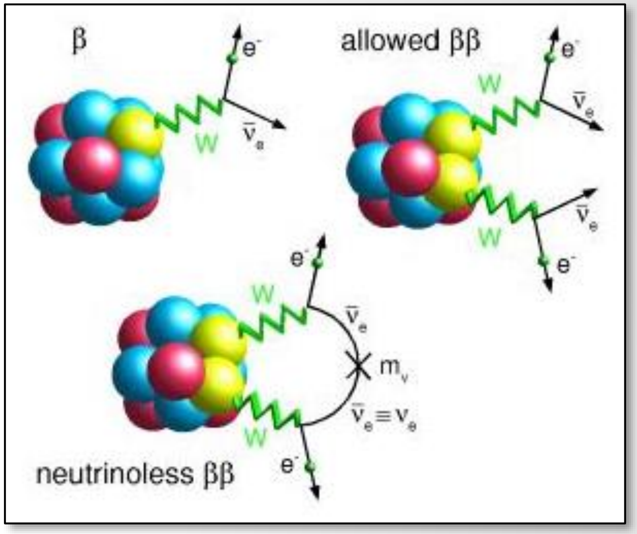
- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Tritium decay, KATRIN: $m_\nu \approx 0.2\ \mathrm{eV}$
  - Probe of exotic interactions (Gonzalez-Alonso et al. 'today)
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos

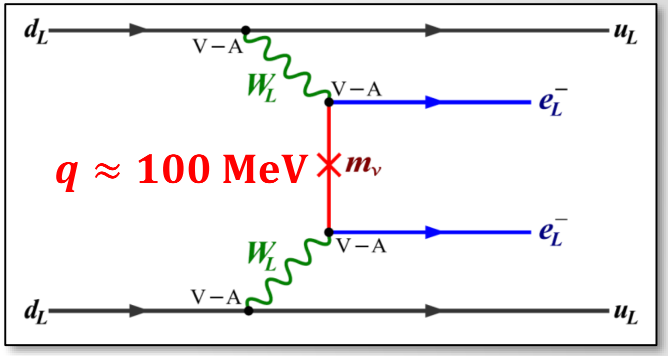


Absolute Neutrino Mass

$0\nu\beta\beta$

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

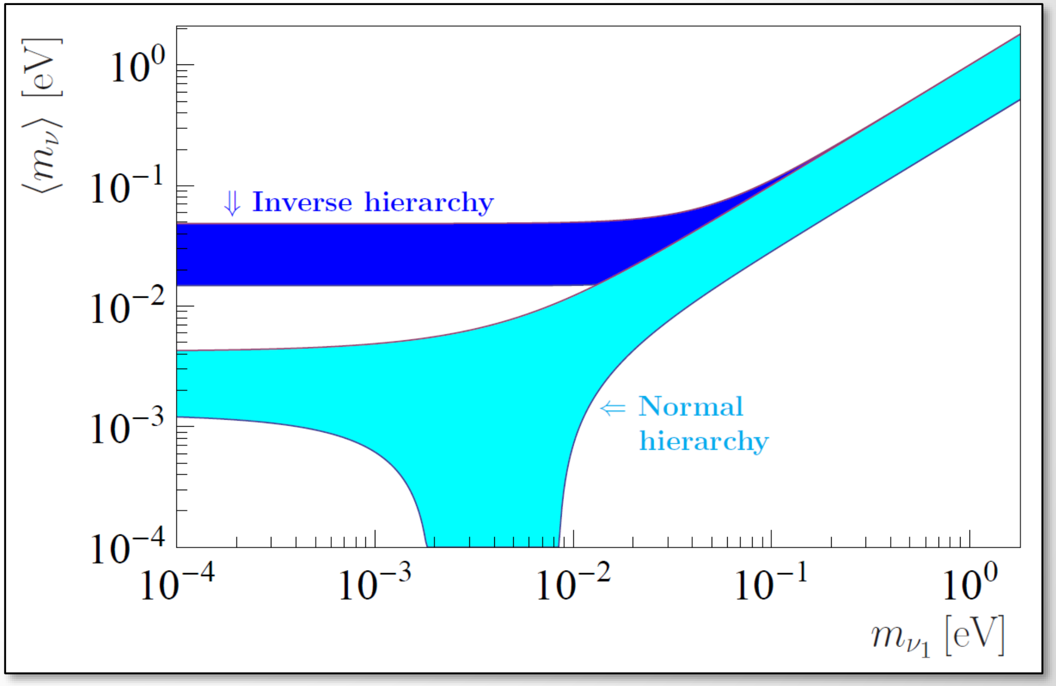
$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$



- 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



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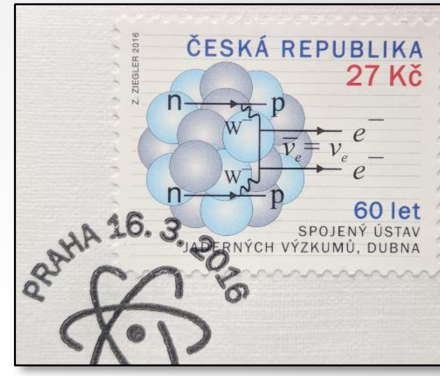

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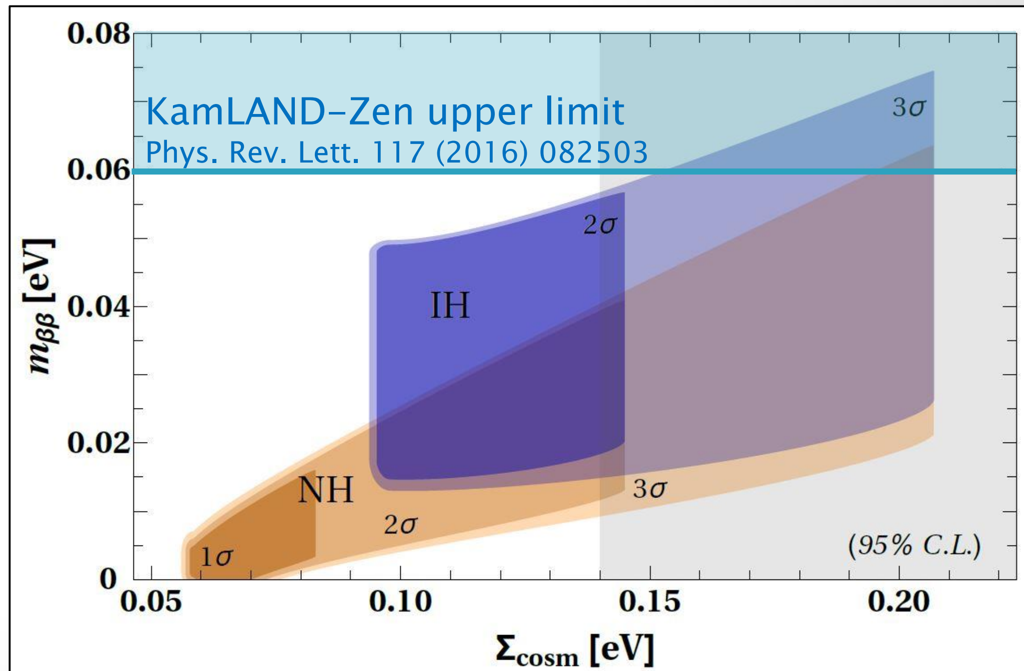

Dell'Oro, Marcocci, Viel, Vissani '18

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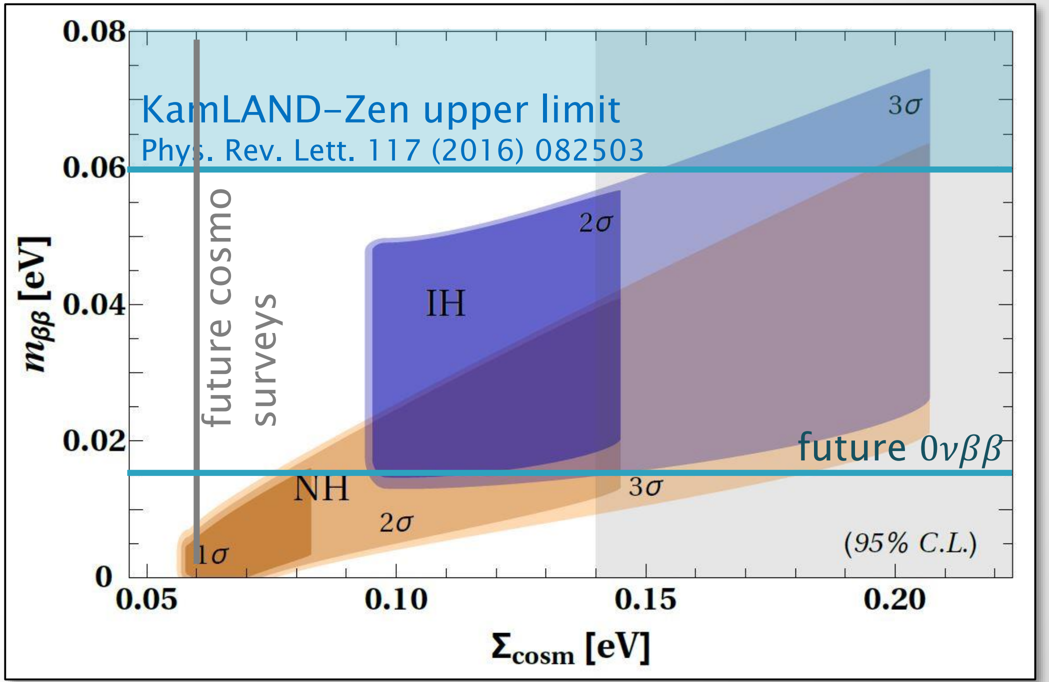

Dell'Oro, Marcocci, Viel, Vissani '18

Absolute Neutrino Mass

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

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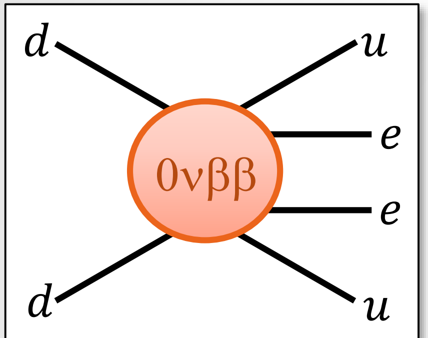
- Plethora of New Physics scenarios



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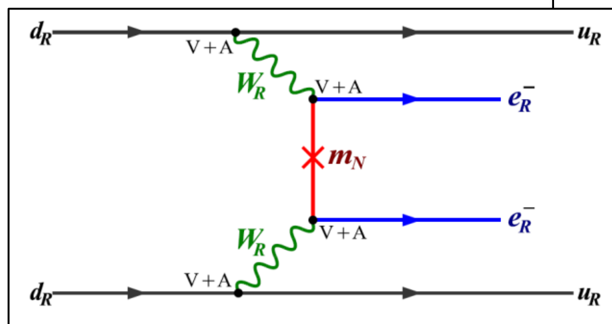
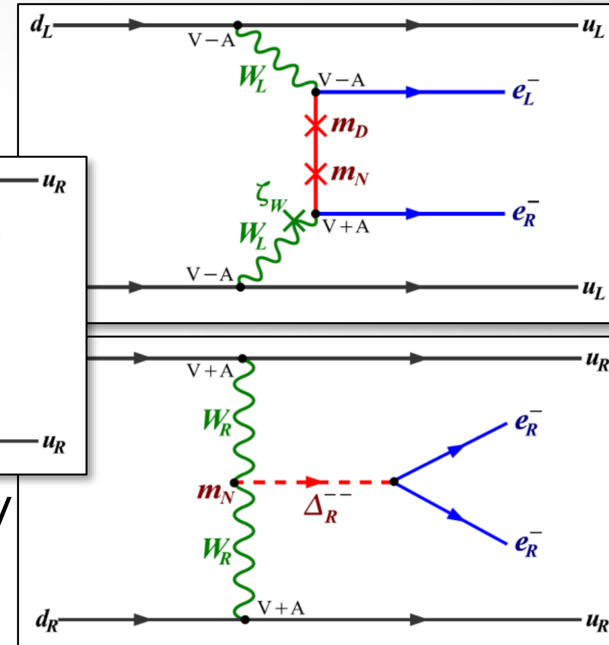
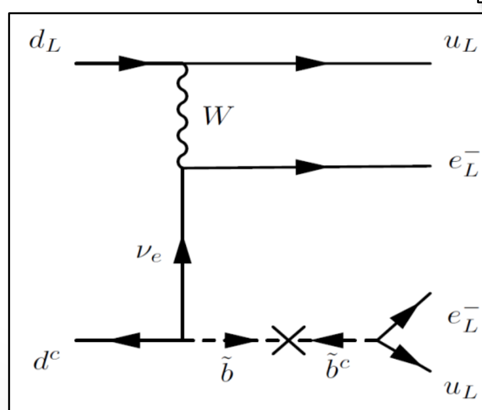
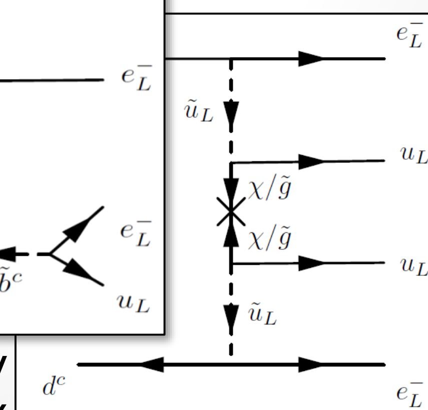




Left-Right Symmetry

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





R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- ...

Absolute Neutrino Mass

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

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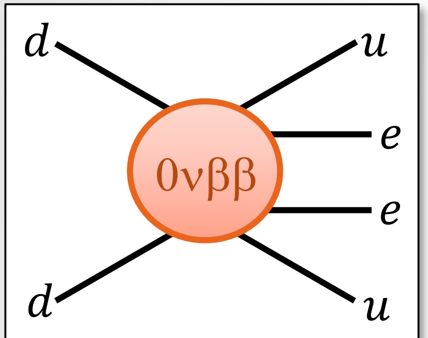
- Examples in Left-Right Symmetry



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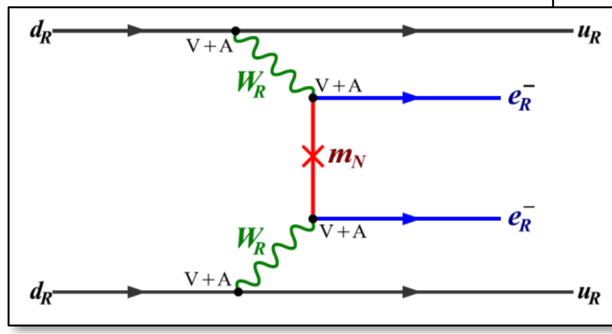
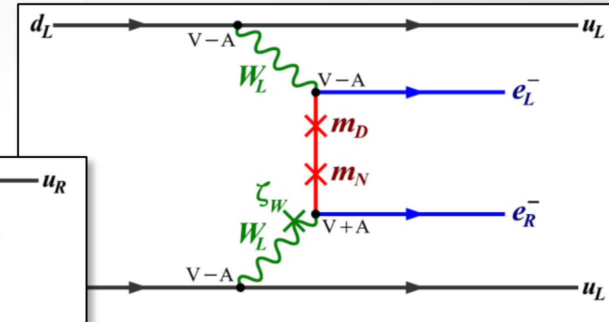
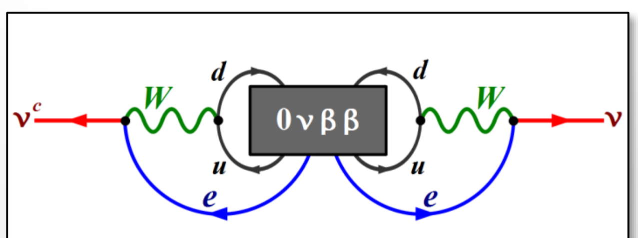


$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$



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

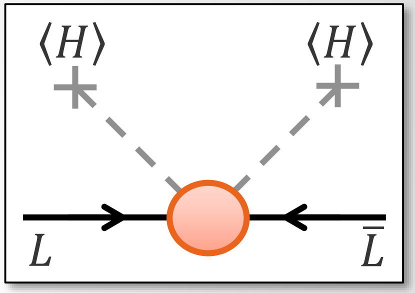
- $0\nu\beta\beta$ probes the TeV scale
- Neutrinos still Majorana



Neutrino Mass Models

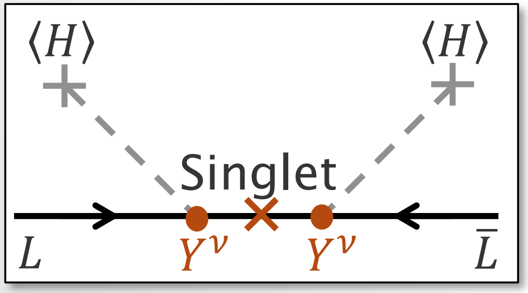
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

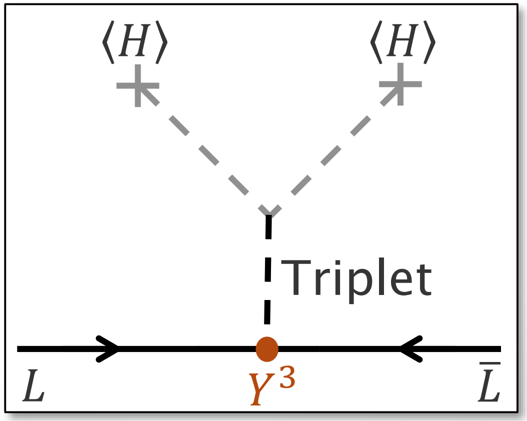


- Seesaw Mechanism

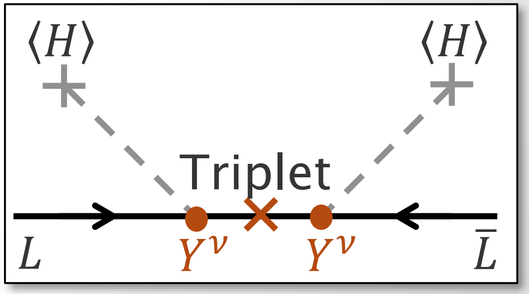
Seesaw I



Seesaw II



Seesaw III



  - GUT scale?
  - Leptogenesis? Naturalness?

Neutrino Mass Models

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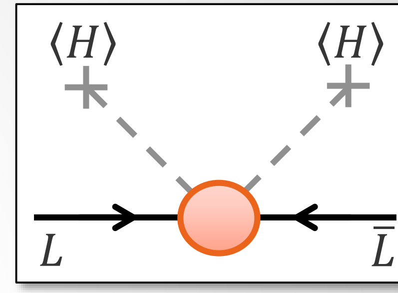
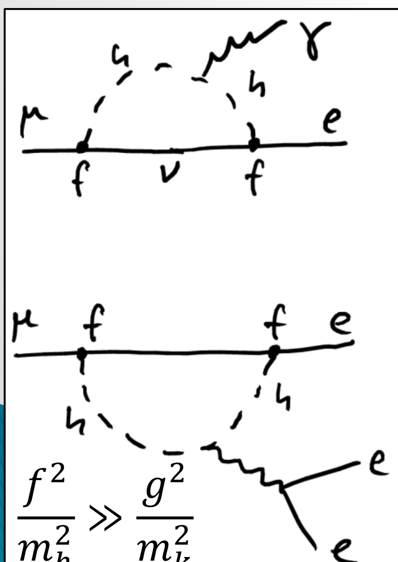
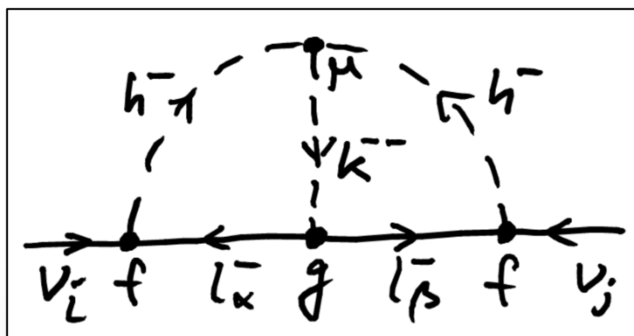
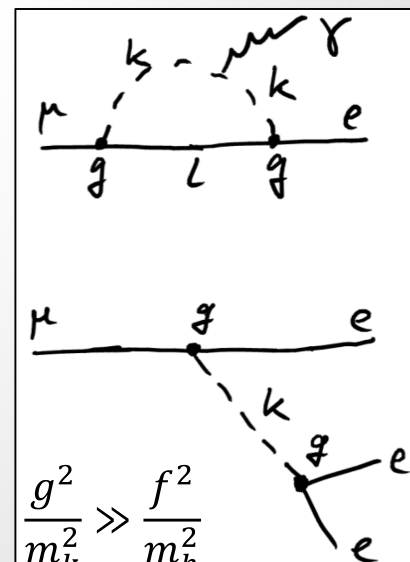


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. Babu-Zee model (Zee '85, Babu '88)





Neutrino masses suppressed at 2-loop



Heavy Sterile Neutrinos

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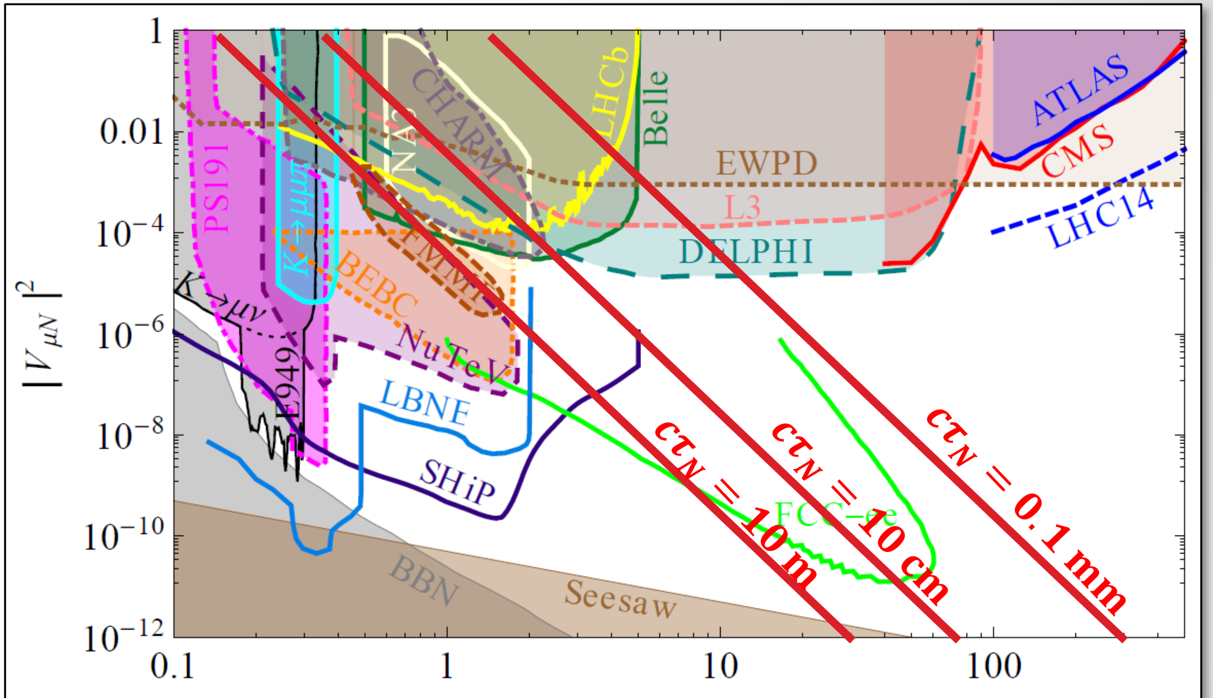
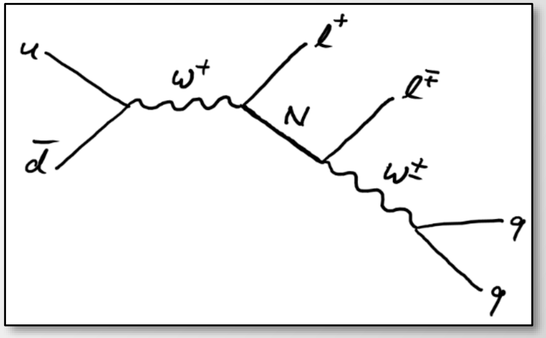
- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
- Peak Searches in Meson Decays
- Beam Dump Experiments
- LNV Meson Decays
- Z Decays
- Electroweak Precision Tests

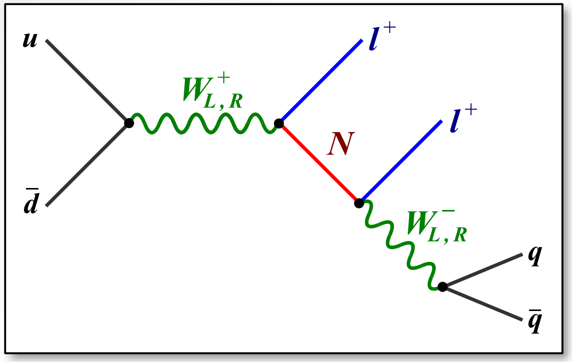


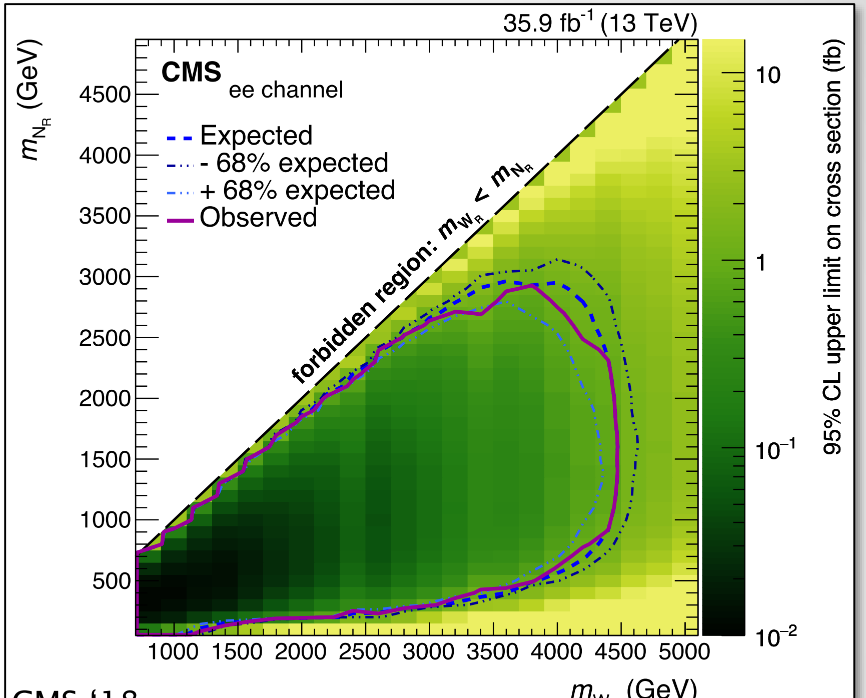
FFD, Dev, Pilaftsis '16



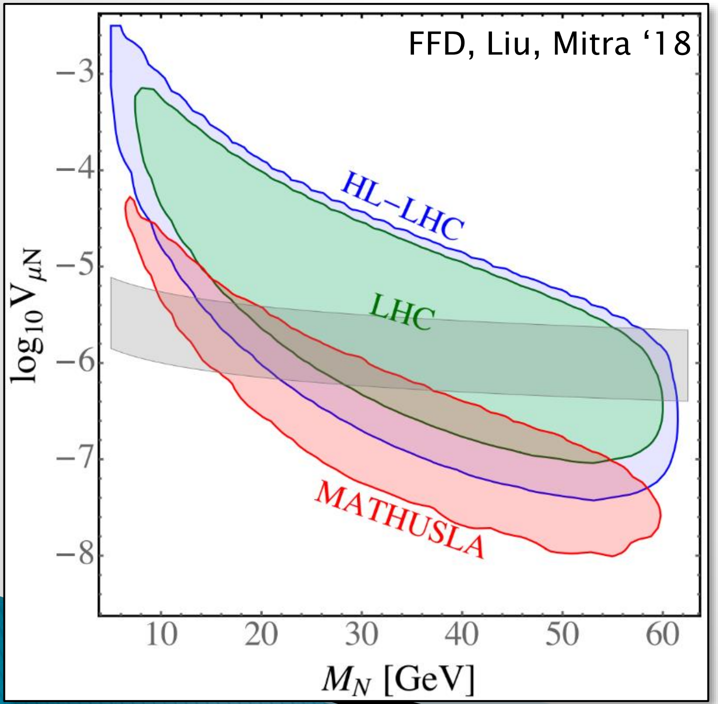
Extended Gauge Sectors

- Left-Right Symmetry





CMS '18



- SM Higgs decays to long-lived heavy neutrinos $pp \to H \to NN$
  - e.g. in $U(1)_{B-L}$ extensions

Lepton Flavour Violation

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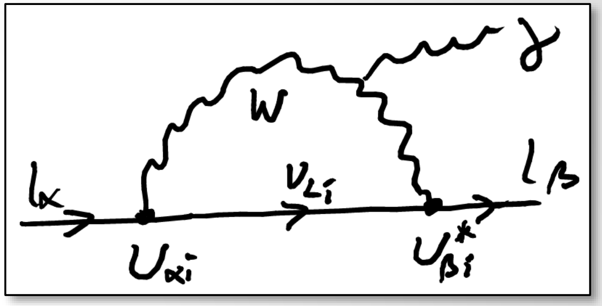
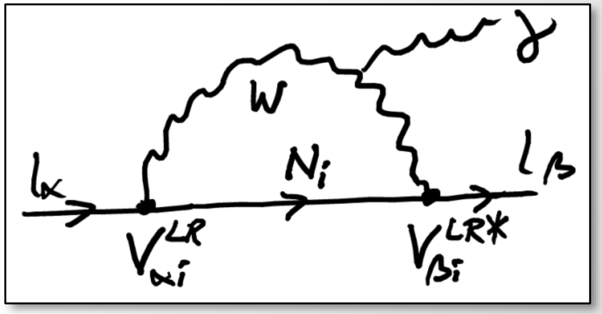
- CLFV in the Seesaw Mechanism
  - Light neutrino exchange
    - Negligible due to small neutrino masses



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

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



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

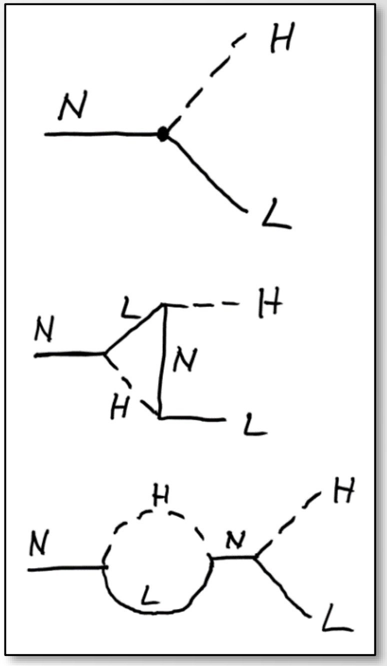
$$\approx 10^{-11}\left(\frac{V^{LR}}{10^{-2}}\right)^4$$

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

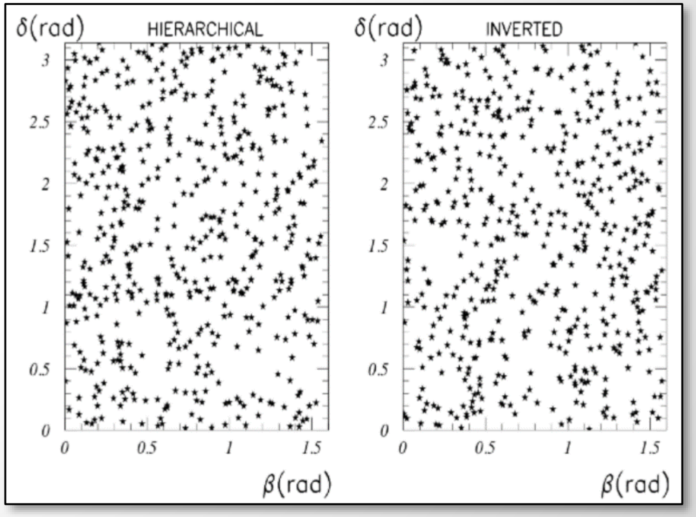
Baryon Asymmetry
CP Violation

- 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

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



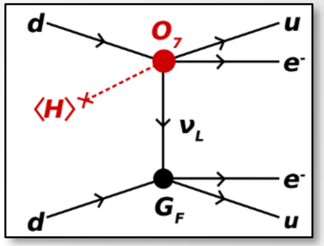
- Observation of δ_{CP} would establish CP violation in lepton sector but connection to baryon asymmetry model-dependent

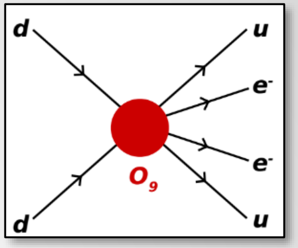


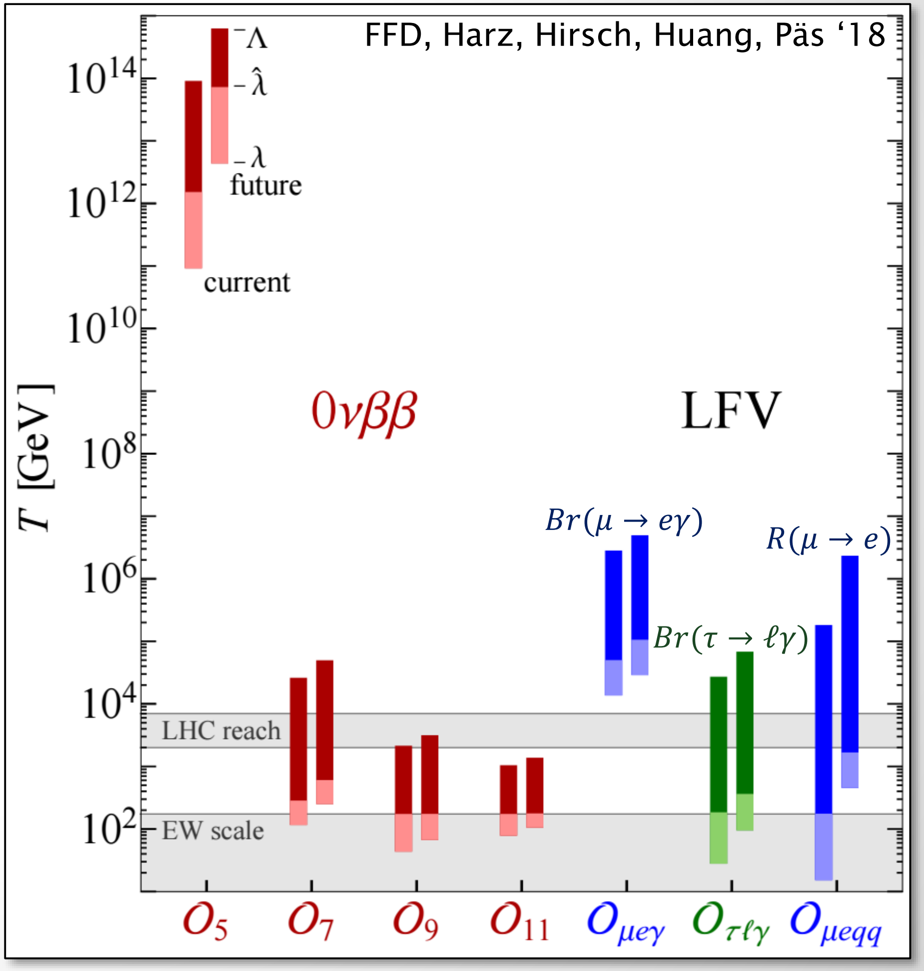
Davidson et al. '07

Baryon Asymmetry
Lepton Number Violation

- What if we observe lepton number violating processes e.g. in $0\nu\beta\beta$?
- Interactions "wash out" lepton (+ baryon with sphalerons) asymmetry
  - gives information at what temperatures operators are in equilibrium
  - corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - **can falsify high-scale baryogenesis scenarios**







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Conclusion

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- Neutrinos much lighter than other fermions
- Lepton Mixing and Possible CP Violation
- Deeper Origin of Neutrino Masses
- ν Physics = New Physics
- Strong Synergies
  - Lepton Flavour and Universality Violation
  - Collider Searches
  - Higgs Physics
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    - e.g. 2 upward-going 10^9 GeV air showers at ANITA

Cherry, Shoemaker '18