Composite Higgs and Dark Matter

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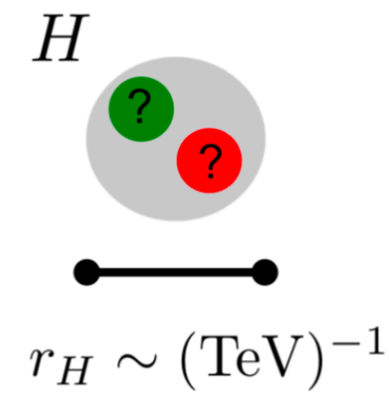
based on: arXiv:1707.07685 (JHEP) *and* arXiv:*1809.09106 (JCAP)*
and work in progress with R. Balkin, E. Salvioni *and* A. Weiler

Composite Higgs - A Reminder

- Higgs is a **bound state** of a new strong sector

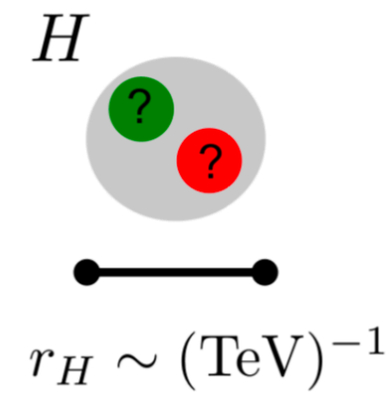
  Description changes above confinement scale (~ TeV)
  → Higgs mass is naturally "screened"



- Analogy to QCD Pions: Higgs arises as (approximate) **Goldstone Boson** and is naturally light

$$\mathcal{G} \xrightarrow[H,\ldots]{f} \mathcal{H}$$

Composite Higgs - A Reminder



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$$\mathcal{G} \xrightarrow[H,\chi]{f} \mathcal{H}$$

- **But:** no reason for Higgs to go alone. → additional pNGB χ

- χ is **naturally light** and **weakly coupled** at low energies

  Frigerio, Pomarol, Riva, Urbano 2012

- If **stable:** natural WIMP candidate

Dark Matter Stability

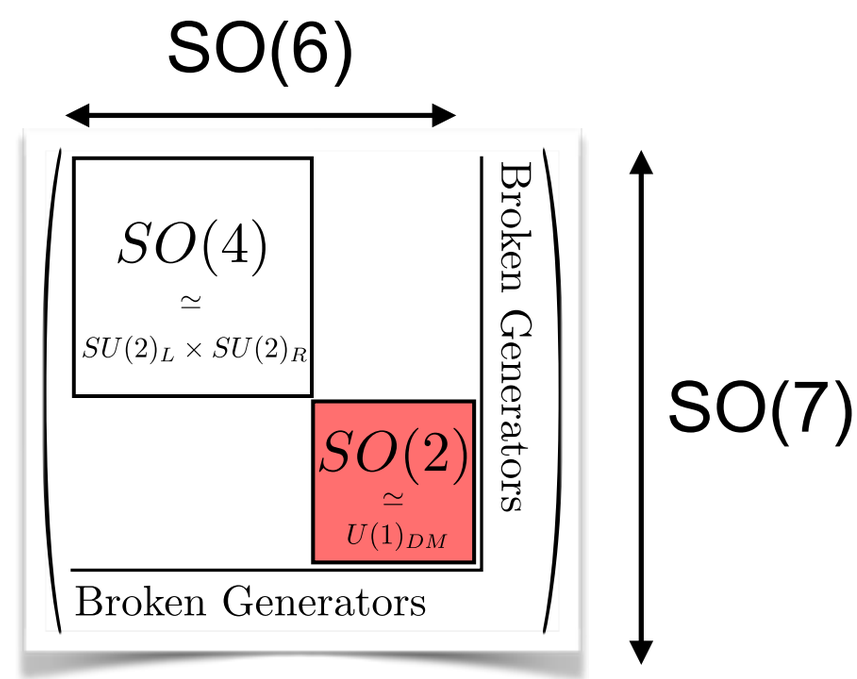
- **Complex** scalar singlet

$$SO(7)/SO(6) \longrightarrow (H,\chi) \sim \mathbf{4}_0 + \mathbf{1}_{\pm 1} \quad \text{of } SO(4)_{U(1)_{\rm DM}}$$

χ charged under exact $U(1)_{\rm DM} \subset SO(6)$

Balkin, MR, Salvioni, Weiler, 1707.07685

Automatically preserved by strong sector
+ can be weakly gauged



pNGB Dark Matter

- Pure **Goldstone** Higgs portal to SM

from non-linear sigma model

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi)$$

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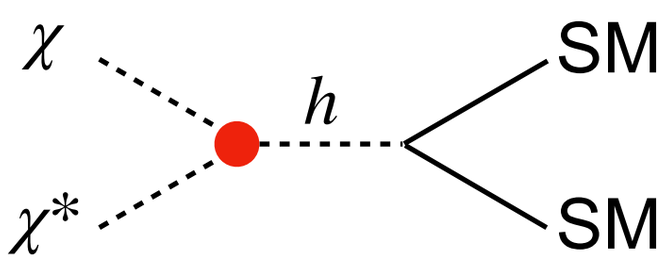
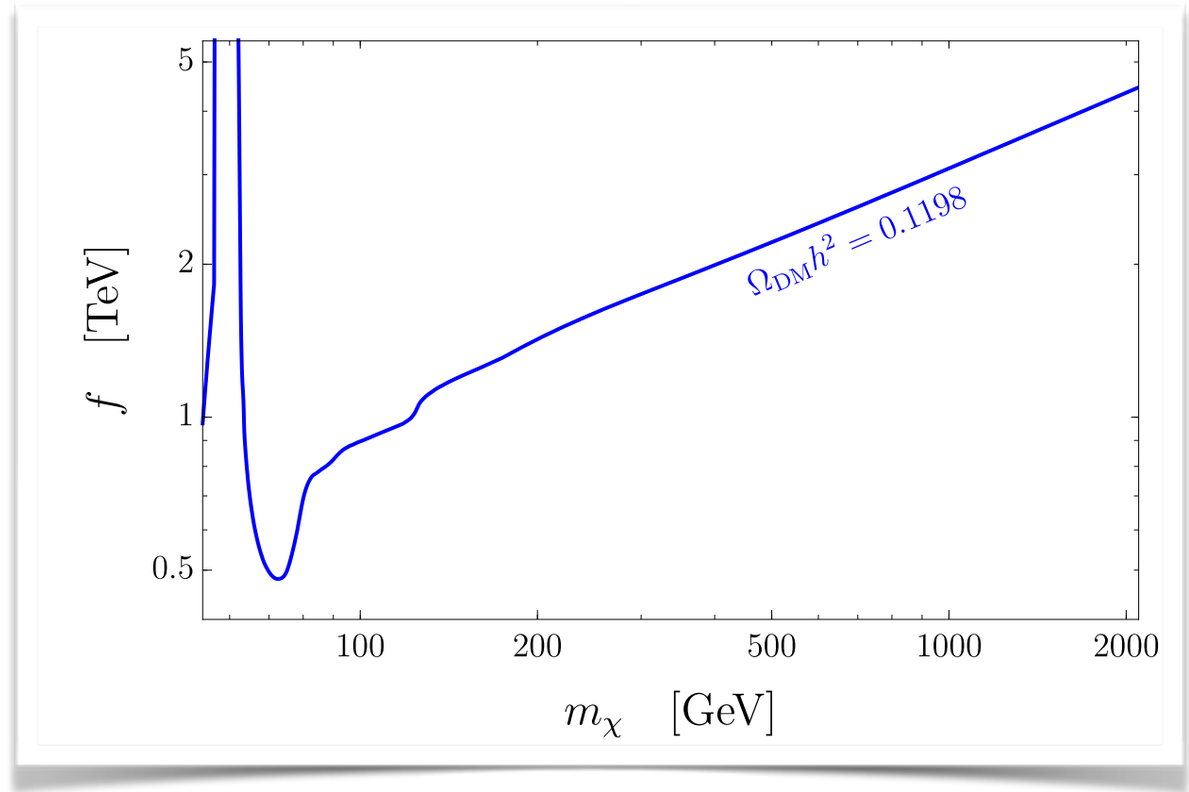
Annihilation



$$\propto \frac{s}{f^2} \simeq \frac{4m_\chi^2}{f^2} \Rightarrow \langle\sigma v\rangle \propto \frac{m_\chi^2}{f^4}$$



Blue: full Boltzmann solution

relic density fixes **one-to-one** correspondence of m_χ and f

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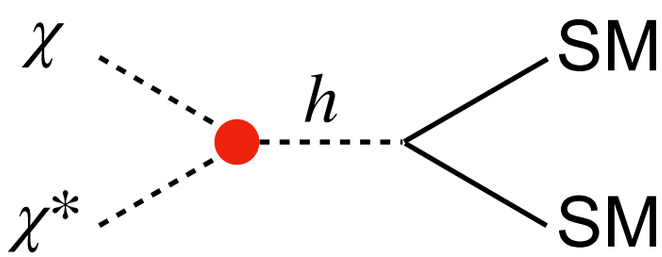

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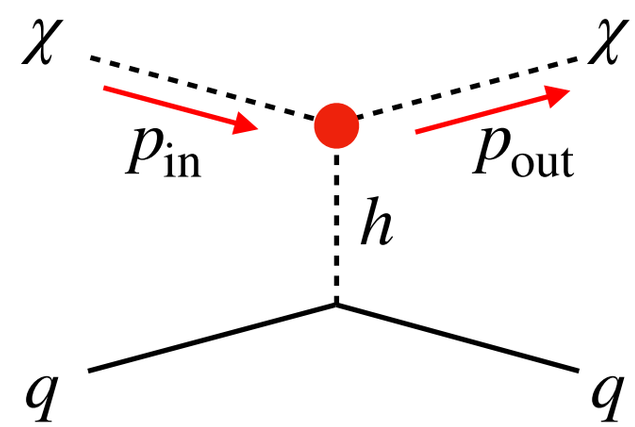
Direct Detection



$$\propto \frac{(p_{\rm in}-p_{\rm out})^2}{f^2} \lesssim \frac{(100\ \text{MeV})^2}{(1\ \text{TeV})^2}$$

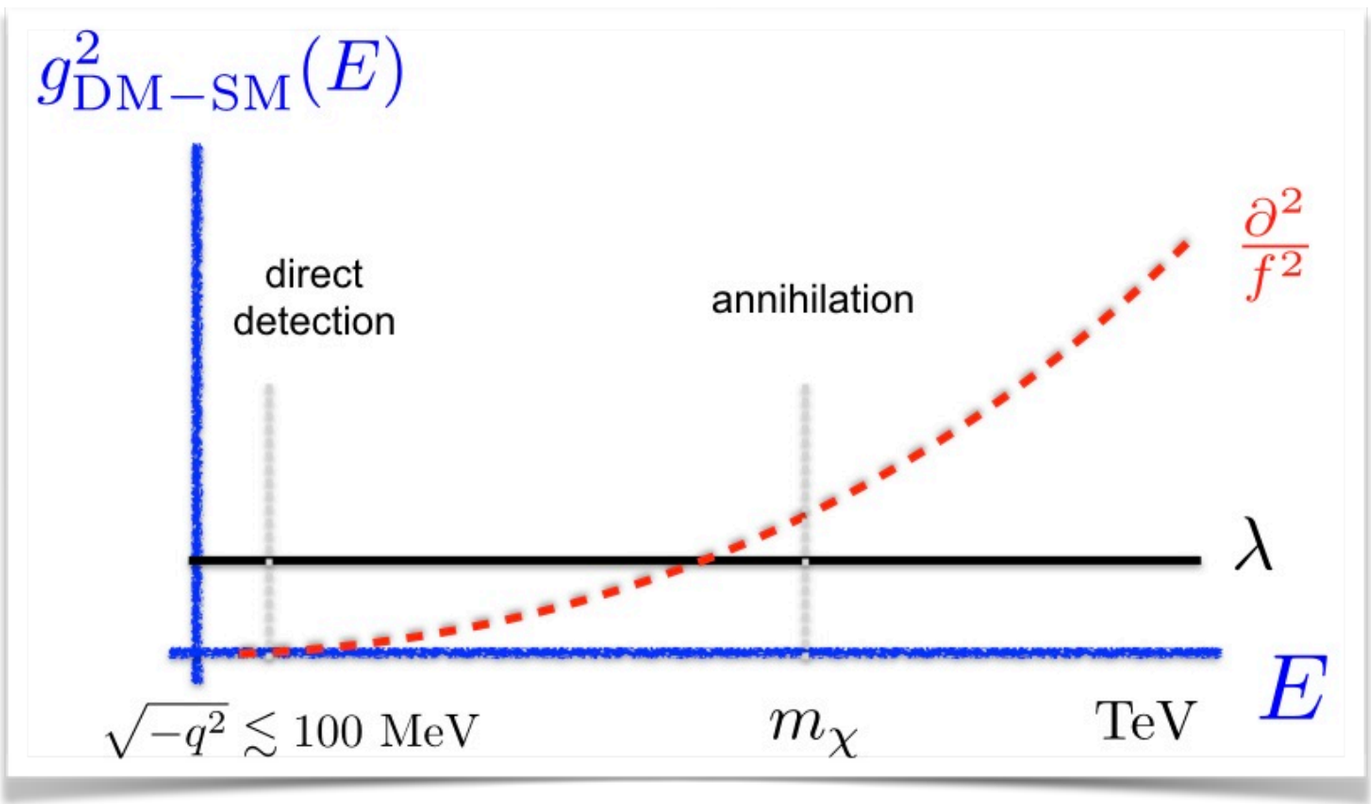
Easily avoids direct detection limits

pNGB Dark Matter

- **BUT:** DM mass requires explicit breaking of DM shift symmetry

generates potential for Higgs and DM

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi)+\lambda h^2\chi^*\chi$$



DD is very sensitive to λ

want to be close to Goldstone limit

$\lambda \ll 1$

Explicit Breaking of global Symmetry

DM **shift** symmetry can be broken by:

1. Embedding of top
2. Embedding of bottom (or lighter quarks)
3. Weakly gauging $U(1)_{\mathrm{DM}}$

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Balkin, MR, Salvioni, Weiler, 1707.07685

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parametrically smaller λ

Balkin, MR, Salvioni, Weiler, 1809.09106

Breaking the Symmetry with the Bottom

- DM **shift** symmetry **only** broken by b_R coupling

$\lambda \sim y_b^2 \ll 10^{-3}$ and $m_\chi \sim \mathcal{O}(100)$ GeV

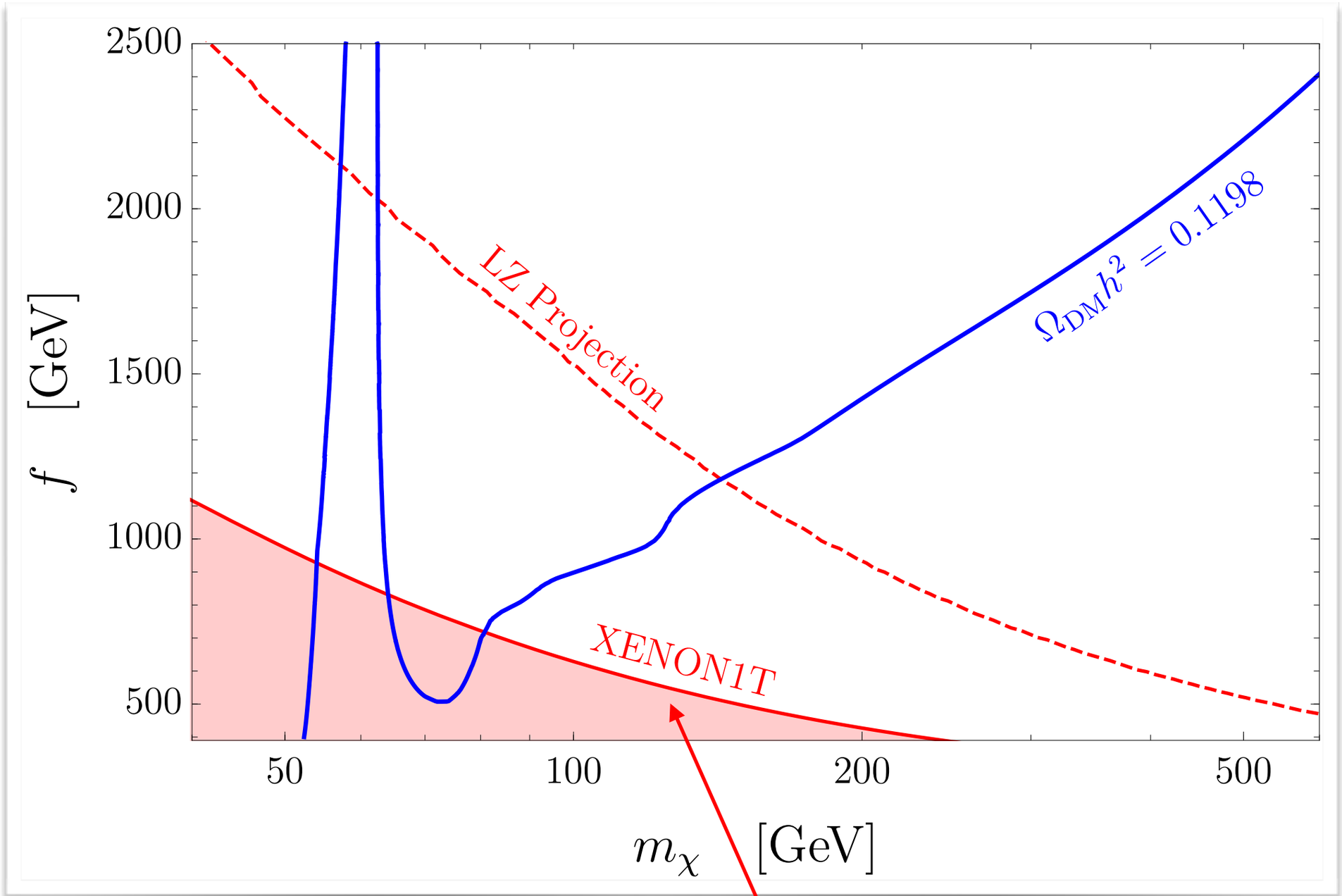
negligible for Dark Matter pheno

- Explicit breaking also generates

$$\frac{y_b}{f^2}\bar{q}_L H b_R |\chi|^2$$

yields DM-nucleon cross-section. $\sigma_{\rm SI}^{\chi N} \sim 10^{-47}$

Breaking the Symmetry with the Bottom

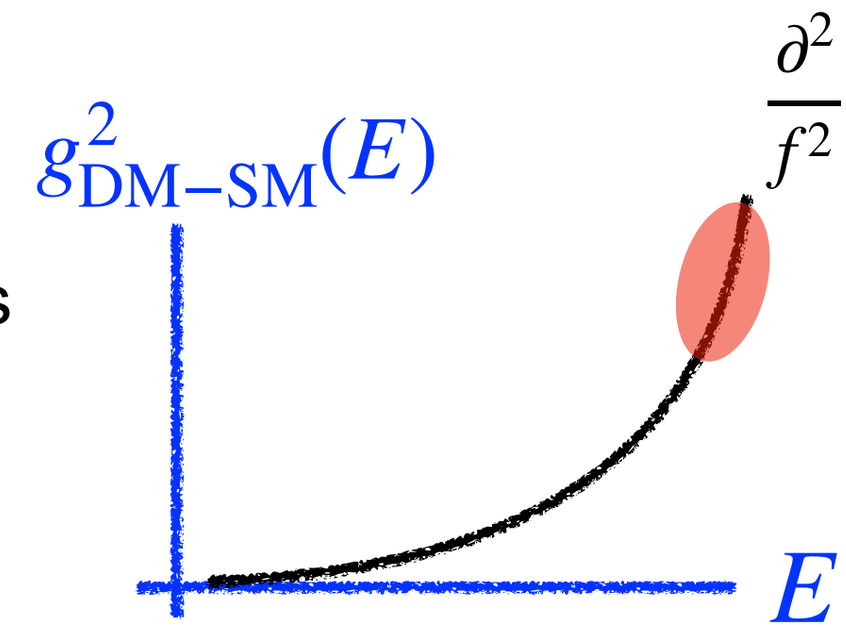


DM-quark coupling: $\frac{y_b}{f^2}\bar{q}_L H b_R |\chi|^2$

Probes for Composite DM

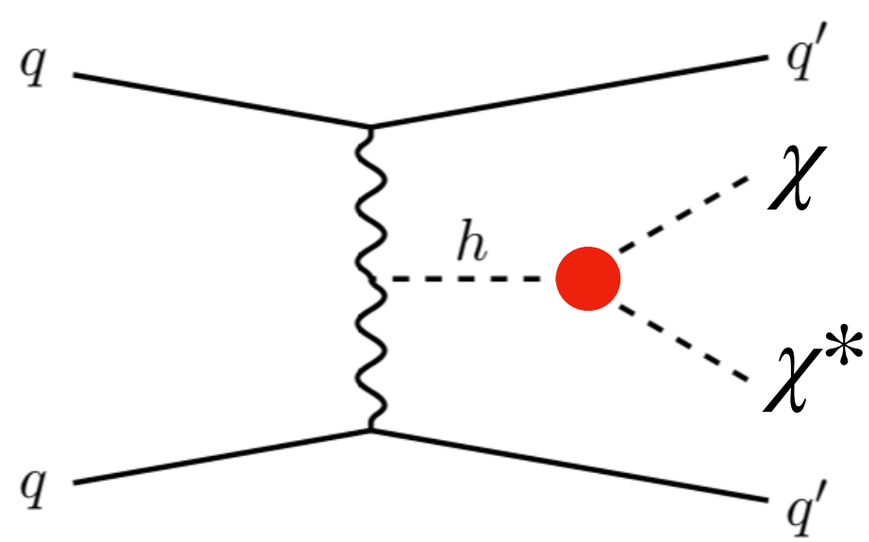
- Indirect DM detection: s-wave annihilation

- Probing the derivative coupling at colliders

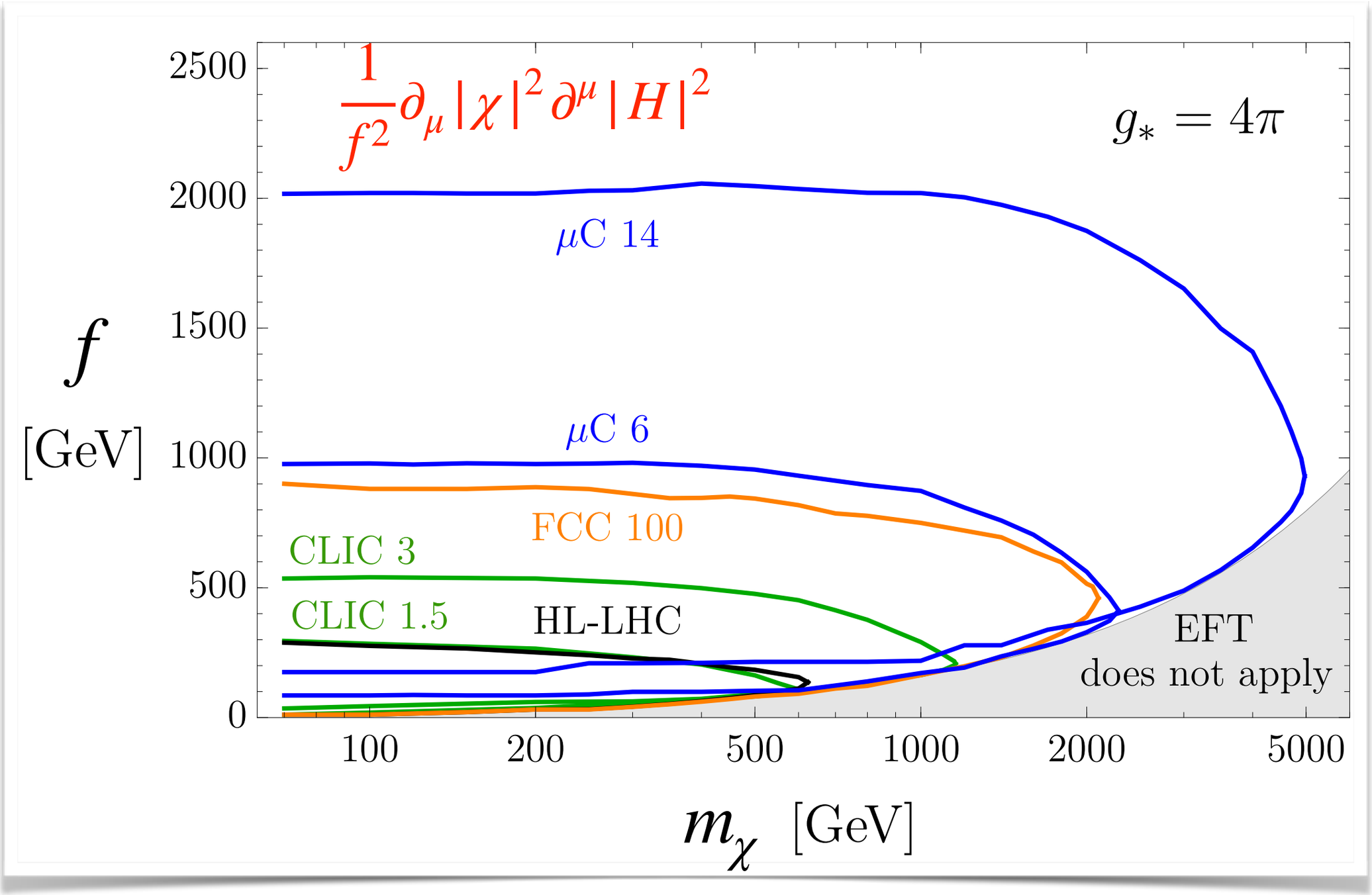


→ VBF production of DM

Work in progress with E. Salvioni and A. Weiler



Derivative Coupling at Colliders



Work in progress with E. Salvioni and A. Weiler

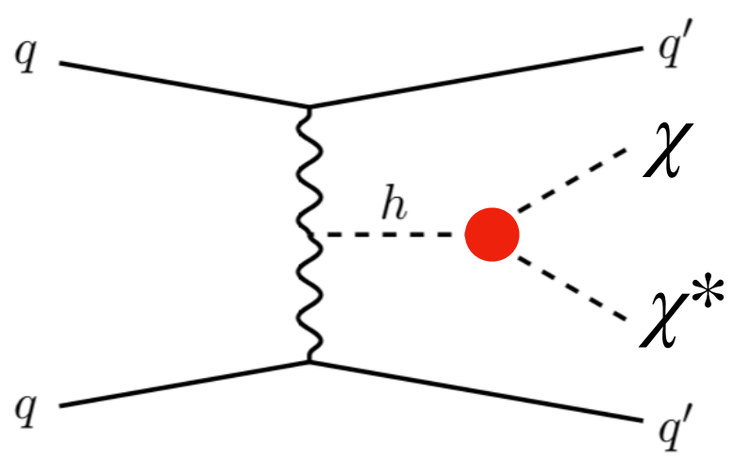
Conclusions

- **pNGB** Dark Matter = motivated WIMP with structurally suppressed direct detection

- **Complementary** Probes are needed:

  - Dark matter indirect detection

  - Probing the energy dependent derivative coupling at colliders

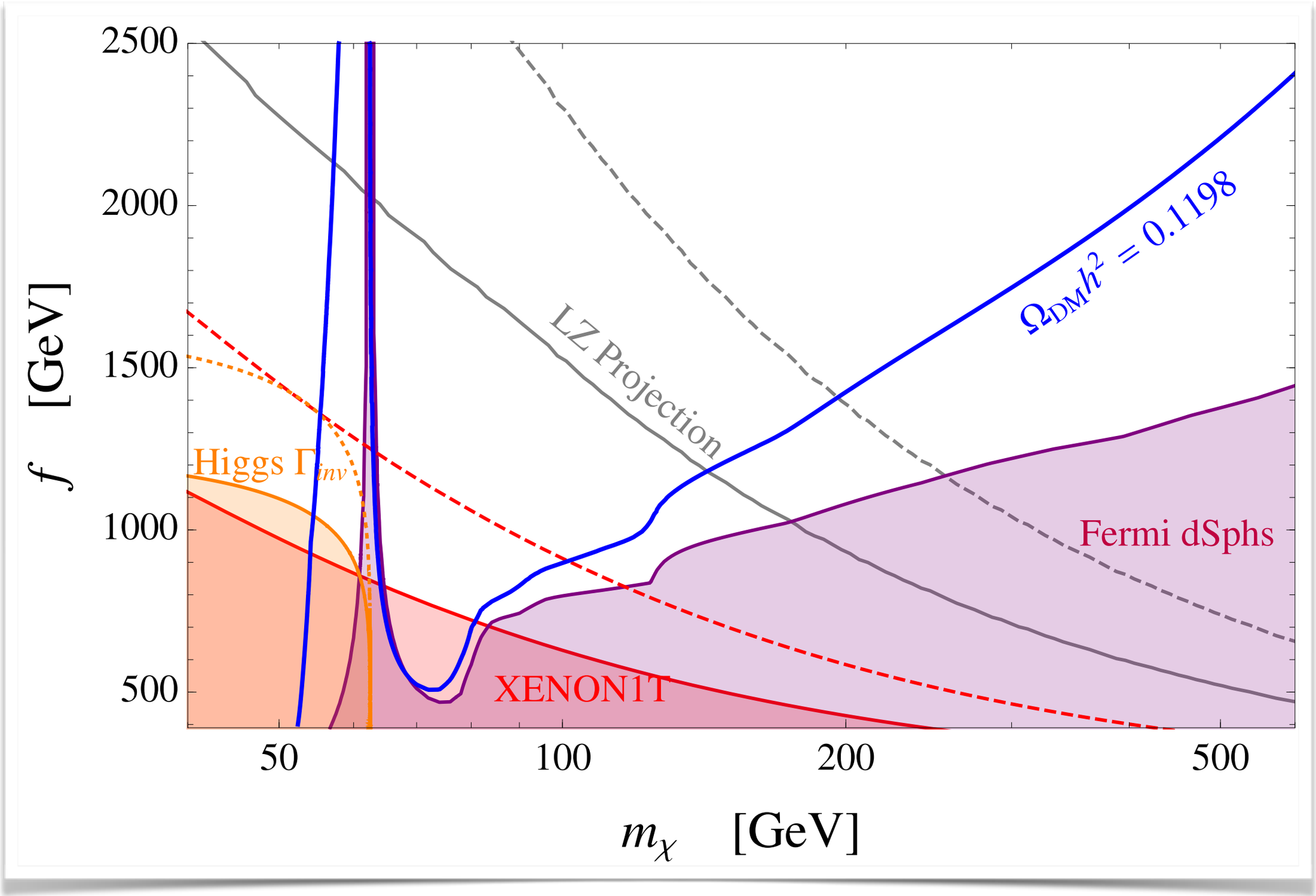


$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi)$$

Work in progress!

Backup

Breaking the Symmetry with the Bottom



SO(7)/SO(6) coset & fermion coupling

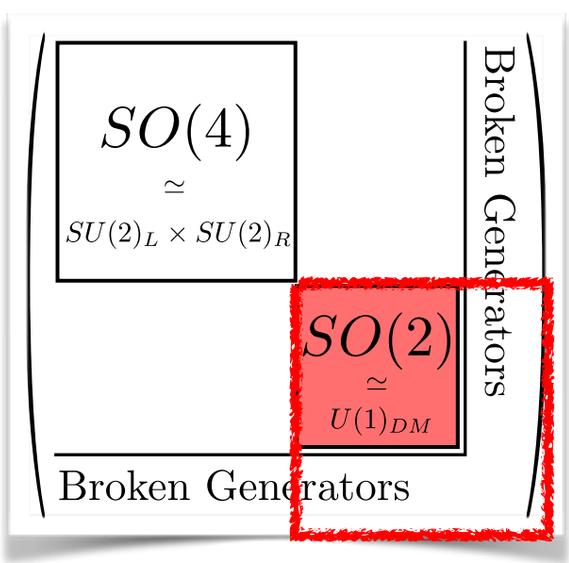
- Yukawas and fermion masses from **partial compositeness**

$$\mathscr{L}_f \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_u \bar{u}_R \mathcal{O}_u + \epsilon_d \bar{d}_R \mathcal{O}_d$$

$\mathcal{O}_i$: fermionic operators of the strong sector

- Pick $SO(7)$ representations for fermions

fixes size of shift-symmetry breaking



$$SO(7) \supset SO(4)_{EW} \times \boxed{SO(3)'}$$

$$\{T^{\mathrm{DM}}, X_{\mathrm{Re}\,\chi}, X_{\mathrm{Im}\,\chi}\}$$

U(1) generator

DM shift-symmetry generators

Fermion Embeddings

$$SO(4) \times SO(3) \cong SU(2)_L \times SU(2)_R \times SU(2)'$$

SO(7) representations:

$$\begin{aligned}
\mathbf{1} &= (\mathbf{1},\mathbf{1},\mathbf{1}) \\
\mathbf{7} &= (\mathbf{2},\mathbf{2},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{3}) \\
\mathbf{21} &= (\mathbf{2},\mathbf{2},\mathbf{3}) \oplus (\mathbf{3},\mathbf{1},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{3}) \\
\mathbf{27} &= (\mathbf{3},\mathbf{3},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2},\mathbf{3}) \oplus (\mathbf{1},\mathbf{1},\mathbf{5}) \oplus (\mathbf{1},\mathbf{1},\mathbf{1})
\end{aligned}$$

Do neither break U(1)
nor DM shift symmetry

$q_L \sim \mathbf{7}$

$t_R \sim \mathbf{21}$