

# *Composite Higgs, Quarks and Leptons, a contemporary view*

Symposium on Fundamental Physics in Memory of Sidney Drell

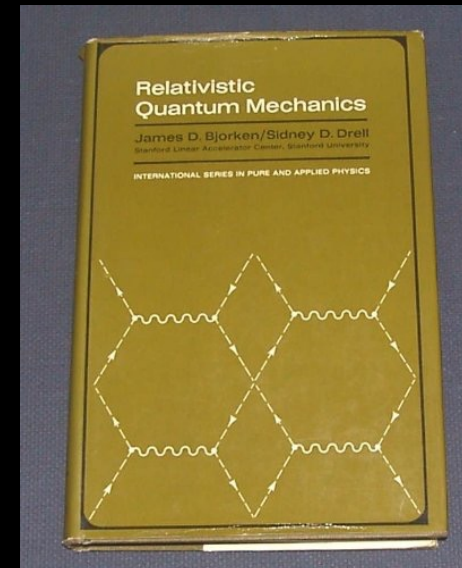
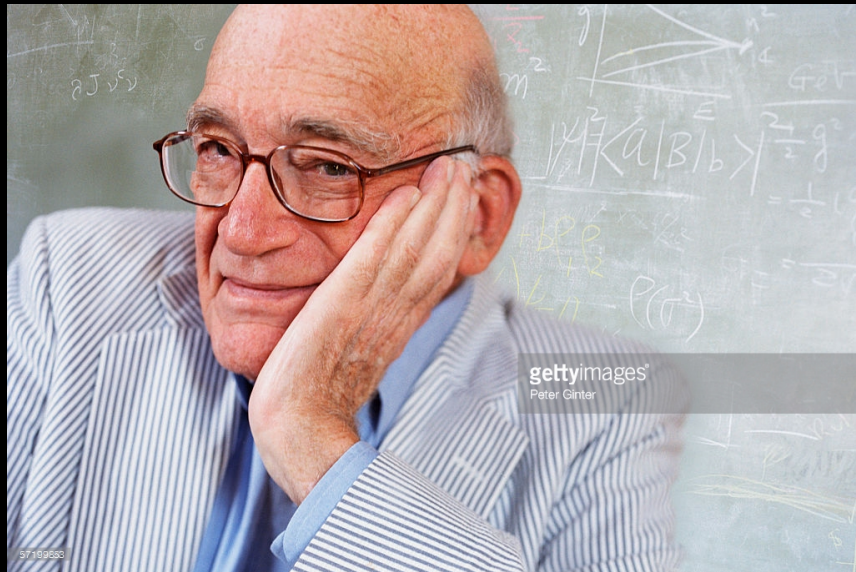
Jan 12, 2018

Ann Nelson

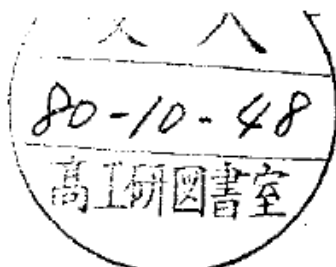
arXiv:0312287,0504252

+recent not yet published work with Michael Park and Devin Walker

# Thanks to Sid Drell



- Always be positive, curious, constructive
- A  
others will think your questions are 'dumb'



SLAC-PUB-2534  
June 1980  
(T/E)

- 2 -

## I. INTRODUCTION

Quarks and leptons are presently viewed as point-like constituents of matter. Direct tests of quantum electrodynamics in high energy electron-positron collisions at center of mass energies up to 32 GeV have confirmed the absence of lepton structure in processes probing distances as small as  $2 \times 10^{-16}$  cm.<sup>1</sup> The behavior of large momentum transfer lepton-hadron interactions is also consistent with the interpretation that point-like quark constituents, as analyzed in perturbative quantum chromodynamics, are the local carriers of the weak and electromagnetic currents within hadrons. However, as the number of generations of quarks and leptons grow, and as the mass ratios between the different generations increases to very large values:  $m_t/m_e \sim 3600$ , the postulate that the quarks and leptons themselves may be composites of a smaller number of more fundamental units becomes theoretically more appealing.<sup>2</sup> Indeed, it would be very attractive on fundamental theoretical grounds to unify quarks with leptons in terms of a small number of common constituents.

In this paper we will be concerned with experimental constraints on lepton and quark substructure which we will express in terms of a general formalism for describing composite particles. The higher energy accelerators and storage rings now being built or planned will permit experiments which can probe for evidence of structure at momentum transfers up to  $\sim 10^3$  GeV, corresponding to a resolution scale of  $\sim 10^{-17}$  cm. However, as we shall show here, the very (almost incredibly) precise measurements of the electron and muon gyromagnetic ratios,  $g_e$  and  $g_\mu$ , put exceedingly restrictive limits on the possibility of lepton internal structure. The critical point is that the lepton  $g$  values are very close to the Dirac value of 2 --

## THE ANOMALOUS MAGNETIC MOMENT AND LIMITS ON FERMION SUBSTRUCTURE\*

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### ABSTRACT

Experimental constraints on possible lepton and quark substructure are analyzed and expressed in terms of a general formalism for describing composite particles in terms of their constituents. In particular, the measured gyromagnetic ratios may very severely restrict possible internal structure of light leptons (electrons and muons) in some models. Simple expressions for hadronic  $g$ -values and electromagnetic radii are given in terms of their quark-gluon infinite momentum frame wave function. The contribution to the anomalous moment of a fermion due to internal structure is shown to vanish as the mass or inverse size scale of the internal state becomes infinitely large.

(Submitted to Physical Review D)

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\*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

# Brodsky-Drell

- anomalous magnetic moments of the electron and muon put very strong limits on lepton compositeness scale  $f$ ! Stronger than colliders
- $a_\mu$   
scale needed), or (m  
model")



SLAC-PUB-2920  
May 1982  
(T)

-2-

## I. INTRODUCTION

This paper examines the realization of chiral symmetry in lattice gauge theories at strong coupling. Our purpose is to explore for possible realizations of unbroken chiral symmetry with massless composite fermions particularly in examples in which the 't Hooft anomaly conditions<sup>1</sup> can be satisfied. It is generally believed that such models may allow construction of composite fermions which are candidates for leptons and quarks. In particular such particles must have the property that their masses are very small compared to their inverse radii, and a massless composite is supposed to be a good starting point for such an object. Unfortunately we find a general result that the effective strong coupling theory is antiferromagnetic in character, choosing to realize the chiral symmetry in the Nambu-Goldstone fashion with massless bosons, which are spin-wave-like excitations, and all fermions massive. This result is independent of the gauge group and representation content of the theory.

This work is an extension of, and follows directly, an earlier study,<sup>2</sup> henceforth referred to as SDQW, which performed a variational block spin calculation for strong coupling lattice gauge theories of both the QCD and the Abelian types. Using the long-range SLAC gradient to preserve chiral symmetry and avoid spectrum doubling in the lattice Hamiltonian, SDQW found in these cases that the chiral symmetry of the theory was realized in the Nambu-Goldstone fashion. In the present paper we extend these results to Hamiltonians with any gauge groups and with the fermions in more than one representation of the gauge group. We also consider purely left-handed fermions, in which cases we find spontaneous breaking of the lattice rotational symmetry as well as of the chiral symmetry.

## COMPOSITE MODELS OF QUARKS AND LEPTONS AND STRONG COUPLING LATTICE GAUGE THEORIES\*

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### ABSTRACT

We extend a previous variational block spin analysis of the realization of chiral symmetry in a strong coupling lattice gauge theory to models which have been suggested as possibly describing massless composite fermions. In all cases we find massive fermion composites and spontaneous breaking of chiral symmetry. We also discuss the relevance of this result to the continuum limit.

Submitted to Physical Review D

\* Work supported by the Department of Energy, contract DE-AC03-76SF00515.



Also: Wilson, 1970; Weinberg 1975; Susskind 1979

# NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

Cargese, 1979

G. 't Hooft

theories: the effective interactions at a large length scale, corresponding to a low energy scale  $\mu_1$ , should follow from the properties at a much smaller length scale, or higher energy scale  $\mu_2$ , without the requirement that various different parameters at the energy scale  $\mu_2$  match with an accuracy of the order of  $\mu_1/\mu_2$ . That would be unnatural. On the other hand, if at the energy scale  $\mu_2$  some parameters would be very small, say

$$\alpha(\mu_2) = \mathcal{O}(\mu_1/\mu_2) , \quad (\text{III1})$$

then this may still be natural, provided that this property would not be spoilt by any higher order effects. We now conjecture that the following dogma should be followed:

- at any energy scale  $\mu$ , a physical parameter or set of physical parameters  $\alpha_i(\mu)$  is allowed to be very small only if the replacement  $\alpha_i(\mu) = 0$  would increase the symmetry of the system. -

In what follows this is what we mean by naturalness. It is clearly a weaker requirement than that of P. Dirac<sup>1)</sup> who insists on having no small numbers at all. It is what one expects if at any mass scale  $\mu > \mu_0$  some ununderstood theory with strong interactions determines a spectrum of particles with various good or bad

# *Model building/Theory*

- Can we even find plausible theories with strong dynamics that produce fermions which are much lighter than compositeness scale?
- theory must not spontaneously break some chiral global symmetry
- model which gives right quantum numbers

# Motivation: The gauge hierarchy problem

- Weak scale: W, Z masses from Higgs condensate  $\langle 0|H|0\rangle = 175\text{GeV}$
- what should this number be? guess would be of order some more fundamental scale

- One guess  $m_P \equiv \sqrt{\frac{1}{G_N}} = 1.2 \times 10^{19}\text{GeV}$

$$V(H) = \lambda |H|^4 - m^2 |H|^2$$

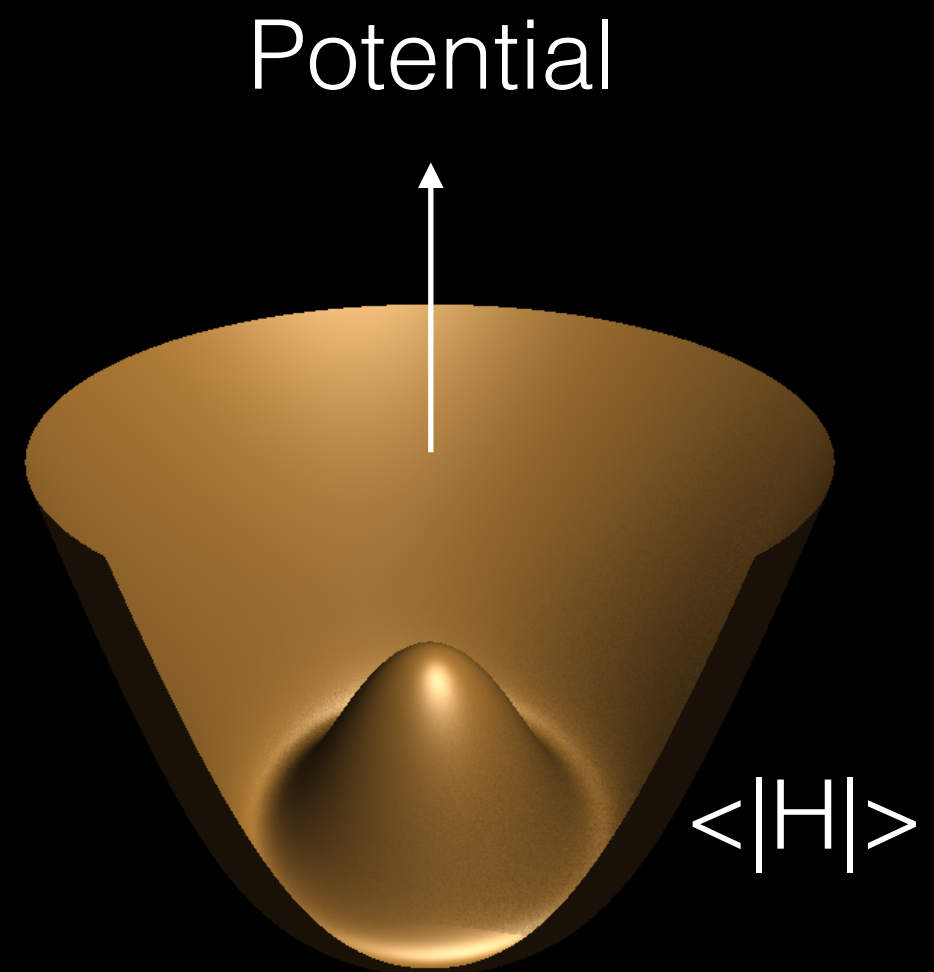
$$m^2 \sim 10^{-34} m_P^2$$



# Can we *calculate* the Higgs potential?

(Albeit in terms of other parameters, which then may in turn be computed ... in still more fundamental theory... either TOE or “turtles all the way down”)

- SM: Two terms
  - quartic
  - quadratic
- Compute from more fundamental theory?
  - supersymmetry
  - strong dynamics
  - new dimensions





40 years of theorists at play. no real theory of composite quarks and leptons but lots of activity

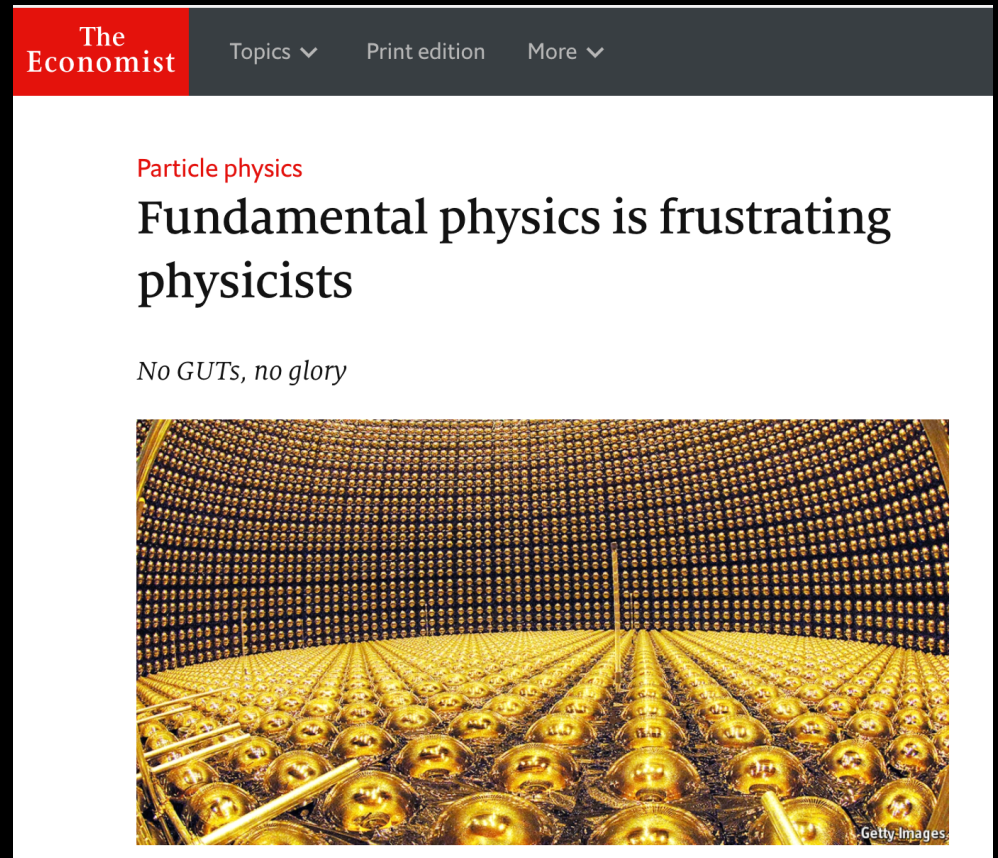




- SM-like Higgs and nothing else so far!  
“Natural” theories becoming less natural/more tuned.



# Crisis?



“With every fudge ... what were once elegant theories get less so. Some researchers are therefore becoming open to the possibility that the truth-is-beauty argument is a trap, and that the universe is, in fact, fundamentally messy.

# *"Modern" theories of compositeness to the rescue?*

- composite Higgs theories revived by new ingredients ("new" =  $\leq 20$  years old)
  - warped extra dimensions (Randall-Sundrum)
  - ADS/CFT
  - PNgB Higgs
  - collective symmetry breaking
- revival of Kaplan's partial compositeness=RS with SM fermions in bulk

# Composite Higgs

*(Georgi and Kaplan, 1983)*

$$\Pi_{ultra} = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\Pi_0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \Pi^+ & H^+ \\ \Pi^- & -\frac{\Pi_0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & H^0 \\ H^- & H^{0*} & \frac{-2}{\sqrt{6}}\eta \end{pmatrix}$$

- low energy description of “ultracolor”  $SU(3) \times SU(3) / SU(3)$  pseudo-Nambu-Goldstone bosons (pNGB)
- Higgs as kaon-like pNGB
- electroweak symmetry breaking = “vacuum misalignment”



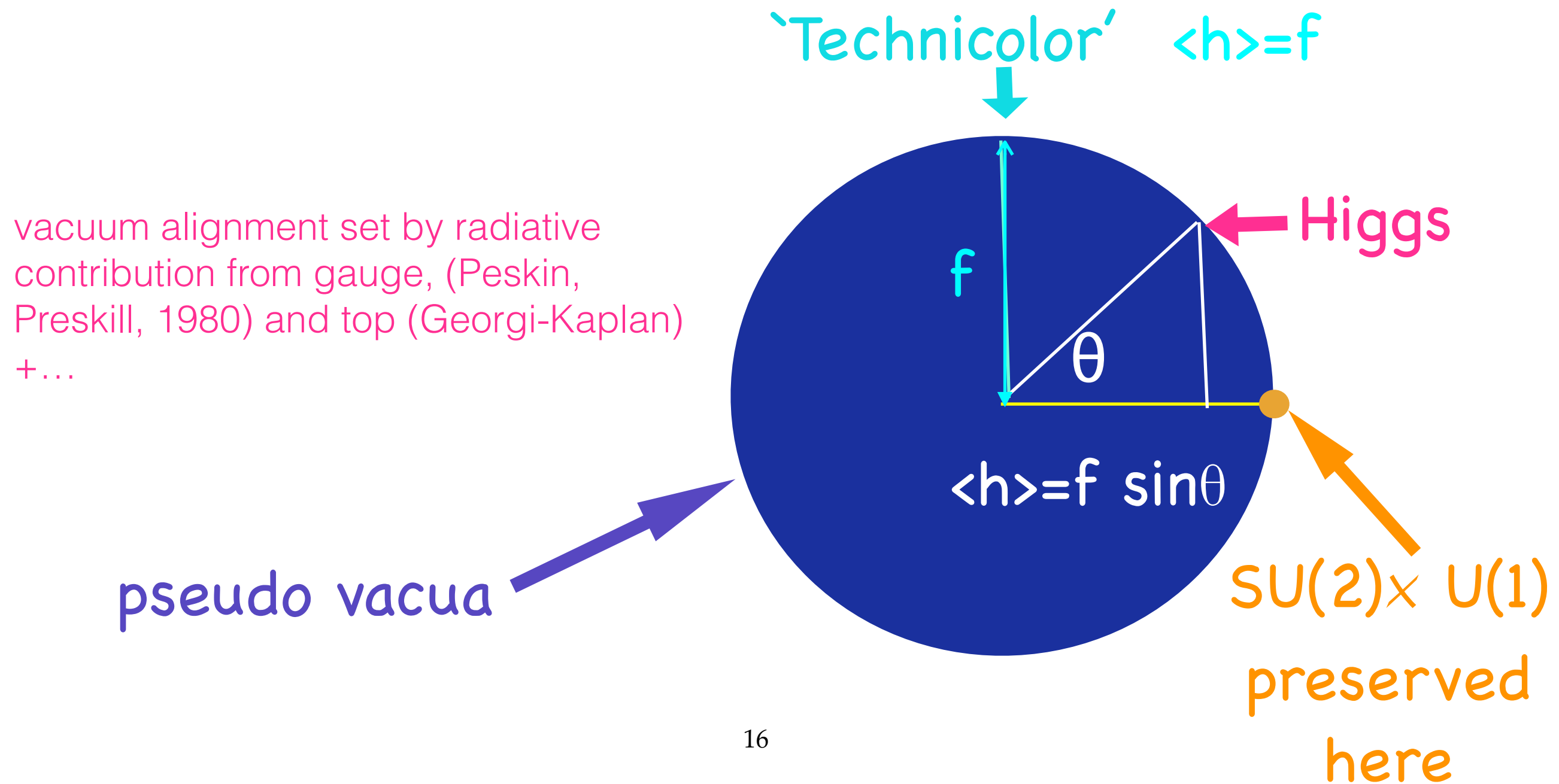
# Weakly coupled description of strong dynamics

$$\mathcal{L}_{QCD} = -\frac{f^2}{4} \text{Tr} D^\mu \Sigma D_\mu \Sigma, \quad \Sigma = e^{\frac{2i\pi_a t_a}{f_\pi}} + \dots$$

- pions, kaons, eta are described via weakly coupled effective theory below  $\sim 4\pi f_\pi$

# Composite Higgs: interpolates between Technicolor and minimal standard model

Georgi Kaplan



# *Problem with composite Higgs*

- In 1983, top mass was unknown
- theory expectation “rule of 3”—top mass around 13 GeV
- small Yukawa = small breaking of nonlinearly realized symmetry
- Georgi-Kaplan could assume top contribution to potential is small

# Shocker

- 1996:  $m_{\text{top}}$  174 GeV,  $\lambda_{\text{top}}=1$
- top contribution dominates gauge correction to Higgs potential by factor of

$$\frac{\frac{3}{8\pi^2} \lambda_t^2}{\frac{3}{64\pi^2} (3g^2 + g'^2)} \approx 7$$

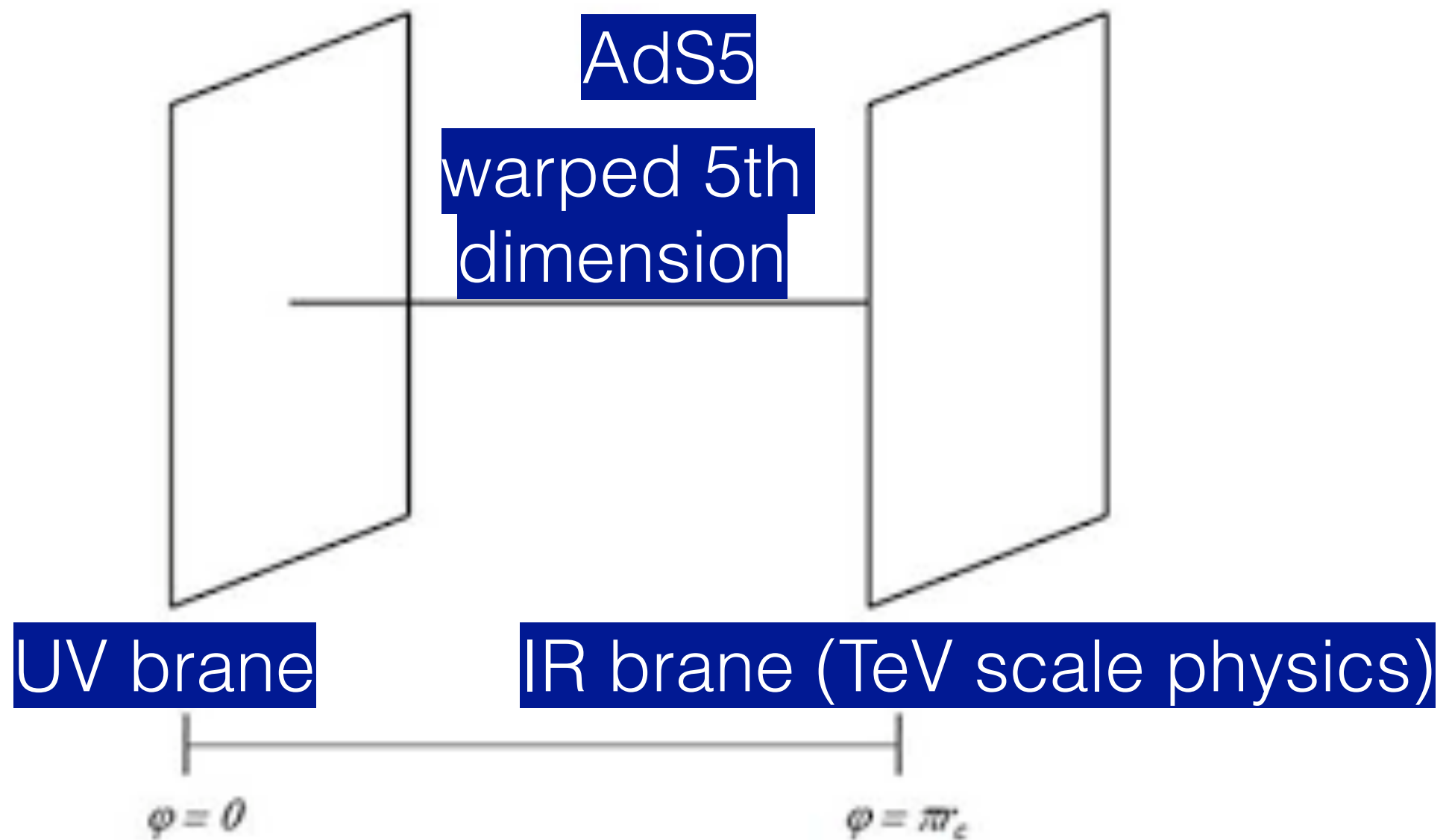
# *Composite Higgs revived by more dimensions*

- Deconstruction: latticized 5th dimension allows 'little' Higgs
- strongly coupled CFT in 4d theory in 5d AdS
- Composite Higgs

(Witten 1999 comment at KITP conference, Arkani-Hamed, Porrati, Randall; Perez-Victoria; Rattazzi & Zaffaroni 2001)

- Contino, Nomura, Pomarol 2003; Agashe, Contino, Pomarol 2004-Minimal, Viable, composite Higgs model

# Randall Sundrum





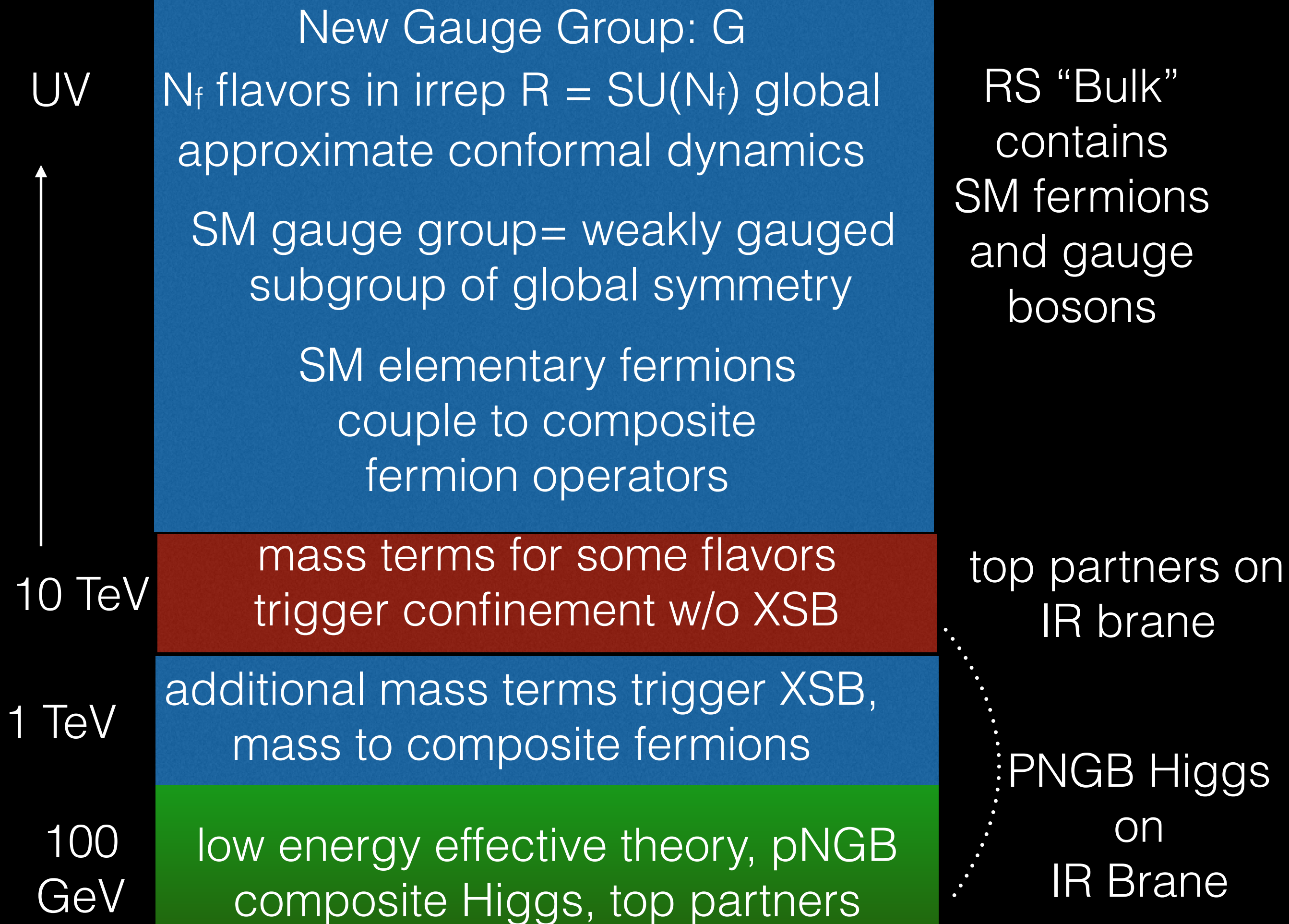
# *partial fermion compositeness*

(D.B. Kaplan, 1991)

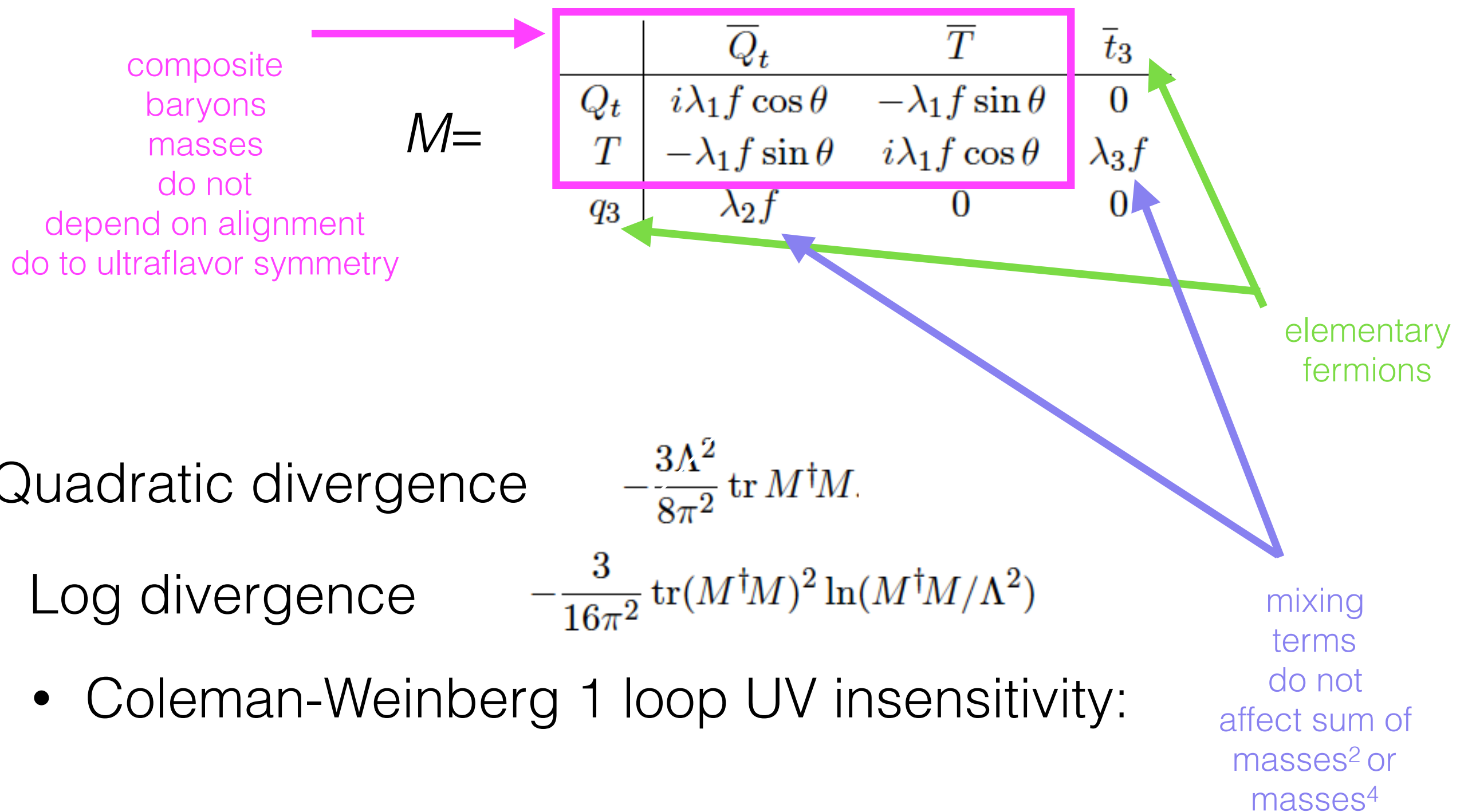
- strongly coupled theory with fermions (“ultrabaryons”), some with same quantum numbers as quarks and leptons
  - Such models are relatively easy to build
- elementary quarks and leptons mix with ultrabaryons.
- composite higgs=ultrameson has coupling to quarks and leptons via this mixing
- observed quarks and leptons are mix of elementary and composite
- dual to Randall-Sundrum “fermions in the bulk”

# *“little” Higgs and top partial compositeness*

- “little Higgs” Higgs is PNCB
- NCBs only have derivative couplings
- non derivative couplings arise via “collective symmetry breaking” (conspiracy of more than 1 coupling to break all symmetries protecting Higgs potential)
- partial top compositeness can easily realize this for top coupling
- top has “partners”—heavy fermions that partially cancel the top coupling contribution to the Higgs potential. These are “ultra-baryons”



# Higgs potential from top Yukawa



$$\frac{\partial}{\partial \theta} \text{Tr } M^\dagger M = 0$$

$$\frac{\partial}{\partial \theta} \text{Tr}(M^\dagger M)^2 = 0$$

# Muon g-2?

- actually few theorists consider possibility of partially composite muon. If muon Yukawa coupling to composite Higgs is due to partial compositeness:  $\phi$ =mixing angle of muon with ultra baryon (assume same for left and right)

$$\frac{m_\mu}{v} \sim 4\pi\phi^2 \qquad a_\mu \sim \phi^2 \left( \frac{m_\mu v}{f^2} \right) \sim \left( \frac{m_\mu^2}{4\pi f^2} \right)$$

$$a_\mu \sim 500 \times 10^{-11} \rightarrow f > 400 \text{ GeV}$$

ultra baryons mixing with muon

$$a_\mu \sim 14 \times 10^{-11} \rightarrow f > 2.5 \text{ TeV}$$

$$m \sim 4\pi f$$

*The Composite Higgs with partially composite fermions is the currently the ideal model for the LHC, given the Higgs discovery (and nothing beyond the SM)*

- looks nearly standard at weak scale
- can be tuned to look standard at any energy
- flexible at accomodating anomalies
- allows for deviations from standard model in Higgs couplings
- provides employment for everyone
  - effective field theory
  - ads/cft
- strong dynamics, lattice gauge theory
- diverse collider signatures, g



"Science knows no boundaries, and efforts to create barriers - whether to keep new ideas within or to prevent new ones from entering from the outside - have universally proved harmful to progress."

Sid Drell, Address at the National Academy of Science, 1988

*Backup*

# Many Possible pNGB Higgs models with top partners

e.g.

- $SU(5)/SO(5)$
  - $SU(6)/Sp(6)$
  - $SU(4)/Sp(4)$  additional scalar
  - $SO(5)/SO(4)$
- room to extend SM gauge
- easy to get from strong 'QCD-like' dynamics with  $SO(N)$  or  $Sp(N)$  gauge groups
- Minimal scalar sector (nothing beyond Higgs, requires more fine-tuning)

# Randall-Sundrum/CFT Dictionary

- “ADS slice” ~ strong dynamics which is nearly conformal for a range of energies (Banks-Zaks fixed point?)
- “IR brane” ~ spontaneous breaking of conformal invariance triggered by relevant operator (fermion mass term?)
- bulk fermions ~ perturbative coupling between elementary fermions and operator containing strongly coupled fields (composite/elementary mixing “Partial Compositeness”)
- bulk gauge fields ~ global symmetry of strong dynamics —break on UV brane to desired gauge group—should contain  $SU(3) \times SU(2) \times U(1)$

# SUSY

- year after year, a heart breaker!
- Still hope for RPV/Effective SUSY/Stealth SUSY/Dirac gaugino/supersoft/supersafe/(generalized)

# QCD-like dynamics and Composite Higgs

- $SU(5)/SO(5)$  “littlest” Higgs (Arkani-Hamed, Cohen, Katz A.N. 2002)
- Composite  $SU(5)/SO(5)$  Little Higgs (Katz, Lee, A.N., Walker 2003)
- $SU(4)/Sp(4)$ ,  $SU(5)/SO(5)$ ,  $SU(6)/Sp(6)$  “Intermediate Higgs” (Katz, A.N., Walker 2005)



# Little Higgs

*N. Arkani-Hamed, A.G. Cohen, H. Georgi;*

*N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E.N.*

- Collective symmetry breaking: allows suppression of UV sensitive corrections to PNCB potential
- In Little Higgs, quartic term in potential arose from UV sensitive terms, all quadratic terms UV insensitive, proportional to masses of top, gauge, Higgs 'partners'
- $v/f$  constrained to be fine tuned by  $Z'$ ,  $W'$  searches
  - Exception: T-parity models
- Complete Composite Little Higgs Model:  
*Katz, A.E.N.*

# SU(4)/Sp(4) nonlinear sigma model

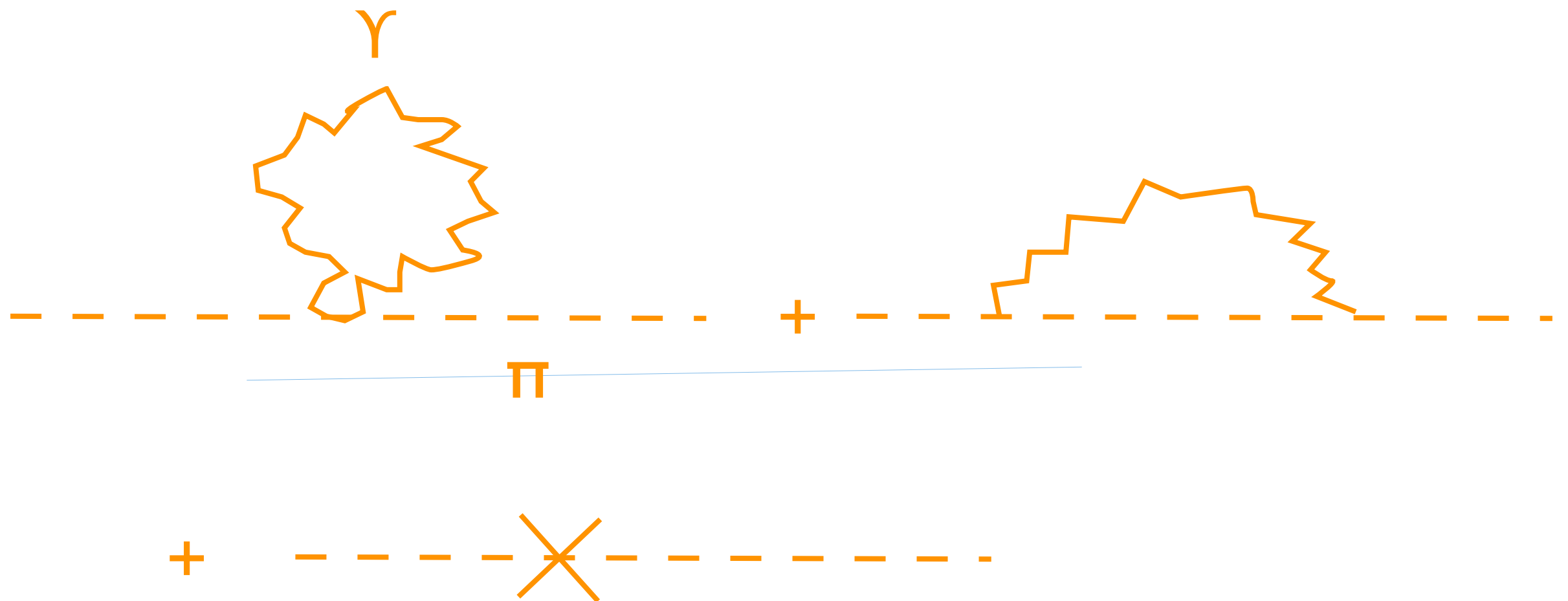
$$\Sigma \rightarrow V \Sigma V^T \quad V \text{ is an } SU(4) \text{ matrix}$$

$$\Sigma(x) = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f} \quad \Sigma_0 = \begin{pmatrix} i\sigma_2 & \\ & i\sigma_2 \end{pmatrix} \quad \Sigma = \begin{pmatrix} 0 & c & 0 & is \\ -c & 0 & -is & 0 \\ 0 & is & 0 & c \\ -is & 0 & -c & 0 \end{pmatrix}$$

$$\Pi = \frac{1}{2\sqrt{2}} \begin{pmatrix} A & H \\ H^\dagger & -A \end{pmatrix} \quad A = \begin{pmatrix} a & \\ & a \end{pmatrix} \quad H = \begin{pmatrix} h^0 + ih_3 & ih_1 + h_2 \\ ih_1 - h_2 & h^0 - ih_3 \end{pmatrix}$$

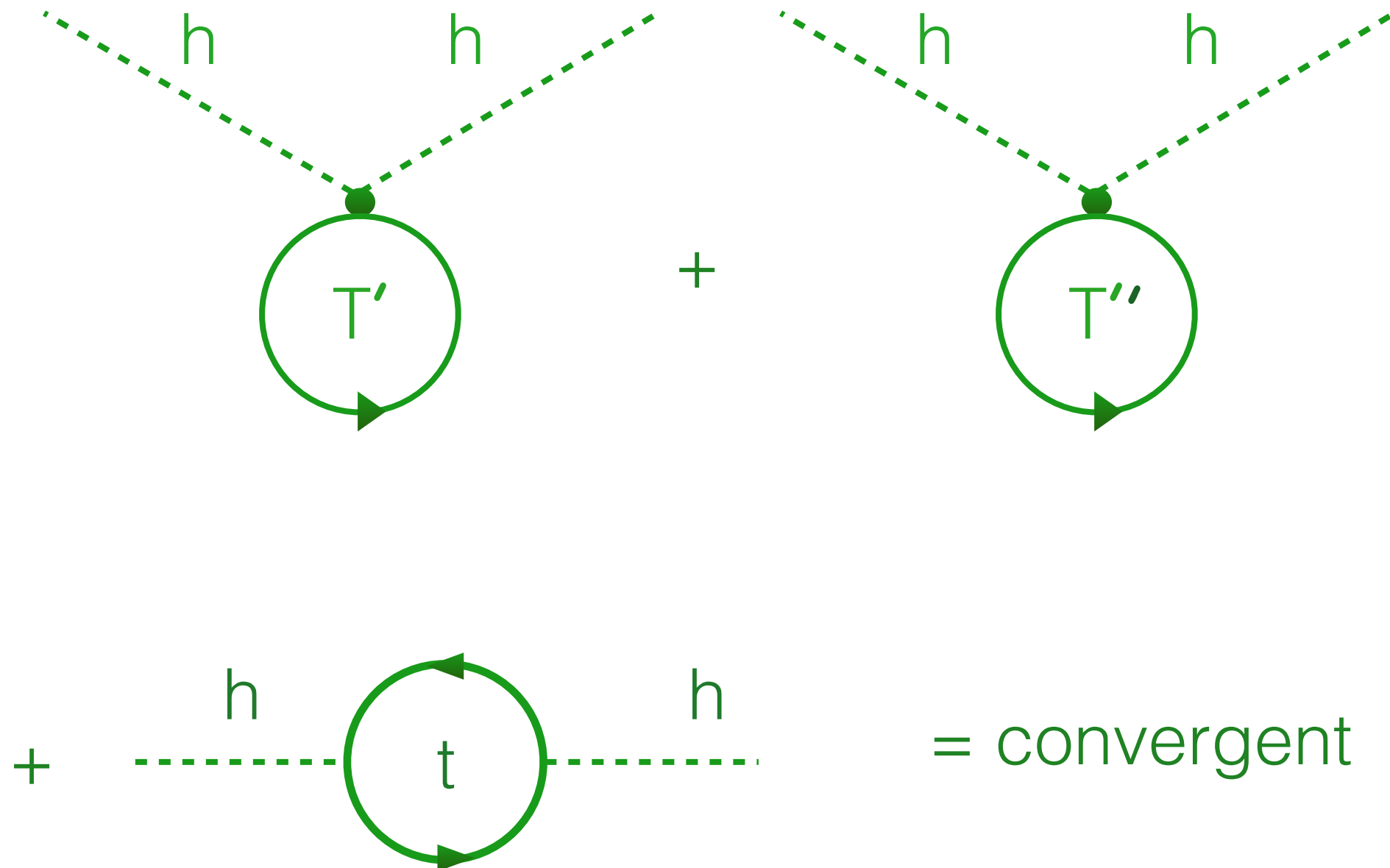
$$\theta = \langle h_0 \rangle / \sqrt{2}f \quad c = \cos \theta \text{ and } s = \sin \theta.$$

# Low energy pion dynamics and naturalness of Higgs potential



$$m_{\pi^+}^2 - m_{\pi^0}^2 \sim \frac{e^2}{16\pi^2} \Lambda^2, \quad \Lambda \sim GeV$$

# Key feature of top partners



# SM-like Higgs

- requires small(-ish) misalignment ( $\langle H \rangle \sim f/2$ )
- Vacuum alignment ingredients in QCD-like theory
  - gauge bosons want to be light
  - fermions want to be heavy
  - UV-sensitive parameters in effective theory (analogs of  $\pi^+ \pi^0$  mass splitting in QCD, etc)

# Approximate Global symmetries in strongly coupled conformal gauge theories

- $SU(N)$ :  $N$  copies of some massless representation
- $U(1)$ : get a  $U(1)$  for each type of irrep, anomaly removes one combination
- $SO(N)$ ,  $SP(N)$ : more complicated to understand—require fixed point including non-gauge interactions

# QCD-like dynamics and Composite Higgs with possible custodial SU(2)

- $SU(4)/SP(4)$  ( Kaplan, Georgi, Dimopoulos 1983)
- $SU(5)/SO(5)$  ( Kaplan, Georgi, 1984)
- $SU(5)/SO(5)$  “littlest” Higgs (Arkani-Hamed, Cohen, Katz A.N. 2002)
- Composite  $SU(5)/SO(5)$  Little Higgs ( Katz, Lee, A.N., Walker 2003)
  - **composite top partners match ‘tHooft anomaly conditions, couple weakly to condensate due to approximate symmetry**
- $SU(4)/Sp(4)$ ,  $SU(5)/SO(5)$ ,  $SU(6)/Sp(6)$  “Intermediate Higgs” (Katz, A.N., Walker 2005)

# Phases of gauge theories

- Trivial ( $\beta > 0$ , too many flavors)
- Conformal ( $\beta = 0$ , large matter index (Banks-Zaks))
- “free magnetic” ( $\beta < 0$ , some susy theories, Seiberg)
- confining, no XSB ( $\beta < 0$ , ‘tHooft anomaly matching, known for some susy theories, conjectured for some nonsusy. Are scalars necessary?)
- confining, XSB ( $\beta < 0$ , QCD-like)



# Many Possible pNGB Higgs models

e.g.

- $SU(5)/SO(5)$
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  - $SU(4)/Sp(4)$  additional scalar
  - $SO(5)/SO(4)$
- room to extend SM gauge
- easy to get from strong 'QCD-like' dynamics with  $SO(N)$  or  $Sp(N)$  gauge groups
- Minimal scalar sector (nothing beyond Higgs, requires more fine-tuning, composite interpretation unknown )