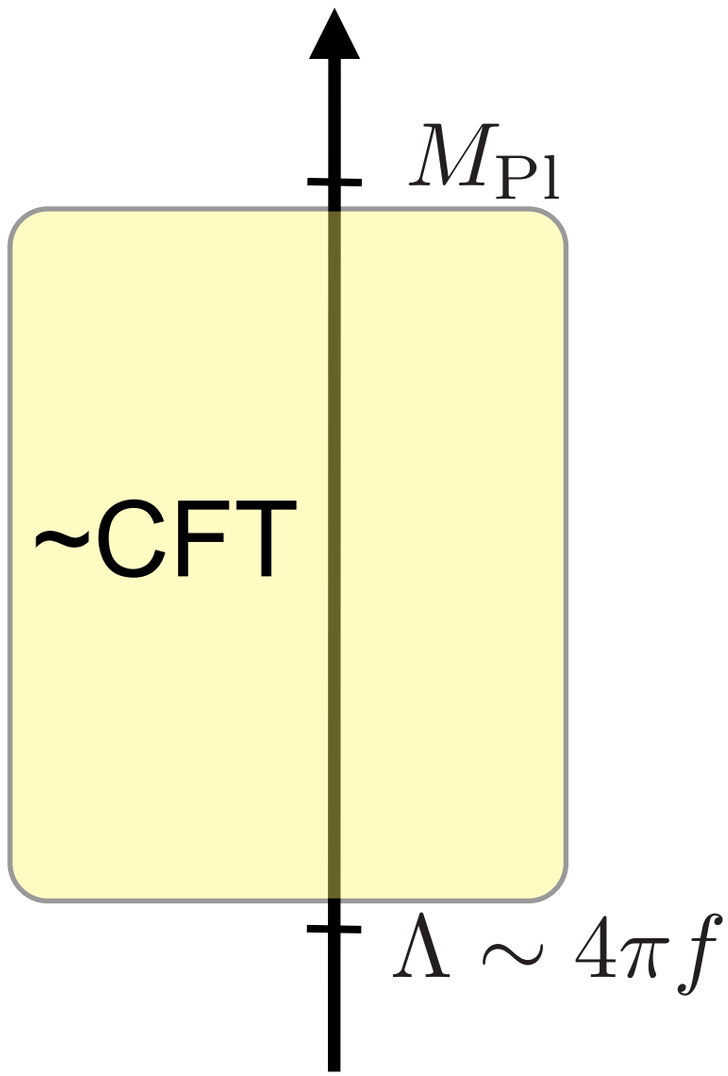
Partial Compositeness

Luca Vecchi

(University of Maryland)

LLNL Lattice BSM Workshop (4/2015)

Strong Dynamics for the TeV scale



Main hurdles:

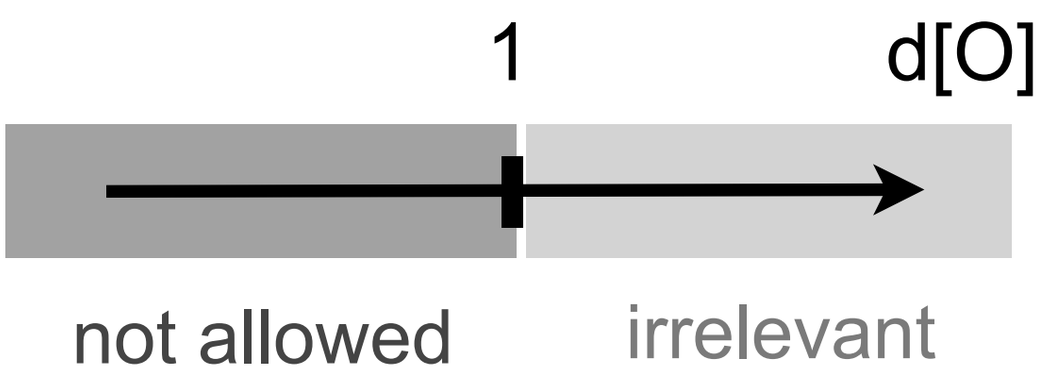
1) Electro-weak data + LHC (Higgs)
2) Flavor
   -- higher-dimensional operators?
   -- **top quark mass?!**

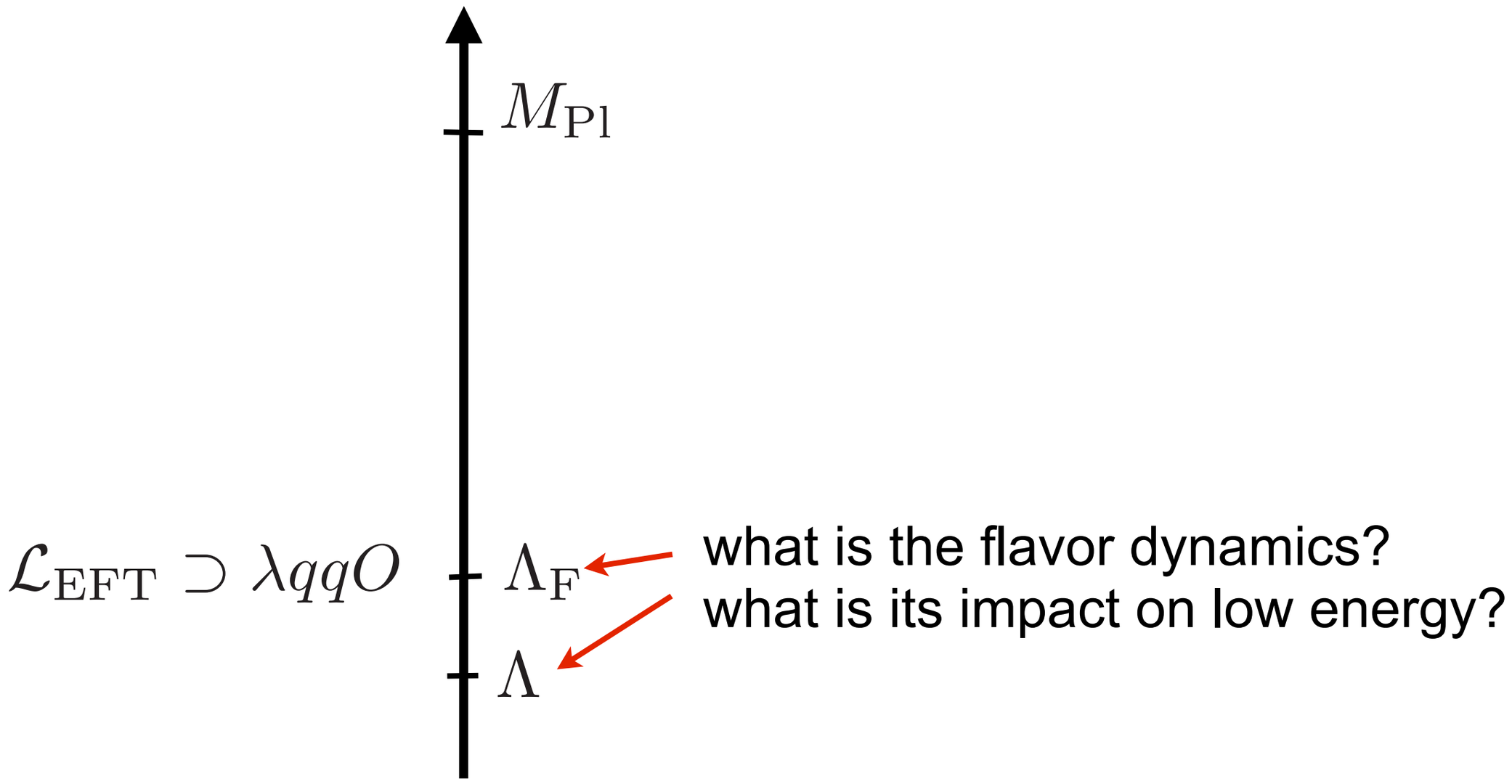
Top quark? and no elementary scalars...

if SM fermions (q) are weakly-coupled to the strong dynamics,
ONLY TWO OPTIONS:

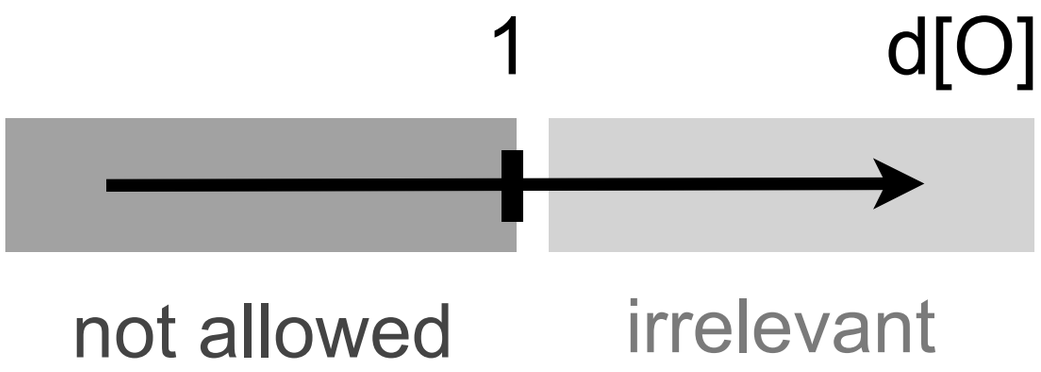
Extended Technicolor	Partial Compositeness
λqqO	λqO
	review by Contino (2010)

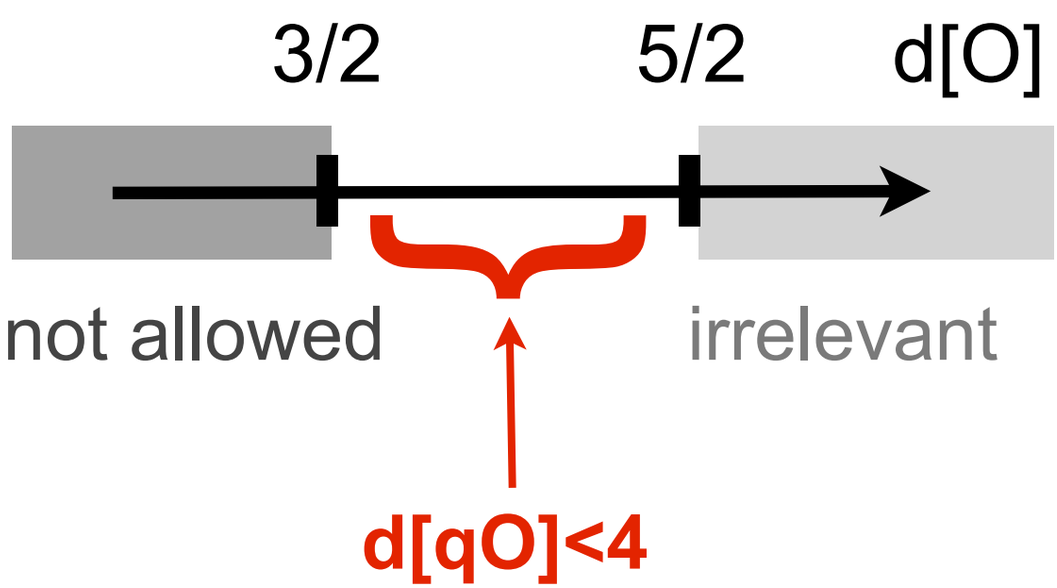
Extended Technicolor λqqO	**Partial Compositeness** λqO

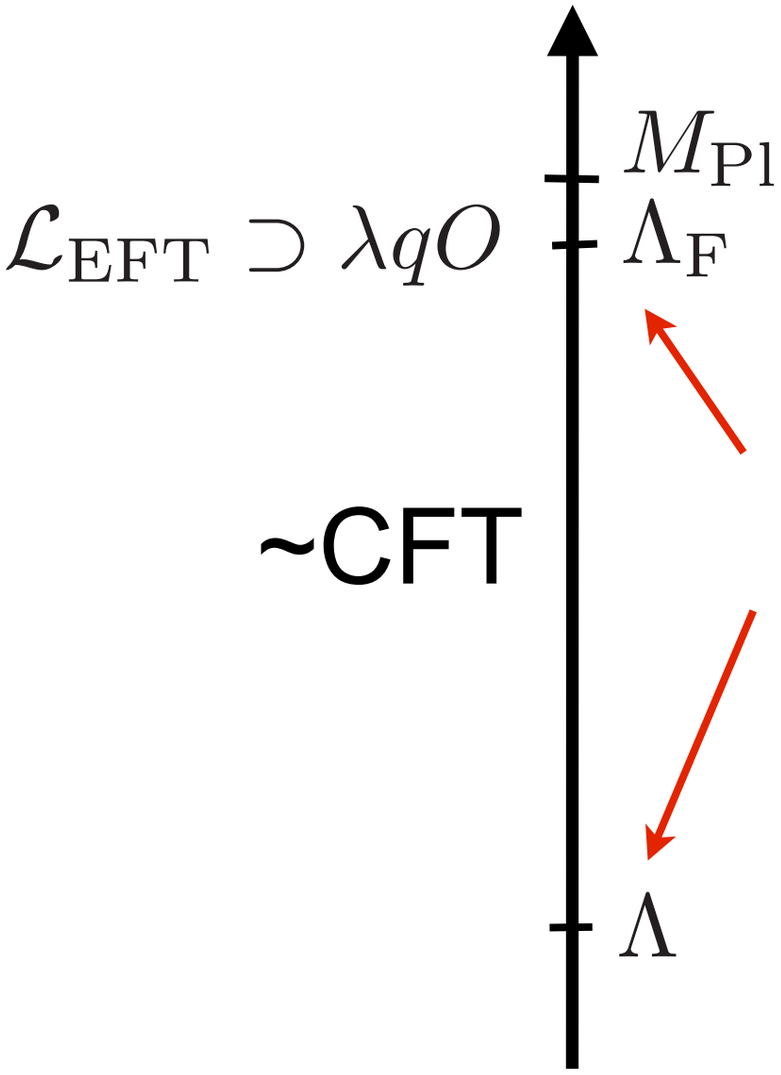



$M_{\rm Pl}$
$\mathcal{L}_{\rm EFT} \supset \lambda qqO$
$\Lambda_{\rm F}$
Λ
what is the flavor dynamics?
what is its impact on low energy?

Extended Technicolor λqqO	**Partial Compositeness** λqO







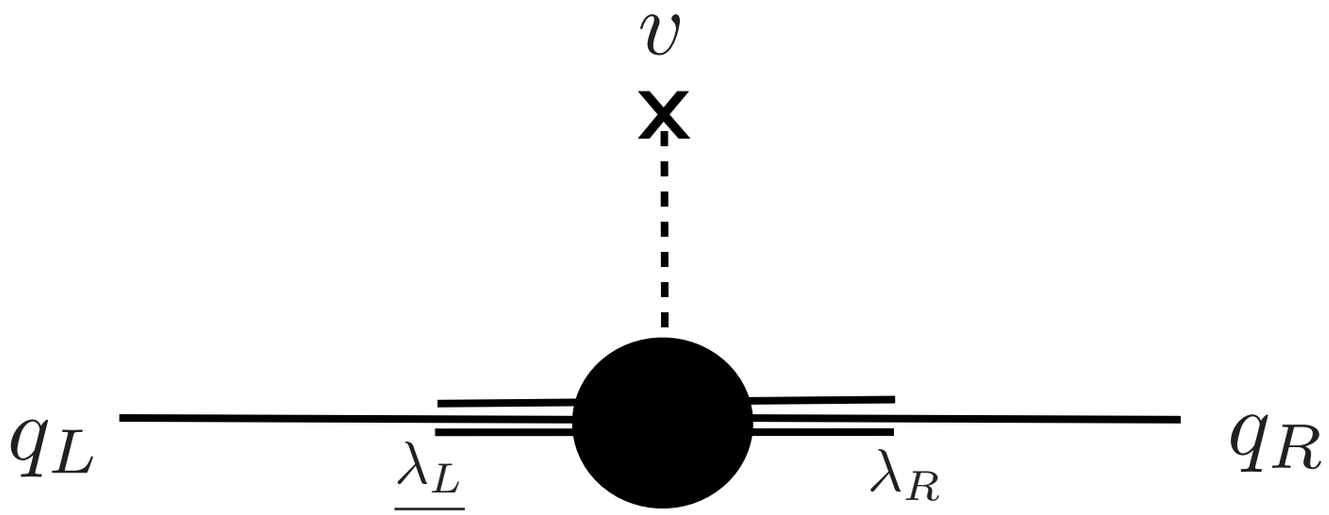
Partial Compositeness

for **d<5/2** no flavor issues to be addressed!

5D Randall-Sundrum scenarios are an effective realization

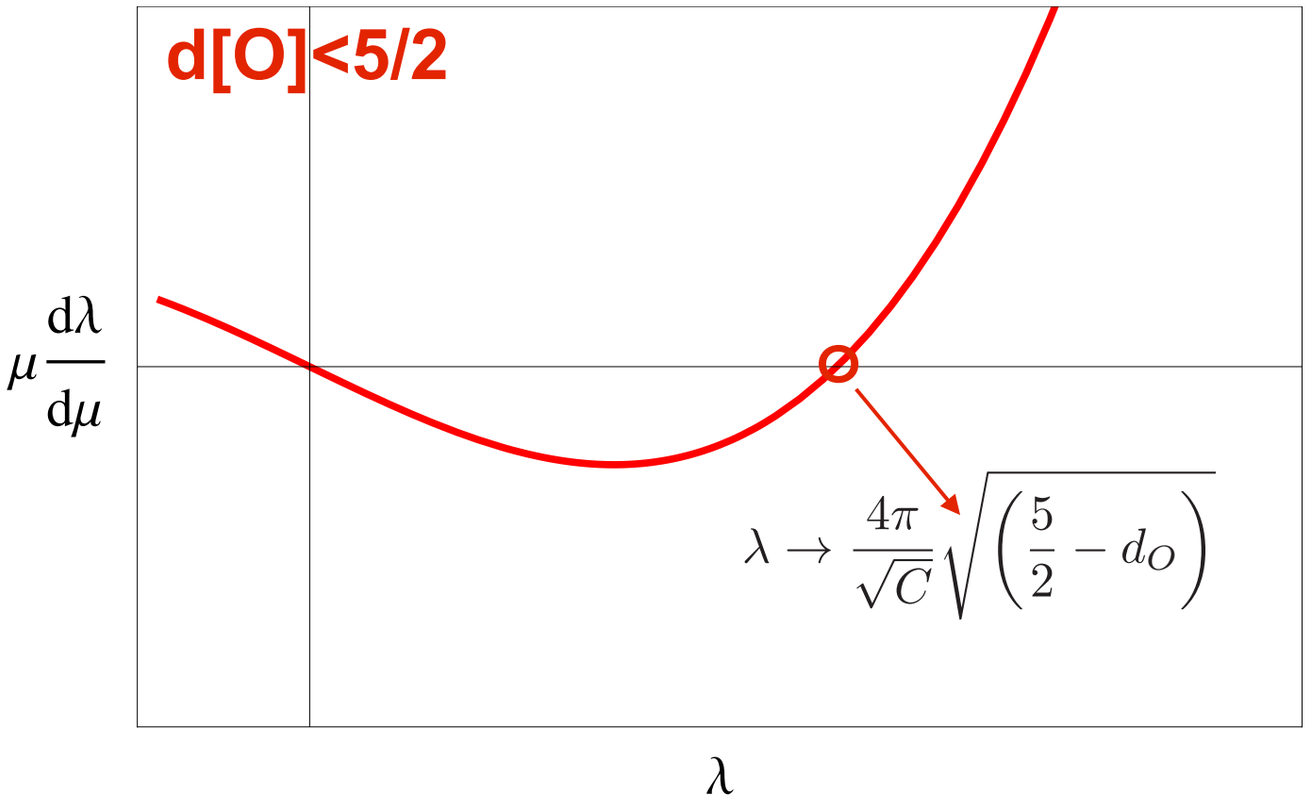
SM Yukawas

SM fermions are “partially composite”...



$$y \sim \frac{1}{4\pi}\lambda_L(\Lambda)\lambda_R(\Lambda)$$

need RG evolution of $\lambda q O$



$$\frac{d\lambda}{d\ln\mu} = \left(d_O - \frac{5}{2}\right)\lambda + \frac{C}{16\pi^2}\lambda^3$$

positive by unitarity

Top quark

the coupling reaches the IR fixed point (perturbative enough)

Lighter fermions

do not reach the IR fixed point $\lambda(\Lambda) \sim \lambda(\mu_0)\left(\frac{\Lambda}{\mu_0}\right)^{d-5/2}$ **mass hierarchy?**

in 5D: Gherghetta-Pomarol (2000), ...

What is $\lambda q O$?

$\lambda \bar{q} \phi \Psi$

...

$\lambda \bar{q} \left(\sigma_{\mu\nu} \Psi^a G^a_{\mu\nu} \right)$

$\lambda q \Psi_1 \Psi_2 \Psi_3$

...

What is $\lambda q O$?

$\lambda \bar{q} \phi \Psi$

...

$\lambda \bar{q} \left(\sigma_{\mu\nu} \Psi^a G^a_{\mu\nu} \right)$ **no asymptotic freedom**

$\lambda q \Psi_1 \Psi_2 \Psi_3$ **best option**

...

$\gamma \simeq -2$ **on the lattice?**

-- unitarity: >-3
-- SU(3) SQCD gives -1.2
-- NJL model: -2 seems possible
-- ...

What can the lattice do for BSM physics?

Here is one example where the lattice is KEY

$$\left(\frac{\Lambda}{\Lambda_{\text{cutoff}}}\right)^{\gamma_*}$$

O(1) NDA estimates are totally useless when it comes to anomalous dimensions!!!

Model-building Wish-list

- ☐ G/H ⊃ Higgs doublet: robust way to get a parametrically light Higgs Georgi-Kaplan (‘80s)
- ☐ H ⊃ custodial SU(2) Sikivie et al. (1980)
- ☐ Realistic phenomenology (ex: **v<f and Higgs mass**)
- ☐ Partners O for the top quark
- ☐ Partners O for **all** SM quarks (to decouple the flavor scale!)
- ☐ Proton is stable
- ☐ Anomalies cancel
- ☐ No Landau poles at low energy
- ☐ A strong IR fixed point (conformal window)
- ☐ **d[O]<5/2 within the CFT?**

Wish-list

Ferretti-Karateev (2013): SU(N)/SO(N), SU(N)/Sp(N) with ≧2 irreps

- [x] G/H ⊃ Higgs doublet
- [x] H ⊃ custodial SU(2)
- [ ] Realistic phenomenology
- [x] Partners O for the top quark
- [ ] Partners O for all SM quarks
- [ ] Proton is stable
- [x] Anomalies cancel
- [ ] No Landau poles at low energy
- [ ] A strong IR fixed point (conformal window)
- [ ] **d[O]<5/2 within the CFT?**

Wish-list **for SU(3) and N_f Dirac flavors...**

- ☑ G/H ⊃ Higgs doublet
- ☑ H ⊃ custodial SU(2)
- ☑ Realistic phenomenology
- ☑ Partners O for the top quark
- ☑ Partners O for all SM quarks
- ☑ Proton is stable
- ☑ Anomalies cancel
- ☑ No Landau poles at low energy
- ☑ A strong IR fixed point (conformal window)
- ☐ **d[O]<5/2 within the CFT?**

An QCD-like SU(3) candidate model with N_f ≥ 9 Dirac flavors

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
T	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	a
D	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{3}-\frac{1}{2}a$
S	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{6}-\frac{1}{2}a$
S'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6}-\frac{1}{2}a$

plus the right handed components

PC

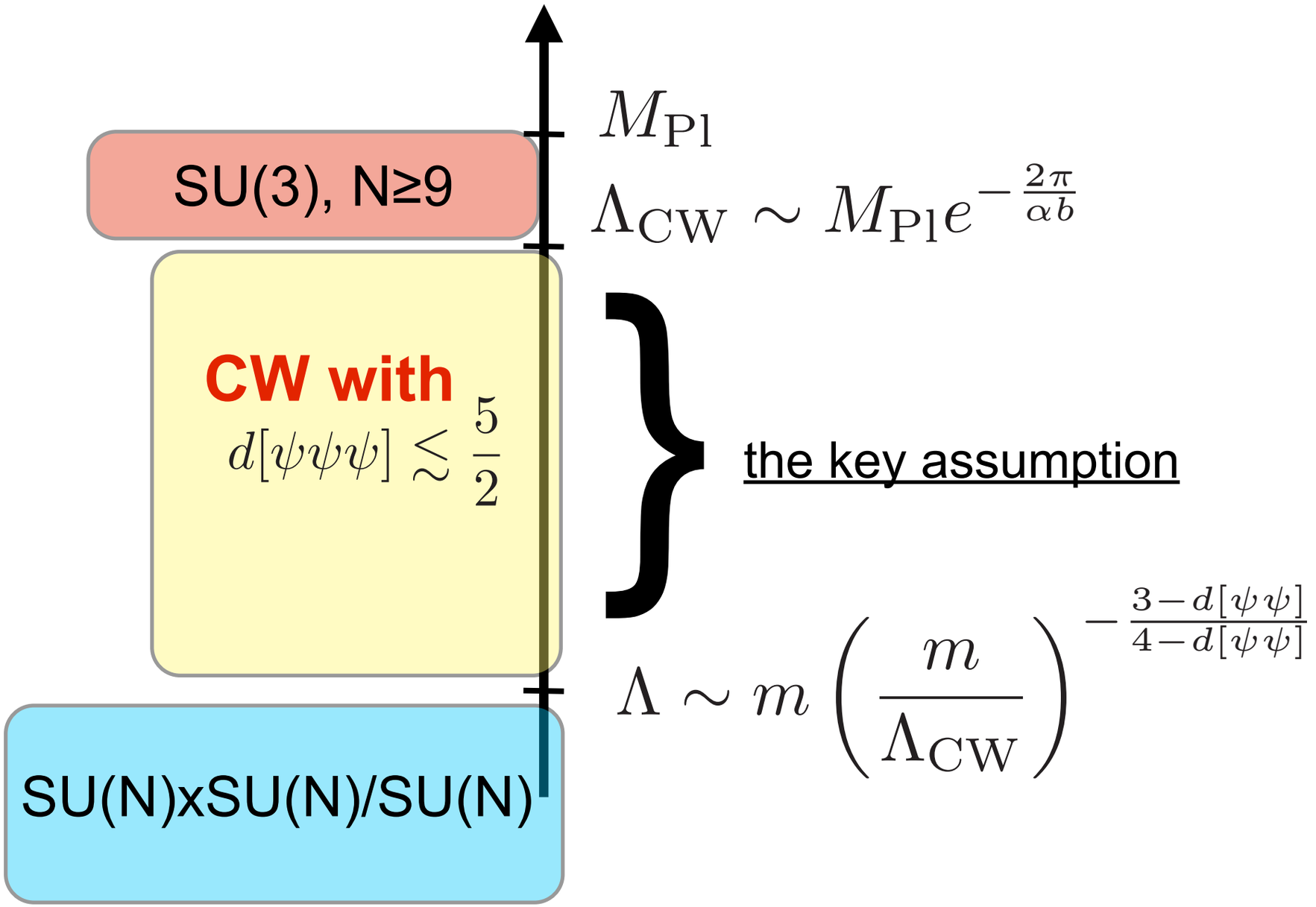
$$\mathcal{L}_{\rm dim-6} = q\overline{TDS} + uTDD + uTSS' + dTSS$$

ETC

$$+\, quD\overline{S} + qd\overline{D}S + \ell e\overline{D}S + \ell e\overline{S'}D + \psi^\dagger_{\rm SM}\gamma\psi_{\rm SM}\psi^\dagger\gamma\psi$$

$$\mathcal{L}_{\rm mass} = -m_T T\overline{T} - m_D D\overline{D} - m_S S\overline{S} - m_{S'} S'\overline{S'} \,.$$

exit CFT


SU(3), N≥9
$M_{\rm Pl}$
$\Lambda_{\rm CW} \sim M_{\rm Pl} e^{-\frac{2\pi}{\alpha b}}$
CW with
$d[\psi\psi\psi] \lesssim \frac{5}{2}$
the key assumption
+
SU(N)xSU(N)/SU(N)
$\Lambda \sim m \left(\frac{m}{\Lambda_{\rm CW}} \right)^{-\frac{3-d[\psi\psi]}{4-d[\psi\psi]}}$

Conclusion

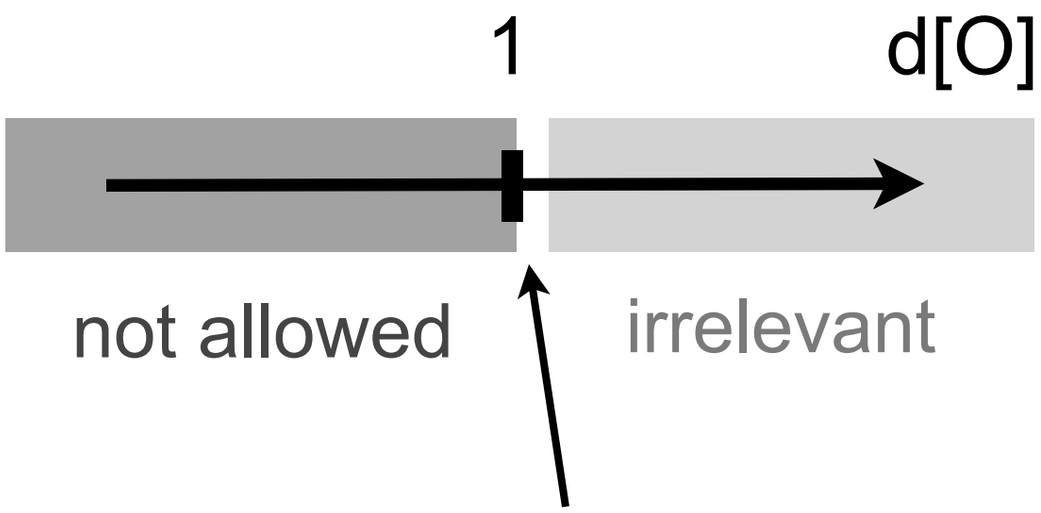
- **2 options: ETC or PC**
- **Partial Compositeness is very attractive**
  -- simple* UV-complete models without fundamental scalars
  -- bonus: may account for fermion mass hierarchy
- **Test the d=5/2 hypothesis on the lattice!**
- **Ex: QCD-like models**
  -- SU(3) gauge with ≥9 Dirac flavors: use existing data?
  -- satisfy all basic requirements that are theoretically under control
  -- have realistic vacuum alignment (v<f) and (PNGB) Higgs mass
  -- very rich collider phenomenology (colored scalars, TC-hadrons)

* ONLY 1 TUNING as in the SM, but numerically MUCH MUCH LESS

Back-up slides

Extended Technicolor

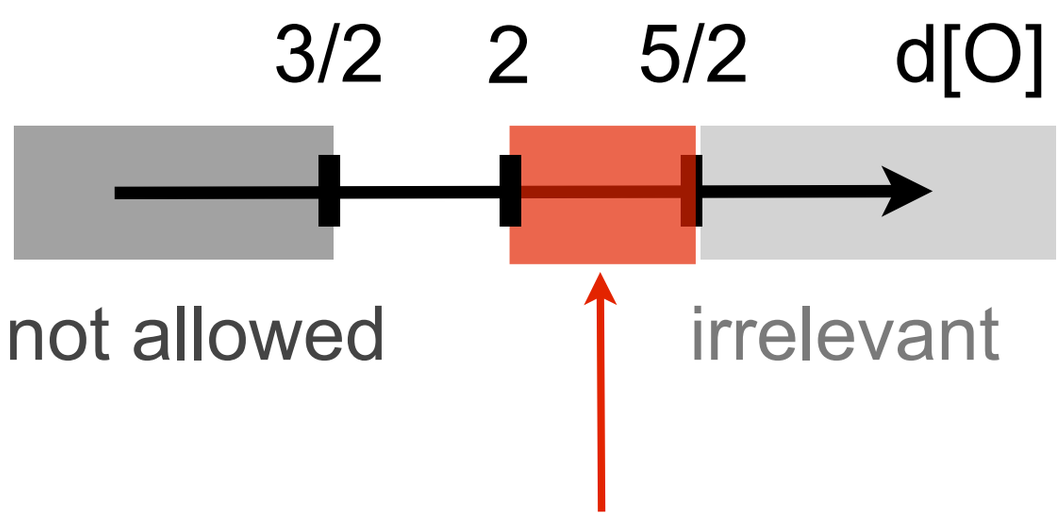
λqqO



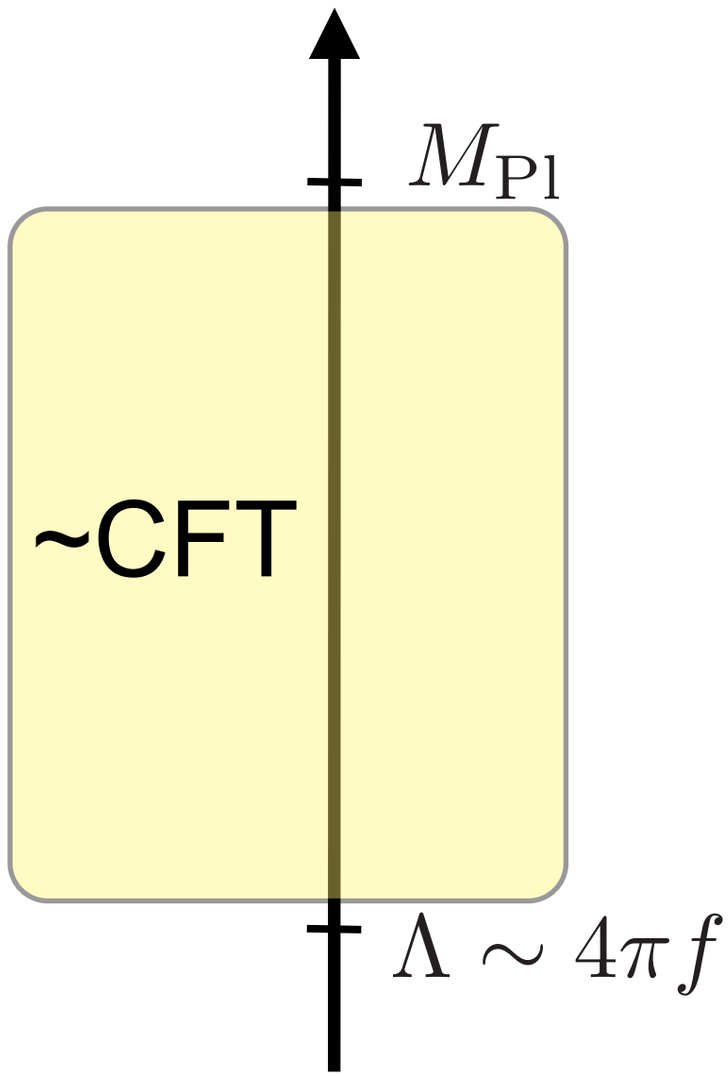
best case scenario: Luty-Okui (2004)

Partial Compositeness

λqO



Strong Dynamics for the TeV scale



Main hurdles:

1) Electro-weak data + **LHC (<u>Higgs</u>)**
2) Flavor
   -- higher-dimensional operators?
   -- top quark mass?!

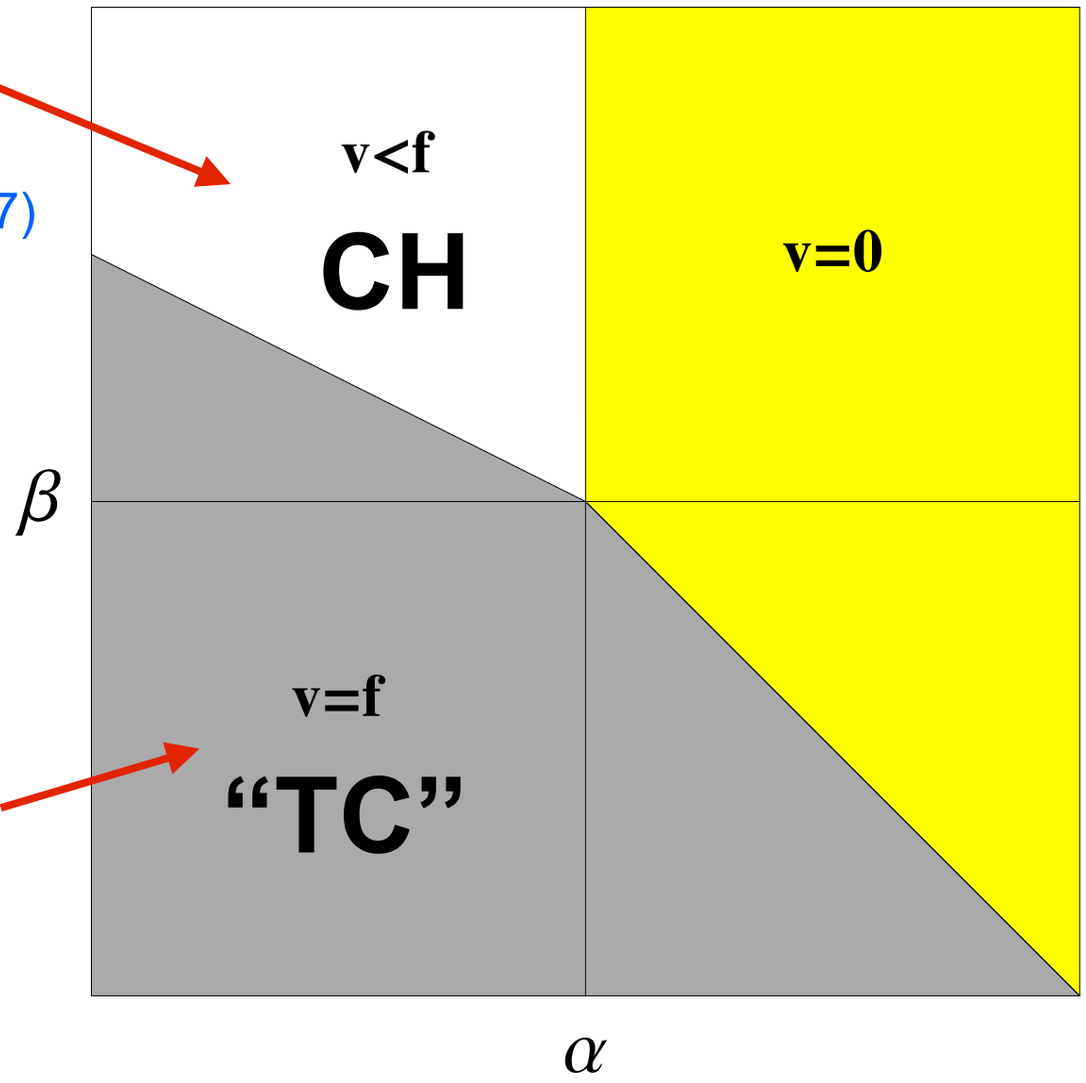
TC or CH? v<f is generic

Vacuum alignment $\Longleftrightarrow$ NGB potential. Example: $V = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$

$$v \equiv f \sin \frac{\langle h \rangle}{f}$$

SM-like Higgs up to v/f<1:
parametric

Giudice et al. (2007)



SM-like Higgs up to v/f=1!!!
accidental

v<f generic ONLY when ≥2 G-breaking parameters of comparable size
PC typically has 2 comparable contributions from top L and R

NGB Higgs is pseudo-scalar?!

When writing the Standard Model Lagrangian we do not demand anything but gauge invariance...

$\lambda \neq 0$

- CP <u>explicitly</u> broken by **yqqh**
- CP <u>spontaneously</u> broken by **v**

  (hZZ proportional to the CP-odd spurion v)

Phenomenology of SU(4)xSU(4)/SU(4) models

$$\text{NGB} = (2,2) + \cancel{(2,2)} + \cancel{(3,1)} + \cancel{(1,3)} + (1,1)$$

under $SU(2)_w \times SU(2)_{\text{cust}} \subset SU(4)_V$

() IR is effectively SU(4)/Sp(4)

-- realistic vacuum alignment

-- the Higgs mass is light (OK for b=4) $m_h^2 = \frac{N_c}{2\pi^2} y_t^4(\Lambda) v^2 \left(\frac{\Lambda}{4\pi f}\right)^2 b$

() 3 accidental symmetries

-- Baryon & Lepton numbers !!!!

-- techni-fermion number (TC-hadrons!)