Neutrino Mass and the Early Universe

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The 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

Outline

- Neutrino portal dark matter in type I seesaw model: limitation
- Type Ib seesaw model
  - Neutrino portal dark matter
  - Resonant leptogenesis

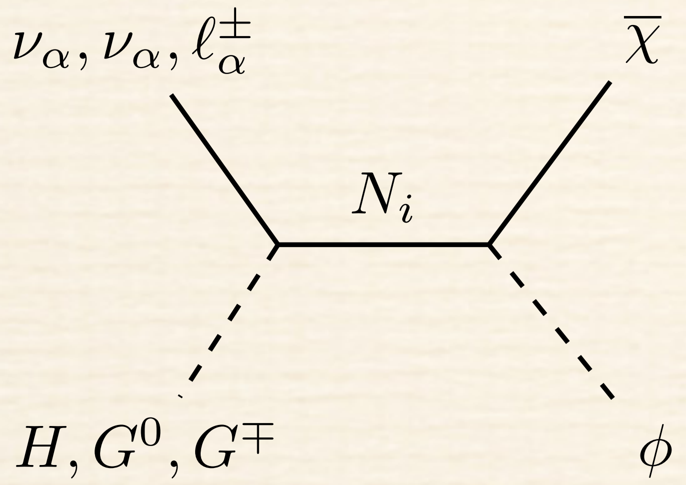
Neutrino Portal Dark Matter

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

dark scalar dark fermion RH neutrino

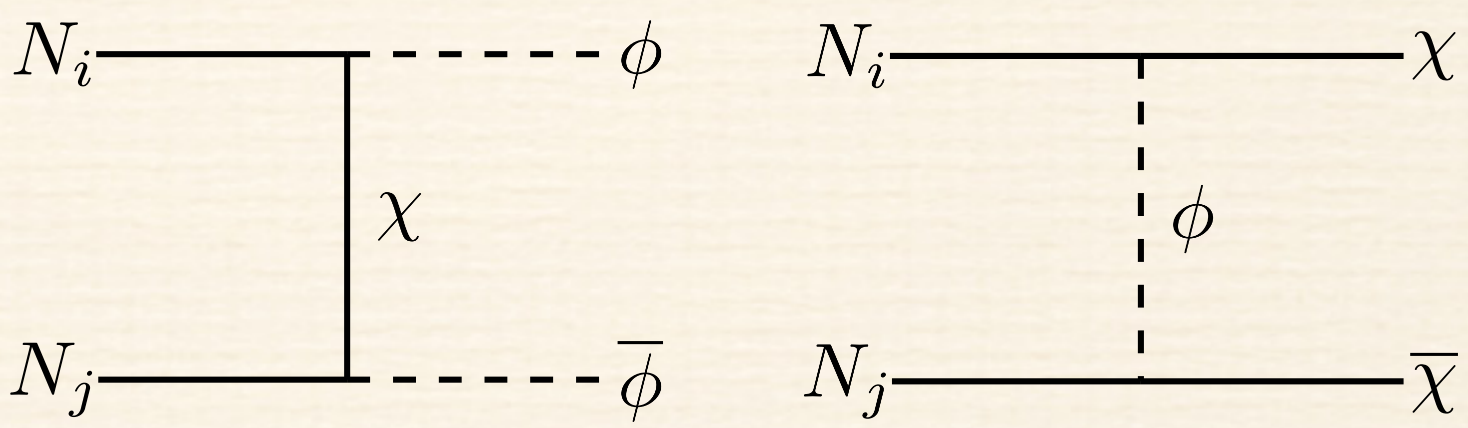
- heavy scalar scenario: $\phi \to \chi N_i$

- Freeze-in production of dark matter:



ν-Yukawa process $\propto Y^2 y^2$

seesaw Yukawa



dark sector process $\propto y^4$

- ν-Yukawa dominance: sizeable Y

Chianese, Fu, King JCAP 03 (2020) 030

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 JCAP 09 (2018) 027

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

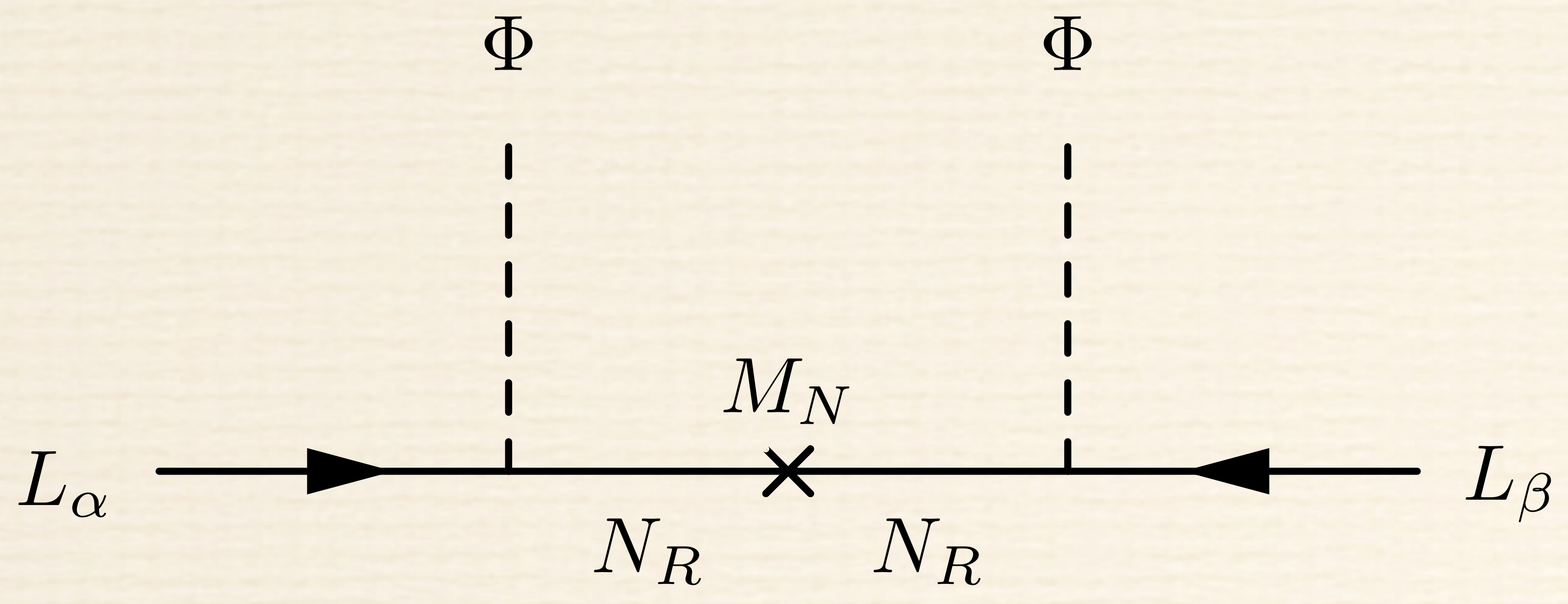
King, Sedgwick, Rowley JHEP 10 (2018) 184

- Production through graviton for superheavy particles Chianese, Fu, King JCAP 01 (2021) 034
- 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)

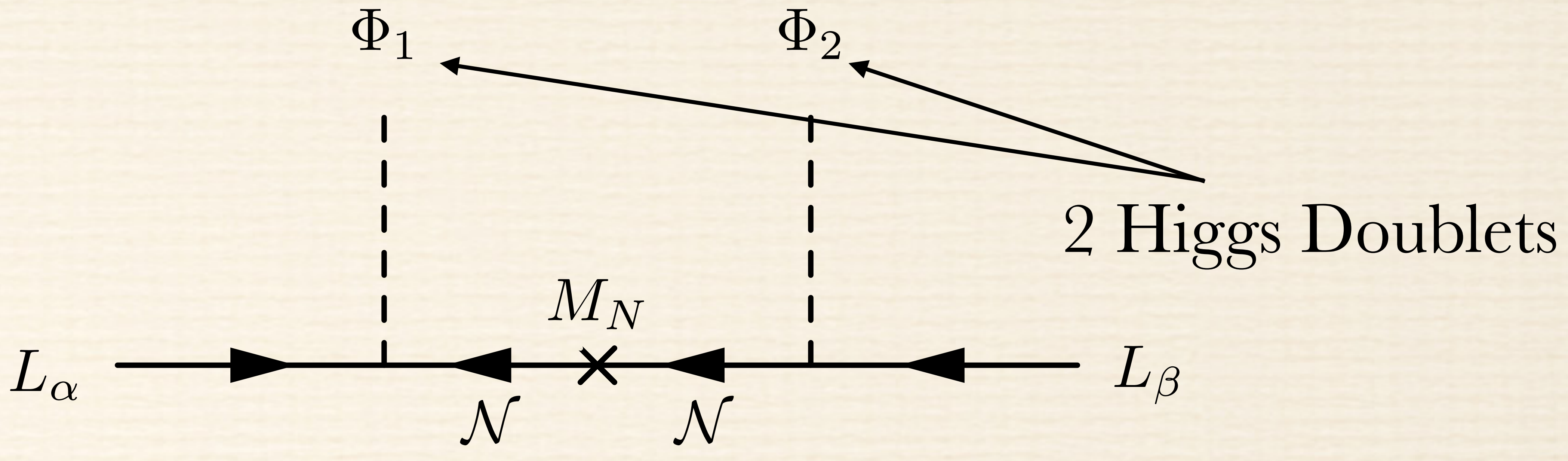


$$m \propto \frac{Y^2 v^2}{M_N}$$

- 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

- Type Ib seesaw mechanism

Hernandez-Garcia, King JHEP 05 (2019) 169



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

- 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	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

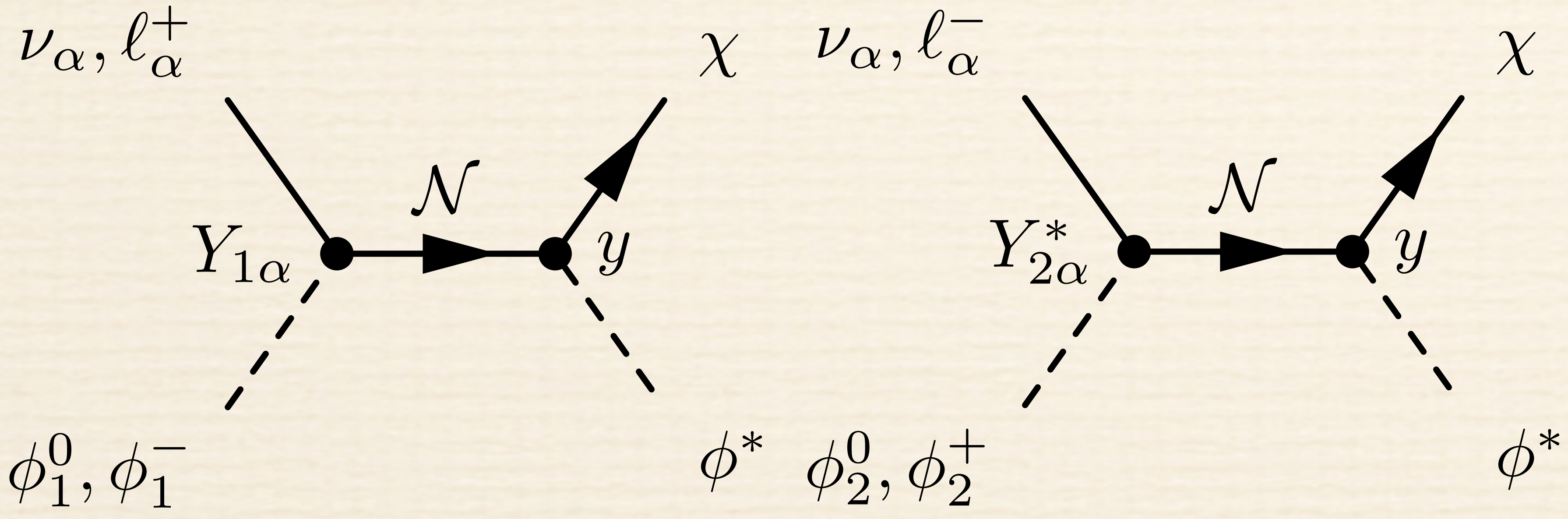
- Seesaw Lagrangian and neutrino portal $\mathcal{N} = (N^c_{R1}, N_{R2})$

Chianese, Fu, King JHEP 05 (2021) 129

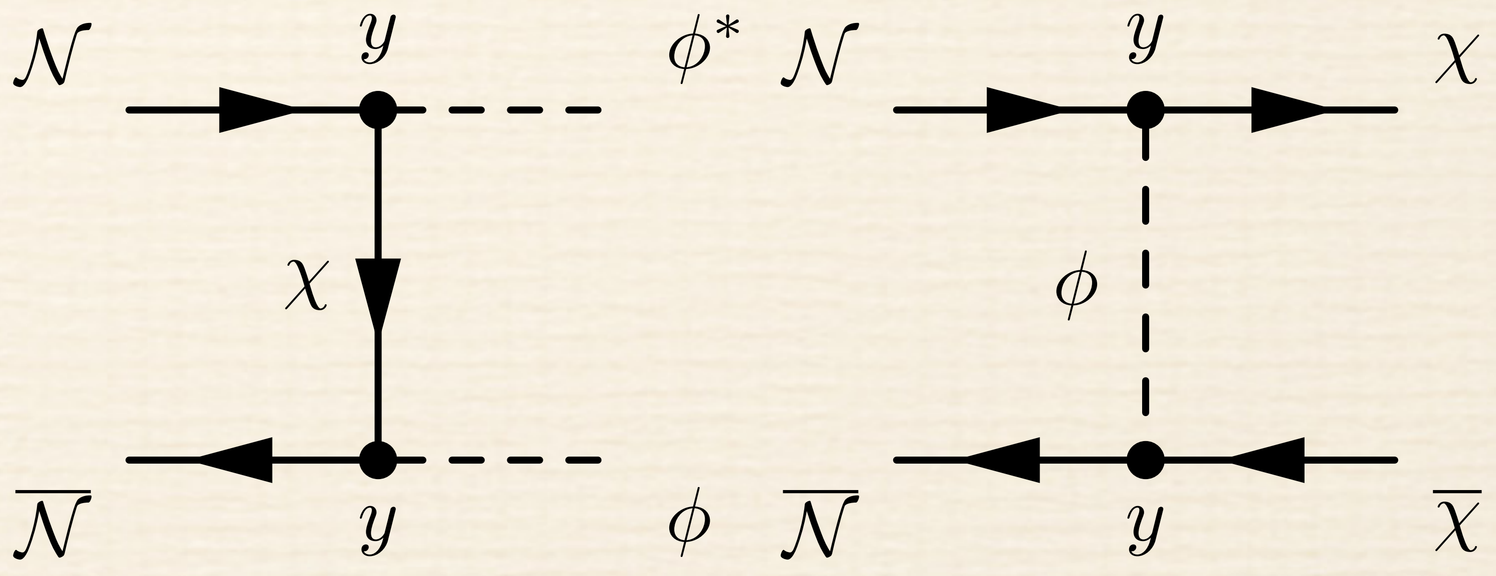
$$\mathcal{L}_{\rm seesawIb} = -Y^*_{1\alpha}\overline{L^c}_\alpha \Phi^*_1 \mathcal{N}_L - Y_{2\alpha}\overline{L}_\alpha \Phi_2 \mathcal{N}_R - M_N \overline{\mathcal{N}_L}\mathcal{N}_R + \text{h.c.}$$

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

- Freeze-in production of dark matter

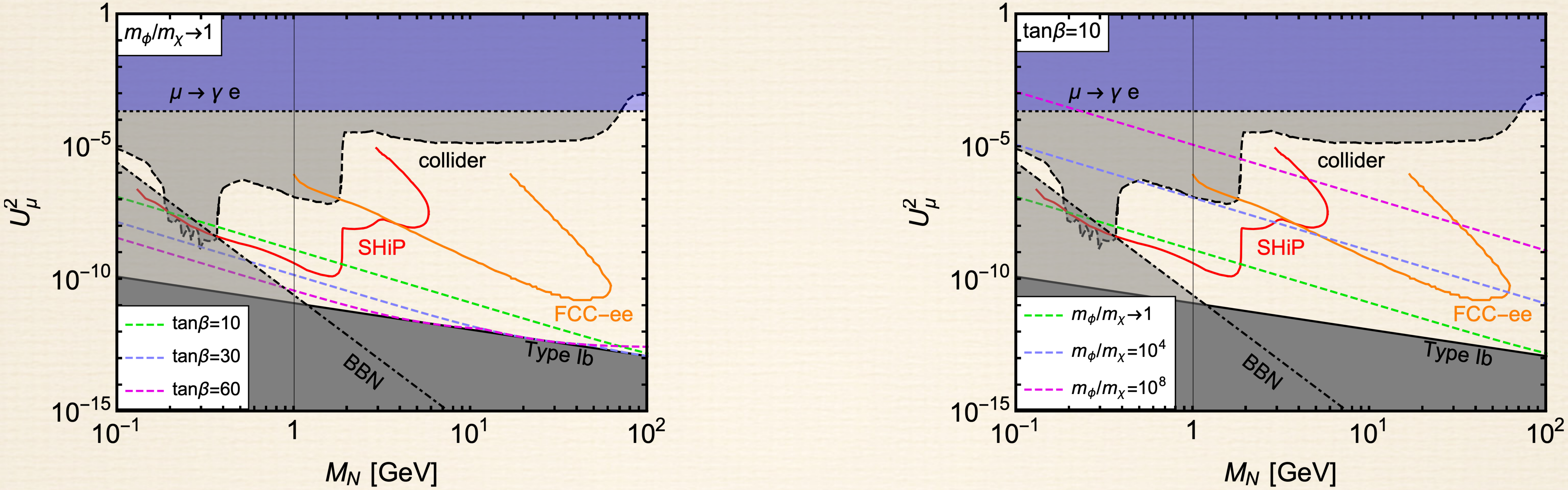


Neutrino-Yukawa processes



Dark sector processes

Relation to Experiments



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- 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 a scalar field

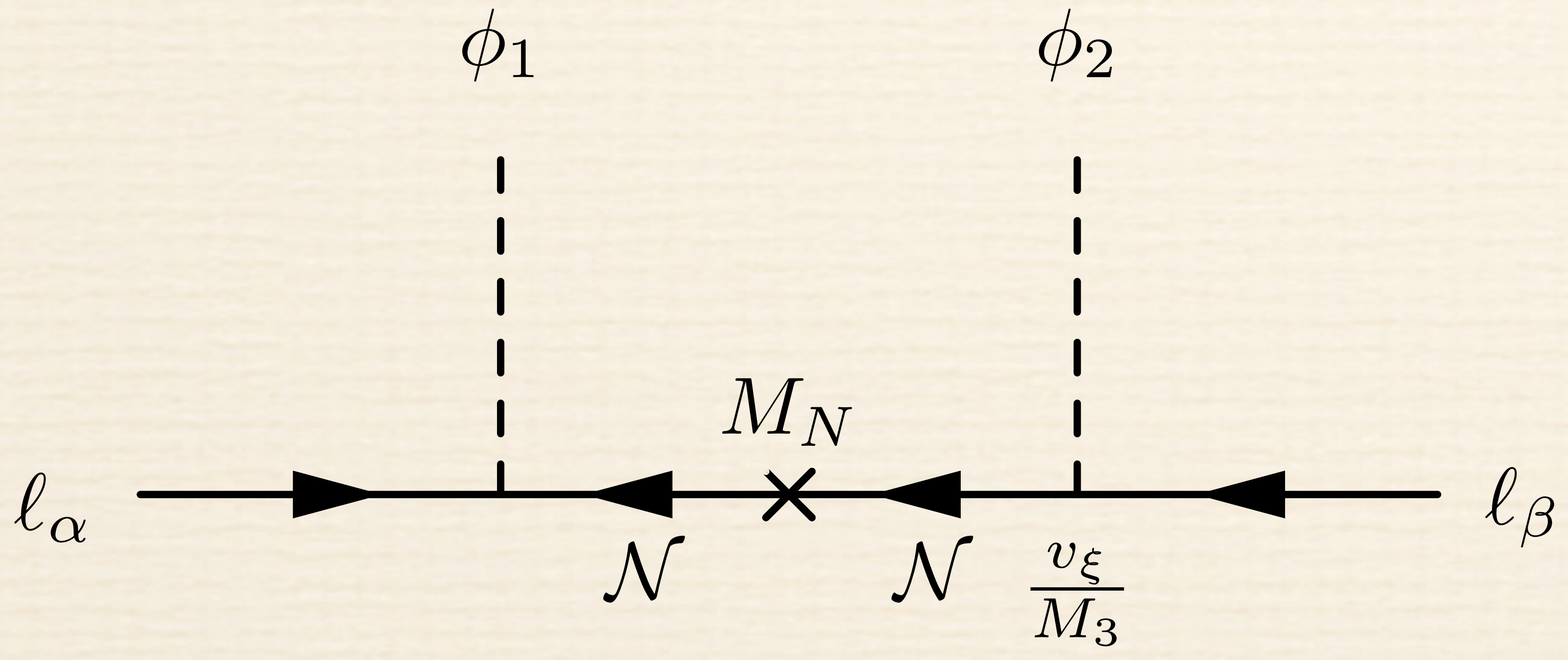
$$\mathcal{L}_{\mathrm{seesawIb}} = -Y_{1\alpha}\overline{\ell}_\alpha\phi_1 N_{R1} - Y_{3\alpha}\overline{\ell}_\alpha\phi_2 N_{R3} - 2Y_{13}\overline{\xi}\,\overline{N^c_{R3}}N_{R1} - 2Y_{23}\xi\overline{N^c_{R3}}N_{R2} - M\overline{N^c_{R1}}N_{R2} - \frac{1}{2}M_3\overline{N^c_{R3}}N_{R3} + \mathrm{h.c.}$$

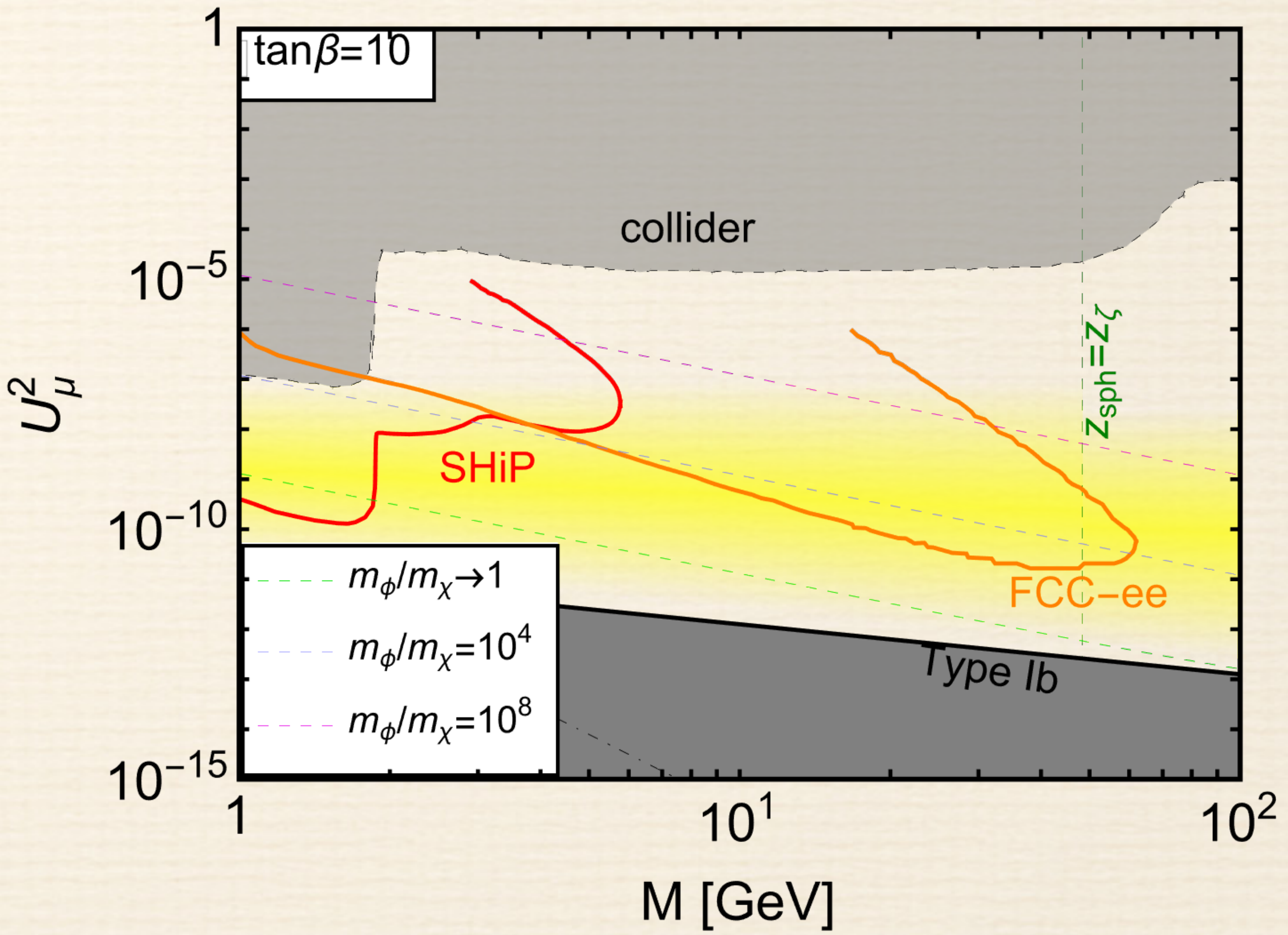
Fu, King Phys.Rev.D 105 (2022) 9, 095001

- After the scalar field gains a VEV, 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





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

Thank You!

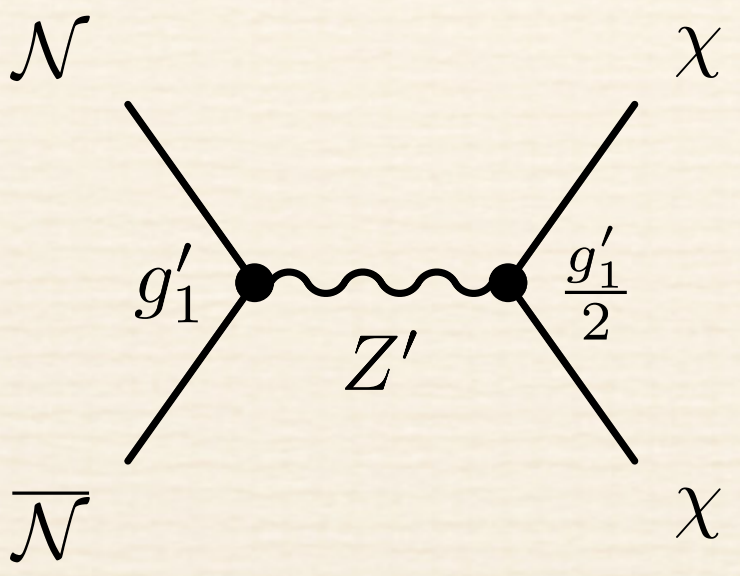
Backups

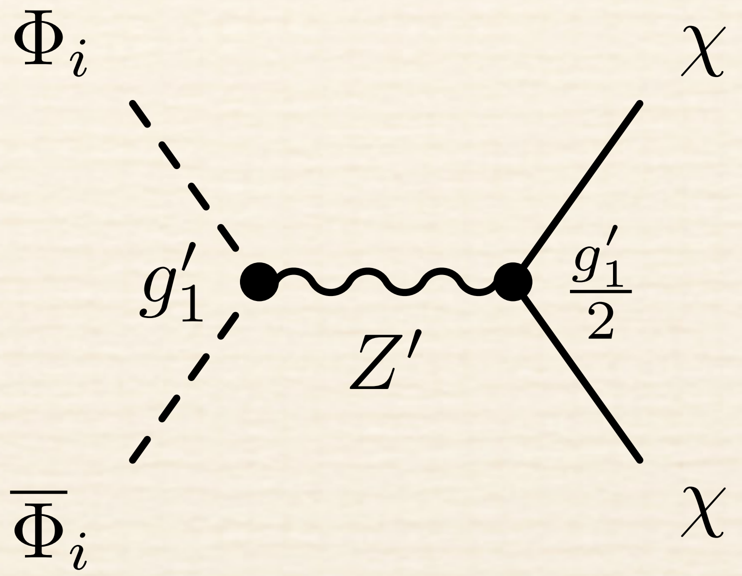
Type Ib Seesaw Model with a U(1)’ Symmetry

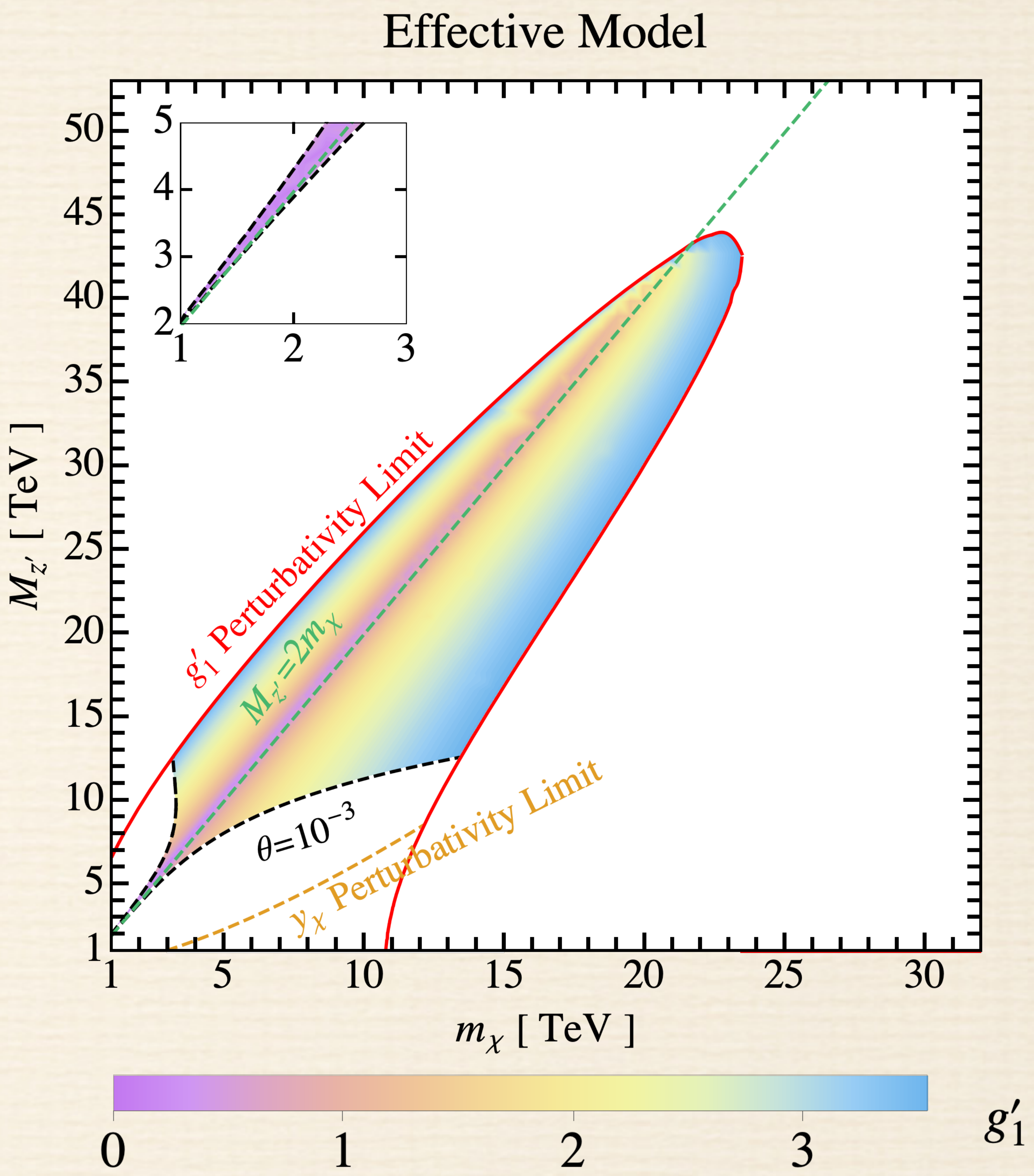
- Dirac neutrino — can be charged under gauge symmetry
- Particles and symmetries

	$\mathcal{N}$	$\chi_{L,R}$	ϕ
$SU(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	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







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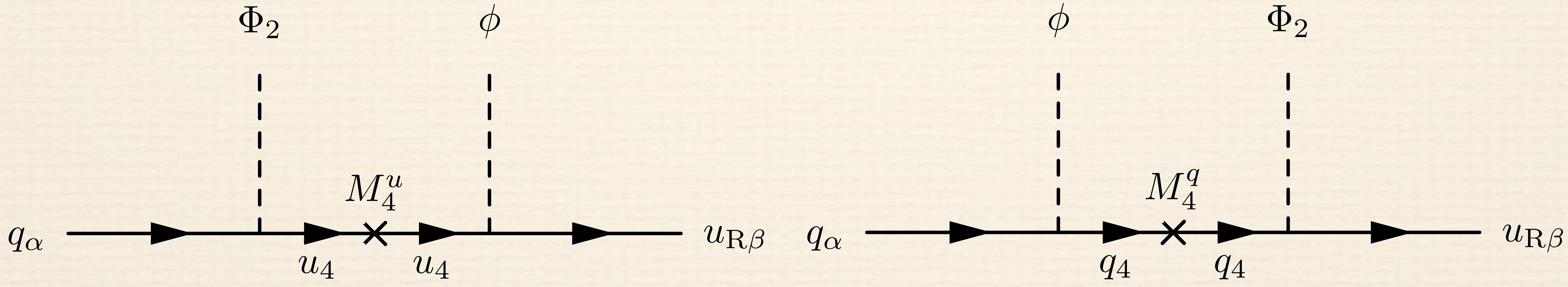
Type Ib Seesaw Model with a U(1)' Symmetry

- 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
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-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 $\overline{q_L}_\alpha \Phi_2 u_{R\beta}\phi$, $\overline{q_L}_\alpha \tilde{\Phi}_1 d_{R\beta}\phi$, $\bar{\ell}_\alpha \tilde{\Phi}_1 e_{R\beta}\phi$
- Fourth family of vector-like fermions: an example of up-type quark mass



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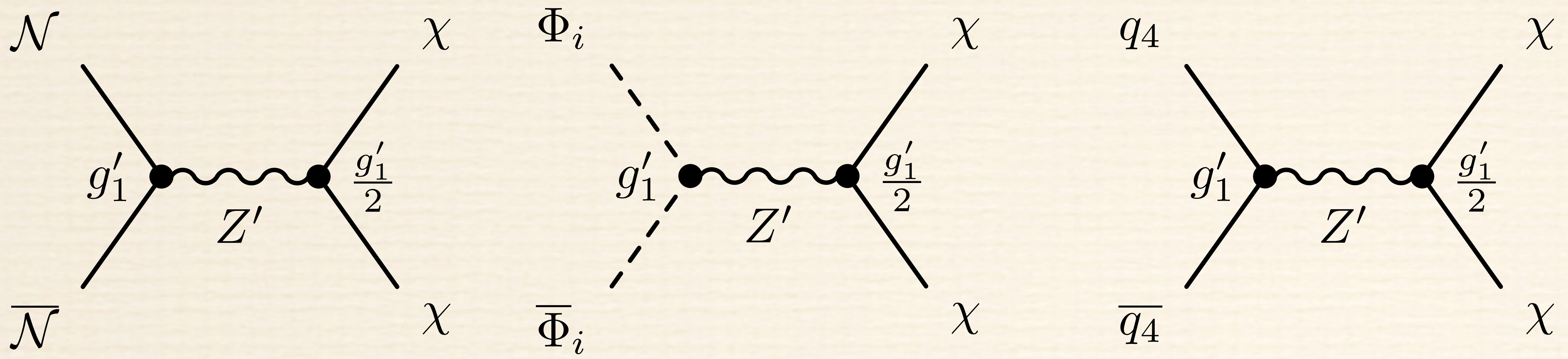
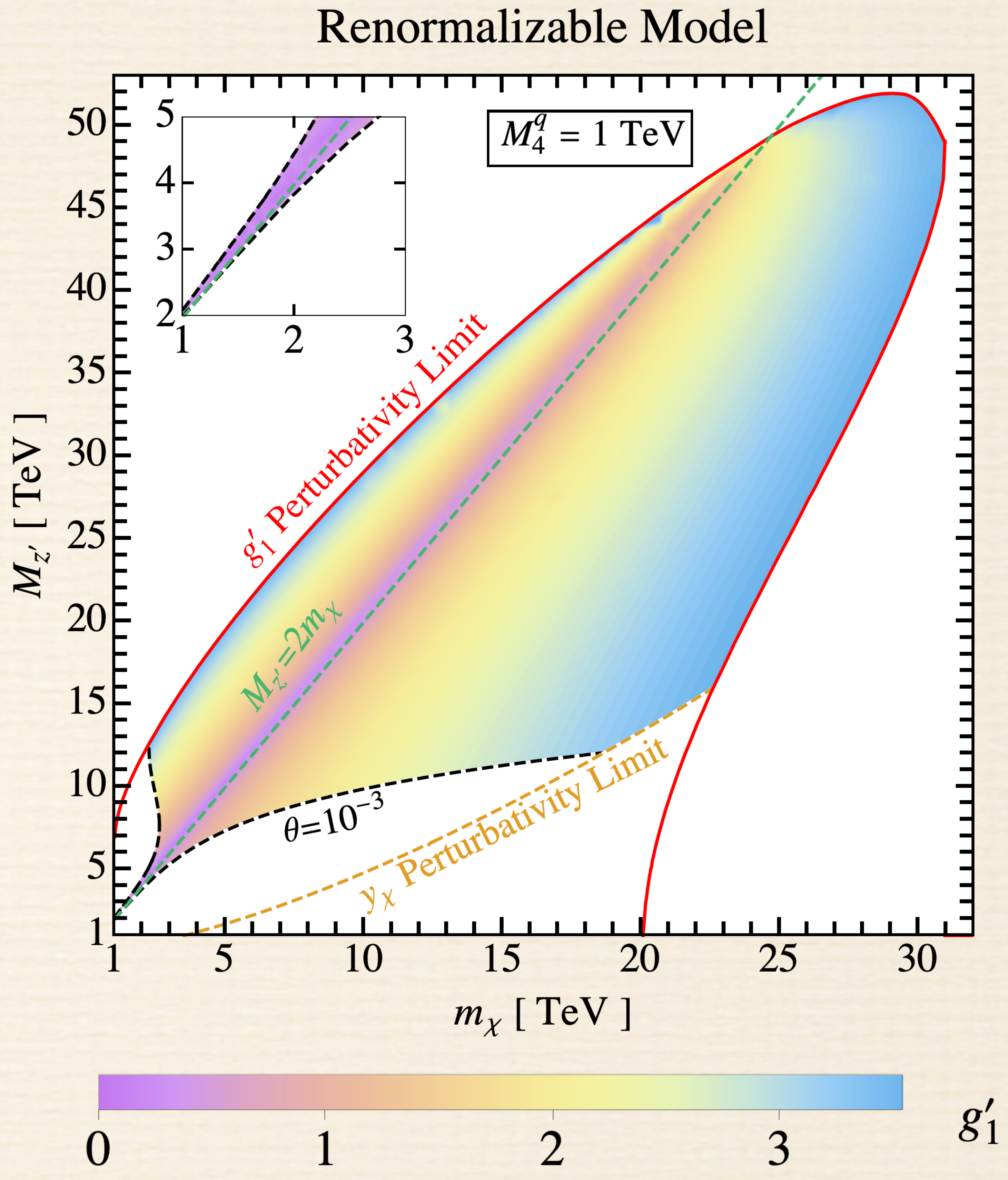
Type Ib Seesaw Model with a U(1)' Symmetry

- 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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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

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

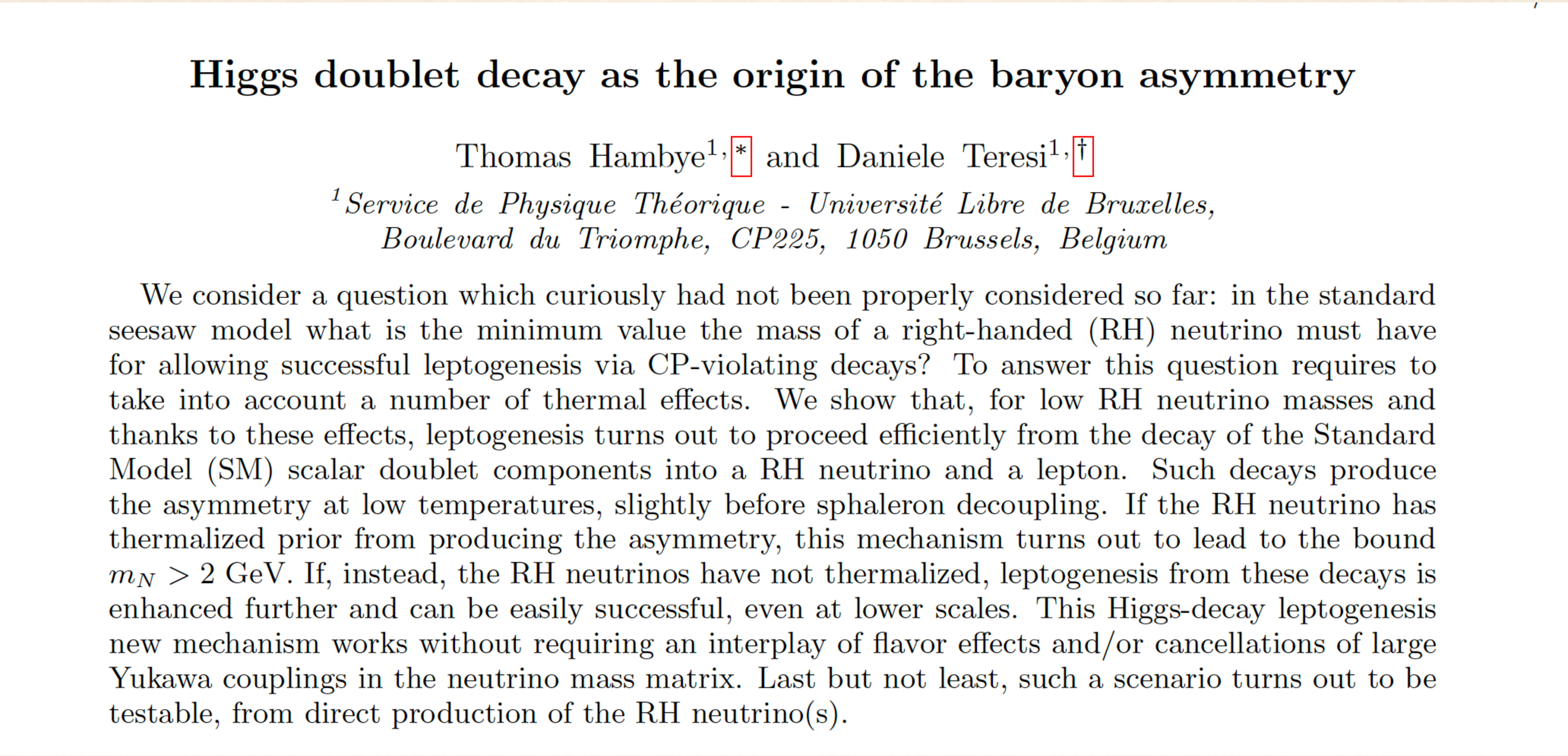
- In the Majorana basis, the phases of Yukawa couplings between RH neutrinos and Higgs bosons differ by $\pi/2$
- In a general theory with Yukawa interaction $e^{i\theta_{ik\alpha}}Y_{ik\alpha}\overline{\ell_{\alpha}}\phi_k n_{R_i}$

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

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

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

Leptogenesis with GeV scale neutrinos



Higgs doublet decay as the origin of the baryon asymmetry

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We consider a question which curiously had not been properly considered so far: in the standard seesaw model what is the minimum value the mass of a right-handed (RH) neutrino must have for allowing successful leptogenesis via CP-violating decays? To answer this question requires to take into account a number of thermal effects. We show that, for low RH neutrino masses and thanks to these effects, leptogenesis turns out to proceed efficiently from the decay of the Standard Model (SM) scalar doublet components into a RH neutrino and a lepton. Such decays produce the asymmetry at low temperatures, slightly before sphaleron decoupling. If the RH neutrino has thermalized prior from producing the asymmetry, this mechanism turns out to lead to the bound $m_N > 2$ GeV. If, instead, the RH neutrinos have not thermalized, leptogenesis from these decays is enhanced further and can be easily successful, even at lower scales. This Higgs-decay leptogenesis new mechanism works without requiring an interplay of flavor effects and/or cancellations of large Yukawa couplings in the neutrino mass matrix. Last but not least, such a scenario turns out to be testable, from direct production of the RH neutrino(s).