GeV neutrino mass models:
Experimental reach vs. theoretical predictions

RWR, Walter Winter – Arxiv 1607.07880 – PRD 94, 073004 (2016)

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Weak interactions and neutrinos (WIN2017)
21/06/2017

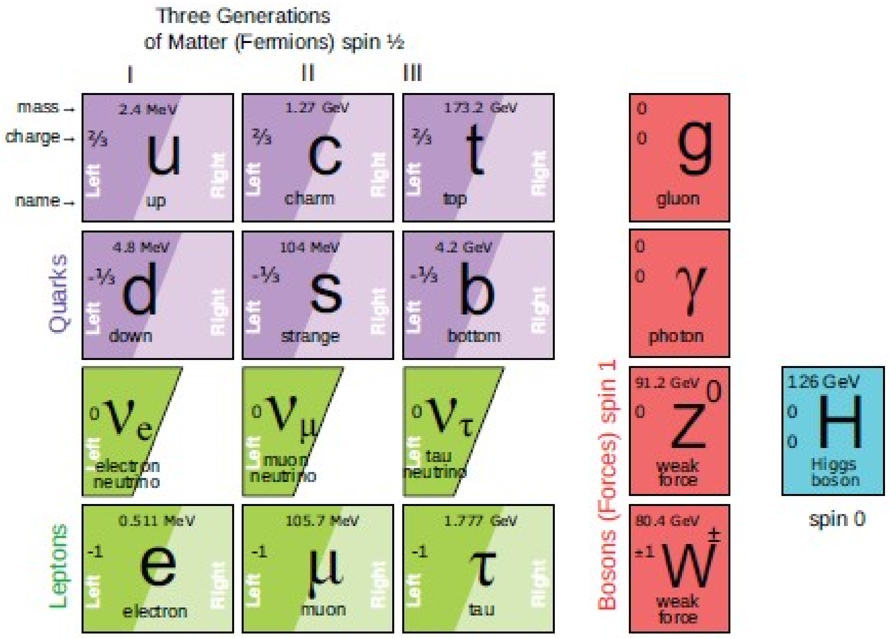
Theory of elementary particle physics

- The Standard Model (SM)

- Successful at describing all observed particle interactions at the LHC and preceding colliders

- Shortcomings: Neutrino masses, dark matter, baryon asymmetry and etc.

- Introducing sterile neutrinos



Beyond the Standard Model

- Possible extension: The Neutrino Minimal Standard Model (nuMSM)

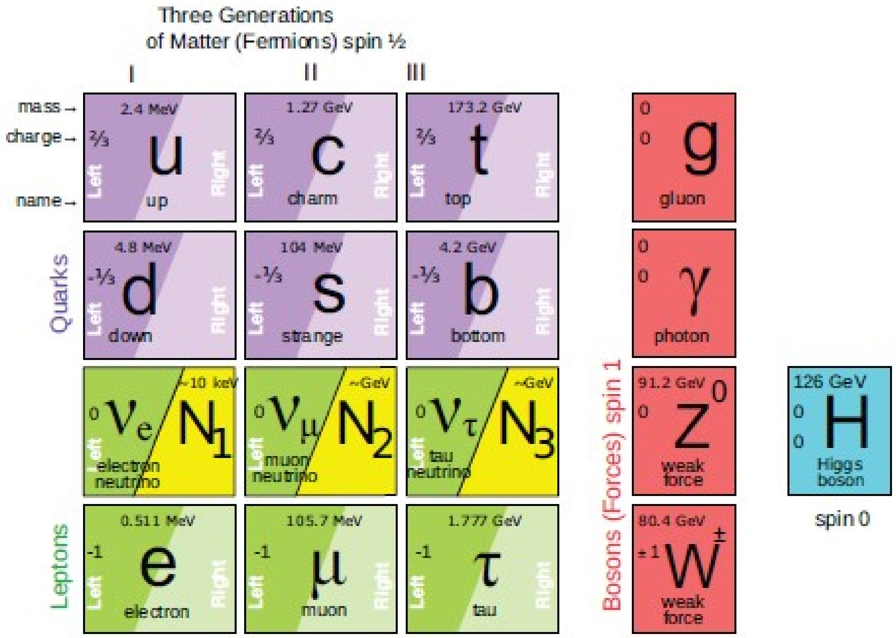
[Asaka, Shaposhnikov; Canetti, Drewes, Frossard,Shaposhnikov; Drewes, Garbrecht; Hernandez, Kekic, Lopez-Pavon, Racker, Salvado..]

- N_1 is dark matter candidate with keV mass and total mixing $|U_I|^2 < 10^{-8}$

  See Totzauer's and Hansen's talk

- N_2 and N_3 with 100 MeV-100 GeV mass: Origin of neutrino masses and baryon asymmetry

  See Das's talk



nuMSM requirements and beyond

- nuMSM: Mass degeneracy $\Delta M / M \leqslant 10^{-3}$ for successful baryon asymmetry
  [Canetti, Drewes, Frossard, Shaposhnikov]

- **We will consider 3 sterile neutrinos at the GeV scale**: No mass degeneracy needed.
  [Drewes, Garbrecht]

- Essentially, we only need three Yukawa/mass matrices

  $$M_l = vY_l, (M_D)_{\alpha I} = vY_{\alpha I} \text{ and } M_R$$

  which appear in the seesaw Lagrangian

  $$L_{\text{Seesaw}} = L_{\text{SM}} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - Y_{\alpha I} \overline{L}_\alpha N_I \Phi - \frac{1}{2} M_R \overline{N}_I^C N_I + h.c.$$

  to calculate the observables

Neutrino masses and mixing

- Seesaw mechanism $m_\nu = -M_D M_R^{-1} M_D^T$ and $M_N = M_R$ with assumption $M_D M_R^{-1} \ll 1$

  [Minkowski; Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra; Schechter, Valle]

- The PMNS mixing matrix $U_{PMNS} = U_l^H U_\nu$ where $U_l^H := (U_l^*)^T$

- The active-sterile mixing matrix $U_{\alpha I} = (U_l^H M_D M_R^{-1} U_N)_{\alpha I}$

- Decay rates depend on $\Gamma(N_I \to l_\alpha X) \propto |U_{\alpha I}|^2$ $X = \text{hadron}$

  [Gorbunov, Shaposhnikov]

- We will focus on the individual active-sterile mixing elements $|U_{\alpha I}|^2$ and total mixing $|U_I|^2 = \sum_\alpha |U_{\alpha I}|^2$ using both model-independent and mass model approaches

Model-independent approach

- We use the Casas-Ibarra parameterization $M_D = U_{PMNS}\sqrt{m_\nu}\,R\sqrt{M_R}$

[Casas, Ibarra]

- Known input $U_{PMNS}(\theta_{12},\theta_{23},\theta_{13},\delta,\alpha_1,\alpha_2), m_\nu(m_1,m_2,m_3)$
  with $m_1 \in [0, 0.23]\,\mathrm{eV}, m_2^2 = \Delta m_{21}^2 + m_1^2, m_3^2 = \Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2$

- Unknown input $M_R(M_1, M_2, M_3)$ with $M_1 < M_2 < M_3$,
  $R(\omega_{12}, \omega_{23}, \omega_{13})$ with $\mathrm{Re}(\omega_{ij}) \in [0, 2\pi]$ and $\mathrm{Im}(\omega_{ij}) \in [-8, 8]$

Model-independent approach continued

- Beside Casas-Ibarra parameterization, we investigated random matrices

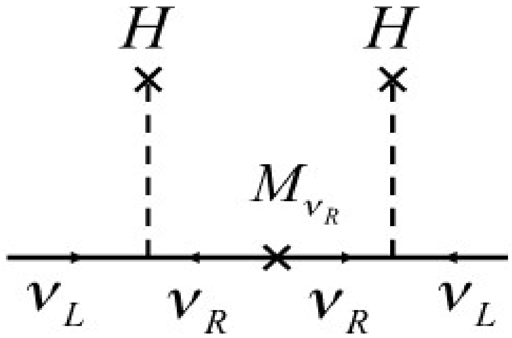
$$Y_l = \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \quad M_D = m_D \begin{pmatrix} c_1 & c_2 & c_3 \\ c_4 & c_5 & c_6 \\ c_7 & c_8 & c_9 \end{pmatrix} \quad M_R = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

- Again, $M_i \in [0.1, 80]\,\mathrm{GeV}$ with $M_1 < M_2 < M_3$
- $c_i : O(1)$ complex numbers
- Rescale m_D so $\sum m_\nu < 0.72\,\mathrm{eV}$ and obey mass square differences

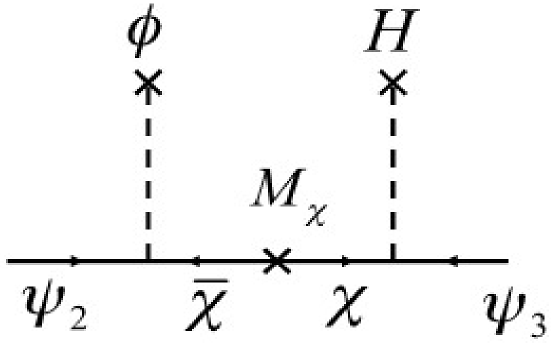
Mass models using symmetries

Froggatt-Nielsen Mechanism [Froggatt, Nielsen]

Froggat and Nielsen took their inspiration from the see-saw mechanism



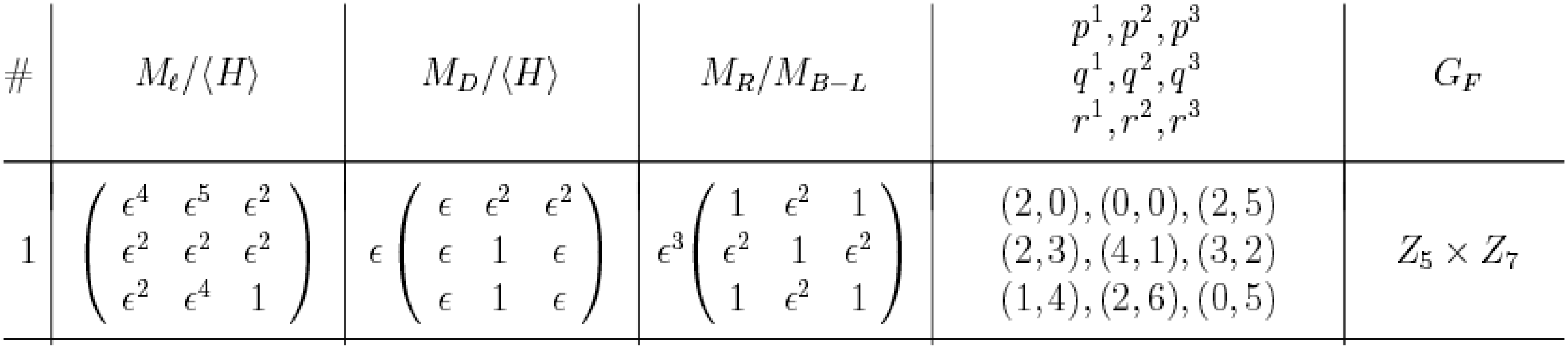
$$\rightarrow \frac{H^2}{M_{\nu_R}}\nu_L\nu_L$$



$$\rightarrow \frac{\phi}{M_\chi}H\psi_2\psi_3$$

Slide from Steve King

Mass models continued



$\#$	$M_\ell/\langle H\rangle$	$M_D/\langle H\rangle$	M_R/M_{B-L}	p^1,p^2,p^3 q^1,q^2,q^3 r^1,r^2,r^3	G_F
1	$\begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon^4 & 1 \end{pmatrix}$	$\epsilon\begin{pmatrix} \epsilon & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon & 1 & \epsilon \end{pmatrix}$	$\epsilon^3\begin{pmatrix} 1 & \epsilon^2 & 1 \\ \epsilon^2 & 1 & \epsilon^2 \\ 1 & \epsilon^2 & 1 \end{pmatrix}$	$(2,0),(0,0),(2,5)$ $(2,3),(4,1),(3,2)$ $(1,4),(2,6),(0,5)$	$Z_5\times Z_7$

[Plentinger, Seidl, Winter]

- We assume $\varepsilon\approx 0.2$ since $m_u:m_c:m_t\approx\varepsilon^8:\varepsilon^4:1$, $m_d:m_s:m_b\approx\varepsilon^5:\varepsilon^2:1$ and $m_e:m_\mu:m_\tau\approx\varepsilon^4:\varepsilon^2:1.$
- Additionally, this value also appears in the CKM mixing matrix and it can possibly explain the neutrino mass ratio due to $\Delta m_{21}^2/|\Delta m_{32}{}^2|=\varepsilon^2$
- Again, $M_i\in[0.1,80]\,\mathrm{GeV}$ with $M_1<M_2<M_3$, $\sum m_\nu<0.72\,\mathrm{eV}$ and $O(1)$ complex numbers

Experimental constraints & future experiments

- All realizations have to obey experimental constraints: Neutrino oscillation data, LFV, neutrinoless double beta decay, direct searches, loop corrections and Big Bang nucleosynthesis

- Future experiments: DUNE, SHiP and FCC

[Adams et. al., Blondel, Graverini, Serra, Shaposhnikov, Alekhin et. al.; Anelli et al.]

See Bian's, Mehta's and Kayser's talk on DUNE

See talk by SHIP Collaboration about SHIP experiment

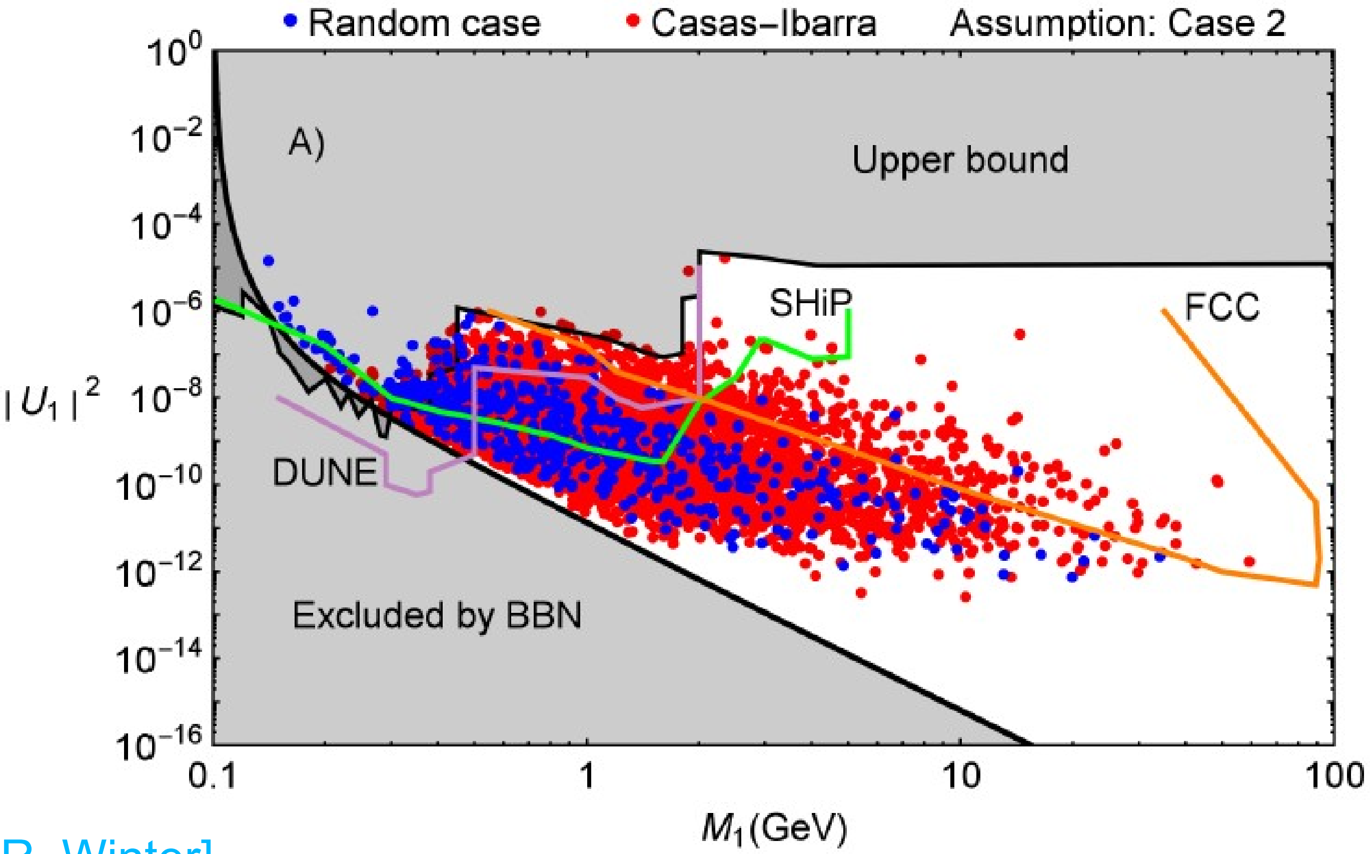
- Sensitivity calculated under the assumption $|U_{eI}|^2 : |U_{\mu I}|^2 : |U_{\tau I}|^2 = 1 : 16 : 3.8$

- Focus on total mixing $|U_I|^2$ and individual mixing elements $|U_{eI}|^2$ and $|U_{\mu I}|^2$ for the lightest sterile neutrino only, i.e. $I = 1$

Model-independent approach – Total mixing

- Casas-Ibarra parameterization can generate the whole parameter space [Drewes, Garbrecht]

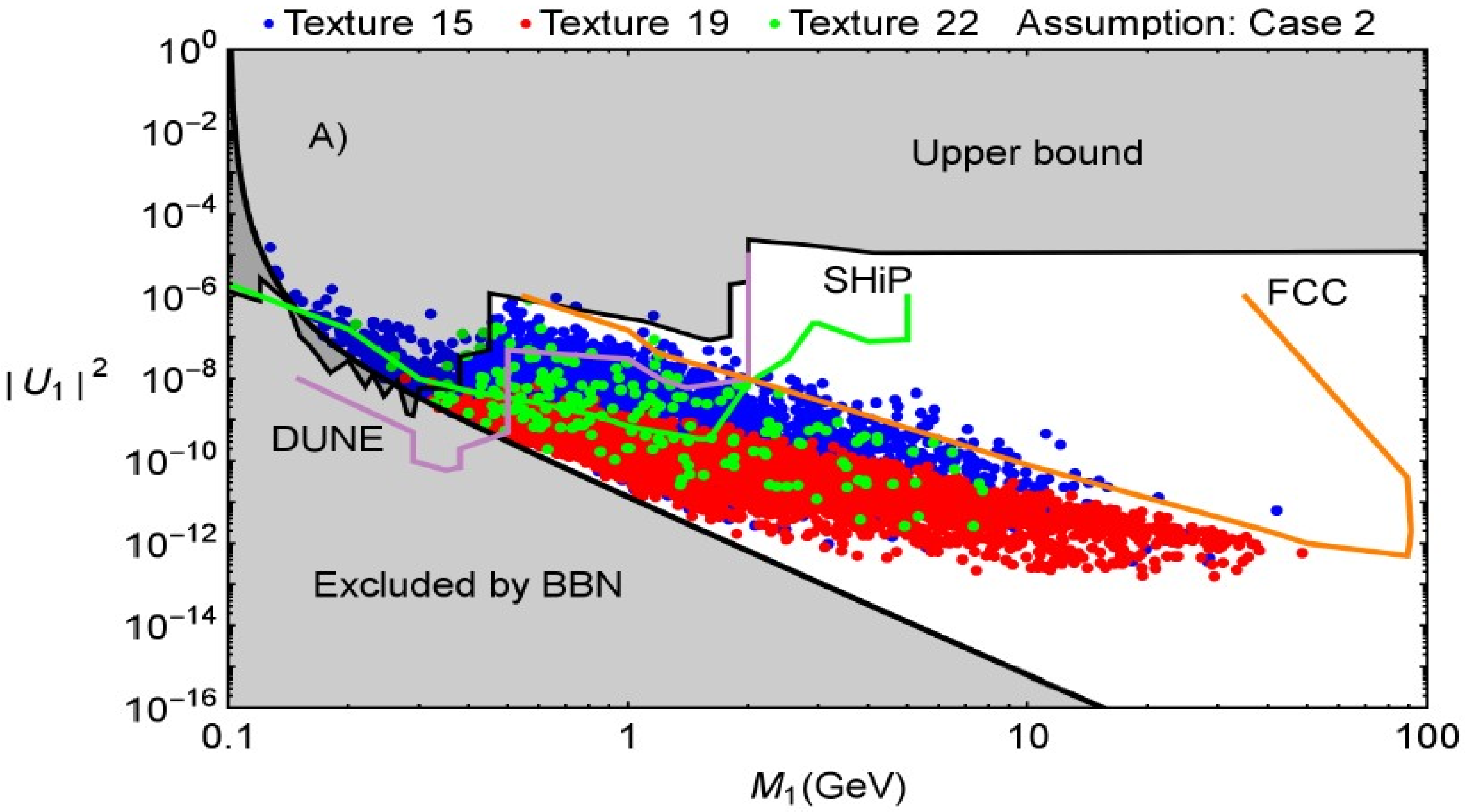
- But still interesting to investigate the scatter plot of the mixing elements



[RWR, Winter]

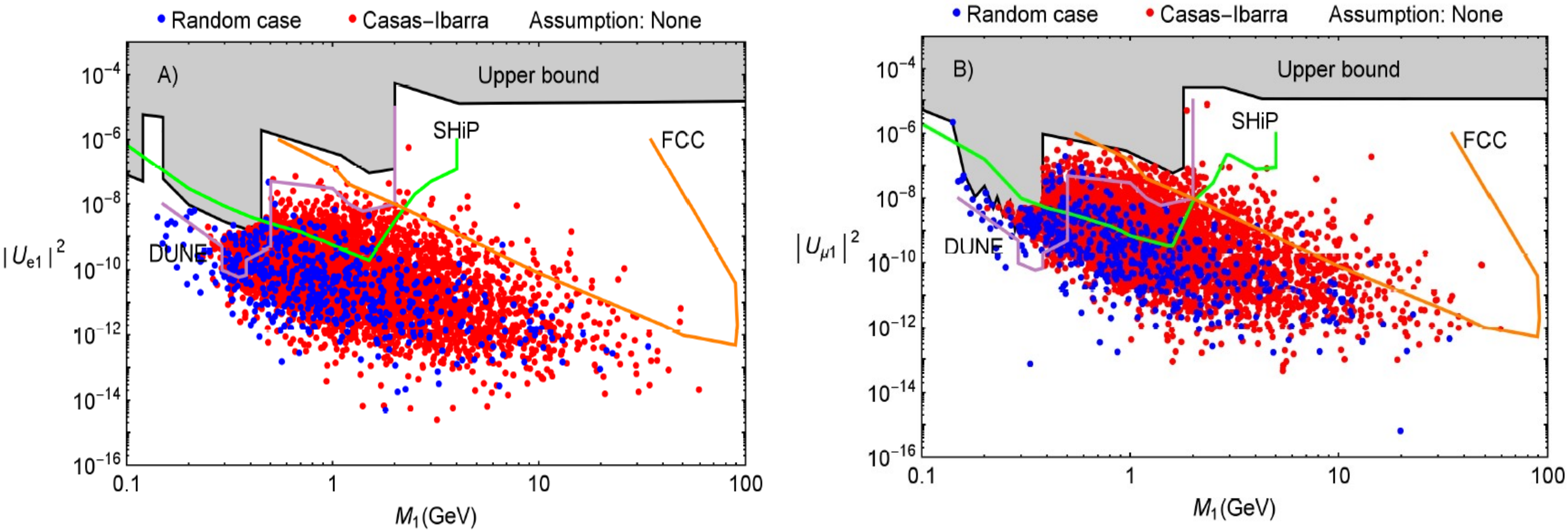
Mass models – Total mixing

Total mixing is partially within reach [RWR, Winter]



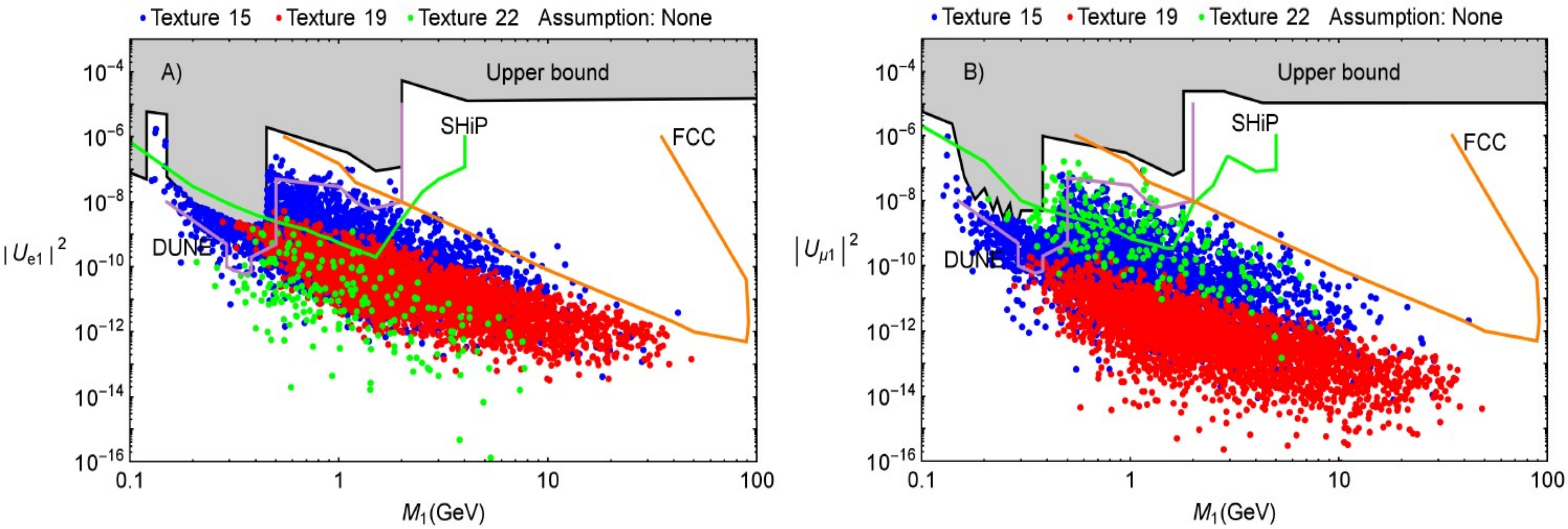
Model-independent approach – Individual mixing

- No preference for particular mixing [RWR, Winter]



Mass models - Individual mixing

- Structure in mass matrices leads to refined mixing [RWR, Winter]



- Therefore, channels such as $N \rightarrow e\pi / eK$ and $N \rightarrow \mu\pi / \mu K$ can resolve this mixing pattern

Summary

- Sterile neutrinos are theoretically motivated and can solve many of the problems in the SM
- Model-independent approach generates the whole parameter space
- Predictions from mass models are more refined in comparison to model-independent approaches
- Potential to exclude parameter space of models by measuring the total mixing
- Important to measure the individual mixing elements to distinguish among models

Back-up

Number of sterile neutrinos and consequences

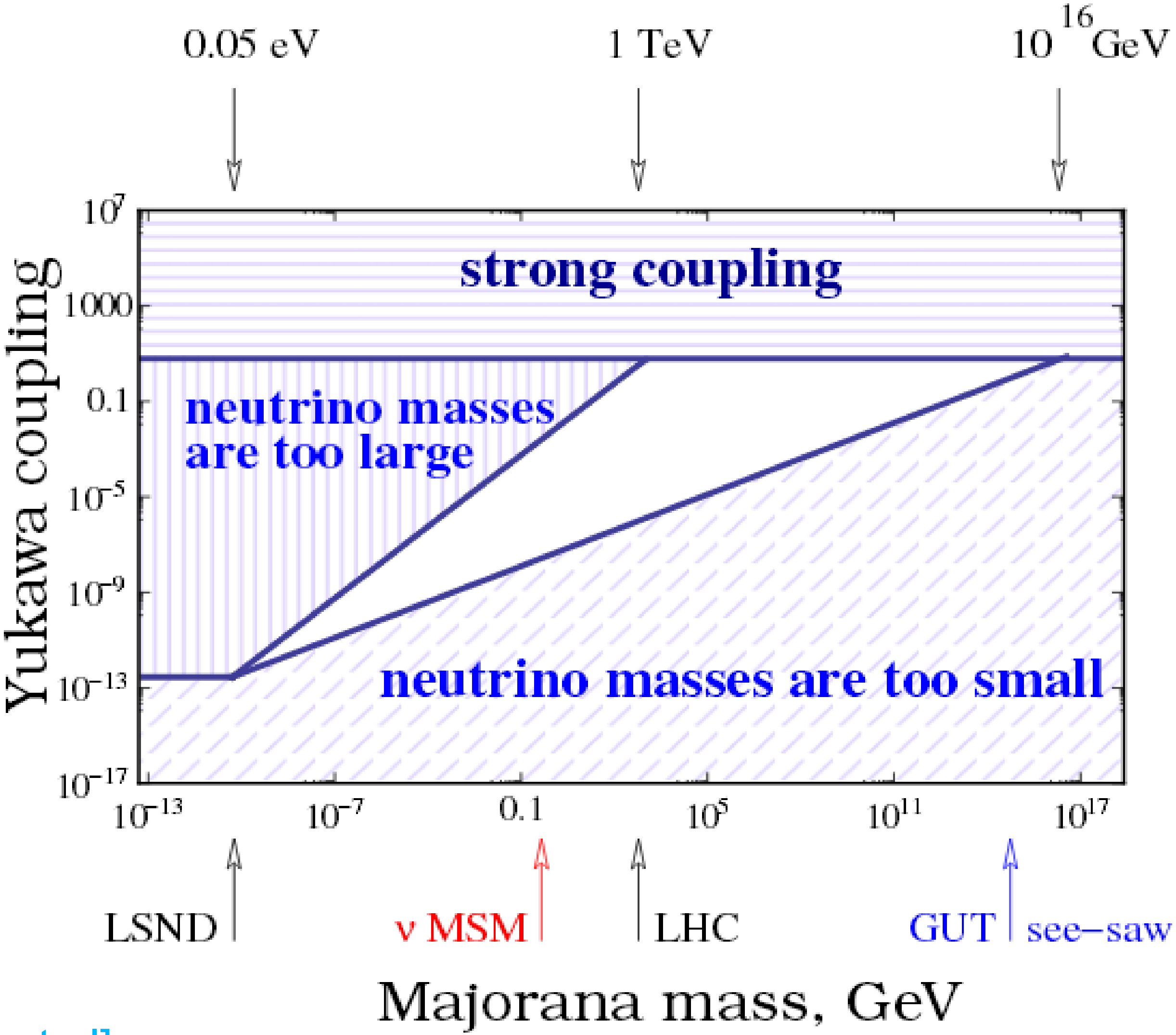
- The Lagrangian becomes

$$L_{\mathrm{Seesaw}} = L_{\mathrm{SM}} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - Y_{\alpha I} \overline{L}_\alpha N_I \Phi - \frac{1}{2} M_R \overline{N}_I^C N_I + h.c.$$

for Majorana neutrinos (Dirac vs Majorana particles)

- Number of sterile neutrinos I and mass scale M_R cannot be fixed by symmetries
- $I=1$: Only one of the active neutrinos gets a mass
- $I=2$: Minimal requirement to explain neutrino masses and baryon asymmetry
- $I=3$: All active neutrinos get masses and all oscillation experiments (including LSND) can be explained together with the baryon asymmetry. If LSND is dropped, dark matter can also be explained
- $I>3$: Different combinations of the above together with extra relativistic degrees of freedom in cosmology, neutrino anomalies etc.

New mass scale and Yukawas



[Abazajian et al]

Experimental constraints

- Neutrino oscillations

$$31.29^o < \theta_{12} < 35.91^o \quad 7.85^o < \theta_{13} < 9.10^o \quad 38.20^o < \theta_{23} < 53.30^o$$

$$7.02 * 10^{-5} < \Delta m_{21}^2 [\mathrm{eV}^2] < 8.09 * 10^{-5} \quad 2.32 * 10^{-3} < \Delta m_{32}^2 [\mathrm{eV}^2] < 2.62 * 10^{-3}$$

[Gonzalez-Garcia, Maltoni, Schwetz]

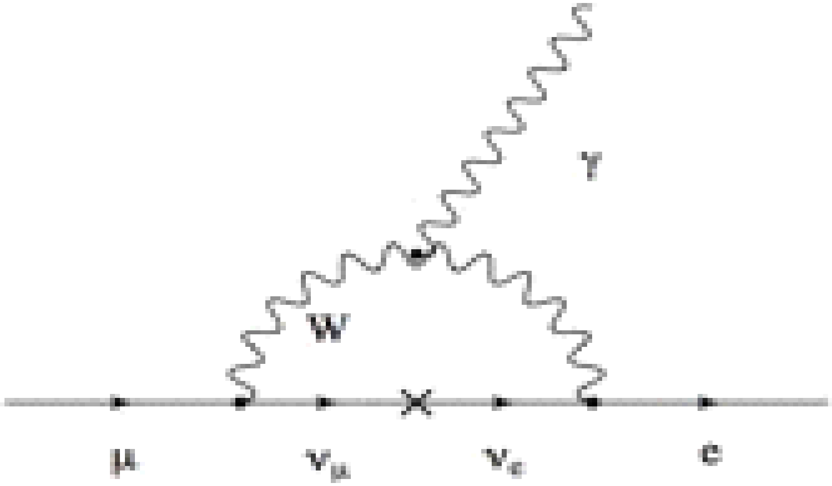
- Lepton flavor violation

$$\mathrm{Br}(\mu \to \gamma e) < 5.7 * 10^{-13}$$

$$\mathrm{Br}(\tau \to \gamma \mu) < 1.5 * 10^{-8}$$

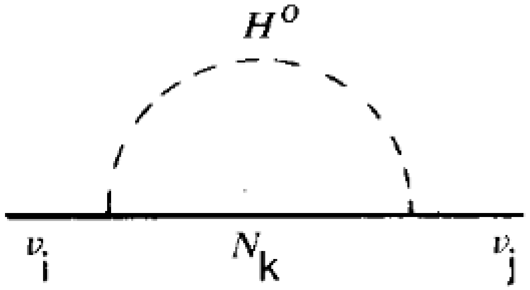
$$\mathrm{Br}(\tau \to \gamma e) < 1.8 * 10^{-8}$$

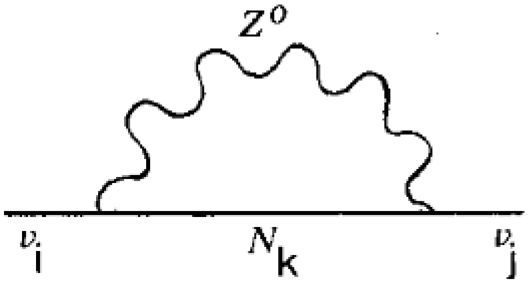
[MEG Collaboration]



Experimental constraints

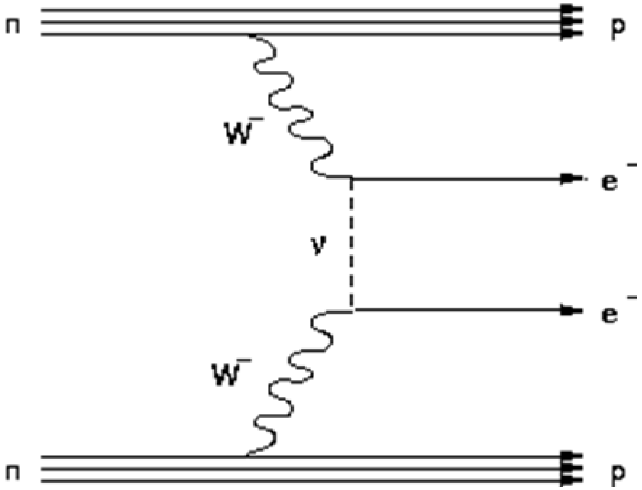
- Loop corrections due to virtual heavy neutrinos [Pilaftsis]





- Neutrinoless double beta decay $m_{\beta\beta} < 0.2\,\mathrm{eV}$

  [GERDA Collaboration]



- Direct searches

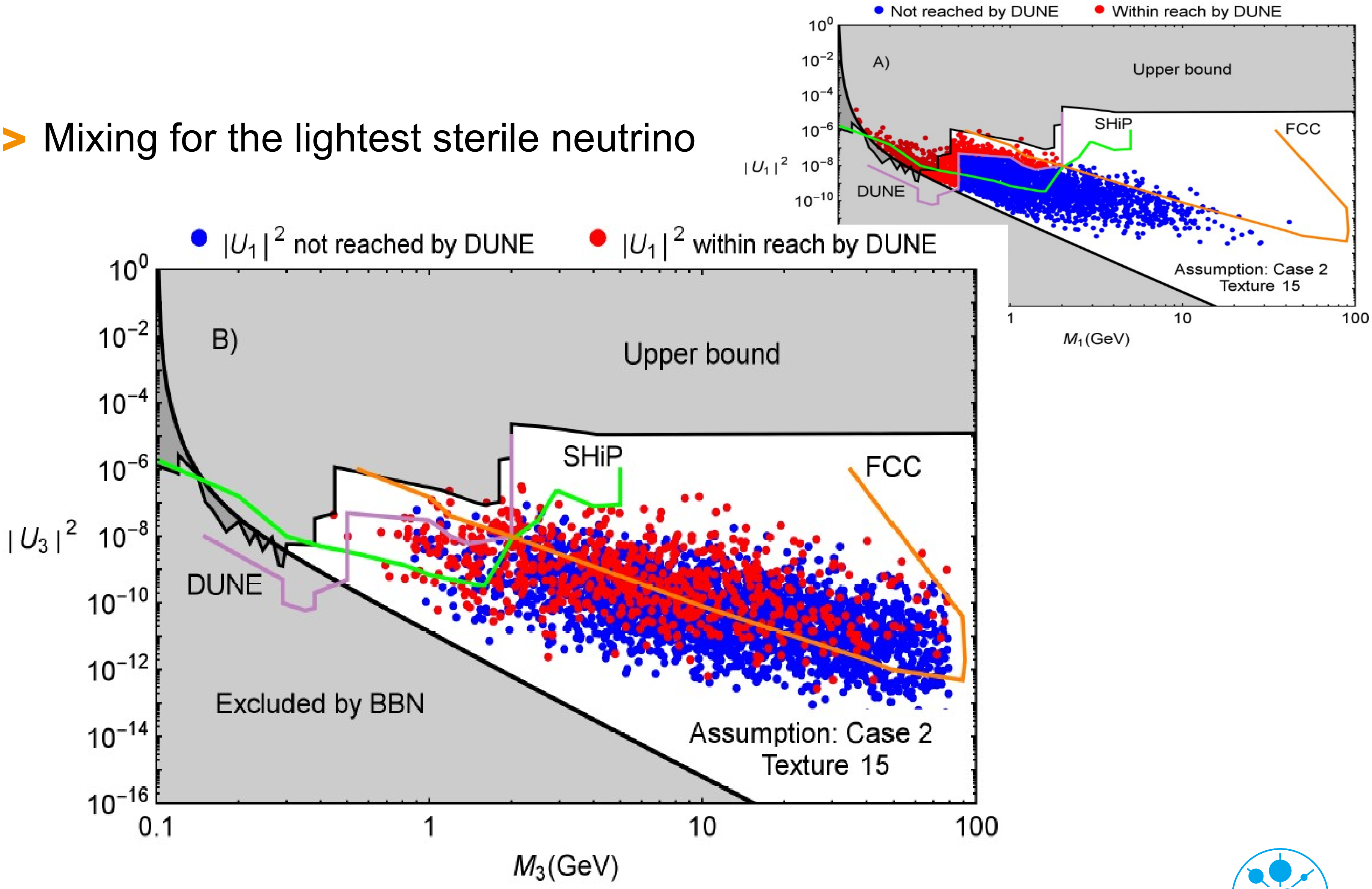
  [CHARM, DELPHI, NuTeV, NOMAD, PS191, etc..]

- Big Bang nucleosynthesis $\tau_N < 0.1\,\mathrm{s}$

  [Dolgov, Hansen, Raffelt, Semikoz, Ruchayskiy, Ivashko]

Complementary among experiments

- Mixing for the lightest sterile neutrino



Total mixing for heaviest sterile neutrino

- FCC constrains the parameter space for heavier sterile neutrinos