

Spontaneously stabilised dark matter from a fermiophobic $U(1)'$ gauge symmetry



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Discrete Symmetries in Model Building

- ❖ Stabilising dark matter candidate
- ❖ Avoid flavor changing processes in 2HDM: type I, type II, ...
- ❖ R-parity in supersymmetry
- ❖ SM: no discrete symmetry, only gauge symmetries and accidental (approximate) global symmetries
- ❖ Spontaneous discrete symmetry from gauge symmetry breaking
 - Suppose there is a $U(1)'$ symmetry under which particles have either integer or half-integer charges
 - The $U(1)'$ symmetry is broken by the VEV of a scalar field which has a integer charge
 - There is a remaining Z_2 symmetry under which only the particles with half-integer $U(1)'$ charges are odd

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

- ❖ Particles and symmetries

	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	Φ_1	Φ_2	N_{R1}	N_{R2}	$\chi_{L,R}$	ϕ
$SU(2)_L$	2	1	1	2	1	2	2	1	1	1	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
$U(1)'$	0	0	0	0	0	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-

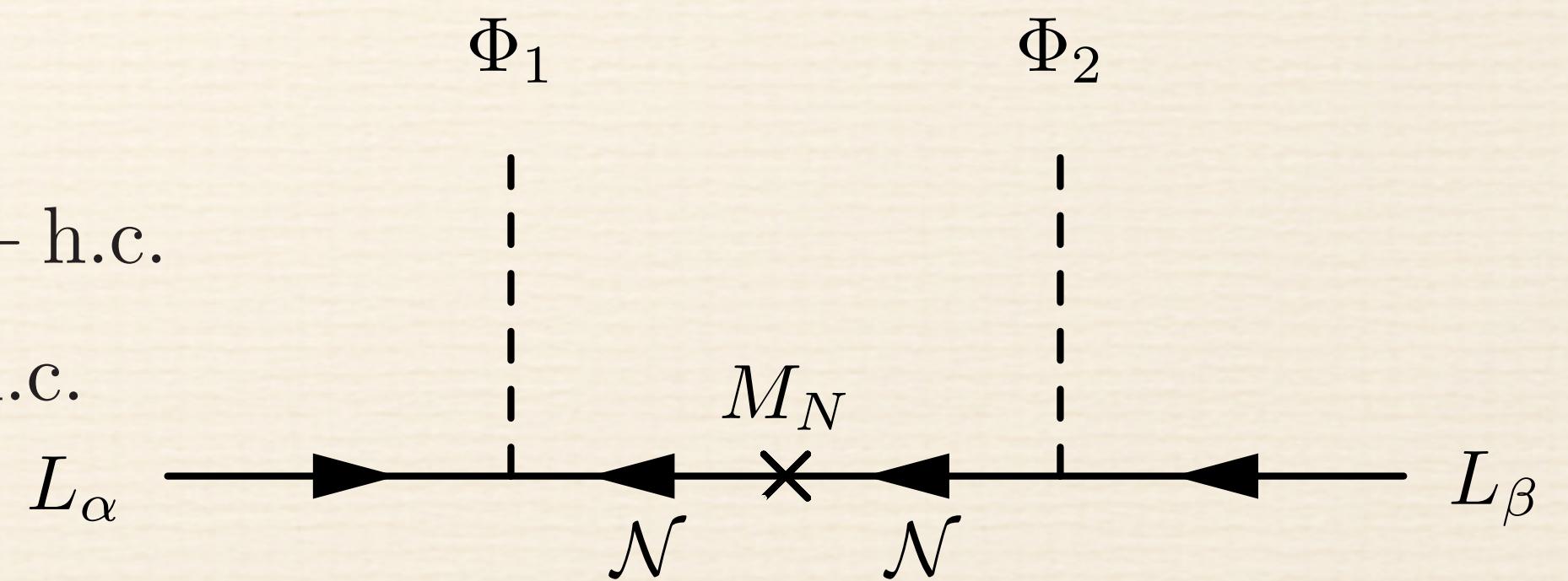
renormalisable operators $\overline{q_L}_\alpha \Phi_2 u_{R\beta} \phi$, $\overline{q_L}_\alpha \tilde{\Phi}_1 d_{R\beta} \phi$, $\bar{\ell}_\alpha \tilde{\Phi}_1 e_{R\beta} \phi$ $\overline{q_L}_\alpha \Phi_1 u_{R\beta} \phi^*$, $\overline{q_L}_\alpha \tilde{\Phi}_2 d_{R\beta} \phi^*$, $\bar{\ell}_\alpha \tilde{\Phi}_2 e_{R\beta} \phi^*$

$$\mathcal{L}_{\text{2HDM}} \supset -Y_{\alpha\beta}^u \overline{q_L}_\alpha \Phi_2 u_{R\beta} - Y_{\alpha\beta}^d \overline{q_L}_\alpha \tilde{\Phi}_1 d_{R\beta} - Y_{\alpha\beta}^e \bar{\ell}_\alpha \tilde{\Phi}_1 e_{R\beta} + \text{h.c.}$$

- ❖ Type Ib Seesaw Lagrangian $\mathcal{N} = (N_{R1}^c, N_{R2})$

$$\mathcal{L}_{\text{seesawIb}} = -Y_{1\alpha} \overline{q_L}_\alpha \Phi_1 N_{R1} - Y_{2\alpha} \overline{q_L}_\alpha \Phi_2 N_{R2} - M \overline{N_{R1}^c} N_{R2} + \text{h.c.}$$

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



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

- ❖ Particles and symmetries

	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	Φ_1	Φ_2	N_{R1}	N_{R2}	$\chi_{L,R}$	ϕ
$SU(2)_L$	2	1	1	2	1	2	2	1	1	1	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
$U(1)'$	0	0	0	0	0	1	-1	-1	1	$\frac{1}{2}$	1

- ❖ Gauge sector

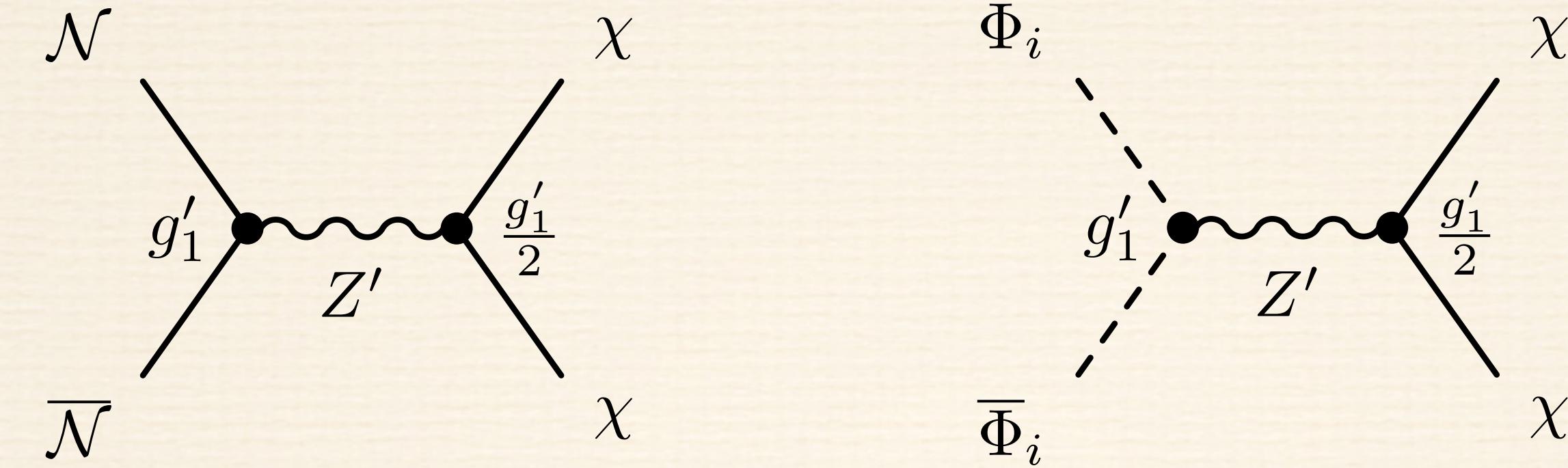
$$\mathcal{L}_{U'(1)} = (D'_\mu \Phi_1)^\dagger D'^\mu \Phi_1 + (D'_\mu \Phi_2)^\dagger D'^\mu \Phi_2 + i\bar{\mathcal{N}} \not{D}' \mathcal{N} + i\bar{\chi_L} \not{D}' \chi_L + i\bar{\chi_R} \not{D}' \chi_R + D'_\mu \bar{\phi} D'^\mu \phi$$

$$D'_\mu = \partial_\mu + i\frac{1}{2}g_2 \boldsymbol{\sigma} \cdot \mathbf{W}_\mu + ig_1 Y B_\mu + ig'_1 Y' B'_\mu$$

- ❖ Dark sector: two Majorana dark fermions $y_\chi^L \bar{\phi} \overline{\chi_L^c} \chi_L + y_\chi^R \bar{\phi} \overline{\chi_R^c} \chi_R + h.c. \implies m_L \overline{\chi_L^c} \chi_L + m_R \overline{\chi_R^c} \chi_R + h.c.$
- ❖ After ϕ gains a VEV, the $U(1)'$ symmetry is broken into a Z_2 symmetry, under which only χ_L and χ_R are charged
- ❖ Hierarchical dark fermion masses: χ_L decouples before the freeze-out of χ_R happens

Freeze-out Production of Dark Matter

- ❖ DM interaction with the thermal bath



- ❖ Breit-Wigner amplitude $|\mathcal{M}|^2 \propto \frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$
- ❖ Freeze-out temperature $X_f \equiv \frac{m_\chi}{T_f} \simeq 27.4 + 1.07 \ln \frac{m_\chi}{1\text{TeV}}$
- ❖ Resonance in DM production when $M_{Z'} \sim 2m_\chi$
- ❖ Free parameters: $m_\chi, M_{Z'}, g'$

Constraints on the Parameters

- ❖ Gauge boson mixing limit

$$\frac{v^2}{4} \begin{pmatrix} g_2^2 & -g_1 g_2 & 2g_2 g'_1 \cos 2\beta \\ -g_1 g_2 & g_1^2 & -2g_1 g'_1 \cos 2\beta \\ 2g_2 g'_1 \cos 2\beta & -2g_1 g'_1 \cos 2\beta & 4g'_1{}^2 \left(1 + \frac{v_\phi^2}{v^2}\right) \end{pmatrix}$$

$$Z \rightarrow Z \cos \theta - Z' \sin \theta, \quad Z' \rightarrow Z' \cos \theta + Z \sin \theta$$

$$\theta \simeq \cos 2\beta \frac{\sqrt{g_1^2 + g_2^2} v^2}{g'_1 v_\phi^2} \lesssim 10^{-3} \implies g'_1 v_\phi^2 \gtrsim (6.7 \text{ TeV})^2$$

- ❖ Perturbativity limit of the U(1)' gauge coupling

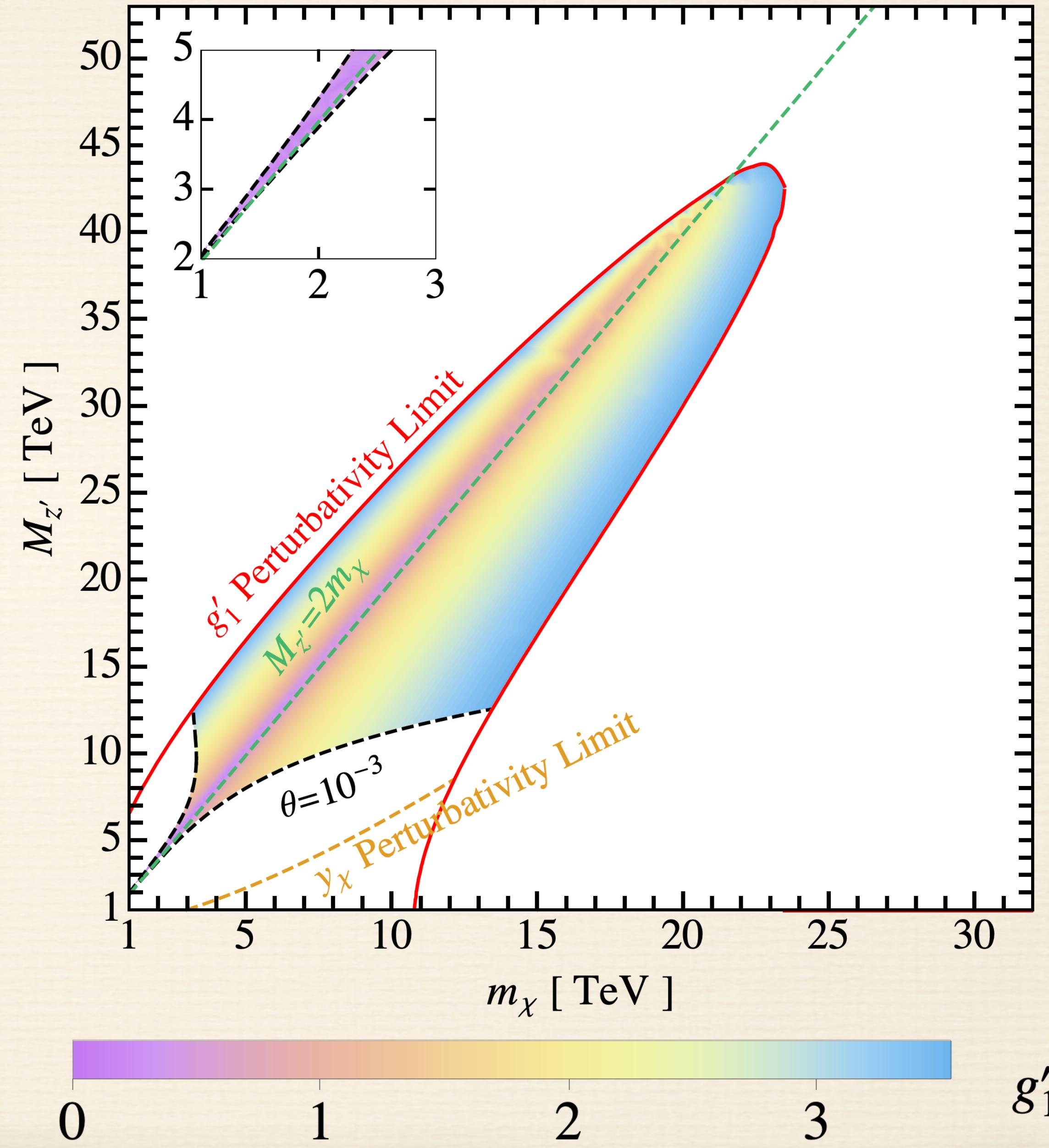
- $M_{Z'} \gg m_\chi$: $v_\phi \ll 7.1 \text{ TeV}$, not compatible with $g'_1 v_\phi^2 \gtrsim (6.7 \text{ TeV})^2$
- $M_{Z'} \ll m_\chi$: $m_\chi < 12.2 \text{ TeV}$, not compatible with $g'_1 v_\phi^2 \gtrsim (6.7 \text{ TeV})^2$
- $M_{Z'} \sim m_\chi$

- ❖ Perturbativity limit of the Yukawa coupling

Result

- ❖ Analytical calculation shows that $M_{Z'}$ and m_χ have to be of the same order to get the correct relic abundance
- ❖ The masses of χ and Z' cannot exceed 24 TeV and 44 TeV respectively
- ❖ The parameter space for $m_\chi < 1$ TeV and $M_{Z'} < 2$ TeV is very unfavored by the massive gauge boson mixing angle
- ❖ Minimum value of g_1' around 0.04

Effective Model



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

- Fourth family of vector-like fermions

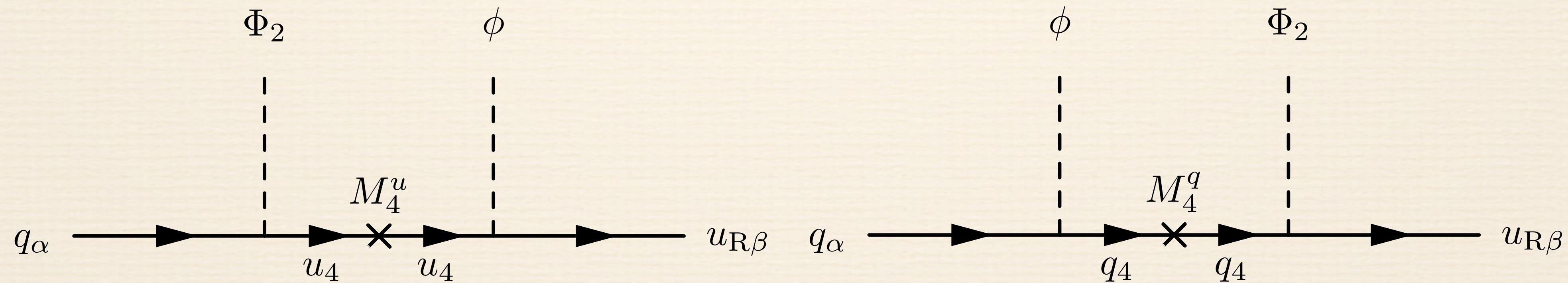
	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	q_4	u_4	d_4	ℓ_4	e_4	Φ_1	Φ_2	\mathcal{N}	$\chi_{L,R}$	ϕ
$SU(2)_L$	2	1	1	2	1	2	1	1	2	1	2	2	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$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

- Yukawa-type interactions and fourth family fermion masses

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} \supset & -Y_{\alpha 4}^{qu} \overline{q_{L\alpha}} \Phi_2 u_4 - Y_{\alpha 4}^{qd} \overline{q_{L\alpha}} \tilde{\Phi}_1 d_4 - Y_{\beta 4}^u \overline{u_{R\beta}} \Phi_2^\dagger q_4 - Y_{\beta 4}^d \overline{d_{R\beta}} \tilde{\Phi}_1^\dagger q_4 - Y_{\alpha 4}^\ell \overline{\ell_{L\alpha}} \tilde{\Phi}_1 e_4 - Y_{\beta 4}^e \overline{e_{R\beta}} \tilde{\Phi}_1^\dagger \ell_4 \\ & - y_{\alpha 4}^q \phi \overline{q_{L\alpha}} q_4 - y_{\beta 4}^u \phi \overline{u_{R\beta}} u_4 - y_{\beta 4}^d \phi \overline{d_{R\beta}} d_4 - y_{\alpha 4}^\ell \phi \overline{\ell_{L\alpha}} \ell_4 - y_{\beta 4}^e \phi \overline{e_{R\beta}} e_4 + \text{h.c.} \end{aligned}$$

$$\mathcal{L}_{\text{mass}} \supset M_4^q \overline{q_4} q_4 + M_4^u \overline{u_4} u_4 + M_4^d \overline{d_4} d_4 + M_4^\ell \overline{\ell_4} \ell_4 + M_4^e \overline{e_4} e_4$$

- Fermion masses: an example of up-type quarks



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}	$\chi_{L,R}$	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

- ❖ Yukawa-type interactions and fourth family fermion masses

$$\mathcal{L}_{\text{2HDM}} \supset -Y_{\alpha\beta}^u \bar{q}_{L\alpha} \Phi_2 u_{R\beta} - Y_{\alpha\beta}^d \bar{q}_{L\alpha} \tilde{\Phi}_1 d_{R\beta} - Y_{\alpha\beta}^e \bar{\ell}_{\alpha} \tilde{\Phi}_1 e_{R\beta} + \text{h.c.}$$

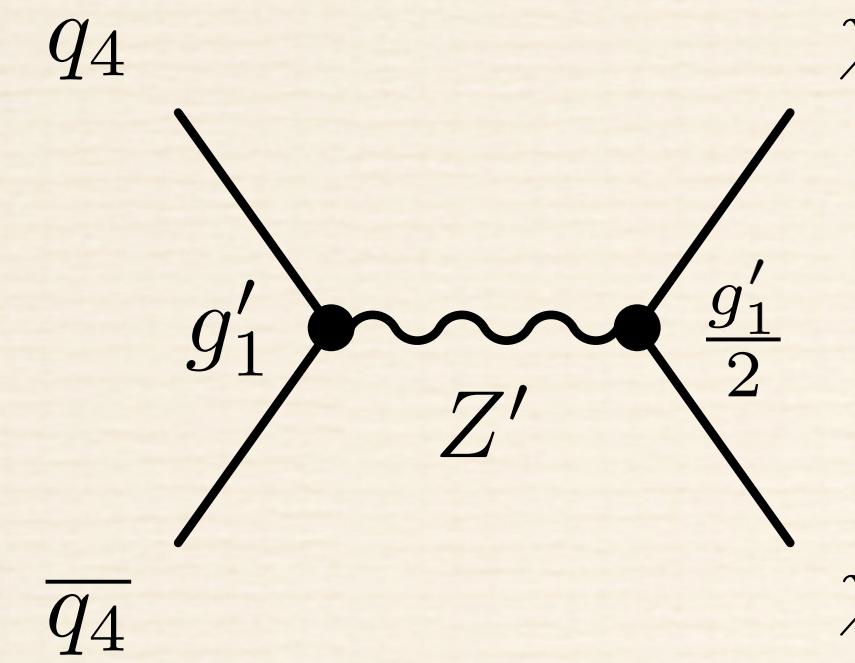
$$Y_{\alpha\beta}^u = \frac{Y_{\alpha 4}^{qu} (y_{\beta 4}^u)^* \langle \phi \rangle}{M_4^u} + \frac{y_{\alpha 4}^q (Y_{\beta 4}^u)^* \langle \phi \rangle}{M_4^q}, \quad Y_{\alpha\beta}^d = \frac{Y_{\alpha 4}^{qd} (y_{\beta 4}^d)^* \langle \phi \rangle}{M_4^d} + \frac{y_{\alpha 4}^q (Y_{\beta 4}^d)^* \langle \phi \rangle}{M_4^q},$$

$$Y_{\alpha\beta}^e = \frac{Y_{\alpha 4}^\ell (y_{\beta 4}^u)^* \langle \phi \rangle}{M_4^e} + \frac{y_{\alpha 4}^\ell (Y_{\beta 4}^u)^* \langle \phi \rangle}{M_4^\ell}$$

- ❖ If q_4 , the lightest fourth family charged fermion, is not too heavy, it makes an extra contribution to the amplitude during the freeze-out

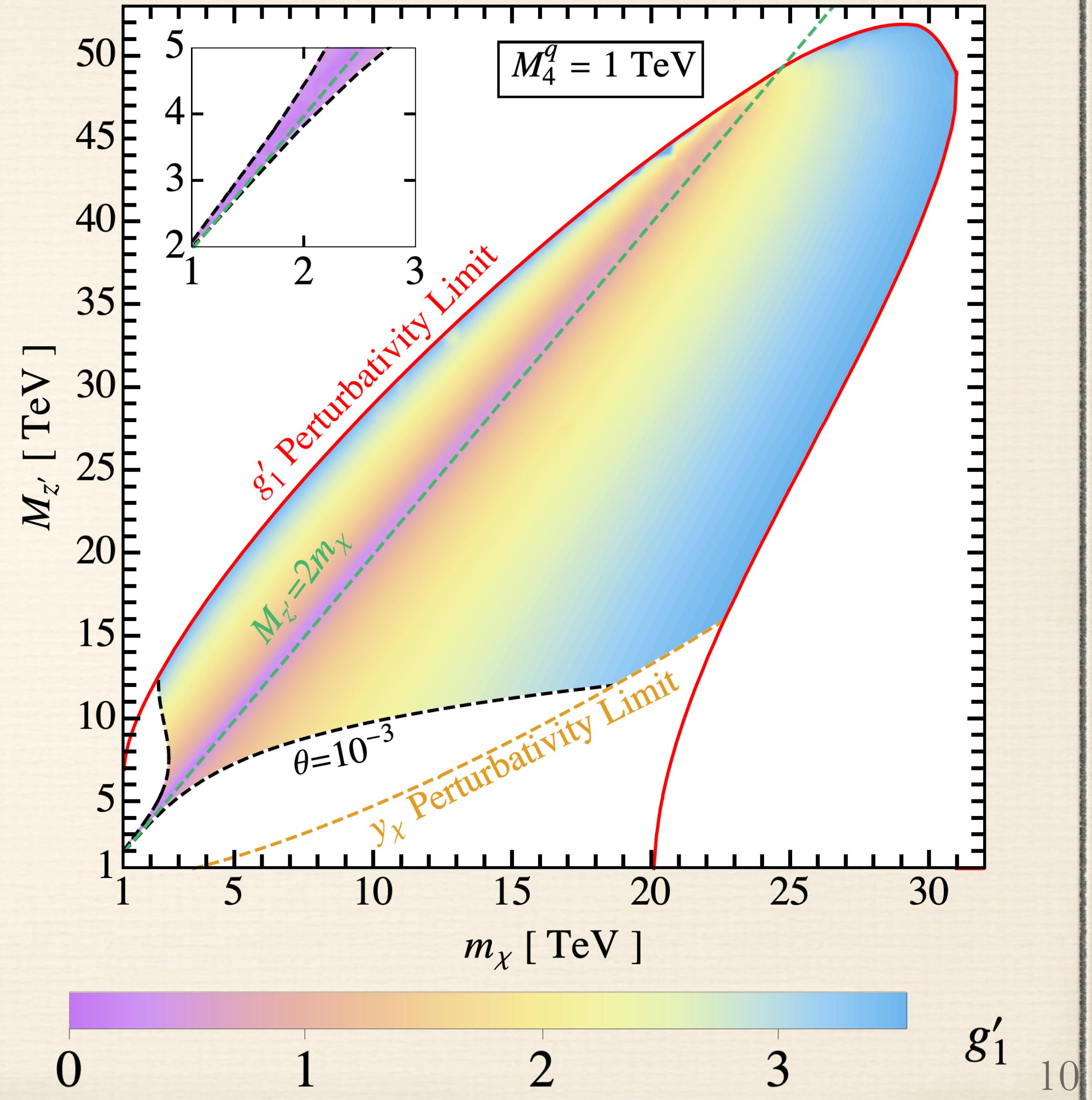
Result

- ❖ Extra contribution from q_4 scattering



- ❖ The mass of q_4 is set to 1 TeV
- ❖ Allowed parameter space is enlarged
- ❖ The maximal masses of χ and Z' increase to 31 TeV and 52 TeV respectively

Renormalizable Model



Summary

- ❖ We have considered the possibility that dark matter is stabilised by a discrete Z_2 symmetry which arises from a subgroup of a $U(1)'$ gauge symmetry, spontaneously broken by integer charged scalars, and under which the chiral quarks and leptons do not carry any charges.
- ❖ After the $U(1)'$ symmetry breaking, the dark matter candidate can only interact with the thermal bath through processes mediated by the $U(1)'$ gauge boson and therefore can be produced thermally in the early universe.
- ❖ We considered a high energy renormalisable model with a complete fourth family of vector-like fermions, where the chiral quark and lepton masses arise from a seesaw-like mechanism.
- ❖ We have explored the allowed parameter space of both the effective and renormalisable models, and found that the dark matter can only be produced correctly when there is no hierarchy between the masses of the dark fermion and the $U(1)'$ gauge boson.

Thank You!