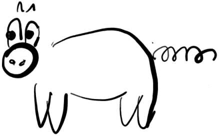
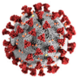
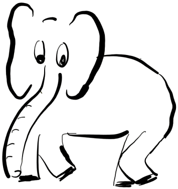


The pNGB Zoo

Gabriele Ferretti
Lyon 2020



Covid Edition

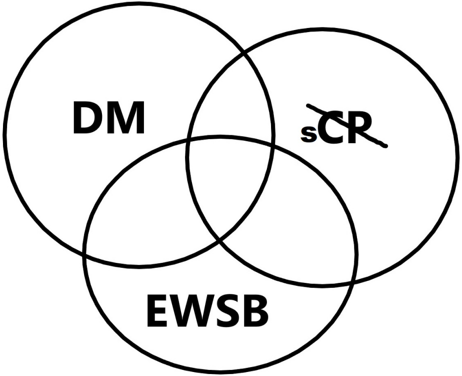


Contrary to other ideas in modern particle physics (SUSY, Extra dimensions...) we know that Nature does make use of the Nambu-Goldstone mechanism:

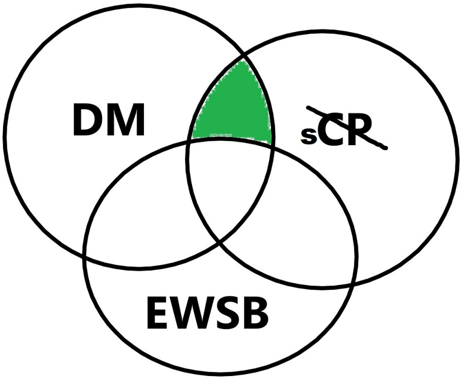
Picture of a pNGB creating a pNGB decaing into two pNGBs in a background of other pNGBs flying around...
Life was easy then.
Still...

That's a pretty dynamical mechanism you got there. It'd be a shame not to use it more often.

One can think of at least three different areas where pNGBs could be relevant. Even more interesting would be to look at the overlaps

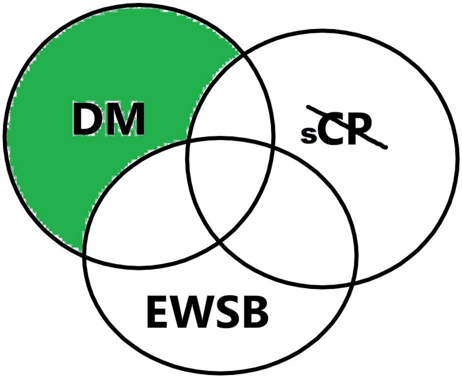


This is the usual (invisible) axion, $10^{-6}\text{eV} < m < 10^{-3}\text{eV}$



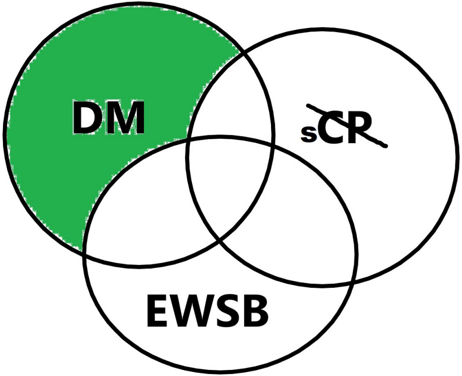
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{\alpha_s}{8\pi f}\, aG\tilde{G} + \frac{1}{f} J^\mu \partial_\mu a$$

The mass range for DM can be greately widened decoupling the problem from CP, e.g. one can go all the way down to $m \approx 10^{-22}\mathrm{eV}$



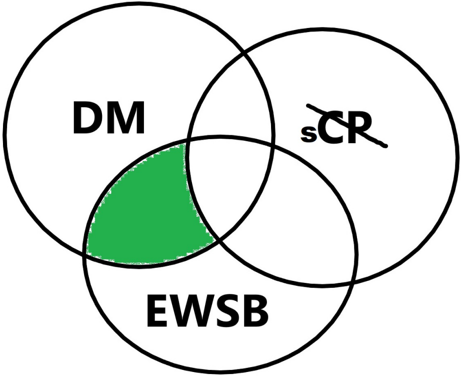
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \cancel{\frac{\alpha_s}{8\pi f} a G\tilde{G}} + \frac{1}{f} J^\mu \partial_\mu a$$

Or all the way up to the WIMP region $m \approx 10^{12}\mathrm{eV}$

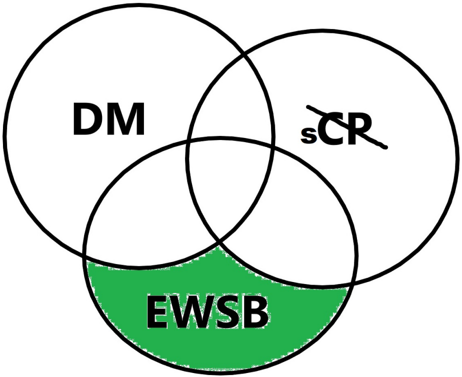


$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{\alpha_s}{8\pi f}\, aG\tilde{G} + \frac{1}{f}J^\mu \partial_\mu a - \frac{1}{2}m^2 a^2$$

And of course this week we heard interesting ideas in this region!



Here I would just like to focus on the applications to EWSB



Instead of looking at the phenomenology of specific models, let me try a more general approach.

All composite Higgs models except the minimal one (MCHM) have additional scalars (ϕ) realized as pseudo Nambu-Goldstone bosons (pNGB), just like the Higgs itself.

Observe that, in strongly coupled gauge theories, the most easily realized symmetry breaking patterns are *not* of the minimal type $SO(5)/SO(4)$.

Thus, *conditionally to some sort of composite Higgs scenario being true, the existence of additional light scalars is generic*. I suggest we classify them not according to a specific model but according to their dynamics.

$\star$ The neutral components of the various multiplets may or may not acquire a vev. If they do, they induce the couplings ($kg^2 v_\phi \times$)

$$\phi_0\, Z_\mu\, Z^\mu, \quad \phi_0\, W^+_\mu\, W^{-\mu}, \quad \phi_+\, Z_\mu\, W^{-\mu}, \quad \phi_{++}\, W^-_\mu\, W^{-\mu}$$

The Higgs is of course the primary example of this. Additional such pNGBs are well studied and well searched for.

$\star$ An interesting (and less studied) class of models is one where *do not arise* (for $\phi_0 \neq h$), or are strongly suppressed.

The absence of these couplings makes this class of models qualitatively different. For instance, the neutral scalars easily evade all LEP bounds and custodial symmetry is preserved at tree level.

Zero is more natural than non-zero.

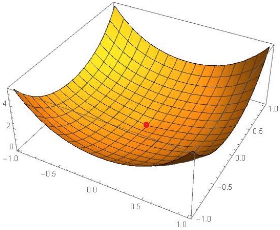
If the pNGB is in a "non-custodial" irrepp than we better hope that this is the case or the model is not viable. But even for custodial combinations I would argue this is true.

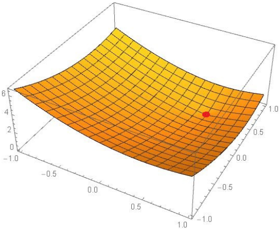
Consider for instance the Georgi-Machacek model, containing a set of scalars also arising in many pNGB constructions:

$$\Phi = \begin{pmatrix} \phi_-^+ & \phi_0^+ & \phi_+^+ \\ \phi_-^0 & \phi_0^0 & \phi_+^0 \\ \phi_-^- & \phi_0^- & \phi_+^- \end{pmatrix}$$

There are two possible independent vevs $v_1 = |\phi_-^+| \equiv |\phi_+^-|$ and $v_2 = |\phi_0^0|$. Custodial symmetry requires $v_1 = v_2$.

My experience constructing potential for pNGBs of this type is that it's much easier to satisfy this by having both $v_1 = 0$ and $v_2 = 0$.





$\star$ There are still dimension 5 interactions now involving vector boson *field strengths*. For neutral ϕ: ($k\frac{gg'}{\Lambda}\times$)

$$\phi G^a_{\mu\nu} \overset{(\sim)}{G}{}^{a\mu\nu}, \quad \phi F_{\mu\nu} \overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi F_{\mu\nu} \overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi Z_{\mu\nu} \overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi W^+_{\mu\nu} \overset{(\sim)}{W}{}^{-\mu\nu}$$

All computable, given a model, via ABJ anomaly of hyperfermions or simply loops of SM fermions like the Higgs. There are models in which ϕ turns out to be glue-phobic $\cancel{\phi GG}$ or photo-phobic $\cancel{\phi FF}$ or both.

$\star$ More exotic possibilities for charged/colored objects:

$$\phi_+ W^-_{\mu\nu} \overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi_+ W^-_{\mu\nu} \overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi_{++} W^-_{\mu\nu} \overset{(\sim)}{W}{}^{-\mu\nu},$$

$$d^{abc}\phi^a G^b_{\mu\nu} \overset{(\sim)}{G}{}^{c\mu\nu}, \quad \phi^a G^a_{\mu\nu} \overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi^a G^a_{\mu\nu} \overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi^a_+ G^a_{\mu\nu} \overset{(\sim)}{W}{}^{-\mu\nu},$$

$\phi^{ab} G^a_{\mu\nu} \overset{(\sim)}{G}{}^{b\mu\nu}$ $\leftarrow$ in the **27** of color :)

$\star$ Interactions with SM fermions are more model dependent

$$\sum \frac{k_\psi m_\psi}{v}\, \phi\, \bar{\psi}(\gamma^5)\psi'$$

They are strongly constrained by flavor, particularly in the I and II generation. There are also models in which ϕ is fermio-phobic.

$\star$ Finally, the most relevant double ϕ interactions comes from the dimension 4 (non-linear) kinetic term "$(D\phi)^2$"

$$c_1\, g\, \phi\, \partial_\mu \phi' V^\mu + c_2\, g^2\, \phi\, \phi' V_\mu V'^\mu$$

$c_1,\ c_2$ are computable in terms of the quantum numbers and the symmetry breaking pattern. There are models in which they are absent for some of the ϕs.
($c_1 \neq 0$ requires $\phi \neq \phi'$ mass eigenstates.)

$\star$ The *mass* of these objects depends on the details of their symmetry breaking potential:

A universal *positive* contribution arises from gauge loops, similar to the pion electromagnetic mass splitting $m^2 \approx \frac{g^2}{16\pi^2}\Lambda^2$.

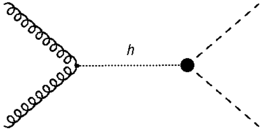
- Neutral pNGBs. Could be quite light, but also very weakly coupled. One can take $m \gtrsim 10$ GeV to avoid bounds from hadronic resonances, but they could also be lighter.
- Electrically charged pNGBs. Heavier, but still they could have $m \lesssim 1$ TeV.
- Colored pNGBs. They can get a large mass $m \gtrsim 1$ TeV.

There are composite Higgs constructions for all of these.
Note that *the stronger they couple, the heavier they are*.

The phenomenology arising from all these possible combinations is very rich and is familiar to all of you and will not be repeated. (ggF, VBF, DY, pNGBstrahlung...)

Here I just point out some corners that have not been looked at as much.

$\star$ There is the possibility of Higgs mediated pair production via $h\phi\phi$, where the Higgs can even be (a bit) off-shell. (Diogo will talk about this [2005.13578].)



⋆ Color triplets and sextets (Thomas' talk) can have Baryon number violating couplings of relevance for $n - \bar{n}$ oscillations. Here I allow myself a bit of model building details [1604.06467].

- Top-partners $\chi\psi\chi$, χ in a real irrep. pNGBs $\pi = \chi\chi$ in the $\mathbf{6}_{-2/3}$ of $SU(3)_c \times U(1)_Y$ with baryon number $B = -1/3$. $\Delta B = 1$ couplings $\pi^{*ab} d_{Ra} d_{Rb}$. (Allowing additional EW pNGBs one can make more couplings $\pi q q' \phi$)
- Top-partners $\psi\chi\psi$, χ in a real irrep. pNGB $\pi = \chi\chi$ in the in the $\mathbf{6}_{4/3}$ with $B = 2/3$. The couplings are now baryon number preserving.
- Top-partners $\chi\psi\chi$, χ in a pseudo-real irrep. pNGBs $\pi = \chi\chi$ in the $\mathbf{3}_{2/3}$ with $B = 1/3$ and $\Delta B = 1$ interaction $\epsilon^{abc} \pi_a d^f_{Rb} d^{f'}_{Rc}$. (Anti-symmetric in f, f'. Flavor violation!)

These couplings also control their decay into jets.

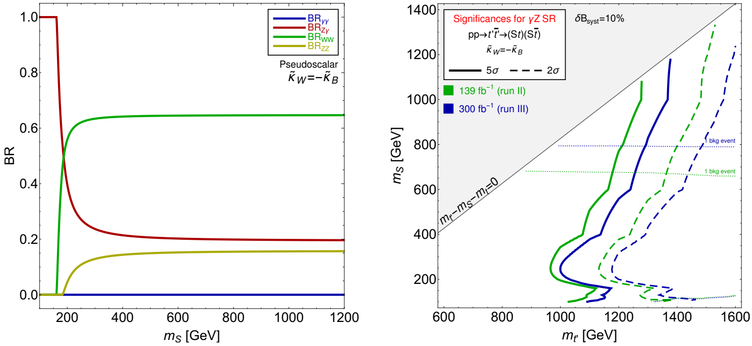
$\star$ Charged pNGBs can also have interesting signatures. For instance a Doubly charged scalar arises in some models, analogous to the one in the Georgi-Machacek model.

If fermio-phobic, it would give rise to signatures such as $\phi^{++} \to W^+ W^+$ which are less studied than the usual di-lepton channels [1610.07354].

$\star$ Lastly, since many partial compositeness models with top-partners come hand-in-hand with some additional pNGBs, one should reassess the searches of VLQs in the light of possible decays in addition to the usual triad $t' \to t\,Z,\ t\,h,\ b\,W$.

Some of these exotic decays $t'/X \to t/b\,\phi$ might even be the most promising discovery channel in some regions of parameter space.

Let me just give the results on the exotic $t' \to t\, S$ case, with S photophobic, as it arises naturally in models of CH [1907.05929]. (Luca might also comment on this.)



Now that I weaseled myself into model building...

Name	G_{HC}	ψ	χ	n_ψ max. $\approx$
M1	$SO(7)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	7
M2	$SO(9)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	7
M3	$SO(7)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	7
M4	$SO(9)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	6
M5	$Sp(4)$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5
M6	$SU(4)$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	8
M7	$SO(10)$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	10
M8	$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	4
M9	$SO(11)$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	4
M10	$SO(10)$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	8
M11	$SU(4)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	10
M12	$SU(5)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	9

Since there were questions about this, let me make two remarks:

I) The global symmetry group of the colored fermions χ is very likely to be broken, giving rise to the colored pNGBs we heard about from Thomas:

$SU(3)_c \subset H \subset G$, where H is the maximal non-chiral symmetry group and is thus unbroken. (Example $H = SO(6) \subset G = SU(6)$.) The two alternatives are thus either H or the full G unbroken.

The full unbroken G would require some composite fermions $\chi\psi\chi$ or $\psi\chi\psi$ to be massless to saturate the 't Hooft anomaly. But this is forbidden if one assumes the persistent mass condition.

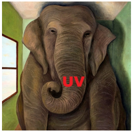
II) The second issue was if one could take $f \to M_{\text{Planck}}$ in these models.

I don't think this is very promising at this stage. The SM is technically valid up to the Planck scale (we sure hope not, though!). However, these models require modification at a much lower scale, making the limit $f \to M_{\text{Planck}}$ overly optimistic. (Not to mention that the fine tuning becomes huge!)

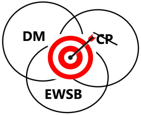
It would be very interesting though to ask that question in a more UV complete theory, (with different fs) and there are already come proposals, also by members of the audience who may want to comment.

If we *realy* want to talk model building, at this point we should probably step-up the game.

I can think of two crucial issues:



I) Face the elephant in the room and try to construct a true UV completion for these models. Here there are the ideas of Cacciapaglia, Vatani and Zhang, which heard about yesterday [1911.05454,2005.12302].



II) Hit the bulls-eye: (DM+CPV+EWSB). Here there is a recent attempt by Gherghetta and Nguyen [2007.10875] I'll briefly comment on.

The initial idea [1604.01127] was to have QCD embedded in a larger group $SU(N+3) \to SU(3)_c \times SU(N)$.

The two groups left after breaking share the same θ from the UV that
1) can be canceled with only one extra fermion,
2) gets a larger mass $m_a^2 f_a^2 \approx \Lambda_3^4 + \Lambda_N^4$.

All of the above requires scalar Higgses. In [2007.10875] is shown how to accomplish this with only fermionic underlying models, by enlarging the breaking structure to
$SU(N+3) \times SU(N) \to SU(3)_c \times SU(N)$.

There is plenty of room for new ideas on model building here. One thing that worries me is how to stay/get out of the conformal region in the IR.

No conclusions, only questions!

- Many connected lines of investigation: Lattice, Long-lived particles, Dark matter candidates, EWPT, Z line shape, Higgs BSM decays, $n - \bar{n}$ oscillations, VLQ exotic decays...
- Are we overlooking other interesting signatures?
- Can we systematize the searches according to this or a better classification?
- Model building? Comments on the recent activities?

THANK YOU!