Dark Matter and Loop-Generated Neutrino Masses

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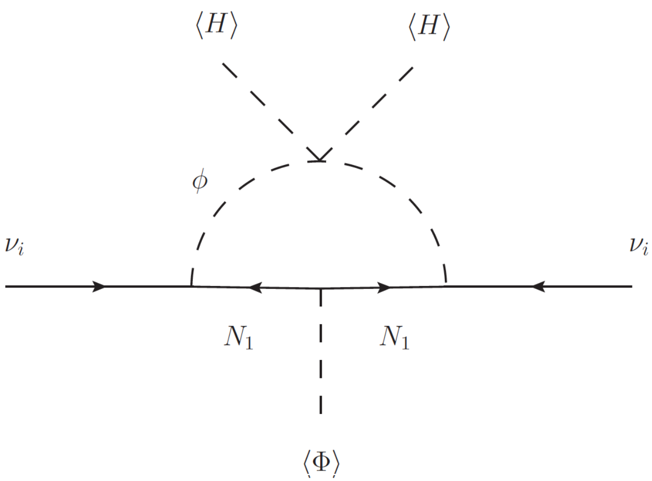
Motivations

- Dark Matter (DM) and massive neutrinos can not be explained in the Standard Model (SM)
- We augment the SM gauge groups by an additional $U(1)_X$ symmetry with a Z' gauge boson and heavy neutrinos
- Both SM particles and heavy neutrinos are charged under $U(1)_X$
- The DM (N_1) stability are protected by $U(1)_X$ (Integer) charge assignment
- Light Neutrinos receive a mass from both Type-I seesaw and radiative corrections with DM running inside loop
- We explore the interplay between neutrinos and DM

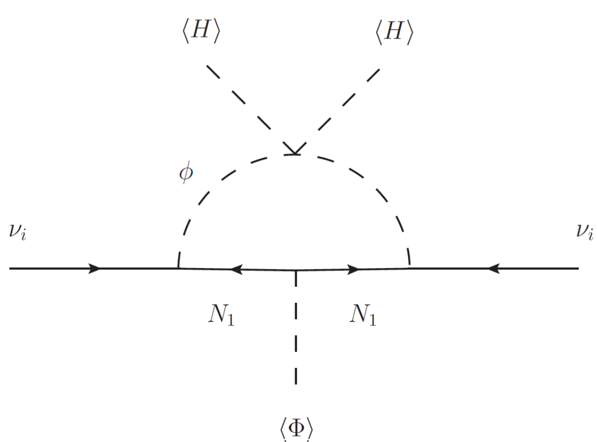
Model

- We begin with 3 heavy neutrinos with $X(N_1)$=-1, X(N2)=X(N3)=-2 (X(H)=0 and X(L)=2). Their Majorana masses come from the vacuum expectation value of Φ_1 and Φ_2 with $X(\Phi_1)$=2 and $X(\Phi_2)$=4.
- An $SU(2)_L$ doublet scalar with $X(\phi)$=-1 is introduced to realize radiative neutrino masses (Ma, hep-ph/0601225)
- The light neutrino mass comes from the Type-I seesaw $LHN_{2,3}$ and radiative corrections with ϕ and N_1 in loop.



Radiative Neutrino mass

- In order to generate neutrino masses radiatively, one must have both lepton number violation and $SU(2)_L$ symmetry breaking
- Lepton number violation comes from the N_1's Majorana mass, i.e., from $<\Phi_1>$
- $SU(2)_L$ symmetry breaking is induced by the <H>, which lifts the mass degeneracy on the two neutral components of ϕ. In this model, the contribution comes from loop diagrams



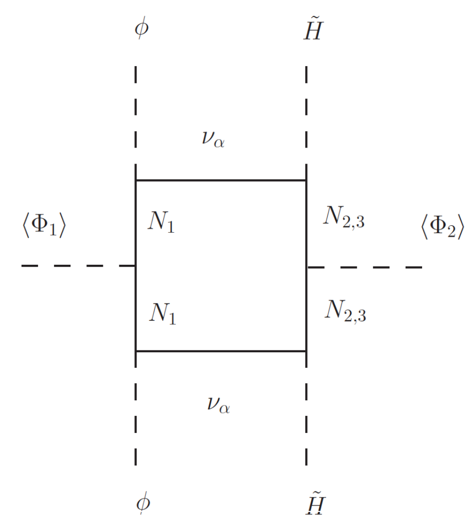


Figure 2: *Radiative contributions to* $m^2_{\phi^0_1} - m^2_{\phi^0_2}$.

Anomaly Cancellation

- With three heavy neutrinos, the model has axial anomalies or N_1 becomes unstable due to one of lepton flavors has X(L)=1
- One will need one more heavy neutrino N_4 with $X(N_4)=1$ opposite to N_1 if the model is anomaly-free and N_1 is stable
- One of lepton flavors has X(L)=0 and the others with X(L)=2

- $[SU(3)]^2U(1)_X$: $A_{33X} = 3(2X_Q - X_u - X_d)$,
- $[SU(2)]^2U(1)_X$: $A_{22X} = 9X_Q + \sum_{j=1}^{3} X_{L_j}$,
- $[U(1)_Y]^2U(1)_X$: $A_{11X} = 2X_Q - 16X_u - 4X_d + 2\sum_{j=1}^{3}(X_{L_j} - 2X_{E_j})$,
- $U(1)_Y[U(1)_X]^2$: $A_{1XX} = 6(X_Q^2 - 2X_u^2 + X_d^2) - 2\sum_{j=1}^{3}(X_{L_j}^2 - X_{E_j}^2)$,
- $[U(1)_X]^3$: $A_{XXX} = 9(2X_Q^3 - X_u^3 - X_d^3) + \sum_{j=1}^{3}(2X_{L_j}^3 - X_{E_j}^3) + \sum_{j=1}^{n} X_{N_j}^3$,
- $[G]^2U(1)_X$: $A_{GGX} = 9(2X_Q - X_u - X_d) + \sum_{j=1}^{3}(2X_{L_j} - X_{E_j}) + \sum_{j=1}^{n} X_{N_j}$,

hep-ph/0408098

$$X_Q = X_u = X_d = -\frac{1}{9}\sum_{j=1}^{3} X_{L_j},$$

$$X_{L_j} = X_{E_j}$$

$$\sum_{j=1}^{3} X_{L_j}^3 + \sum_{j=1}^{n} X_{N_j}^3 = 0,$$

$$\sum_{j=1}^{3} X_{L_j} + \sum_{j=1}^{n} X_{N_j} = 0,$$

Model

- For demonstration, we choose $X(L_\tau)=0$ and $X(L_e)=2=X(L_\mu)$.
- The Lagrangian becomes:

$$\mathcal{L} \supset \sum_{\alpha=e}^{\mu} \sum_{i=2}^{3} y_{\alpha i} \left(L_\alpha \cdot H\right) N_i + \sum_{\alpha=e}^{\mu} \lambda_\alpha \left(L_\alpha \cdot \phi\right) N_1 + \lambda_{N_4} \left(L_\tau \cdot \phi\right) N_4 + h.c.\,.$$

Field	$L_{e,\mu}$	L_τ	H	N_1	N_4	N_2	N_3	ϕ	Φ_1	Φ_2
$SU(2)_L$	2	2	2	1	1	1	1	2	1	1
$U(1)_Y$	-1/2	1/2	1/2	0	0	0	0	1/2	0	0
$U(1)_X$	2	0	0	-1	1	-2	-2	-1	2	4

Model

- The neutrino mass matrix is, where f_{ij} are loop functions,

$$m = \begin{pmatrix} m_L & m_D \\ m_D^T & M \end{pmatrix} \qquad m_L = \begin{pmatrix} \lambda_e^2 f_{11} & \lambda_e \lambda_\mu f_{11} & \lambda_e \lambda_{N_4} f_{41} \\ \lambda_\mu \lambda_e f_{11} & \lambda_\mu^2 f_{11} & \lambda_\mu \lambda_{N_4} f_{41} \\ \lambda_{N_4} \lambda_e f_{41} & \lambda_{N_4} \lambda_\mu f_{41} & \lambda_{N_4}^2 f_{44} \end{pmatrix}$$

$$M = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix} \qquad m_D = v \begin{pmatrix} 0 & y_{e2} & y_{e3} \\ 0 & y_{\mu 2} & y_{\mu 3} \\ 0 & 0 & 0 \end{pmatrix}$$

- We take into account the N_1-N_4 mixing since $m_{14} N_1 N_4$ can exist

$$\begin{pmatrix} N_4 \\ N_1 \end{pmatrix}_f = U_{41} \begin{pmatrix} N_4 \\ N_1 \end{pmatrix}_m = \begin{pmatrix} \cos\theta_{41} & -\sin\theta_{41}\, e^{i\alpha_{41}} \\ \sin\theta_{41} & \cos\theta_{41}\, e^{i\alpha_{41}} \end{pmatrix} \begin{pmatrix} N_4 \\ N_1 \end{pmatrix}_m$$

Observables

- The PMNS mixing matrix and Δm_ν^2 (PDG Phys. Rev. D86, 010001 (2012))
- The DM relic abundance (Planck 1303.5076)

	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{23}$	$\sin^2 2\theta_{13}$	Δm_{sol}^2 (eV^2)	$\lvert\Delta m_{atm}^2\rvert$ (eV^2)	$\Omega_{\rm DM} h^2$
best-fit	0.857	1	0.095	7.50×10^{-5}	2.32×10^{-3}	0.120
1σ	0.024	0.301	0.01	2×10^{-6}	1×10^{-4}	3.1×10^{-3}

- The lepton flavor violation constrains, for example:

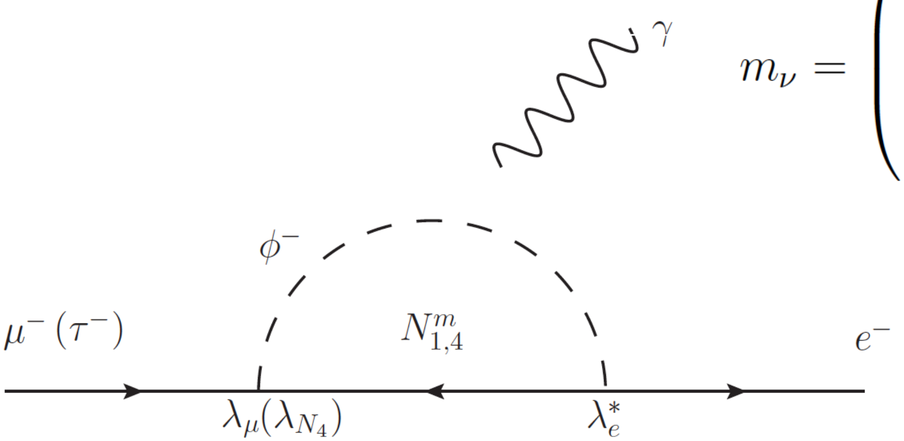
Br(τ-> e γ)< $3.3*10^{-8}$ (PDG Phys. Rev. D86, 010001 (2012))

Br(μ -> e γ)< $5.7*10^{-13}$ (MEG Nucl.Phys.Proc.Suppl. 248-250 (2014) 29-34)

Lepton Flavor Violation

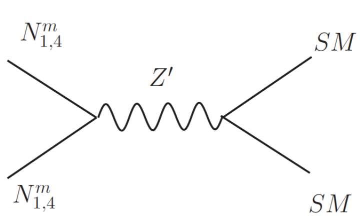
- N_1 and ϕ can also induce lepton flavor violation radiatively
- To avoid stringent bounds on μ-> e γ and simplify computation, we simply set λ_μ=0 => the vanishing (2,3) element in the mass matrix

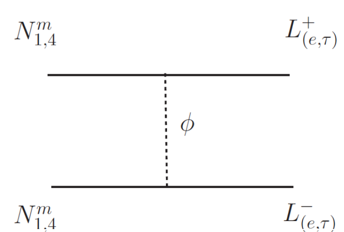
$$m_\nu = \begin{pmatrix} \lambda_e^2 f_{11} + \frac{y_{e2}^2}{m_{N_2}} + \frac{y_{e3}^2}{m_{N_3}} & \frac{y_{e2}y_{\mu 2}}{m_{N_2}} + \frac{y_{e3}y_{\mu 3}}{m_{N_3}} & \lambda_e \lambda_{N_4} f_{41} \\ \frac{y_{e2}y_{\mu 2}}{m_{N_2}} + \frac{y_{e3}y_{\mu 3}}{m_{N_3}} & \frac{y_{\mu 2}^2}{m_{N_2}} + \frac{y_{\mu 3}^2}{m_{N_3}} & 0 \\ \lambda_e \lambda_{N_4} f_{41} & 0 & \lambda_{N_4}^2 f_{44} \end{pmatrix}$$

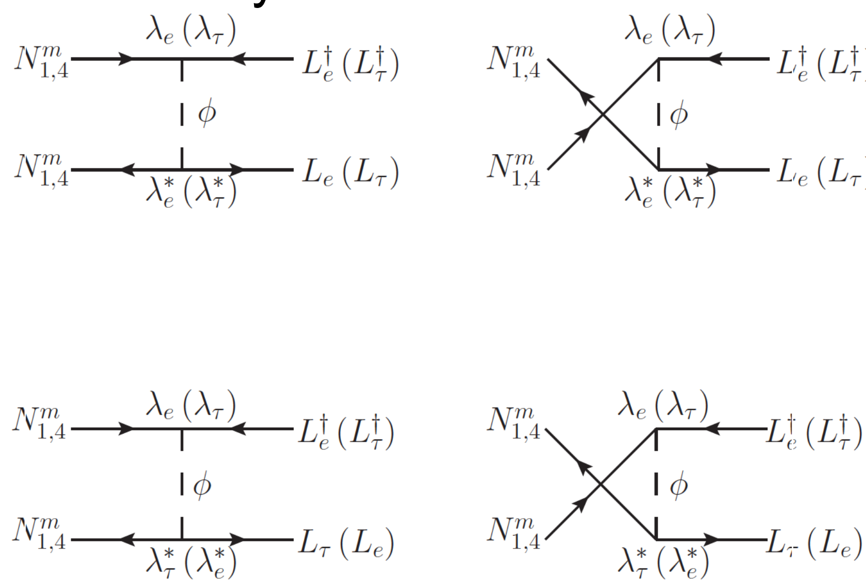


DM Relic Density

- N_1 (also N_4) can (co-)annihilate into SM particles via the Z' or ϕ exchange
- We investigate the ϕ exchange processes only to see the connection between DM and the neutrino sector
- The observed DM density is used as a lower bound since including Z' interactions can only decrease the DM density





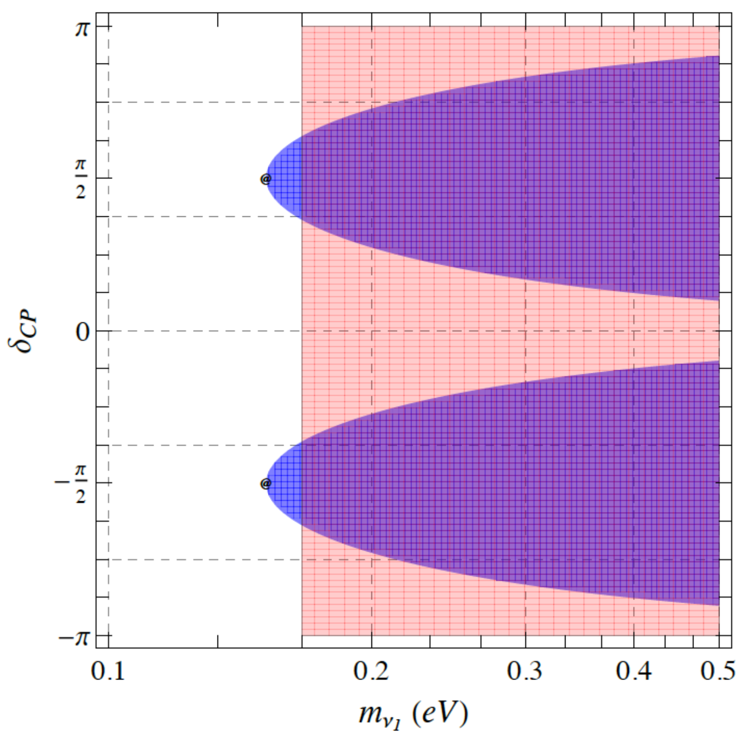


Preliminary Results

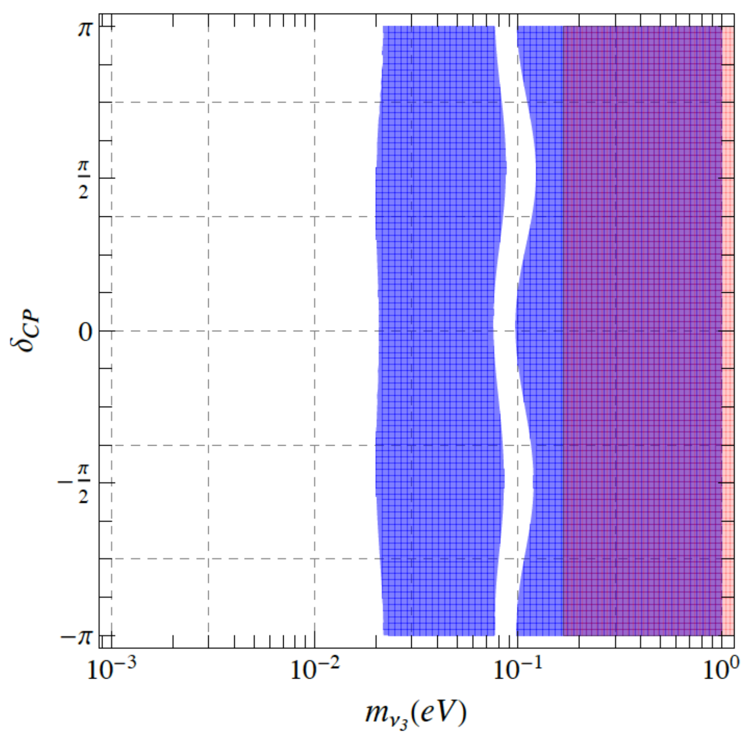
- We check if one can reproduce the PMNS matrix with the previous neutrino mass matrix with the vanishing (2,3) element
- We include cosmological constraints: $\sum m_\nu \lesssim 0.5$ eV

$$m_\nu = \begin{pmatrix} \lambda_e^2 f_{11} + \frac{y_{e2}^2}{m_{N_2}} + \frac{y_{e3}^2}{m_{N_3}} & \frac{y_{e2}y_{\mu 2}}{m_{N_2}} + \frac{y_{e3}y_{\mu 3}}{m_{N_3}} & \lambda_e \lambda_{N_4} f_{41} \\ \frac{y_{e2}y_{\mu 2}}{m_{N_2}} + \frac{y_{e3}y_{\mu 3}}{m_{N_3}} & \frac{y_{\mu 2}^2}{m_{N_2}} + \frac{y_{\mu 3}^2}{m_{N_3}} & 0 \\ \lambda_e \lambda_{N_4} f_{41} & 0 & \lambda_{N_4}^2 f_{44} \end{pmatrix}$$

Normal Hierarchy



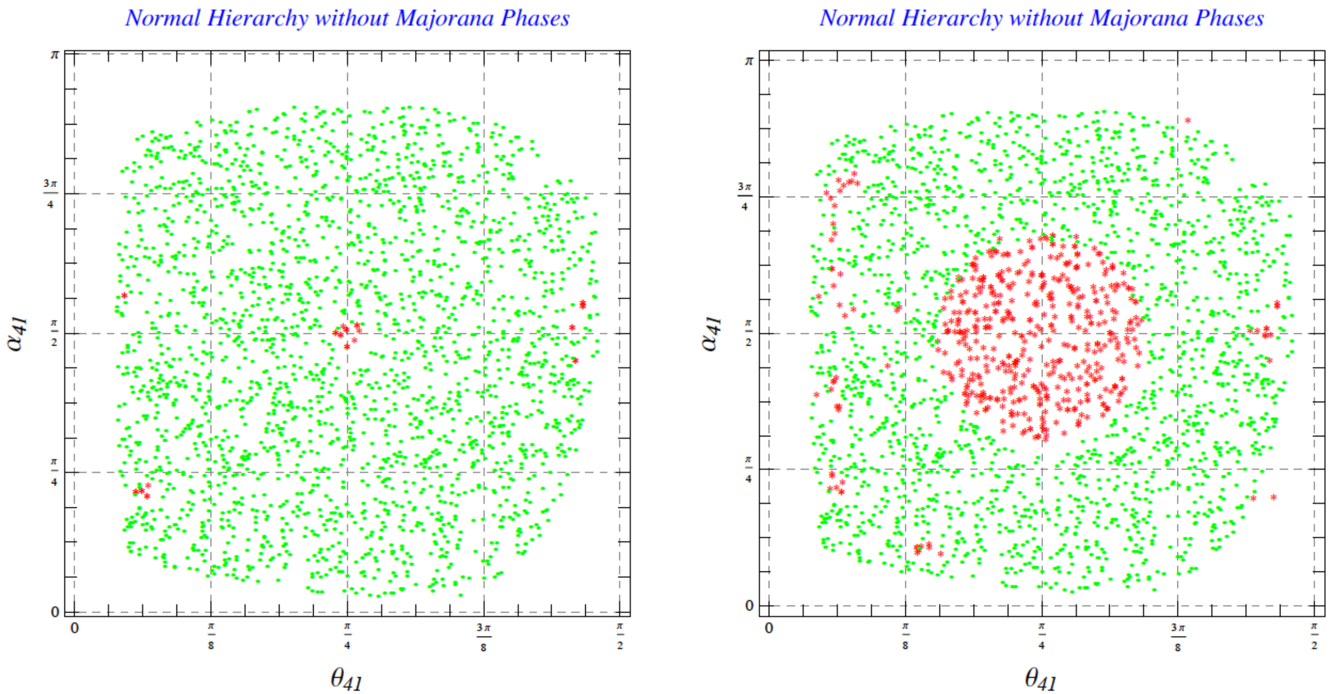
Inverted Hierarchy



Preliminary Results

- For the NH case, we choose zero Majorana phases with benchmark masses

m_{ν_1}	δ_{CP}	m_ϕ	m_{N_1}	m_{N_4}	m_{N_2}	m_{N_3}
0.15 eV	$\pi/2$	1200 GeV	1000 GeV	1010 GeV	2000 GeV	3000 GeV



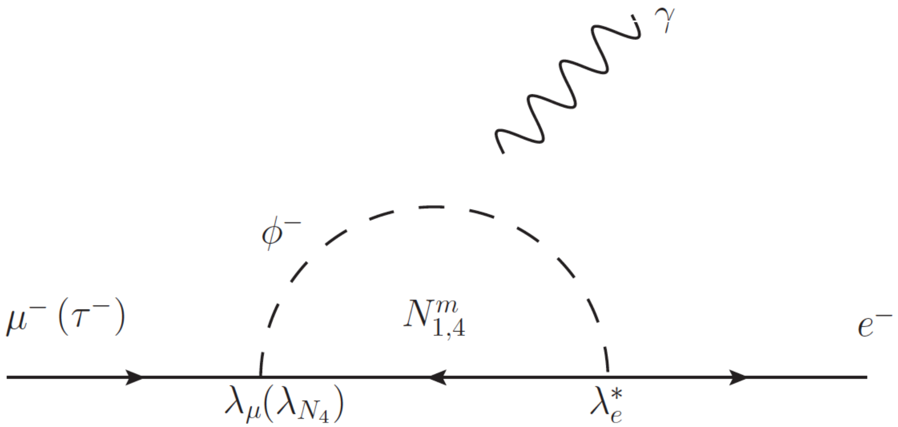
Left panel: perturbativity ($\lambda < 4\pi$) and $Br(\tau \to e\gamma)$

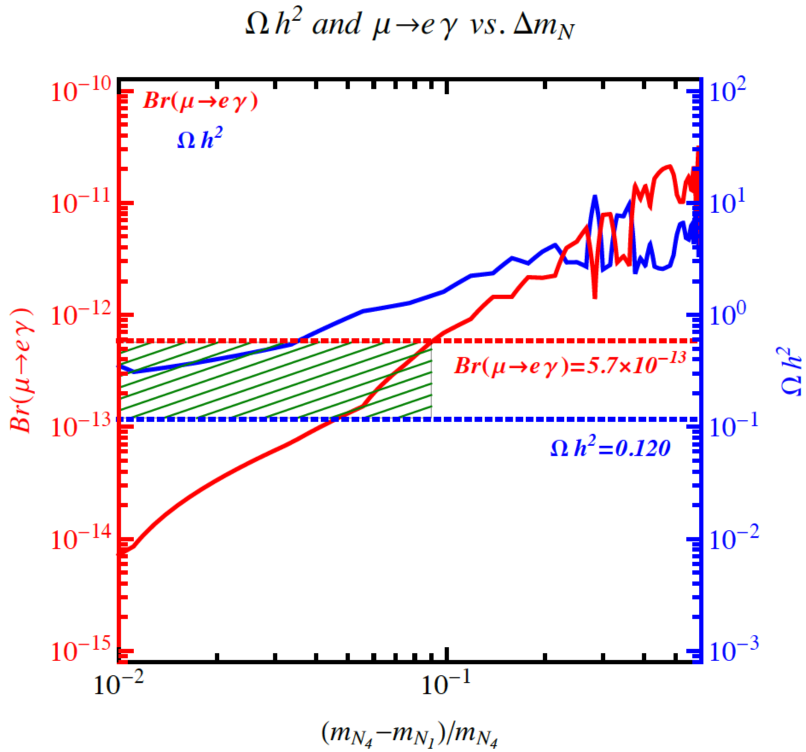
Right panel: perturbativity, $Br(\tau \to e\gamma)$ and the DM relic abundace

Preliminary Results

- With a different charge assignment: $X(L_\mu)=0$ and $X(L_e)=2=X(L_\tau)$, We show how Br(μ-> e γ) and the DM abundance depends on the difference between m_{N_4} and m_{N_1}

θ_{41}	α_{41}	λ_τ	m_{ν_1}	δ_{CP}
0.15	2.25	0	0.15 eV	$\pi/2$
m_ϕ	m_{N_4}	m_{N_2}	m_{N_3}	
1200 GeV	1000 GeV	2000 GeV	3000 GeV	





Conclusions

- We propose a *hybrid* neutrino mass model: type-I seesaw with four heavy neutrinos plus radiative contributions in the context of $U(1)_X$
- One of heavy neutrinos as the DM candidate is stable due to charge assignment with odd $U(1)_X$
- DM annihilations and lepton flavor violation are controlled by the same couplings constant => interplay between DM and neutrinos
- The model can reproduce the neutrino mixing matrix, mass spectrum and the correct DM abundance with considerably large lepton flavor violation, that could be tested in the near feature.