Charged Composite Scalar Dark Matter

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DESY Theory Workshop
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based on arXiv:1707.07685 [hep-ph]

with R. Balkin, E. Salvioni *and* A. Weiler

Composite Higgs - A Reminder

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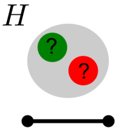
- A light elementary scalar is **unnatural**

- Possible solution: Higgs is a **bound state** of a new strong sector

  Description changes above confinement scale ($\sim$ TeV)
  $\rightarrow$ Higgs mass is naturally ”screened”



$r_H \sim (\mathrm{TeV})^{-1}$

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

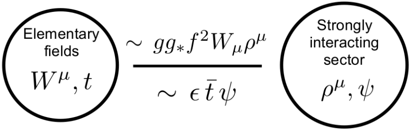
$$\mathcal{G} \xrightarrow[H,\ldots]{f} \mathcal{H}$$

Minimal Model: $SO(5) \xrightarrow[H]{f} SO(4)$

Agashe, Contino, Pomarol 2004

Composite Higgs - A Reminder

- Elementary sector couples **linearly** to strong sector



$$\mathcal{G} \xrightarrow{f} \mathcal{H}$$
$$H, \chi, \ldots$$
$$m_{\rho,\psi} \sim g_* f$$

Elementary particles mix with strong sector resonances

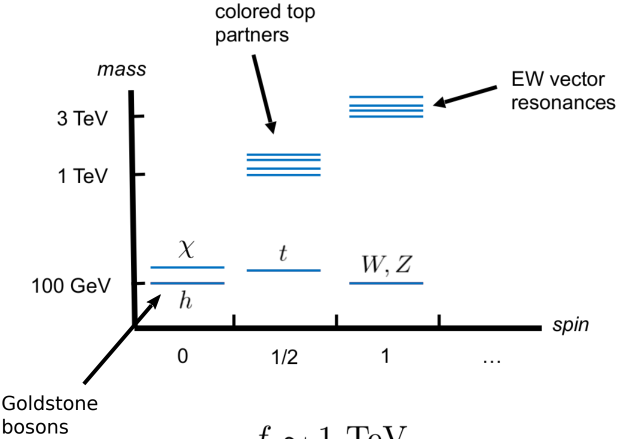
$\Rightarrow$ SM particles are **partially composite** Kaplan 1991

- Elementary couplings g, ϵ break global symmetry
  $\rightarrow$ Breaking generates Higgs potential at loop level

Strongest contribution from top + fermion resonances (**Top Partners**)

$$\mathcal{L} \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_t \bar{t}_R \mathcal{O}_t$$

Sketch of Particle Spectrum



$$f \sim 1\ \text{TeV}$$

Composite Scalar Dark Matter

- Bottom-up perspective: no reason for Higgs to go alone

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

Additional pNGB χ as WIMP Frigerio et al. 2012

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

Dark matter stability?

Composite Scalar Dark Matter

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Dark matter stability?

Extended symmetry structure can provide symmetry to stabilize the dark matter!

No additional symmetry or parity needed!

Charged Composite Scalar Dark Matter

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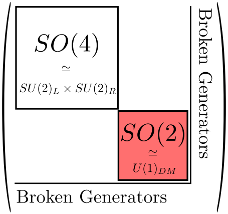
- Extend coset to $SO(7)/SO(6)$

$$SO(7) \xrightarrow{f} SO(6) \quad \Rightarrow \quad (H, \chi) \sim \mathbf{4}_0 + \mathbf{1}_{\pm 1}$$

Balkin, MR, Salvioni, Weiler, 1707.07685

- DM candidate is a **complex scalar** charged under **conserved** $U(1)_{\mathrm{DM}}$

$$U(1)_{\mathrm{DM}} \subset SO(6): \qquad \chi \to e^{i\alpha}\chi$$



$$\Sigma \sim e^{i\pi^a X^a/f}\begin{pmatrix}0\\0\\0\\0\\0\\0\\1\end{pmatrix}, \qquad \vec{\pi} \sim \begin{pmatrix}h_1\\h_2\\h_3\\h_4\\ \mathrm{Im}(\chi)\\ \mathrm{Re}(\chi)\end{pmatrix}$$

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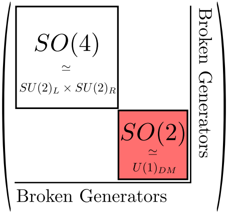

Elementary Fermions in $\mathbf{7} \sim SO(7)$ respect $U(1)_{\mathrm{DM}}$

BUT break Goldstone shift-symmetry

Charged Composite Scalar Dark Matter

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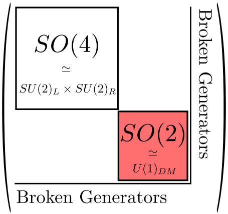

$U(1)_{\mathrm{DM}} \subset SO(6)$ automatically preserved by UV-completion

$\Rightarrow$ UV-Safe Stabilization

Dark Matter Phenomenology

Low-Energy Effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \underbrace{\mathcal{L}_{nl\sigma m} + \mathcal{L}_t}_{\text{tree-level}} - \underbrace{V_{\text{eff}}}_{\text{one-loop}}$$

Dark Matter Phenomenology

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$$\frac{m_t}{f^2}\bar{t}t\chi^*\chi$$

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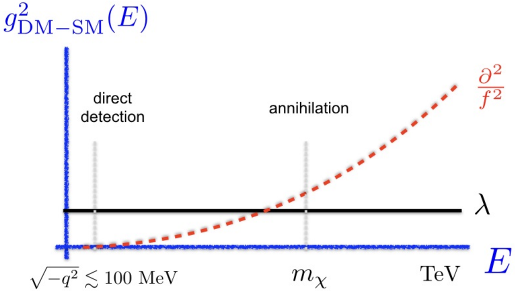

Direct Detection

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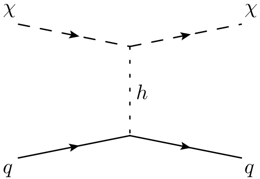
- Higgs exchange in t-channel dominates χN scattering



$$\propto \frac{\lambda}{m_h^2}$$

- Derivative interactions negligible $\quad \frac{-q^2}{f^2} \ll 1$

- Spin-Independent χN cross-section determined by λ

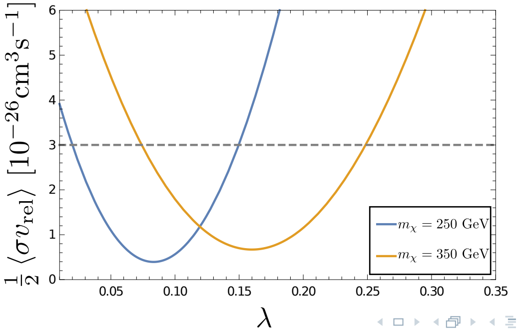
$$\sigma_{\mathrm{SI}}^{\chi N} \simeq \frac{f_N^2}{\pi} \frac{m_N^4 \lambda^2}{m_\chi^2 m_h^4} = 4 \times 10^{-46}\mathrm{cm}^2 \left(\frac{\lambda}{0.03}\right)^2 \left(\frac{300\ \mathrm{GeV}}{m_\chi}\right)^2$$

Relic Abundance

- Annihilation mainly through Higgs portal into WW, ZZ, hh, tt
- Interplay of derivative and portal coupling $\mathcal{L} \sim \frac{v}{f^2}\partial_\mu h \partial^\mu |\chi|^2 - 2v\lambda h|\chi|^2$

$$\sigma \propto \left(\frac{2m_\chi^2}{f^2} - \lambda\right)^2$$

fixed m_χ: two values of λ reproduce right RA



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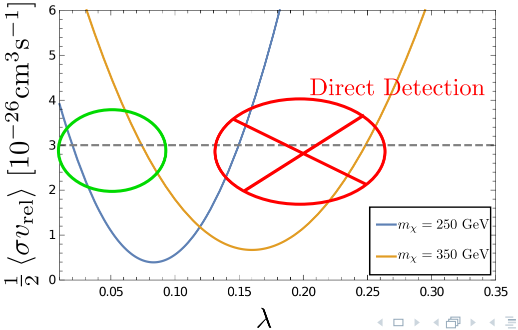

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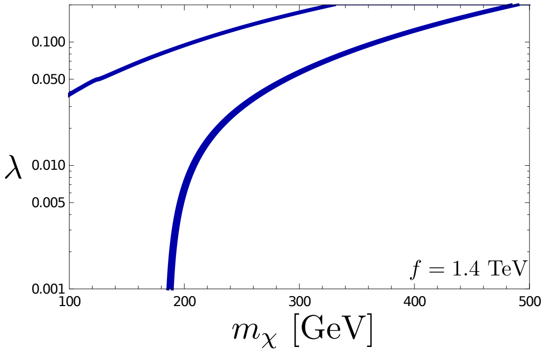

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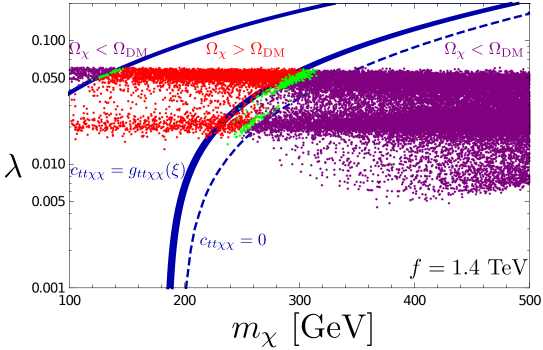
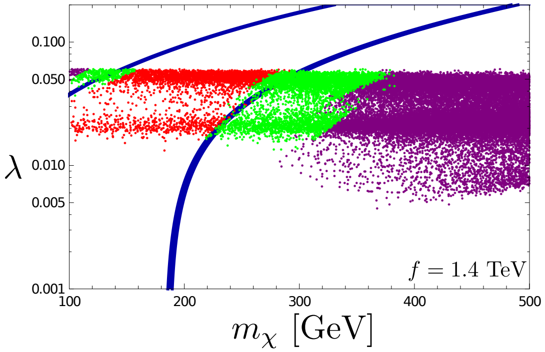


Green: $\Omega_\chi = \Omega_{\rm DM} \pm 5\%$

All points satisfy collider constraints (next slide)

Relic Abundance



Caveat:
Large loop corrections to $\frac{1}{f^2}\partial_\mu|H|^2\partial^\mu|\chi|^2$

$\Rightarrow$ irreducible uncertainty of 50%

Green: $\Omega_\chi = \Omega_{\mathrm{DM}} \pm 50\%$

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Relic Abundance

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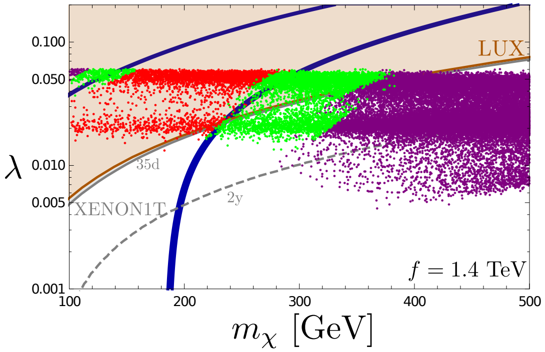

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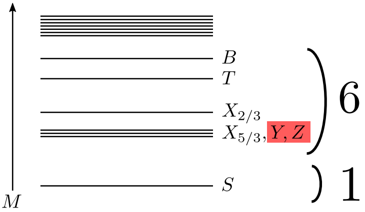
Collider Phenomenology

- Top Partners are **colored** and can be produced at hadron colliders

- They come in complete $SO(6)$ representations

$SO(7)/SO(6)$: $\quad \mathbf{7} = \mathbf{6} + \mathbf{1}$



$U(1)_{\mathrm{DM}}$ charged Top Partners Y, Z

stop-like Signatures $Y \to t + \chi$

Current Bounds

$M_S > 1$ TeV, $\quad M_T > 1.2$ TeV, $\quad M_{X_{5/3}} > 1.2$ TeV, $\quad M_{Y,Z} > 1.4$ TeV

Conclusions

- DM as pNGB in $SO(7)/SO(6)$ Composite Higgs model
- Natural and UV-Safe symmetry protecting the DM
- Viable mass range $200 - 400$ GeV will be fully tested by XENON1T
- New LHC signals from $U(1)_{\mathrm{DM}}$ charged top partners

Outlook:

$U(1)_{\mathrm{DM}}$ can be gauged $\rightarrow$ very different phenomenology (work in progress)

Backup

One-Loop Scalar Potential

$$V(h,\chi) = \frac{1}{2}\mu_h^2 h^2 + \frac{\lambda_h}{4} h^4 + \mu_{\mathrm{DM}}^2 \chi^*\chi + \lambda_{\mathrm{DM}}(\chi^*\chi)^2 + \lambda h^2 \chi^*\chi$$

- Portal coupling λ important for DM-Pheno
- Integrate out vector and fermion resonances and compute Coleman-Weinberg Potential S. R. Coleman, E. J. Weinberg '73
  $\rightarrow$ Require sum rules on model parameters for finite potential

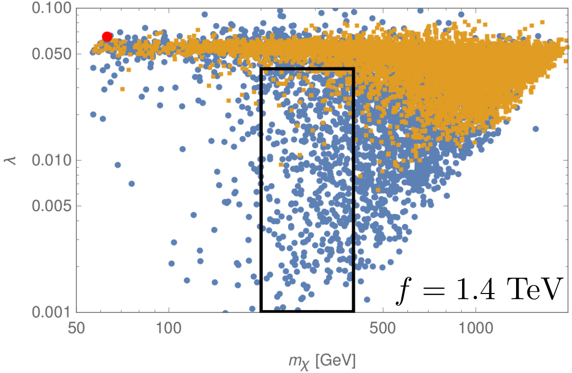
  Marzocca et al. '12, Pomarol, Riva '12

Numerical Scans

- One layer of fermionic resonances: $m_\chi \sim \frac{m_h}{2}, \lambda \sim \frac{\lambda_h}{2} \sim 0.06$

  Ruled out by direct detection bounds!

- Two Layers of fermionic resonances



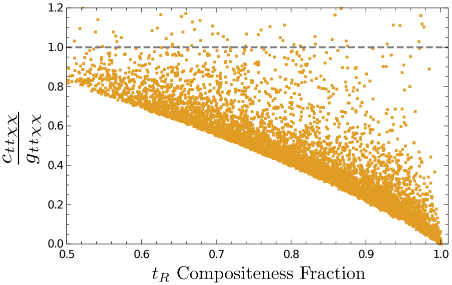
Orange: Top Partner masses above 1 TeV

Fermion-Goldstone Couplings

Top interactions: $\mathcal{L}_t \sim -2c_{tt\chi\chi}\frac{m_t}{v^2}\bar{t}t\chi^*\chi \quad \Rightarrow \sigma \propto \left(\frac{2m_\chi^2}{f^2} - \lambda\right)^2 + f(c_{tt\chi\chi})$

Mixing Contributions to $c_{tt\chi\chi}$ Azatov, Galloway '12

$$c_{tt\chi\chi} = g_{tt\chi\chi}(\xi) + \mathcal{O}\left(\xi\left(\epsilon_t/m_\psi\right)^2\right), \quad \xi = v^2/f^2$$



Fully composite t_R respects full $\mathcal{G}$ symmetry

$\Rightarrow$ Non-derivative couplings vanish

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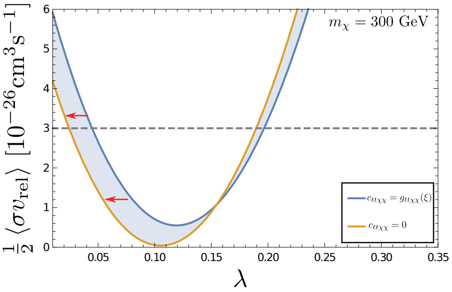


Shifts relic abundance to smaller λ

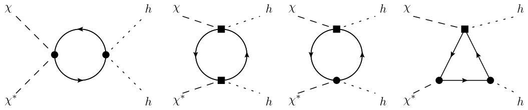
One Loop Finite Momentum Corrections

We use tree-level and one-loop couplings in V_{eff} for DM annihilation

BUT derivative interactions in $\mathcal{L}_{nl\sigma m}$

$$\mathcal{L}_{nl\sigma m} \supset \frac{c}{f^2} \partial_\mu |H|^2 \partial^\mu |\chi|^2$$

receive large corrections



$$c^{\text{tree}} = 1, \qquad c^{1-\text{loop}} = \frac{N_c}{2\pi^2 f^2} \left(\epsilon_T^2 - \frac{\epsilon_Q^2}{8} \right) \log \frac{\Lambda^2}{m_\psi^2}$$

$\Rightarrow$ Assign 50% theoretical uncertainty to annihilation cross-section

Estimate of inverse Tuning (1 Layer Model)

$$\frac{1}{\Delta} \sim 2\xi \qquad \approx 6\% \text{ for } f = 1.4\,\text{TeV}$$

Numerical estimate: $$\Delta = \max_i \left| \frac{\partial \log \xi}{\partial \log c_i} \right|$$