The Dark Top

(arXiv:0808.1290)

w/ Jesse Thaler

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Harvard University

LEPP Particle Theory Seminar, 11/05/08

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  - Top Partners
    - Motivated by (little) hierarchy problem...

Top Loops and the Little Hierarchy

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  - A light Higgs ($m_h < 200$ GeV)
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- Need to cut off these loops at a scale lower than Λ
  - Can introduce partners related to top by an approximate symmetry which protects Higgs mass (e.g., SUSY)
  - Need other partners as well, but they are not as urgent

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- Requires somewhat exotic symmetry structure to have non-colored top partners...but lets build it!

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- But wait! Top Yukawa $\lambda_t q h t^c$ poses a problem
  - Reintroduces quadratic sensitivity $m_h^2 \sim -3\lambda_t^2 \Lambda^2/(8\pi^2)$
  - Embed top quarks into SU(3) → no coupling!

Little Higgs Review

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$$\mathscr{L}_{top} = \lambda_1 \mathscr{L}_1 + \lambda_2 \mathscr{L}_2 \approx \lambda_t q h t^c + \ldots$$

  - This ensures a one-loop cancellation, i.e., divergence is cut off by "top partners" at symmetry breaking scale f

$$m_h^2 \sim \frac{f^2 \log \frac{\Lambda}{f}}{(4\pi)^2}$$

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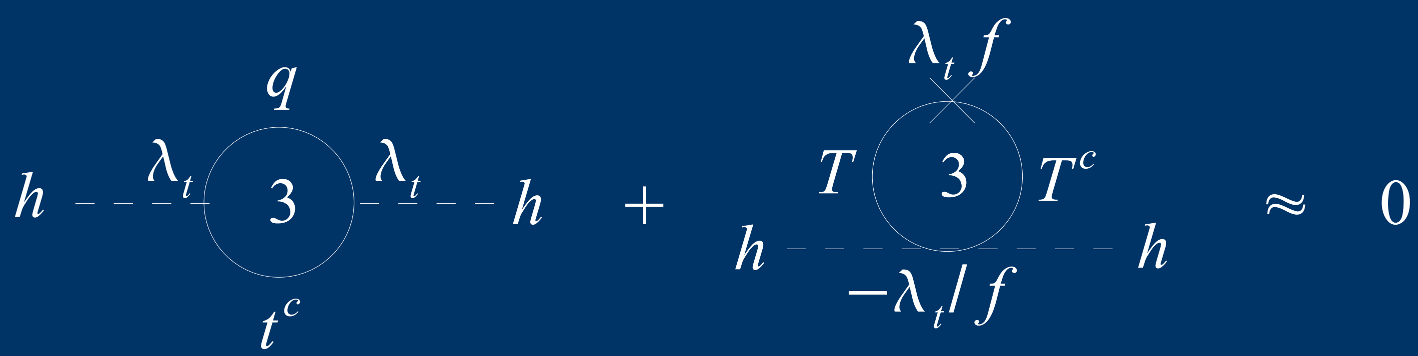
- But not clear why we even need other (problematic) partners at the same scale as the top partner
  - Making only top partners light helps to ease this tension!
    [see, e.g., "The Intermediate Higgs" -- Katz, Nelson, Walker]

One Loop Cancellation

- In (some) Little Higgs theories with T-parity, the top Yukawa structure is very simple, and looks like:

$$\mathscr{L}_{top} = \lambda_t \left(q\, h\, t^c + \left(f - \frac{h^{\dagger} h}{2f}\right) T\, T^c + \ldots \right)$$



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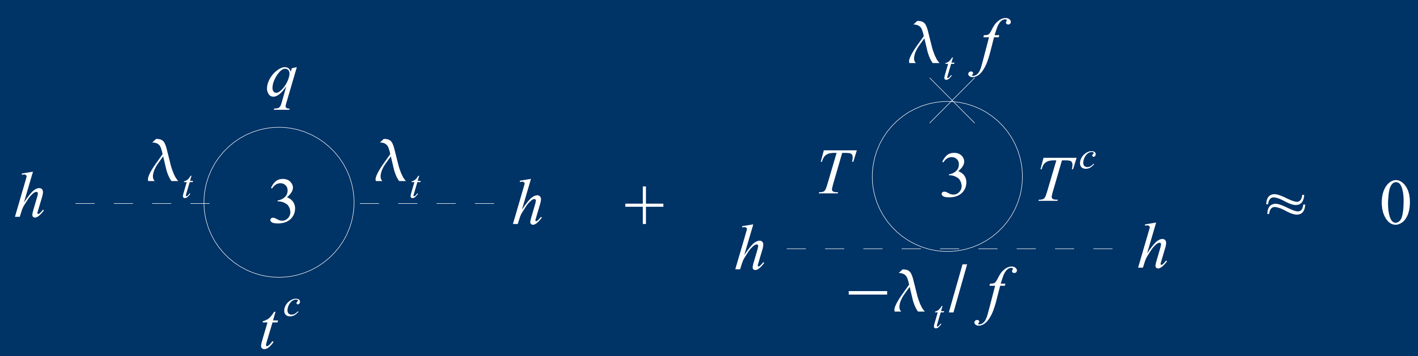

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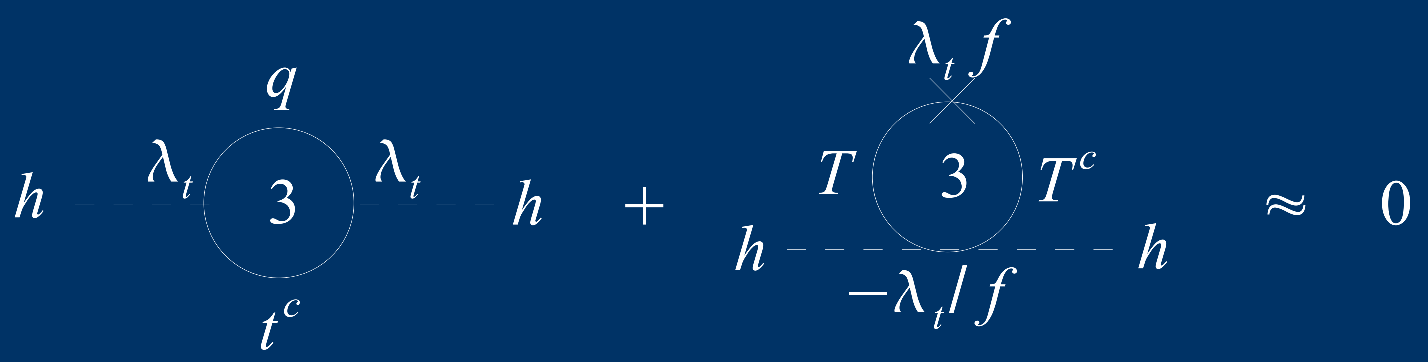

- Note that the cancellation would also go through if the top partners were non-colored, and charged under a different SU(3)...
- If a non-colored top partner is the lightest T-odd particle, it could be dark matter!

Generic Dark Tops

- There is a simple way to recreate this structure:
  - Higgs is a PGB contained in a G/H nonlinear Σ field, where G contains both $SU(3)_C$ and $SU(2)_W$

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- Trades "collective breaking" for a UV assumption → Existence of consistent UV completions important!
- Ideally we'd also generate a tree-level Higgs quartic
  - The models I'll show you today don't do this

Product Group Model

- Let's use the simple SU(3)/SU(2) structure!

(Ignore U(1) factors for simplicity)

$SU(3)_C x SU(2)_W$

gauged

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  - But...UV completions having correct structure can be written down (e.g., in AdS_5)

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  - In fact, in this limit, thermal relic abundance arguments can *predict* the dark matter mass as a function of m_h

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- 5-year WMAP results:

$$0.1075 \leq \Omega_{DM} h^2 \leq 0.1211$$

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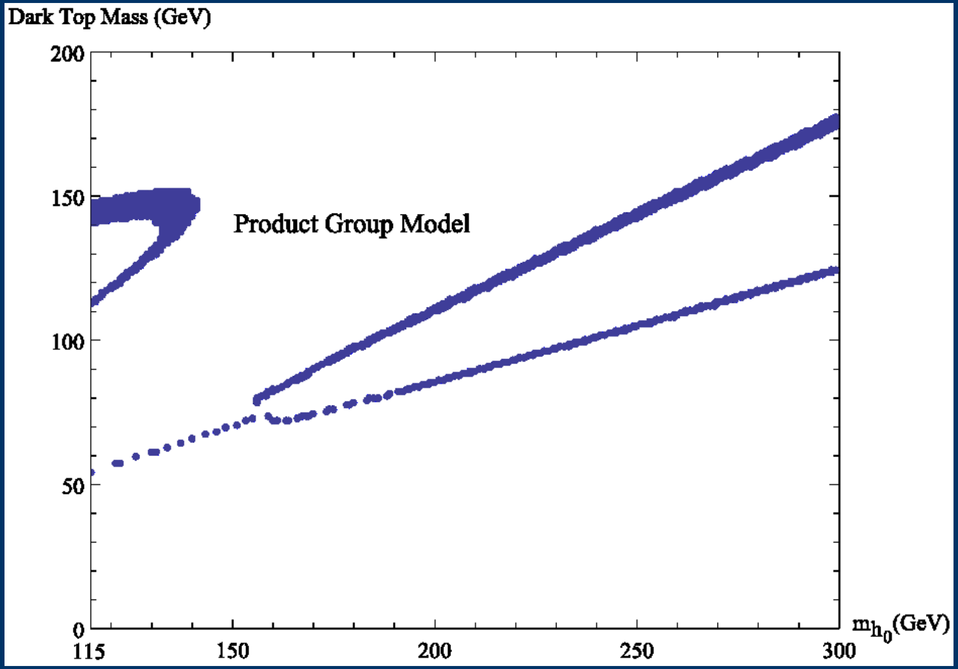

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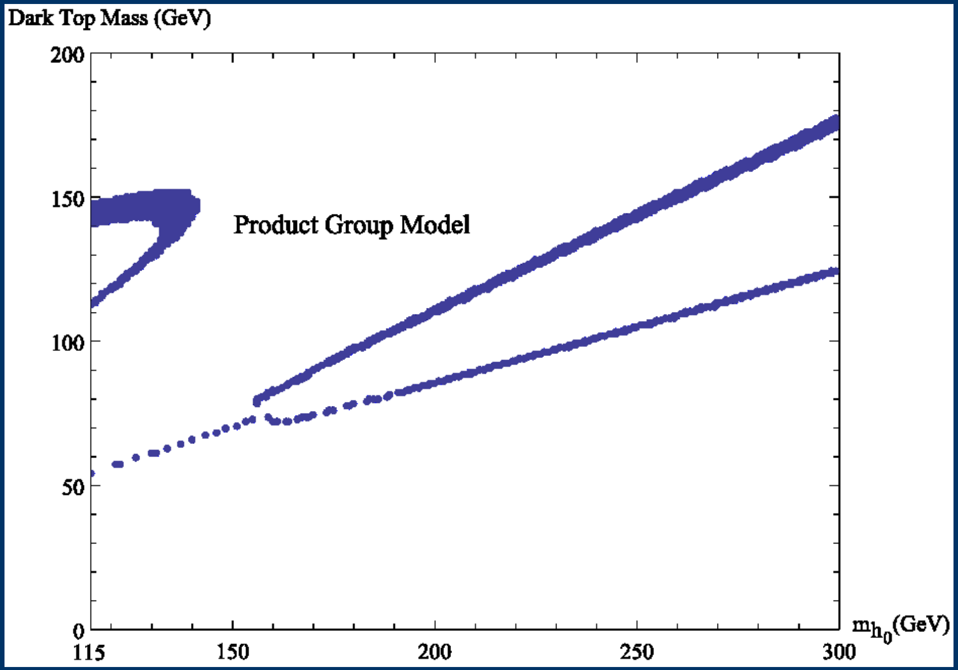

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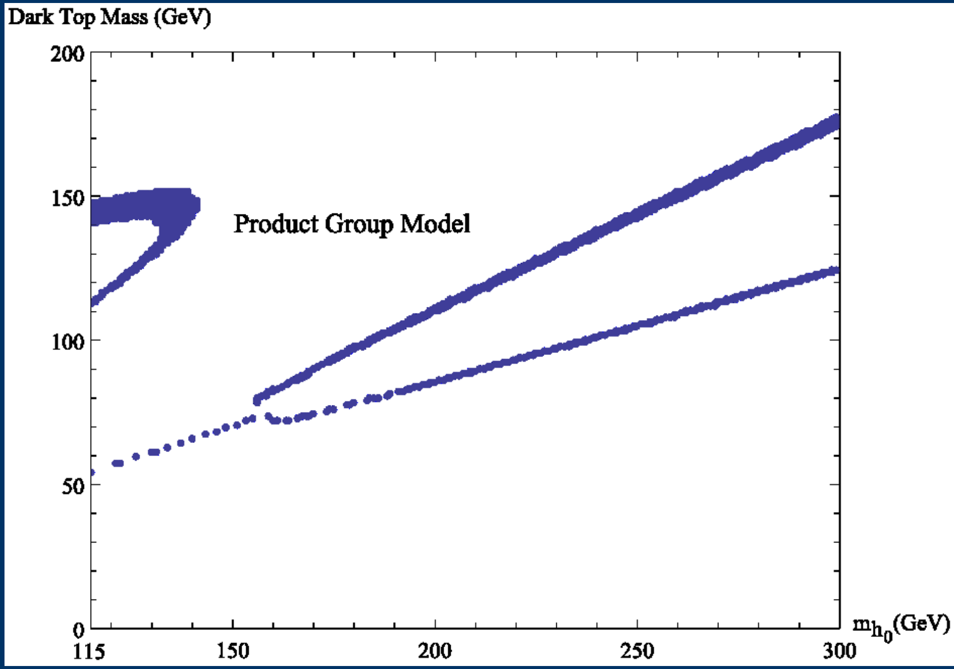

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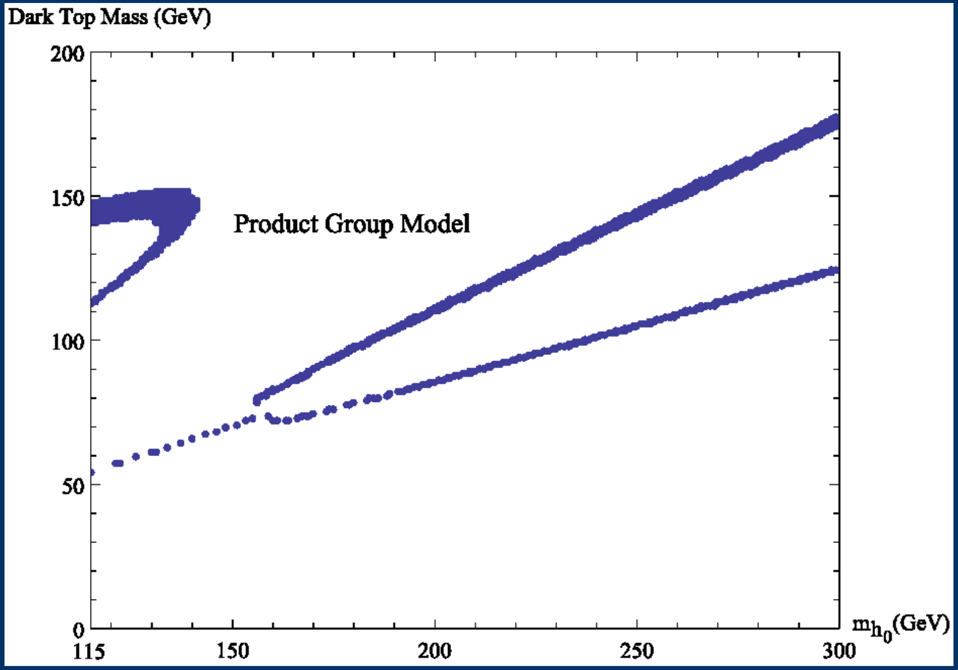

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  - Much of light Higgs region ruled out by CDMS (more on bounds later)

- Use more efficient annihilation to increase DM mass
  - UV dependent 4-fermion operators $\sim (\bar{q}\bar{\sigma}^\mu q)(\bar{T}\bar{\sigma}_\mu T)$
  - Find a dark top with SU(2) quantum numbers!

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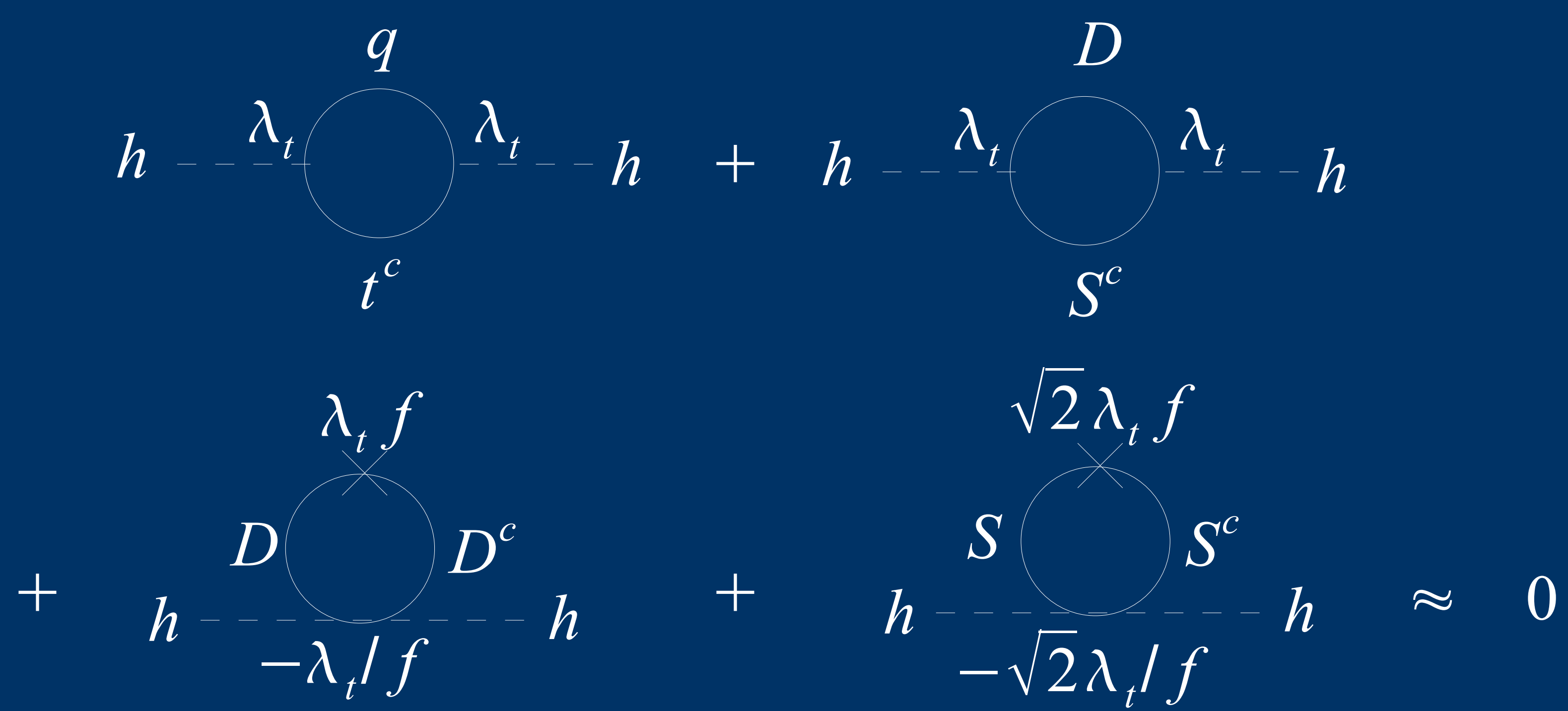
– Notice that there is an additional Yukawa-like coupling $D\, h\, S^c$ but this is compensated for by the $\sqrt{2}$ factor



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  - The three mass eigenstates have masses:

$$m_1 \approx \lambda_t f \left[1 - \frac{v^2}{f^2} + \ldots \right] \qquad m_2 \approx \lambda_t f \left[1 - \frac{v^2}{2 f^2} + \ldots \right] \qquad m_3 \approx \lambda_t f \left[\sqrt{2} + \ldots \right]$$

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  - The lightest mass eigenstate T_1 is neutral, almost pure SU(2) doublet, and has a coupling to the physical Higgs

$$\mathscr{L} \approx -\lambda_t \left(\frac{\sqrt{2}\, v}{f} h_0 T_1 T_1^c \right)$$

(actually a factor of ~2 larger than in the product group model)

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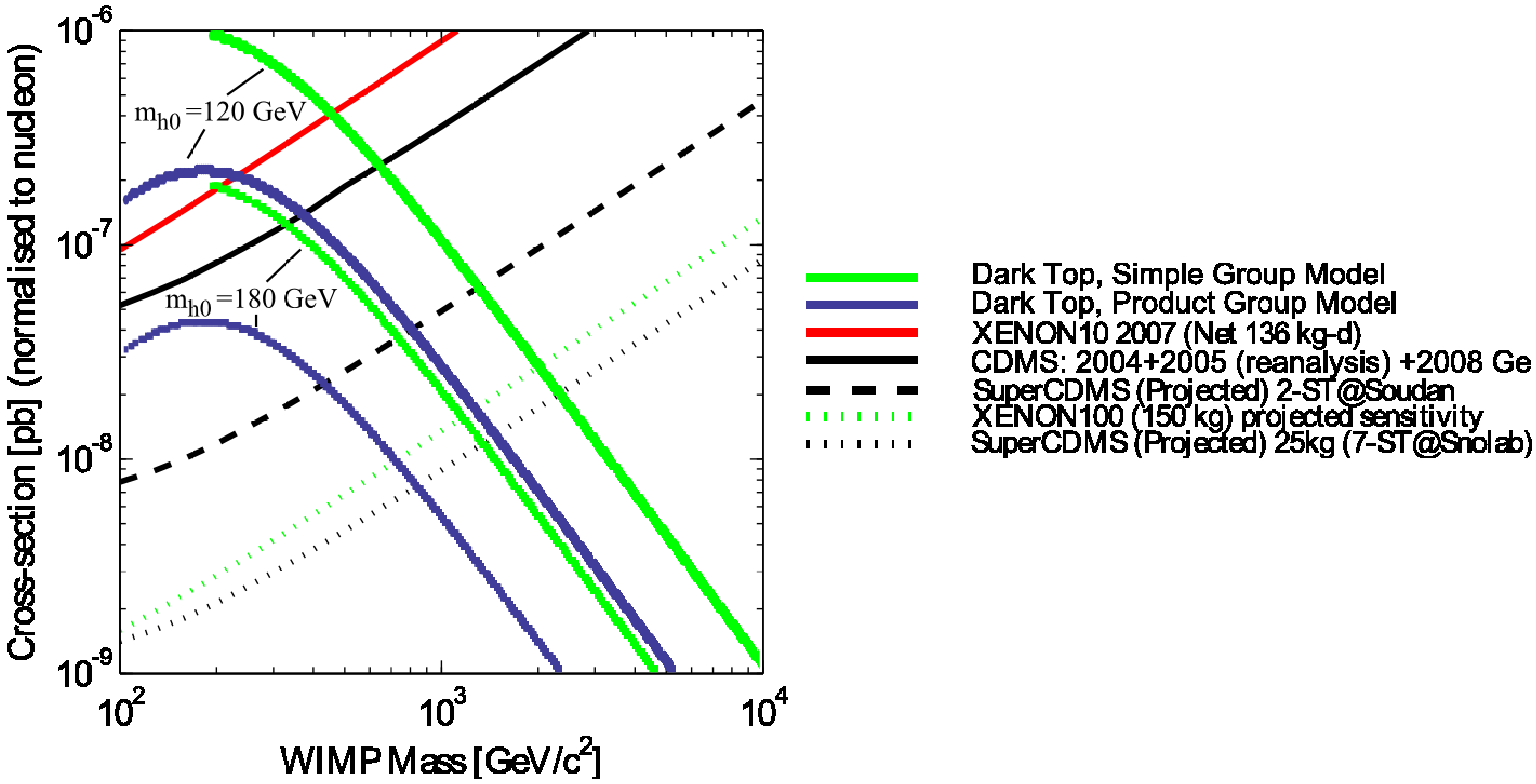
    - Introduce Majorana mass for the doublet larger than ~ 200 keV through an operator

$$\mathscr{L}_{split} = \frac{\Phi^\dagger Q^c \Phi^\dagger Q^c}{M_{split}}$$

    - Then direct detection bounds only come from Higgs exchange

Direct Detection Bounds

– Scattering through Higgs exchange gives the bounds:

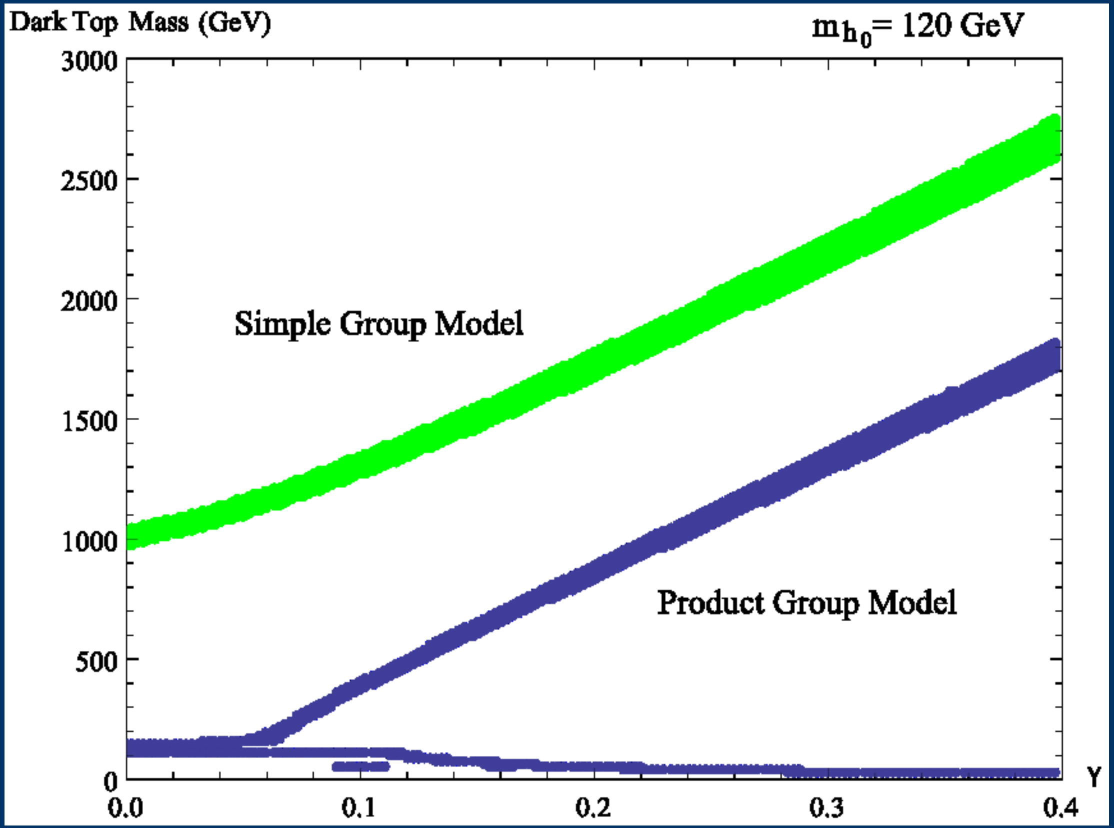


Four-Fermion Operators

- Depending on the UV physics, there could also be 4-fermion operators like:

$$\frac{\gamma}{f^2}(\bar{q}\bar{\sigma}^{\mu}q)(\bar{T}\bar{\sigma}_{\mu}T)$$

  - Come from integrating out resonances of the strong sector
  - Can be sizable if T is mostly composite



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- One can explicitly calculate the corrections to the Higgs potential (in 5D) to see a cancellation

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UV		IR
$SU(3)_C \times SU(2)_W$	$SU(6)$	$SU(6) \to SU(5)$
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$$Q[\overline{21}] = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & q_{1\mathrm{r}} & q_{2\mathrm{r}} & 0 \\ 0 & 0 & 0 & q_{1\mathrm{g}} & q_{2\mathrm{g}} & 0 \\ 0 & 0 & 0 & q_{1\mathrm{b}} & q_{2\mathrm{b}} & 0 \\ q_{1\mathrm{r}} & q_{1\mathrm{g}} & q_{1\mathrm{b}} & 0 & 0 & D_1 \\ q_{2\mathrm{r}} & q_{2\mathrm{g}} & q_{2\mathrm{b}} & 0 & 0 & D_2 \\ 0 & 0 & 0 & D_1 & D_2 & \sqrt{2}S \end{pmatrix} \qquad Q^c[6] = \begin{pmatrix} t^c_r \\ t^c_g \\ t^c_b \\ D^c_1 \\ D^c_2 \\ S^c \end{pmatrix}$$

- "Zeroed out" fields all have (-, +) boundary conditions

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UV | IR

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$$\Rightarrow \quad \delta m_h^2 \propto \int \frac{p^3\,dp}{8\pi^2} \frac{f^2 \hat{\lambda}^4 p^4 (G_{++} - G_{-+})^2 (G^c_{++})^2}{(1 + \hat{\lambda}^2 f^2 p^2 G_{++} G^c_{++})(1 + \hat{\lambda}^2 f^2 p^2 G_{-+} G^c_{++})}$$

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- What is going on?
  - The momentum scale cutting off the top loop is effectively near the 1st KK mass of (-,+) top partners
  - This is approximately the *same* scale that cuts off the dark top loop, and this is guaranteed by the bulk SU(6) symmetry
  - Thus the cancellation we have engineered can go through

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  - In general Q and Q^c regulated by different (KK) scales
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  - Can check that such "bad" models don't exhibit the cancellation in 5D
  - Strong constraint on model building!

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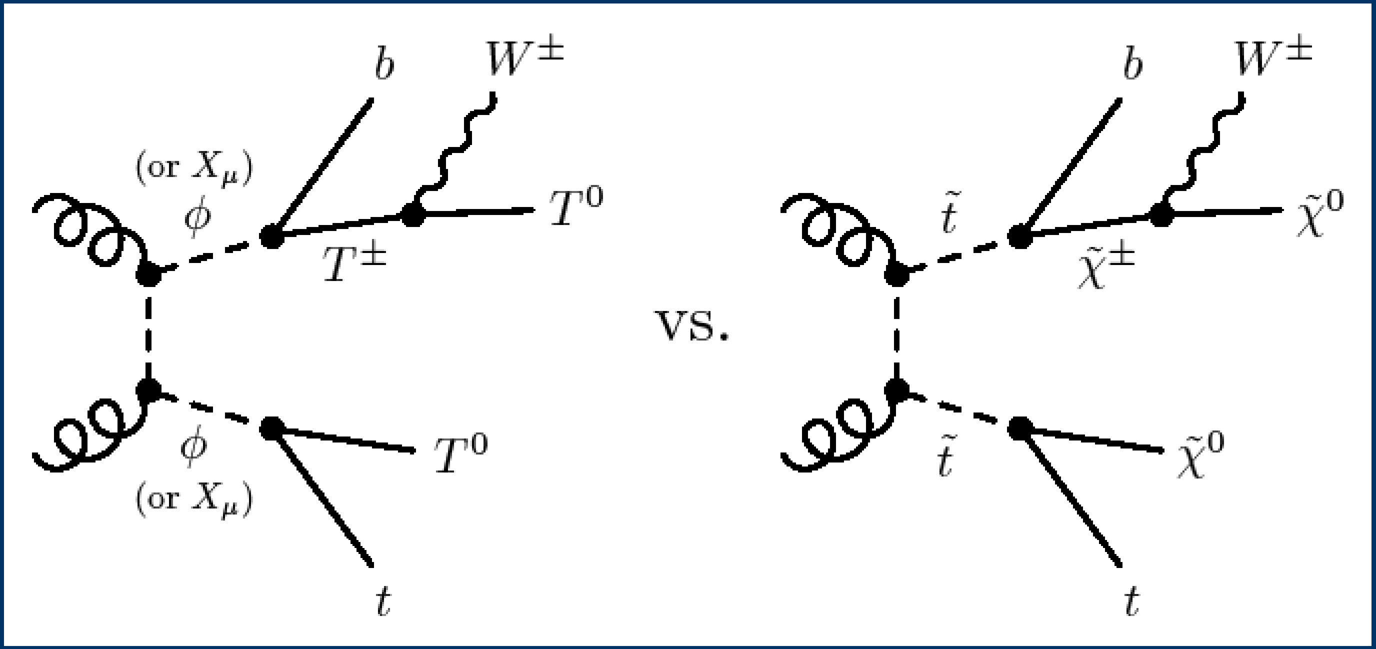
  - Decay topologies look very similar to stops in SUSY!



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- Nature may suprise us!