GeV neutrino mass models: Experimental reach vs. theoretical predictions

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Rasmus W. Rasmussen
Matter and the Universe
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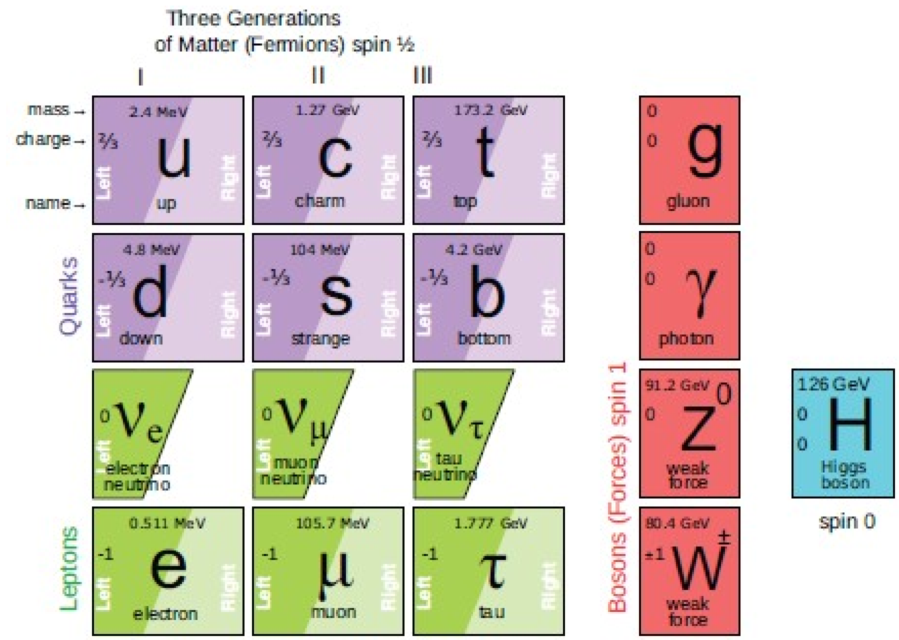
DESY

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



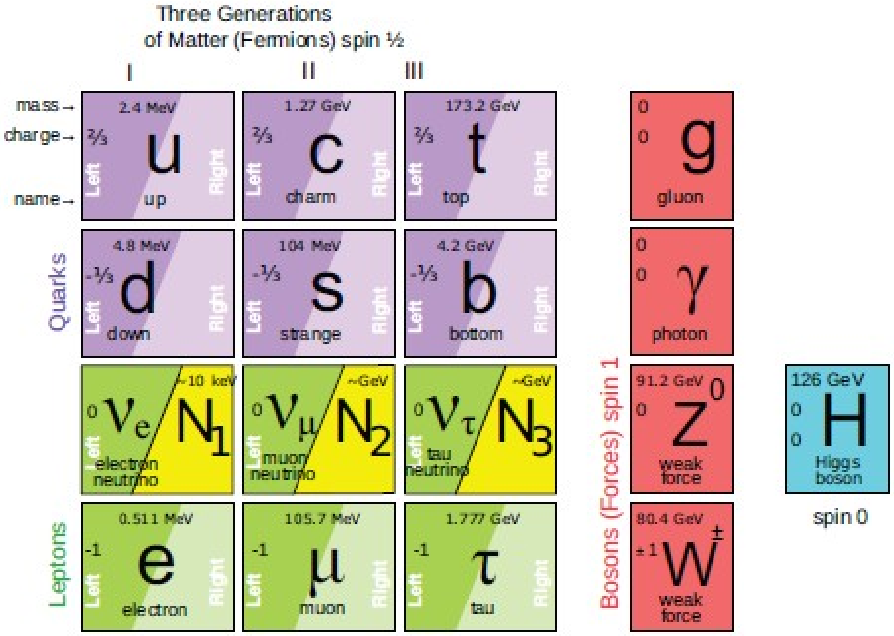
Beyond the SM

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

[Asaka, Shaposhnikov (2005); Canetti, Drewes, Frossard,Shaposhnikov (2012); Drewes, Garbrecht (2015); Hernandez, Kekic, Lopez-Pavon, Racker, Salvado (2016)..]

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

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



nuMSM requirements and beyond

- nuMSM: Mass degeneracy $\Delta M / M \leqslant 10^{-3}$ for successful baryon asymmetry [Canetti, Drewes, Frossard, Shaposhnikov (2012)]

- **We will consider 3 sterile neutrinos at the GeV scale**: No mass degeneracy needed. [Drewes, Garbrecht (2012)]

- 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 (1977); Gell-Mann, Ramond, Slansky (1979); Yanagida (1980); Mohapatra (1980); Schechter, Valle (1980)]
- 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 (2007)]
- We will focus on the individual mixing element $|U_{\alpha I}|^2$ and total mixing $|U_I|^2 = \sum_\alpha |U_{\alpha I}|^2$ for sterile neutrino

Generic assumptions

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

  [Casas, Ibarra (2001)]

- Here $m_\nu = \mathrm{diag}(m_1, m_2, m_3)$ and $M_R = \mathrm{diag}(M_1, M_2, M_3)$ with $m_1 \in [0, 0.23]\,\mathrm{eV}$ and $M_i \in [0.1, 80]\,\mathrm{GeV}$ with $M_1 < M_2 < M_3$

- The complex matrix R have to satisfy $R^T R = 1$. This means it can be parameterized by rotation matrices with a complex angle

$$R = \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} & c_{12} c_{23} - s_{12} s_{23} s_{13} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} & -c_{12} s_{23} - s_{12} c_{23} s_{13} & c_{23} c_{13} \end{bmatrix}$$

- where $c_{ij} = \cos(\omega_{ij})$ and $s_{ij} = \sin(\omega_{ij})$ with $\mathrm{Re}(\omega_{ij}) \in [0, 2\pi]$ and $\mathrm{Im}(\omega_{ij}) \in [-8, 8]$

Generic assumptions 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 $M_1 < M_2 < M_3$
- $O(1)$ comeplex numbers: $|c_i| = k_i \in [0.2, 5]$ and $\arg(c_i) = \phi_i \in [0, 2\pi]$
- Rescale m_D so $\sum m_\nu < 0.72\,\mathrm{eV}$ and obey mass square differences

Flavor models

> Flavor symmetric mass models in the Froggatt-Nielsen (FN) framework

[Froggatt, Nielsen (1979)]

#	$M_\ell/\langle H\rangle$	$M_D/\langle H\rangle$	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	$\begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon^4 & 1 \end{pmatrix}$	$\epsilon\begin{pmatrix} \epsilon & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon & 1 & \epsilon \end{pmatrix}$	$\epsilon^3\begin{pmatrix} 1 & \epsilon^2 & 1 \\ \epsilon^2 & 1 & \epsilon^2 \\ 1 & \epsilon^2 & 1 \end{pmatrix}$	$(2,0),(0,0),(2,5)$ $(2,3),(4,1),(3,2)$ $(1,4),(2,6),(0,5)$	$Z_5 \times Z_7$
2	$\epsilon\begin{pmatrix} \epsilon^4 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \\ \epsilon^3 & \epsilon^4 & 1 \end{pmatrix}$	$\epsilon\begin{pmatrix} \epsilon & \epsilon^3 & \epsilon \\ \epsilon & 1 & \epsilon^3 \\ \epsilon & \epsilon^2 & \epsilon \end{pmatrix}$	$\epsilon^2\begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon^2 \\ \epsilon & \epsilon^2 & 1 \end{pmatrix}$	$(2,2),(3,2),(2,5)$ $(0,1),(2,2),(4,2)$ $(2,6),(3,4),(1,0)$	$Z_5 \times Z_7$
3	$\epsilon\begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^5 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon^2 & 1 \end{pmatrix}$	$\epsilon^2\begin{pmatrix} \epsilon & \epsilon & \epsilon^3 \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$	$\epsilon\begin{pmatrix} \epsilon & \epsilon & \epsilon^5 \\ \epsilon & 1 & \epsilon^4 \\ \epsilon^5 & \epsilon^4 & 1 \end{pmatrix}$	$(3,7),(3,0),(2,7)$ $(1,5),(3,6),(3,2)$ $(1,4),(2,4),(2,0)$	$Z_5 \times Z_8$

[Plentinger, Seidl, Winter (2007)]

Flavor models continued

- We assume $\varepsilon \approx 0.2$ since

  $$m_u : m_c : m_t \approx \varepsilon^8 : \varepsilon^4 : 1 \ , \ m_d : m_s : m_b \approx \varepsilon^5 : \varepsilon^2 : 1 \text{ and } m_e : m_\mu : m_\tau \approx \varepsilon^4 : \varepsilon^2 : 1.$$

- Additionally, this value also appears in the CKM mixing matrix and it can possibly explain the neutrino mass ratio due to $\Delta m_{21}^2 / |\Delta m_{32}{}^2| = \varepsilon^2$

  $$m_1 : m_2 : m_3 \approx \varepsilon^2 : \varepsilon : 1 \ , \ m_1 : m_2 : m_3 \approx 1 : 1 : \varepsilon \quad \text{and} \quad m_1 : m_2 : m_3 \approx 1 : 1 : 1.$$

  (Normal hierarchy) (Inverted hierarchy) (Quasi-degenerate)

- 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 $|c_i| = k_i \in [0.2, 5]$ and $\arg(c_i) = \phi_i \in [0, 2\pi]$

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

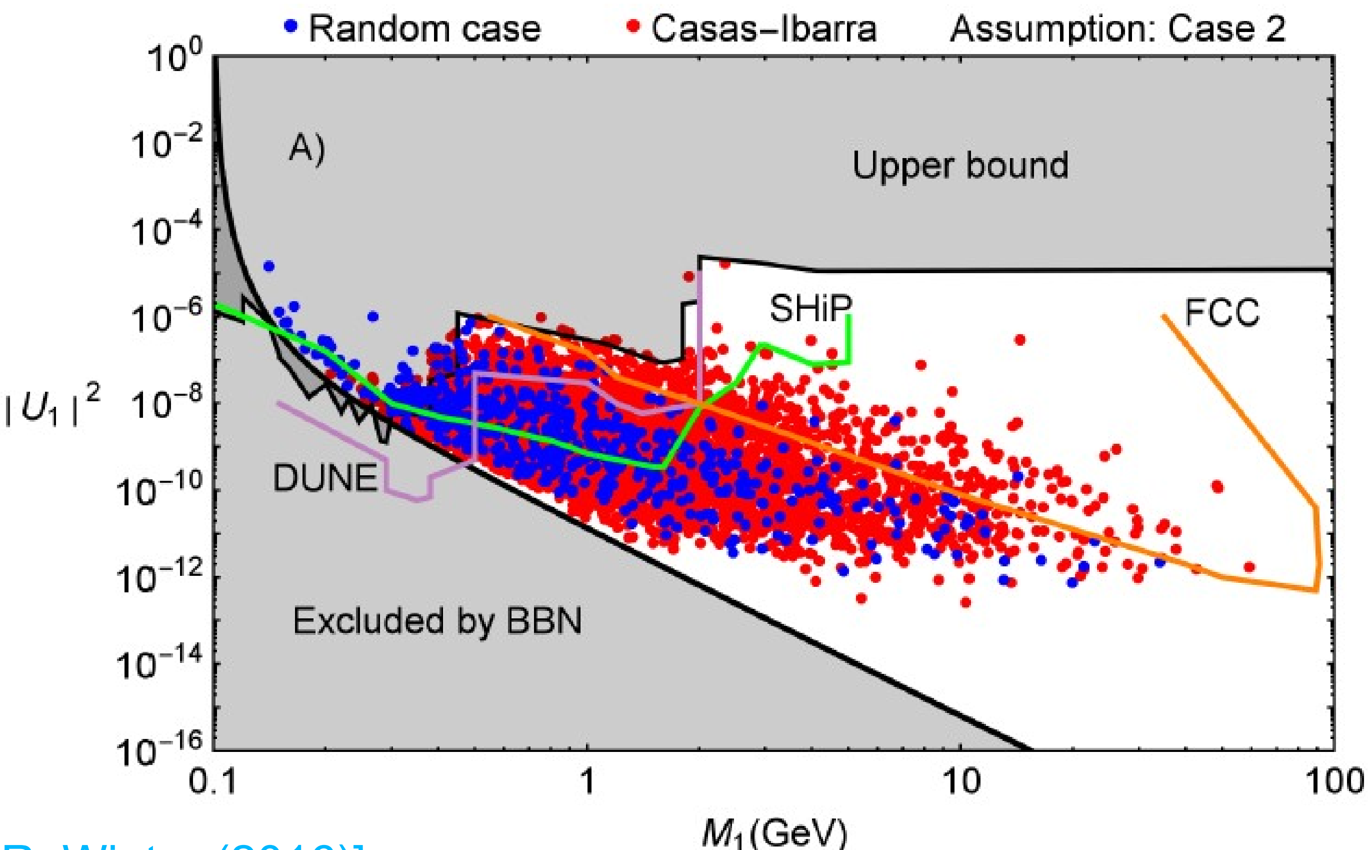
  [Adams et. al. (2013), Blondel, Graverini, Serra, Shaposhnikov (2014), Alekhin et. al. (2015); Anelli et al. (2015)]

- 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 $|U_{\mu I}|^2$

Generic assumption – Total active-sterile mixing for N1

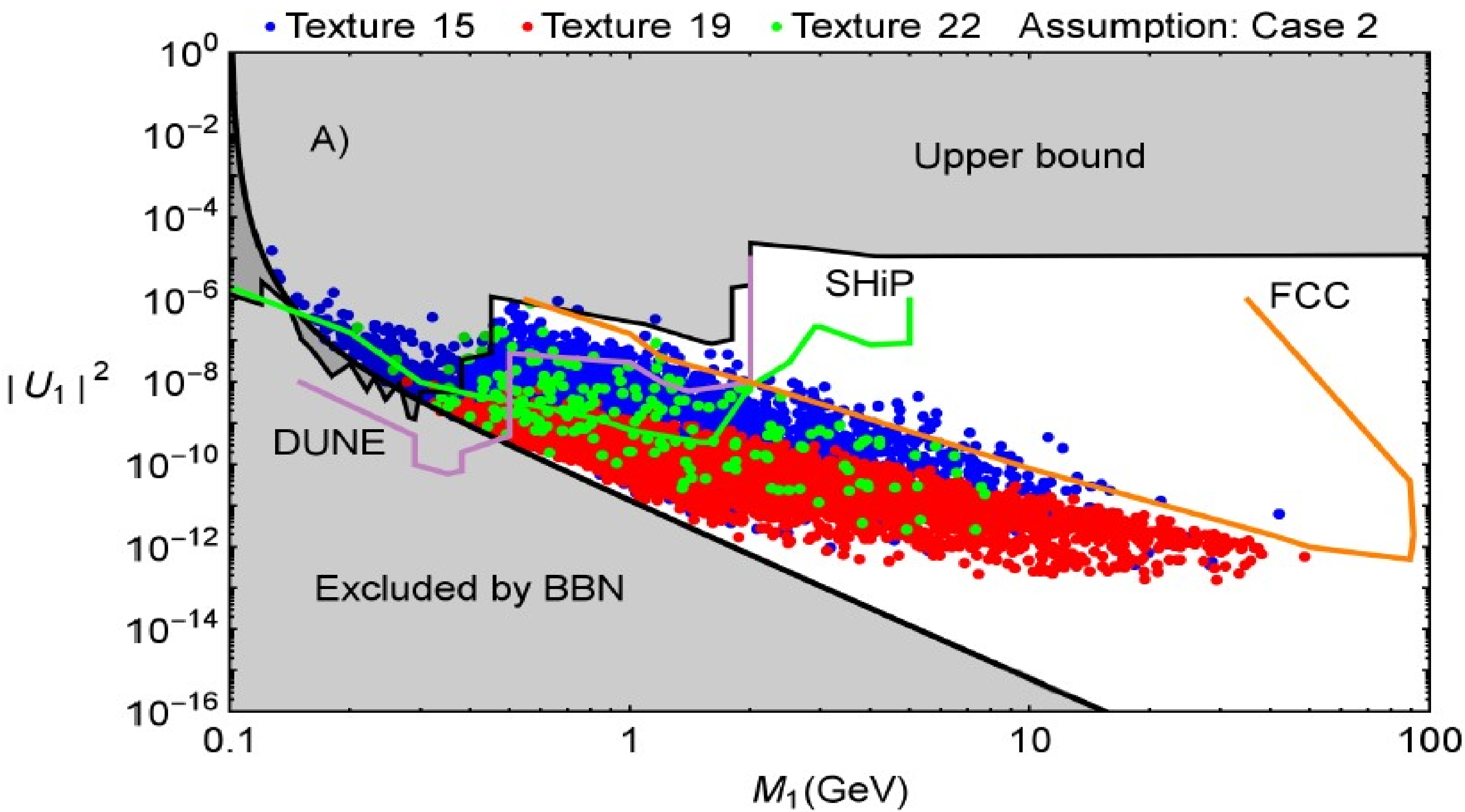
- Casas-Ibarra parameterization can generate the whole parameter space [Drewes, Garbrecht (2015)]
- But still interesting to investigate the scatter plot of the mixing elements



[RWR, Winter (2016)]

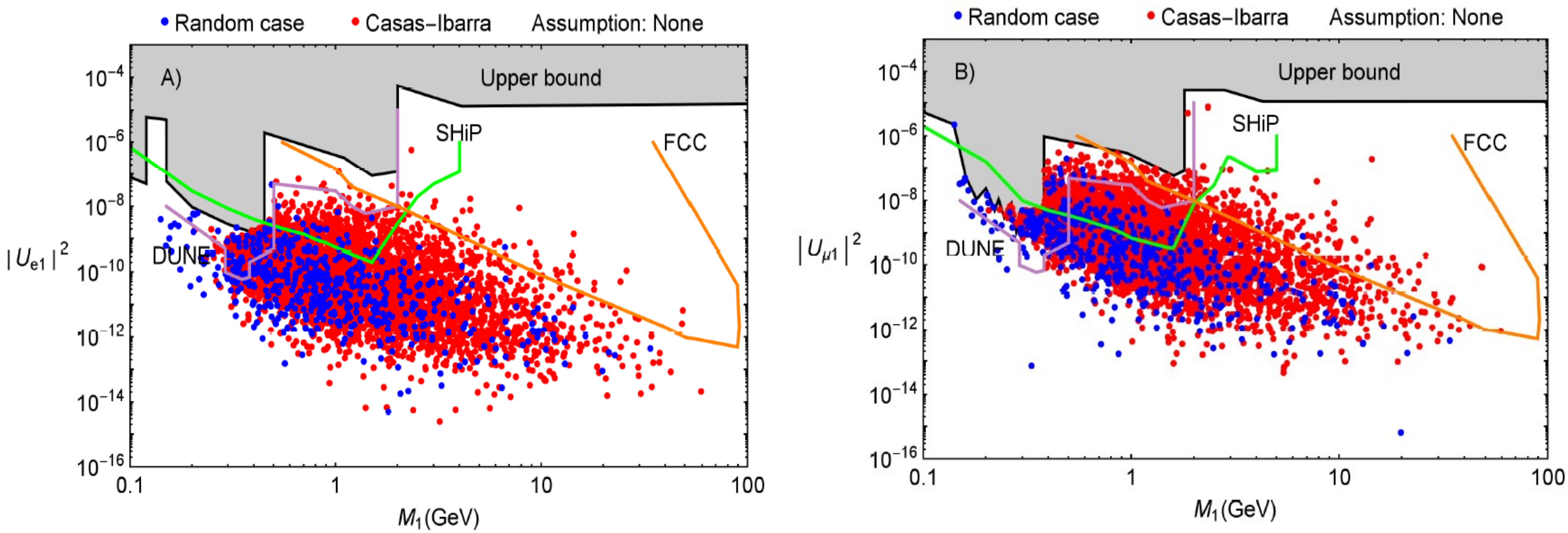
Flavor models – Total active-sterile mixing for N1

Total mixing is partially within reach [RWR, Winter (2016)]



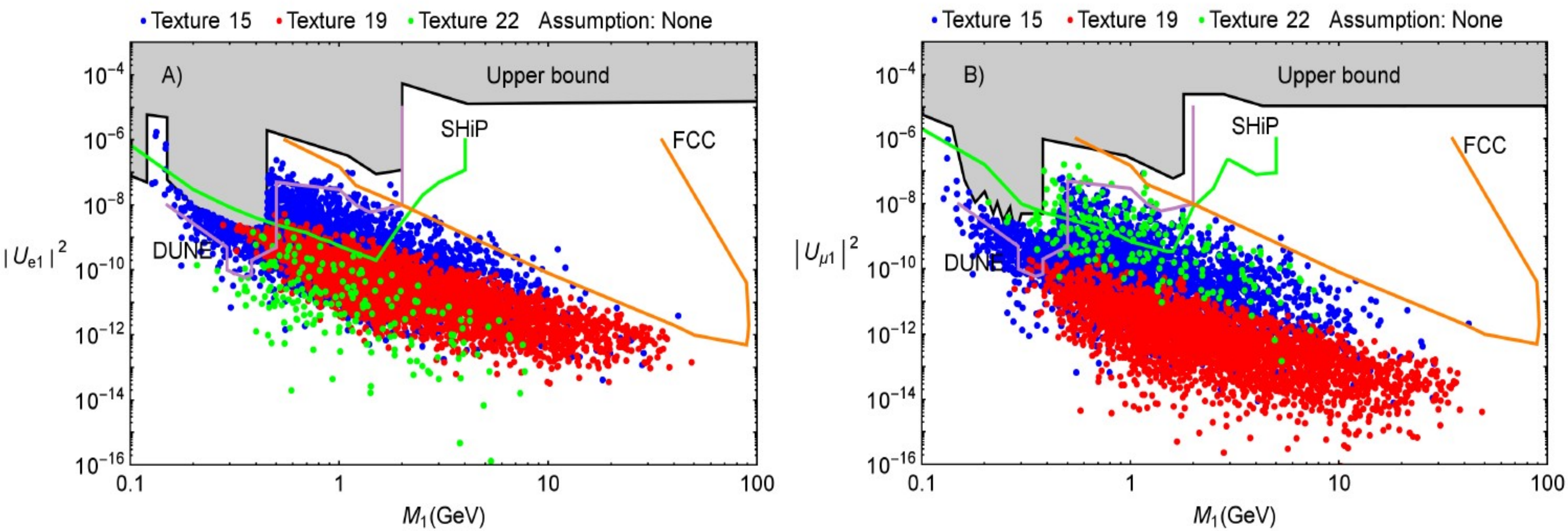
Generic assumptions - Individual mixing elements for N1

- No preference for particular mixing [RWR, Winter (2016)]



Flavor models - Individual mixing elements for N1

- Structure in mass matrices leads to refined mixing [RWR, Winter (2016)]



- 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
- Generic assumptions generates the whole parameter space
- Predictions from flavor models are more refined in comparison to generic assumptions
- Potential to exclude parameter space of models by measuring the total mixing
- Important to measure the individual mixing elements

Back-up

Number of sterile neutrinos and consequences

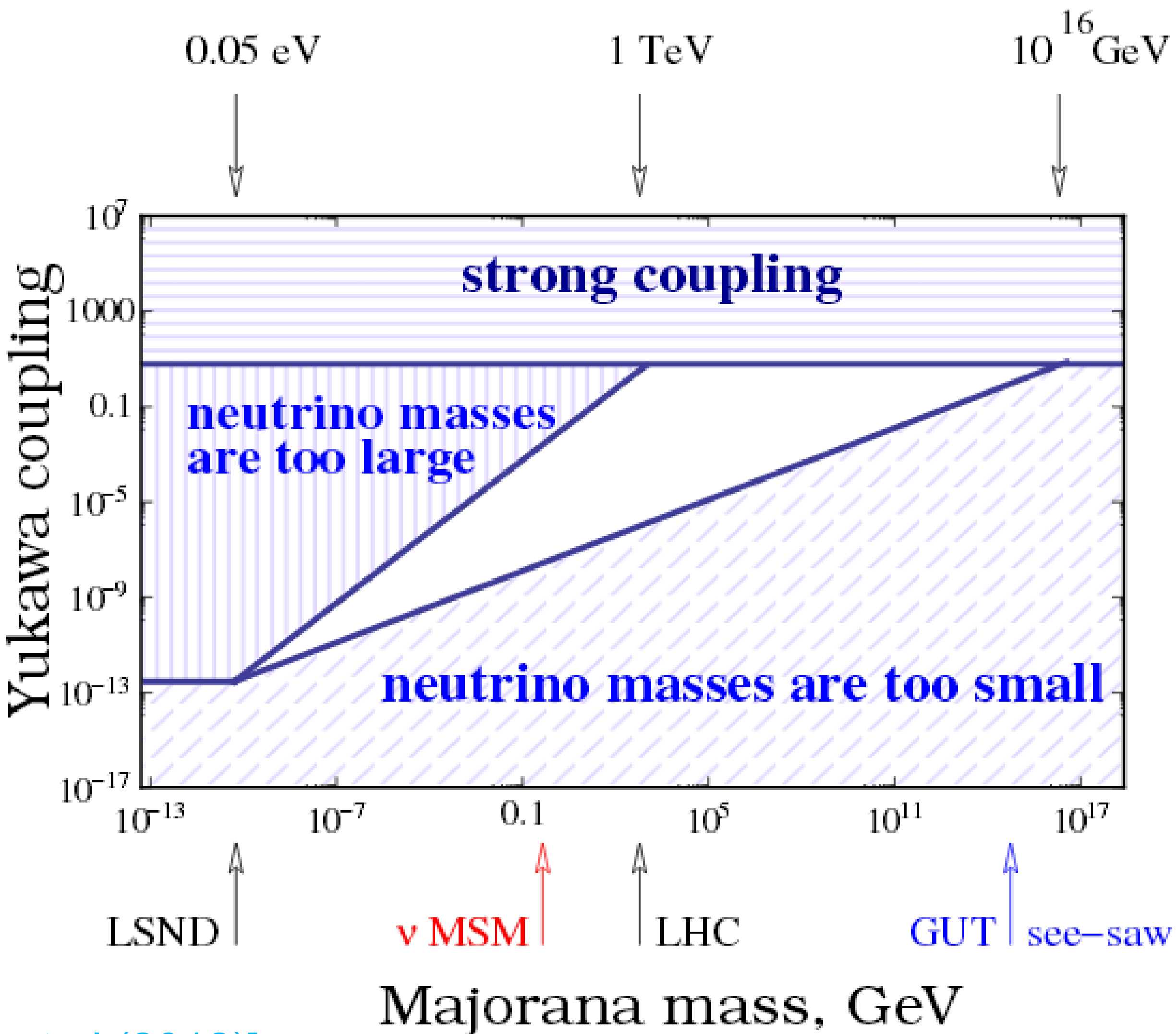
- The Lagrangian becomes

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

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.

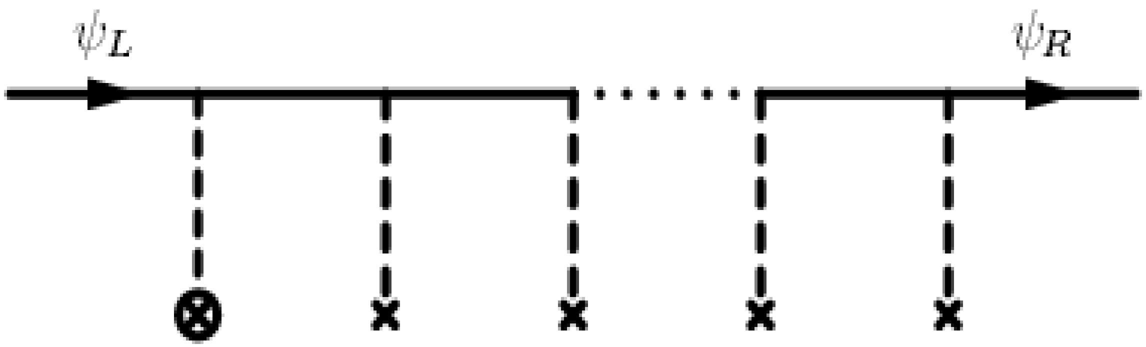
New mass scale and Yukawas



[Abazajian et al (2012)]

Froggatt-Nielsen mechanism

- Pictorial diagram of generating fermion mass terms with flavons acquiring universal VEVs v_f and heavy fermions with universal mass M_F



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 (2016)]

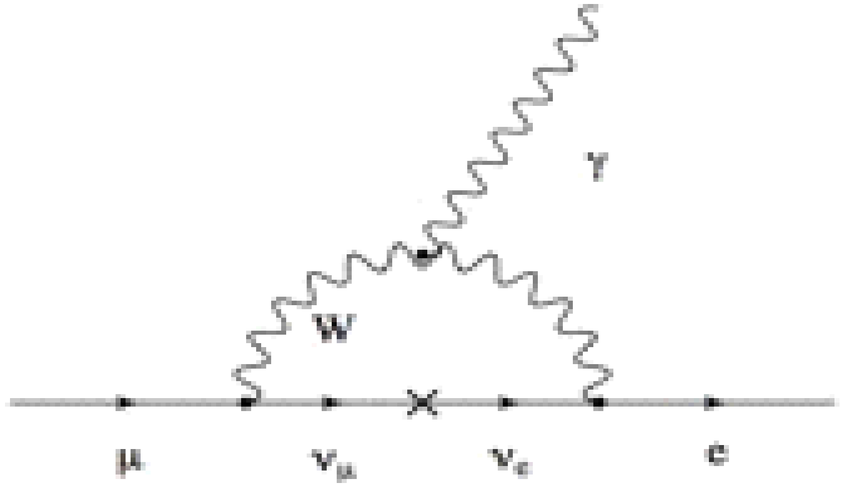
- Lepton flavor violation

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

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

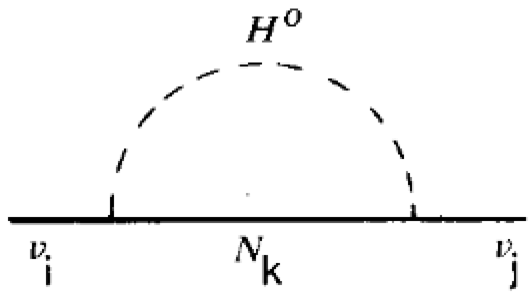
$$\mathrm{Br}(\tau \to \gamma\, e) < 1.8 * 10^{-8}$$

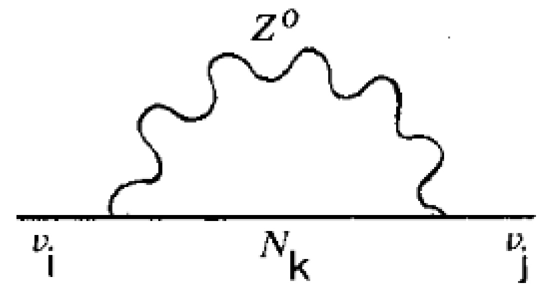
[MEG Collaboration (2013)]



Experimental constraints

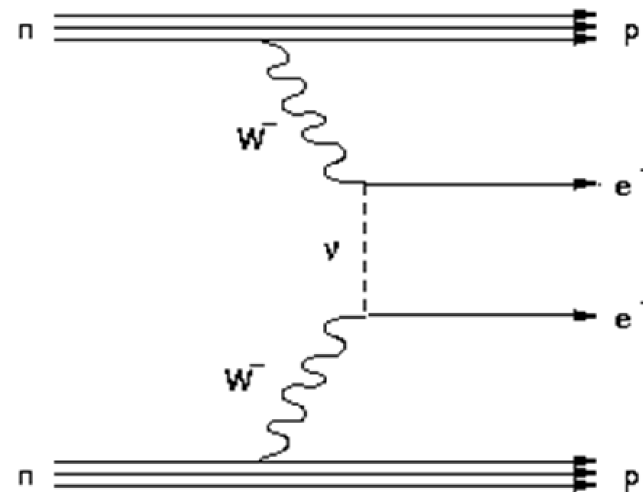
- Loop corrections due to virtual heavy neutrinos [Pilaftsis (1992)]





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

  [GERDA Collaboration (2013)]



- Direct searches

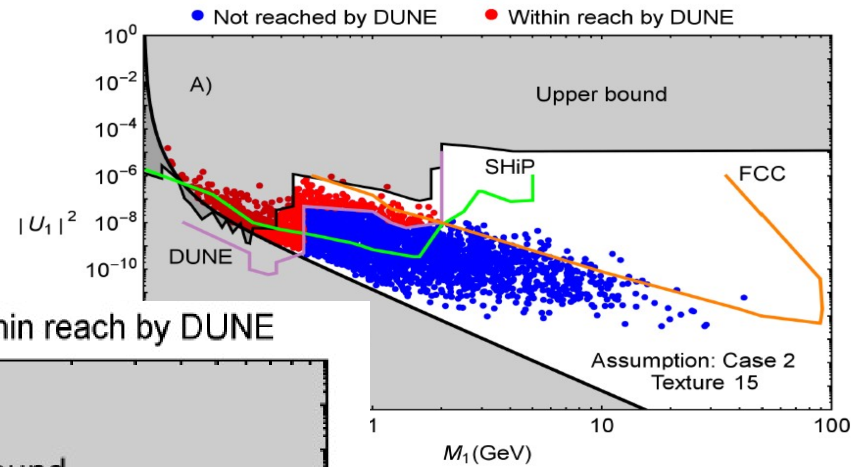
  [CHARM (1995), DELPHI (1997), NuTeV (1999), NOMAD (2001), PS191 (2012) etc..]

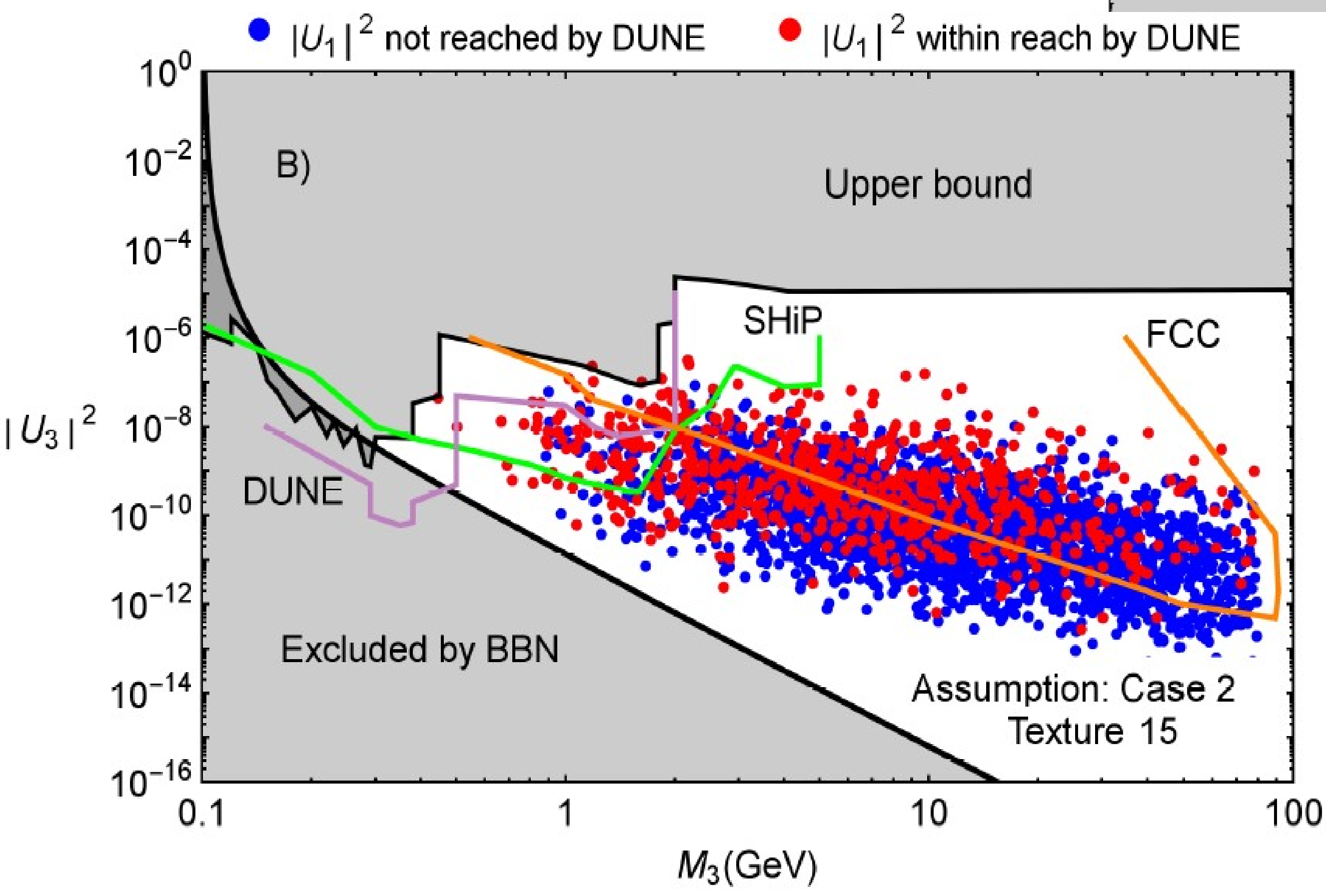
- Big Bang nucleosynthesis $\tau_N < 0.1\,\mathrm{s}$

  [Dolgov, Hansen, Raffelt, Semikoz (2000), Ruchayskiy, Ivashko (2012)]

Complementary among experiments

> Mixing for the lightest sterile neutrino





Total mixing for N3

> FCC constrains the parameter space for heavier sterile neutrinos