भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

17th International Conference on Interconnections between Particle Physics and Cosmology

PPC - 2024

UNIVERSITY OF HYDERABAD
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Comprehensive Phenomenology of Dirac Scotogenic Model: Novel Low Mass Dark Matter

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arXiv:2409.18513

Outline

- Introduction (SM and its Shortcomings)
- Scotogenic Model
- Dirac Scotogenic Model
- Dark Matter
- Charged Lepton Flavor Violation
- Higgs Vacuum Stability
- Conclusions

Introduction

The Standard Model (SM)

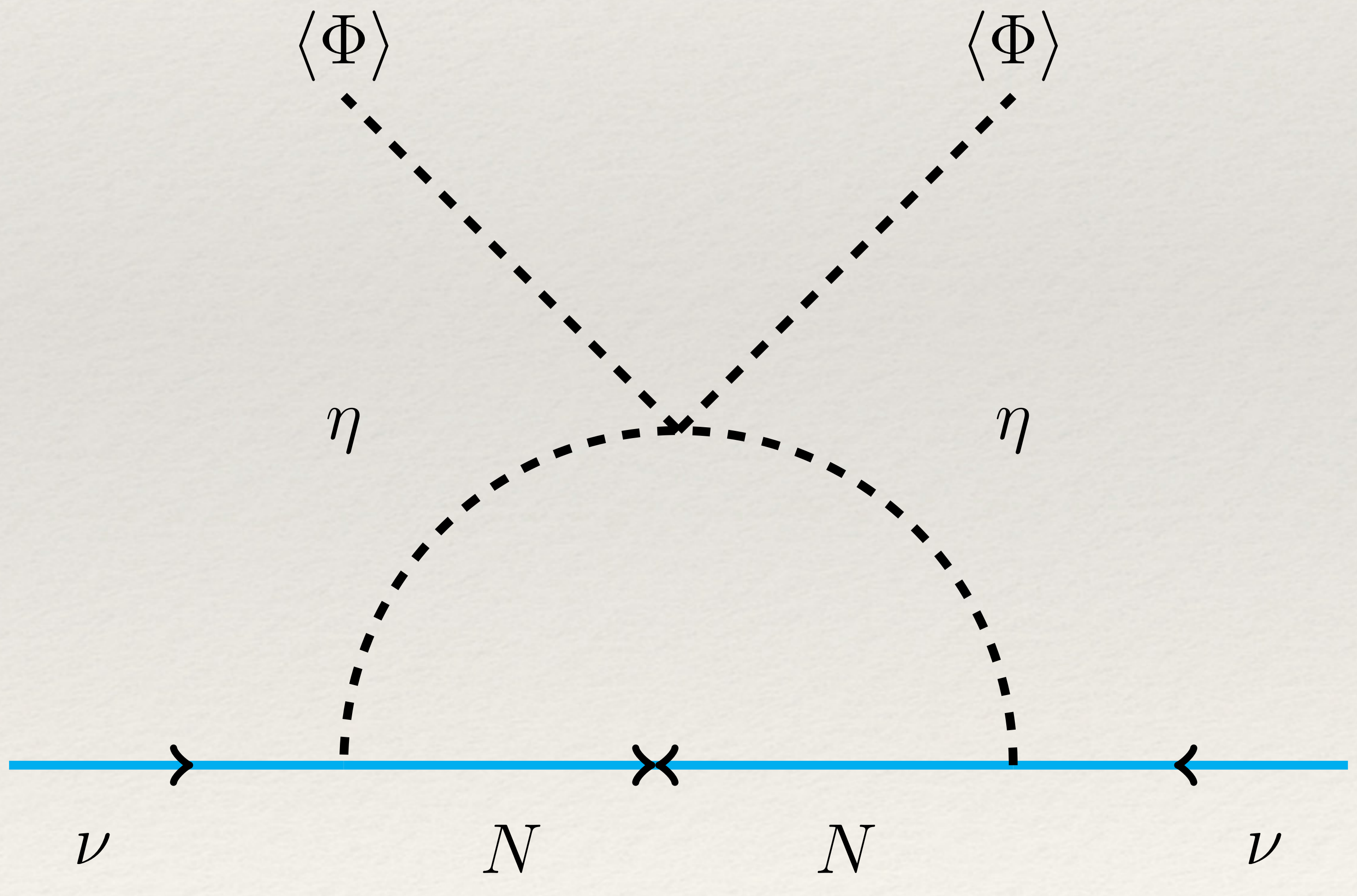
- A quantum field theory which provides a very good understanding of three of the four fundamental forces: Strong, Weak, and EM.
- It is based on the "Gauge Principle". $SU(3)_C \times SU(2)_L \times U(1)_Y$
- It contains three generations of leptons and quarks with Gauge bosons and Higgs boson.
- SM stands as a remarkably successful theoretical framework, providing a comprehensive description of all known particles and their interactions with very great accuracy.

Shortcomings of SM

- Neutrino Mass
- Dark Matter
- Matter-antimatter asymmetry
- Muon’s anomalous magnetic dipole moment
- Electroweak Vacuum Stability Problem

Scotogenic Model

- Minimal extension of SM (Proposed by Ernest Ma in 2006)
- It provides tiny neutrino mass and dark matter stability simultaneously within the same framework.
- Light neutrino masses are generated via the one-loop radiative seesaw mechanism.
- Two newly added BSM fields: Scalar doublet η and Fermion singlet N.
- A new symmetry Z_2 : new fields are odd under Z_2 and SM fields are even under Z_2.
- Two possible DM candidates: Neutral Scalar η^0 / Neutral Fermion N_1



Leading neutrino mass generation diagram.

Dirac Scotogenic Model

- It is a theoretical framework for obtaining stable dark matter and naturally small Dirac neutrino masses generated at the loop level.
- This is achieved through the symmetry breaking of the global $U(1)_{B-L}$symmetry already present in the SM.
- Dirac/Majorana nature of neutrinos is intimately connected with the $U(1)_{B-L}$ symmetry of the SM and its possible breaking pattern.
- $U(1)_{B-L} \to Z_m \equiv Z_{2n+1}$ with $n \in \mathbb{Z}^+ \Rightarrow$ neutrinos are Dirac particles
- $U(1)_{B-L} \to Z_m \equiv Z_{2n}$ with $n \in \mathbb{Z}^+ \Rightarrow$ neutrinos can be Dirac or Majorana
- Lepton doublet $L_i \nsim \omega^n$ under $Z_{2n} \Rightarrow$ Dirac neutrinos
- Lepton doublet $L_i \sim \omega^n$ under $Z_{2n} \Rightarrow$ Majorana neutrinos; where $\omega^{2n} = 1$ or $\omega = \exp \dfrac{2\pi i}{2n}$

The Model Setup

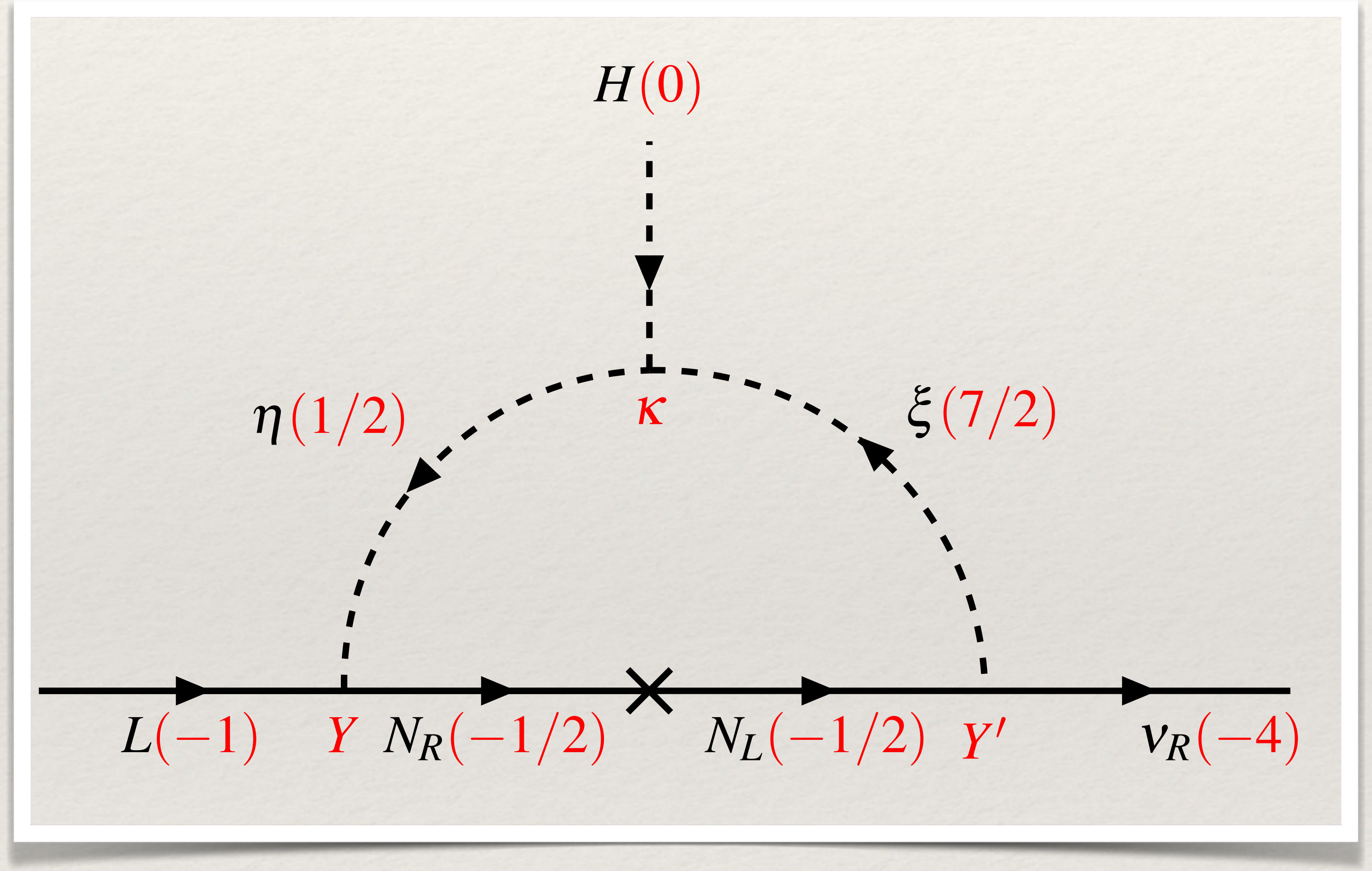
$(-4,-4,5)$ Chiral solutions to $U(1)_{B-L}$ anomaly cancellation conditions (forbidding the tree-level neutrino Yukawa couplings).

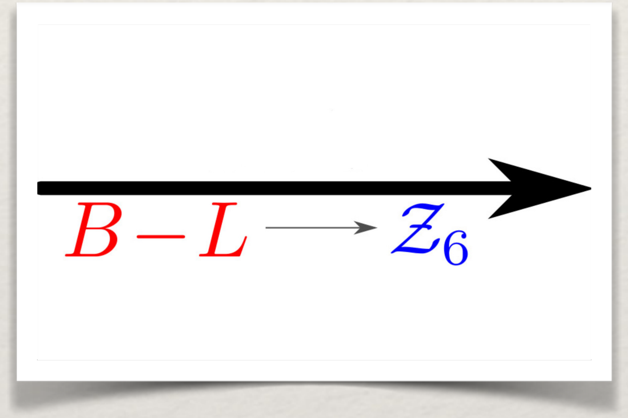
	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \rightarrow \mathcal{Z}_6$
Fermions	L_i	$(\mathbf{2}, -1/2)$	$-1 \rightarrow \omega^4$
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5) \rightarrow (\omega^4, \omega^4, \omega^4)$
	N_{L_j}	$(\mathbf{1}, 0)$	$-1/2 \rightarrow \omega^5$
	N_{R_j}	$(\mathbf{1}, 0)$	$-1/2 \rightarrow \omega^5$
Scalars	H	$(\mathbf{2}, 1/2)$	$0 \rightarrow 1$
	η	$(\mathbf{2}, 1/2)$	$1/2 \rightarrow \omega$
	ξ	$(\mathbf{1}, 0)$	$7/2 \rightarrow \omega$

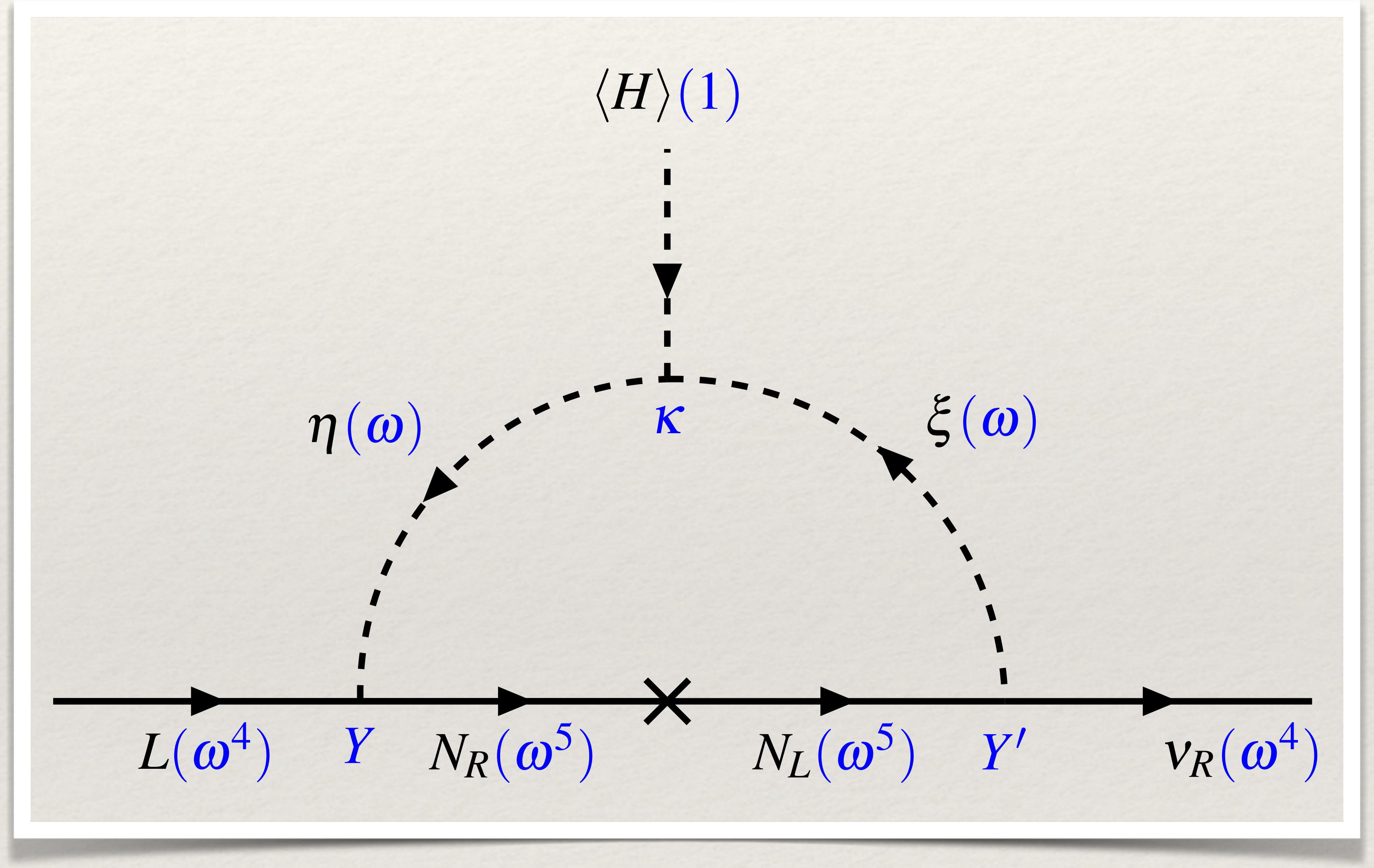
B-L charge for Higgs is zero to preserve Yukawa terms for fermions that give mass to them.

Breaking Pattern of $U(1)_{B-L}$ Symmetry

- The $U(1)_{B-L} \to Z_6$ breaking happens because of the presence of the soft-term $(\kappa\,\eta^\dagger H \xi + h.c.)$







- This residual Z_6 symmetry simultaneously protects the Dirac nature of neutrinos and the stability of DM.

The Scalar Potential

- The general form of the scalar potential is given by

$$V = -\mu_H^2 H^\dagger H + \mu_\eta^2 \eta^\dagger \eta + \mu_\xi^2 \xi^* \xi + \frac{1}{2}\lambda_1 (H^\dagger H)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \frac{1}{2}\lambda_3 (\xi^* \xi)^2$$

$$+\lambda_4 (H^\dagger H)(\eta^\dagger \eta) + \lambda_5 (H^\dagger \eta)(\eta^\dagger H) + \lambda_6 (H^\dagger H)(\xi^* \xi) + \lambda_7 (\eta^\dagger \eta)(\xi^* \xi) + (\kappa\, \eta^\dagger H \xi + h.c.)$$

- Fleshing out the $SU(2)_L$ components of the scalars, we can write

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \qquad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$$

$$H^0 = \frac{1}{\sqrt{2}}(v + h + iA) \quad \eta^0 = \frac{1}{\sqrt{2}}(\eta_R + i\eta_I) \qquad \xi = \frac{1}{\sqrt{2}}(\xi_R + i\xi_I)$$

Mass spectrum

- The tree-level masses of the physical scalar states after symmetry-breaking

$$m_h^2 = \lambda_1 v^2 \qquad\qquad m_{\eta^\pm}^2 = \mu_\eta^2 + \frac{\lambda_4}{2} v^2$$

- The real/imaginary part of ξ will mix with the real/imaginary part of η , and the mass eigenstates for the real/imaginary part of neutral scalars ξ and η^0 are given by

$$m_{1R}^2 = m_{1I}^2 = \left(\mu_\xi^2 + \lambda_6 \frac{v^2}{2}\right)\cos^2\theta + \left(\mu_\eta^2 + (\lambda_4 + \lambda_5)\frac{v^2}{2}\right)\sin^2\theta - 2\kappa v \sin\theta\cos\theta \equiv m_\xi^2$$

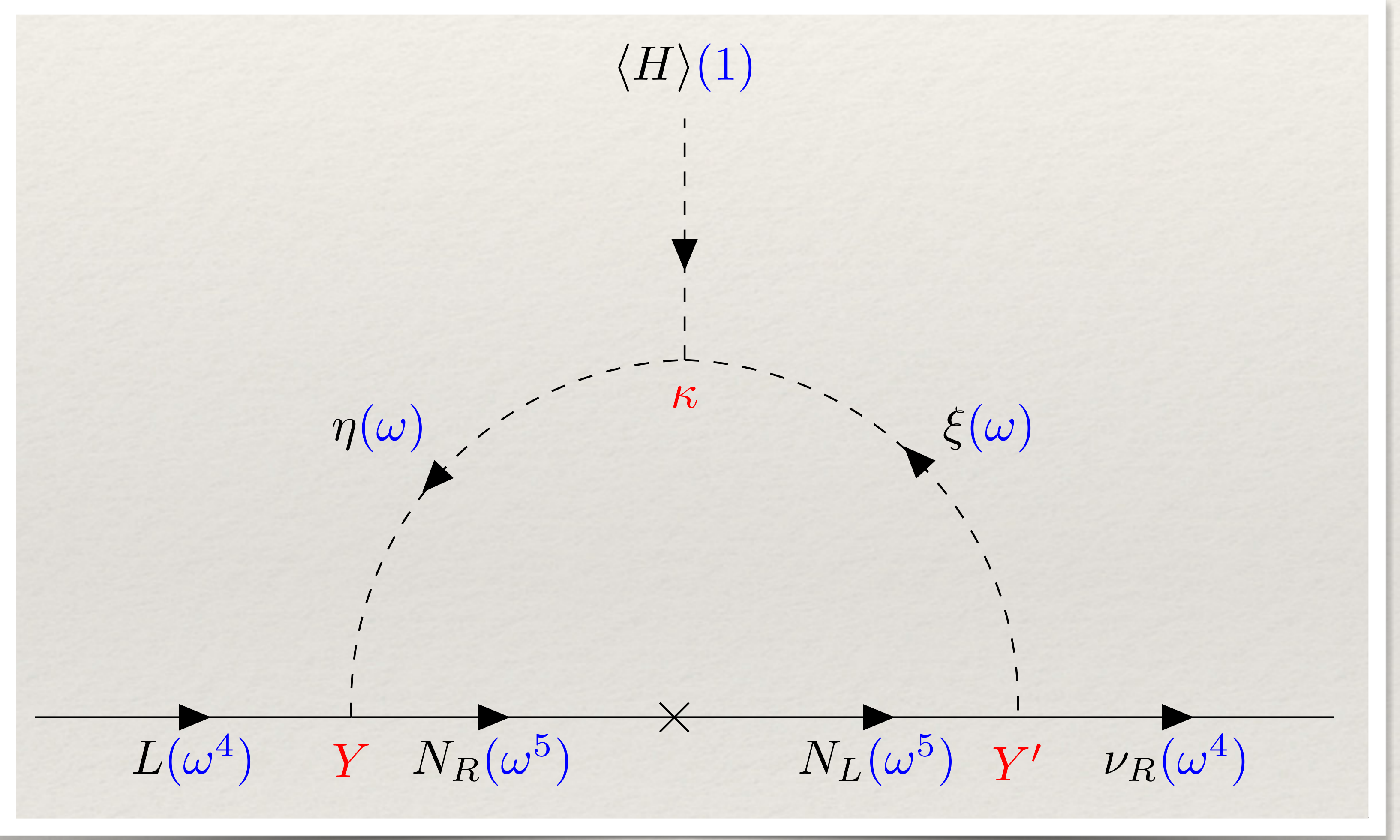
$$m_{2R}^2 = m_{2I}^2 = \left(\mu_\xi^2 + \lambda_6 \frac{v^2}{2}\right)\sin^2\theta + \left(\mu_\eta^2 + (\lambda_4 + \lambda_5)\frac{v^2}{2}\right)\cos^2\theta + 2\kappa v \sin\theta\cos\theta \equiv m_{\eta^0}^2$$

- Where, the singlet-doublet mixing angle $\tan 2\theta = \dfrac{\sqrt{2}\kappa\, v}{(\mu_\xi^2 - \mu_\eta^2) + (\lambda_6 - \lambda_4 - \lambda_5)\frac{v^2}{2}} \ll 1$

Neutrino Mass

- The relevant Yukawa Lagrangian for neutrino masses is given by

$$\mathscr{L}_Y \supset Y_{il}\bar{L}_i\tilde{\eta}N_{R_l} + Y'_{li}\bar{N}_{L_l}\nu_{R_i}\xi + M_{lm}\bar{N}_{R_l}N_{L_m} + h.c.$$



Leading neutrino mass generation diagram.

- We can calculate neutrino masses from the above fig.

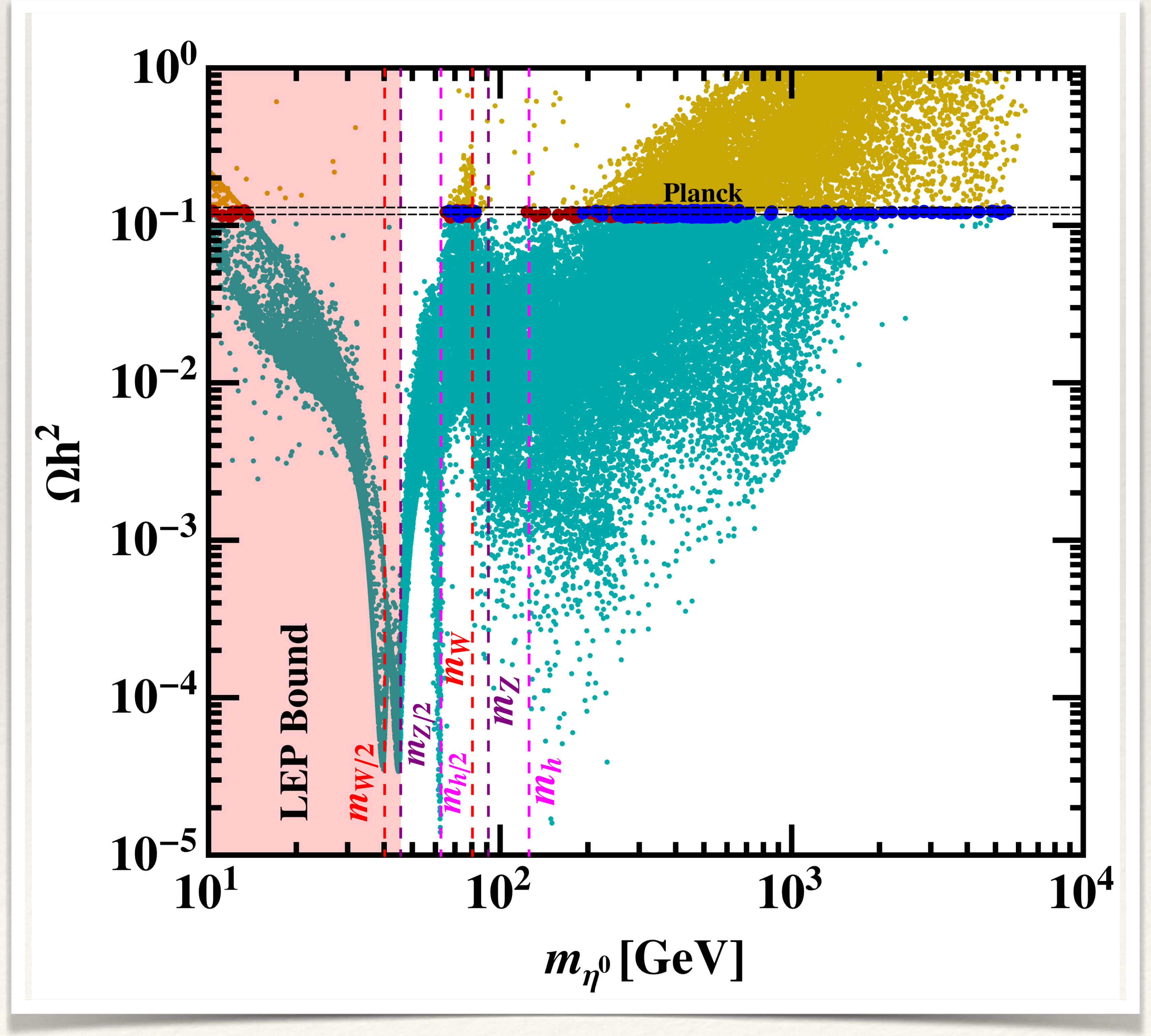
$$(M_\nu)_{ij} = \frac{1}{16\pi^2}\sum_{k=1}^{3} Y_{ik}Y'_{kj}\frac{\kappa v}{m_\xi^2 - m_\eta^2}M_k\sum_{l=1}^{2}(-1)^l B_0(0,m_l^2, M_k^2)\,.$$

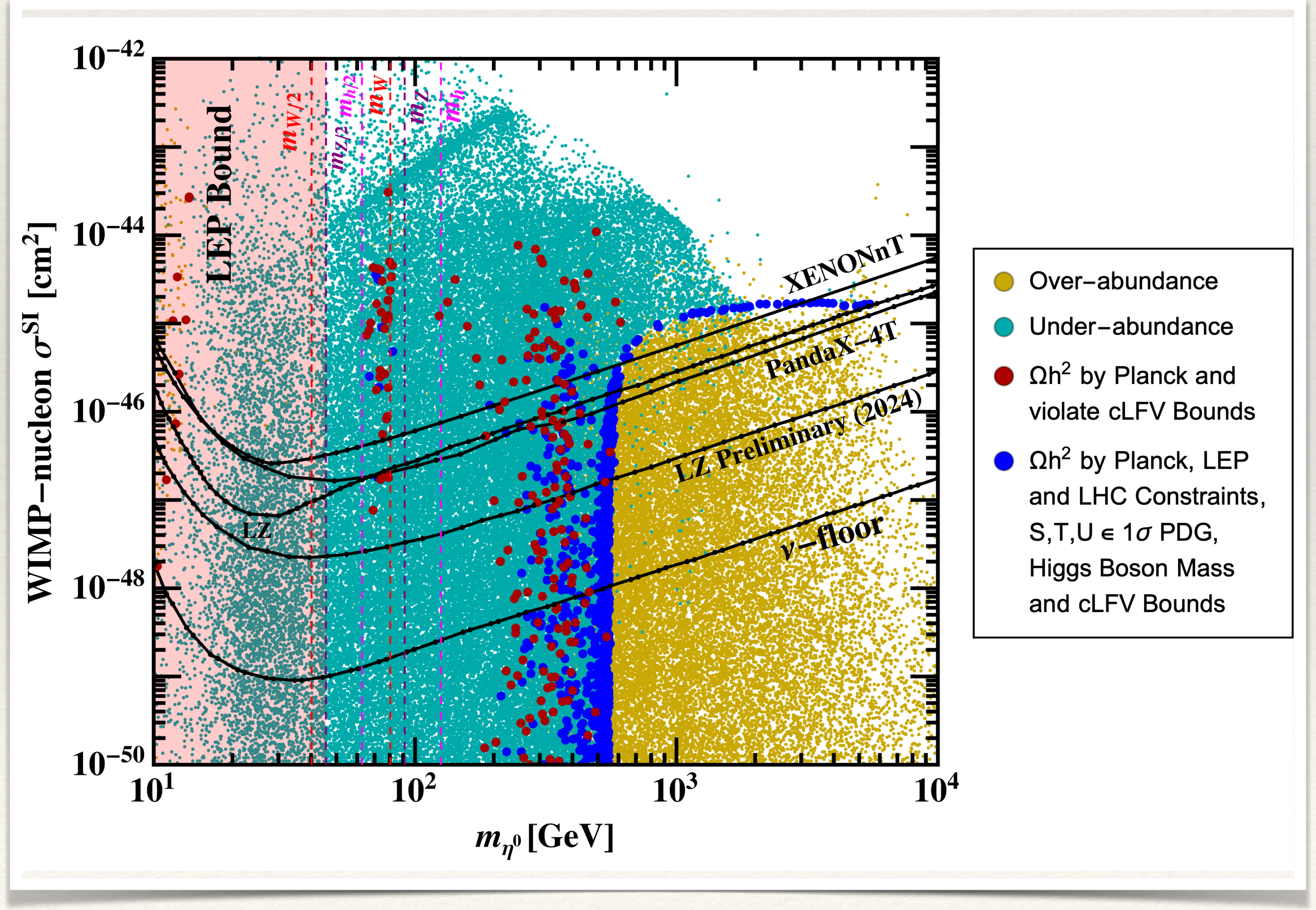
Phenomenology

- We performed a detailed numerical scan for the model parameters with various experimental and theoretical constraints.
- We have implemented the model in SARAH-4.14.5 and SPheno-4.0.5 to calculate all the vertices, mass matrices and tadpole equations.
- Thermal components to the DM relic abundance, as well as the DM nucleon scattering cross-sections, are determined by micrOMEGAS-5.2.13.

Doublet Scalar DM

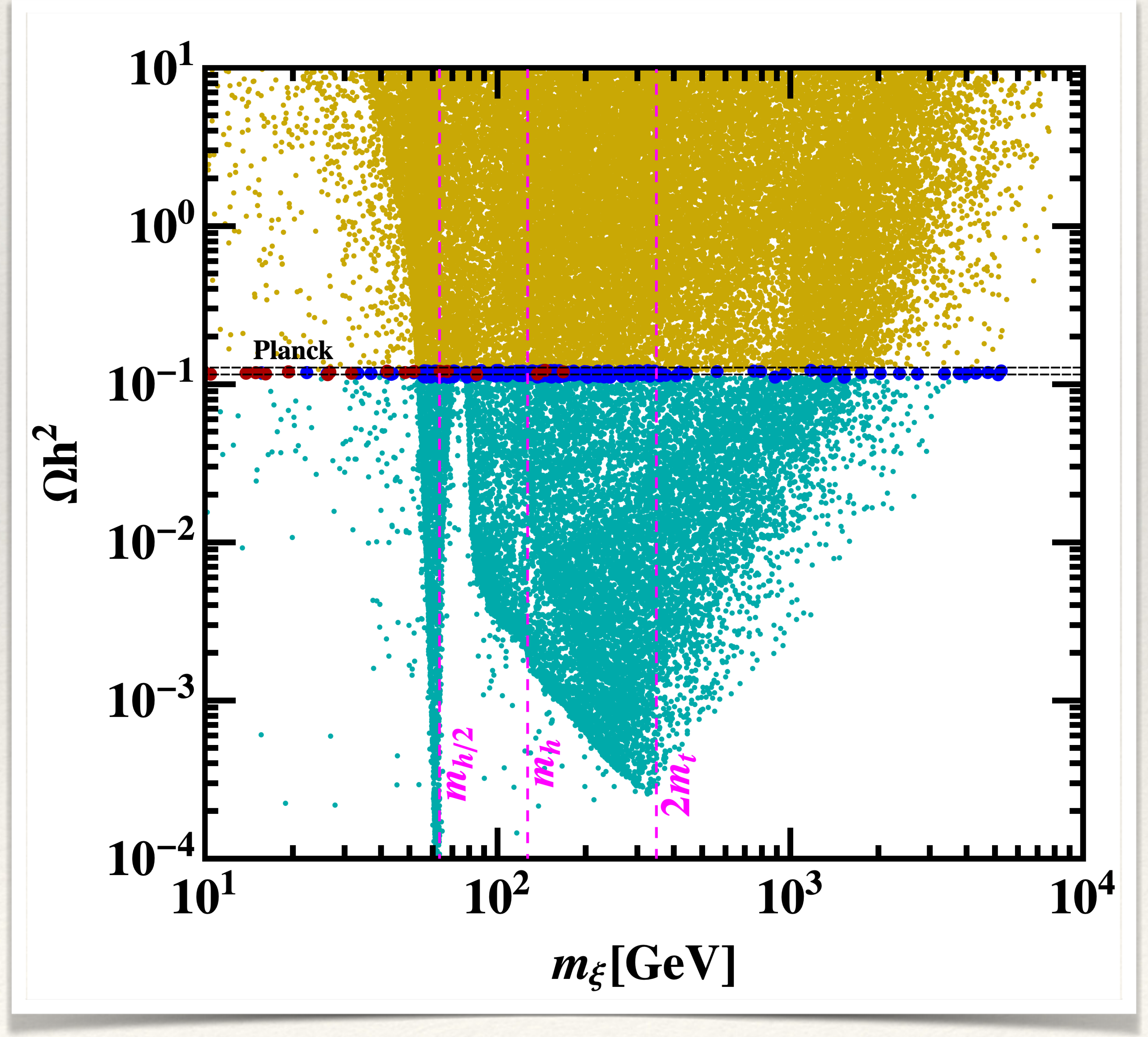
- The combination of all relevant constraints leads to an allowed mass range of $m_{\eta^0} \sim 70$ GeV - 80 GeV and $m_{\eta^0} \sim 200$ GeV - 600 GeV for mainly doublet scalar DM.

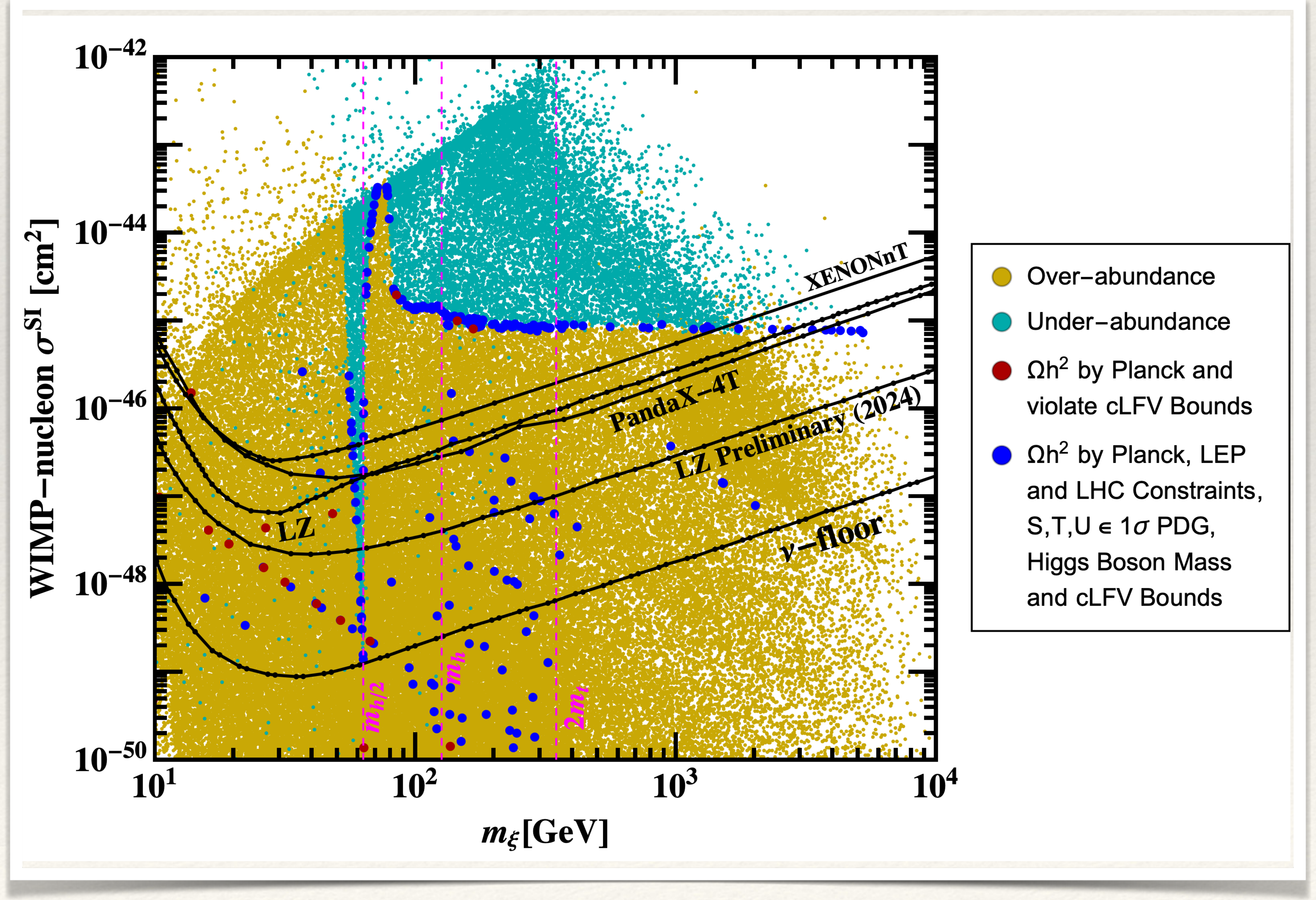




Singlet Scalar DM

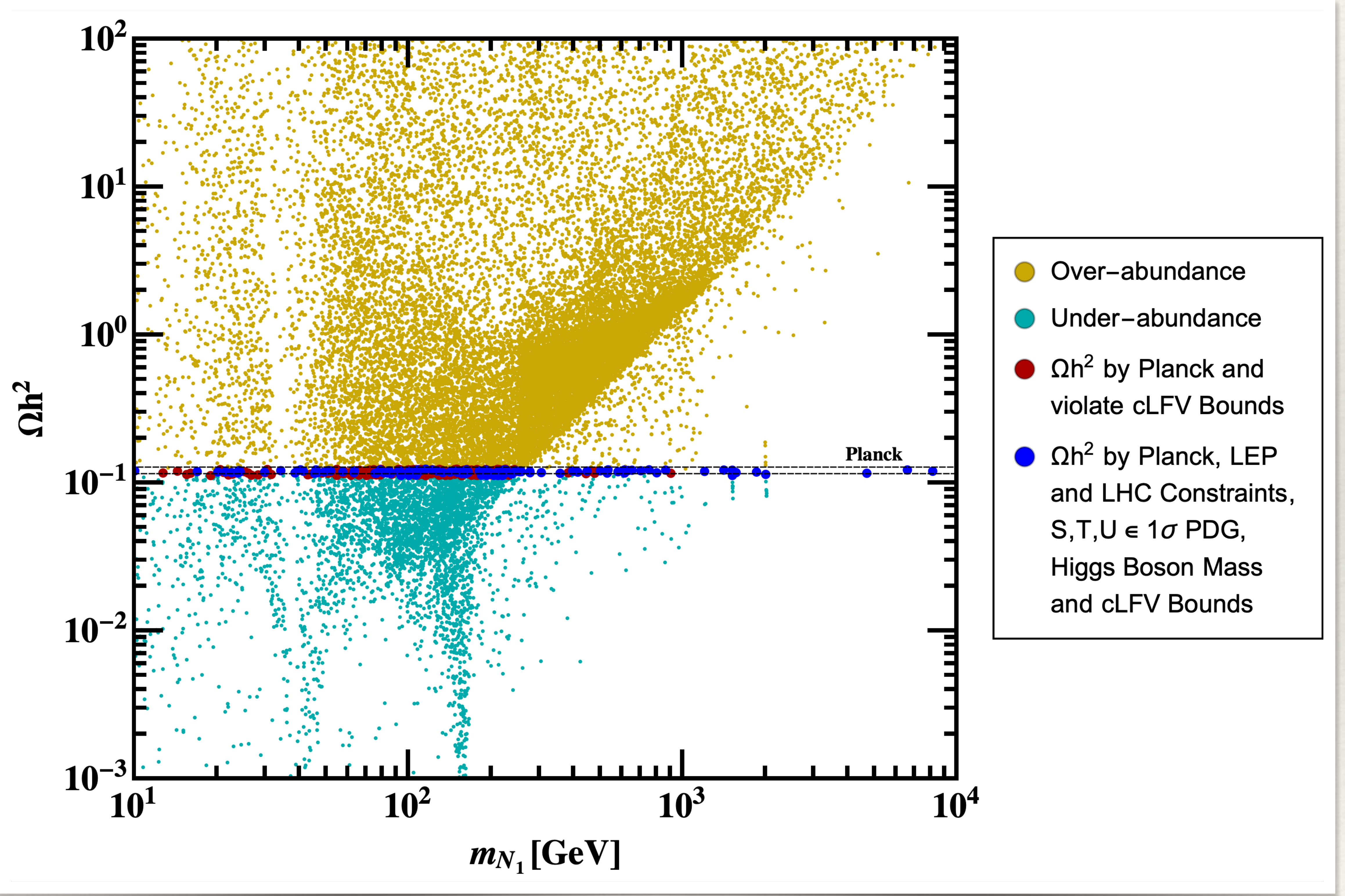
- The combination of all relevant constraints leads to an allowed mass range of $m_\xi \sim$ 10 GeV - 2 TeV (co-annihilation) and $m_\xi \sim$ 3.5 TeV - 5.2 TeV (hierarchical) for singlet scalar DM.





Fermionic DM

- For the fermionic DM case, co-annihilation involving dark scalars is crucial, providing a wide range of viable parameter space.
- The low-mass region is allowed due to co-annihilation channels involving the singlet scalar, a distinctive feature of the Dirac Scotogenic model which distinguishes it from the canonical Majorana Scotogenic model.



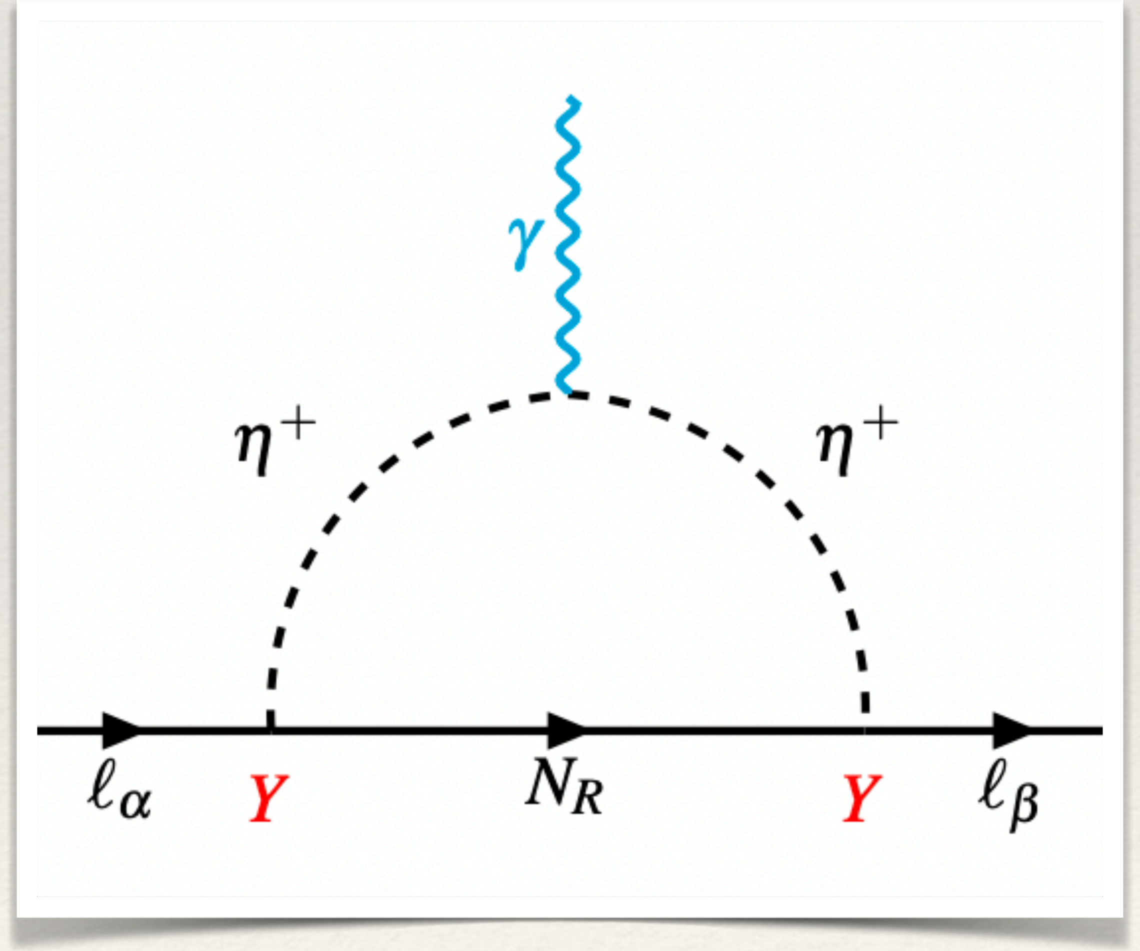
Charged Lepton Flavor violation

- The strongest constraints to cLFV come from the family of non-standard lepton decays $\ell_\alpha \to \ell_\beta \gamma$
- In our framework, the leading contribution to $\ell_\alpha \to \ell_\beta \gamma$ comes at the one-loop level through the mediation of the charged scalar η^+.

- The branching ratio of this process is given by

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta \gamma) = \mathrm{Br}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu_\beta}\right) \times \frac{3\alpha_{em}}{16\pi G_F^2} \left| \sum_i \frac{Y_{\beta i} Y_{\alpha i}^*}{m_{\eta^-}^2} j\left(\frac{M_{N_i}^2}{m_{\eta^-}^2}\right) \right|^2$$

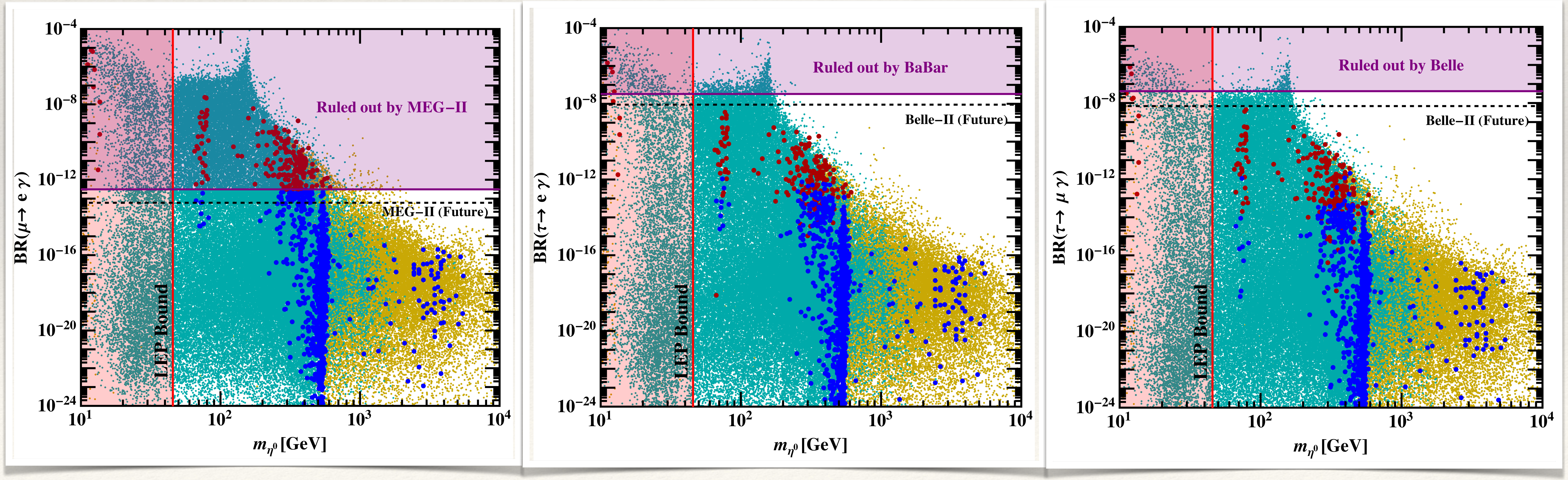
where $j(x) = \dfrac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log(x)}{12(1-x)^4}$



One loop feynman diagram for the process $\ell_\alpha \to \ell_\beta \gamma$

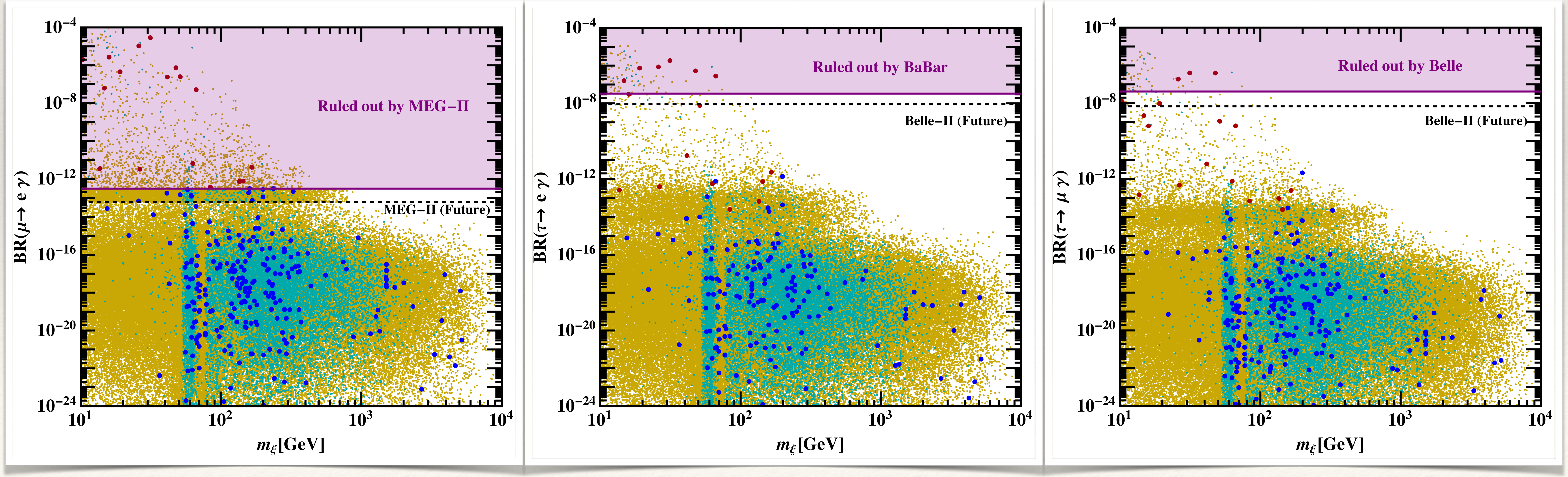
Charged Lepton Flavor Violation

- Doublet scalar DM case



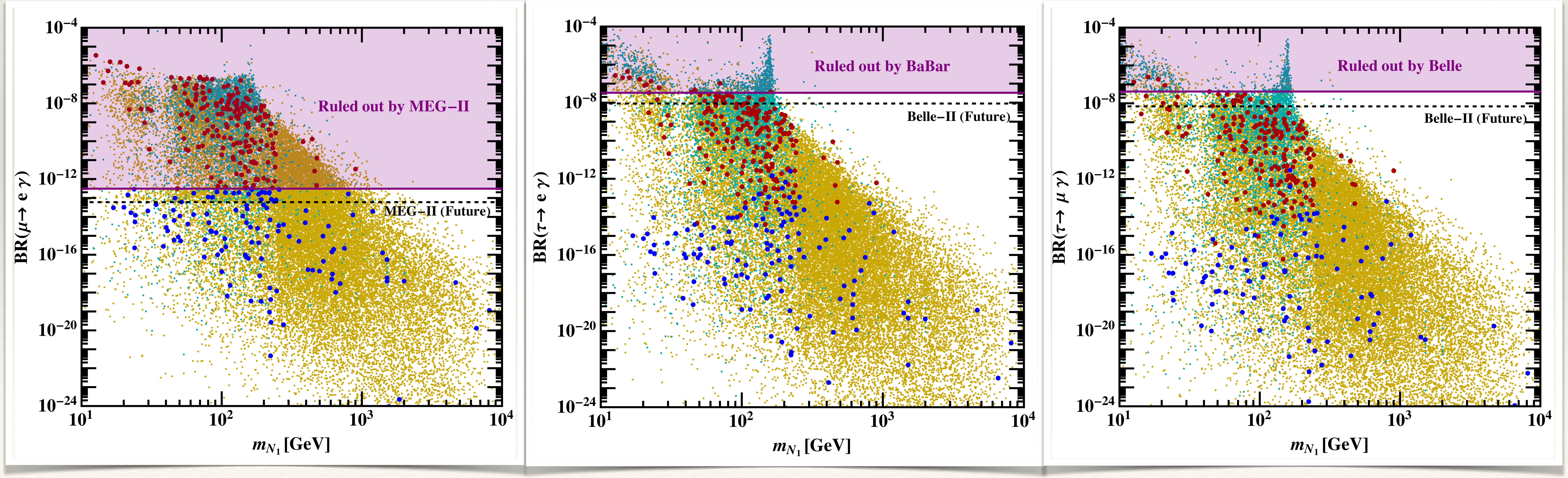
Charged Lepton Flavor Violation

- Singlet scalar DM case



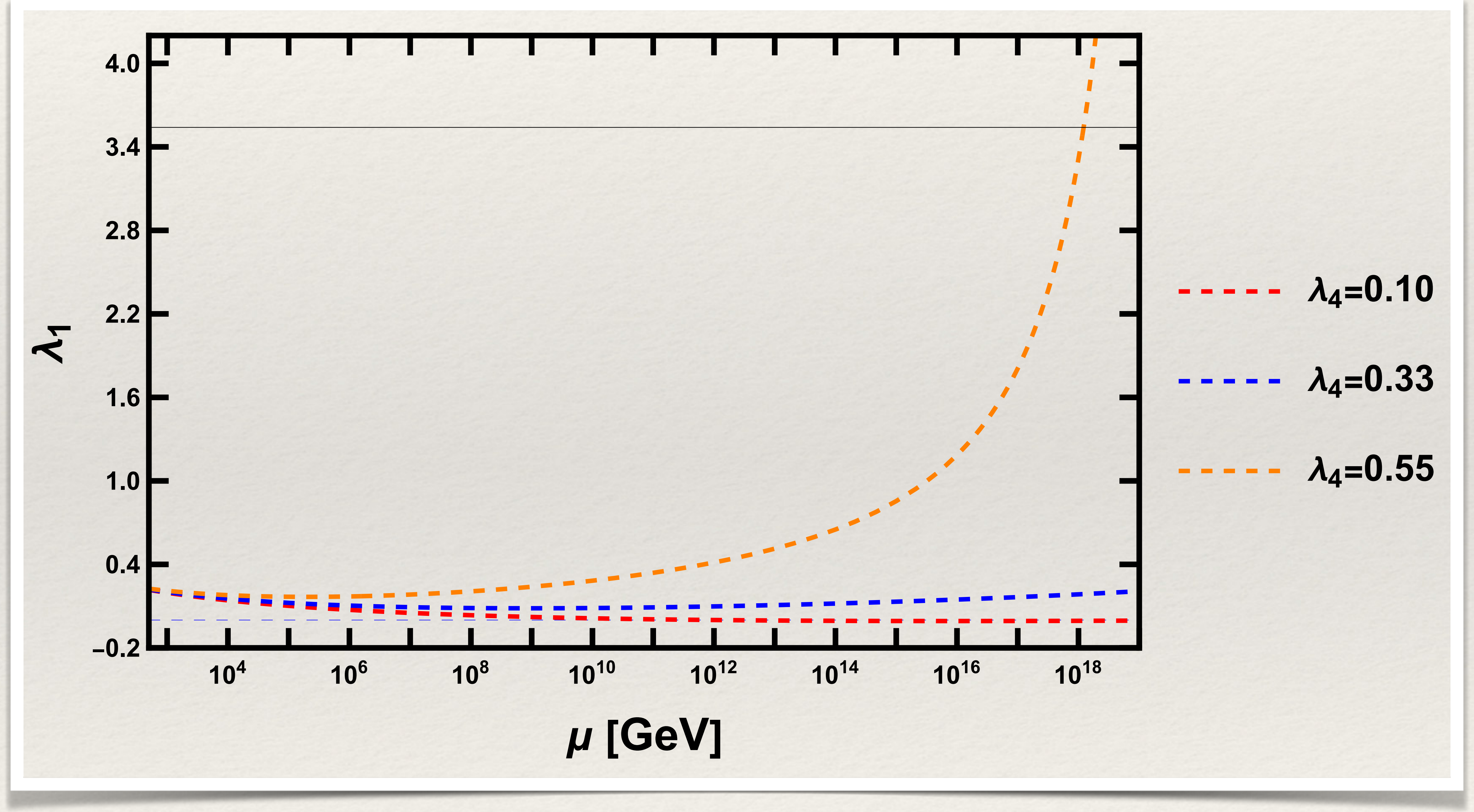
Charged Lepton Flavor Violation

- Fermionic DM case



Higgs Vacuum Stability in the Dirac Scotogenic Model

- The structure of the EW vacuum of the SM has been thoroughly studied and is known to be metastable.
- We analyse the conditions under which the vacuum of the Dirac Scotogenic model can be stabilized up to the Planck scale.
- In our analysis, we observe a notable dependence of the running of the quartic Higgs self-coupling (λ_1) on the interaction couplings λ_4 , λ_5 and λ_6 of the scalar potential.
- The EW vacuum can remain completely stable for all three types of possible DM candidates: dark doublet scalar, dark singlet scalar and dark fermion.



Conclusions

- We have thoroughly analysed the phenomenology of the Dirac scotogenic model, including neutrino masses and mixing, DM relic abundance, stability of the electroweak vacuum and charged lepton flavor violation.
- For the doublet scalar DM case, two distinct mass regions are viable: a low mass region near half Higgs mass and a medium mass region just above the top quark mass.
- For the singlet scalar DM case, allowed parameter space reduces to $m_\xi \sim 10$ GeV - 2 TeV as the higher mass region is ruled by latest preliminary results of LZ collaboration.
- In the fermionic DM case, a wide range of viable parameter space is allowed by considering co-annihilation channels involving dark scalars.
- When the DM is either the doublet scalar or the fermion, the cLFV rates may fall within the sensitivity of future experimental searches, offering promising prospects for detection.

Thank you for your attention!