DARK MATTER IN COMPOSITE HIGGS MODELS

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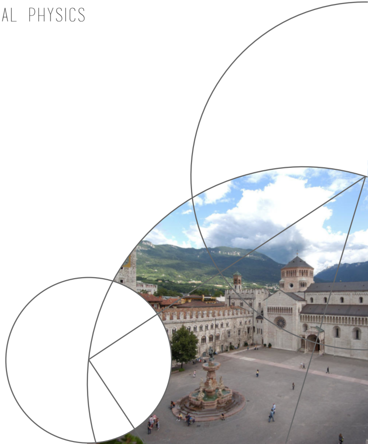
INTERDISCIPLINARY APPROACH TO QCD-LIKE COMPOSITE DARK MATTER. ECT* TRENTO



October 4, 2018

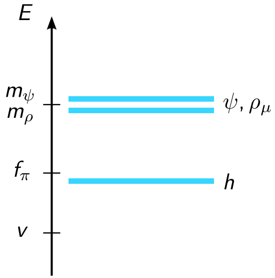
TRENTO

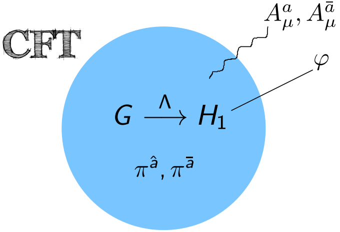
ISTITUTO NAZIONALE PER L'ASSICURAZIONE CONTRO GLI INFORTUNI SUL LAVORO

COMPOSITE HIGGS

- One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics
  KAPLAN, GEORGI '84

- It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD
  AGASHE, CONTINO, POMAROL '04





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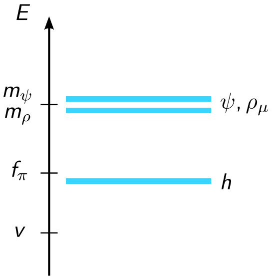
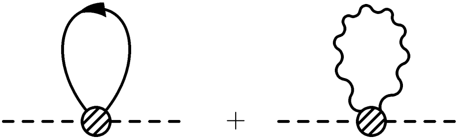


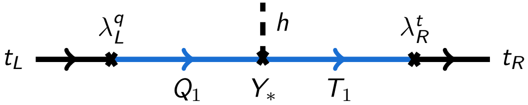


They can naturally lead to a light Higgs $\quad m_\pi^2 = m_h^2 \sim g_{\rm el}^2 \Lambda^2 / 16\pi^2$

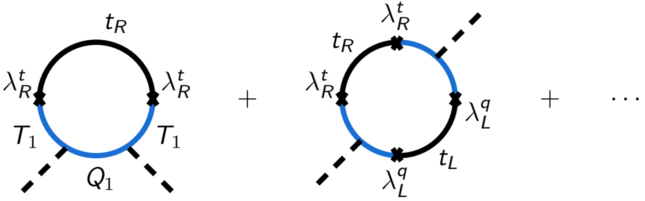
COMPOSITE HIGGS

- ⋆ The gauge contribution is aligned in the direction that preserves the gauge symmetry WITTEN '83

- ⋆ However, the linear mixings $\lambda_L^q \bar{q}_{\alpha L} (\Delta_q^\alpha)^I (\mathcal{O}_L^q)_I + \lambda_R^t \bar{t}_R \Delta_t^I (\mathcal{O}_R^t)_I + \text{h.c.}$ needed to generate the fermion masses



break the NGB symmetry and will be also responsible for EWSB



A LOW ENERGY THEORY

Strongly interacting physics is tough but we can learn a big deal of what happens to the pNGBs with the help of

- ⋆ the CCWZ construction
- ⋆ a spurion analysis

If $U = \exp(i\Pi^a X^a/f)$ and $\omega_\mu = -iU^{-1}D_\mu U = d_\mu^a X^a + E_\mu^i T^i$,

$$\mathcal{L}_\Pi = \frac{1}{2} f^2 \mathrm{Tr}\,(d_\mu d^\mu) + \mathcal{O}(\partial^4) + V_{\mathrm{gauge}}(\Pi) + V_{\mathrm{ferm}}(\Pi) + \mathcal{L}_{\mathrm{Yuk}}(\Pi, \psi_i)$$

where

- ⋆ $V(\Pi) = V_{\mathrm{ferm}}(\Pi) + V_{\mathrm{gauge}}(\Pi)$ is loop induced
- ⋆ $\mathcal{L}_{\mathrm{Yuk}}(\Pi, \psi_i)$ is tree level

and both are dictated by the breaking of the global symmetry

A LOW ENERGY THEORY

We can make some spurion analysis using the dressed spurions

$$\Delta^{\alpha}_{qD}(\Pi) = U^{-1}\Delta^{\alpha}_{q} U = \bigoplus_{m} \Delta^{\alpha m}_{q}(\Pi), \qquad \ldots$$

and some naive dimensional analysis

$$V_{\text{ferm}}(\Pi) \sim m_*^4 \frac{N_c}{16\pi^2}\left[\left(\frac{\lambda}{g_*}\right)^2 \sum_j c_j V_j(\Pi) + \left(\frac{\lambda}{g_*}\right)^4 \sum_k c'_k V'_k(\Pi)\right] + \ldots$$

with $m_* \sim g_* f$, and

$$V_{j_0}(\Pi) \propto \Delta^{\alpha j_0 \dagger}_{q}(\Pi)\Delta^{\alpha j_0}_{q}(\Pi), \qquad \ldots$$

Similarly,

$$\mathcal{L}_{\text{Yuk}} \supset \sum_m y_m \bar{q}_{\alpha L} \Delta^{\alpha m}_{q}(\Pi) t_R$$

THE QUESTION OF DM

- One way to have a DM candidate is to add some pNGB which are stable via some parity of the strong sector

- One typically uses the fact that for a symmetric coset, $[X^a, X^b] = i f_{abk} T^k$ and therefore,

$$d_\mu = \frac{1}{f}\partial_\mu \Pi - \frac{i}{2f^2}\left[\Pi, \partial_\mu \Pi\right]_X - \frac{1}{6f^3}\left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]_X + \frac{1}{24f^4}\left[\Pi, \left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]\right]_X + \ldots,$$

and

$$\mathcal{L}_\sigma = \frac{1}{2} f^2 \mathrm{Tr}\left(d_\mu d^\mu\right) + \mathcal{O}(\partial^4) \sim 1 + \frac{1}{f^2} + \frac{1}{f^4} + \ldots + \mathcal{O}(\partial^4)$$

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The question of DM

- We can then promote the accidental $\mathbb{Z}_2$ symmetry of $\text{Tr}(d_\mu d^\mu)$ to a symmetry of the strong sector under which some pNGBs will be odd

$$H \to H \qquad \Phi \to -\Phi$$

- One needs to be sure that this parity is respected by the fermion linear mixings

$$\mathcal{L}_{\text{mix}} \sim \lambda_q \bar{q}_{\alpha L} (\Delta_q^\alpha)^I (\mathcal{O}_q)_I + \lambda_u \bar{u}_R (\Delta_u)^I (\mathcal{O}_u)_I + \lambda_d \bar{d}_R (\Delta_d)^I (\mathcal{O}_d)_I + \text{h.c.} \; .$$

and therefore by $V(\Pi)$ and $\mathcal{L}_{\text{Yuk}}(\Pi, \psi_i)$

- Then the lightest $\mathbb{Z}_2$-odd scalar will be stable and a DM candidate!

COMPOSITE DARK MATTER

SOME RELEVANT EXAMPLES

- ⋆ $SO(6)/SO(5) \cong SU(4)/Sp(4) \Rightarrow \mathbf{4} \oplus \mathbf{1}$ GRIPAIOS ET AL '09, FRIGERIO ET AL '12
- ⋆ $SO(7)/SO(6) \Rightarrow \mathbf{4} \oplus \mathbf{1} \oplus \mathbf{1}$

  DM singlet and real singlet responsible for EW PT CHALA ET AL '16

  Complex DM singlet BALKIN ET AL '17
- ⋆ $SO(7)/G_2 \Rightarrow \mathbf{4} \oplus \mathbf{3}$ not symmetric! CHALA, AC, BALLESTEROS '17

  DM EW triplet

  DM singlet plus a charged scalar
- ⋆ $SO(6) \times SO(4) \times SO(2)$: $\mathbf{4} \oplus \mathbf{4}$ MRAZEK ET AL 11
- ⋆ $SU(7)/[SU(6) \times U(1)]$: complex $\mathbf{2} \oplus \mathbf{2} \oplus \mathbf{1} \oplus \mathbf{1}$ no $SO(4)$ BARNARD ET AL '17
- ⋆ $SU(4) \times SU(4)/SU(4)$: $\mathbf{4} \oplus \mathbf{4} \oplus \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{3}$ WU ET AL '17

THE CASE OF THE SINGLET

GRIPAIOS, POMAROL, RIVA, SERRA 09 FRIGERIO, POMAROL, RIVA, URBANO 12

Let's study first the singlet case. Then

$$\mathcal{L}_\sigma = |D_\mu H|^2 \left[1 - \frac{S^2}{3f^2}\right] + \frac{1}{2}(\partial_\mu S)^2 \left[1 - 2\frac{|H|^2}{3f^2}\right] + \frac{1}{3f^2}\partial_\mu |H|^2 (S\partial_\mu S) + \cdots$$

plus

$$V(H,S) \supset \mu_S^2 S^2 + \lambda S^2 |H|^2, \quad \mathcal{L}_{\text{Yuk}} \supset \frac{S^2}{f^2}\left(c_t y_t \bar{q}_L \tilde{H} t_R + c_b y_b \bar{q}_L H b_R + \text{h.c.}\right)$$

- ⋆ The derivative interactions come with $\mathcal{O}(1)$ numbers fixed by the coset
- ⋆ c_t, c_b, μ_S^2 and λ depend on the specific details of the global symmetry breaking

$$\lambda \lesssim \mu_S^2/f^2 \Rightarrow m_s^2 = \mu_s^2 + \lambda v^2 \approx \mu_s^2$$

THE CASE OF THE SINGLET

GRIPAIOS, POMAROL, RIVA, SERRA 09 FRIGERIO, POMAROL, RIVA, URBANO 12

We can consider three main cases

- ⋆ S shift symmetry is broken by the top quark:

$$c_t \sim 1, \quad \lambda \approx \frac{N_c}{16\pi^2} c y_t^2 g_\rho^2 \lesssim \lambda_h, \qquad m_s \sim f \gg m_h$$

- ⋆ S shift symmetry is broken by the bottom quark

$$c_t = 0, \quad c_b \sim 1, \quad \lambda \approx \frac{N_c}{16\pi^2} \bar{c} y_b^2 g_\rho^2 \ll \lambda_h, \quad m_s \approx c' \sqrt{\frac{N_c}{16\pi^2}} \lambda_{b_R} m_\rho$$

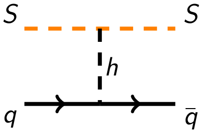
- ⋆ S shift symmetry is preserved by the SM fermions LATER

THE CASE OF THE SINGLET

DIREC DETECTION

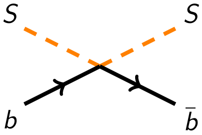
The derivative coupling is irrelevant for direct detection, so one should only care of the portal coupling $\lambda S^2 |H|^2$

- ⋆ In the top driven case, there is a m_S^2-suppressed tree-level contribution proportional to λ



$$\sigma = \frac{\lambda^2 m_N^4 f_N^2}{\pi m_h^4 m_S^2} \sim 4 \times 10^{-46} \mathrm{cm}^2 \left(\frac{\lambda}{0.03}\right)^2 \left(\frac{300\,\mathrm{GeV}}{m_S}\right)^2$$

- ⋆ In the bottom driven case, direct detection goes via the $S^2 bb$ vertex



$$\sigma = \frac{m_N^4 \tilde{f}_N^2}{4\pi f^4 m_S^2} \sim 10^{-47} cm^2 \left(\frac{1\,\mathrm{TeV}}{f}\right)^4 \left(\frac{100\,\mathrm{GeV}}{m_S}\right)^2$$

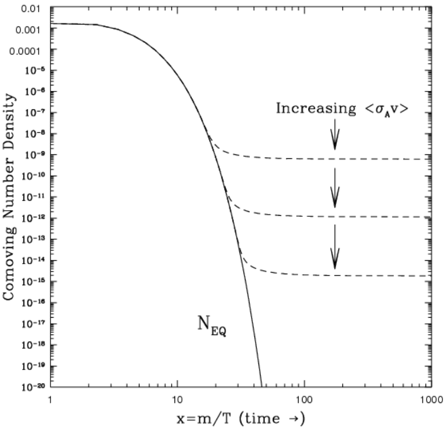
RELIC ABUNDANCE

The singlet S can provide the DM relic abundance via the usual freezout mechanism

$$\Omega\, h^2 \sim \frac{3 \times 10^{-27}}{\langle \sigma\, v \rangle}\,\text{cm}\,\text{s}^{-1}\,,$$

if $\Omega\, h^2 \sim [\Omega\, h^2]_{\text{DM}} \sim 0.11$, it must have

$$\langle \sigma\, v \rangle \sim 3 \times 10^{-26}\,\text{cm}\,\text{s}^{-1}$$



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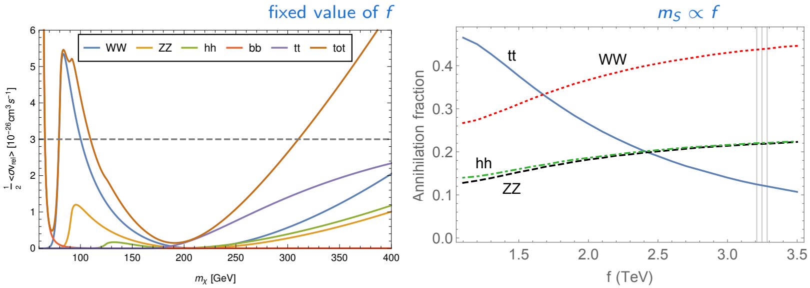


BALKIN, RUHDORFER, SALVIONI, WEILER, 17 BALLESTEROS, AC, CHALA, 17

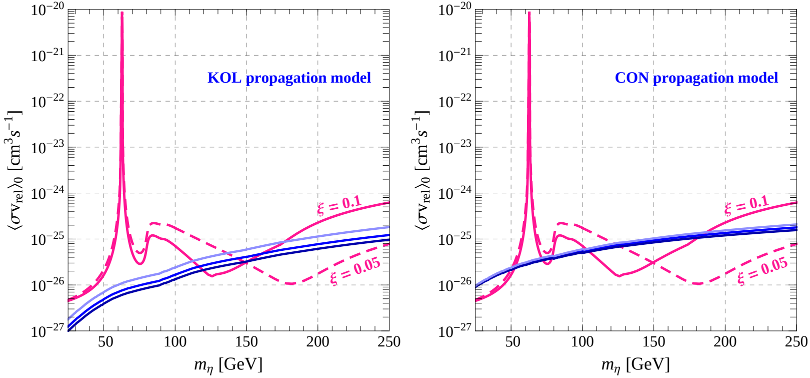
Dominant anihilation channels

- At large mass,
  - $t\bar{t}$ via $1/f \times (v/f)$ contact interaction.
  - hh, WW, ZZ via $1/f^2(S\partial_\mu S)\partial^\mu|H|^2$ GOLDSTONE EQUIVALENCE THEOREM
- At very small mass, $b\bar{b}$

INDIRECT DETECTION

Antiproton spectrum (e.g. PAMELA)

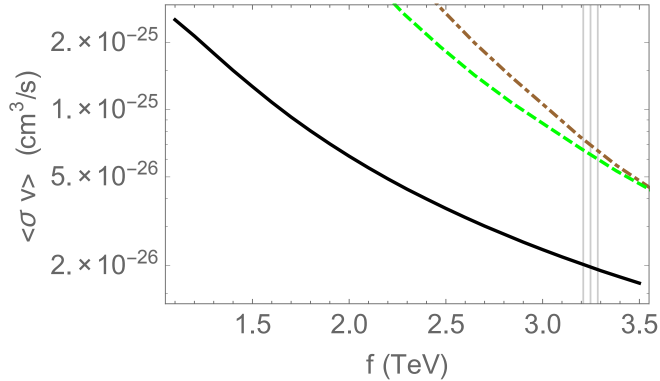
$$\left.\frac{dN}{dE}\right|_{\bar{p}} = \sum_f BR_f \times \left.\frac{dN}{dE}\right|_{\bar{p}}^{f} \qquad Q_{\bar{p}} = \frac{1}{2}\left[\frac{\rho_{\rm DM}(r)}{m_S}\right]^2 \langle\sigma v\rangle_0 \frac{dN}{dE}_{\bar{p}}$$



MARZOCCA, URBANO, 14

INDIRECT DETECTION

Bounds from *WW* decay from DM annihilation in the center of the Milky Way (HESS and projected CTA) can also be important



COLLIDER SEARCHES

⋆ EWPT: modification of hVV coupling

$$R_{hVV} = \frac{g_{hVV}}{g^{SM}_{hVV}} = \sqrt{1 - v^2/f^2} \quad \Rightarrow \quad f \gtrsim 900 \text{ GeV}$$

GHOSH, SALVAREZZA, SENIA 15

⋆ Modification of Higgs production and decay

$$R_\gamma = \frac{\sigma(gg \to h) \times BR(h \to \gamma\gamma)}{\sigma_{SM}(gg \to h) \times BR_{SM}(h \to \gamma\gamma)} \sim 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) \Rightarrow f \gtrsim 800 \text{ GeV}$$

⋆ Monojet searches are not competitive

⋆ Invisible Higgs decay: If $m_S < m_h/2$ the Higgs can decay into SS

$$\Gamma_{\text{inv}}(h \to SS) \approx \frac{m_h^3 v^2}{32\pi f^4 (1 - v^2/f^2)} \sqrt{1 - \frac{4m_S^2}{m_h^2}}, \qquad \text{BR}_{\text{inv}} = \frac{\Gamma_{\text{inv}}}{\Gamma^{\xi}_{\text{SM}} + \Gamma_{\text{inv}}}$$

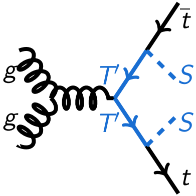
$\text{BR}_{\text{inv}} < 0.24$ @ 95 C.L.

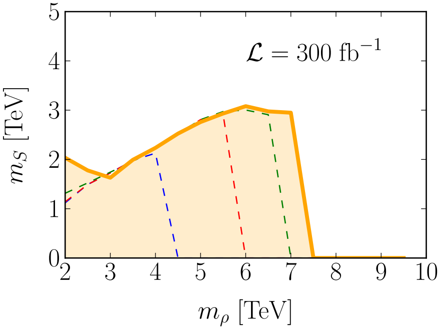
COLLIDER SEARCHES

The presence of light top partners $m_\Psi < m_* = g_* f$ is a natural expectation in these models. Assuming they come in a $\mathbf{5}$ of SO(5)

SERRA 15

$$\mathrm{BR}(T, X_{2/3} \to ht) \sim \mathrm{BR}(T, X_{2/3} \to Zt) \sim 0.5$$
$$\mathrm{BR}(B \to W^- t) \sim \mathrm{BR}(X_{5/3} \to W^+ t) \sim \mathrm{BR}(T' \to St) \sim 1$$



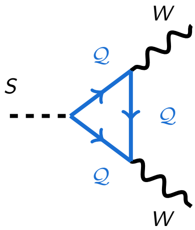


100 TEV CHALA, GROEBER, SPANNOWSKY '18

ANOMALOUS COUPLINGS

- ⋆ In principle, $SO(6)/SO(5)$ admits a Wess-Zumino-Witten term

$$\mathcal{L}_{\mathrm{WZW}} = \frac{S}{f}\frac{\epsilon^{\mu\nu\rho\sigma}}{48\pi^2} c_W \left[g^2 W^a_{\mu\nu} W^a_{\rho\sigma} - g'^2 B_{\mu\nu} B_{\rho\sigma}\right]$$



- ⋆ The specific value of c_W will depend on its UV completion but known examples lead to $c_W \neq 0$ FERRETI 16
- ⋆ There are other cosets like $SO(7)/SO(6), SO(7)/G_2, \ldots$ which are not anomalous

A COMPLEX DM CANDIDATE

BALKIN, RUHDORFER, SALVIONI, WEILER 17

- The unbroken $SO(6)$ subgroup of the coset $SO(7)/SO(6)$ contains a $SO(2)$ symmetry exchanging S and a new scalar singlet S'
- Contrary to the previous cases, $SO(2) \cong U(1)_S$ is not external to the algebra, so no further assumptions of the strong sector are required
- One only needs to assure that the fermion linear mixings respect such subgroup!
- It can even be gauged! BALKIN, RUHDORFER, SALVIONI, WEILER 17

A complex DM candidate

Balkin, Ruhdorfer, Salvioni, Weiler 18

- ⋆ We make $SO(2) \cong U(1)_D$ gauge, and embed all fermions in such a way that they preserve the shift symmetry. Then

$$m_{\mathbb{S}} \sim g_D f \approx 100\,\text{GeV} \left(\frac{\alpha_D}{10^{-3}}\right)^{1/2} \left(\frac{m_\rho}{5\,\text{TeV}}\right), \qquad \lambda = 0 \text{ (at one loop)}$$

- ⋆ Kinetic mixing can be forbidden with the help of an accidental symmetry

$$|(\partial^\mu - i g_D A_D^\mu)\mathbb{S}|^2 - \frac{1}{4} F_D^{\mu\nu} F_{D\mu\nu} + \frac{1}{2} m_{\gamma_D}^2 A_{D\mu} A_D^\mu$$

- ⋆ This implies that the dark photon is stable if $m_{\gamma_D} < 2 m_{\mathbb{S}}$ (m_{γ_D} Stückelberg mass)

A COMPLEX DM CANDIDATE

BALKIN, RUHDORFER, SALVIONI, WEILER 18

$m_{\gamma_D} < 6 \times 10^{-4}$ eV	✓/ X	γ_D is dark radiation today, strong constraints from SE of $\chi\chi^* \to$ SM
6×10^{-4} eV $< m_{\gamma_D} \lesssim 3m_\chi/25$	X	γ_D is relativistic at freeze-out, ruled out by warm DM bounds/overabundant
$3m_\chi/25 < m_{\gamma_D} < m_\chi$	X	γ_D is non-relativistic at freeze-out, overabundant
$m_\chi \lesssim m_{\gamma_D} < 2m_\chi$	✓	both γ_D and χ are cold DM
$2m_\chi < m_{\gamma_D}$	✓	γ_D is unstable

THE CASE OF SO7/G2

BALLESTEROS, AC, CHALA 17

- ⋆ The group is non-anomalous but $SO(7)/G_2$ is not symmetric!

- ⋆ It delivers a $\mathbf{7}$ of G_2, that decomposes under $SU(2)\times SU(2)\subset G_2$ as

$$\mathbf{7} = (\mathbf{2},\mathbf{2})\oplus(\mathbf{3},\mathbf{1})$$

- ⋆ Depending on which $SU(2)$ is weakly gauged, it means that

$$\mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 \quad \text{or} \quad \mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0$$

  under the EW group

- ⋆ If the $\mathbb{Z}_2$ is successfully enforced it will provide a natural version of Higgs portal DM or the Inert Triplet Model

THE CASE OF SO7/G2

BALLESTEROS, AC, CHALA 17

Even though the coset is not symmetric, $f^2 \mathrm{Tr}(d_\mu d^\mu)$ only features even powers of $1/f$

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We make

$$q_L \sim \mathbf{35} = \mathbf{1} \oplus \mathbf{7} \oplus \mathbf{27}, \quad t_R \sim \mathbf{1}$$

leading to

$$V(\Pi) \approx m_*^2 f^2 \frac{N_c}{16\pi^2} y_t^2 \left[c_1 V_1(\Pi) + c_2 V_2(\Pi)\right],$$

with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

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with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

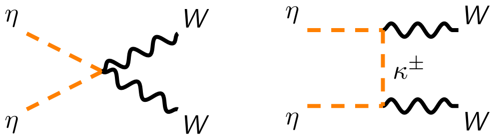
A NATURAL INERT TRIPLET MODEL

CO - ANNIHILATIONS

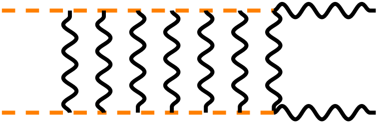
- ⋆ EW gauge bosons induce a radiative splitting between the neutral and the charged components

$$\Delta m_{\Phi} = g m_W \sin^2\theta_W/2 \sim 166\,\text{MeV}$$

- ⋆ The coannihilation is dominated by gauge interactions

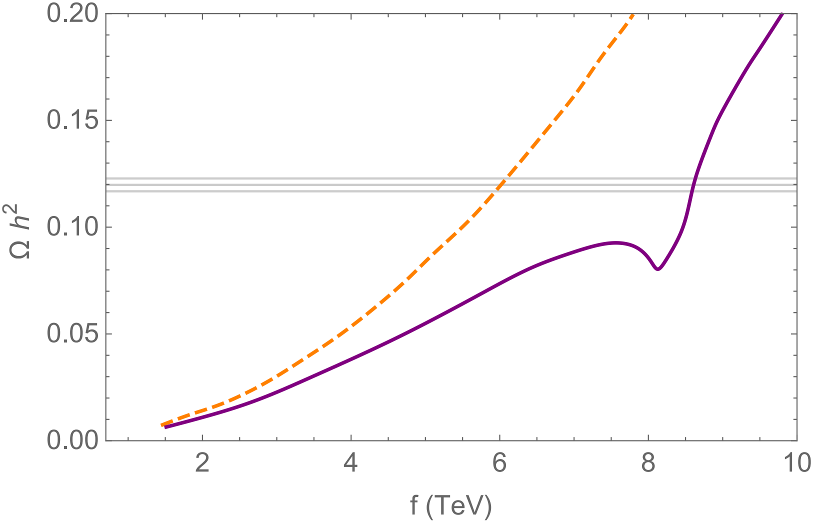


- ⋆ Sommerfeld enhancement and bound state production are important! $g m_{\Phi}/m_W \gg 1$ CIRELLI ET AL 07



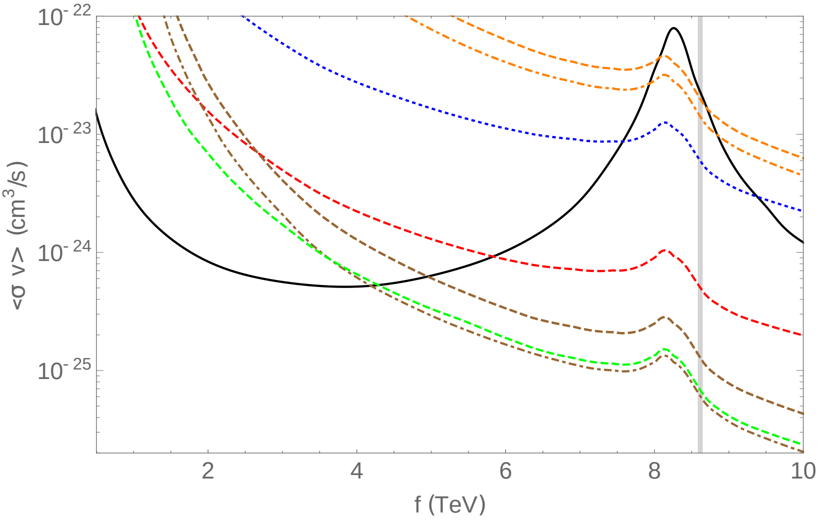
A NATURAL INERT TRIPLET MODEL

CO - ANNIHILATIONS RECAST OF CIRELLI ET AL 07



A NATURAL INERT TRIPLET MODEL

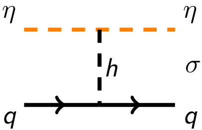
INDIRECT DETECTION



A NATURAL INERT TRIPLET MODEL

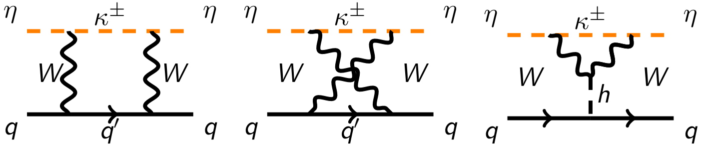
DIRECT DETECTION

- There is a m_Φ^2-suppressed tree-level contribution proportional to $\lambda_{H\Phi}$



$$\sigma = \lambda_{H\Phi}^2 m_N^4 f_N^2/(\pi m_h^4 m_\Phi^2), \quad f_N = \sum_q \langle N|\bar{q}q|N\rangle \approx 0.3$$

- But there are also m_Φ-independent loop induced contributions



They were computed in the heavy WIMP effective theory HILL, SOLLON, 13

$$\sigma(\eta N \to \eta N)_{\text{HWET}} = 1.3^{+0.4+0.4}_{-0.5-0.3} \times 10^{-2}\,\text{zb}$$

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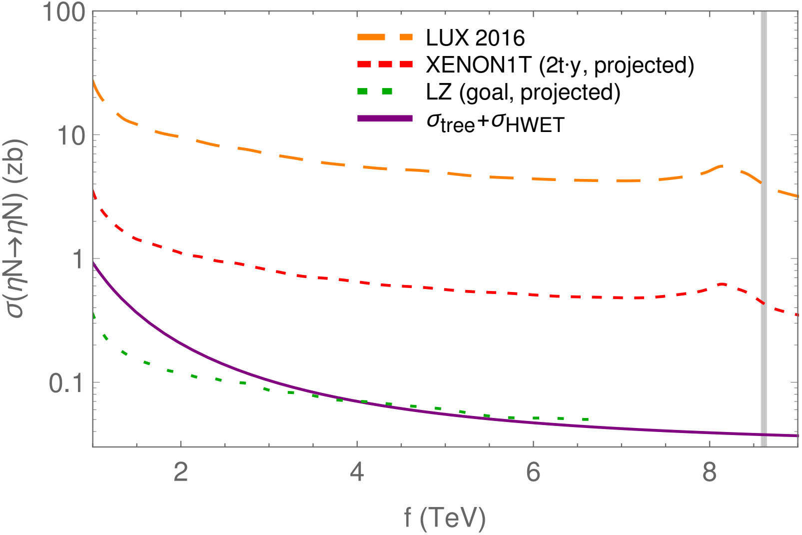


A COMPOSITE 2HDM

MA, CACCIAPAGLIA 15; WU, MA, ZHANG, CACCIAPAGLIA 17

- $SU(N)_{\text{TC}}$ with 4 flavors, leading to $SU(4) \times SU(4) \to SU(4)_D$

	SU(N)	SU(2)$_L$	U(1)$_Y$
$\psi_L = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$	$\square$	**2**	0
$\psi_R = \begin{pmatrix} \psi_3 \\ \psi_4 \end{pmatrix}$	$\square$	**1** **1**	1/2 -1/2

- $\mathbf{15} = (\mathbf{2}, \mathbf{2}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{1}, \mathbf{1})$ NGBs parametrized as

$$\Sigma = \exp\left(i\Pi/f\right) \qquad \Pi = \frac{1}{2}\begin{pmatrix} \sigma_i \Delta^i + s/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma_i N^i - s/\sqrt{2} \end{pmatrix}$$

- There is a parity symmetry

$$\Sigma \to P\Sigma^T P, \qquad P = \begin{pmatrix} \sigma_2 & 0 \\ 0 & -\sigma_2 \end{pmatrix}, \quad \begin{cases} s \to s, H_1 \to H_1 \\ H_2 \to -H_2, \Delta \to -\Delta, N \to -N \end{cases}$$

A Composite 2HDM

Wu, Ma, Zhang, Cacciapaglia 17

- ⋆ Four main parameters: $\sin^2\theta$, the top Yukawa Y_t, Y_0 and

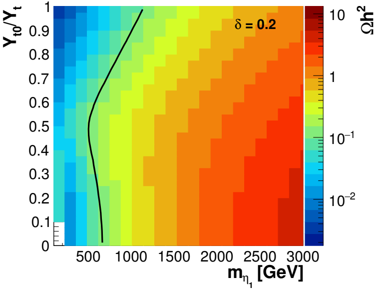
$$\delta = \frac{m_{\psi_L} - m_{\psi_R}}{m_{\psi_L} + m_{\psi_R}},$$

- ⋆ The Z_2-odd states mix to each other, for
  - $\delta > 0$: DM is roughly the neutral component of the $(\mathbf{1},\mathbf{3})$
  - $\delta < 0$: DM is roughly the neutral component of $(\mathbf{2},\mathbf{2})$ & $(\mathbf{3},\mathbf{1})$
- ⋆ The mass splitting is small so co-annihilation is important

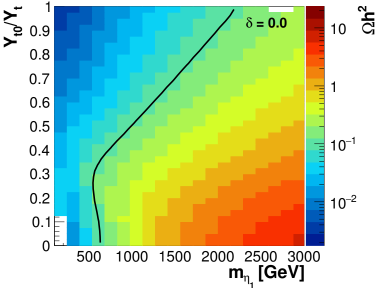
$$\langle \sigma_{ab} v_{rel}^{ab} \rangle = \langle \sigma v \rangle_{\pi_a\pi_b \to VV} + \langle \sigma v \rangle_{\pi_a\pi_b \to Vh_1} + \langle \sigma v \rangle_{\pi_a\pi_b \to Vs} + \langle \sigma v \rangle_{\pi_a\pi_b \to f\bar{f}} + \langle \sigma v \rangle_{\pi_a\pi_b \to h_1 h_1} + \langle \sigma v \rangle_{\pi_a\pi_b \to ss} + \langle \sigma v \rangle_{\pi_a\pi_b \to h_1 s}$$

A COMPOSITE 2HDM

RELIC ABUNDANCE



$\delta = 0$



$\delta = 0.2$

Main annihilation channels:

- ⋆ $t\bar{t}$
- ⋆ VV, hh
- ⋆ and maybe $t\bar{b}$

OTHER UV COMPLETIONS

FERRETTI 16

	ψ	χ	G/H
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\frac{SU(5)}{SO(5)}\ \frac{SU(6)}{SO(6)}$
$SO(N_{\rm HC})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$Sp(2N_{\rm HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$\frac{SU(5)}{SO(5)}\ \frac{SU(6)}{Sp(6)}$
$SU(N_{\rm HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$\frac{SU(5)}{SO(5)}\ \frac{SU(3)\times SU(3)'}{SU(3)_D}$
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	
$Sp(2N_{\rm HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$\frac{SU(4)}{Sp(4)}\ \frac{SU(6)}{SO(6)}$
$SO(N_{\rm HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$SO(N_{\rm HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\ \frac{SU(6)}{SO(6)}$
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\ \frac{SU(3)\times SU(3)'}{SU(3)_D}$

Some caveats:

- ⋆ custodial symmetry
- ⋆ hyper-color singlets as top partners

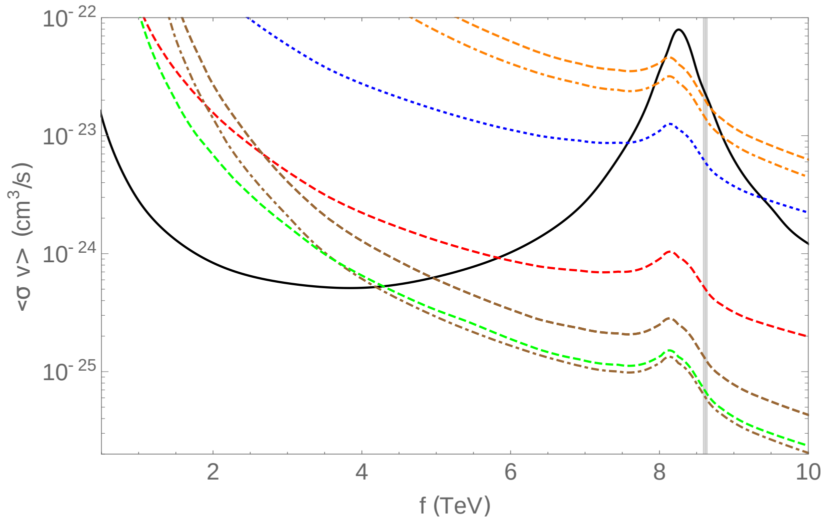
CONCLUSIONS

- ⋆ CHMs can naturally provide DM candidates with masses $\sim$ few hundred GeV and suppressed DM direct detection
- ⋆ They offer a nice complementarity with collider searches
- ⋆ There is a large set of models but they exhibit some robust features
- ⋆ There is still work to do charting possible UV completions with stable dark pions
- ⋆ The dark pion mass required by relic abundance can mek custodial symmetry not necessary

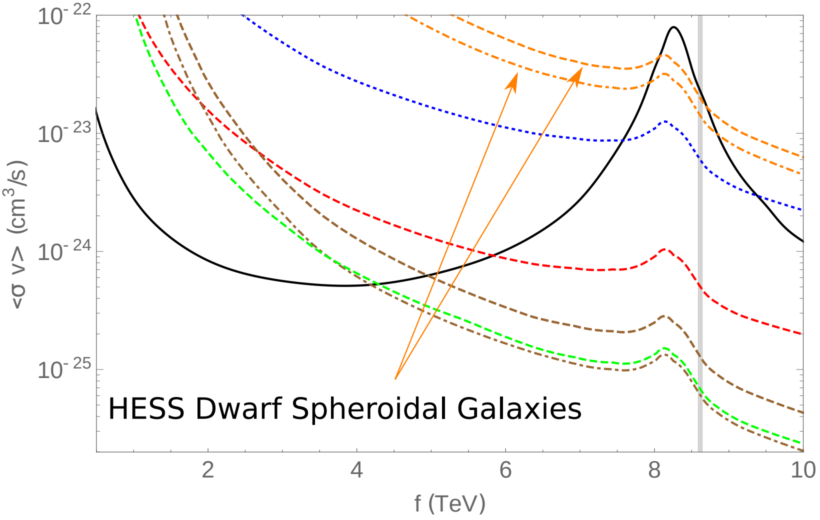
THANKS!

EXTRA STUFF

INDIRECT DETECTION



INDIRECT DETECTION



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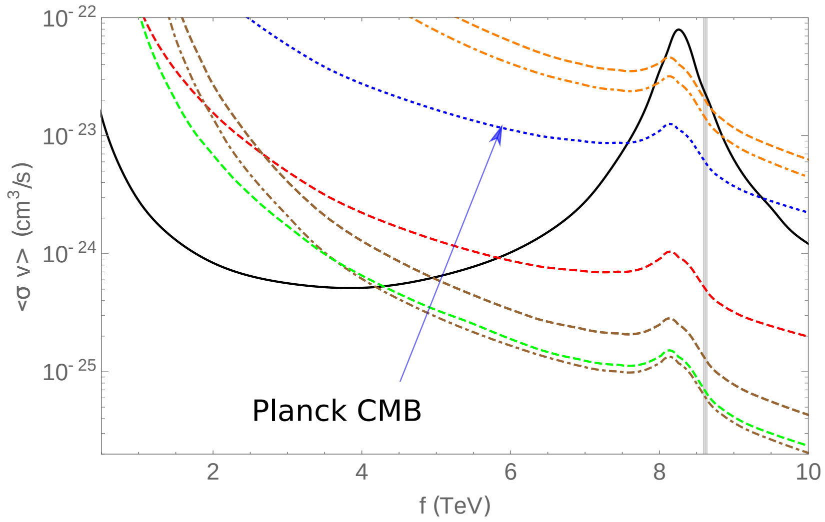

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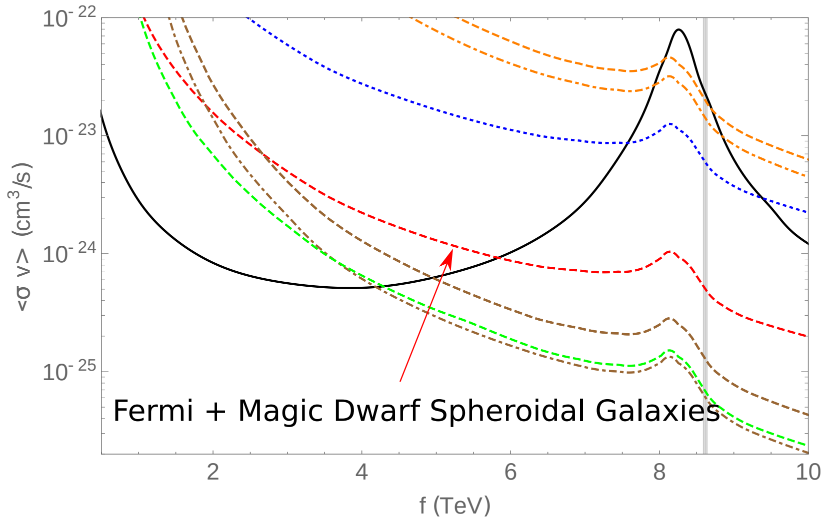

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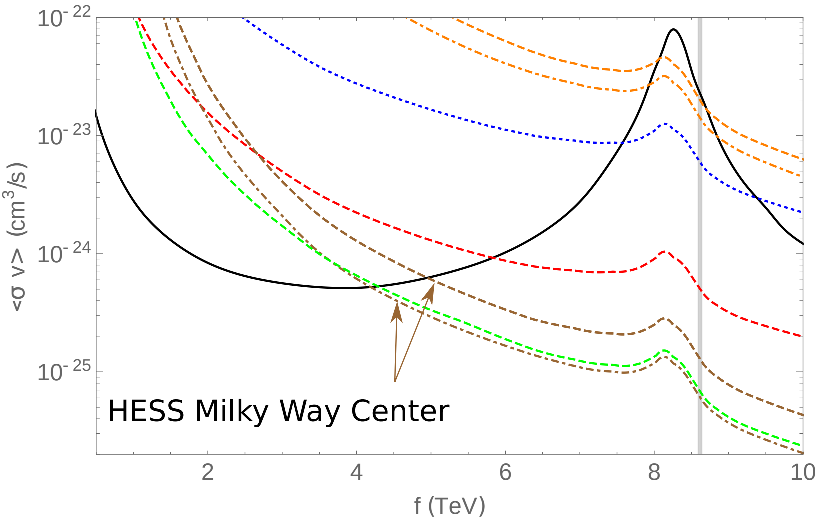

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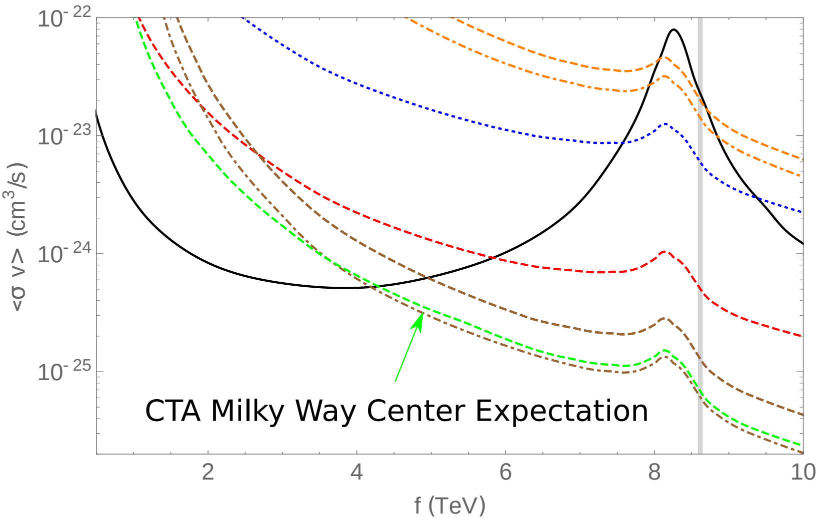
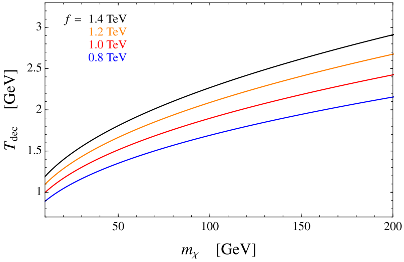
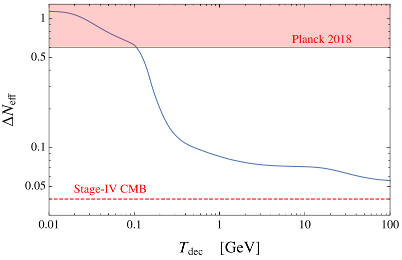


A COMPLEX DM CANDIDATE

MASSLESS DARK PHOTON





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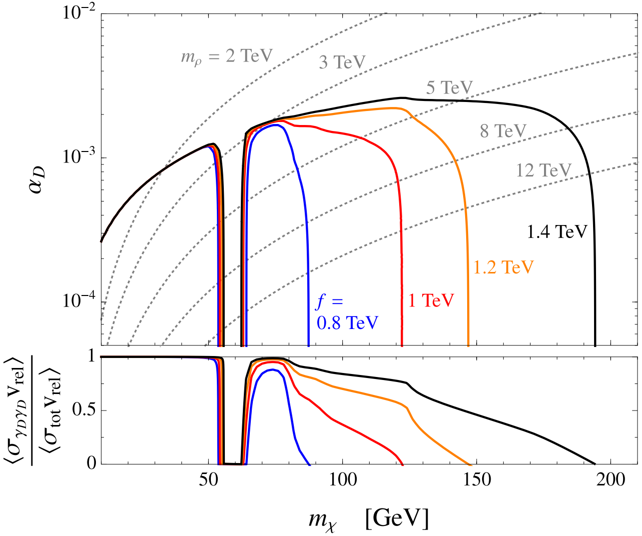

A COMPLEX DM CANDIDATE

MASSLESS DARK PHOTON