COMPOSITE HIGGS, COMPOSITE MEDIATOR

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UC Riverside Particle Theory

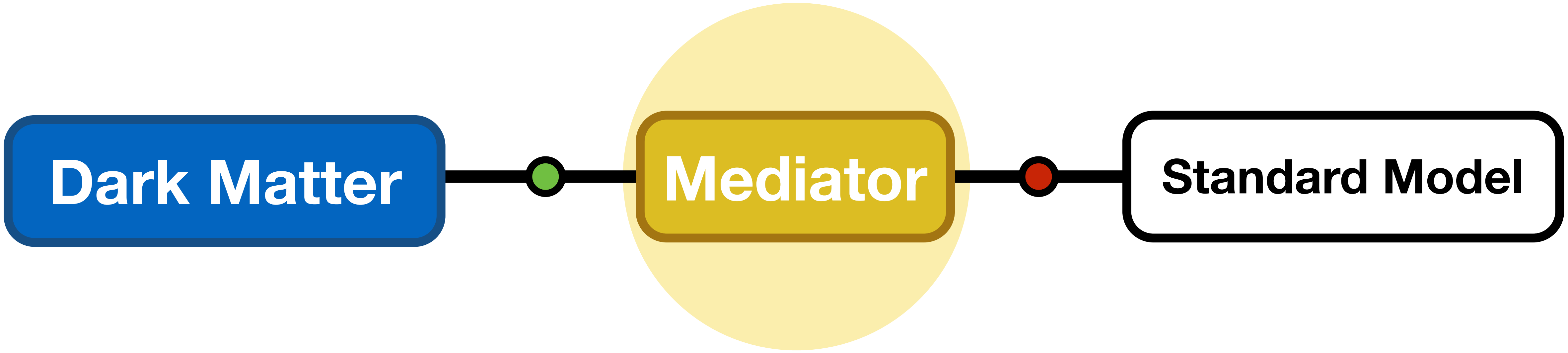
with Javi Serra and Alex Wijancgo

30 April 2018

KITP CONFERENCE ON
Dark matter detection and detectability:
paradigm confirmation or shift?

Julio Navarro

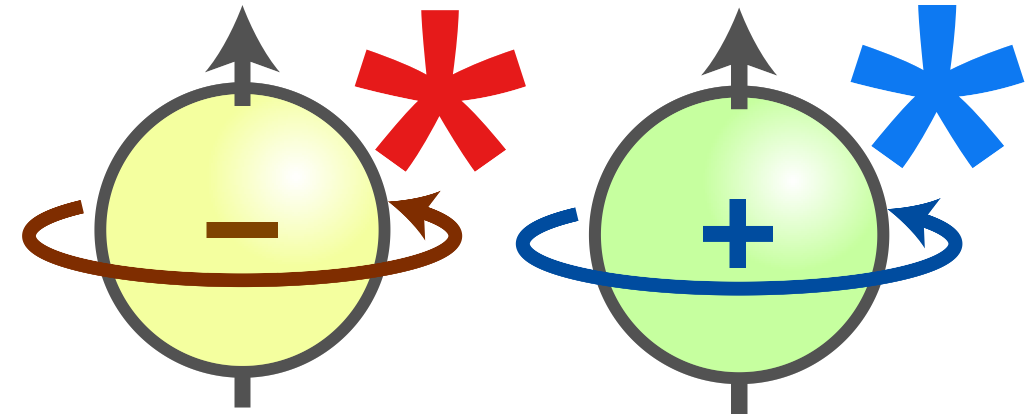
Dark Sectors with Light Mediators



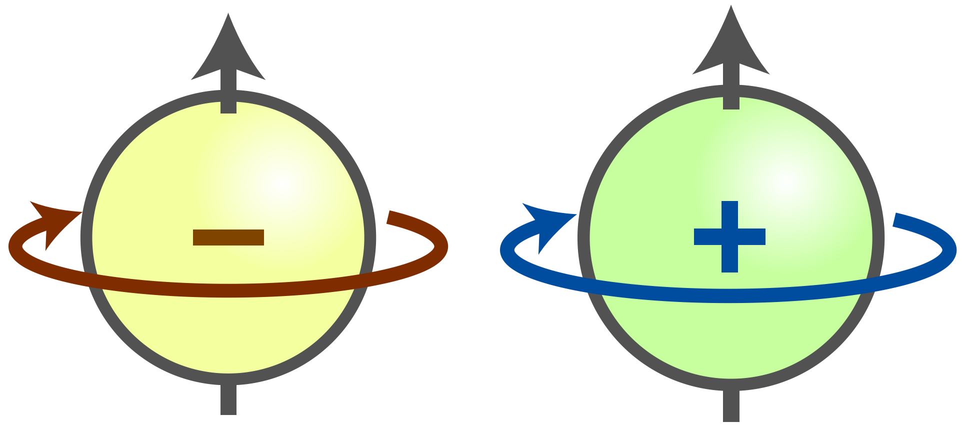
Review: Dark Sectors 2016 Workshop (1608.08632)

Gauge Invariance

In Standard Model, these are totally different fermions



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



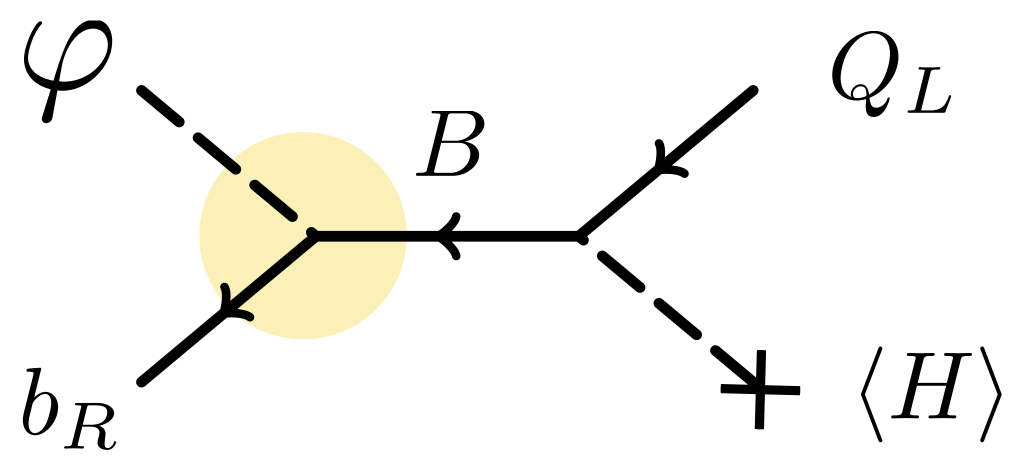
See, e.g.
Bell et al. 1503.07874
Kahlhoefer et al. 1510.02110
Bell et al. 1612.03475
Ko et al. 1701.04131
+ many others

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

How to UV complete?

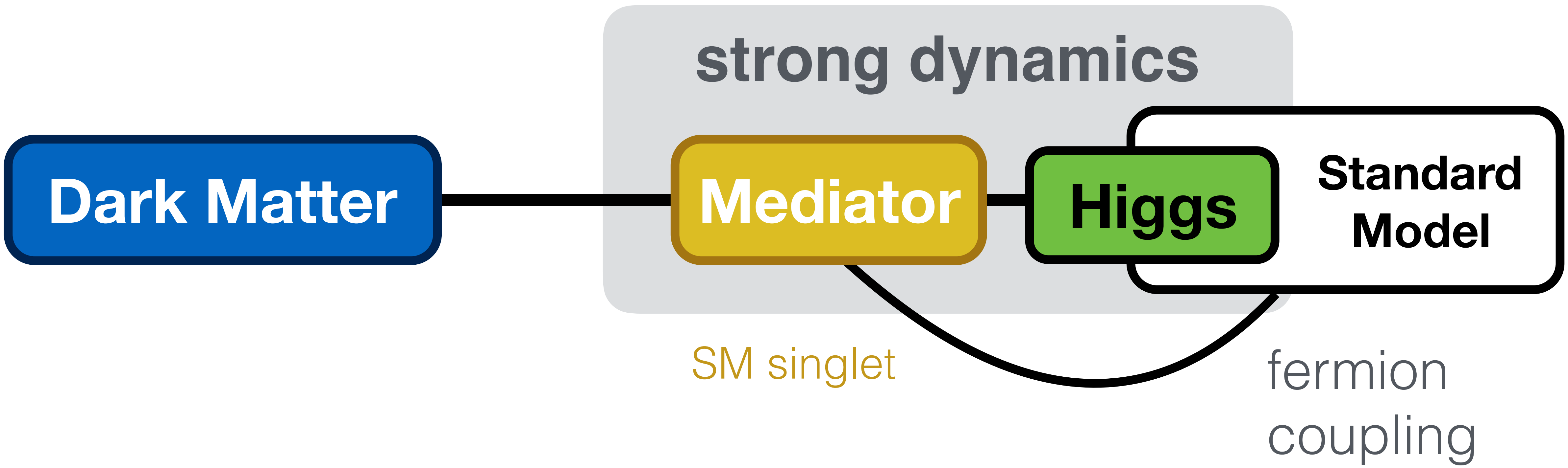
1. **≥ 2 Higgs Doublet Model**
   for example, the next-to-minimal SUSY SM
   e.g. Ipek et al. 1404.3716, Berlin et al. 1502.06000

2. **Heavy Vector-like Fermions**
   … then decouple them
   Fan et al. 1507.06993

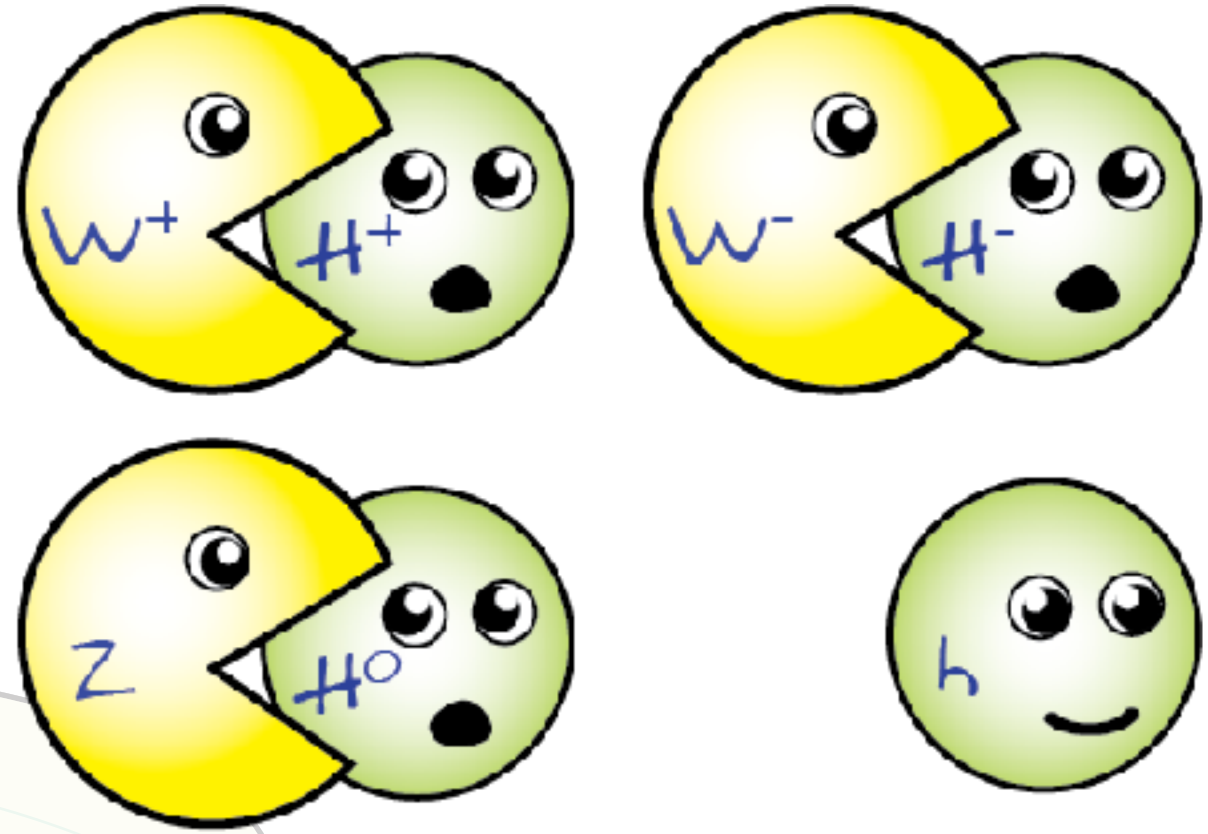


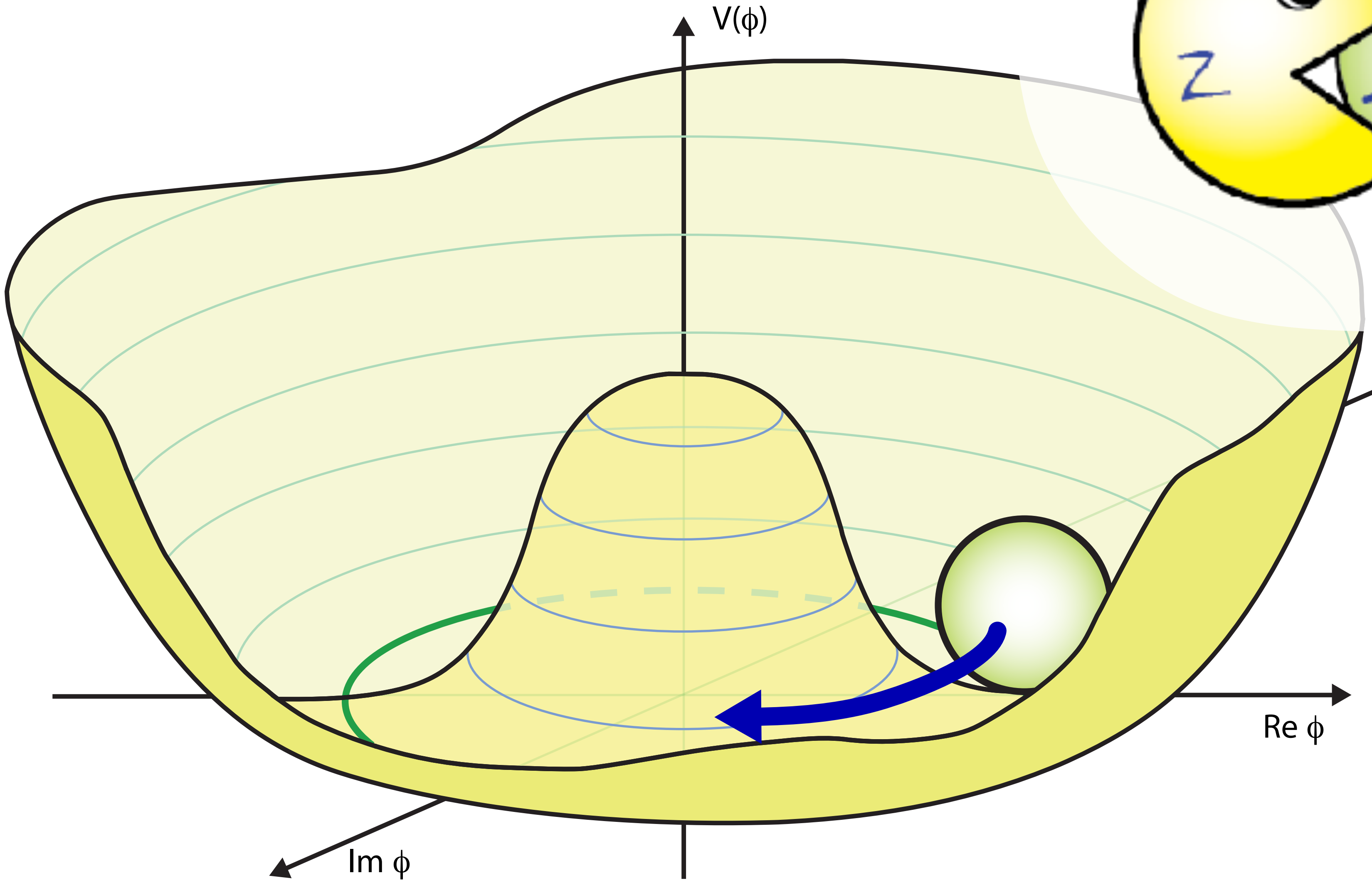
How to UV complete? This talk.

3. **Non-minimal composite Higgs**
   Gauge-singlet pseudoscalars
   … predictive, but heavy states decouple
   … connects to Hierarchy problem



Composite Higgs

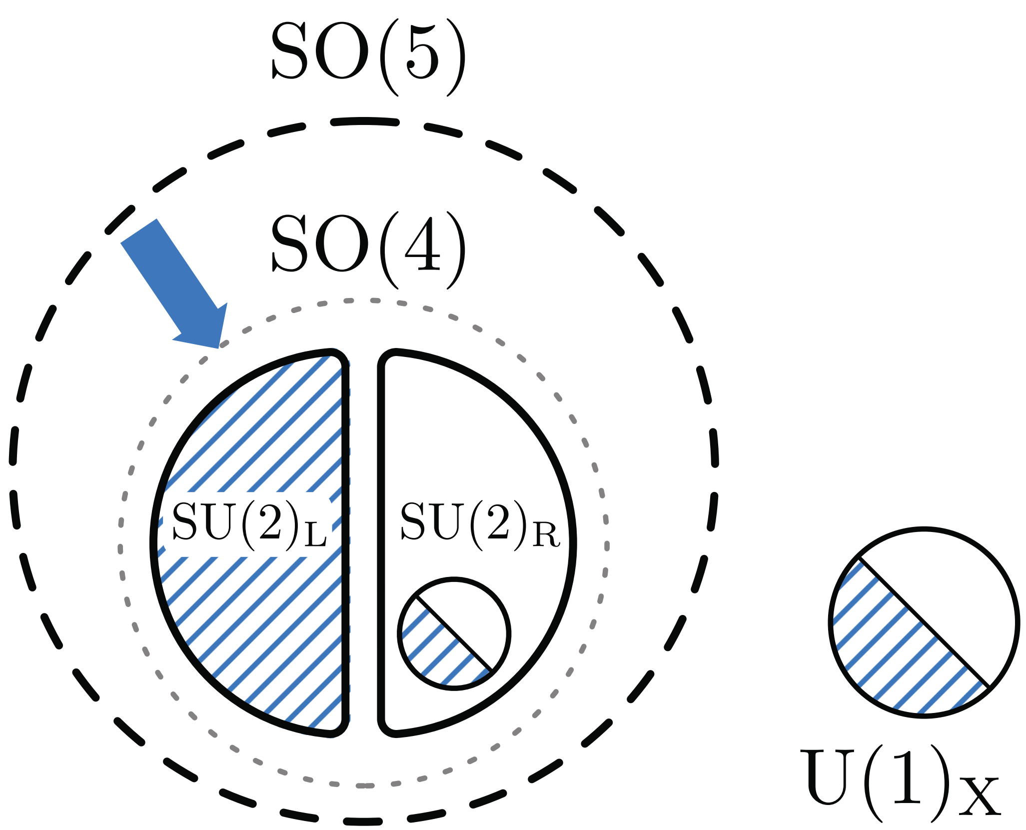




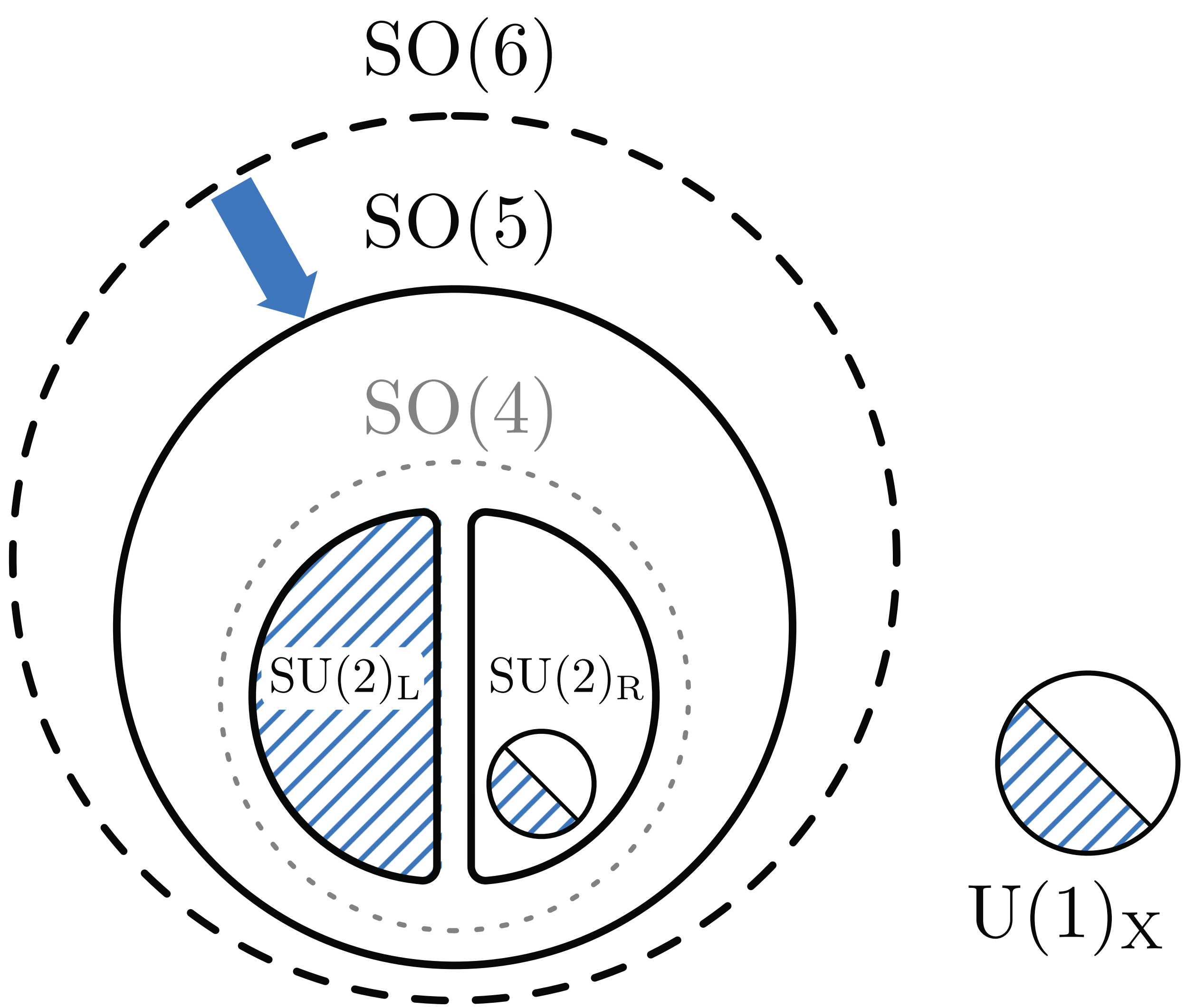
Kaplan & Georgi ’84 (Phys. Lett B136 & Phys. Lett. B145)

Composite Higgs + Singlet

Gauged symmetry in blue



Minimal Composite Higgs



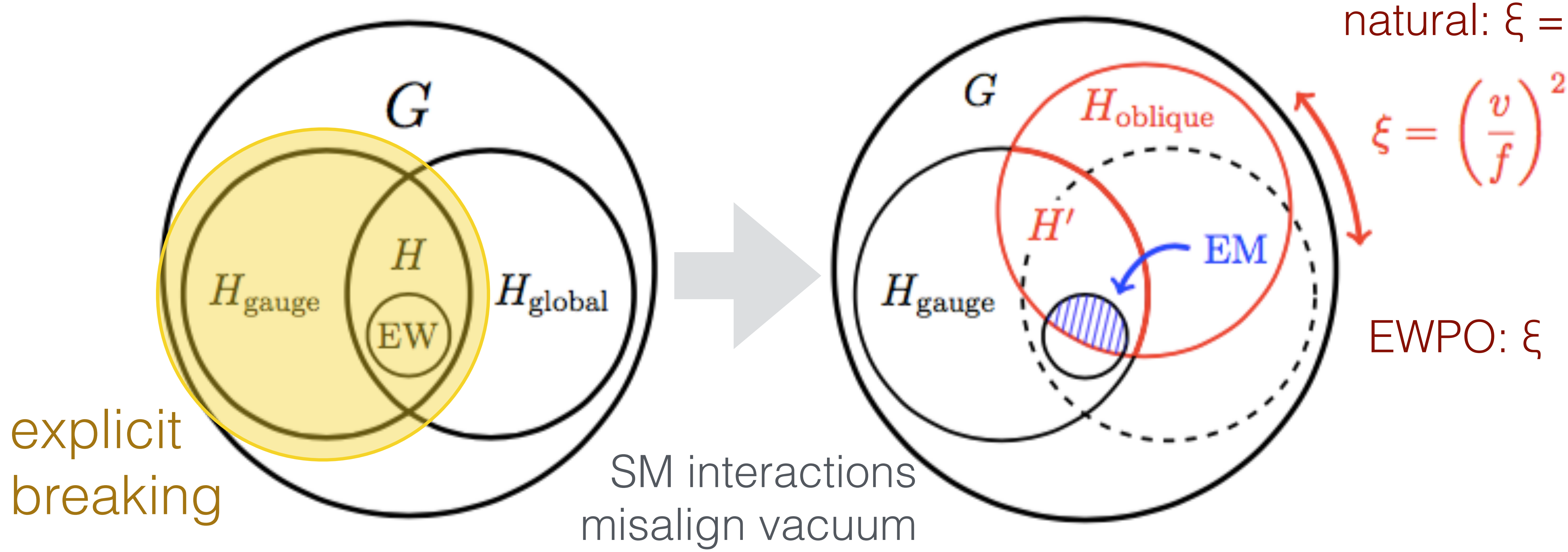
Next-to-Minimal Composite Higgs

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

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

Explicit & Electroweak Breaking

tuning parameter
decoupled: $\xi = 0$
natural: $\xi = 1$



EWPO: $\xi \ll 1$

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

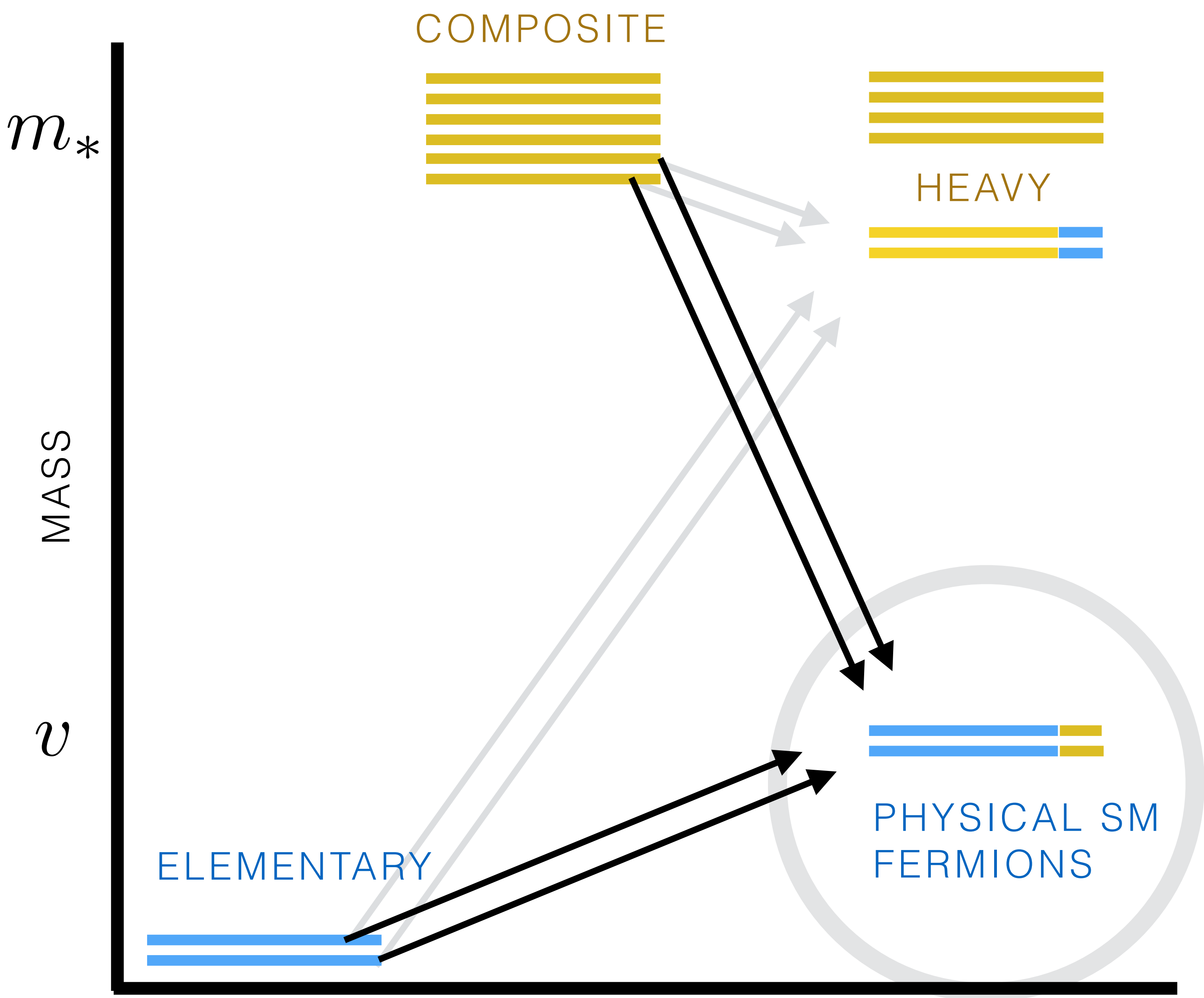
FT & Csaki 1602.04228, adapted from M. Safari's Ph.D thesis

Partial Compositeness

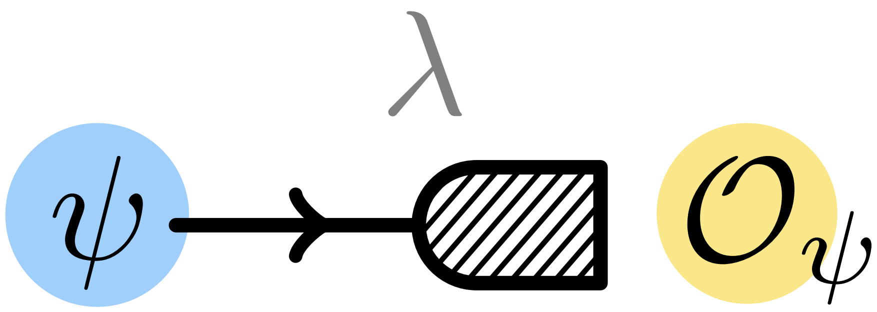
SU(2)L SU(2)R

$$\mathbf{6} = \mathbf{4} + \mathbf{1} + \mathbf{1} = (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1})$$

DOUBLET



$$\mathcal{L} \supset \lambda \bar{\psi} \mathcal{O}_\psi + \text{h.c.}$$



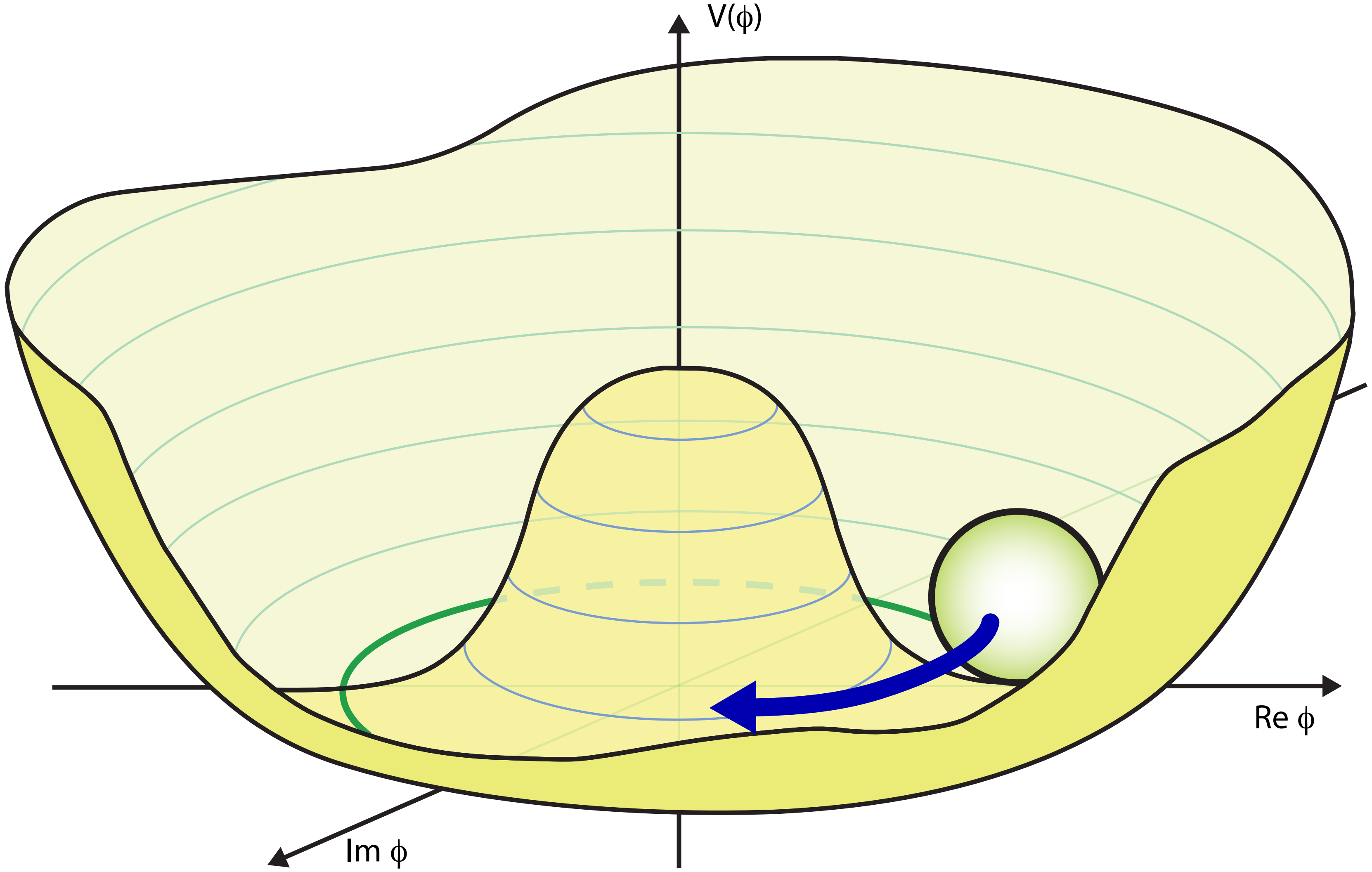
t_L & b_L only

6 fermionic composites

Elementary fields are not SO(6) multiplets, mix with composite operators.

Non-linear realization

$$\Sigma = e^{iT^A \pi^A(x)/f} \Sigma_0$$



An SO(6) basis

VEV $\Sigma_0 = (0,0,0,0,0,1)^T$

$$\Sigma = \frac{1}{f}\begin{pmatrix} 0 & 0 & 0 & h & \eta & \sqrt{f^2 - h^2 - \eta^2} \end{pmatrix}$$

BROKEN

$$T_2^\alpha = \frac{i}{\sqrt{2}}\left(\begin{array}{cccc|cc} & & & & & -\delta_1^\alpha \\ & & & & & -\delta_2^\alpha \\ & & & & & -\delta_3^\alpha \\ & & & & & -\delta_4^\alpha \\ \hline & & & & 0 & \\ \delta_1^\alpha & \delta_2^\alpha & \delta_3^\alpha & \delta_4^\alpha & & 0 \end{array}\right)$$

$$T_\eta = \frac{i}{\sqrt{2}}\left(\begin{array}{cccc|cc} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & 0 & & \\ \hline & & & & & -1 \\ & & & & 1 & \end{array}\right)$$

MEDIATOR U(1) SYM

Reminder: SO(6) ⊃ SO(4) ≃ $SU(2)_L \times SU(2)_R$ (custodial symmetry)

What the theory looks like

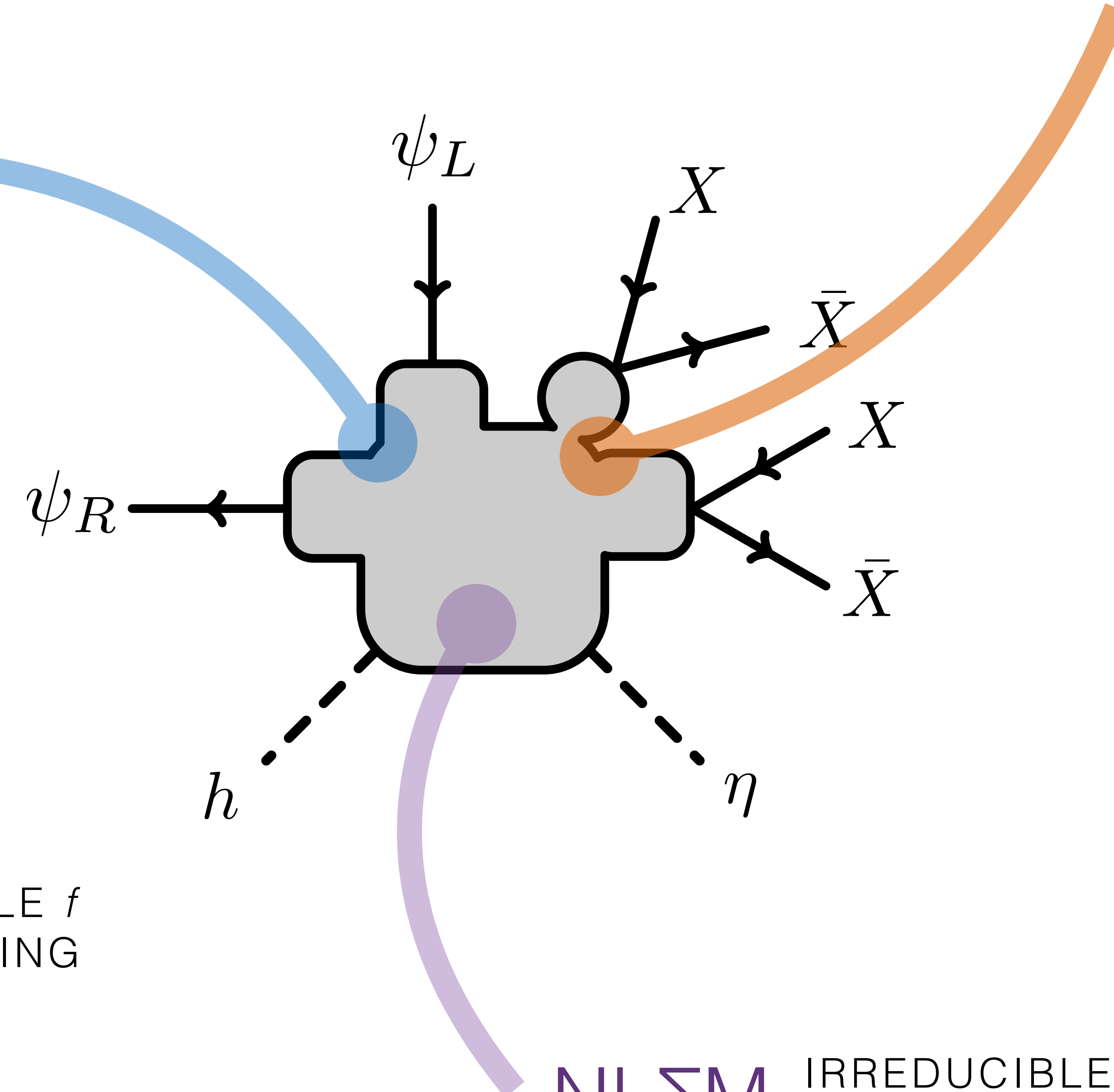
Use Σ and spurions to write invariants

visible matter embedding

CHOICES LEAD TO
- HIGGS POTENTIAL
- MEDIATOR POTENTIAL

dark matter embedding

CHOICES LEAD TO MEDIATOR POTENTIAL



OUTPUTS:
MEDIATOR MASS AS A FUNCTION OF DISCRETE CHOICES AND DM MASS

COMPOSITE HIGGS
SPECIFY BREAKING SCALE *f*
GIVES MEASURE OF TUNING

$$\xi = \left(\frac{v}{f}\right)^2$$

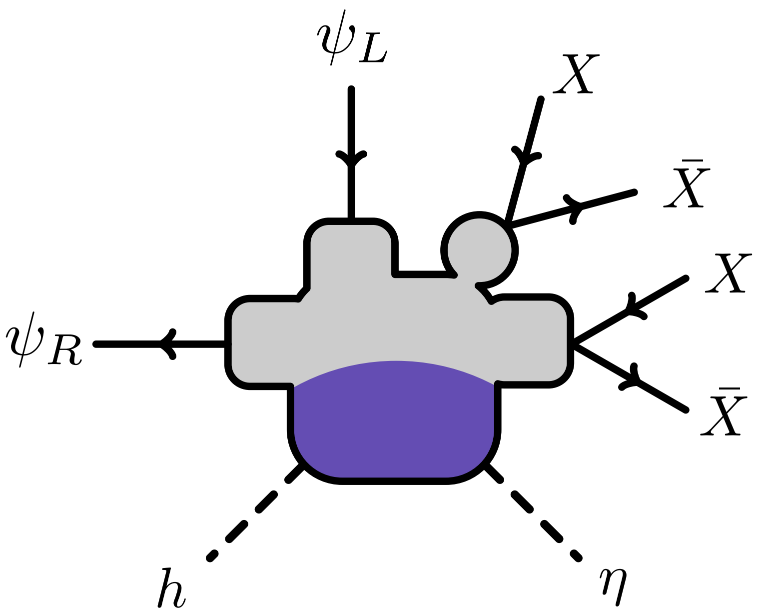
NLΣM IRREDUCIBLE INTERACTIONS

Non-linear Σ Model

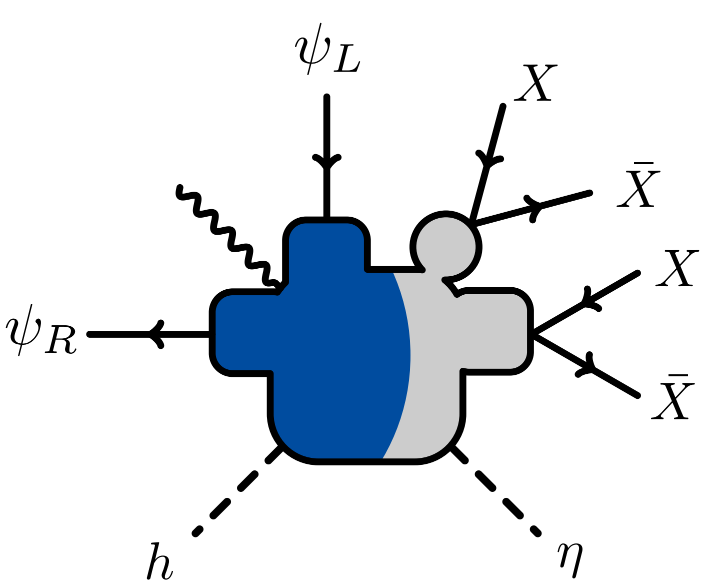
$$\frac{f^2}{2}\left|D_\mu\Sigma\right|^2 = \frac{(\partial_\mu h)^2}{2} + \frac{(\partial_\mu \eta)^2}{2}$$

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

$$+\frac{g^2}{4}h^2\left(W_\mu^+ W^{\mu-} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right)$$



NONLINEAR



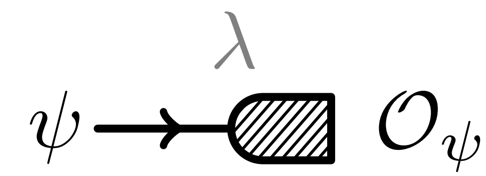
HIGGS-GAUGE INTERACTIONS

HIGGS POTENTIAL GIVES:

$$h \to v + h\sqrt{1-\xi}$$

η-SM coupling: right-handed embed

$$(\mathbf{2},\mathbf{2})_{\frac{2}{3}}: \quad Q = \frac{1}{\sqrt{2}}\left(ib_L\,,\; b_L\,,\; it_L\,,\; -t_L\,,\; 0\,,\; 0\right)^T$$

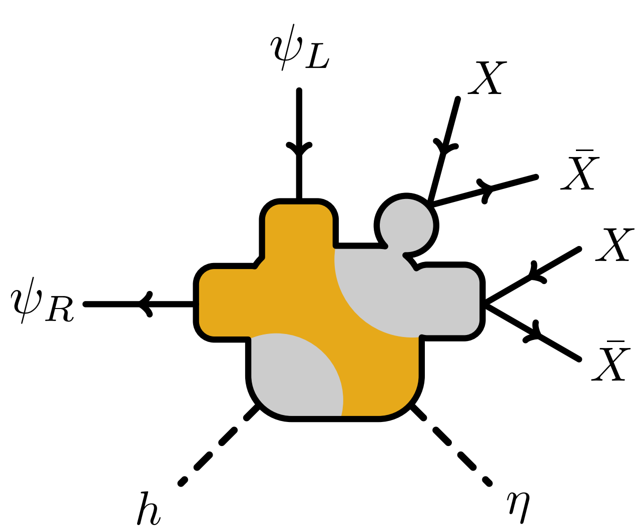


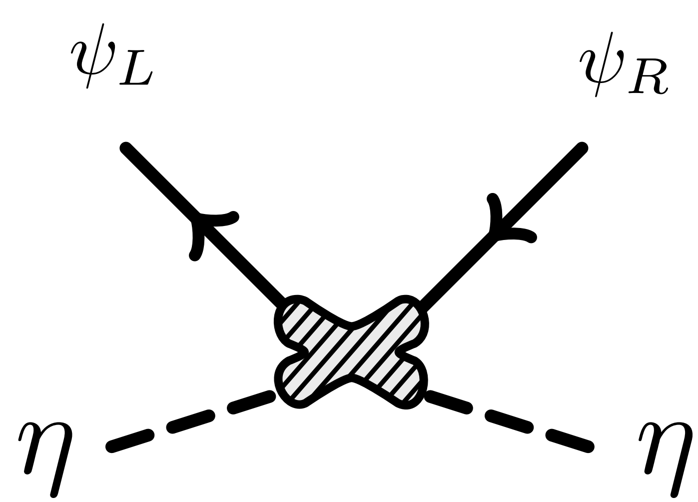
$$(\mathbf{2},\mathbf{2})_{\frac{2}{3}}: \quad T = \left(0\,,\; 0\,,\; 0\,,\; 0\,,\; i\delta_t t_R\,,\; t_R\right)^T$$

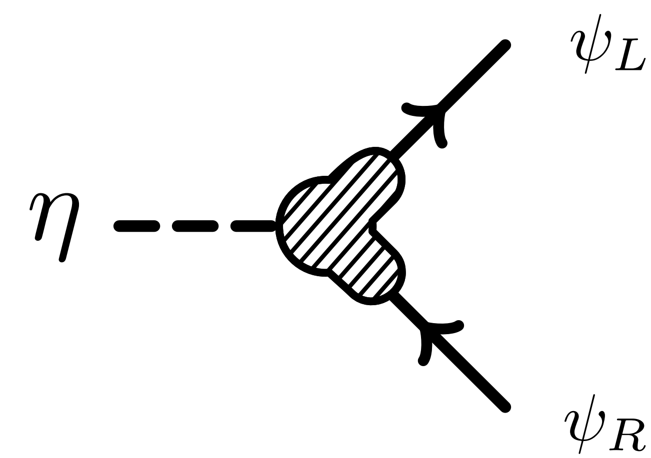
CHOICE: δ PARAMETER

$$\Sigma = \frac{1}{f}\begin{pmatrix}0 & 0 & 0 & h & \eta & \sqrt{f^2-h^2-\eta^2}\end{pmatrix}$$

$$\mathcal{L} \supset y_t f(\bar{Q}\Sigma)(\Sigma^T T) = -\frac{y_t}{\sqrt{2}} h\bar{t}_L t_R \left(\sqrt{1-\frac{h^2}{f^2}-\frac{\eta^2}{f^2}} + i\delta_t \frac{\eta}{f}\right)$$





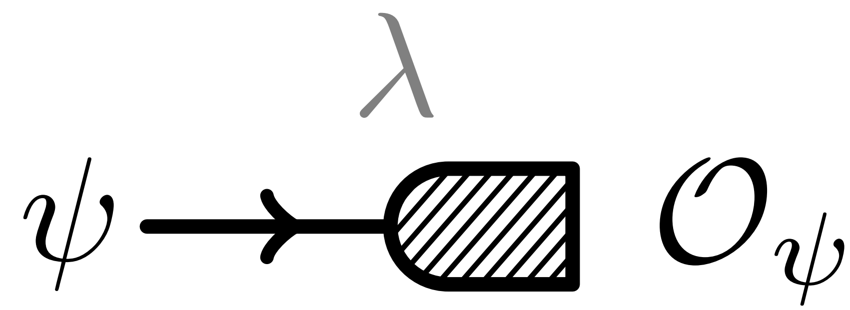


Dark matter: same thing again?

Introduce dark matter as elementary Dirac fermion

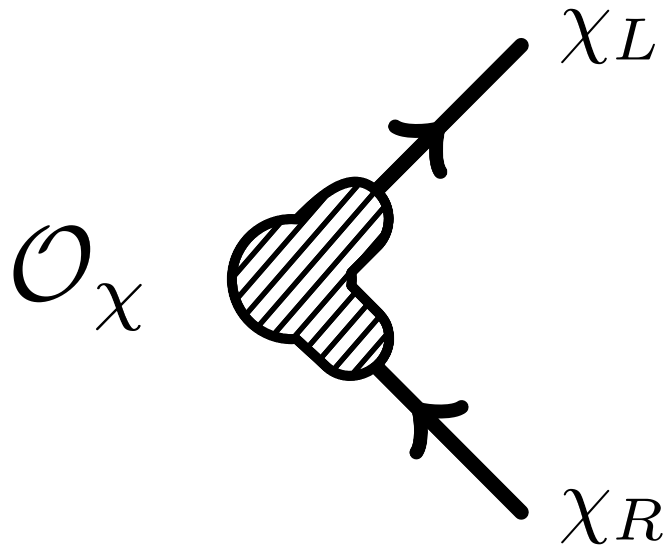
Why not use this again?

Why should such a particle be stable?



Better option: bilinear mixing

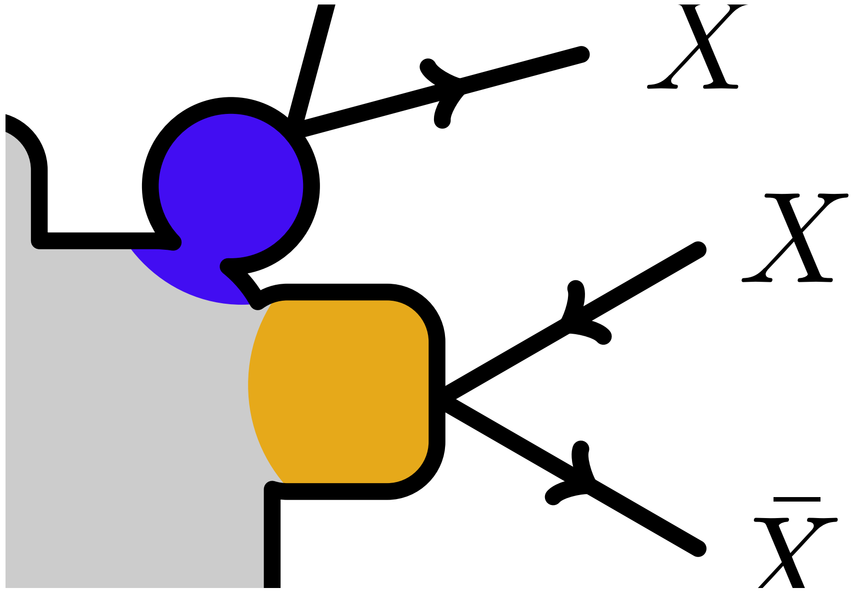
TECHNICOLOR-LIKE MASS GENERATION



Doesn't work for visible matter (flavor)
But preserves $\chi \to -\chi$

Sets the mass scale to *f*

Dark Matter: bilinear coupling

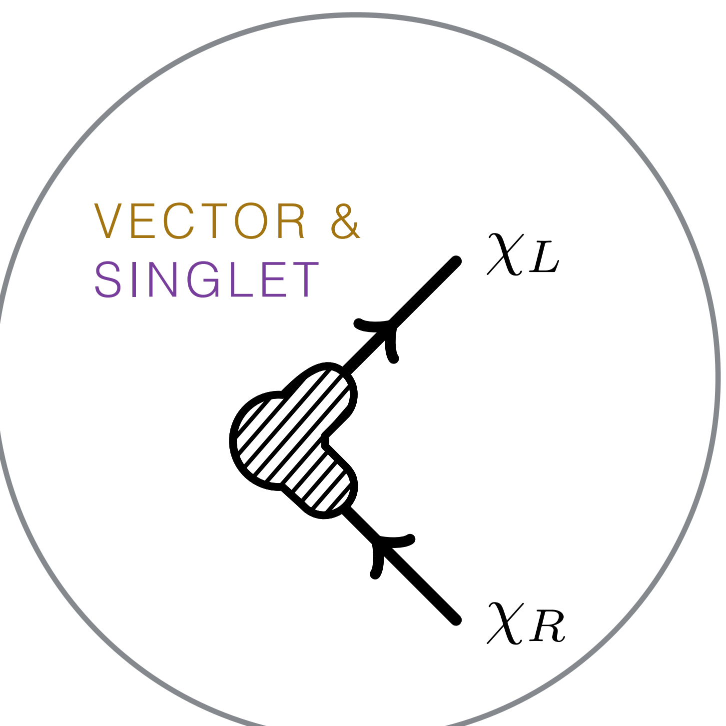


$$\mathcal{L} \supset -y'_\chi f \, \bar{\chi}_L \chi_R$$

SINGLET

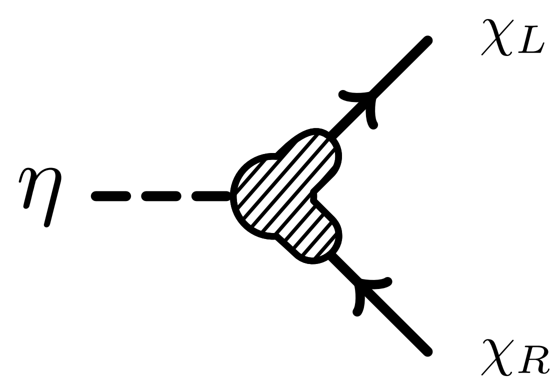
$$\mathcal{L} \supset -y_\chi f \, \left(\Sigma^T \mathbb{X}\right)$$

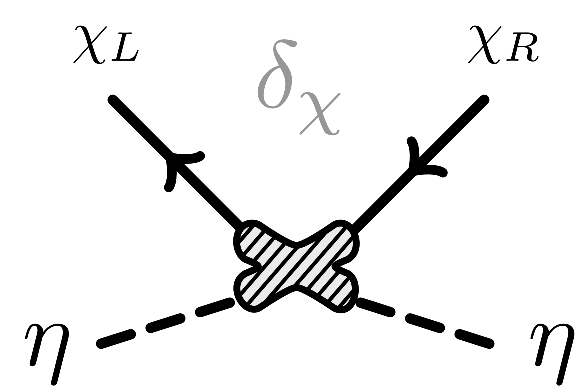
VECTOR



$$\mathbb{X} = (0\,,\ 0\,,\ 0\,,\ 0\,,\ i\,\bar{\chi}_L\chi_R\,,\ \delta_\chi\,\bar{\chi}_L\chi_R\,)^T$$

$$\Sigma = \frac{1}{f}\begin{pmatrix}0 & 0 & 0 & h & \eta & \sqrt{f^2 - h^2 - \eta^2}\end{pmatrix}$$



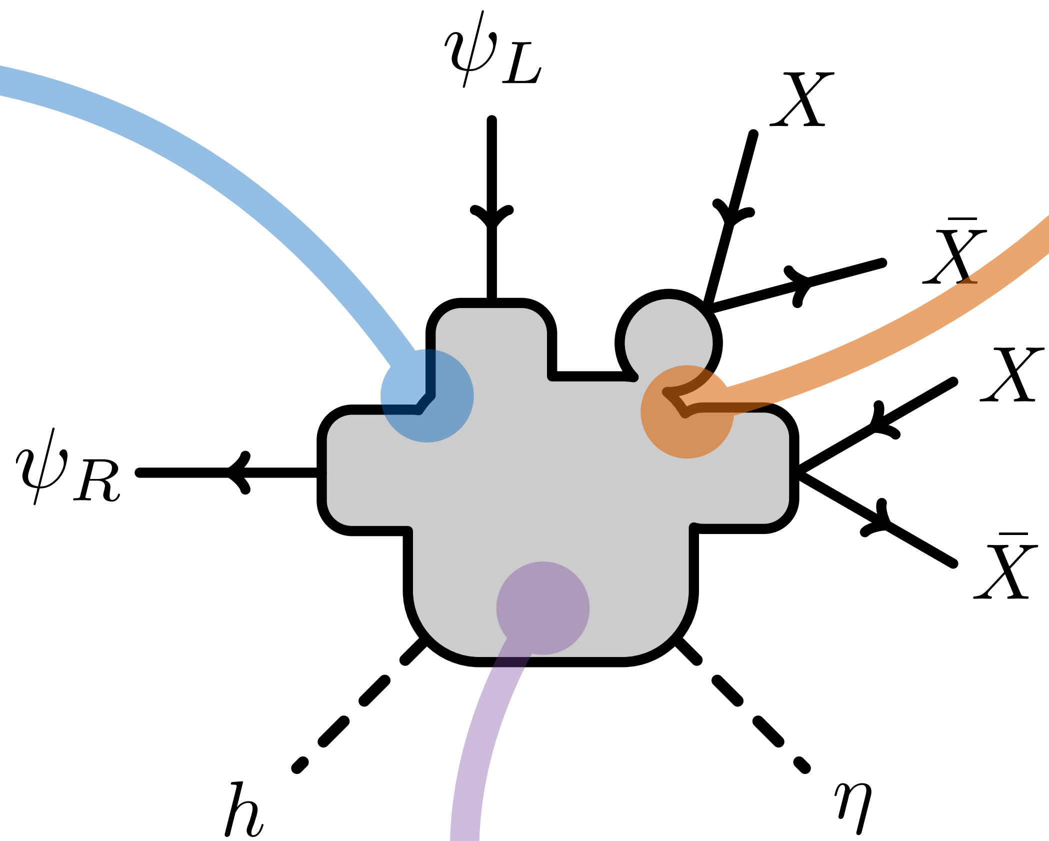


+ HIGGS COUPLINGS

What does this buy us?

visible matter embedding

CHOICES LEAD TO
- HIGGS POTENTIAL
- MEDIATOR POTENTIAL



dark matter embedding

CHOICES LEAD TO MEDIATOR POTENTIAL

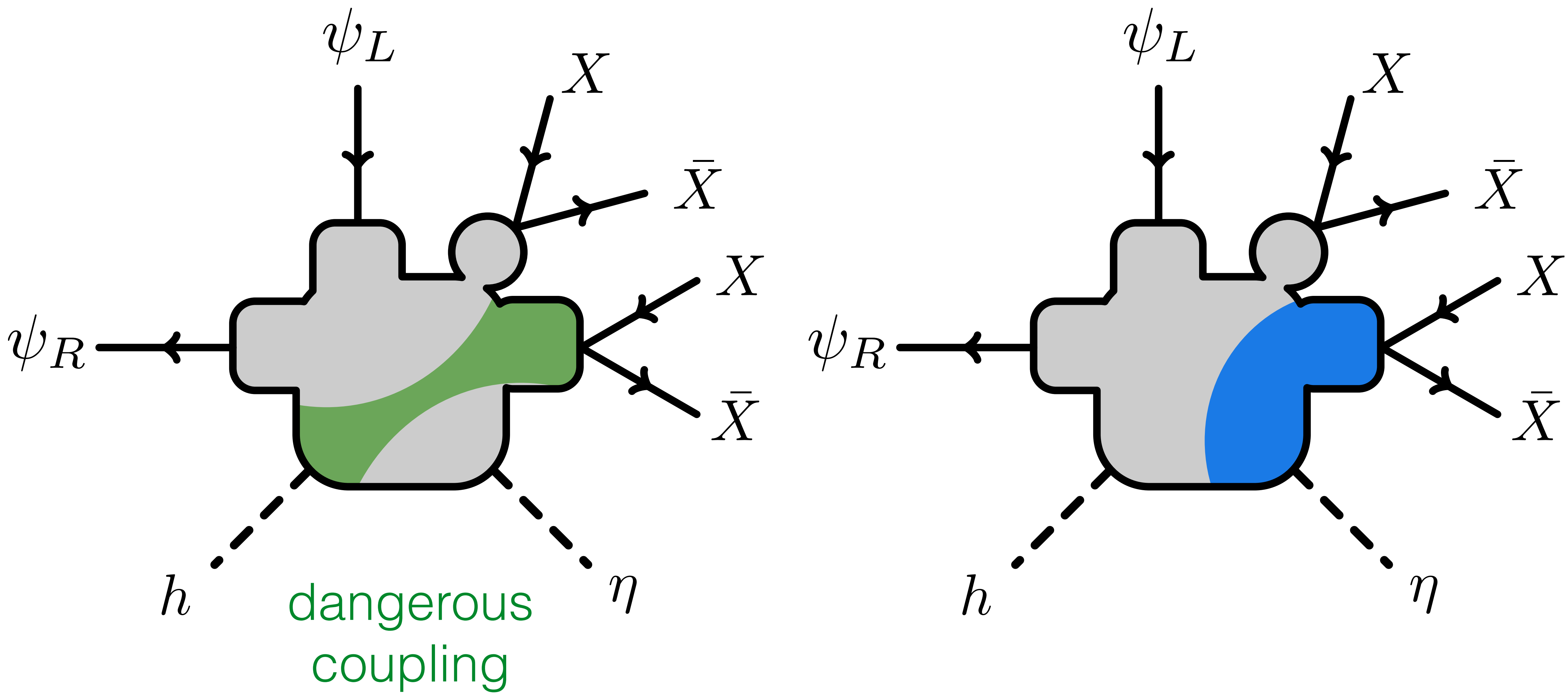
OUTPUTS:
MEDIATOR MASS AS A FUNCTION OF DISCRETE CHOICES AND DM MASS

COMPOSITE HIGGS
SPECIFY BREAKING SCALE *f*
GIVES MEASURE OF TUNING

$$\xi = \left(\frac{v}{f}\right)^2$$

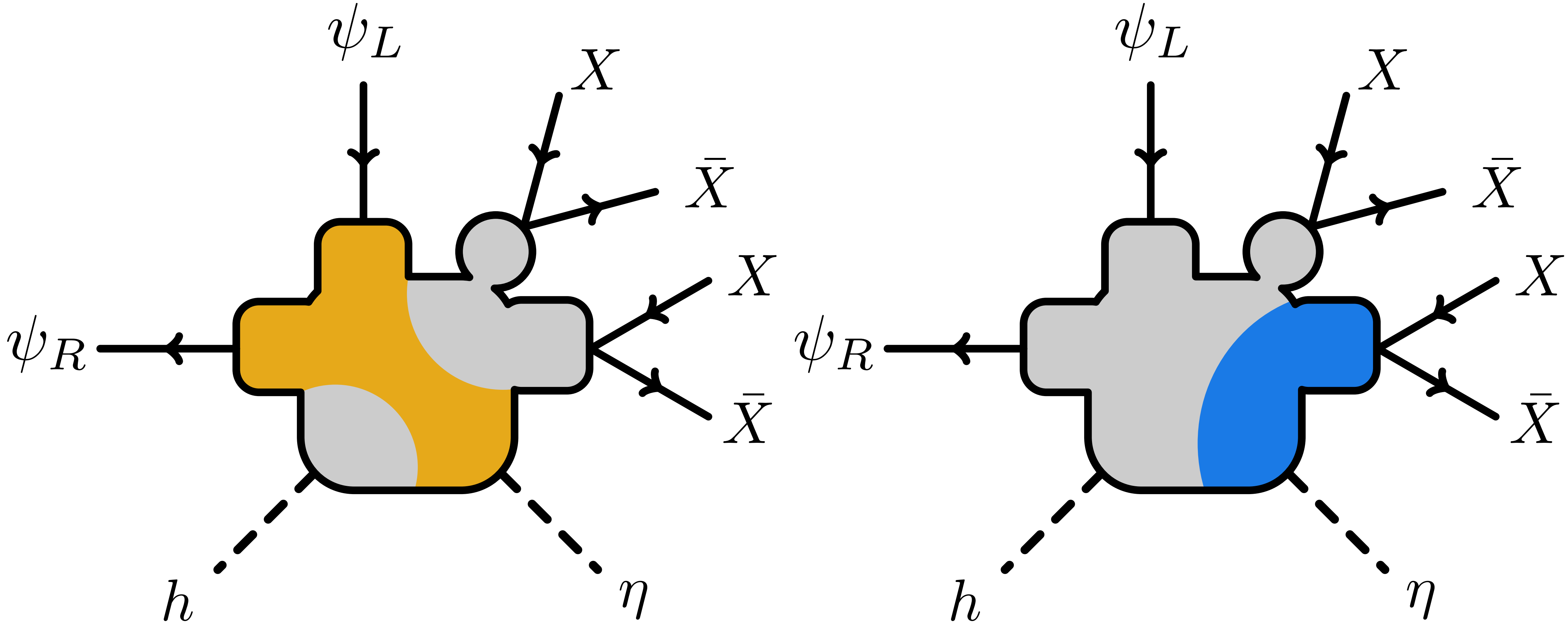
NLΣM IRREDUCIBLE INTERACTIONS

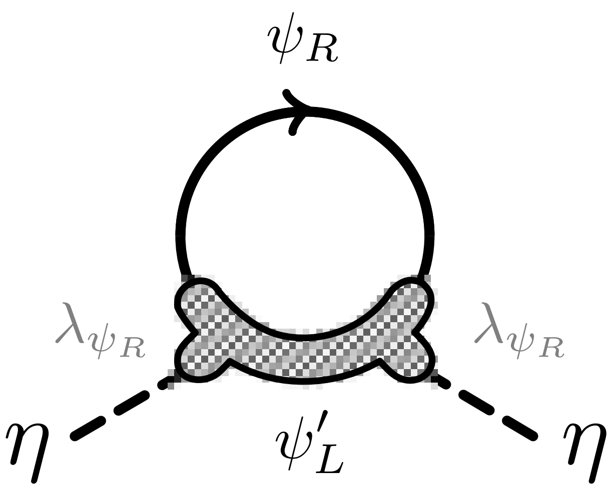
Dark Sector Couplings



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.

Mediator Mass

CHOOSE ONE NON-TRIVIAL REP

Standard Model	Approximate contribution to m_η^2 from fermion loops
$t_R\ (\mathcal{O}_\text{t})$	$(\delta_t^2-1)\frac{3y_t}{8\pi^2}\frac{m_*^3}{f} \approx (1\ \text{TeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_t^2-1)$
$b_R\ (\mathcal{O}_\text{b})$	$(\delta_b^2-1)\frac{3y_b}{8\pi^2}\frac{m_*^3}{f} \approx (130\ \text{GeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_b^2-1)$
$\tau_R\ (\mathcal{O}_\text{b})$	$(\delta_\tau^2-1)\frac{y_\tau}{8\pi^2}\frac{m_*^3}{f} \approx (60\ \text{GeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_\tau^2-1)$

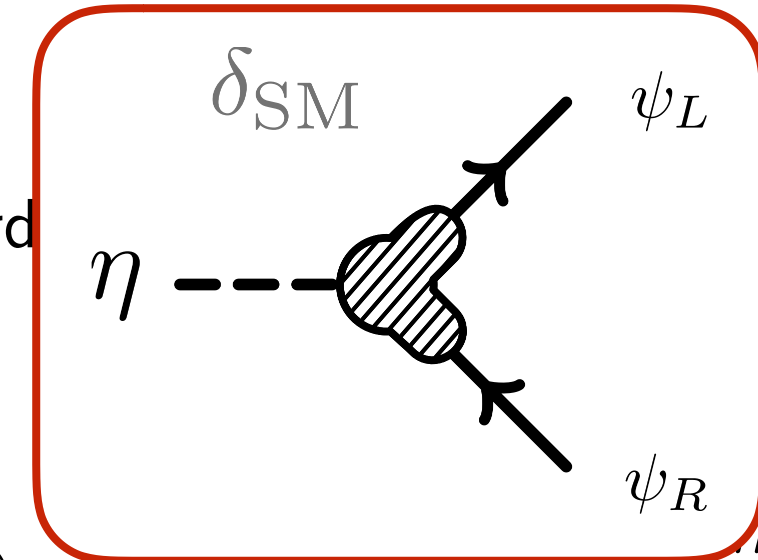
Dark Matter	Approximate contribution to m_η^2 from dark matter loops
Vector $(\mathcal{O}_\chi)$	$(1-\delta_\chi^2)\frac{y_\chi^2 m_*^2}{8\pi^2} \approx (70\ \text{GeV})^2 \left(\frac{m_*}{3\ \text{TeV}}\right)^2 \left(\frac{y_\chi}{0.2}\right)^2 (1-\delta_\chi^2)$
Singlet $(\mathcal{O}'_\chi)$	$\frac{m_\chi^{(\mathbf{1})} m_\chi^{(\mathbf{6})} m_*^2}{8\pi^2 f^2} \approx (10\ \text{GeV})^2 \left(\frac{m_*}{3\ \text{TeV}}\right)^2 \left(\frac{1\ \text{TeV}}{f}\right)^2 \left[\frac{m_\chi^{(\mathbf{1})} m_\chi^{(\mathbf{6})}}{(25\ \text{GeV})^2}\right]$

$\delta = 1$ corresponds to unbroken $U(1)_\eta$

Mediator Mass

$$\mathbb{X} = (0\,,\ 0\,,\ 0\,,\ 0\,,\ i\,\bar{\chi}_L \chi_R\,,\ \delta_\chi\,\bar{\chi}_L\chi_R)^T$$

$$T = (0\,,\ 0\,,\ 0\,,\ 0\,,\ i\delta_t t_R\,,\ t_R)$$



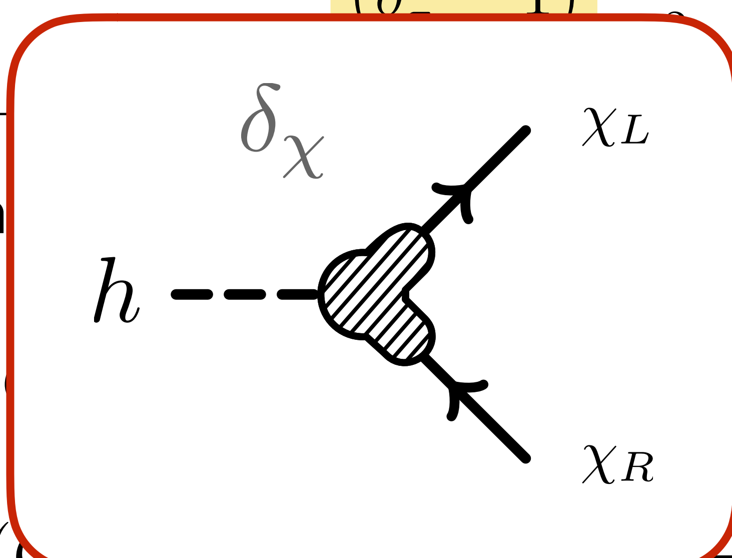
NON-TRIVIAL REP

Standard ... contribution to m_η^2 from fermion loops

$t_R\ (\mathcal{O}_t)$ ... $\frac{m_*^3}{f} \approx (1\ \text{TeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_t^2 - 1)$

$b_R\ (\mathcal{O}_b)$ $(\delta_b^2 - 1)\frac{\ }{8\pi^2}\frac{m_*^3}{f} \approx (130\ \text{GeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_b^2 - 1)$

$\tau_R\ (\mathcal{O}_b)$ $(\delta_\tau^2 - 1)\frac{y_\tau}{\ }\frac{m_*^3}{f} \approx (60\ \text{GeV})^2 \left(\frac{m_*}{3\,\text{TeV}}\right)^3 \left(\frac{\text{TeV}}{f}\right)(\delta_\tau^2 - 1)$



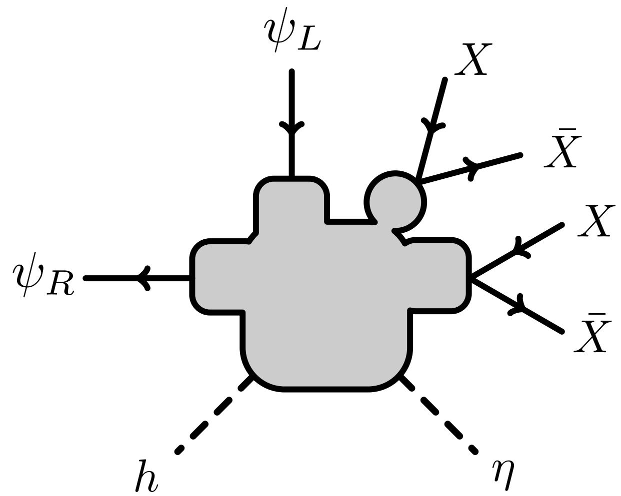
Dark Ma... contribution to m_η^2 from dark matter loops

Vector (... $\frac{m_*^2}{\ }\approx (70\ \text{GeV})^2 \left(\frac{m_*}{3\ \text{TeV}}\right)^2 \left(\frac{y_\chi}{0.2}\right)^2 (1 - \delta_\chi^2)$

Singlet ($\mathcal{O}_\chi$) ... $\frac{m_*^2}{8\pi^2 f^2} \approx (10\ \text{GeV})^2 \left(\frac{m_*}{3\ \text{TeV}}\right)^2 \left(\frac{1\ \text{TeV}}{f}\right)^2 \left[\frac{m_\chi^{(1)} m_\chi^{(6)}}{(25\ \text{GeV})^2}\right]$

$\delta = 1$ corresponds to unbroken $U(1)_\eta$

Punchline

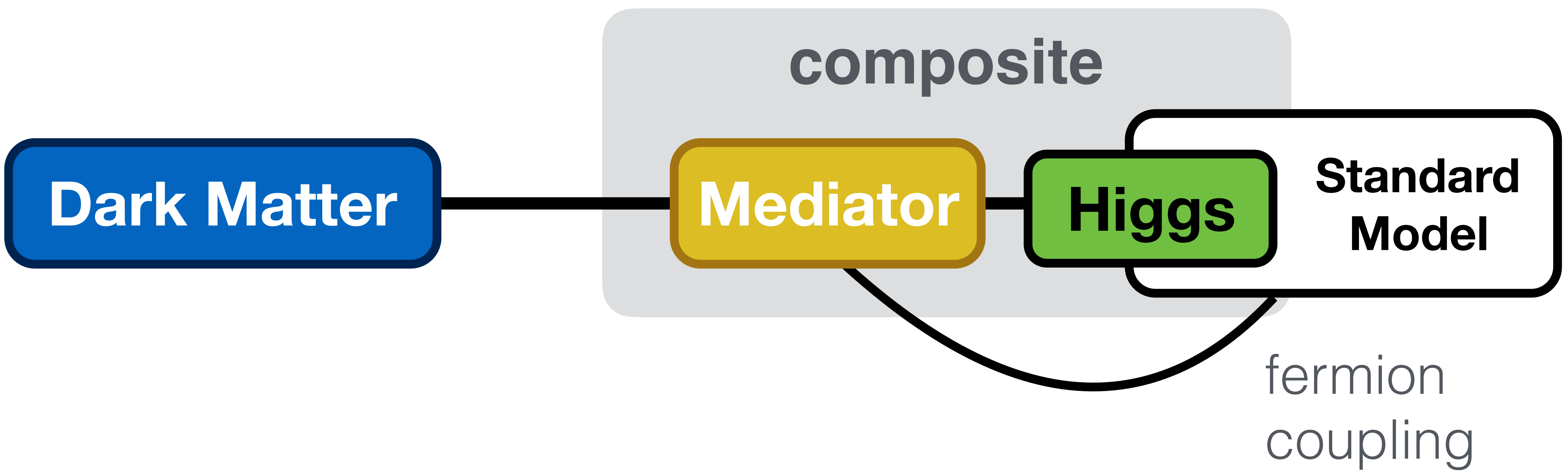


New completion of pseudoscalar mediator

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

Small number of parameters + discrete choices

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



EXTRA **SLIDES**

Pseudoscalar Mediators

assume
Dirac X

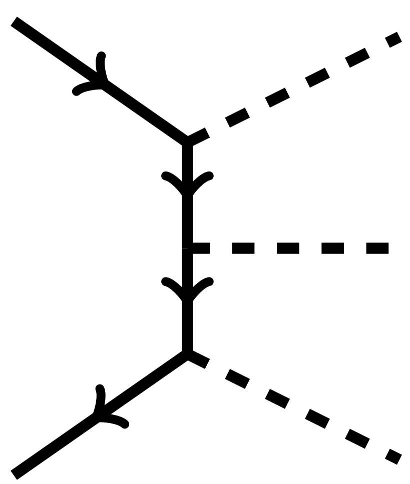
$$(\bar{X}\, i\gamma^5 X)\ (\bar{q}\, i\gamma^5 q)$$

see, e.g.
Kumar & Marfatia 1305.1611

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

suppressed
direct detection

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



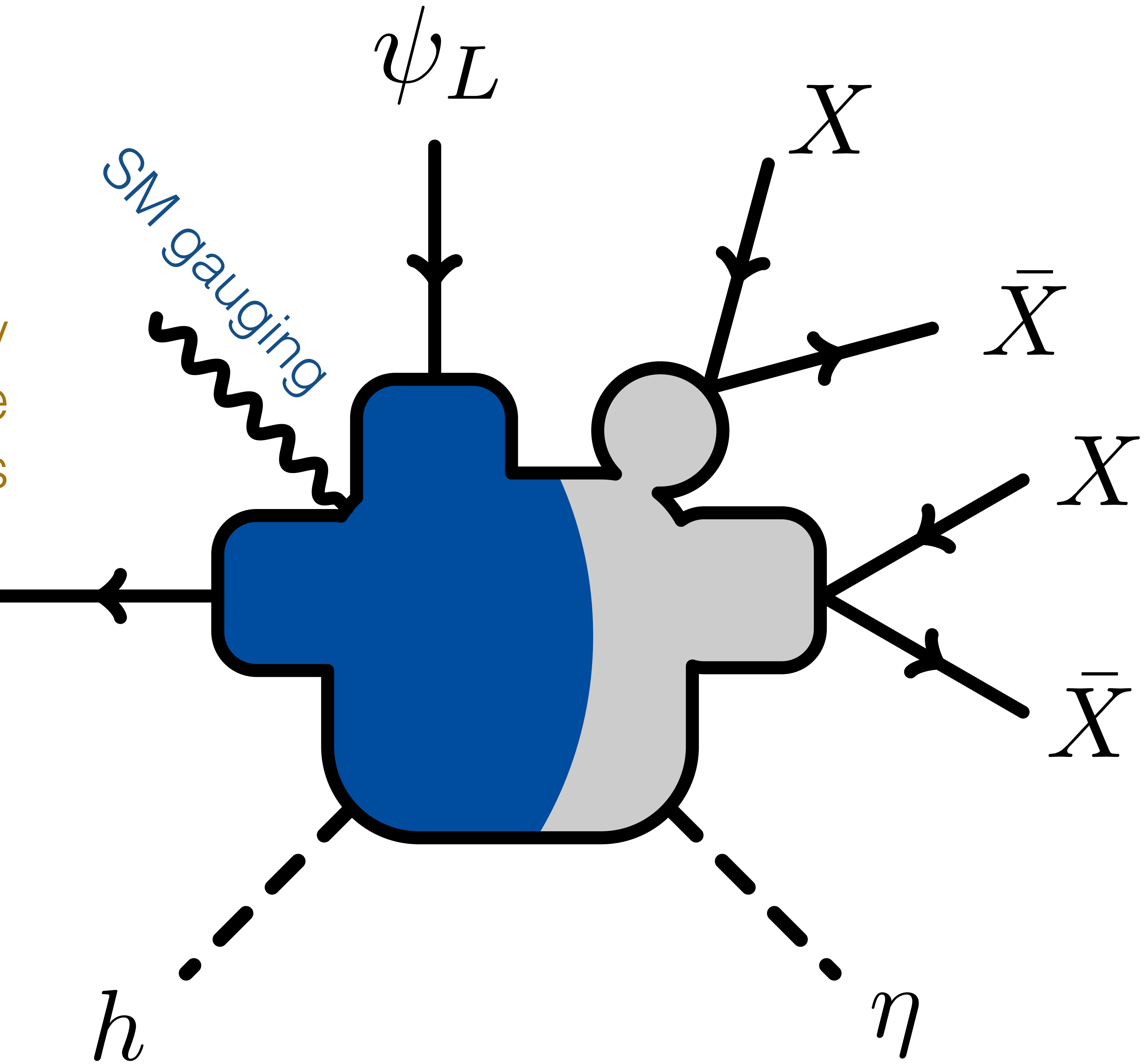
s-wave annihilation in s-channel or to three on-shell pseudoscalars

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

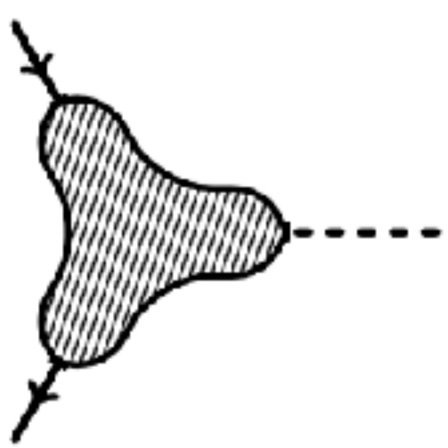
SO(5)/SO(4) & the Standard Model

described by usual minimal composite Higgs

partially
composite
SM fermions



“5D flavor”



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