UNIVERSITY OF Southampton

Neutrino Mass and the Early Universe:

Dark Matter and Leptogenesis

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Cosmology from Home 2022

Outline

- Neutrino portal dark matter in type I seesaw model: limitation
- Type Ib seesaw model and its cosmological properties
  - Neutrino portal dark matter
  - Resonant leptogenesis
  - Vector portal dark matter (a bonus)

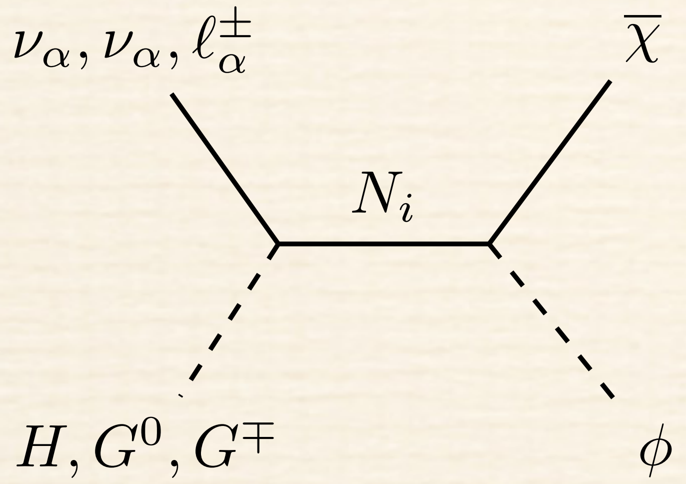
Neutrino Portal Dark Matter

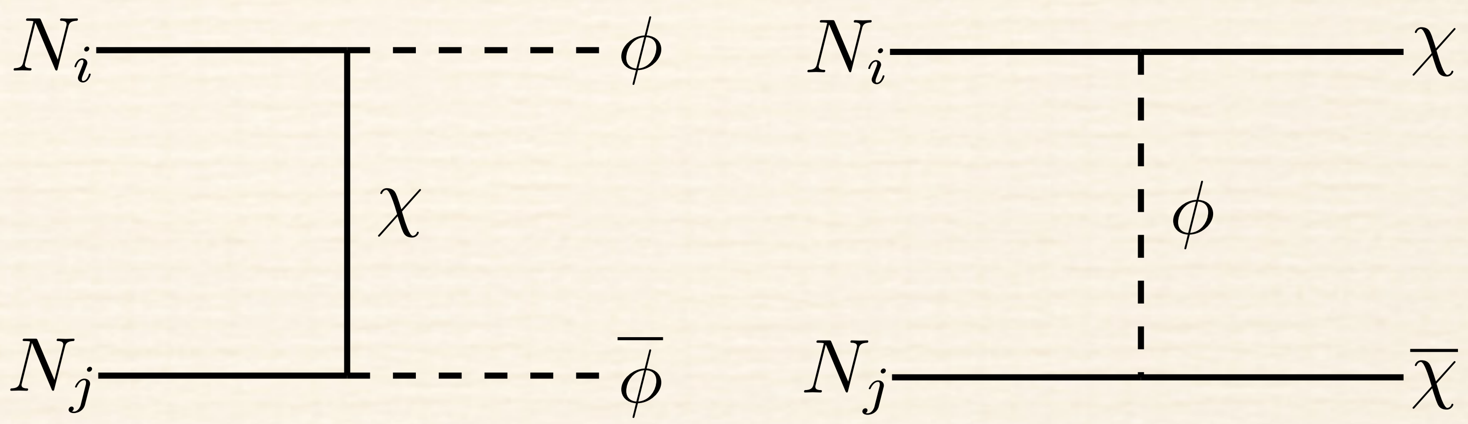
- General neutrino portal: $y_i \phi \overline{\chi} N_i$ the dark particles are charged under a Z_2 symmetry

  dark scalar (ϕ) dark fermion ($\overline{\chi}$) RH neutrino (N_i)

- heavy scalar scenario: $\phi \to \chi N_i$

- Freeze-in production of dark matter:





ν-Yukawa process $\propto Y^2 y^2$ dark sector process $\propto y^4$

↑ seesaw Yukawa

Chianese, Fu, King 1910.12916

- ν-Yukawa dominance: sizeable Y

Neutrino Portal Dark Matter in the Littlest Seesaw model

- Littlest Seesaw model: a highly predictive version of type I seesaw model with 2 RHNs
- ν-Yukawa interaction can dominate dark matter production when the RHN mass is above 4 TeV

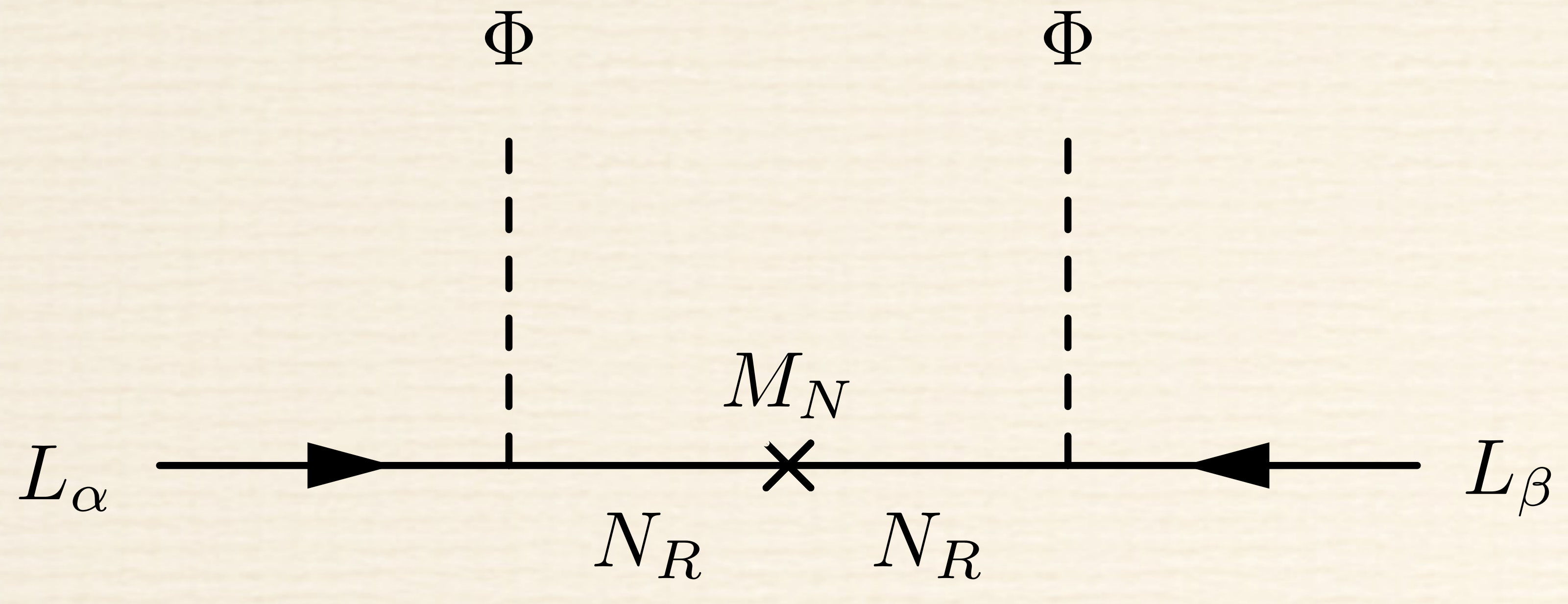
  Chianese, King 1806.10606
- Leptogenesis in the Littlest Seesaw model: $M_{R1} = 5.1 \times 10^{10}\ \text{GeV},\ M_{R2} = 3.3 \times 10^{14}\ \text{GeV}$

  King, Sedgwick, Rowley 1808.01005
- Production through graviton for superheavy particles Chianese, Fu, King 2009.01847
- Nevertheless, a ν-Yukawa dominant region can be found, but it is very hard to be tested by experiments

**Q: Can we find a model where ν-Yukawa dominance can appear for GeV scale heavy neutrino?
And perhaps compatible with leptogenesis?**

Type Ib Seesaw Model

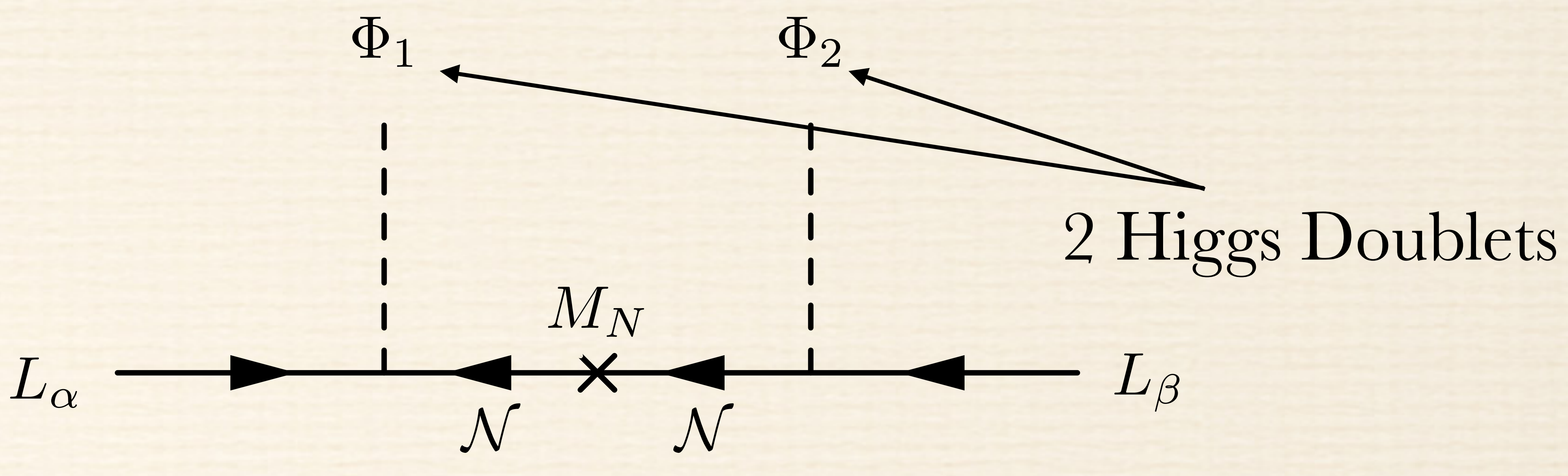
- Traditional type I seesaw mechanism (type Ia)



$$m \propto \frac{Y^2 v^2}{M_N}$$

- Type Ib seesaw mechanism

Hernandez-Garcia, King (2019)



$$m \propto \frac{Y_1 Y_2 v_1 v_2}{M_N}$$

- At least 2 Majorana RH neutrinos + 1 Higgs
- 1 Yukawa coupling for each RH neutrino
- 2 free parameters after considering neutrino mass an mixing: M_{R1} and M_{R2}
- To have a sizeable coupling, the right-handed neutrino has to be above TeV scale

- 1 Dirac neutrino +2 Higgs
- 1 Yukawa coupling for each Higgs
- 3 free parameters after considering neutrino mass an mixing: Y_1, Y_2 and M_N
- One of Y_1, Y_2 can be small while the other one is sizeable, providing GeV scale heavy neutrino

Neutrino Portal Dark Matter

Type Ib Seesaw Model with a Neutrino Portal

- Particles and symmetries

	Q_α	$u_{R\beta}$	$d_{R\beta}$	L_α	$e_{R\beta}$	Φ_1	Φ_2	$N_{\rm R1}$	$N_{\rm R2}$	ϕ	$\chi_{L,R}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0	0
Z_3	1	ω	ω	1	ω	ω	ω^2	ω^2	ω	ω	ω^2
Z_2	+	+	+	+	+	+	+	+	+	$-$	$-$

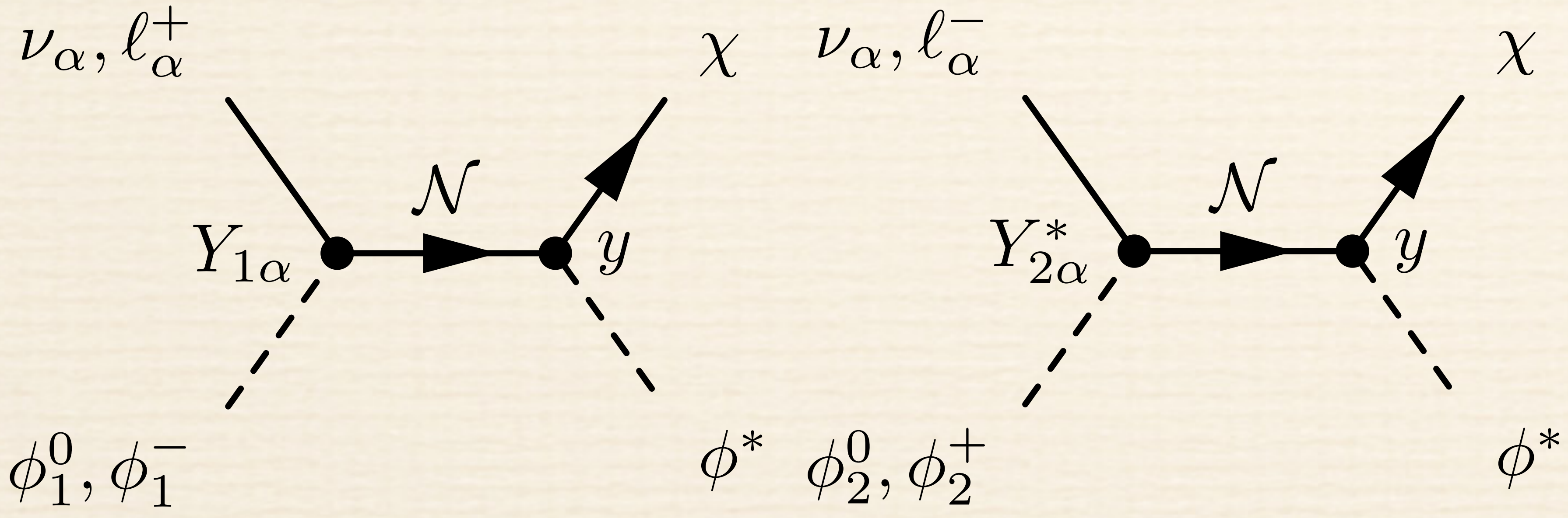
- Seesaw Lagrangian and neutrino portal $\mathcal{N} = (N_{R1}^c, N_{R2})$

Chianese, Fu, King 2102.07780

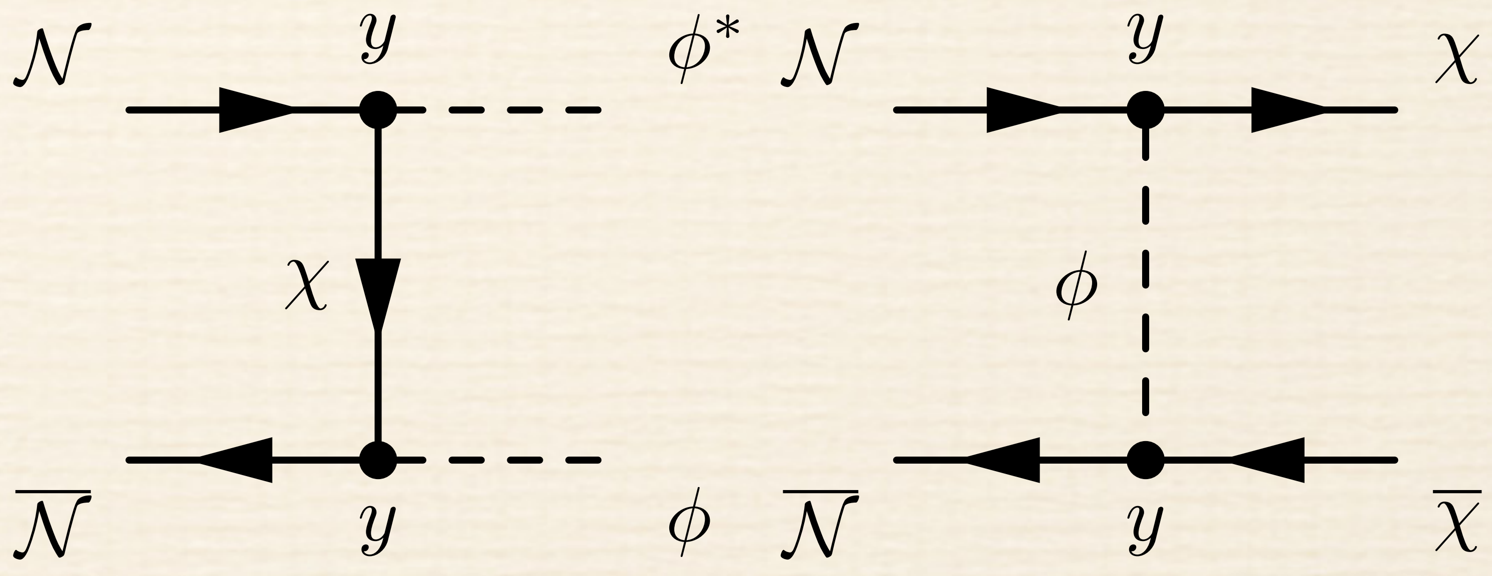
$$\mathcal{L}_{\rm seesawIb} = -Y_{1\alpha}^* \overline{L^c}_\alpha \Phi_1^* \mathcal{N}_L - Y_{2\alpha} \overline{L}_\alpha \Phi_2 \mathcal{N}_R - M_N \overline{\mathcal{N}_L} \mathcal{N}_R + \text{h.c.}$$

$$\mathcal{L}_{\rm N_R portal} = y\phi\,\overline{\chi}\mathcal{N} + \text{h.c.}$$

- Freeze-in production of dark matter

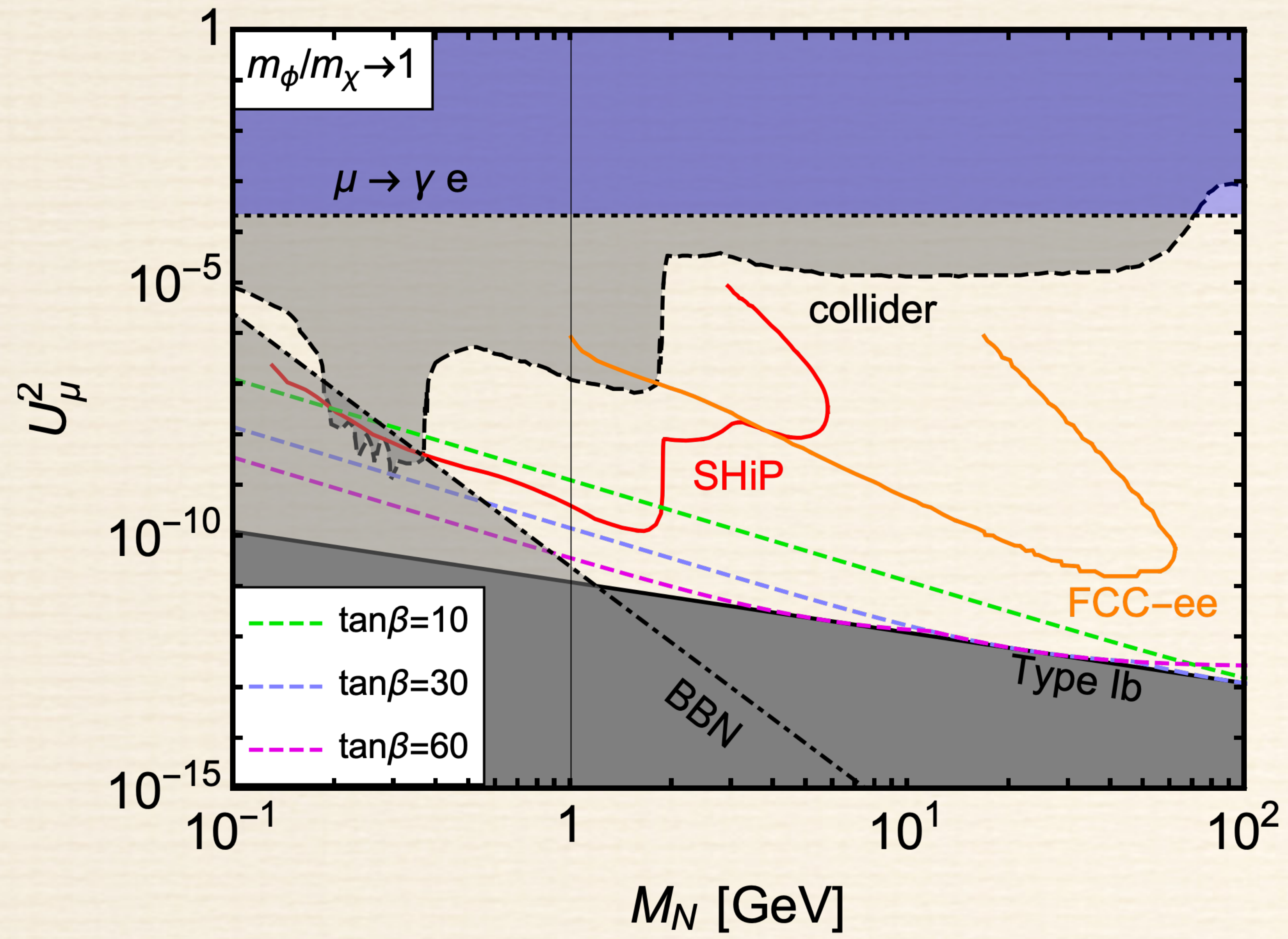


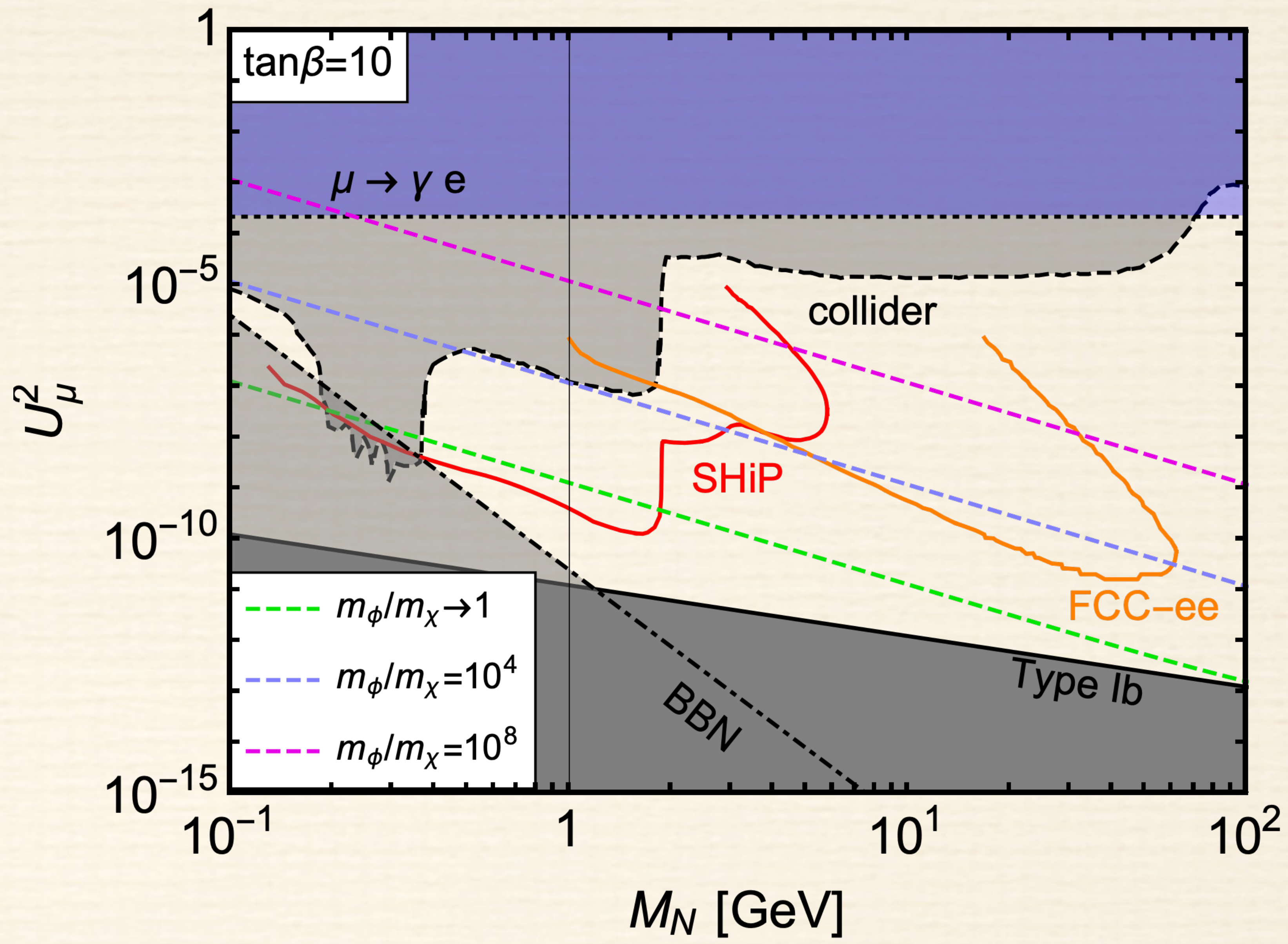
Neutrino-Yukawa processes



Dark sector processes

Relation to Experiments





Chianese, Fu, King 2102.07780

- 2 key parameters:
  - tanβ: the ratio of VEVs of the Higgs v_2/v_1
  - m_ϕ/m_χ: For hierarchical mass spectrum, the dark matter production depends on m_ϕ/m_χ
- U^2: active-sterile neutrino mixing strength

- The strongest constraint is given by ν_μ mixing
- ν-Yukawa dominance is allowed above the coloured dashed lines
- Less constrained as tanβ increases
- More constrained as m_ϕ/m_χ increases

Leptogenesis

Resonant Leptogenesis in Type Ib Seesaw Model

- An extended model with a superheavy third RHN and scalar field

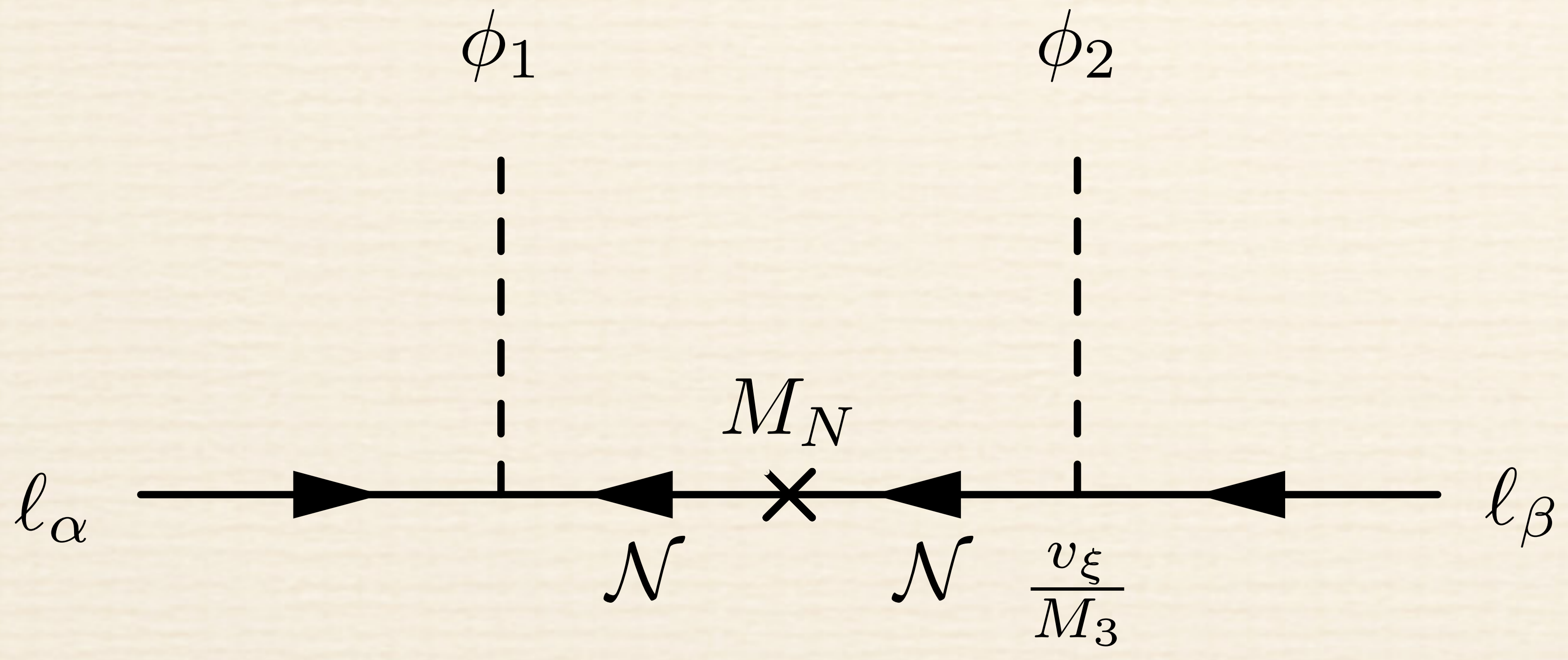
$$\mathcal{L}_{\text{seesawIb}} = -Y_{1\alpha}\overline{\ell}_\alpha \phi_1 N_{R1} - Y_{3\alpha}\overline{\ell}_\alpha \phi_2 N_{R3} - 2Y_{13}\overline{\xi}\,\overline{N^c_{R3}} N_{R1} - 2Y_{23}\xi \overline{N^c_{R3}} N_{R2}$$
$$- M\overline{N^c_{R1}} N_{R2} - \frac{1}{2} M_3 \overline{N^c_{R3}} N_{R3} + \text{h.c.}$$

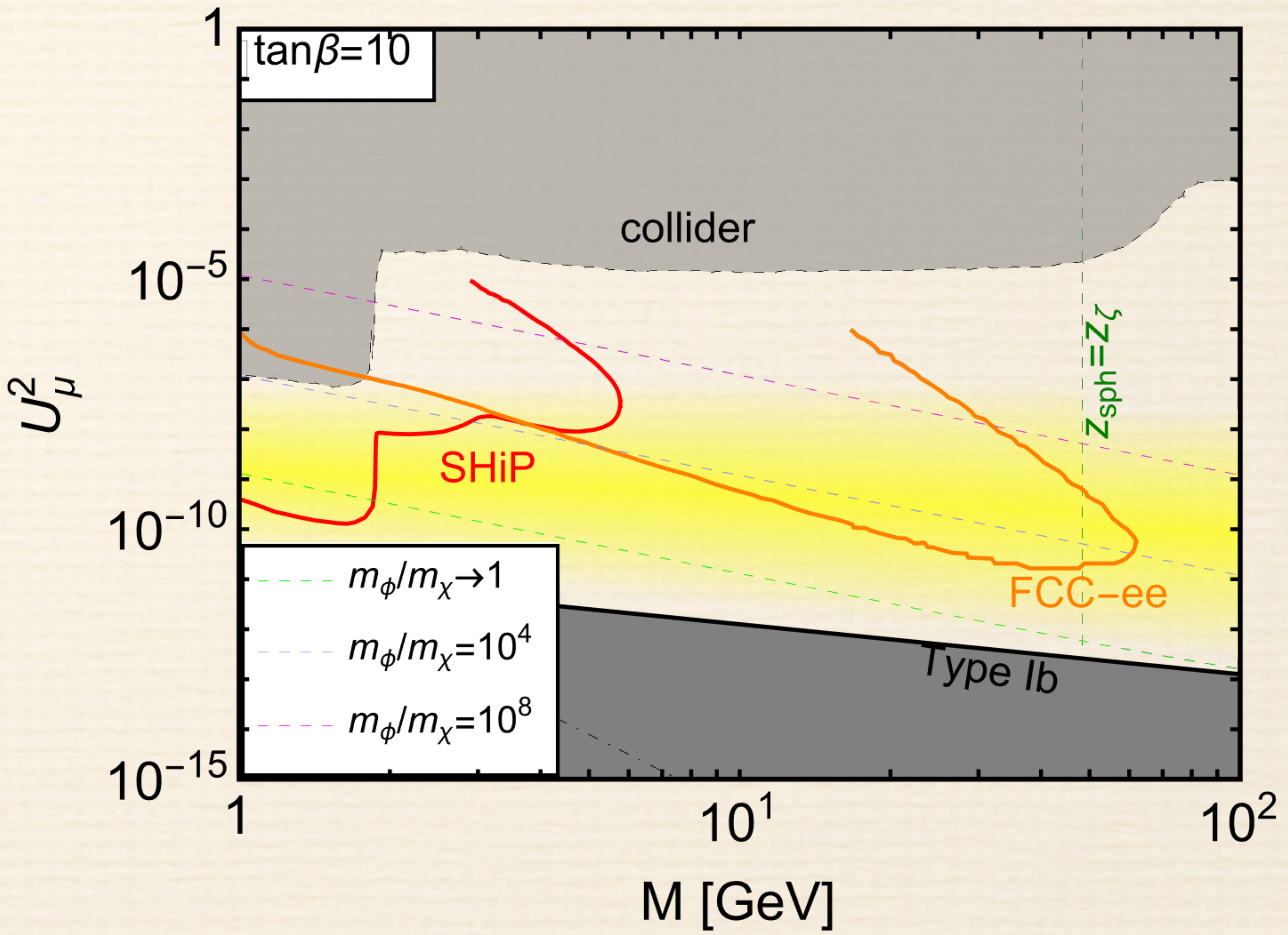
Fu, King 2107.01486

- N_{R1} and N_{R2} gain mass splitting through mixing with N_{R3}

$$M_N = \begin{pmatrix} 0 & M & M_{13} \\ M & 0 & M_{23} \\ M_{13} & M_{23} & M_3 \end{pmatrix} \qquad \Delta M_{12} = \frac{\Re\left[(M_{13} - M_{23})^2\right]}{2M_{33}}$$

- Type Ib seesaw mechanism can be realised effectively at low scale





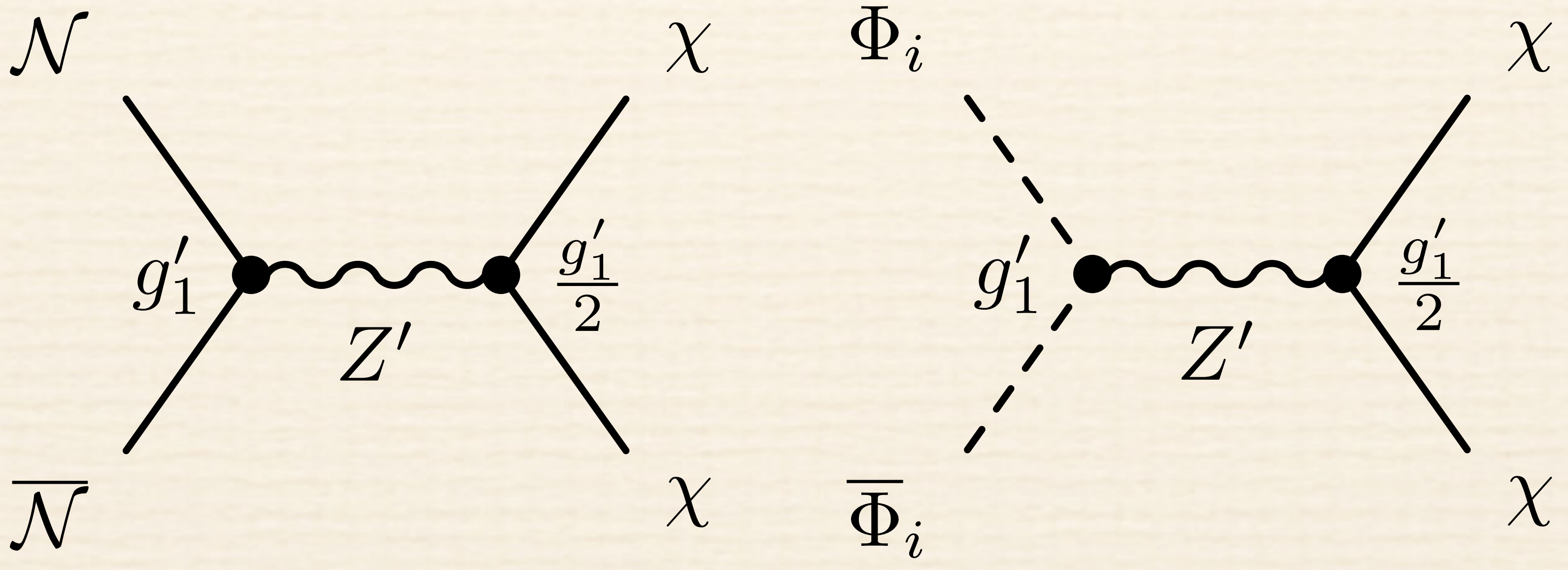
Vector Portal

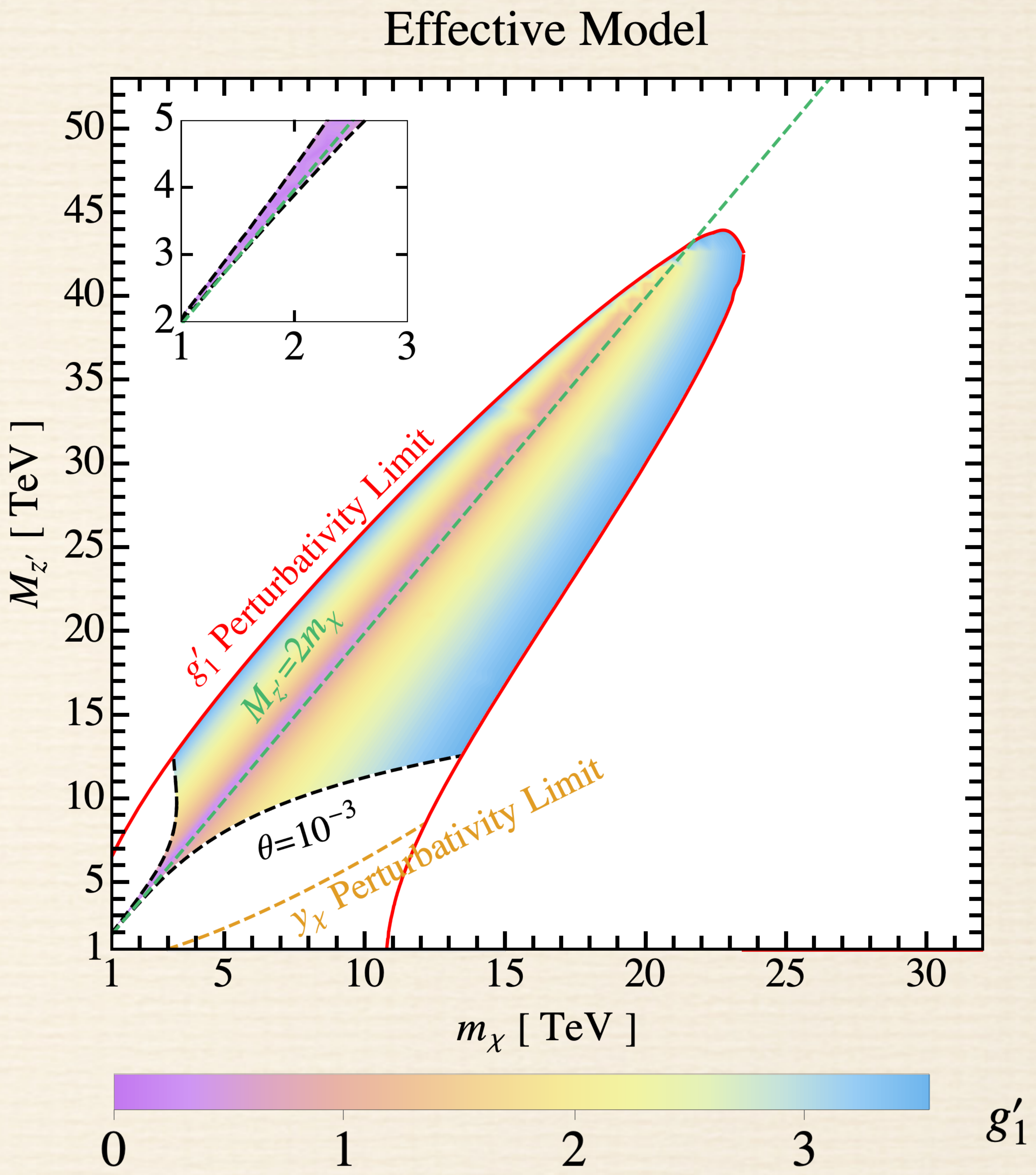
Type Ib Seesaw Model with a U(1)’ Symmetry

- Dirac neutrino — can be charged under gauge symmetry
- Particles and symmetries

	$\mathcal{N}$	$\chi_{L,R}$	ϕ
$SU(2)_L$	**1**	**1**	**1**
$U(1)_Y$	0	0	0
$U(1)'$	1	$\frac{1}{2}$	1

- Majorana dark matter candidate $y_\chi^L \overline{\phi}\, \overline{\chi_L^c} \chi_L + y_\chi^R \overline{\phi}\, \overline{\chi_R^c} \chi_R + h.c.$
- After ϕ gains a VEV, the U(1)’ symmetry is broken into a Z_2 symmetry, under which only χ is charged
- Freeze-out production of DM





Fu, King 2110.00588

Summary

- Features of Type Ib Seesaw Model
  - 3 free parameters after considering neutrino mass and mixing
  - Allow a connection between dark matter and neutrino physics through neutrino portal with GeV scale heavy neutrino
  - Resonant leptogenesis can be realised
  - A Dirac neutrino that can be charged under a U(1)’ gauge symmetry

Thank You!

Leptogenesis in Type Ib Seesaw Model

- In the minimal type Ib seesaw model, the correct asymmetry cannot be produced because the heavy neutrino mass is completely degenerate
- Minimal extension of the type Ib seesaw model: a pseudo-Dirac neutrino

$$\mathcal{L}_{\rm seesawIb} = \quad -Y_{1\alpha}\overline{\ell}_\alpha\phi_1 N_{R1} - Y_{2\alpha}\overline{\ell}_\alpha\phi_2 N_{R2} - M\overline{N^c_{R1}}N_{R2} - \Delta M\,\overline{N^c_{R2}}N_{R2} + \text{h.c.}$$

- In the Majorana basis, the phases of Yukawa couplings between RH neutrinos and Higgs bosons differ by π/2
- In a general theory with Yukawa interaction $e^{i\theta_{ik\alpha}}Y_{ik\alpha}\overline{\ell_\alpha}\phi_k n_{R_i}$

$$\left(\epsilon_{n_i}^{\rm wave-function}\right)_{k\alpha} \propto \sum_{j\neq i}\sum_{l,\beta} Y_{ik\alpha}Y_{jk\alpha}Y_{il\beta}Y_{jl\beta}\sin\left(\theta_{ik\alpha}-\theta_{jk\alpha}+\theta_{il\beta}-\theta_{jl\beta}\right)$$

- In the extension of the type Ib seesaw model with a superheavy third RHN and scalar field, an extra phase difference is developed as $(\theta_2-\theta_1)$

$$\tan\theta_1 \simeq -\frac{1}{2MM_{33}}\Im\left[(M_{13}+M_{23})^2\right], \quad \tan\theta_2 \simeq \frac{1}{2MM_{33}}\Im\left[(M_{13}-M_{23})^2\right].$$

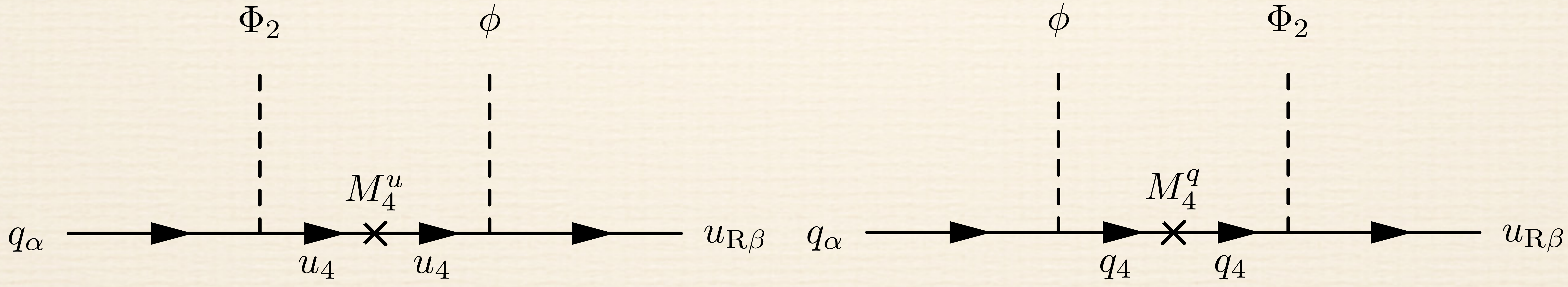
Type Ib Seesaw Model with a U(1)' Symmetry

- Fourth family of vector-like fermions

	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	q_4	u_4	d_4	ℓ_4	e_4	Φ_1	Φ_2	$\mathcal{N}$	χ_R	ϕ
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0
$U(1)'$	0	0	0	0	0	-1	1	1	-1	1	1	-1	1	$\frac{1}{2}$	1

- Due to the U(1)' charges of the Higgs doublets, the charged fermions can only gain mass from non-renormalisable operators $\overline{q_L}_\alpha \Phi_2 u_{R\beta}\phi$, $\overline{q_L}_\alpha \tilde{\Phi}_1 d_{R\beta}\phi$, $\overline{\ell}_\alpha \tilde{\Phi}_1 e_{R\beta}\phi$

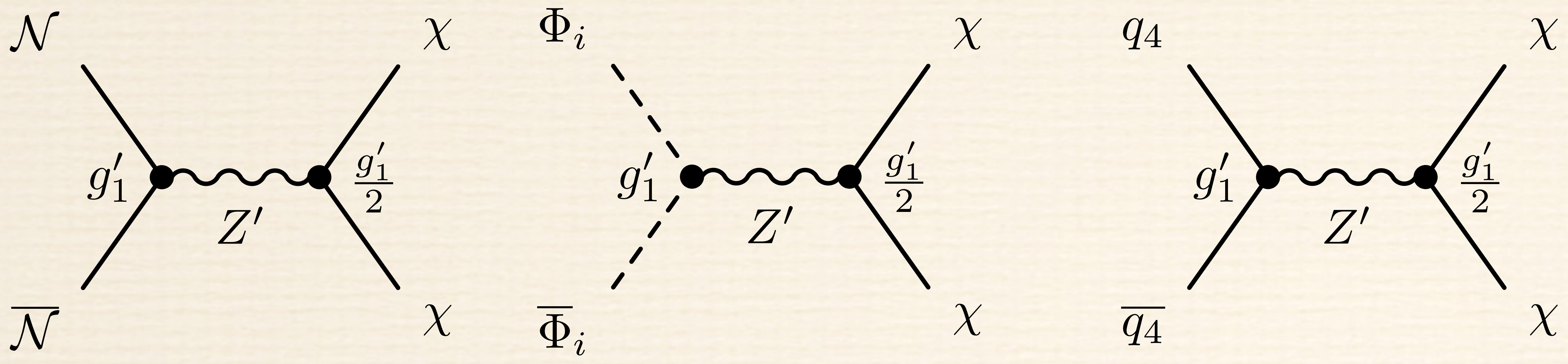
- Fourth family of vector-like fermions: an example of up-type quark mass



Fu, King 2110.00588

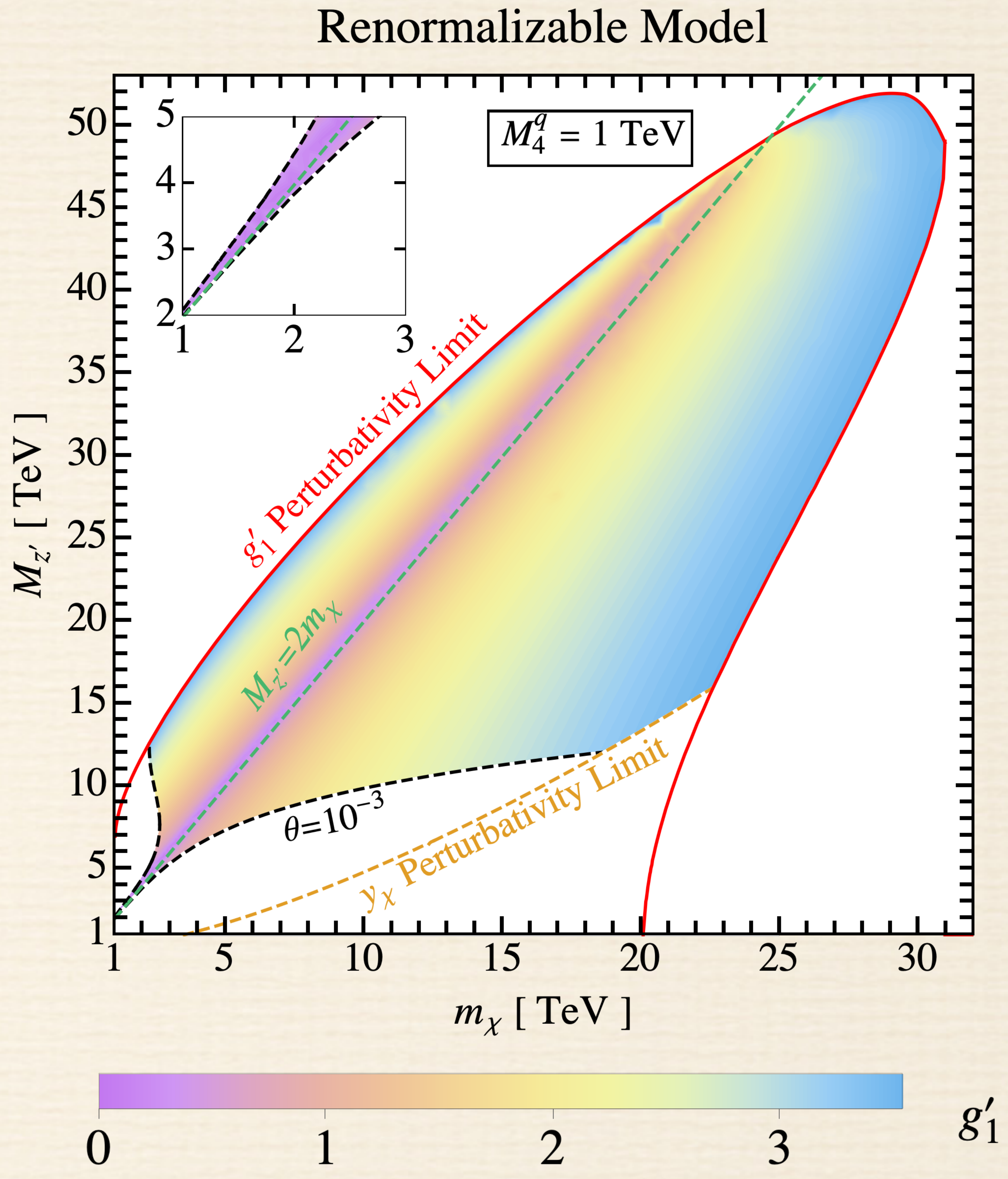
Type Ib Seesaw Model with a U(1)' Symmetry

- Freeze-out production of DM



- Resonance in DM production when $M_{Z'} \sim 2m_\chi$
  - Boltzmann suppression below the freeze-out temperature $T_f \sim m_\chi/20$
  - Resonant amplitude

$$|\mathcal{M}|^2 \propto \frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$



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