RH neutrino dark matter in a flavoured *B-L* model

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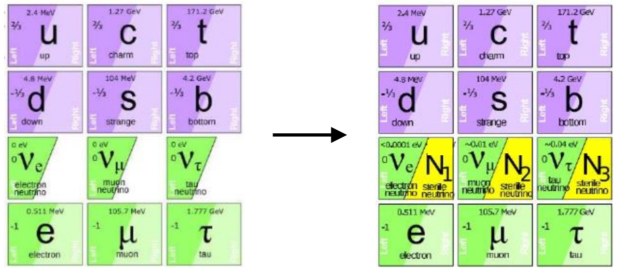
RH Neutrino Dark Matter

- Simple, well-motivated extension of Standard Model is addition of $3\ \nu_R$



- Very massive ν_R ($\mathrm{M} \gtrsim 10^9$ GeV) can explain:
  - Smallness of active neutrino masses via seesaw mechanism
  - Observed baryon asymmetry via thermal leptogenesis

- However, *two* ν_R are sufficient for both see-saw and leptogenesis

(Frampton, Glashow, Yanagida '02)

- Why include the 3rd ν_R at all? ⟶ Dark Matter!

ν_R DM *and* high-scale see-saw

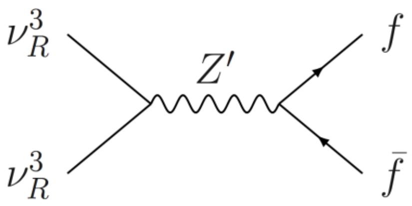
- Many studies of RH/sterile neutrino DM …
  Often with ~keV DM, and all 3 ν_R below the EW scale (e.g. "νMSM" Asaka, Shaposhnikov '05)

Alternative approach: assume two ν_R remain very massive

- Keep full benefit of see-saw, and (non-resonant) leptogenesis

- But, need a production mechanism for lightest ν_R
  Obvious choice: a new gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$



- ν_R^3 produced via thermal freeze-out (i.e. WIMP)
- Majorana mass for ν_R^3 generated by spontaneous symmetry breaking
  (partially) explains hierarchy in ν_R masses

Choosing a U(1) symmetry

Interested in vectorial $U(1)$ symmetries that allow:

- Two ν_R have large Majorana masses for leptogenesis
- Lightest ν_R charged under $U(1)$ and is DM

→ Completely fixes lepton charge

$$Q_l = (0, 0, -1)$$

In quark sector, assume

- Suppression of FCNCs ($K - K$ and $D^0 - D^0$mixing)

Anomaly cancellation (SM+3ν_R) then restricts to a *single-parameter* class:

$$Q_q = \left(a, a, \frac{1}{3} - 2a\right)$$

Choosing a U(1) symmetry

One parameter family of U(1) symmetries:

$$Q_l = (0, 0, -1) \quad Q_q = \left(a, a, \frac{1}{3} - 2a\right)$$

- Particularly interesting case is $\boldsymbol{a = 0}$
  - *Flavoured* $B - L$ symmetry
  - Anomaly cancellation within each generation (like SM)
  - Likely the least constrained choice, since only 3rd gen charged

Flavoured B-L

- $U(1)_{(B-L)_3}$: $B-L$ gauge symmetry under which only 3rd generation charged

	$q_L^3,\, b_R,\, t_R$	$\ell_L^3,\, \tau_R,\, \nu_R^3$	H	Φ
$Q_{(B-L)_3}$	$+1/3$	-1	0	$+2$

- Introduce $\Phi(+2)$ to spontaneously break symmetry

- Also generates Majorana mass for dark matter $\chi = (-\varepsilon\nu_R^{3*},\, \nu_R^3)^T$

$$\mathcal{L} = \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi + \frac{g}{2}Z'_\mu\bar{\chi}\gamma^5\gamma^\mu\chi - (\frac{y}{2}\bar{\chi}\Phi P_R\chi + h.c.)$$

Yukawa Structure

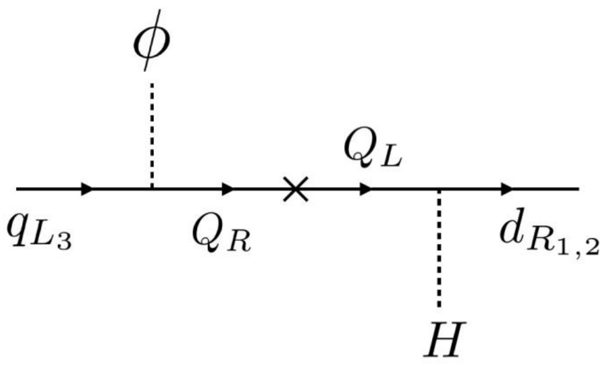
- However, off-diagonal Yukawa couplings involving 3rd generation are now forbidden

$$Y_d = \begin{pmatrix} \hat{Y}_d^{2\times 2} & 0 \\ 0 & Y_b \end{pmatrix}$$

→ Require a mechanism to generate these upon $U(1)_{(B-L)_3}$ breaking

Two general possibilities:

- Additional Higgs doublets charged under $U(1)_{(B-L)_3}$
- New vector-like fermions



DM Stability

- Impose $\mathbb{Z}_2$ symmetry to guarantee DM stability

  RH ν DM (-), everything else (+)

- Forbids dangerous Yukawa couplings

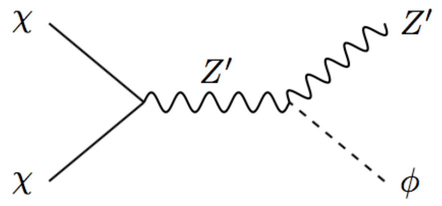
$$Y_\nu = \begin{pmatrix} \hat{Y}_\nu^{2\times 2} & 0 \\ -\frac{Y_L' \phi_l}{M_L} Y_L^T & 0 \end{pmatrix}$$

- Simultaneously solves potential problem with light RH neutrino raising active neutrino masses, and washing out lepton asymmetry

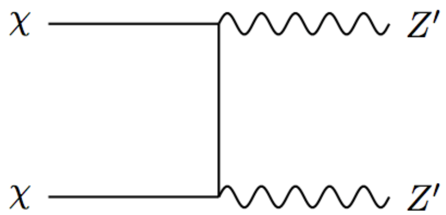
$$\frac{1}{M_{\nu_R}} \simeq \begin{pmatrix} \frac{1}{\hat{M}_{\nu_R}^{2\times 2}} & 0 \\ 0 & \frac{1}{m_\chi} \end{pmatrix}$$

DM Annihilation

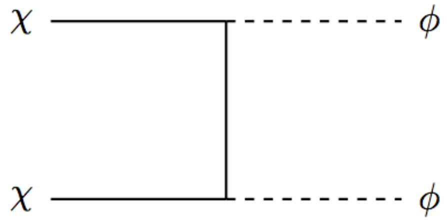
Four main annihilation channels:



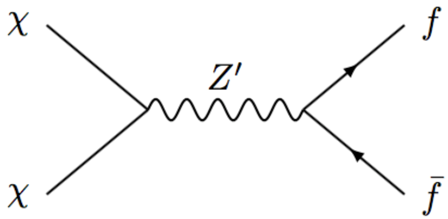
s-wave, dominates when kinematically open



s-wave, p-wave enhanced if $m_\chi > m_{Z'}$



p-wave



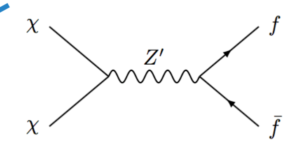
p-wave

Relic density

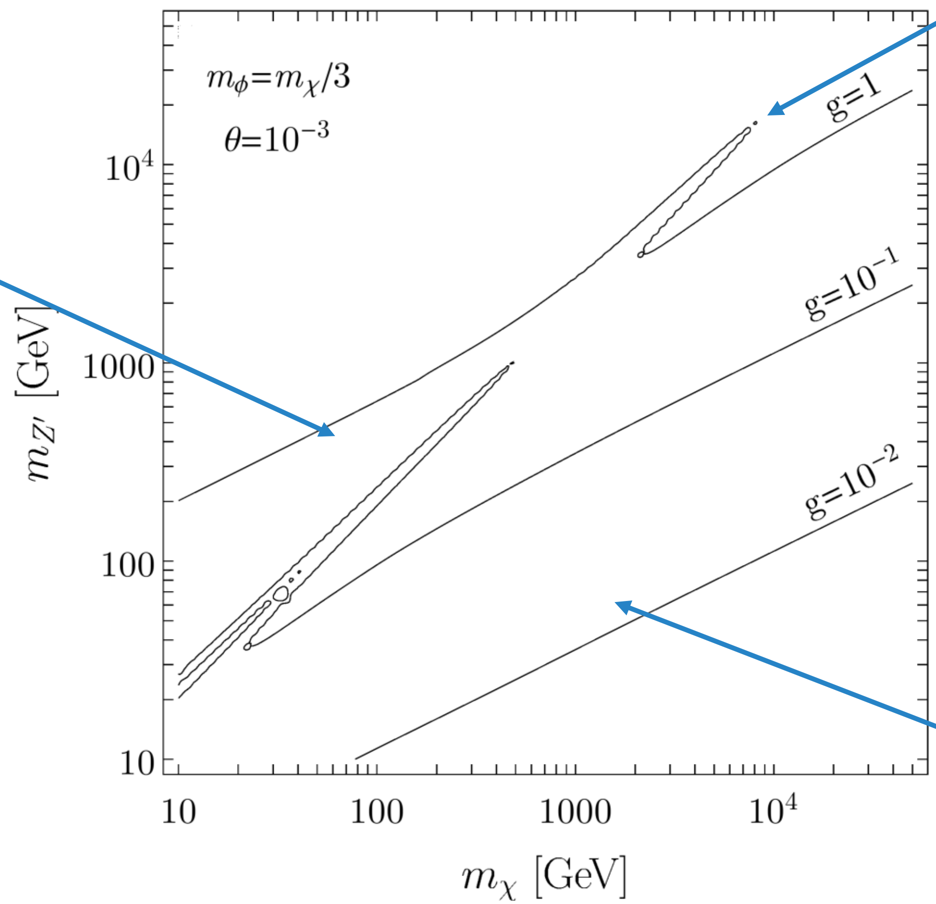
- Fix gauge coupling to satisfy correct relic density

  → 5 free parameters: m_χ, $m_{Z'}$, m_ϕ, θ (ϕ-h mixing), ϵ (Z-Z' mixing)

$m_\chi \approx m_{Z'}/2$



$\chi\chi \to \phi\,\phi$
$\chi\chi \to ff$



$\chi\chi \to \phi Z'$
$(\chi\chi \to Z'\,Z')$

Unitarity/perturbativity

- Even in simplified models, partial wave perturbative unitarity gives strong bounds

$\phi\phi$, $Z'_L Z'_L$:

$$m_\phi < \frac{\sqrt{\pi} m_{Z'}}{g}$$

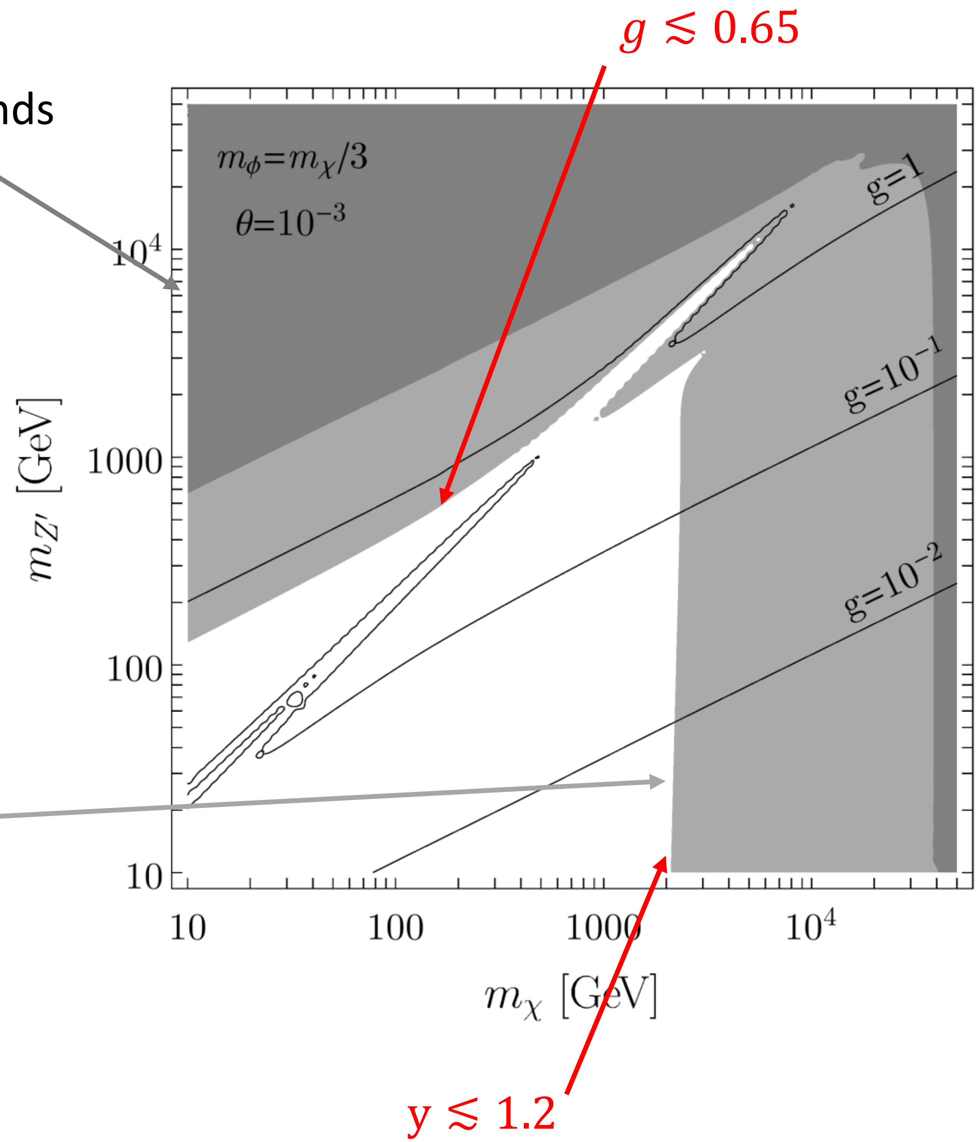
$\chi\chi \to \chi\chi$:

$$m_\chi < \frac{\sqrt{\pi} m_{Z'}}{g}, \qquad g < \sqrt{4\pi}$$

- Can also impose perturbativity of couplings to high scales
  (i.e. no Landau pole below M_{Pl})

→ *Significantly* stronger bounds

$$m_\chi \lesssim 2\text{ TeV}$$



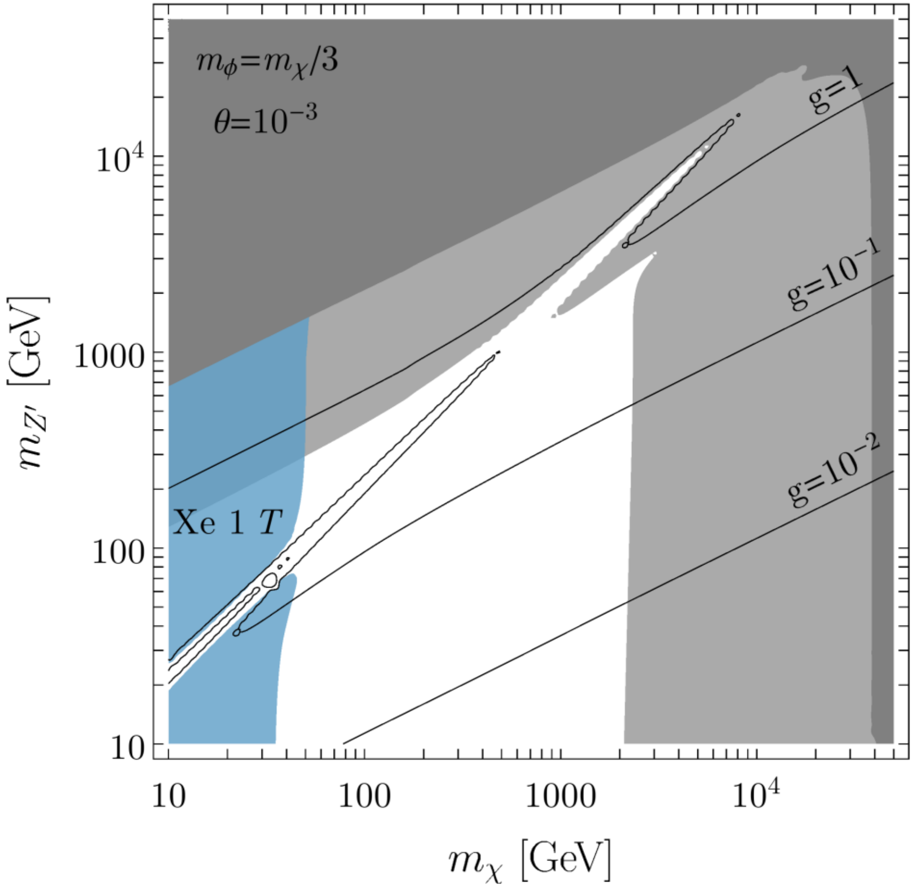
DM Direct Detection

- SI DM-nucleon scattering mediated by Z' is velocity suppressed
- Further suppression due to lack of Z' coupling to light quarks
- Higgs-ϕ mixing leads to spin-independent scattering

$$\mathcal{L} \supset (\phi^\dagger \phi)(H^\dagger H)$$

- At the very least, radiatively generated at two-loop

$\theta = 10^{-3}$



Limits even for very small mixing angles

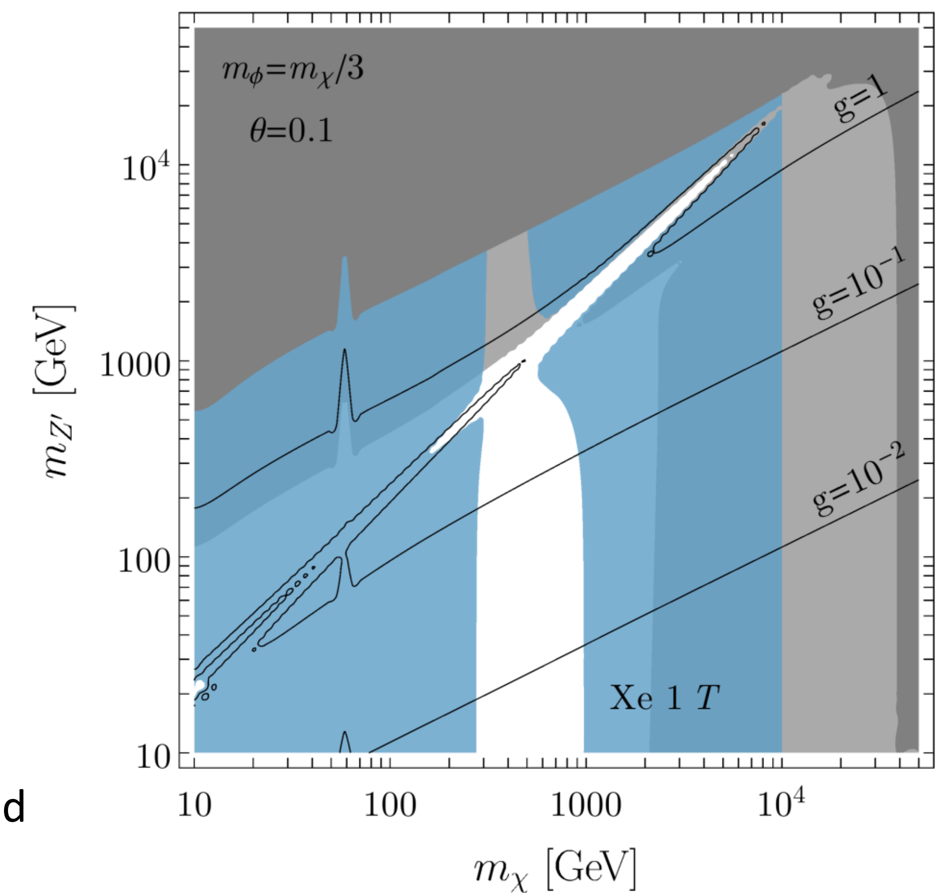
DM Direct Detection

- SI DM-nucleon scattering mediated by Z' is velocity suppressed
- Further suppression due to lack of Z' coupling to light quarks
- Higgs-ϕ mixing leads to spin-independent scattering

$$\mathcal{L} \supset (\phi^\dagger \phi)(H^\dagger H)$$

- At the very least, radiatively generated at two-loop

$\theta = 0.1$



Larger mixing angles *strongly* constrained!

DM Indirect Detection

- $\chi\chi \to \phi Z'$ and $\chi\chi \to Z'Z'$ annihilation are s-wave

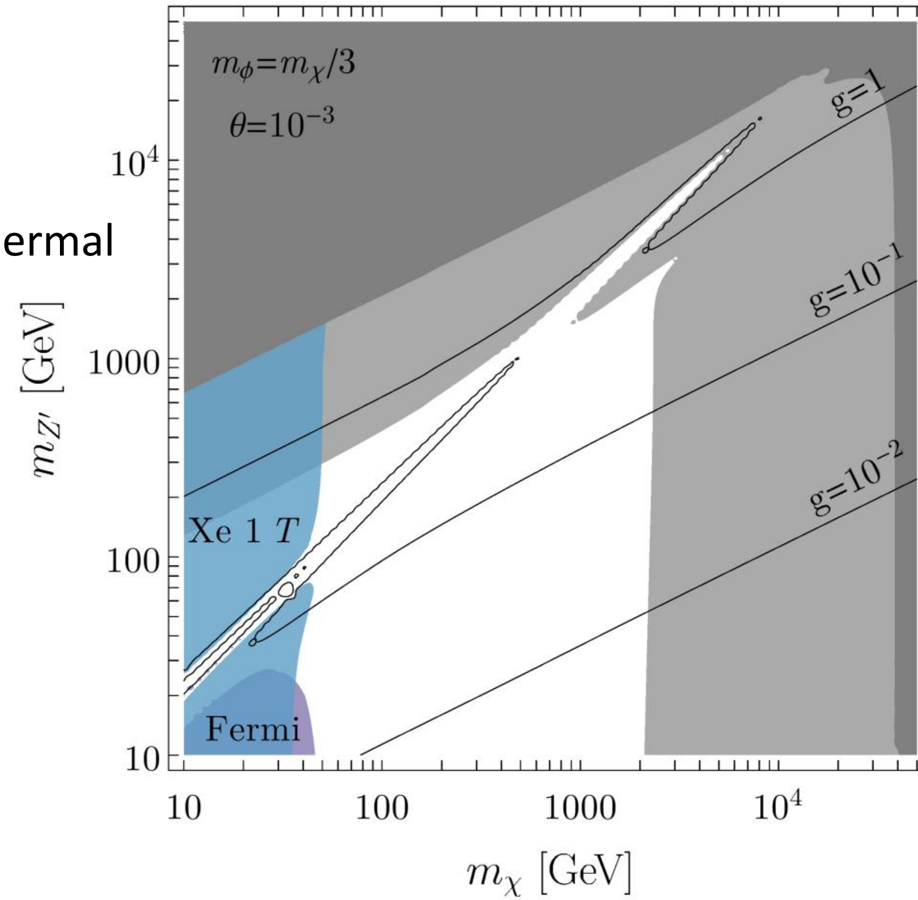
  → in principle lead to gamma-ray signals

- $\chi\chi \to Z'Z'$: p-wave enhanced by $m_\chi^4/m_{Z'}^4$

  → xsec today suppressed compared to thermal relic xsec

- Only need to consider $\chi\chi \to \phi Z'$
  - Multibody SM final-state (eg. $\phi Z' \to bbbb$)
  - Significant Z' BR to ν

→ Current Fermi dwarf limits very weak



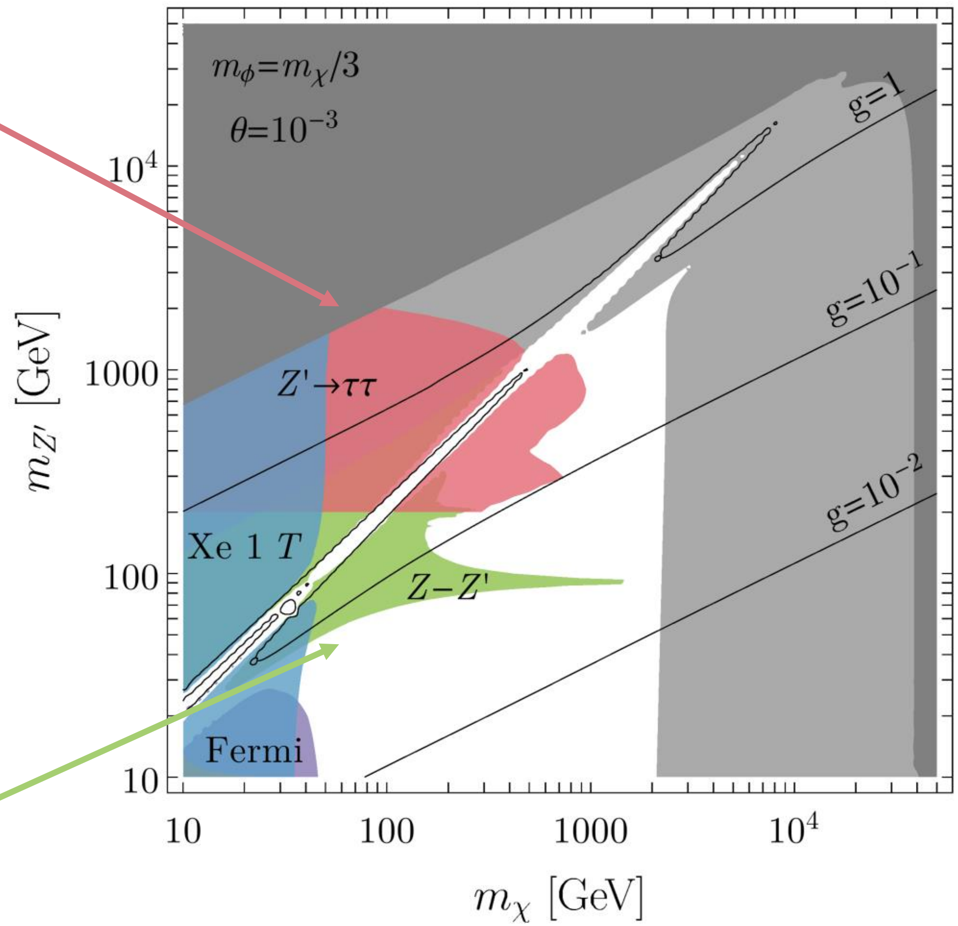
Collider bounds

- Collider bounds relatively weak due to suppressed $bb \to Z'$ cross-section
- Stronger limits if coupling to light leptons after rotation to mass basis

- Also have Z - Z' kinetic mixing
- Generated by RGE evolution, even if vanishing at high scales (e.g. Λ_{GUT})

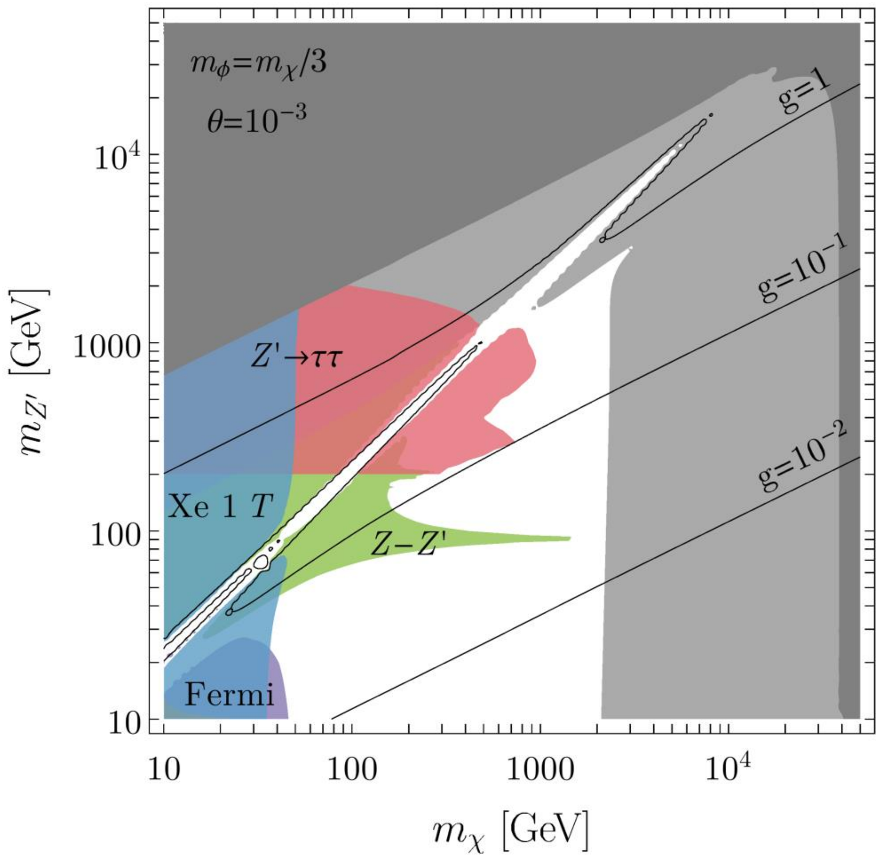
$$\varepsilon(m_{Z'}) \sim \frac{2 g_Y g'}{9\pi^2} \log \frac{\Lambda}{m_{Z'}}$$

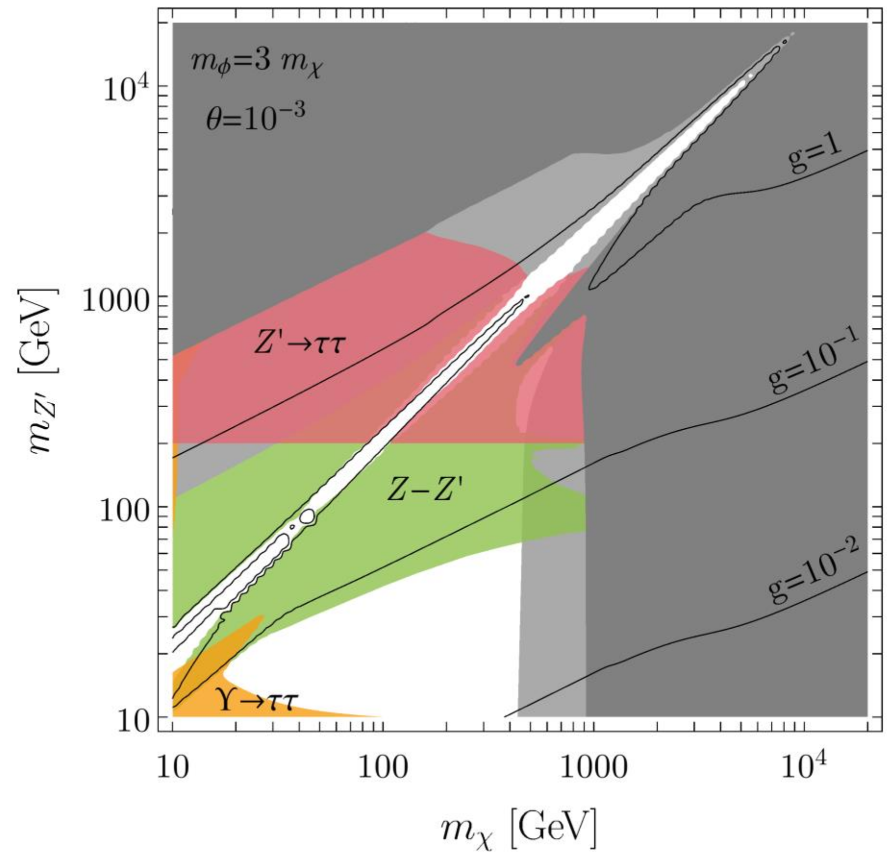
EW precision → $\varepsilon \leq 10^{-1} - 10^{-2}$



$m_\phi = 3m_\chi$

- For heavy scalar, $\chi\chi \to \phi Z'$ annihilation channel forbidden
- Larger gauge coupling required for correct relic density
  - $\to$ stronger perturbativity constraints
- Reduced direct detection bound due to increased m_ϕ





Summary

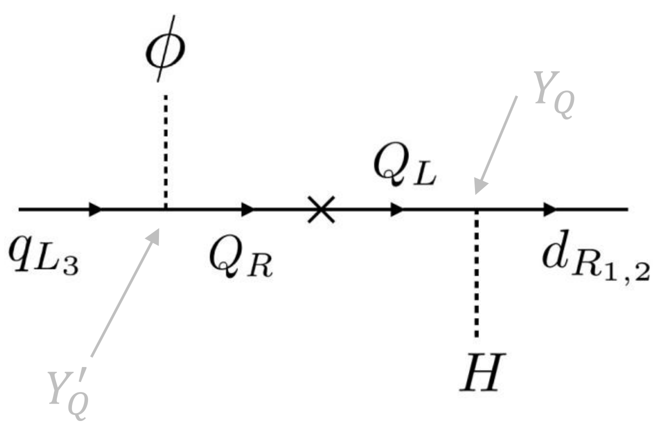
- Lightest RH neutrino can provide WIMP dark matter candidate in minimal gauged $U(1)$ extensions
- Consistent with high-scale see-saw and leptogenesis
- Anomaly cancellation restricts possible symmetries:
  An interesting (and least constrained) model is *flavoured B-L* symmetry
- Significant viable parameter space remains to be explored
- Requiring perturbativity up to M_{Pl} gives a strong upper bound on DM mass ($m_\chi \lesssim 2$ TeV)
- Also interesting connection to B-physics anomalies
  (see talk by Chengcheng Han)

Backup

Yukawa Structure

For general 3x3 Yukawa couplings, introduce:

- $U(1)_{(B-L)_3}$ neutral *V-L* fermions: $Q_{L,R}, U_{L,R}, D_{L,R}, L_{L,R}, E_{L,R}, N_{L,R}$
- SM singlet scalars ($U(1)'$ *breaking*): $\phi_l(+1), \phi_q(+\frac{1}{3})$



$$\begin{pmatrix} \bar{q}_{L_{1,2}} & \bar{q}_L^3 \end{pmatrix} H \begin{pmatrix} \hat{Y}_d^{2\times 2} & -\frac{Y'_D \phi_q^*}{M_D} Y_D \\ -\frac{Y'_Q \phi_q}{M_Q} Y_Q^T & Y_b \end{pmatrix} \begin{pmatrix} d_{R_{1,2}} \\ b_R \end{pmatrix}$$

Higgs-ϕ Mixing ($\theta = 0.1$)

- Large Higgs-ϕ mixing even more strongly constrained by direct detection
- Exception when $m_\phi \approx m_h$ due to destructive interference