Partial compositeness, UV completions and ALPs

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LIO International Conference
IPNL Lyon,
23-27 November 2015

PLAN

The goal of this talk is to review some aspects "composite Higgs" dynamics [Georgi, Kaplan] and "partial compositeness" [Kaplan] with an eye on its UV completions and possible phenomenological consequences, in particular ALPs and DM.

- Present the basic ideas in the context of the minimal model $SO(5)/SO(4)$.
- Discuss the possible UV completion and the "new" minimal models.
- Review some of the salient phenomenological features of some of the UV completions already in the literature.

Although the word “compositeness” could be used in all cases when particles (Higgs in this case) arise as bound states, I will focus on the case where the Higgs is a pNGB, which does have the advantage of naturally explaining its lightness.

At this stage non-minimal technicolor is still included in the picture.

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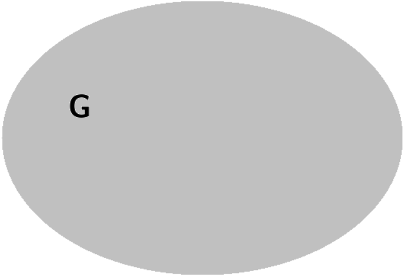

Let G be the global symmetry group of the Lagrangian of the strong sector.

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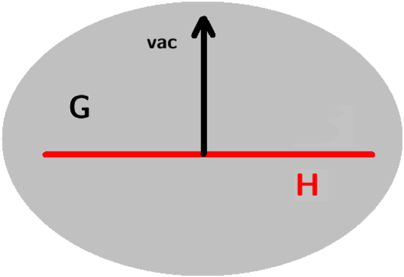

Let the vacuum break G to a subgroub H.

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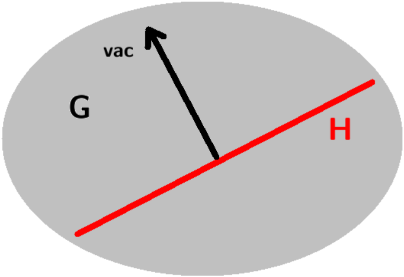

As far as the strong dynamics goes, *H* can be rotated at will: $e^{i(\langle\pi\rangle+\pi)} = e^{i\pi'}$

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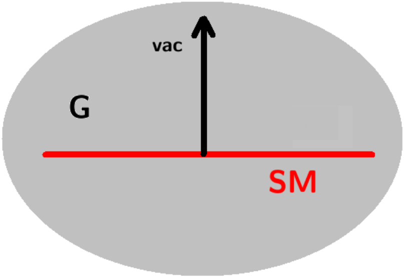

Only after coupling to the Standard Model SM, breaking G, does the orientation have meaning.

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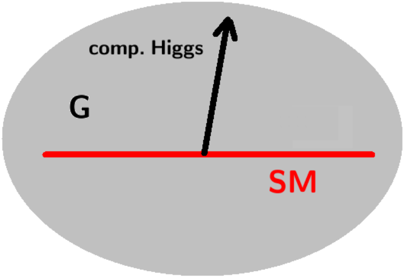

The "Composite Higgs" limit occurs when the misalignment is small.

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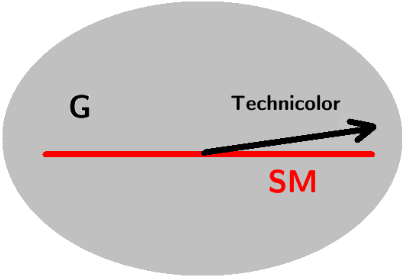

This requires some fine-tuning or some additional protection mechanism. Otherwise one expects non-minimal technicolor as the generic case.

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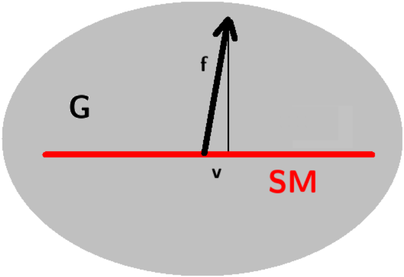


$\xi = v^2/f^2$ controls the physics of the model.

How do we describe/model this type of dynamics?
Various alternatives:

- Just use the CCWZ construction. This is guaranteed to work but does not address the issue of the underlying dynamics.
- Use extra dimensions and holography to construct *calculable* models, that even include a geometric realization of partial compositeness.
- Stay in 4D with elementary scalars. (Requires extra protection, e.g. SUSY).
- Stay in 4D with only fermions. (Inherently *strongly coupled*.)

I will start with a general overview of the simplest model using CCWZ, but then I will unapologetically switch my attention to the constructions based on 4D fermionic theories.

The simplest realistic model is based on the coset $G/H = SO(5)/SO(4)$. The number of pNGBs is $\dim(G/H) = 4$, just right to accommodate the complex Higgs doublet, transforming in the $(\mathbf{2}, \mathbf{2})$ of $SO(4)$.

The pNGBs can be parameterized by a 5-dim vector

$$\Sigma = \exp\left(\frac{i}{f} h_a T^a\right) \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

transforming under the full $SO(5)$.
(T^a are the four broken generators.)

Minimally coupling to the SM gauge bosons via $D_\mu\Sigma$ and going to the unitary gauge $(h_1, h_2, h_3, h_4) = (0, 0, 0, \langle h\rangle + h)$ yields

$$\frac{1}{2}D^\mu\Sigma^T\cdot D_\mu\Sigma = \frac{1}{2}(\partial h)^2 + \left(\frac{f}{2}\sin\left(\frac{\langle h\rangle + h}{f}\right)\right)^2\left(g^2W^2 + \frac{g^2+g'^2}{2}Z^2\right)$$

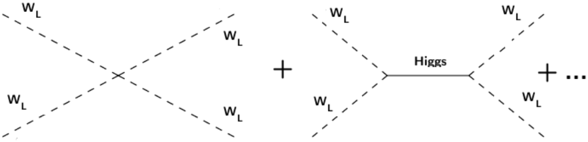
to be compared with the SM lagrangian

$$\frac{1}{2}D^\mu\Sigma^T\cdot D_\mu\Sigma = \frac{1}{2}(\partial h)^2 + \left(\frac{\langle h\rangle + h}{2}\right)^2\left(g^2W^2 + \frac{g^2+g'^2}{2}Z^2\right)$$

formally obtained from the former by taking the $f \to \infty$ limit. The vector boson masses are the same as in the SM if we set $v = f\sin(\langle h\rangle/f) = 246$ GeV, but the Higgs couplings are modified:

$g_{hVV}/g_{hVV}^{\mathrm{SM}} = \sqrt{1-\xi}, \quad g_{hhVV}/g_{hhVV}^{\mathrm{SM}} = 1-2\xi,$ etc...

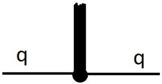
Because $g_{hVV} \neq g_{hVV}^{\text{SM}}$, the high energy behavior of the $W_L W_L$ scattering amplitude is only partially mitigated and one still need new physics at a scale $\approx 4\pi f$



$$\mathcal{A} \approx \frac{s}{v^2}(1 - \sqrt{1-\xi}) - (\sqrt{1-\xi})^2 \frac{m_h^2}{v^2} \frac{s}{s - m_h^2} + \cdots$$

We also need to give a mass to the fermions.
Here we have two schools...

The bilinear school (as in Technicolor)



Start at $\Lambda_{\rm UV}$ with terms like

$$\mathcal{L} \supset \frac{\lambda_t}{\Lambda_{\rm UV}^{d-1}} \overline{Q}_L \mathcal{O} t_R + \text{ h.c.}$$

where $\mathcal{O}$ is a scalar operator of dimension d carrying the Higgs quantum numbers.
Running down to the scale Λ, where the dynamics responsible for the symmetry breaking kicks in, one gets

$$m_t \approx \lambda_t v \left(\frac{\Lambda}{\Lambda_{\rm UV}} \right)^{d-1}$$

The linear school (as in Partial Compositeness) 

Start at Λ_{UV} with terms like

$$\mathcal{L} \supset \frac{\lambda_{Q_L}}{\Lambda_{\text{UV}}^{d_L-5/2}} \overline{\mathcal{O}_R} Q_L + \frac{\lambda_{t_R}}{\Lambda_{\text{UV}}^{d_R-5/2}} \overline{\mathcal{O}_L} t_R + \text{ h.c.}$$

where now $\mathcal{O}_{R,L}$ are fermionic operators of dimension $d_{R,L}$ carrying the quarks quantum numbers.

Now the mass of the top is given by the combined diagram

yielding

$$m_t \approx \lambda_{Q_L} \lambda_{t_R} v \left(\frac{\Lambda}{\Lambda_{\text{UV}}} \right)^{d_L+d_R-5}$$

In both cases, these SM couplings break the full global symmetry G of the strongly coupled theory. The breaking can be modeled by spurion fields, formally transforming under G. This amounts to embedding the SM fermions into an incomplete multiplet of a representation of G. For instance returning to the minimal model of partial compositeness $SO(5)/SO(4)$, we could look among the "smallest" irreps of $SO(5)$. One finds, after matching the physical masses:

$$g_{hff}/g_{hff}^{\mathrm{SM}} = \begin{cases} \sqrt{1-\xi} & \text{for the spinorial } \mathbf{4} \text{ of } SO(5) \\ \frac{1-2\xi}{\sqrt{1-\xi}} & \text{for the vectorial } \mathbf{5} \text{ of } SO(5) \end{cases}$$

(The vectorial irrep is preferable when comparing the predictions for the $Z \to b\bar{b}$ branching ratio [Agashe et al.: 0605341].)

As promised, I would like now to change gear and ask whether it is possible to realize models of partial compositeness with a strongly coupled gauge theory with only fermionic matter.

I will fist bore you with some details about the classification of the various alternatives. I know that some of you have heard the story last year but there has been a couple of developments since then and I feel compelled to mention them briefly.

The idea is to start with the Higgsless Standard Model

$$\mathcal{L}_{\text{SM0}} = -\frac{1}{4} \sum_{V=GWB} F^2_{\mu\nu}(V) + i \sum_{\psi=QudLe} \bar{\psi}\, \not{D}\psi$$

with gauge group $G_{\text{SM}} = SU(3) \times SU(2) \times U(1)$ and couple it to a theory $\mathcal{L}_{\text{comp.}}$ with hypercolor gauge group G_{HC} and global symmetry structure $G \to H$ such that

$$\underset{\Lambda = 5 \sim 10\ \text{TeV}}{\mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}}} \quad \longrightarrow \quad \mathcal{L}_{\text{SM}} + \cdots$$

($\mathcal{L}_{\text{SM}} + \cdots$ is the full SM plus possibly light extra matter from bound states of $\mathcal{L}_{\text{comp.}}$.)

Our goal is to find candidates for $\mathcal{L}_{\text{comp.}}$ and $\mathcal{L}_{\text{int.}}$ and to study their properties.

The interaction lagrangian $\mathcal{L}_{\text{int.}}$ typically contains a set of four-fermi interactions between hyperfermions and SM fermions, so the UV completion is only partial at this stage. However, we can imagine it being generated by integrating out d.o.f. from a theory $\mathcal{L}_{\text{UV}}$. (At a much higher scale because of e.g. flavor constraints.)

$$\begin{array}{ccc} \mathcal{L}_{\text{UV}} & \longrightarrow & \mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \cdots \\ \Lambda_{\text{UV}} > 10^4 \text{ TeV} & & \Lambda = 5 \sim 10 \text{ TeV} \end{array}$$

I will not attempt to construct such theory and will concentrate on the physics at the $5 \sim 10$ TeV scale, encoded in $\mathcal{L}_{\text{comp.}}$ and $\mathcal{L}_{\text{int.}}$

We need to accomplish two separate tasks:

- Give mass to the vector bosons.
- Give a mass to the fermions. (In particular the top quark.)

Let's start with the first one.

The three "basic" cosets one can realize with fermionic matter

For a set of n irreps of the hypercolor group:

$(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$\langle \tilde{\psi}\psi \rangle \neq 0 \Rightarrow SU(n) \times SU(n)'/SU(n)_D$
ψ_α Pseudoreal	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/Sp(n)$
ψ_α Real	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/SO(n)$

(The $U(1)$ factors need to be studied separately because of possible ABJ anomalies.)

The first case is just like ordinary QCD: $\langle \tilde{\psi}^{\alpha a i}\psi_{\alpha a j} \rangle \propto \delta^i_j$ breaks $SU(n) \times SU(n)' \to SU(n)_D$
In the other two cases, a real/pseudo-real irrep of the hypercolor group possesses a symmetric/anti-symmetric invariant tensor $t^{ab} = \delta^{ab}/\epsilon^{ab}$ making the condensate $t^{ab}\langle \psi^{\alpha i}_a \psi^j_{\alpha b} \rangle$ also symmetric/anti-symmetric in i and j, breaking $SU(n) \to SO(n)$ or $Sp(n)$.

As far as the EW sector is concerned, the possible minimal custodial cosets of this type are

4 $(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$
4 ψ_α Pseudoreal	$SU(4)/Sp(4)$
5 ψ_α Real	$SU(5)/SO(5)$

E.g. $SU(4)/SO(4)$ is not acceptable since the pNGB are only in the symmetric irrep $(\mathbf{3},\mathbf{3})$ of $SO(4) = SU(2)_L \times SU(2)_R$ and thus we do not get the Higgs irrep $(\mathbf{2},\mathbf{2})$.

pNGB content under $SU(2)_L \times SU(2)_R$:

- $\mathbf{Ad}$ of $SU(4)_D \to (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + 2 \times (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
- $\mathbf{A}_2$ of $Sp(4) \to (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
- $\mathbf{S}_2$ of $SO(5) \to (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Since we want to obtain the top partners, we also need to embed the color group $SU(3)_c$ into the global symmetry of $\mathcal{L}_{\text{comp.}}$.

The minimal field content allowing an anomaly-free embedding of unbroken $SU(3)_c$ are

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ Complex	$SU(3) \times SU(3)' \to SU(3)_D \equiv SU(3)_c$
$6\ \chi_\alpha$ Pseudoreal	$SU(6) \to Sp(6) \supset SU(3)_c$
$6\ \chi_\alpha$ Real	$SU(6) \to SO(6) \supset SU(3)_c$

In this case, we don't *need* to have a condensate and one could also use bare masses avoiding extra pNGBs.

One could also try anomaly matching to see whether the condensate *must* form or there can be naturally massless composite fermions
[Cacciapaglia, Parolini: 1511.05163]

In summary, we require:

- $G \to H \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\text{cus.}}} \supset G_{\text{SM}}$
- The MAC should not break neither G_{HC} nor $G_{\text{cus.}}$.
- G_{SM} free of 't Hooft anomalies. (We need to gauge it.)
- $G/H \ni (\mathbf{1}, \mathbf{2}, \mathbf{2})_0$ of $G_{\text{cus.}}$. (The Higgs boson.)
- Fermionic hypercolor singlets $\in (\mathbf{3}, \mathbf{2})_{1/6}$ and $(\mathbf{3}, \mathbf{1})_{2/3}$ of G_{SM}. (The partners to the third family (t_L, b_L) and t_R.)
- B and L symmetry.

We shall restrict to the case where G_{HC} is simple and the fermion content is non chiral.

In many cases it is not possible to construct partners to all the SM fermions, so one could try a compromise: Use "partial compositeness" for the top sector and the usual bilinear term for the lighter fermions. [G.F.: 1404.7137, Matsedonskyi: 1411.4638, Cacciapaglia et al.: 1501.03818].

In *both* the bilinear and the linear scheme, if one wants to decouple the $\Lambda_{\rm UV}$ scale, one must assume (and eventually prove!) that the composite operators relevant to the top quark acquire a large negative anomalous dimension:
"ψ^2" must go from $d = 3$ to $d \approx 1$,
"ψ^3" must go from $d = 9/2$ to $d \approx 5/2$

I would argue that the second scenario is preferable since it does not require additional fine-tuning, but the strength of this argument is debatable...

Let us first consider the case where we have only one type of $G_{\rm HC}$ irrep. for the fermions.

In this case one has a "unified" coset including all of $G_{\rm cus.}$. (See also [Frigerio, Serra, Varagnolo: 1103.2997])

R	PR	C
$\frac{SU(n)}{SO(n)}$	$\frac{SU(n)}{Sp(n)}$	$\frac{SU(n)\times SU(n)'}{SU(n)_D} U(1)$

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The C case is interesting and was constructed in [Vecchi: 1506.00623] with $G_{\mathrm{HC}} = SU(3)$. The minimal case is for $n = 7$ but for $n = 9$ one has fermionic partners for all SM fermions. The construction also works for $G_{\mathrm{HC}} = SU(6)$ and E_6.

We can move on to consider the case where the EW physics and the QCD physics are controlled by two different irreps.

For instance, we could try to use 5 real irreps to get the EW coset $SU(5)/SO(5)$ and 3 complex pairs of irreps to get $SU(3) \times SU(3)'/SU(3)_c$. All other combinations of R, PR and C irreps are possible. (Together with D. Karateev, we classified these cases except for when complex irreps are used to generate the EW coset.)

	R	PR	C
R	$\frac{SU(5)}{SO(5)} \frac{SU(6)}{SO(6)} U(1)$	$\frac{SU(4)}{Sp(4)} \frac{SU(6)}{SO(6)} U(1)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D} \frac{SU(6)}{SO(6)} U(1)^2$
PR	$\frac{SU(5)}{SO(5)} \frac{SU(6)}{Sp(6)} U(1)$	$\frac{SU(4)}{Sp(4)} \frac{SU(6)}{Sp(6)} U(1)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D} \frac{SU(6)}{Sp(6)} U(1)^2$
C	$\frac{SU(5)}{SO(5)} \frac{SU(3)\times SU(3)'}{SU(3)_D} U(1)^2$	$\frac{SU(4)}{Sp(4)} \frac{SU(3)\times SU(3)'}{SU(3)_D} U(1)^2$	$\frac{SU(4)\times SU(4)'}{SU(4)_D} \frac{SU(3)\times SU(3)'}{SU(3)_D} U(1)^3$

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	R	PR	C
R	$\frac{SU(5)}{SO(5)}\,\frac{SU(6)}{SO(6)}\,U(1)$	$\frac{SU(4)}{Sp(4)}\,\frac{SU(6)}{SO(6)}\,U(1)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(6)}{SO(6)}\,U(1)^2$
PR	$\frac{SU(5)}{SO(5)}\,\frac{SU(6)}{Sp(6)}\,U(1)$	$\cancel{\frac{SU(4)}{Sp(4)}\,\frac{SU(6)}{Sp(6)}\,U(1)}$	$\cancel{\frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(6)}{Sp(6)}\,U(1)^2}$
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Three of them do not give fermionic partners.

For completeness, the full list of solutions is

$$\frac{G}{H} = \frac{SU(5)}{SO(5)} \frac{SU(6)}{SO(6)} U(1)$$

G_{HC}	ψ	χ	Restrictions
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} \geq 55$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} \geq 15$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\mathrm{HC}} = 7, 9$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} = 7, 9$

$$\frac{G}{H} = \frac{SU(5)}{SO(5)} \frac{SU(6)}{Sp(6)} U(1)$$

G_{HC}	ψ	χ	Restrictions
$Sp(2N_{\mathrm{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\mathrm{HC}} \geq 12$
$Sp(2N_{\mathrm{HC}})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\mathrm{HC}} \geq 4$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\mathrm{HC}} = 11, 13$

$$\frac{G}{H} = \frac{SU(5)}{SO(5)} \frac{SU(3) \times SU(3)'}{SU(3)_D} U(1)^2$$

G_{HC}	ψ	$(\chi, \tilde{\chi})$	Restrictions
$SU(N_{\text{HC}})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\text{HC}} = 4$ $(\star)$
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{\text{HC}} = 10, 14$

$$\frac{G}{H} = \frac{SU(4)}{Sp(4)} \frac{SU(6)}{SO(6)} U(1)$$

G_{HC}	ψ	χ	Restrictions
$Sp(2N_{\text{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\text{HC}} \leq 36$ $(\star\star)$
$SO(N_{\text{HC}})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 11, 13$

$(\star)$ [G.F.: 1404.7137] $(\star\star)$ [Barnard, Gherghetta, Ray: 1311.6562]

$$\frac{G}{H} = \frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(6)}{SO(6)}\,U(1)^2$$

G_{HC}	$(\psi,\tilde{\psi})$	χ	Restrictions
$SO(N_{\mathrm{HC}})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=10$
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\mathrm{HC}}=4\quad(\star)$

$$\frac{G}{H} = \frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(3)\times SU(3)'}{SU(3)_D}\,U(1)^3$$

G_{HC}	$(\psi,\tilde{\psi})$	$(\chi,\tilde{\chi})$	Restrictions
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_3,\overline{\mathbf{A}}_3)$	$N_{\mathrm{HC}}=7$
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\mathrm{HC}}\geq 5$
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\mathrm{HC}}\geq 5$
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}\geq 5\quad(\star\star)$
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}\geq 8$

$(\star)$ "switched model" $(\star\star)$ "large N_{HC} model" [Golterman, Shamir: 1502.00390]

A closer look at the extra neutral scalars

An unavoidable feature of these UV models is the presence of additional neutral pNGB.

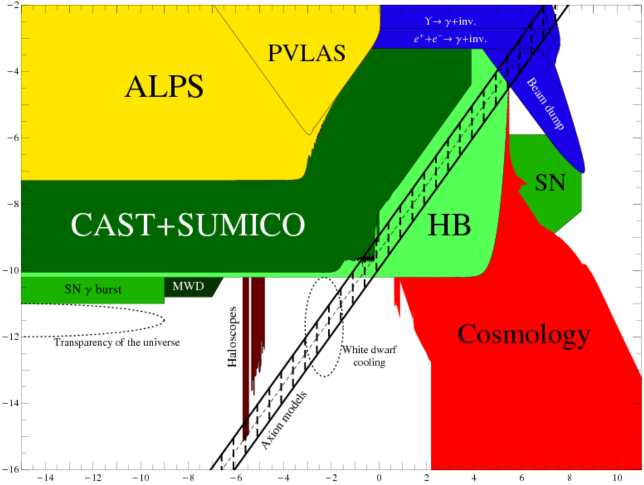
Some of them might even be stable (or stable enough) to provide a good Dark Matter candidate.

We need to understand

- The existence of possible symmetries stabilizing them (including SM gauge and fermi fields)
- The role of the WZW term
- The constraints from Cosmology

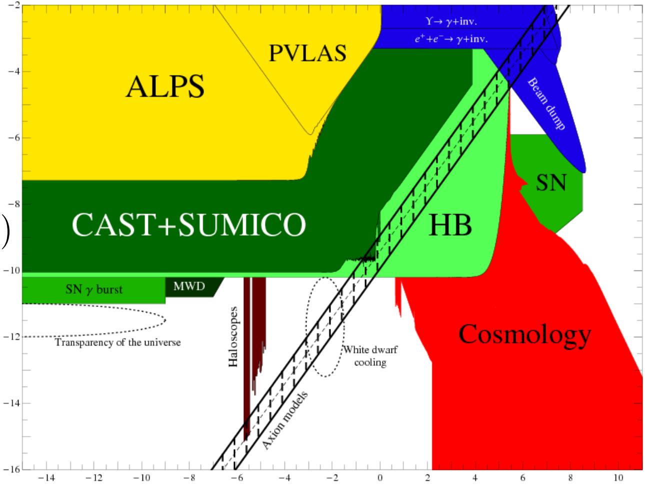
Even without the DM motivation, such particles are generic predictions of the models and their dynamics must be understood.
Let us start with a look at the current experimental situation:

[Cadamuro: 1210.3196]



[Cadamuro: 1210.3196]

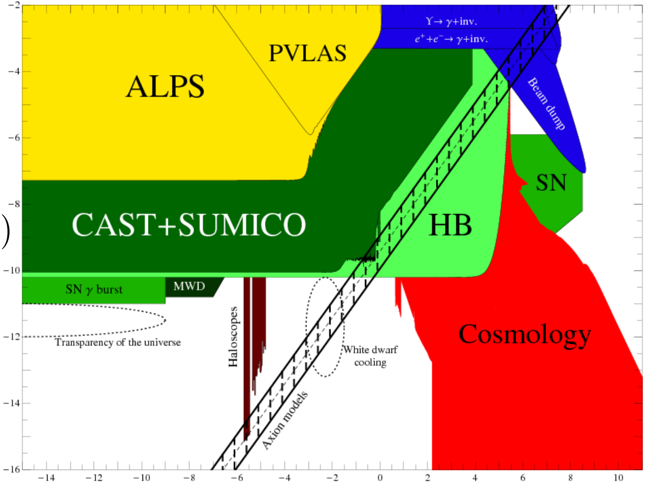
$\log_{10}\left(g_{\phi\gamma\gamma}[\mathrm{GeV}^{-1}]\right)$



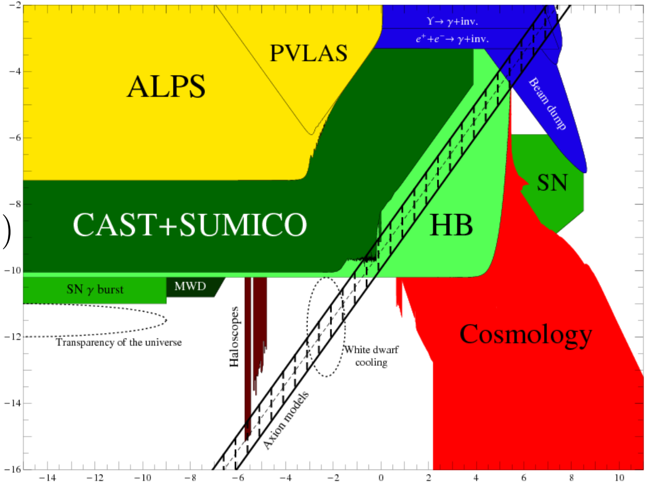
[Cadamuro: 1210.3196]

$\log_{10}\left(g_{\phi\gamma\gamma}[\mathrm{GeV}^{-1}]\right)$

$g_{\phi\gamma\gamma} \approx \frac{\alpha}{2\pi f_\phi}$



[Cadamuro: 1210.3196]



$\log_{10}\left(g_{\phi\gamma\gamma}[\mathrm{GeV}^{-1}]\right)$

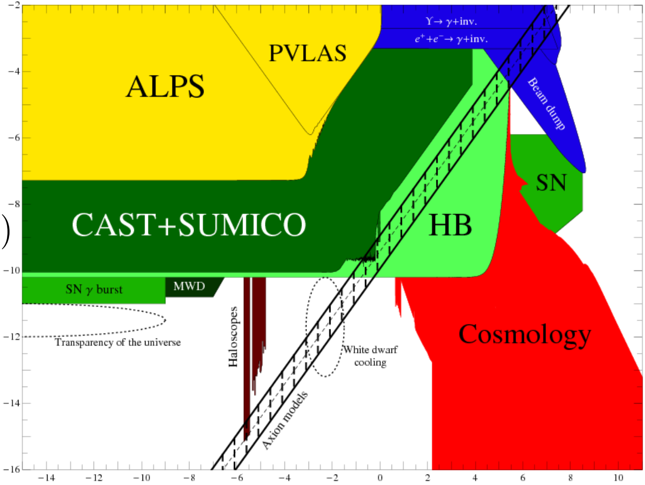
$g_{\phi\gamma\gamma} \approx \frac{\alpha}{2\pi f_\phi}$

$\log_{10}\left(m_\phi[\mathrm{eV}]\right)$

[Cadamuro: 1210.3196]

$\log_{10}\left(g_{\phi\gamma\gamma}[\mathrm{GeV}^{-1}]\right)$

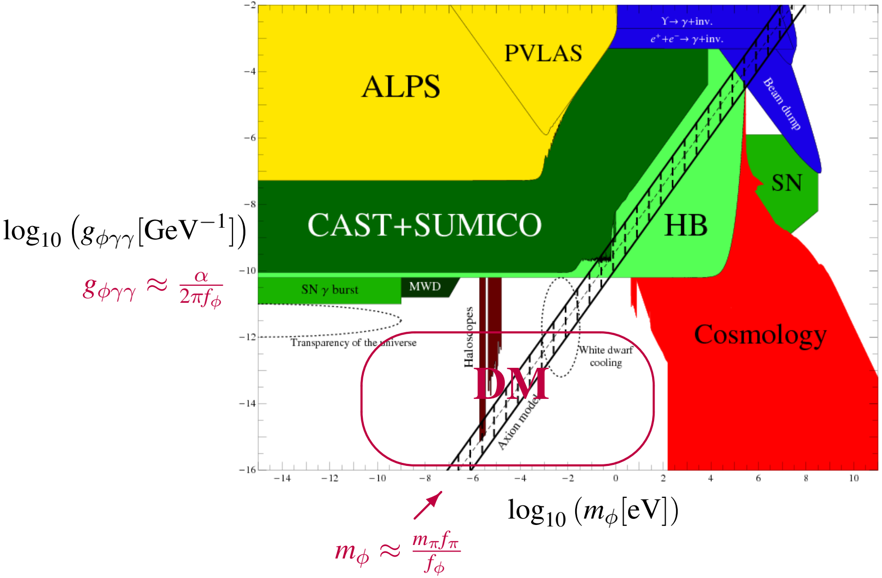
$g_{\phi\gamma\gamma} \approx \frac{\alpha}{2\pi f_\phi}$



$\log_{10}\left(m_\phi[\mathrm{eV}]\right)$

$m_\phi \approx \frac{m_\pi f_\pi}{f_\phi}$

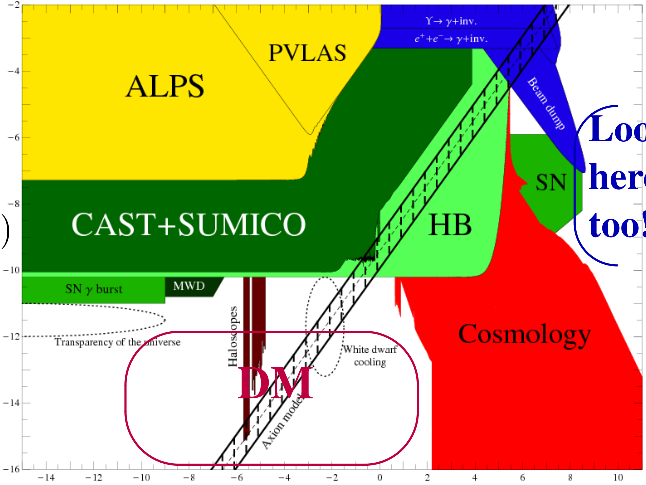
[Cadamuro: 1210.3196]



[Cadamuro: 1210.3196]

$\log_{10}\left(g_{\phi\gamma\gamma}[\mathrm{GeV}^{-1}]\right)$

$g_{\phi\gamma\gamma} \approx \frac{\alpha}{2\pi f_\phi}$



Look here too!

$\log_{10}\left(m_\phi[\mathrm{eV}]\right)$

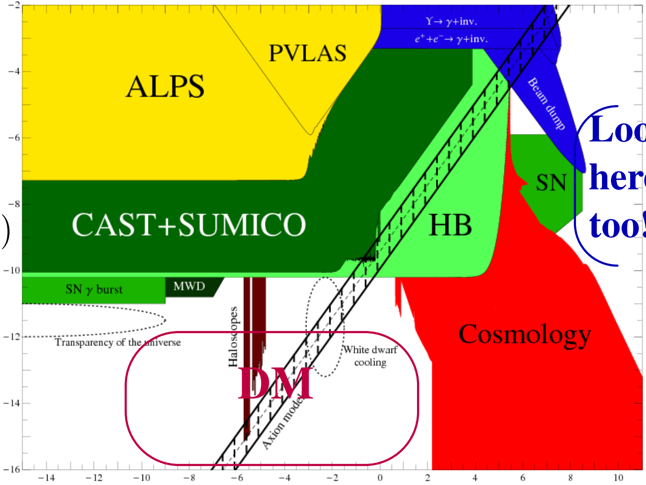
$m_\phi \approx \frac{m_\pi f_\pi}{f_\phi}$

[Cadamuro: 1210.3196]

$f_\phi \approx 1\text{TeV} \rightarrow$

$\log_{10}\left(g_{\phi\gamma\gamma}[\text{GeV}^{-1}]\right)$

$g_{\phi\gamma\gamma} \approx \frac{\alpha}{2\pi f_\phi}$



Look here too!

$\log_{10}\left(m_\phi[\text{eV}]\right)$

$m_\phi \approx \frac{m_\pi f_\pi}{f_\phi}$

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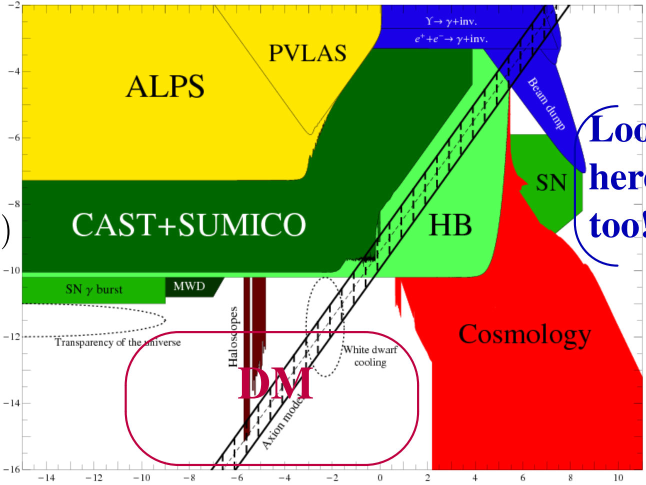


Look here too!

$\log_{10}\left(m_\phi[\text{eV}]\right)$

$m_\phi \approx \frac{m_\pi f_\pi}{f_\phi}$

few GeV

I will focus on the case where the EW and QCD cosets are separated.

All such models have a composite would-be axion [Kim] that must be given an additional mass in order to avoid the usual bounds on the PQWW axion.

	$G_{\rm HC}$	$SU(3)_c$	$U(1)_\psi$	$U(1)_\chi$
ψ	R_1	$\mathbf{1}$	1	0
χ	R_2	$\mathbf{3}, \overline{\mathbf{3}}$	0	1

A linear combination of $U(1)_\psi$ and $U(1)_\chi$ is $G_{\rm HC}$ anomaly free but it necessarily has a $SU(3)_c$ anomaly.

The other $G_{\rm HC}$ anomalous combination gives rise to a super-heavy $\eta'_{\rm HC}$ by the 't Hooft mechanism.

If ψ xor/and χ are in a pair of complex irreps, there will also be one/two extra vector-like unbroken $U(1)$'s.

We must give these particles a mass $\gtrsim$ few GeV in addition to $m_\pi f_\pi / f$, e.g.

$$H' = -\mathcal{L}_{4\mathrm{f}} = \frac{1}{\Lambda_{\mathrm{UV}}^2}\left(c_1 \chi^2 \tilde{\chi}^2 + c_2 \psi^4 + \ldots\right)$$

For typical values of the parameters, using Dashen's formula:

$$m^2 = \frac{1}{f^2}\langle [Q,[Q,H']]\rangle \approx \frac{\Lambda^6}{f^2 \Lambda_{\mathrm{UV}}^2} \approx \frac{(5\times 10^3\ \mathrm{GeV})^6}{(800\ \mathrm{GeV})^2 (10^8\ \mathrm{GeV})^2} \approx (1.5\,\mathrm{GeV})^2$$

but a fairly large range of masses is possible. Note however that Λ_{UV} cannot be arbitrarily large.

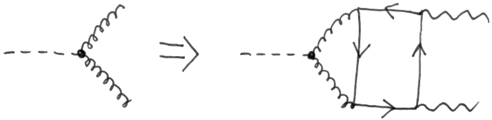
Clearly this precludes the possibility of solving the strong CP problem in this framework – not surprising given that $f \approx$ TeV.

For the remaining cases we must analyze the different cosets separately [Cacciapaglia, G.F., Frigerio: in progress].

This analysis will be valid independently of the way we arrived at the coset, so in principle it applies for non minimal models of technicolor as well.

No extra neutral pNGB arises from the “color” cosets and we can focus on the “EW” ones.

This means that the remaining pNGB will not have any anomalous coupling with the gluons $\approx \phi G\tilde{G}$ and thus, in principle, may not have any anomalous coupling $\approx \phi F\tilde{F}$ with the photon either.



Let us start with $SU(4)/Sp(4)$

The model comprises 5 real pNGBs combined into $H = (H_0, H_+)$, the usual Higgs doublet and a real singlet η. Here we want to look at the properties of η [Gripaios et al. 0902.1483, Frigerio et al. 1204.2808].

One can find a transformation that takes $\eta \to -\eta$ and $H \to +H$ [Frigerio et al. 1204.2808] and leaves the ordinary (non-anomalous) piece of the effective lagrangian invariant.

This transformation is easily preserved by the SM gauging of the non-anomalous piece and *may* be preserved in the coupling to the SM fermions by an appropriate choice of spurions and couplings.

The WZW term on the other hand, is not invariant and yields the anomalous coupling

$$\mathcal{L}_{\mathrm{WZW}} \supset \frac{\alpha_{\mathrm{e.m.}} A}{2\pi f} \int \eta \left(\frac{W_+ \tilde{W}_-}{1 - \cos 2\theta_W} + \frac{F\tilde{Z}}{\sin 2\theta_W} + \frac{\cos^2 2\theta_W \, Z\tilde{Z}}{\sin^2 2\theta_W} \right)$$

Notice however that the anomalous coupling to two photons is absent.

The above analysis means that the η in this model is unstable. But how unstable is it?

The leading decay mode comes from the anomaly. For $m_\eta \ll m_Z$ the most relevant process is $\eta \to \gamma\nu\bar{\nu}$ via an off-shell Z:

$$\Gamma_{\eta\to\gamma\nu\bar{\nu}} = \frac{\alpha^3}{256\pi^4 \sin^4 2\theta_W m_Z^4} \frac{m_\eta^7}{f^2} = 4.5 \times 10^{-19}\ \mathrm{GeV}^{-4} \frac{m_\eta^7}{f^2}$$

Taking $f = 1$ TeV and $\Gamma_{\gamma\nu\bar{\nu}} < \Gamma_{\mathrm{Universe}} = 1.5 \times 10^{-42}$ GeV yields $m_\eta < 3.2$ MeV.

Notice that decreasing the η mass by 10 increases the lifetime by a factor 10^7.

The decay $Z \to \eta\eta$ is forbidden and the decay $h \to \eta\eta$ can be estimated, still with $f = 1$ TeV

$$\Gamma_{h\to\eta\eta} < \frac{1}{32\pi}\frac{v^2 m_h^3}{f^4} = 1.2 \text{ MeV}$$

which is acceptable.

More problematic is the relic density. Given the very small cross-section, thermal production overcloses the universe. Need to investigate non-thermal production modes. (Freeze in? [Hall et al.: 0911.1120]. Work in progress...)

Moving on to $SU(5)/SO(5)$

This coset already appeared in the early literature [Dugan, Georgi, Kaplan]. The UV completion in the spirit of partial compositeness was discussed in [G.F.: 1404.7137].

The coset comprises 14 real pNGBs: one Higgs doublet H, one Y-neutral triplet Φ_0, a charged one $\Phi_\pm$ and a singlet η neutral under the whole $G_{\rm SM}$.

Along the same lines as the previous coset, one can find a (unique) transformation that reverses the signs all fields except H, but, again, the WZW term is not invariant. The difference now is that both η and ϕ_0^0, the e.m. neutral component of Φ_0, have an anomalous coupling with the photon

$$\mathcal{L}_{\rm WZW} \supset \frac{\alpha_{\rm e.m.} A}{2\pi f} \int \left(\frac{1}{\sqrt{5}} \eta + \phi_0^0 \right) \; F\tilde{F}$$

While the charged triplet and the other linear combination of η and ϕ_0^0 do not appear in the anomaly term, these fields mix with the above due to both gauge and Yukawa couplings.

There is thus no dark matter candidate in this model, although the extra neutral fields and their decays into two photons are an interesting prediction.

In particular, one expects, after EW-breaking by vacuum misalignment, a gran total of 6 electrically neutral $h, \eta, \eta', \phi_1^0, \phi_2^0, \phi_3^0$, 2 charged $\phi_1^\pm, \phi_2^\pm$ and 1 doubly charged $\phi^{\pm\pm}$ pNGB.

Above I have included the η' arising from “outside” the coset – the generic prediction of all UV completion of these kinds of models of partial compositeness. Both η and η' could be much lighter than the EW scale.

Lastly we consider $SU(4) \times SU(4)'/SU(4)_D$

This coset was recently discussed in [Ma, Cacciapaglia: 1508.07014]. In this case there are 15 real pNGBs combined into two isospin triplets Δ, N, two Higgs doublets H_1, H_2 and a singlet s.

This coset is more interesting from the DM perspective because it allows for a different type of $\mathbb{Z}_2$ symmetry that is preserved by the WZW term.

The technical reason for this is that the symmetry is of a "charge conjugation" type $U \to PU^T P$ rather than a "parity" type $U \to PU^\dagger P$.

The SM gauge bosons are unaffected by this symmetry and it is possible also to arrange the Yukawa couplings to preserve it.

The WZW term is the same as for the $SU(4)/Sp(4)$ theory, in the sense that it only couples the singlet s to the topological terms and that the pure photon term $sF\tilde{F}$ is absent.

$$\mathcal{L}_{\mathrm{WZW}} \supset \frac{\alpha_{\mathrm{e.m.}} A}{2\pi f} \int s \left(\frac{W_+ \tilde{W}_-}{1 - \cos 2\theta_W} + \frac{F\tilde{Z}}{\sin 2\theta_W} + \frac{\cos^2 2\theta_W \, Z\tilde{Z}}{\sin^2 2\theta_W} \right)$$

The scalar s behaves in a very similar way to the η of $SU(4)/Sp(4)$.

But now we also have three more neutral fields (the neutral components of Δ, N and H_2) that do not have anomalous couplings at all and are odd under the transformation above.

The lightest one may provide a better DM candidate albeit with some assumptions on the Yukawa couplings. One should also understand how mass generation works for the other fermions and whether this can be achieved without spoiling the exact symmetry or introducing unacceptable flavor violation.

Non-minimal cosets can be studied along the same lines. Of course they present a richer (too rich?) phenomenology.

Thinking of the pNGBs as a $n \times n$ matrix $U = \exp(i\Pi/f)$ and embedding the SM fields into the "upper-left" corner one can always find sufficiently decoupled pNGBs in the "lower-right corner". This embedding however gives rise to half-integer charges for the cases where the unbroken group is $Sp(n)$ or $SU(n)$.

One can also embed the SM group differently, to avoid this problem. The next-to-minimal symplectic case $SU(6)/Sp(6)$ is interesting in this respect and should be analyzed in greater detail (in progress...).

CONCLUSIONS

- We presented the basic ideas behind the concept of "Higgs as a pNGB" and "partial compositeness".
- The minimal case $SO(5)/SO(4)$ has the advantage of being easily analyzed and introducing the minimum amount of extra ingredients but does not easily allow for a UV completion.
- In the context of UV completions with 4 dim gauge theories and fermionic matter, there is a whole set of possibilities that has been classified but not fully analysed.
- A general prediction of all the models with two different irreps is the existence of a light ($\approx$ MeV) pseudo-scalar coupling to the QCD topological density.
- Some models also present possible DM candidate, although their dynamics requires further study.