COMPOSITE HIGGS, COMPOSITE MEDIATOR

NONLINEAR PORTAL TO THE DARK SECTOR

Flip Tanedo

UC Riverside Particle Theory

w/ Javi Serra & Alex Wijangco

CERN TRIUMF

work in preparation

5 April 2017, UC Irvine

Dark Matter @ LHC

slide *Inception*

RECENT LHC RESULTS

List of CMS/ATLAS DM searches

K. Hahn Aspen 2017 talk

X	Dataset	Documentation
jet or hadronic V	2016, 12.9 fb-1	EXO-16-037, 1703.01651
photon	2016, 12.9 fb-1	EXO-16-039
Z(ll)	2016, 12.9 fb-1	EXO-16-038
Higgs (γγ)	2015, 2.3 fb-1	EXO-16-011
Higgs (bb), with γγ combo	2015, 2.3 fb-1	EXO-16-012
tt (hadronic, semileptonic)	2015, 2.2 fb-1	EXO-16-005
tt (dileptonic + tt combination)	2016, 2.2 fb-1	EXO-16-028
t hadronic	2016, 12.9 fb-1	EXO-16-040
bb	2015, 2.2 fb-1	B2G-15-007

Not really X	Dataset	Documentation
dijets	2016, 12.9 fb-1	EXO-16-032, 1611.03568
boosted dijets	2016, 2.7 fb-1	EXO-16-030
dijets	2016, 27+36 fb-1	EXO-16-056

S. Schramm 2016 Moriond talk

Summary

ATLAS EXPERIMENT
UNIVERSITÉ DE GENÈVE

Analysis summary table

Analysis	Dataset	Public link	
Production search:			
E_T^{miss}+jet	2015	Paper: EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05	
$E_T^{miss}+Z(\to \ell\ell)$	2015+2016	Note: ATLAS-CONF-2016-056	new!
$E_T^{miss}+W/Z(\to qq)$	2015	Paper: EXOT-2015-08	new!
$E_T^{miss}+H(\to bb)$	2015	Note: ATLAS-CONF-2016-019	
$E_T^{miss}+H(\to \gamma\gamma)$	2015+2016	Note: ATLAS-CONF-2016-087	new!
$E_T^{miss}+H(\to \ell\ell\ell\ell)$	2015	Note: ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note: ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note: ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note: ATLAS-CONF-2016-076	new!
Mediator search:			
Dijet	2015+2016	Note: ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note: ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note: ATLAS-CONF-2016-070	new!
Summary plots:			
Mediator searches	2015+2016	Plot: Summary plot page	new!
Search combination	2015+2016	Plot: Summary plot page	new!

Trovato, Cosmic Visions talk (2017)

3 Apr 17

Feng 19

Jonathan Feng, DM@LHC (@UCI); Christopher Nolan 2010

photo courtesy of Yangyang Chen's prolific Facebook feed (from Monday)

Pseudoscalar Mediators

assume
Dirac X

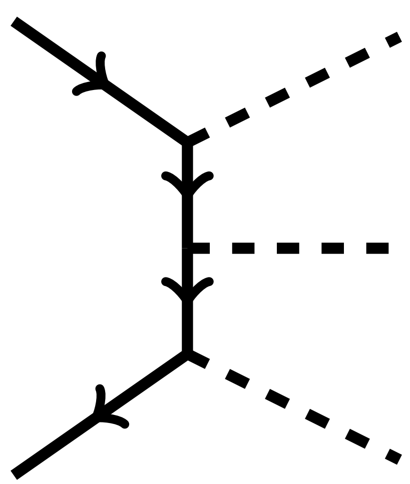
$$(\bar{X}\, i\gamma^5 X)\ (\bar{q}\, i\gamma^5 q)$$

see, e.g.
Kumar & Marfatia 1305.1611

$$\sigma_{\text{spin dependent}} \propto q^2 \times q^2$$

suppressed
direct detection

$$\sigma_{\text{spin independent}} = 0$$

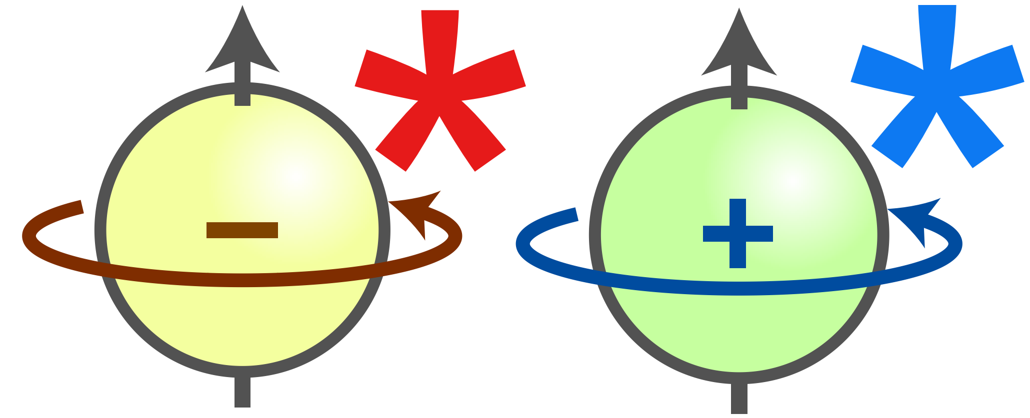


s-wave annihilation in s-channel or to three on-shell pseudoscalars

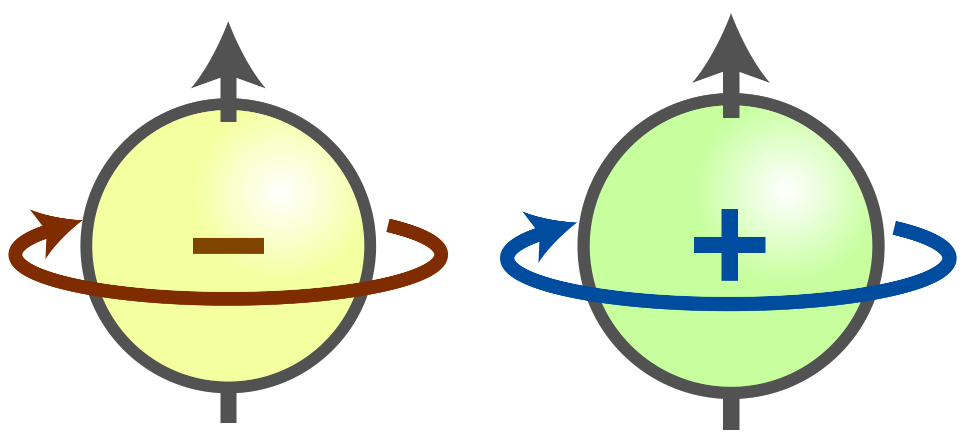
Indirect detection:
Boehm et al. 1401.6458
FT & UCI folks 1404.6528, 1503.05919
Berlin et al. 1502.06000

Gauge Invariance

In Standard Model, these
are totally different fermions



$$\varphi \bar{f} i\gamma^5 f = i\varphi f_L f_R - i\varphi \bar{f}_L \bar{f}_R$$



See, e.g.
Bell et al. 1503.07874
Kahlhoefer et al. 1510.02110
Bell et al. 1612.03475
Ko et al. 1701.04131
+ many others

www.quantumdiaries.org/2011/06/19/helicity-chirality-mass-and-the-higgs/

How to UV complete?

1. **≥ 2 Higgs Doublet Model** SEE DORIVAL'S TALK / SEE MARTIN BAUER'S TALK

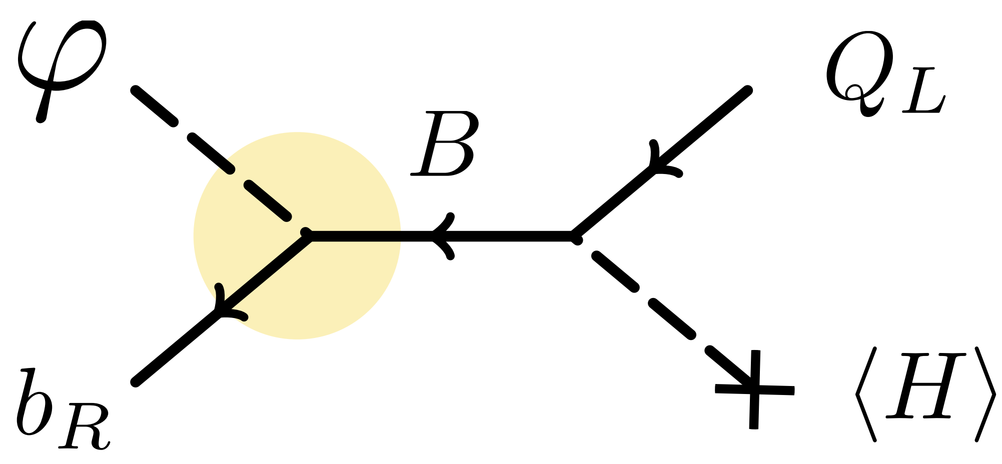
   for example, the next-to-minimal SUSY SM

   e.g. Ipek et al. 1404.3716, Berlin et al. 1502.06000

2. **Heavy Vector-like Fermions**

   for example, the next-to-minimal SUSY SM

   Fan et al. 1507.06993



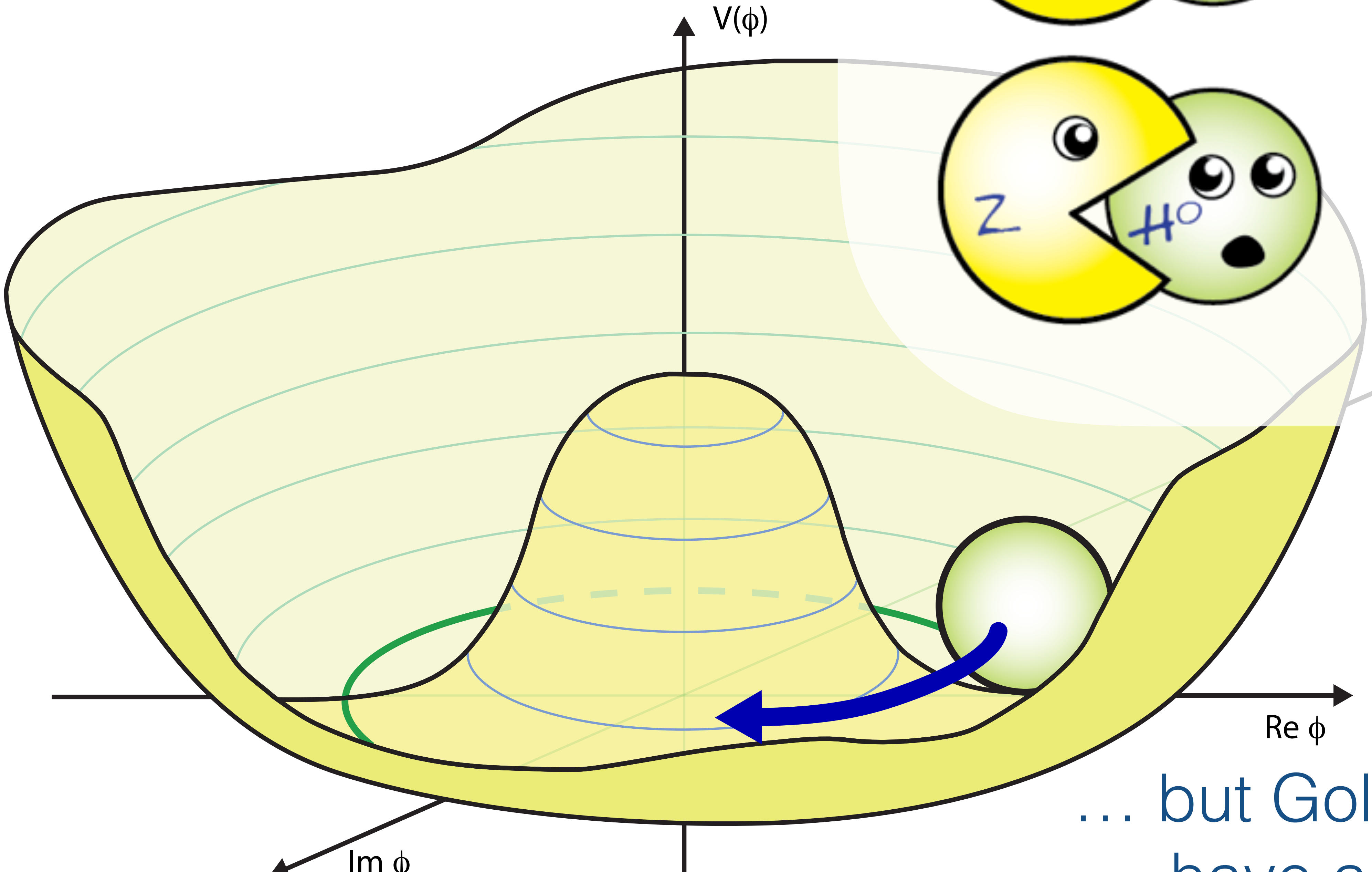
How to UV complete? This talk.

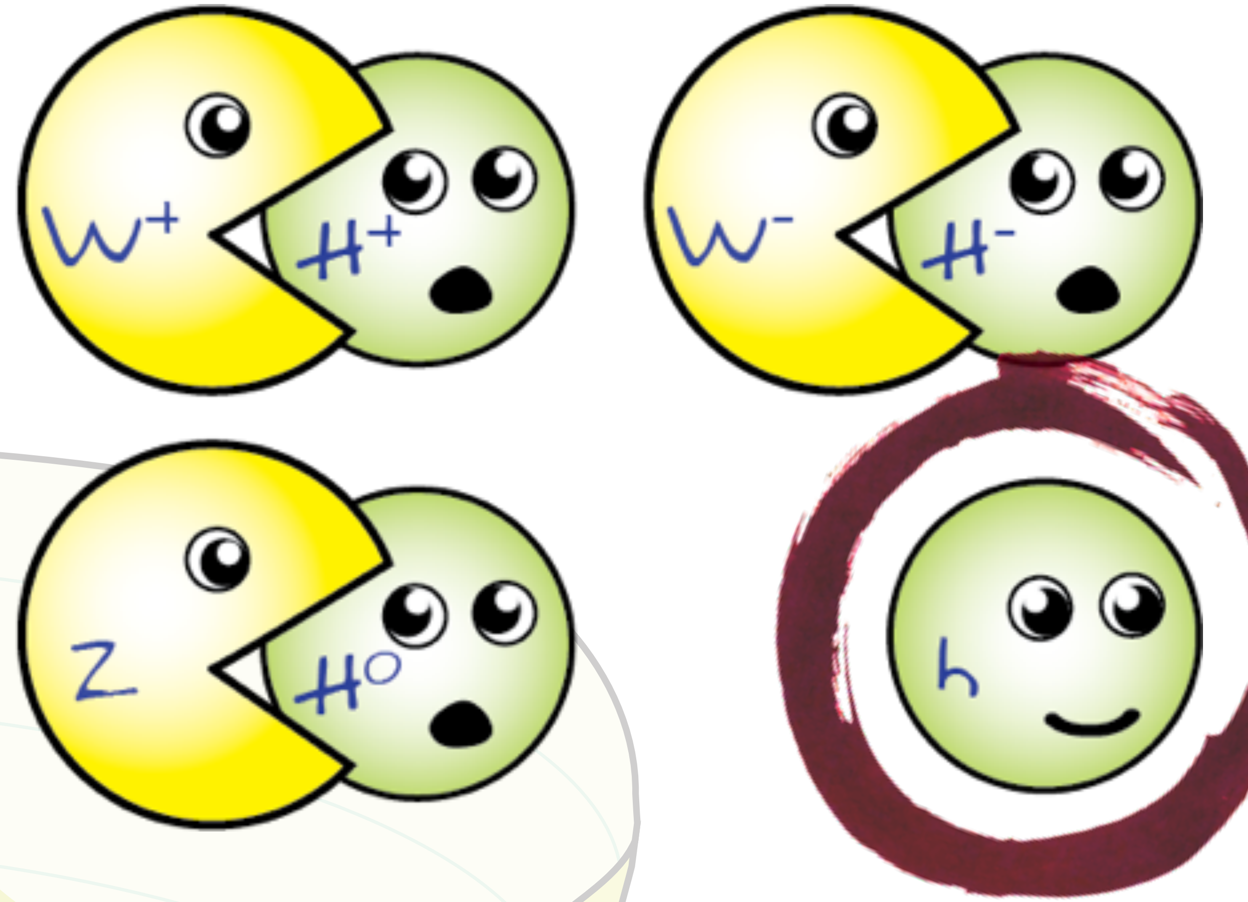
3. **Non-minimal composite Higgs**
   Easy to get gauge-singlet pseudoscalars
   … no tan β
   … heavy fermions can decouple
   … connects to Hierarchy problem
   … interactions from nonlinear Σ model

Composite Higgs

$$\mathrm{SO}(5)/\mathrm{SO}(4)$$

SM lives here

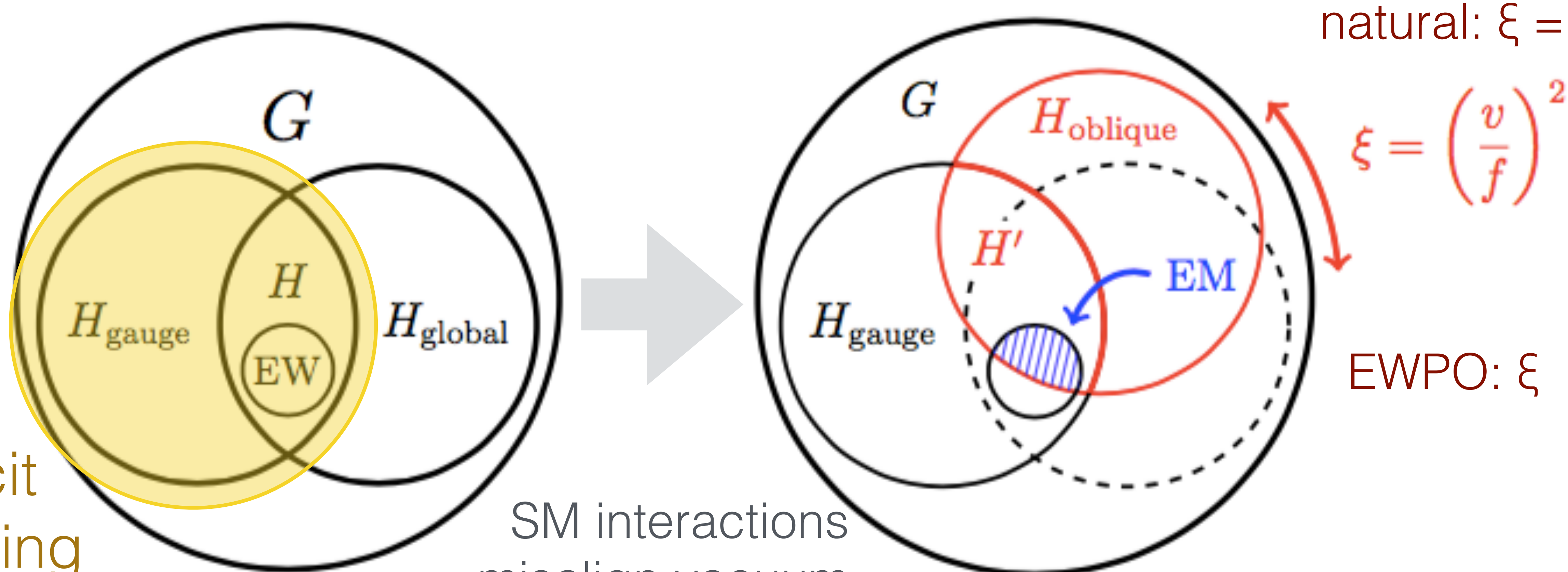




… but Goldstones don't have a potential?

Kaplan & Georgi '84 (Phys. Lett B136 & Phys. Lett. B145)

Explicit & Electroweak Breaking



Loops of gauge bosons, fermions generate electroweak-breaking Higgs potential

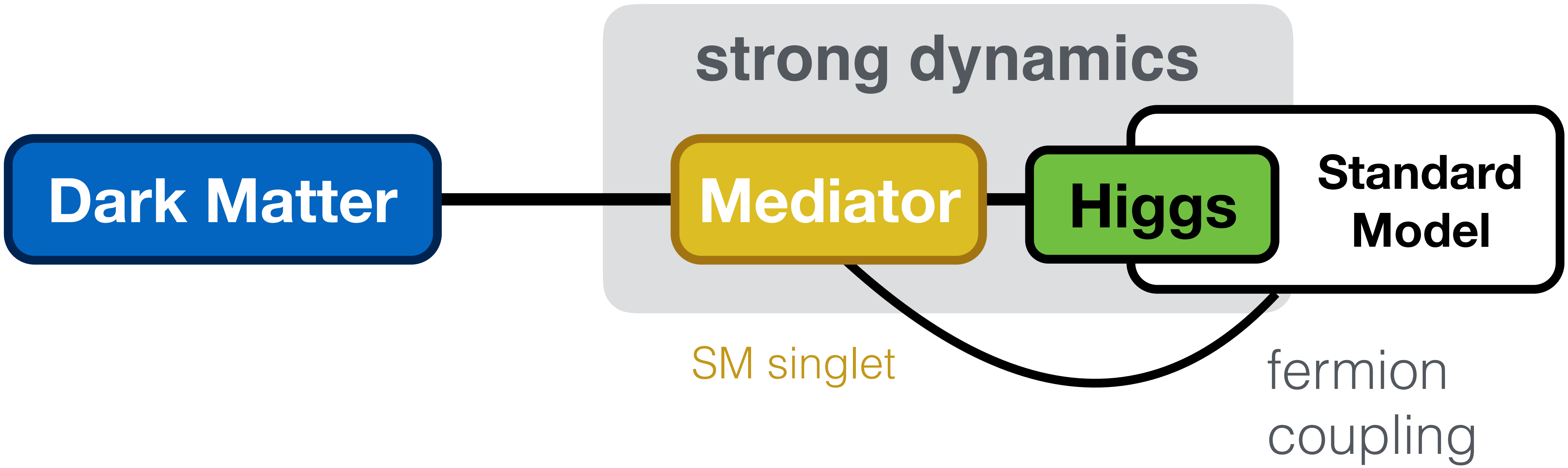
FT & Csaki 1602.04228, adapted from M. Safari's Ph.D thesis

Larger coset space? $\mathrm{SO}(6)/\mathrm{SO}(5)$

Same composite Higgs… with **extra Goldstone**:

Serra et al. 0902.1483, "Beyond MCHM"

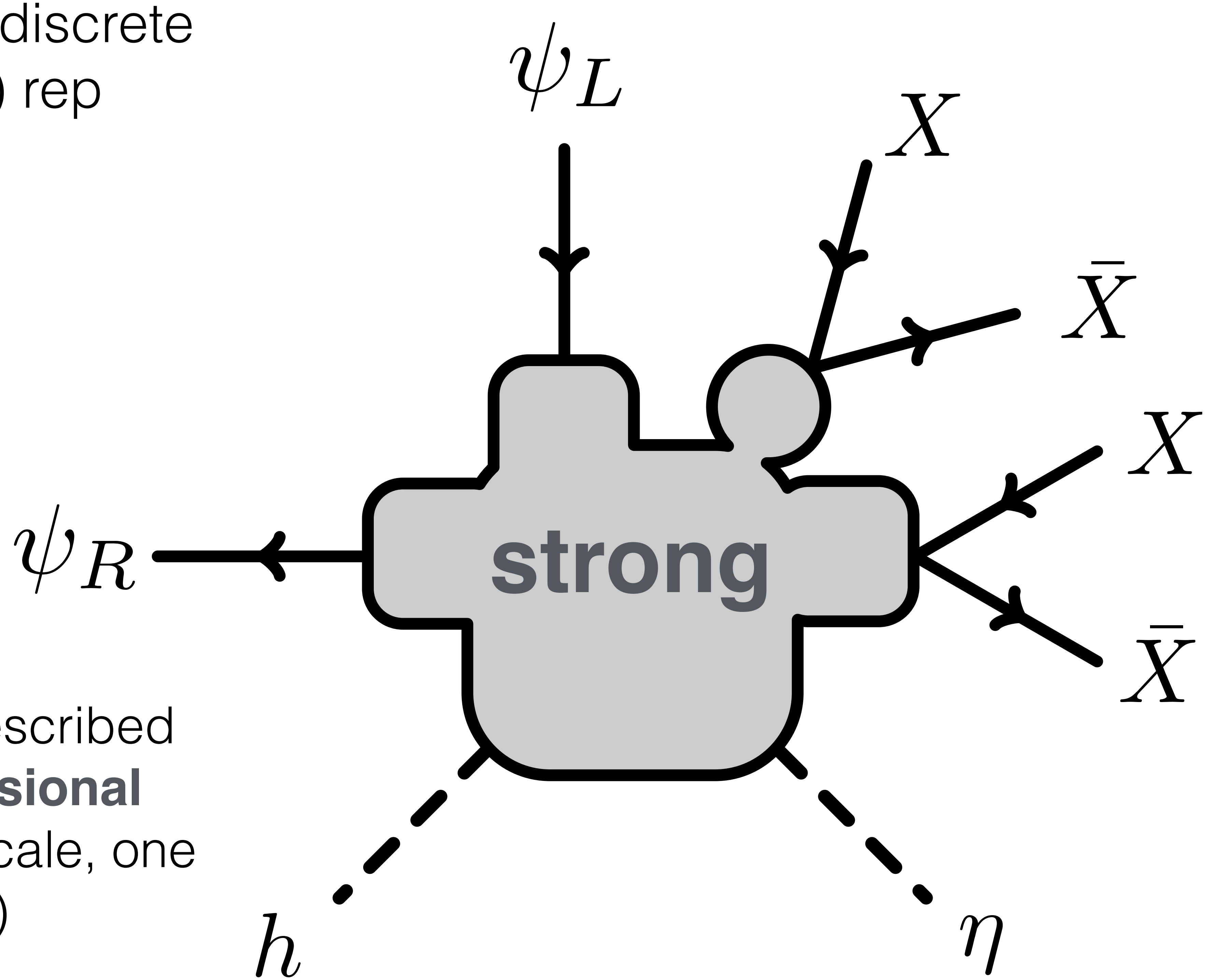
Singlet Mediator



Singlet as DM: Frigerio et al. 1204.2808, Marzocca et al. 1404.7419, Fonseca et al. 1501.05957, Carmona et al. 1504.00332, Antipin et al.1503.08749 , **Related:** Poland & Thaler 0808.1290; Asano and Kitano 1406.6374

What the theory looks like

each knob is a discrete choice of SO(6) rep



strong sector described by **naive dimensional analysis** (one scale, one coupling ansatz)

I think this looks kind of like a cow.

Non-linear Σ Model (irreducible)

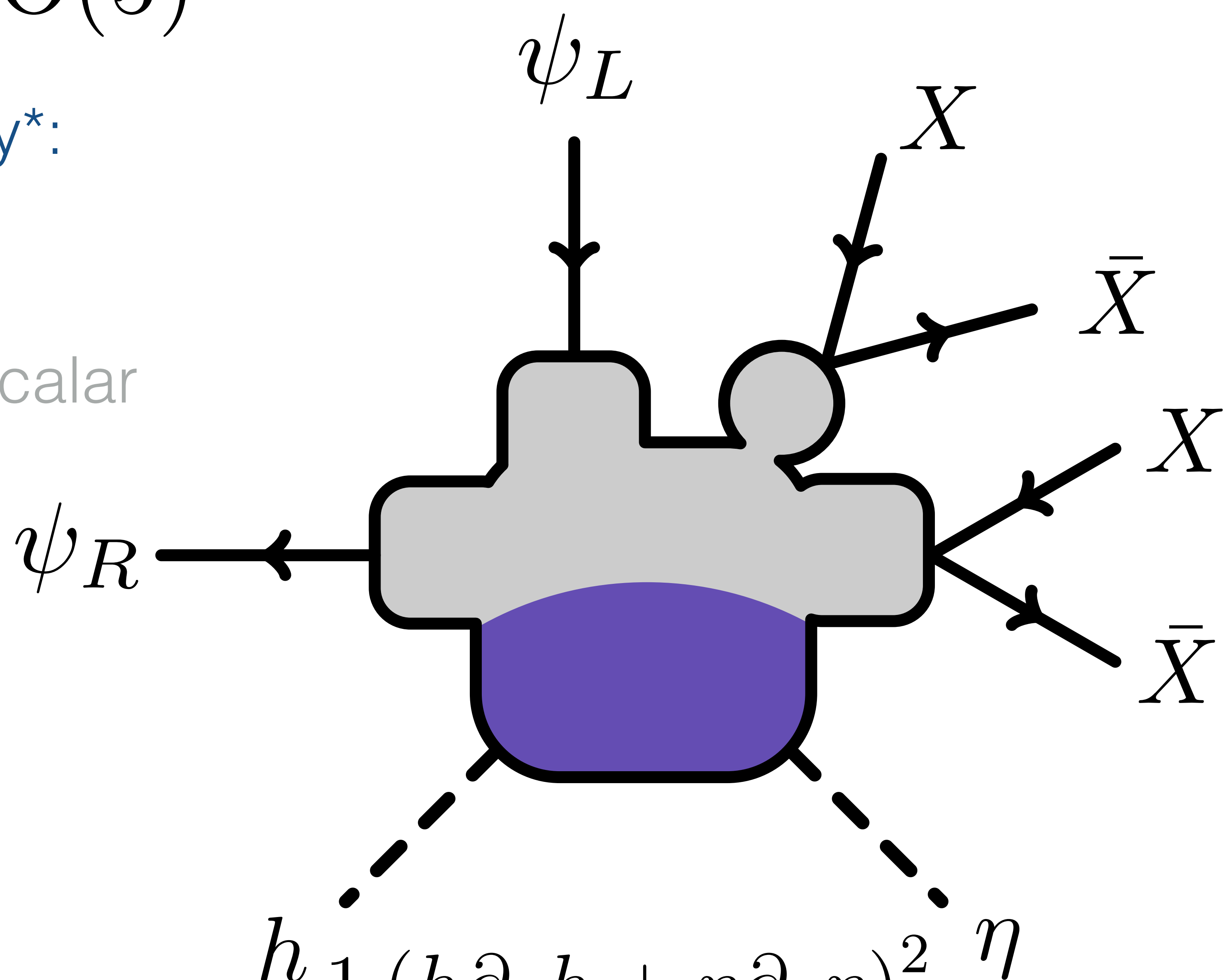
$\mathrm{SO}(6)/\mathrm{SO}(5)$

CP symmetry*:

$h \to h$

$\eta \to -\eta$

η a pseudoscalar

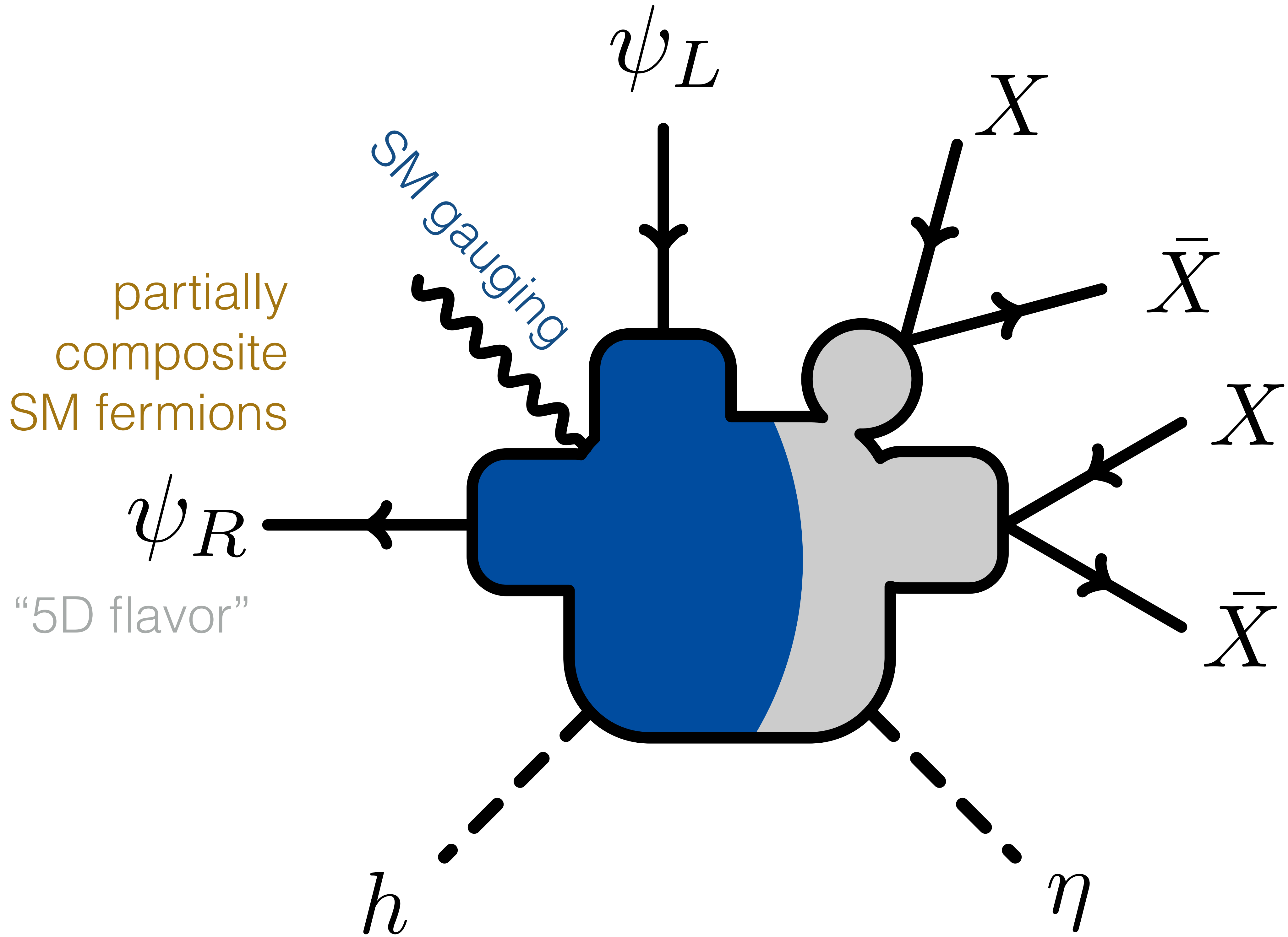


$$\frac{1}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta)^2}{f^2 - h^2 - \eta^2}$$

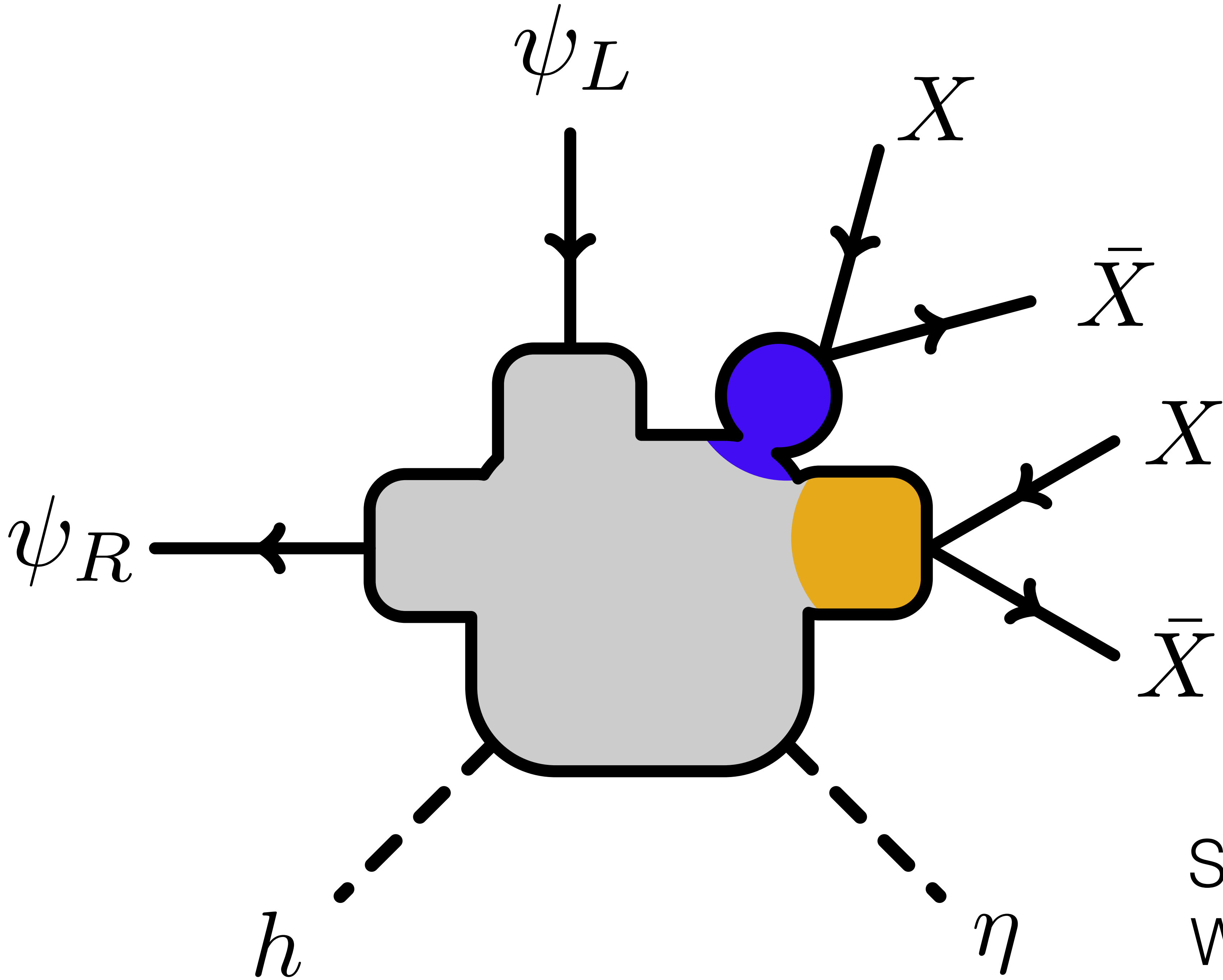
* — may be violated at $O(\partial^4)$

SO(5)/SO(4) & the Standard Model

described by usual minimal composite Higgs



Dark Matter: bilinear coupling

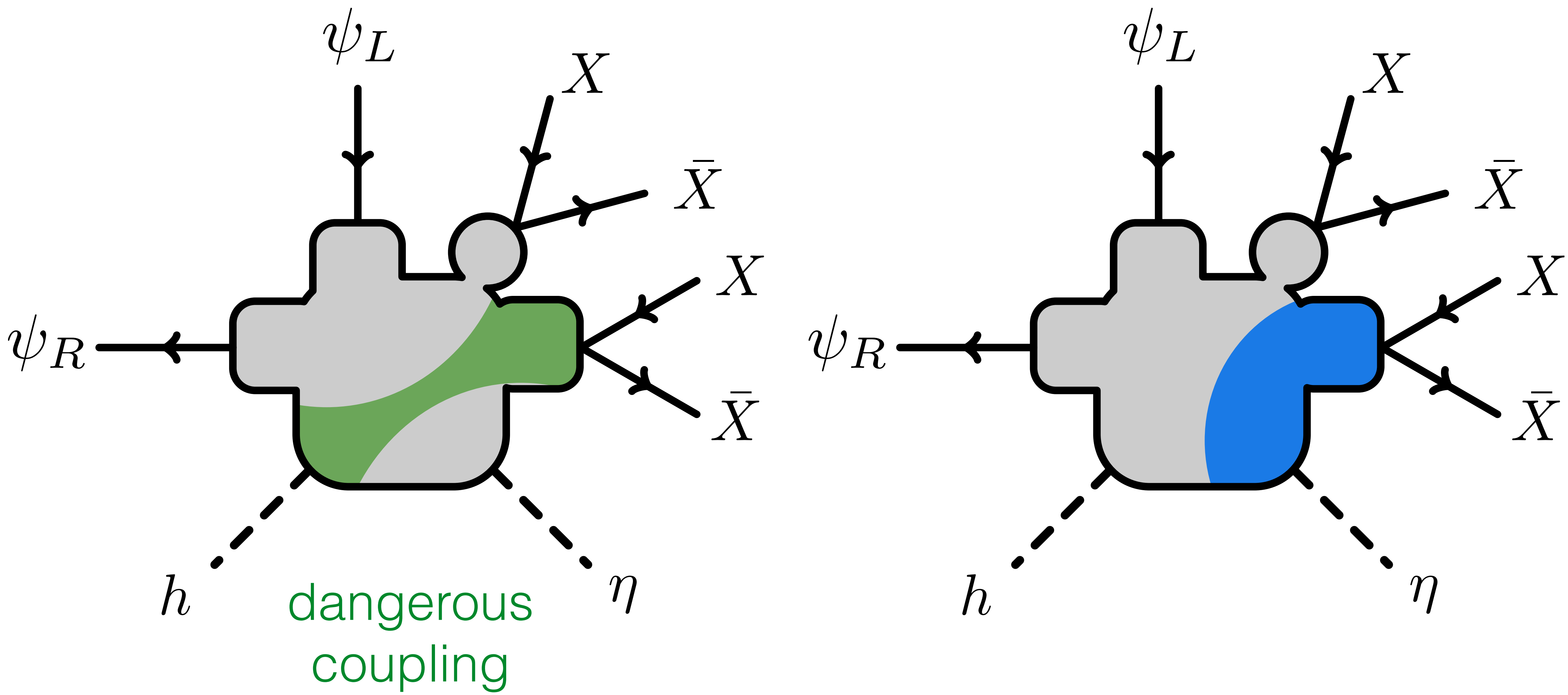


two bilinear interactions with dark matter

technicolor-like

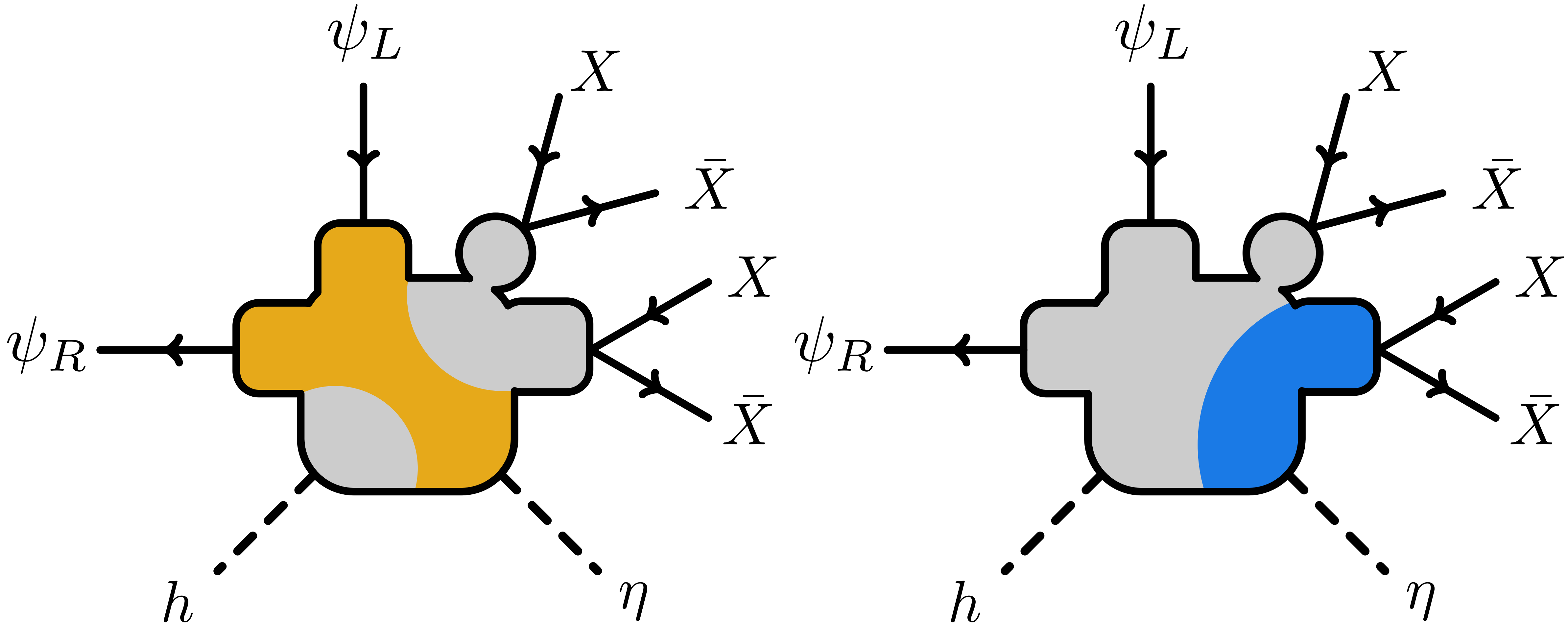
Solves "dark μ problem"
Why is mX WIMP-scale?
Because of breaking scale

Dark Sector Couplings



These are determined once you specify the order parameters of explicit breaking.

Mediator Coupling



Fermion loops give mediator mass

Interaction strength $\Longleftrightarrow$ mediator mass

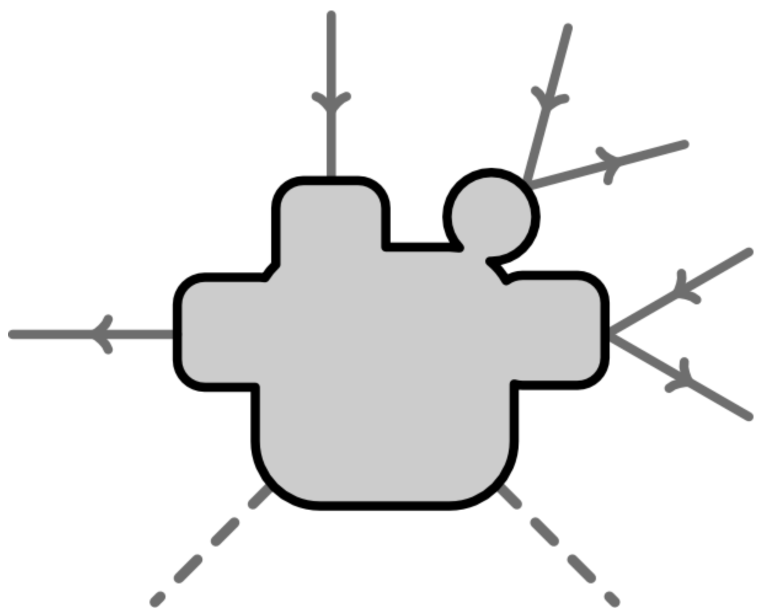
So finding a thermal relic is … kind of a miracle.

What do you get?

Input:

composite Higgs parameters, adapted to SO(6)

dark matter representation(s)



gray box

explicit breaking loops

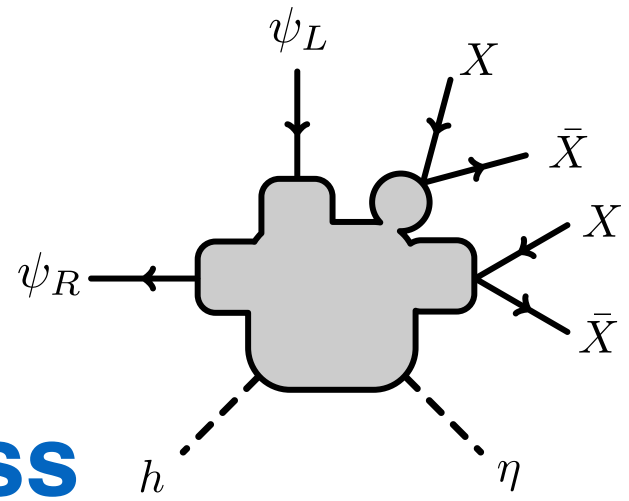
nonlinear interactions

Output:

Pseudoscalar mediator / “Higgs” portal models

Range of interactions, spectra

Punchline



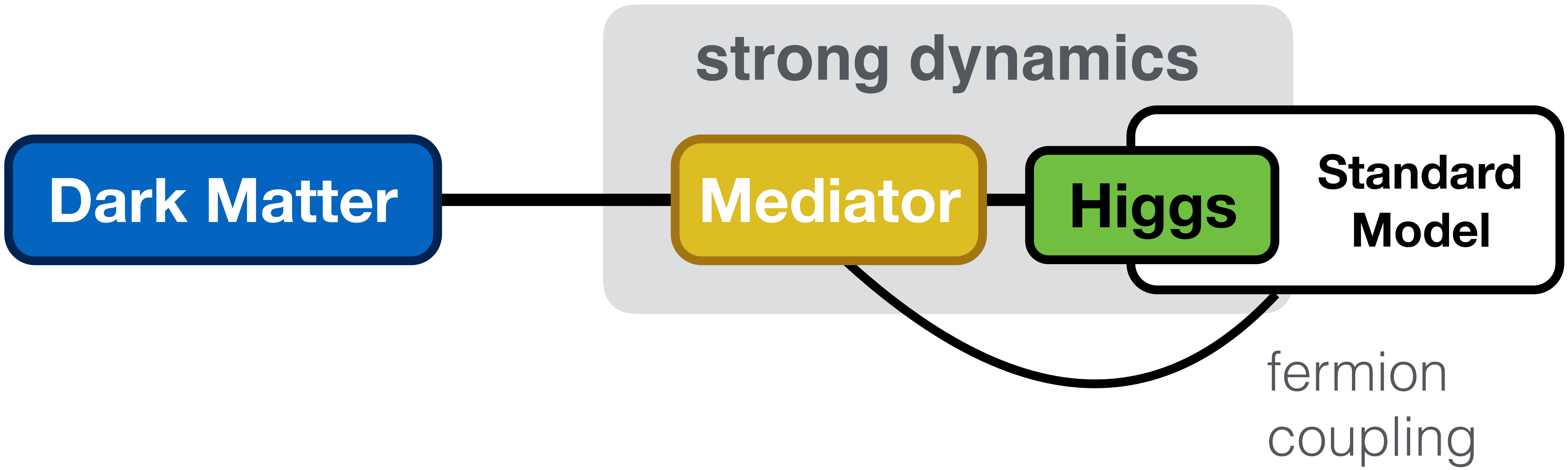
New completion of pseudoscalar mediator

Connects **dark matter** and **Higgs naturalness**

Small number of parameters + discrete choices

In some sense, variant of "**WIMP**"

… can survive direct detection

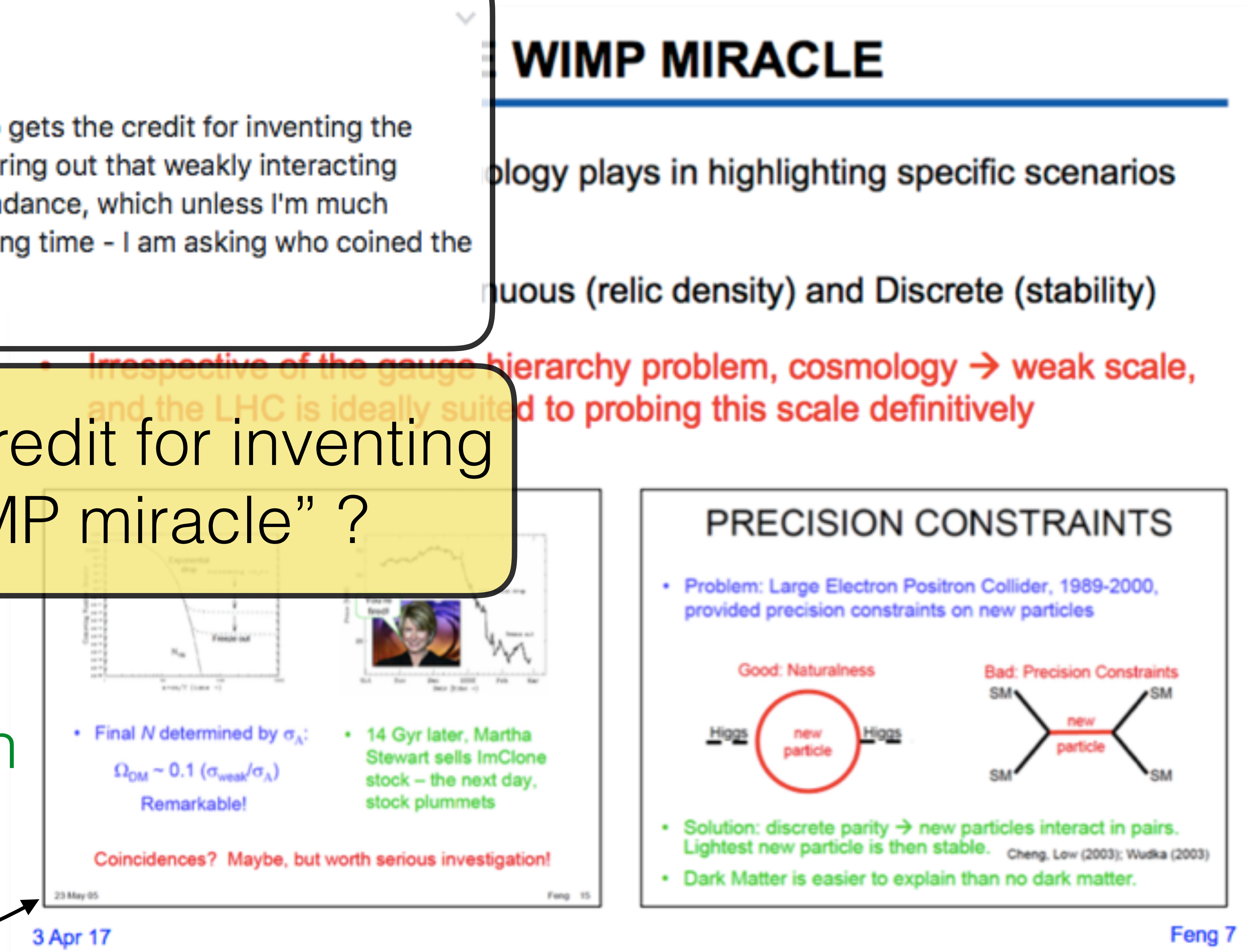


Make Dark Matter "WIMPs" Again

Can Kılıç
January 20 ·

physics crowdsourcing question: who gets the credit for inventing the phrase "WIMP miracle"? NOT for figuring out that weakly interacting thermal relics give the right relic abundance, which unless I'm much mistaken precedes the phrase by a long time - I am asking who coined the specific phrase (and when).

"who gets the credit for inventing the phrase "WIMP miracle" ?



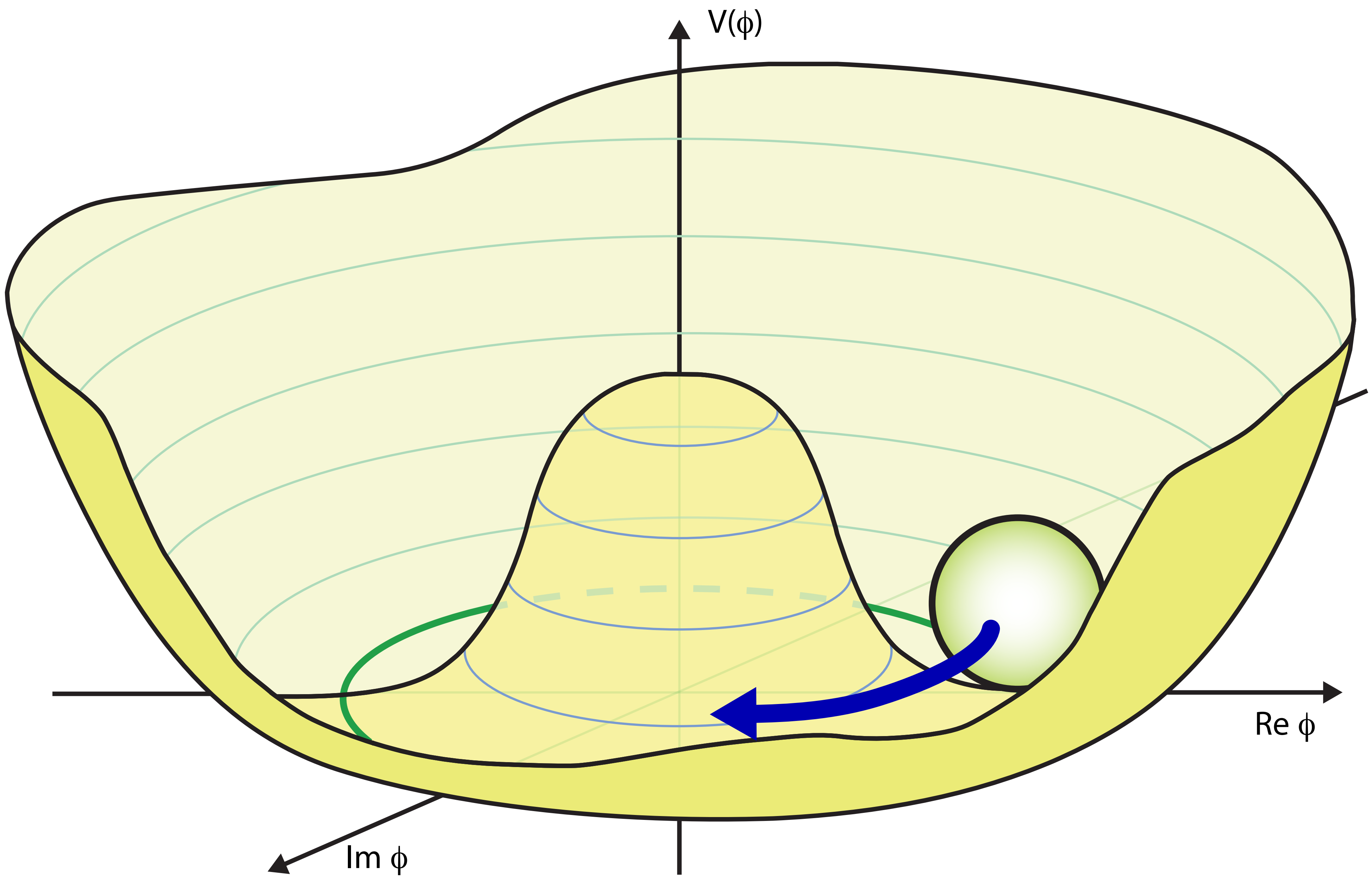
it may have been this talk? (2005)

Jonathan Feng, DM@LHC17; with apologies to Prateek 1610.04611

EXTRA **SLIDES**

Goldstone Bosons

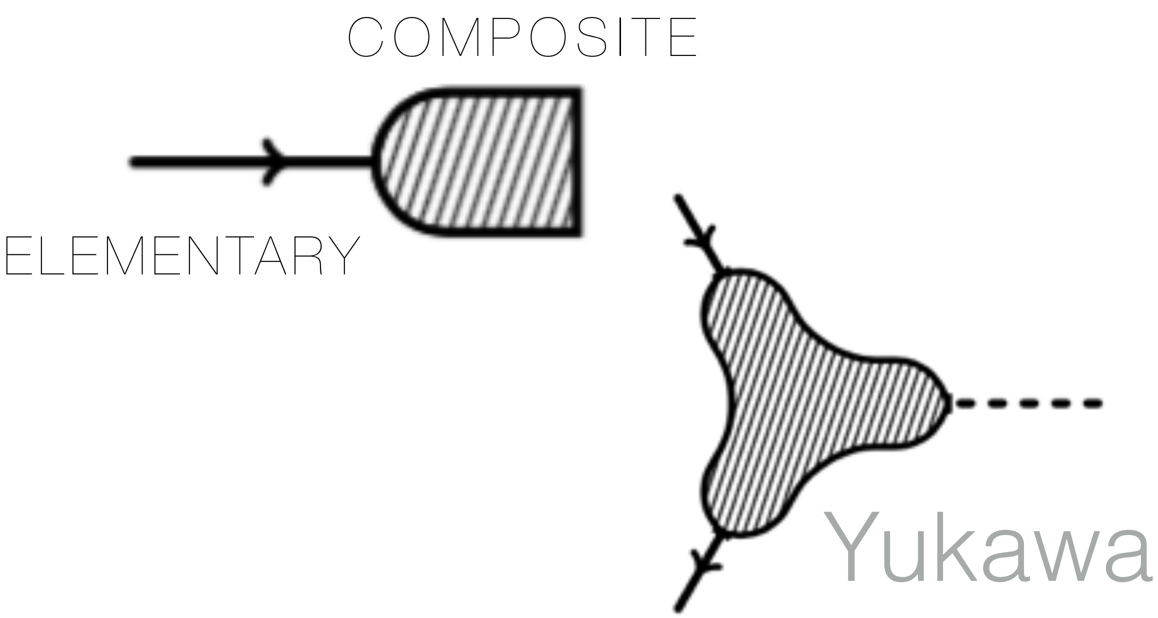
Recipe: spontaneously break symmetry. Transform along broken direction. Promote transformation parameter to a field. That's your Goldstone.



Original source unknown… maybe Nature Physics 7, 2–3 (2011) ?

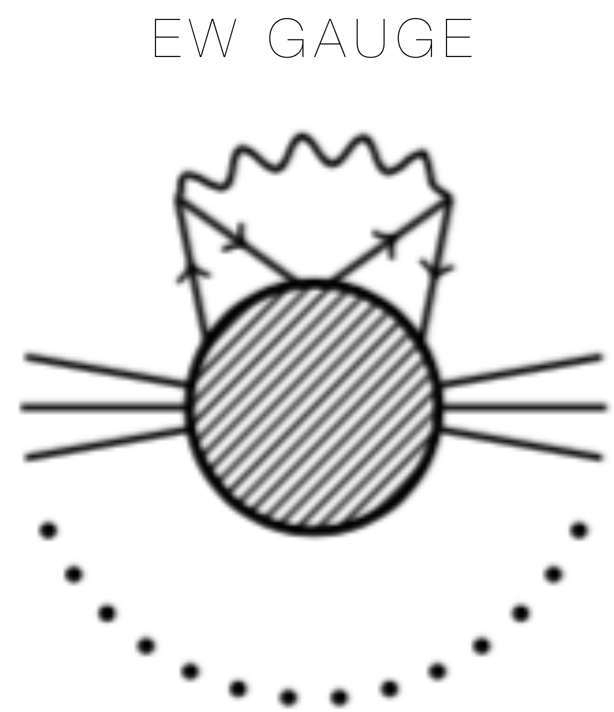
Explicit Breaking

"conformal / 5D flavor"



Partial Compositeness
Elementary fermions are incomplete SO(6)-plets

Kaplan Nucl Phys. B365 '91



Electroweak Gauging
EW gauge loops discriminate elements of an SO(6)-plet

Kaplan Georgi PLB 136 '84

Reviews: e.g. FT & Csaki 1602.04228; Panico & Wulzer 1506.01961

A convenient SO(6) basis

$$T^1_{L,R} = \frac{i}{2}\left(\begin{array}{cccc|cc} & & & \pm 1 & & \\ & & -1 & & & \\ & 1 & & & & \\ \mp 1 & & & & & \\ \hline & & & & 0 & \\ & & & & & 0 \end{array}\right) \qquad T^\alpha_{\mathbf{1}} = \frac{i}{\sqrt{2}}\left(\begin{array}{cccc|cc} & & & & -\delta^\alpha_1 & \\ & & & & -\delta^\alpha_2 & \\ & & & & -\delta^\alpha_3 & \\ & & & & -\delta^\alpha_4 & \\ \hline \delta^\alpha_1 & \delta^\alpha_2 & \delta^\alpha_3 & \delta^\alpha_4 & 0 & \\ & & & & & 0 \end{array}\right)$$

$$T^2_{L,R} = \frac{i}{2}\left(\begin{array}{cccc|cc} & & 1 & & & \\ & & & \mp 1 & & \\ -1 & & & & & \\ & \pm 1 & & & & \\ \hline & & & & 0 & \\ & & & & & 0 \end{array}\right) \qquad T^\alpha_{\mathbf{2}} = \frac{i}{\sqrt{2}}\left(\begin{array}{cccc|cc} & & & & & -\delta^\alpha_1 \\ & & & & & -\delta^\alpha_2 \\ & & & & & -\delta^\alpha_3 \\ & & & & & -\delta^\alpha_4 \\ \hline & & & & 0 & \\ \delta^\alpha_1 & \delta^\alpha_2 & \delta^\alpha_3 & \delta^\alpha_4 & & 0 \end{array}\right)$$

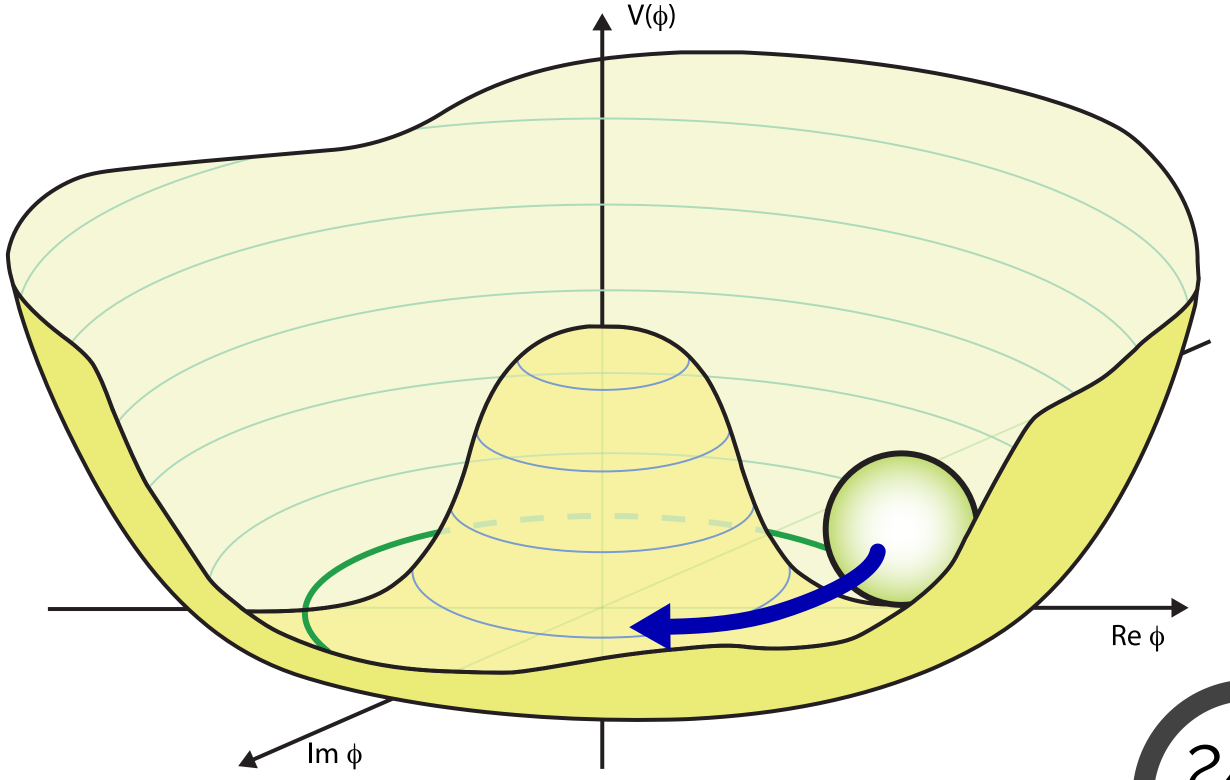
$$T^3_{L,R} = \frac{i}{2}\left(\begin{array}{cccc|cc} & -1 & & & & \\ 1 & & & & & \\ & & & \mp 1 & & \\ & & \pm 1 & & & \\ \hline & & & & 0 & \\ & & & & & 0 \end{array}\right) \qquad T_\eta = \frac{i}{\sqrt{2}}\left(\begin{array}{cccc|cc} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & 0 & & \\ \hline & & & & & -1 \\ & & & & 1 & \end{array}\right)$$

Goldstone Parameterization

$$U = \frac{1}{f}\begin{pmatrix} f\mathbb{1}_{3\times 3} & \cdot & \cdot & \cdot \\ \cdot & f - \frac{h^2}{f+\sqrt{f^2-h^2-\eta^2}} & -\frac{h\eta}{f+\sqrt{f^2-h^2-\eta^2}} & h \\ \cdot & -\frac{h\eta}{f+\sqrt{f^2-h^2-\eta^2}} & f - \frac{\eta^2}{f+\sqrt{f^2-h^2-\eta^2}} & \eta \\ \cdot & -h & -\eta & \sqrt{f^2-h^2-\eta^2} \end{pmatrix}$$

U(1) associated with singlet

$$\Sigma = U(0,\cdots,1)^T = \frac{1}{f}\begin{pmatrix}0 & 0 & 0 & h & \eta & \sqrt{f^2-h^2-\eta^2}\end{pmatrix}$$



Naive Dimensional Analysis

one scale, one coupling ansatz

mass scale of new resonances

bosons

fermions

$$\mathcal{L} = \frac{m_*^4}{g_*^2}\hat{\mathcal{L}}\left(\frac{\partial}{m_*}, \frac{g_* \Phi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}}\right)$$

characteristic resonance coupling

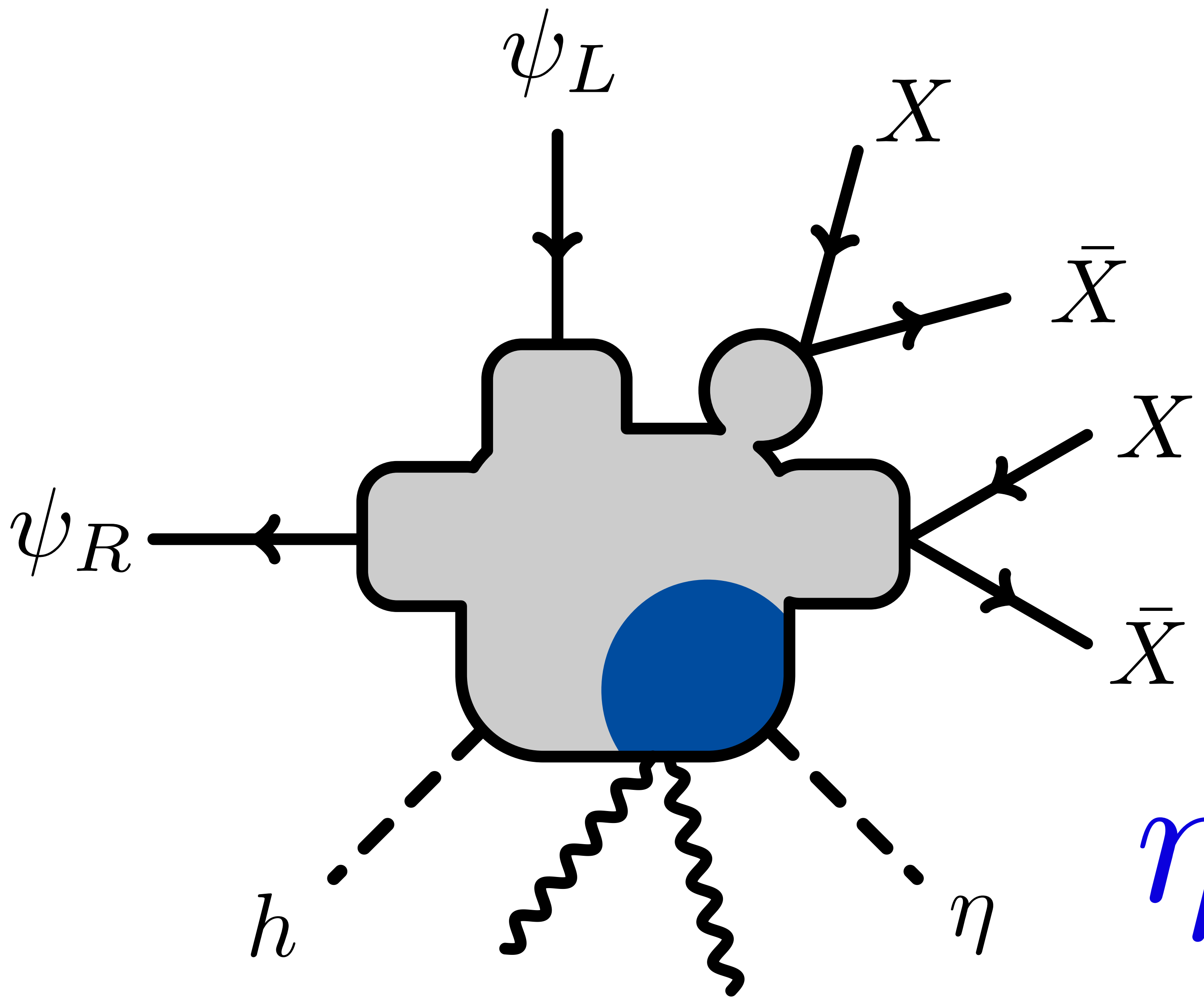
$$g_* = \frac{m_*}{f}$$

breaking scale

scaling from: mass and $\hbar$ dimensional analysis

Georgi & Manohar '84;see e.g. Panico & Wulzer 1506.01961 for a review

Axion-like gauge interactions



$\eta F\tilde{F}$

generated by SM loops and UV fermion content