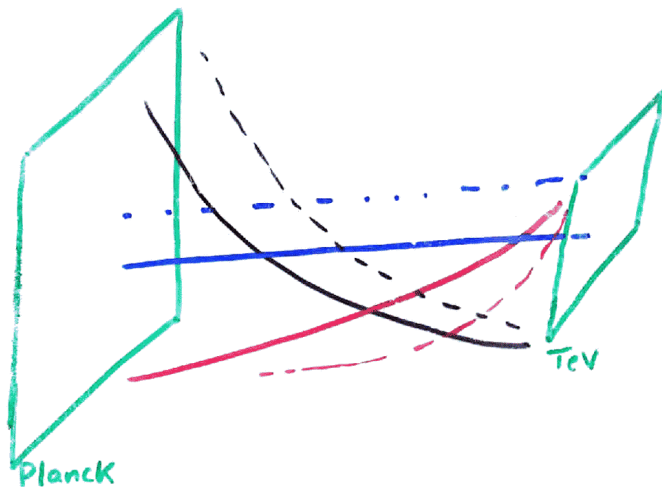Raman Sundrum

Structure & Safety

from

Warped Compactifications

Planck   TeV

2

STRONG DYNAMICS

AT THE WEAK SCALE

70's   QCD

Technicolor   Susskind, Weinberg

80's   Composite Higgs

Georgi, Kaplan

Walking Technicolor

Holdom.
Appelquist, Wijewardhana

90's   Partial Compositeness

D.B. Kaplan

(Eg. $\gamma-\rho$ mixing)

00's   Partial Walking Compositeness

Dual to Bulk SM in RS1
+ earlier hints Nelson, Strassler (SUSY)

3

TOOLS OF THE TRADE

Strong Interactions Expt.

$1/N_{color}$

Scale invariance

Renormalization Group γ_0

Flavor Symmetry

Unitarity

Naive Dimensional Analysis

Dynamical Assumptions

5/3

TOOLS OF THE TRADE

~~Strong Interactions Expt.~~

$1/N_{color}$ ✓

Scale invariance $\longrightarrow SO(4,2)$

Renormalization Group $\gamma_0 \longrightarrow \frac{1}{\Delta\gamma_0} \ll 1$

Flavor Symmetry ✓

Unitarity ✓

Naive Dimensional Analysis ✓

Dynamical Assumptions

↓↓↓

5D Warped Effective Field Theory

RS + AdS/CFT : H. Verlinde '99 ; remarks by Maldacena, Witten ; Grubser '99) Verlinde² '00 ; Arkani-Hamed, Porrati, Randall '00 ; Rattazzi, Zaffaroni '00 ; Perez-Victoria '01 .

TOO MUCH PREDICTIVITY?

Many experimental observables IR-dominated in warped EFT...

Davoudiasl, Hewett, Rizzo '00

Chang, Misano, Nakano, Okada, Yamaguchi '00

Huber, Shafi '01

Csaki, Erlich, Terning '02
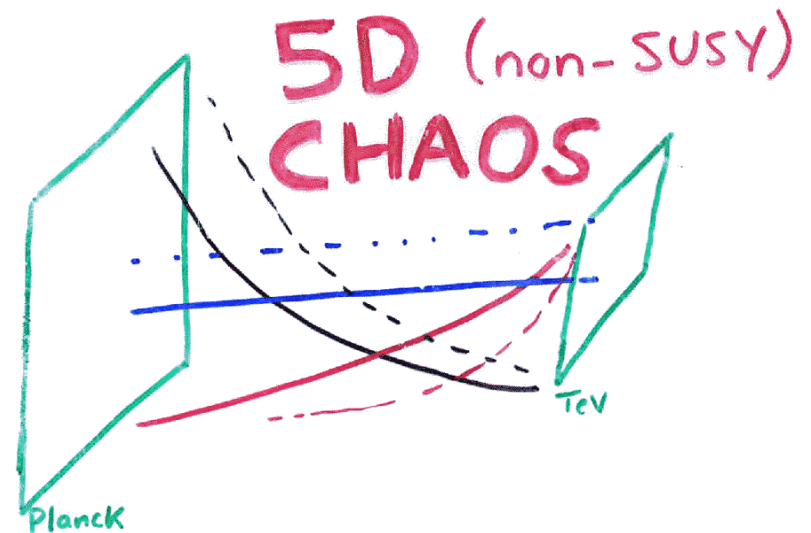
Hewett, Petriello, Rizzo '02

Burdman '02.

⇒ Major conflicts with compositeness & electroweak precision tests.

6/1   Raman Sundrum

Structure & Safety
from
Warped Compactifications

5D (non-SUSY)
CHAOS

Planck   TeV

⇒ 4D COSMOS

7

PARTICLE DATA BOOK
for string theorists

Protons are highly, highly stable

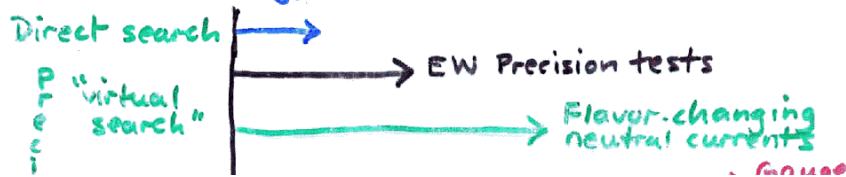$$\frac{G_{Newton}}{G_{Fermi}} \sim 10^{-30}$$

Gauge couplings, $g_i \sim O(1)$

Yukawas $Y_t \sim 1$, $Y_e/Y_t \sim 10^{-6}$

CKM mixing $W^{\pm}$ $V_{ij} \to d_{L,j}$ $u_{L,i}$ larger, the more similar m_i, m_j

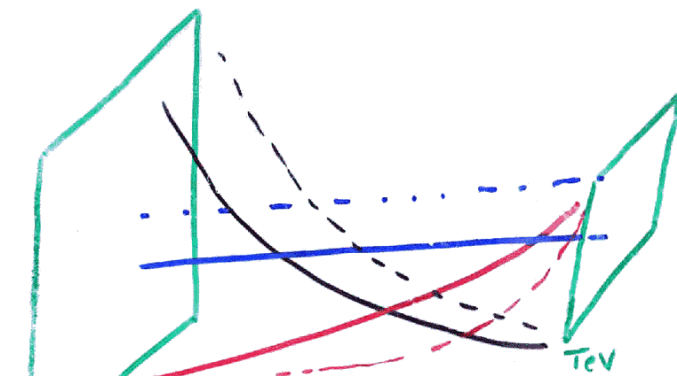$\not{P}$ chiral theory, $\not{T}$ from CKM phase

ν's have tiny, tiny masses & oscillate.

Dark Matter consistent with stable, neutral, weak-scale, weakly interacting particle

Dark Energy $\sim (10^{-3}eV)^4 \lll m_{e^-}^4$

Direct search

P "virtual
r search"
e
c
i

→ EW Precision tests

→ Flavor-changing neutral currents

8/1   Raman Sundrum

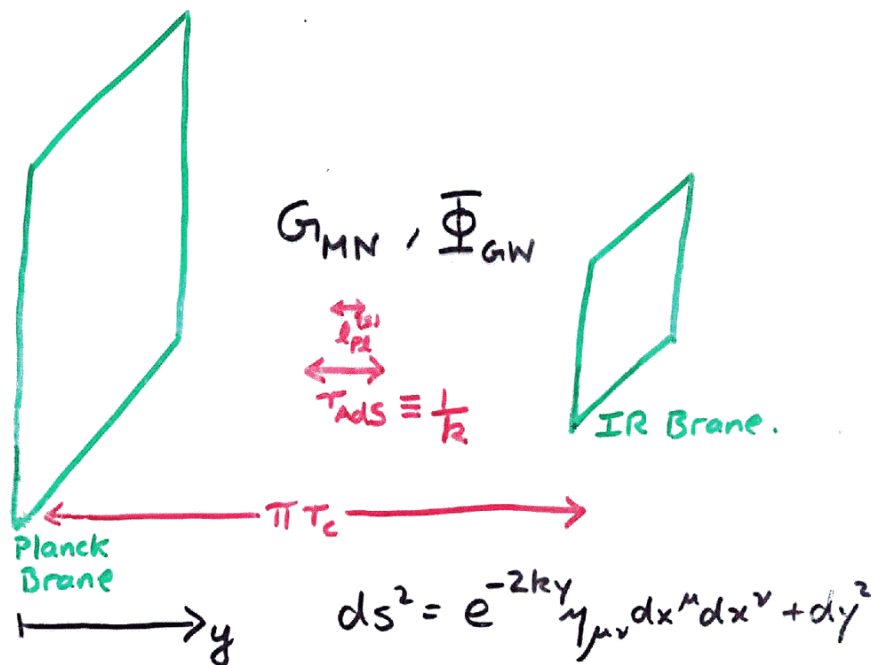# Structure & Safety
from
Warped Compactifications

TeV

Structure arises from wavefunction overlaps of extra-dimensional profiles of light 4D fields

Flat Space:
    Arkani-Hamed, Schmaltz '00
Flat shortcomings!
Delgado, Pomarol, Quirós '00

9

WARPED HIERARCHY
& WARPED EFT

Randall, Sundrum '99

G_{MN}, Φ_{GW}

$r_{AdS} \equiv \frac{1}{k}$

IR Brane.

πr_c

Planck Brane

$\longrightarrow y$

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

$$\boxed{m_{4D} \sim m_{5D}\, e^{-ky}}$$

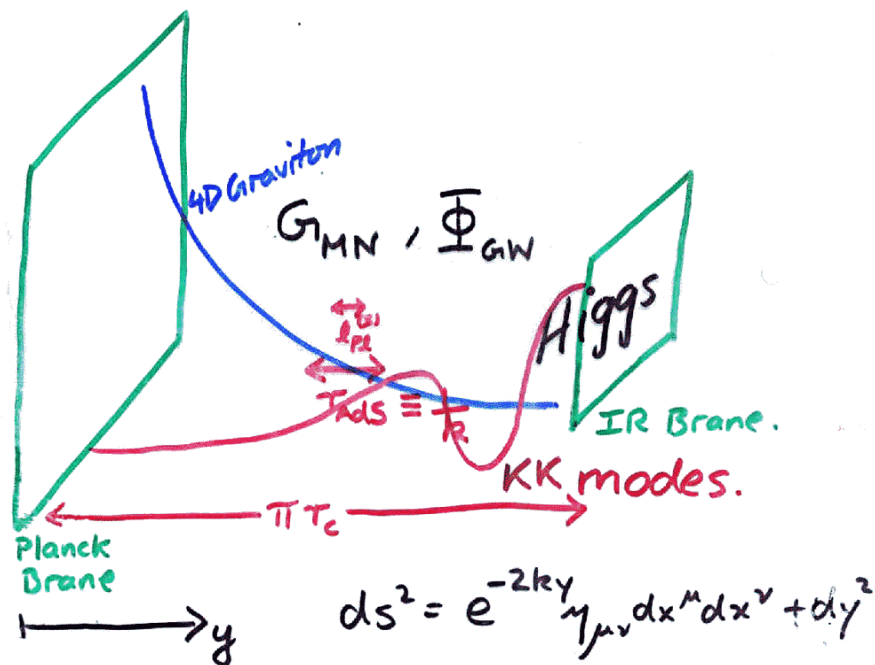$$\Lambda_{UV\,4D} \sim \Lambda_{UV\,5D}\, e^{-ky}$$

TUNES:

$$k\pi\langle r_c \rangle \sim \frac{k}{m_{\Phi\,5D}}$$

Single Fine tuning For 4D cosmological

9/9

WARPED HIERARCHY
& WARPED EFT

Randall, Sundrum '99

4D Graviton

G_{MN}, Φ_{GW}

Higgs

$r_{AdS} \equiv \frac{1}{k}$

IR Brane.

KK modes.

πr_c

Planck Brane

$\longrightarrow y$

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

$$\boxed{m_{4D} \sim m_{5D}\, e^{-ky}}$$

$$\Lambda_{UV\,4D} \sim \Lambda_{UV\,5D}\, e^{-ky}$$

TUNES:

$$k\pi\langle r_c \rangle \sim \frac{k}{m_{\Phi\,5D}} \sim \ln\left(\frac{M_{Pl\,4D}}{m_{Higgs\,4D}}\right) \sim 30$$

Single Fine tuning For 4D cosmological

11

CHAOS ON THE BORDERS

Boundary Conditions   Gherghetta, Pomarol '00

UV |———————| IR $\equiv$ $\frac{S^1}{Z_2 \times Z_2}$

Dirichlet, Neumann

5D	b.c.	Low energy 4D EFT $\ll m_{KK}$	If $m_{5D} \neq 0$?
A_M^a	A_μ: N N	4D gauge field	No survivors to 4D EFT
	A_5^a: DN DN	A_5^a = Goldstone	
	A_μ: N D	"Higgsless" massive gauge field Csaki, Grojean, Pilo, Terning '03	
	A_μ: D N	"Custodial" global symmetry	
$\begin{pmatrix}\Psi_L\\\Psi_R\end{pmatrix}=\begin{pmatrix}\Psi_L\\\Psi_L^c\end{pmatrix}$	Ψ_L: N N	4D Ψ_L chiral	Survive
	D D	4D Ψ_L^c chiral	
	D N	—	
	N D	—	
Φ		—	Always, no survivors. $m_{5D}^2 < 0$?
G_{MN}	$G_{\mu\nu}$: N N	Massless 4D graviton + radion	

12

$A_{M = \mu, 5}$

A_μ(NN)

Pl. A_5(NN)   IR
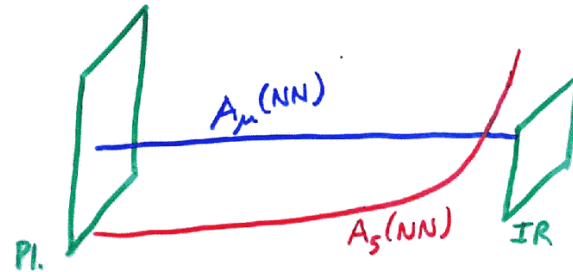
4D Gauge Couplings

$$\frac{1}{g_4^2} = \frac{\pi r_c}{g_5^2} = \frac{\ln\left(\frac{M_{Pl\ 4D}}{m_{IR\ 4D}}\right)}{k\,g_5^2} + loop$$
log-running

Pomarol '00; Goldberger, Nomura, Smith '02;
Randall, Schwartz '02; Contino, Creminelli, Trincherini;
Choi, Kim² '02; Goldberger, Rothstein '02; Agashe, Delgado,
Sundrum '02

4D (pseudo-) Goldstone bosons $\equiv$ SSB at IR scale.

4D "Custodial" global symmetries:
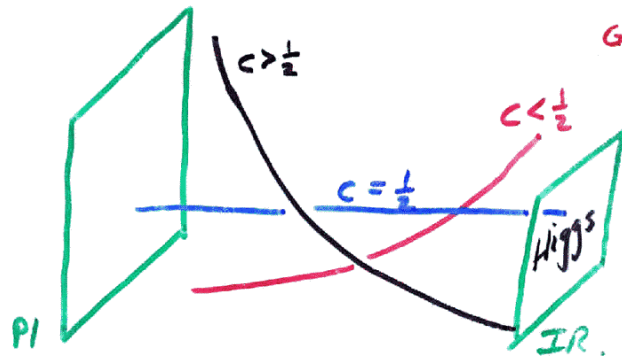KK excitations approximately respect.

13

$$\Psi_{5D} = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \begin{pmatrix} \Psi_L \\ \Psi_L^c \end{pmatrix}$$

in representations of $G_{5D\ gauge}$

$\Psi_L \quad N_{Pl} \quad N_{IR}$: 4D chiral fermions in representations
$\Psi_R \quad D_{Pl} \quad D_{IR}$ of $H_{4D\ gauge}$

$$m_{\Psi_{5D}} \equiv c\,k$$

↑ profiles v. sensitive to this

Gherghetta Pomarol '00

Huber, Shafi;

~~Agashe~~ Agashe, Delgado, May, Sundrum '03

Agashe, Perez '04

$c > \frac{1}{2}$
$c < \frac{1}{2}$
$c = \frac{1}{2}$
Higgs

Pl   IR

=> Yukawa Hierarchies $Y_{ij} \sim \Psi_i \Psi_j (g_5 \sqrt{k}) Q_{ij}^{(1)}$

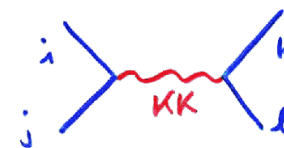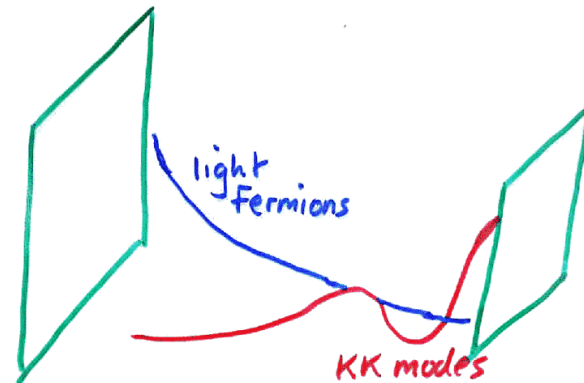$$\Psi_i = \begin{cases} e^{(\frac{1}{2}-c_i)k\pi r_c} & c_i > \frac{1}{2} \\ \sqrt{\frac{1}{2}-c_i} & c_i < \frac{1}{2} \end{cases}$$
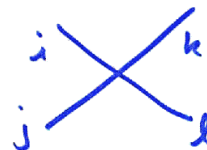
CKM mixing angles: $V_{ij} \sim \Psi_i/\Psi_j > m_i/m_j$

14

SAFETY IN THE BULK

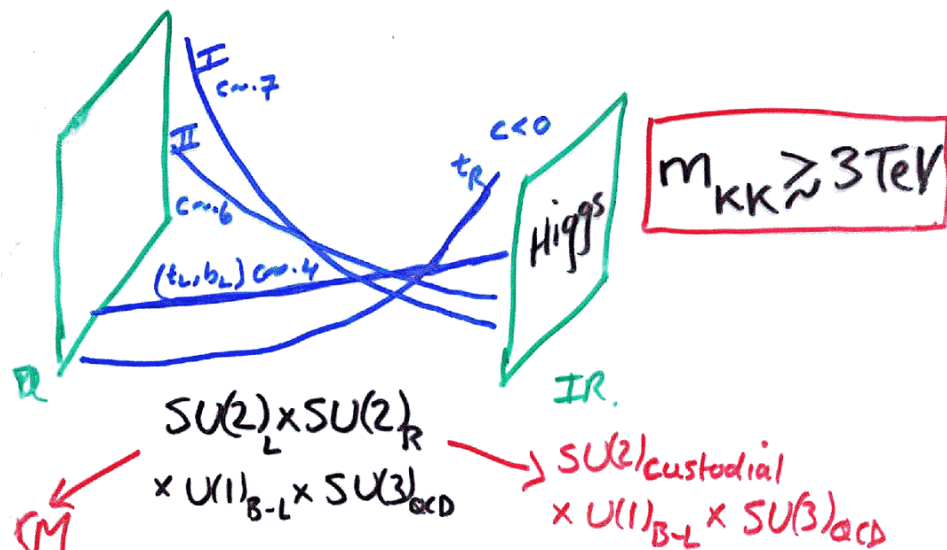FCNC's, compositeness effects, EDM's, S parameter, ...

light fermions

KK modes

i   k
j   KK   l   suppressed by wavefunction overlaps

i   k
j   l   suppressed by 4D scale $\gg$ IR scale.

15

CUSTODIANS OF A
WARPED WORLD

Electroweak Precision Tests

Agashe, Delgado, May, Sundrum '03

I $c \sim .7$

II

$c \sim 6$ t_R

$(t_L, b_L) \, c \sim .4$ $c < 0$

Higgs $\boxed{m_{KK} \gtrsim 3 \, TeV}$

IR.

UV

$SU(2)_L \times SU(2)_R$
$\times U(1)_{B-L} \times SU(3)_{QCD}$

SM

$\longrightarrow SU(2)_{custodial}$
$\times U(1)_{B-L} \times SU(3)_{QCD}$

T-parameter:
(drop B-L
for simplicity)

$\langle H \rangle \langle H \rangle \quad \langle H \rangle \langle H \rangle$

Z $W^3_{R\,KK}$ Z

t, t_{KK}

$W^\pm$ $W^\pm_{R\,KK}$ $W^\pm$
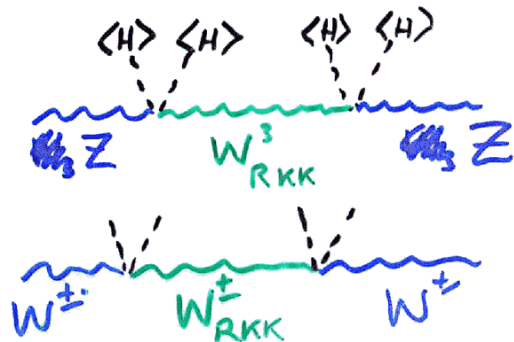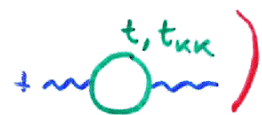
16

UNIFICATION
(at SUSY-GUTs precision)

Agashe, Contino, Sundrum (checking)

Custodial sym. of KK modes

$SO(10)$
$\times$ Baryon no.

SM   + fermions
in "split
multiplets" $SO(10) \times$ Baryon no.
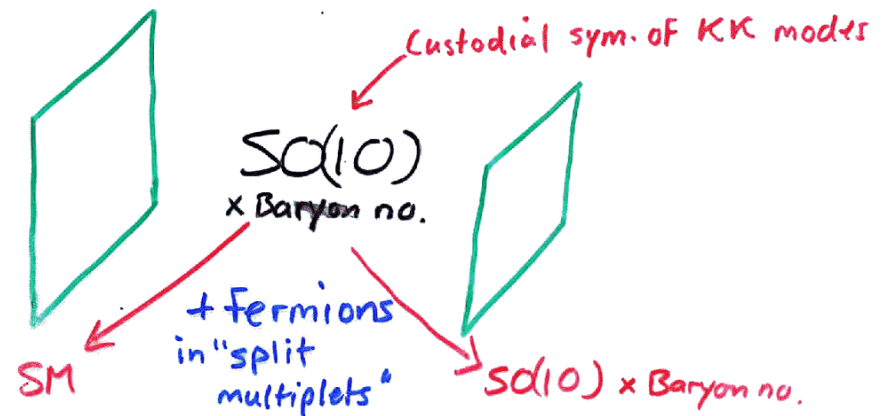
Flat extra dimensions:

Kawamura '99 '01;
Altarelli, Feruglio '01;
Hall, Nomura '01;
Hebecker, March-Russell '01

$\Rightarrow$ Differential running dominated by
SM gauge fields, I & II generations,
III generation only partially.

$\frac{1}{g_i^2}$

$\ln E$

$10^{15} \, GeV$
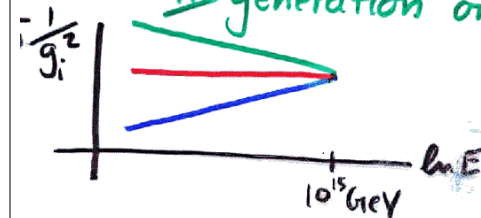
DARK MATTER
Agashe, Servant '04
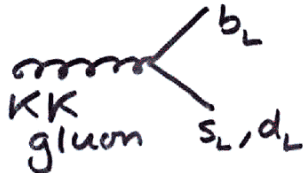
= "baryonic" $\nu_{R\,KK}$

17

TOP TO Bottom

$t_{\underline{R}}$-quark is ~~too~~ substantially composite & precision measurements of t-couplings should reveal this.   *Kim, Kim, Song '02*

b_{L} (& t_{L}) are next most composite $\Rightarrow$

KK gluon b_L s_L, d_L

will appear in upcoming measurements of

$B \to \rho\rho$ & fit to $B\text{-}\bar{B}$, V_{ub},
$B_s\text{-}\bar{B}_s$ mixing $B \to \psi K_s$
~~b \to s \ell^+\ell^-~~

at Babar, Belle, Tevatron, LHC

18

HIGGS = A_5

*Contino, Nomura, Pomarol '03
incorporating precision tests:
Agashe, Contino, Pomarol,
to appear.*

$SO(5)_{EW} \times U(1)_{B-L} \times SU(3)_{QCD}$.

Higgs = 4 of $SO(4)$

Pl   TeV

SM

$SO(4)_{EW} \times U(1)_{B-L} \times SU(3)_{QCD}$

$\equiv SU(2)_L \times SU(2)_R \xrightarrow{\langle H \rangle} SU(2)_{custodial}$
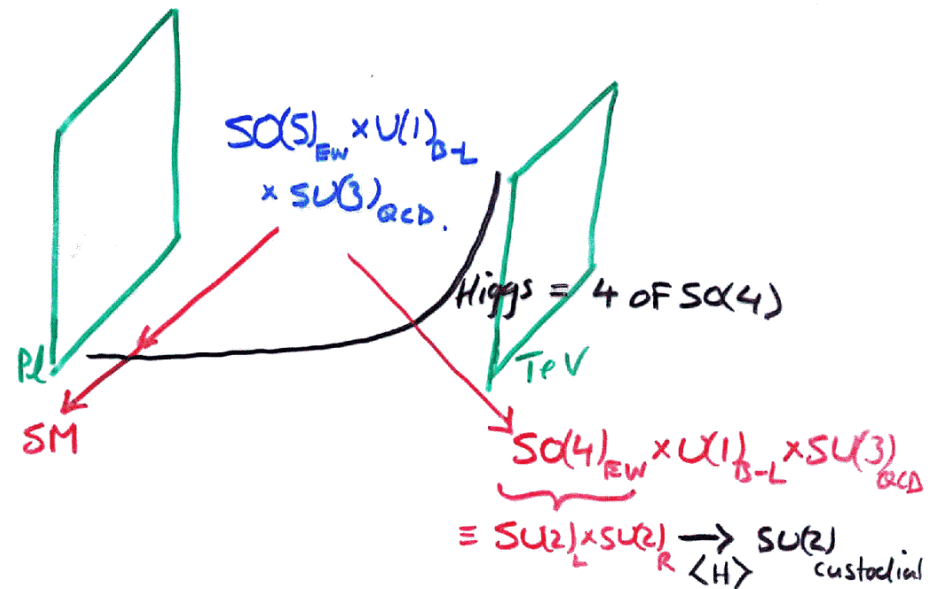
RADIATIVE ELECTROWEAK ~~SYMMETRY~~

$H = A_5$ ◯ $H = A_5$ $+ \cdots$ generates EWSB
         t Higgs potential!

Fine-tuning for weak scale $\sim 10\%$

19

FUTURE DIRECTIONS

Collider Signals, KK search

t-quark studies

m_ν

Cosmology: BBN — easy

     EW phase transition

     — tricky Creminelli, Nicolis, Rattazzi

     Baryogenesis — ?

Stringy origins — Maximal high scale SUSY

     — Non-minimal IR brane structure.