Dilaton Phenomenology

(Inspecting the Higgs for new *strongly* interacting *dynamics*)

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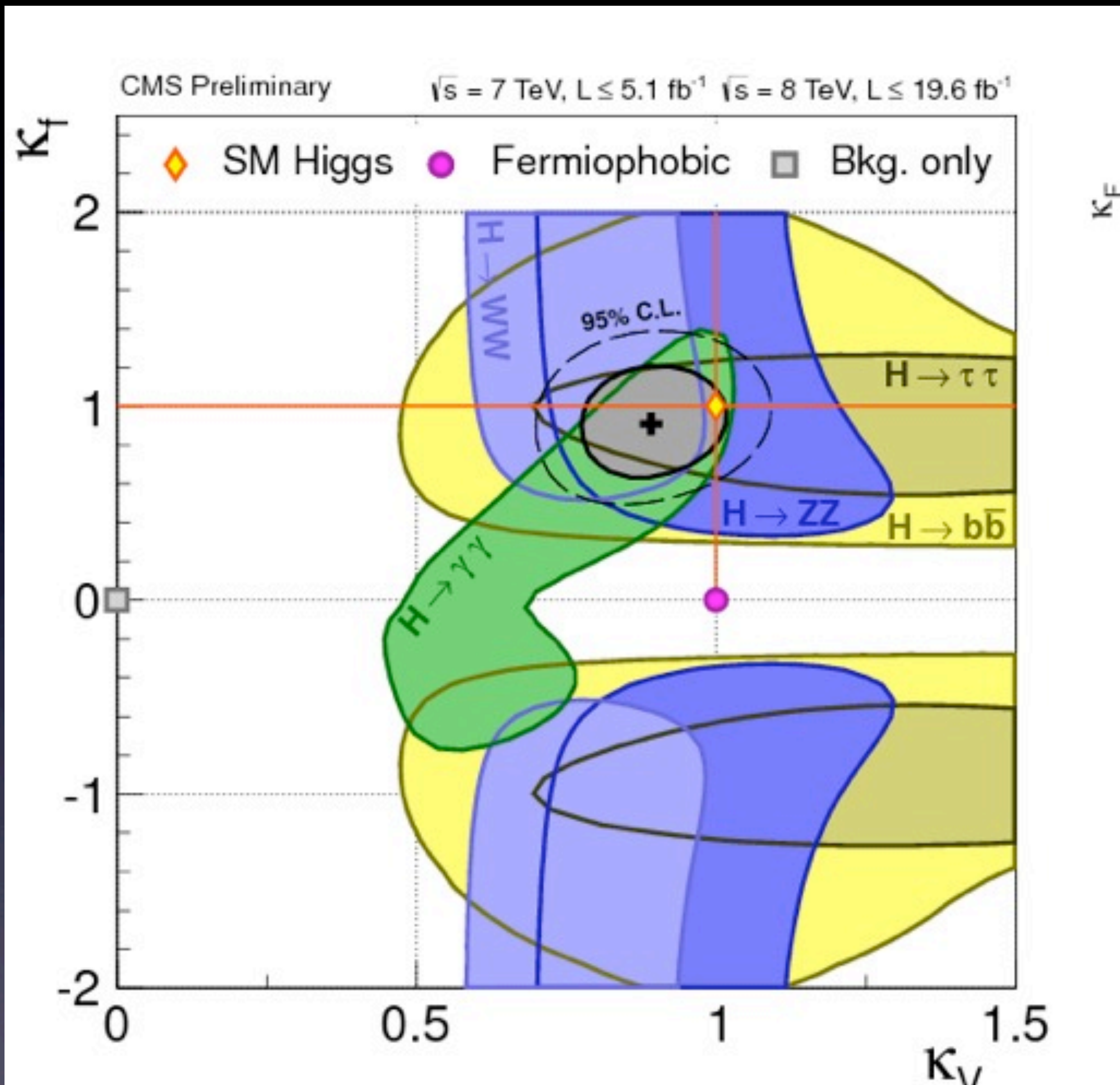
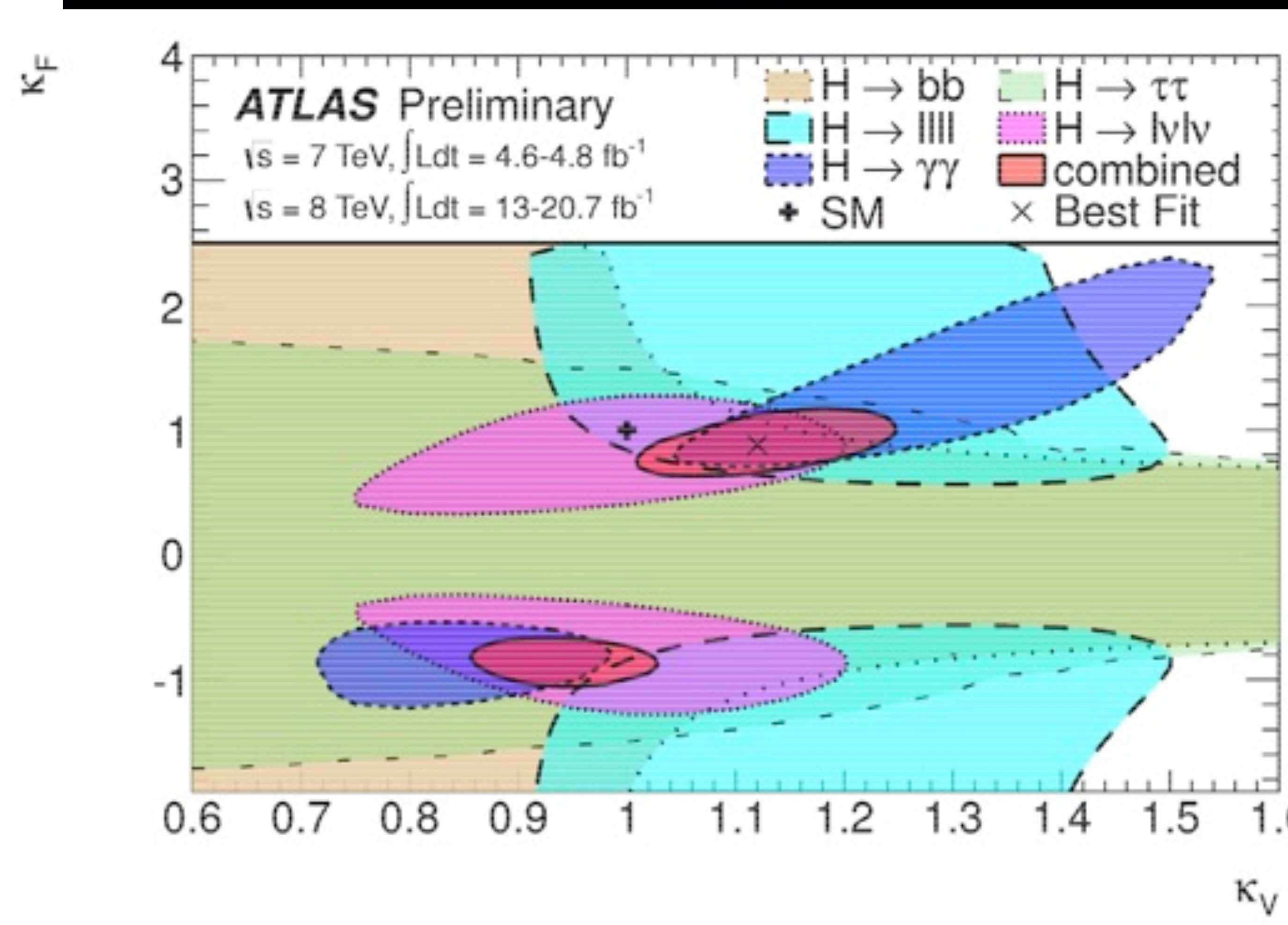
Higgs-like

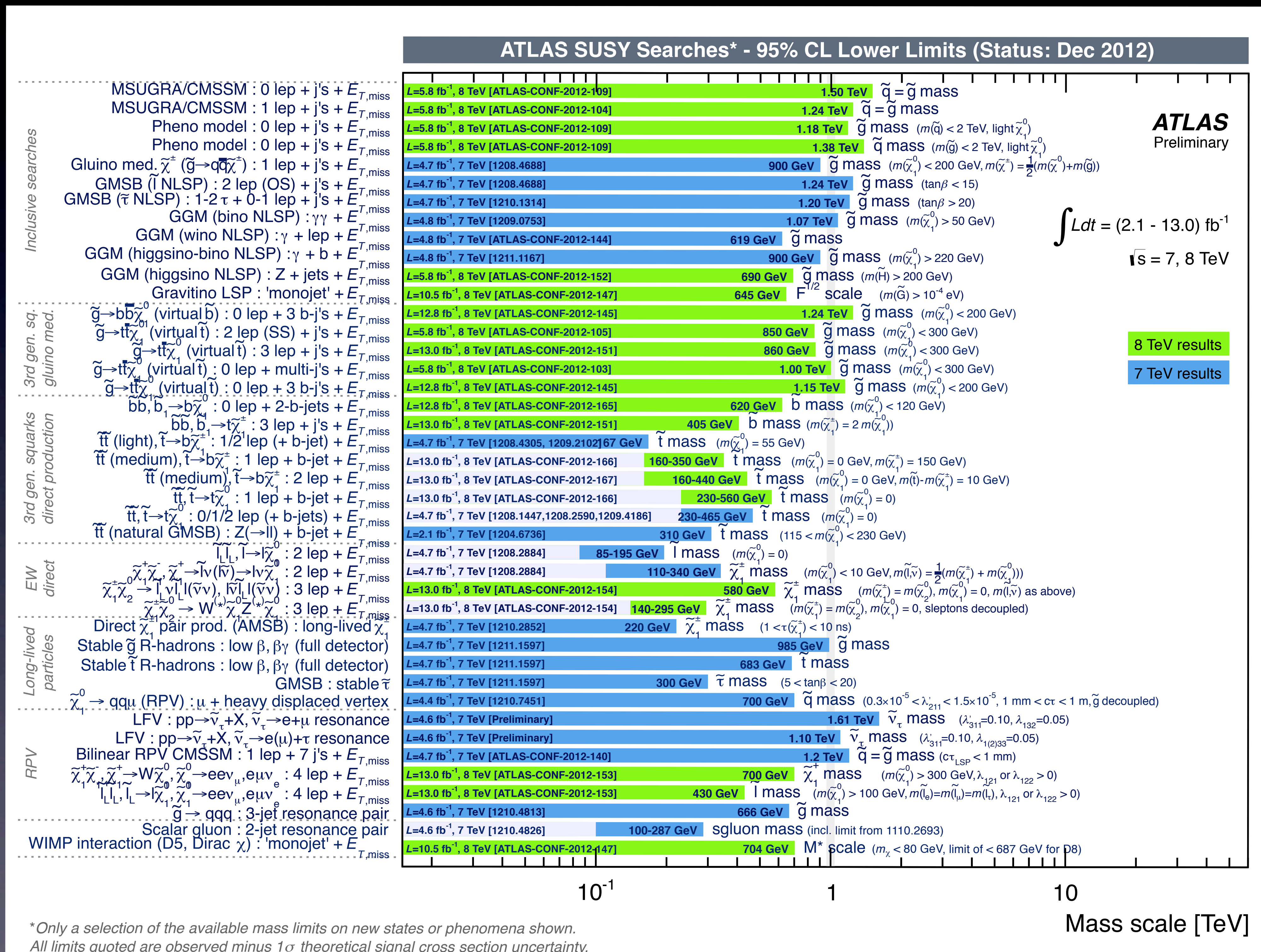




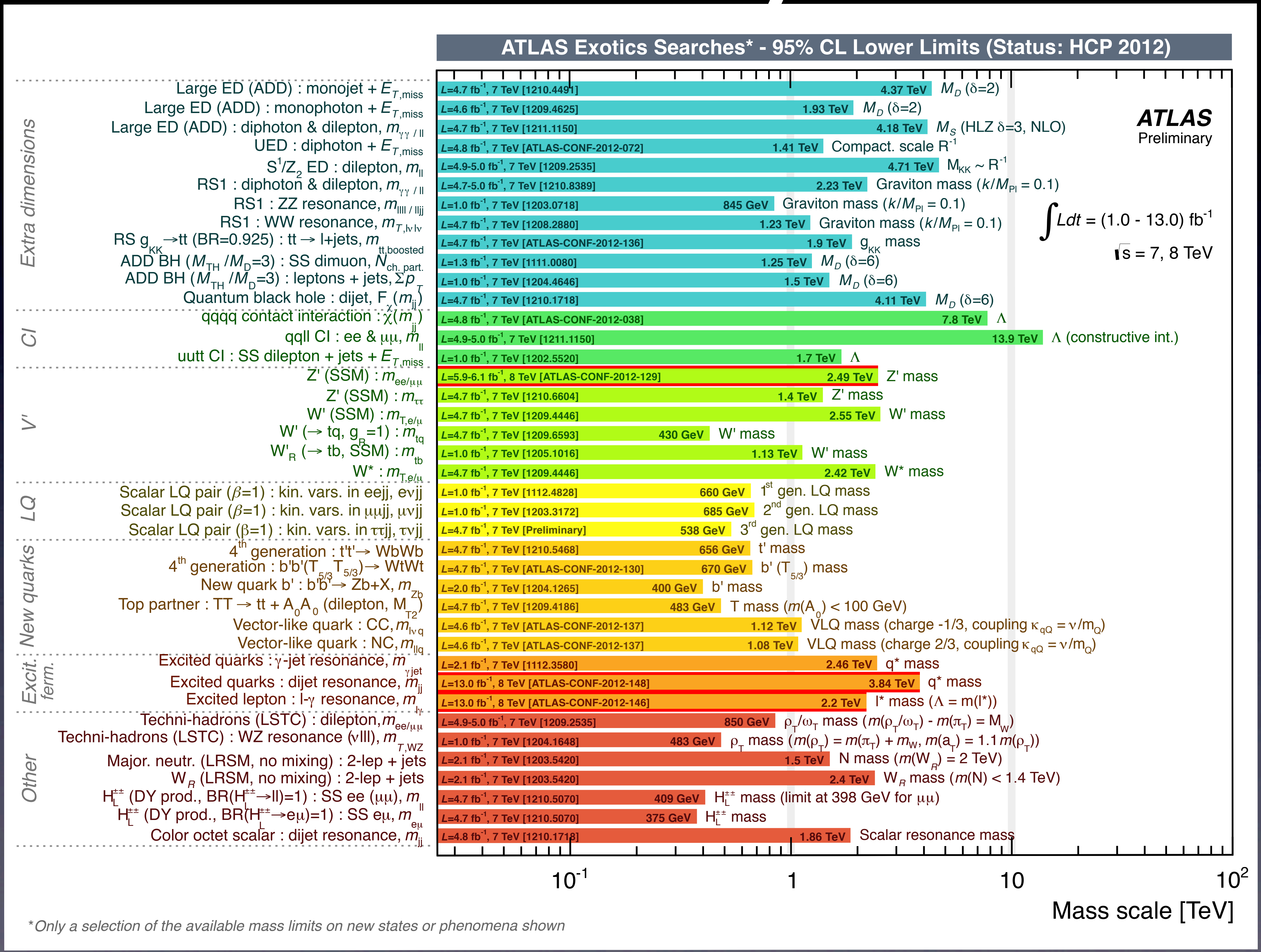
The resonance is at ~126 GeV and it is SM-Higgs-like

10% -ish deviations still allowed

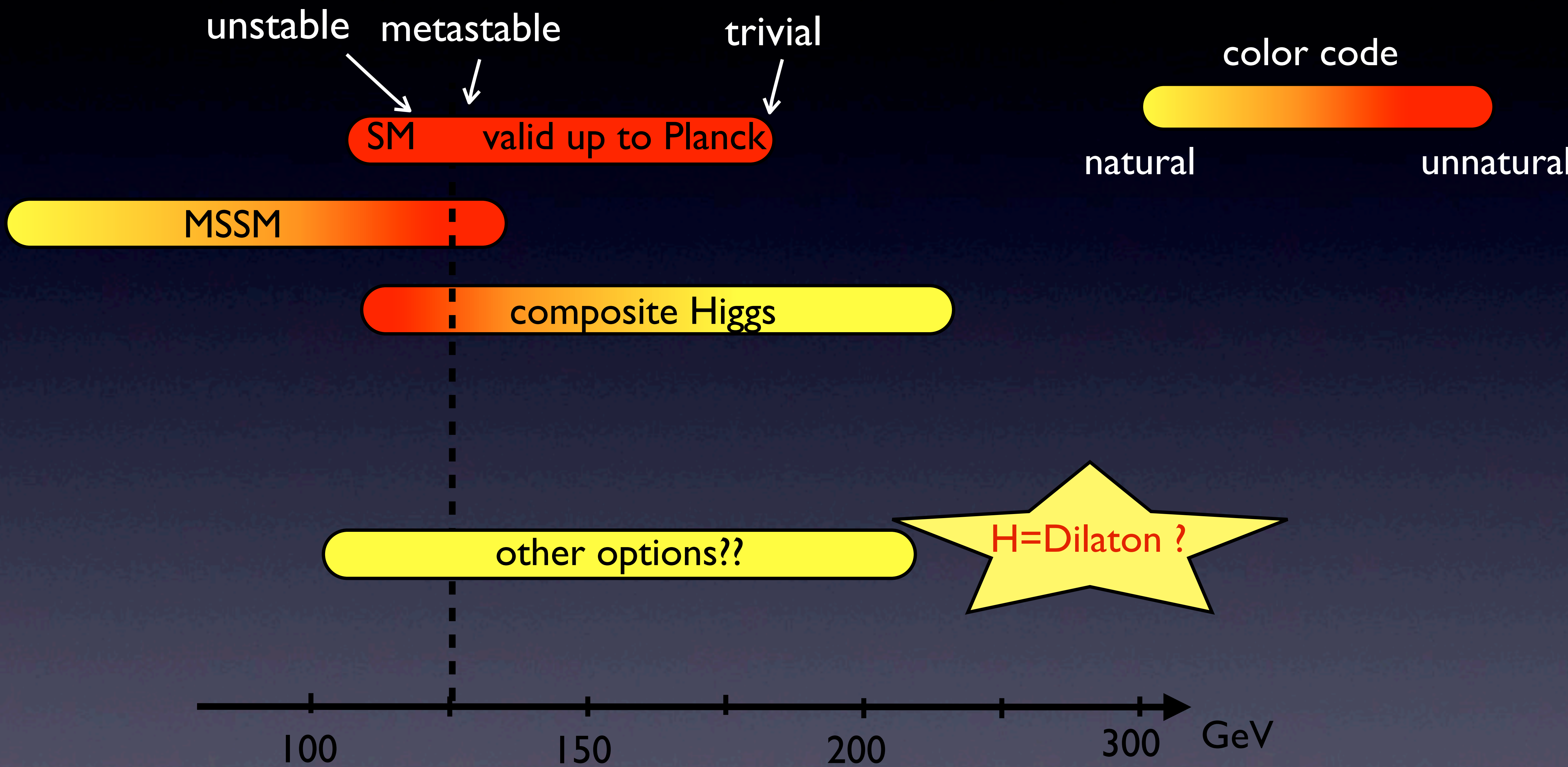
Non-discovery SUSY



Non-discovery exotics



Status of light scalars



All models seem to be under strain

Strongly coupled EWSB

- Higgsless and pure Technicolor models are dead
- Composite Higgs models fine tuned
- Give up on SC-EWSB?

The Higgs:

- Couplings determined by ~ conformal invariance of SM (e.g. low energy theorems)
  - m_H is only classical explicit breaking
- VEV breaks conformality spontaneously

Higgs-like dilaton

- Can envision a model of strong dynamics at at conformal fixed point
- To reproduce data need conformal symmetry spontaneously broken at f ~ v

$$\kappa_f \sim \kappa_V \sim \frac{v}{f}$$

Questions I will discuss:

- Can a dilaton fit the data?
- Can a dilaton be light? (below Λ=4πf)

More general discussion of (maybe non-higgslike) dilatons

Some recent work:

Csáki, JH, Lee ’07
Goldberger, Grinstein, Skiba ’07
Fan, Goldberger, Ross, Skiba ’09
Csáki, Bellazzini, JH, Serra, Terning ’12
Chacko, Mishra ’12
Chacko, Mishra, Franceschini ’12
Chacko, Mishra, Stolarski ’13
Csáki, Bellazzini, JH, Serra, Terning ’13
Coradeschi, Lodone, Pappadopulo, Rattazzi, Vitale ’13

Scale Transformations

Dilatations:

$$x \to x' = e^{-\alpha} x$$

Operators transform:

$$\mathcal{O}(x) \to \mathcal{O}'(x) = e^{\alpha\Delta}\mathcal{O}(e^{\alpha} x)$$

Δ is the full quantum operator dimension

Linearized transformation of action:

$$S \longrightarrow S + \sum_i \int d^4x \, \alpha g_i (\Delta_i - 4) \mathcal{O}_i(x)$$

Spontaneous breaking

CFT operator gets VEV:

$$\langle \mathcal{O}(x) \rangle = f^{\Delta}$$

Single corresponding goldstone boson:

Low, Manohar '01

$$\sigma(x) \to \sigma(e^{\alpha} x) + \alpha f$$

Non-linear realization in effective theory:

$$f \to f\,\chi \equiv f\, e^{\sigma/f}$$

Restores symmetry to LEEFT

Dilaton Couplings

- Presume have a strongly coupled conformal sector coupled to weak sector
- Strong sector has spont. broken scale invariance
- derive interactions of mass eigenstates with dilaton

Dilaton-Composite Couplings

Longitudinal components of W,Z, 3rd generation

UV lagrangian

$$\mathcal{L}_{CFT}^{UV} = \sum_i g_i \mathcal{O}_i^{UV}$$

Allow explicit breaking

$$[g_i] = 4 - \Delta_i^{UV}$$

In IR, different dof

$$\mathcal{L}_{CFT}^{IR} = \sum_j c_j \left(\Pi g_i^{n_i}\right) \mathcal{O}_j^{IR} \chi^{m_j} \qquad m_j = 4 - \Delta_j^{IR} - \sum_i n_i (4 - \Delta_i^{UV})$$

compensate

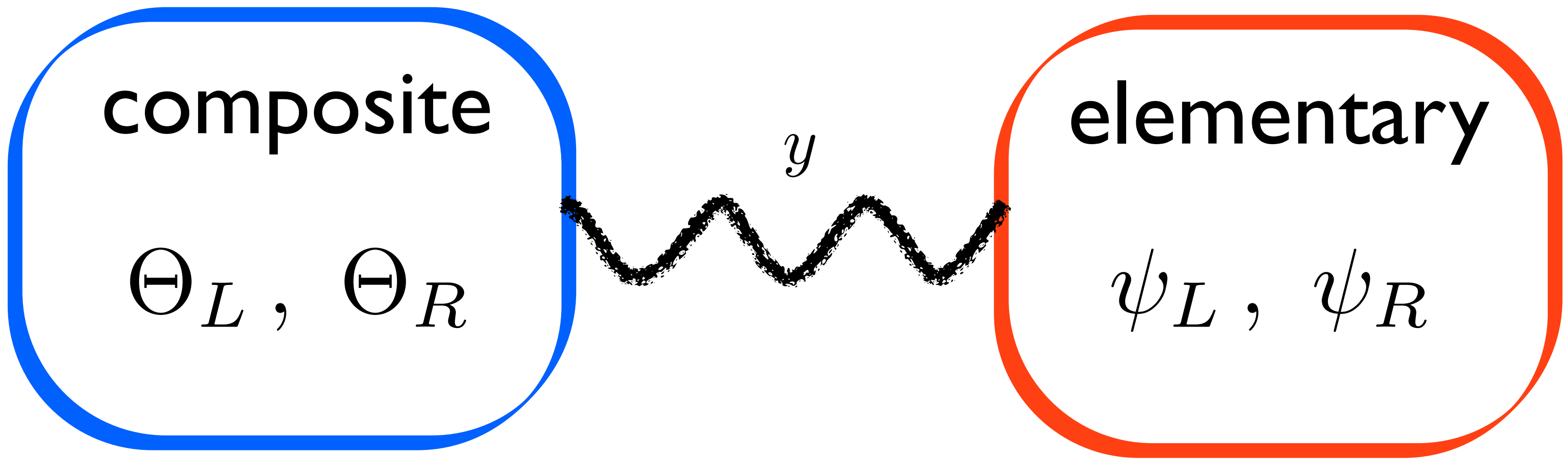
Single power of exp. breaking: $\mathcal{L}_{breaking}^{IR} = \sum_j c_j \, g_i \, \left(\Delta_i^{UV} - \Delta_j^{IR}\right) \mathcal{O}_j^{IR} \frac{\sigma}{f}$

No exp. breaking: $\mathcal{L}_{symmetric}^{IR} = \sum_j c_j \, \left(4 - \Delta_j^{IR}\right) \mathcal{O}_j^{IR} \frac{\sigma}{f}$

$$\frac{\sigma}{f} T_\mu^\mu = \frac{v}{f} \sigma \left\{ \underbrace{\left[2 m_W^2 W_\mu^2 + m_Z^2 Z^2 + m_\psi \psi\psi \ldots\right]}_{\text{rescaled tree-level SM}} + \underbrace{2 \frac{\beta_s}{g} G_{\mu\nu}^2 + 2 \frac{\beta}{e} F_{\mu\nu}^2}_{\text{SM beta-functions}} \right\}$$

Dilaton-Fermion Couplings

Partial Compsiteness



$$\mathcal{L}_{mix} = y_L \psi_L \Theta_R + y_R \psi_R \Theta_L$$

$[y_{R,L}] = -\gamma_{L,R}$ $\qquad 3/2 \qquad 5/2+\gamma_R$

Exponential running of y's generates large mass hierarchies

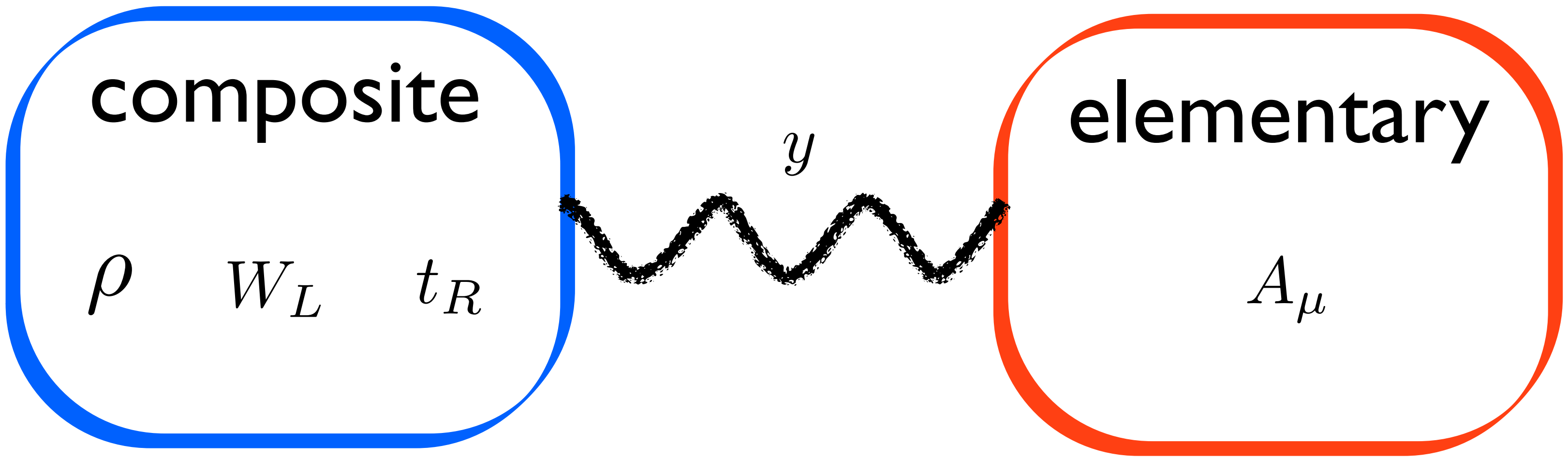
integrate out heavy composites and compensate:

$$\mathcal{L}_{eff} = -M\, y_L\, y_R\, \psi_L \psi_R \chi^m \qquad m\ =\ \Delta^{UV}_{\psi_L} - \Delta^{IR}_{\psi_L} + \Delta^{UV}_{\psi_R} - \Delta^{IR}_{\psi_R} + \Delta^{UV}_{\Theta_L} + \Delta^{UV}_{\Theta_R} - 4$$

$$\boxed{\mathcal{L} \supset m_\psi\, \psi_L \psi_R \left[1 + \frac{\sigma}{f}(1+\gamma_L+\gamma_R)\right]}$$

Enhancement in couplings to partially composite fermions

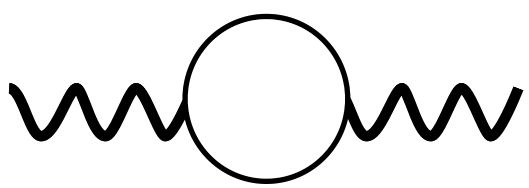
Couplings to massless gauge fields



$$\mathcal{L}_{mix} \supset -\frac{1}{4g^2}F_{\mu\nu}^2 + A_\mu \mathcal{J}^\mu$$

coupling to CFT and fundamental currents

integrate out the CFT: $-\frac{1}{4g^2(\mu)}F_{\mu\nu}^2$



$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} - \frac{b_{UV}}{8\pi^2}\log\frac{\Lambda}{f} - \frac{b_{IR}}{8\pi^2}\log\frac{f}{\mu} - \frac{b_{elem}}{8\pi^2}\log\frac{\Lambda}{\mu}$$

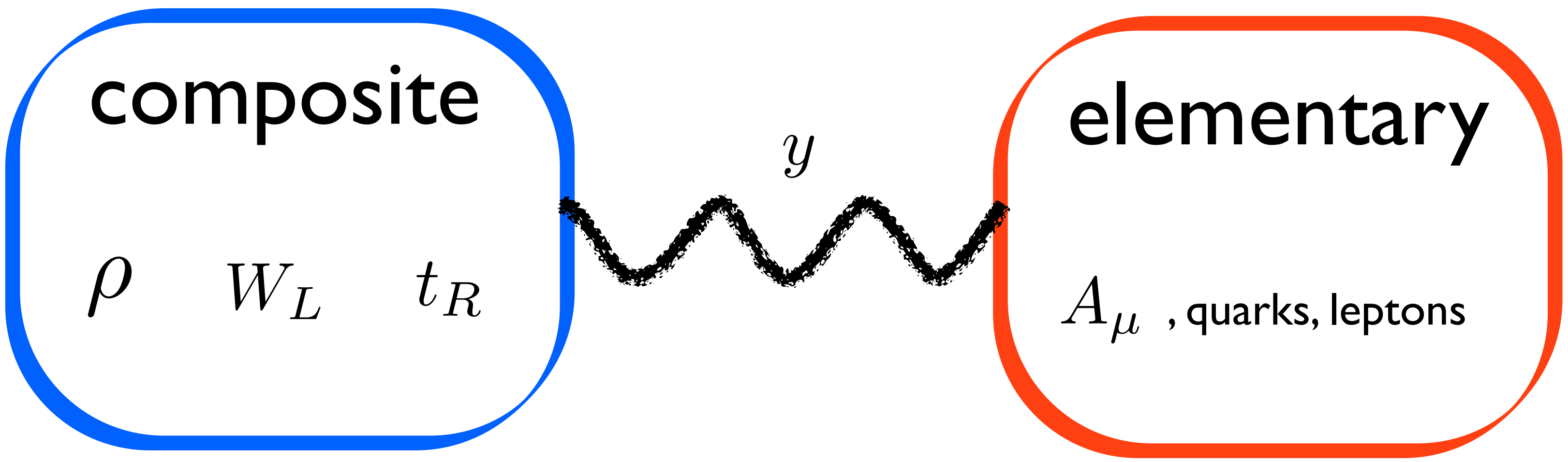
compensate: $f \longrightarrow f\chi = f e^{\sigma/f}$ $\longrightarrow$

$$\mathcal{L} = -\frac{1}{2}\left(\frac{\beta_{IR}}{g} - \frac{\beta_{UV}}{g}\right)\frac{\sigma}{v}F_{\mu\nu}^2$$

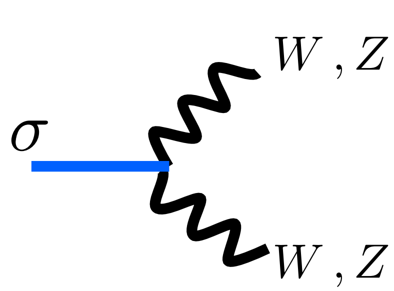
Depends on UV contributions to β-function

UV completion - embedding of SM gauge group

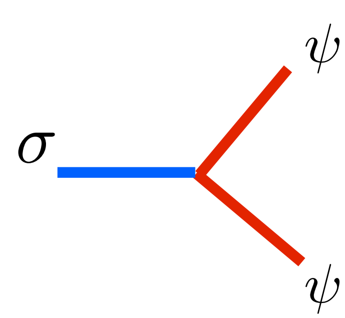
Couplings - Summary



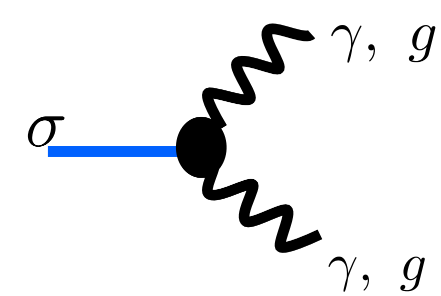
$$\mathcal{L} = \overbrace{\frac{v}{f}}^{\text{overall rescaling}} \sigma \left\{ \left[2m_W^2 W_\mu^2 + m_Z^2 Z^2 + m_\psi \psi \overbrace{(1+\gamma)}^{\text{anomalous dim.}} \psi \ldots \right] + 2 \overbrace{(\beta_{UV} - \beta_{IR})}^{\text{beta-functions}} / g \, F_{\mu\nu}^2 \right\}$$



$SM \times \frac{v}{f}$



$SM \times \frac{v}{f}(1+\gamma)$



$\frac{v}{f}(\beta_{UV} - \beta_{IR} + loops)$

EWP and Flavor

Non-standard couplings = oblique parameters

$$\Delta\hat{T} = -\frac{3\alpha}{16\pi\cos^2\theta_W}(1-c_V^2)\log\left(\frac{\Lambda^2}{m_h^2}\right)\ ,\quad \Delta\hat{S} = +\frac{\alpha}{48\pi\sin^2\theta_W}(1-c_V^2)\log\left(\frac{\Lambda^2}{m_h^2}\right)$$

other contributions from strong dynamics expected

Flavor: $y^i_{L\,a}y^j_{R\,b}\Sigma^{ab}\frac{v}{\sqrt{2}}\psi^i_L\psi^j_R\left[1+\frac{\sigma}{f}\left(1+\gamma^a_L+\gamma^b_L\right)+\ldots\right]$

dilaton interactions & masses not diagonalized simultaneously - tree level FCNC

$$\psi^i_L\psi^j_R\left[m_i\left(1+\frac{\sigma}{f}\right)\delta_{ij}+a_{ij}\sqrt{m_i m_j}\frac{\sigma}{f}+\ldots\right]$$

4F ops: $\sim a_{ij}\sqrt{m_i m_j}/(m_{dil}^2 f^2)$

require flavor symmetry: $SU(3)_q\times SU(3)_d\times SU(2)_u$

Can it be light?

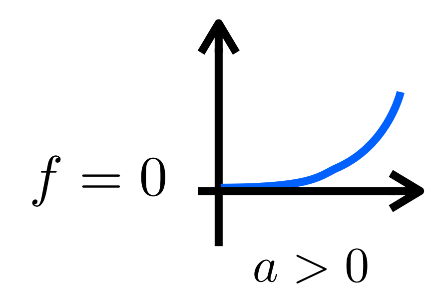
The Dilaton Quartic

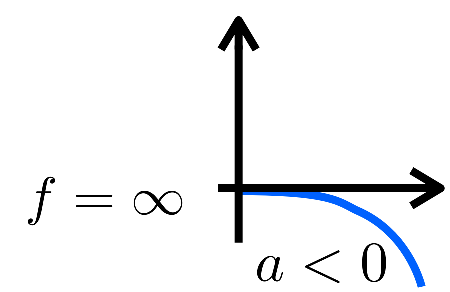
Most general terms invariant under dilatations:

$$\mathcal{L}_{eff} = \sum_{n,m \geqslant 0} \frac{a_{n,m}}{(4\pi)^{2(n-1)}\, f^{2(n-2)}} \frac{\partial^{2n}\chi^m}{\chi^{2n+m-4}}$$

$$= -\underbrace{a_{0,0}\,(4\pi)^2 f^4\chi^4}_{\text{dilaton quartic}} + \frac{f^2}{2}(\partial_\mu\chi)^2 + \frac{a_{2,4}}{(4\pi)^2}\frac{(\partial\chi)^4}{\chi^4} + \ldots$$

$$S = \int d^4x \frac{f^2}{2}(\partial\chi)^2 - af^4\chi^4 + \text{higher derivatives}$$

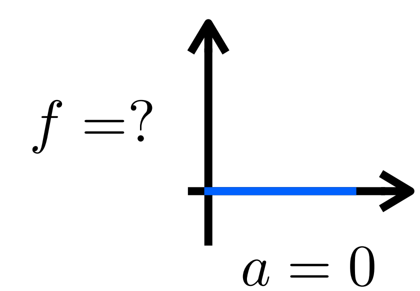




Obstruction to SBSI:

Fubini '76

- a > 0 → f = 0 (no breaking)
- a < 0 → f = ∞ (runaway)
- a = 0 → f = anything (flat direction)



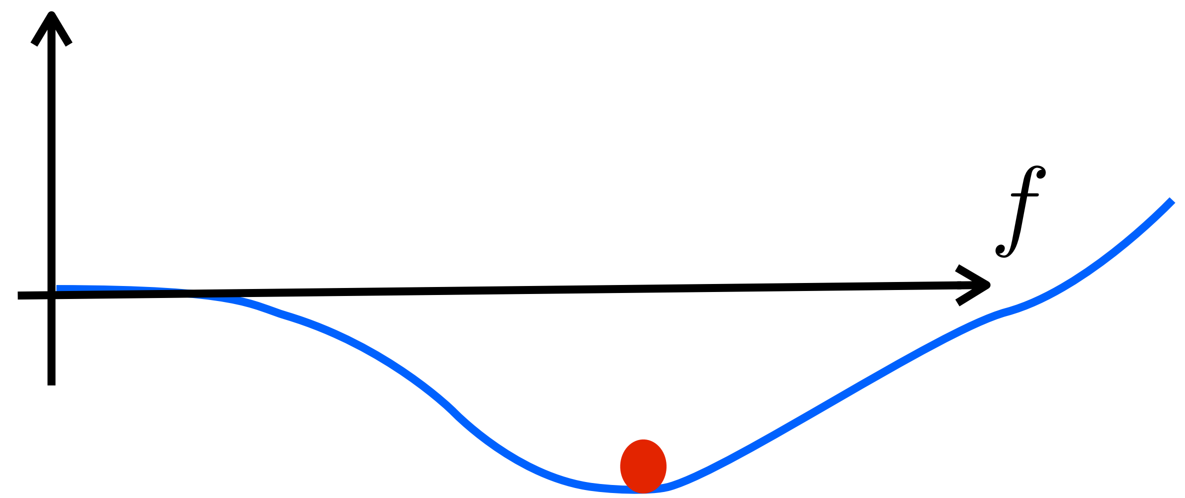
Near-Marginal Deformation

$$\delta S = \int d^4x \lambda(\mu) \mathcal{O}$$

Quartic has dependence on near marginal coupling:

$$V(\chi) = a\chi^4 \longrightarrow \boxed{V = \chi^4 F(\lambda(\chi))}$$

slowly varying function of f



Deformation can stabilize f away from origin

$$V' = f^3 \left[4F(\lambda(f)) + \beta F'(\lambda(f))\right] = 0$$

The Dilaton Mass

Expanding the potential:

$$m_{dil}^2 = f^2\beta\left[\beta F'' + 4F' + \beta' F'\right] \simeq 4f^2\beta F'(\lambda(f)) = -16f^2F(\lambda(f))$$

small, so dilaton is light, right?

F is the cosmological constant in f units:

$$F_{NDA} \sim \frac{\Lambda^4}{16\pi^2 f^4} \sim 16\pi^2$$

Need *large* β to find minimum $V' = f^3\left[4F(\lambda(f)) + \beta F'(\lambda(f))\right] = 0$

Theory not conformal at scale f - **no light dilaton**

$$m_{dil}^2 \sim 256\pi^2 f^2 \sim \Lambda^2$$ **3 TeV *not* 125 GeV**

OR we can *tune* away the quartic to get a near flat-direction

Higgslike Radion?

What about f?

$$f^{(RS)} = \frac{1}{R'}\sqrt{12(M_* R)^3} = \frac{N_{\text{CFT}}}{R'}$$

Higgsless dilaton:

$$\frac{v}{f^{(RS)}} = \frac{2}{g}\frac{1}{N\sqrt{\log\frac{R'}{R}}}$$

Heavy IR Higgs

$$\frac{v}{f^{(RS)}} = \frac{vR'}{N}$$

Far too small to be consistent with LHC data

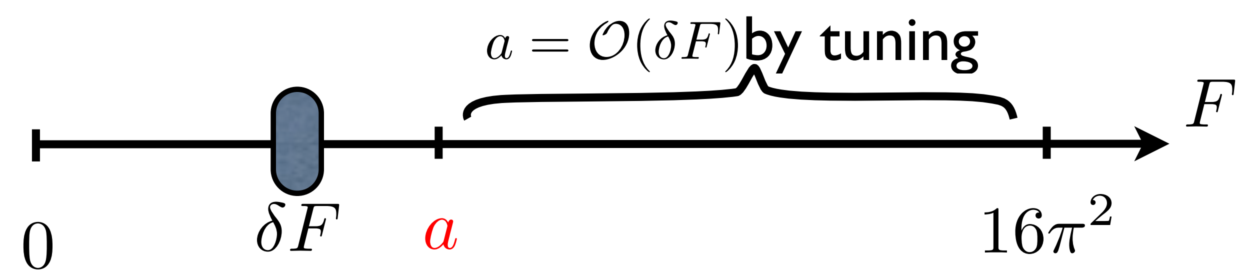
It does suppress mass (once quartic tuning imposed):

$$m_{dil}^2 = \frac{16}{NR'^2}\left(v_1\sqrt{-\delta a} - \frac{\delta a}{2}\right)\epsilon$$

Light Dilaton?

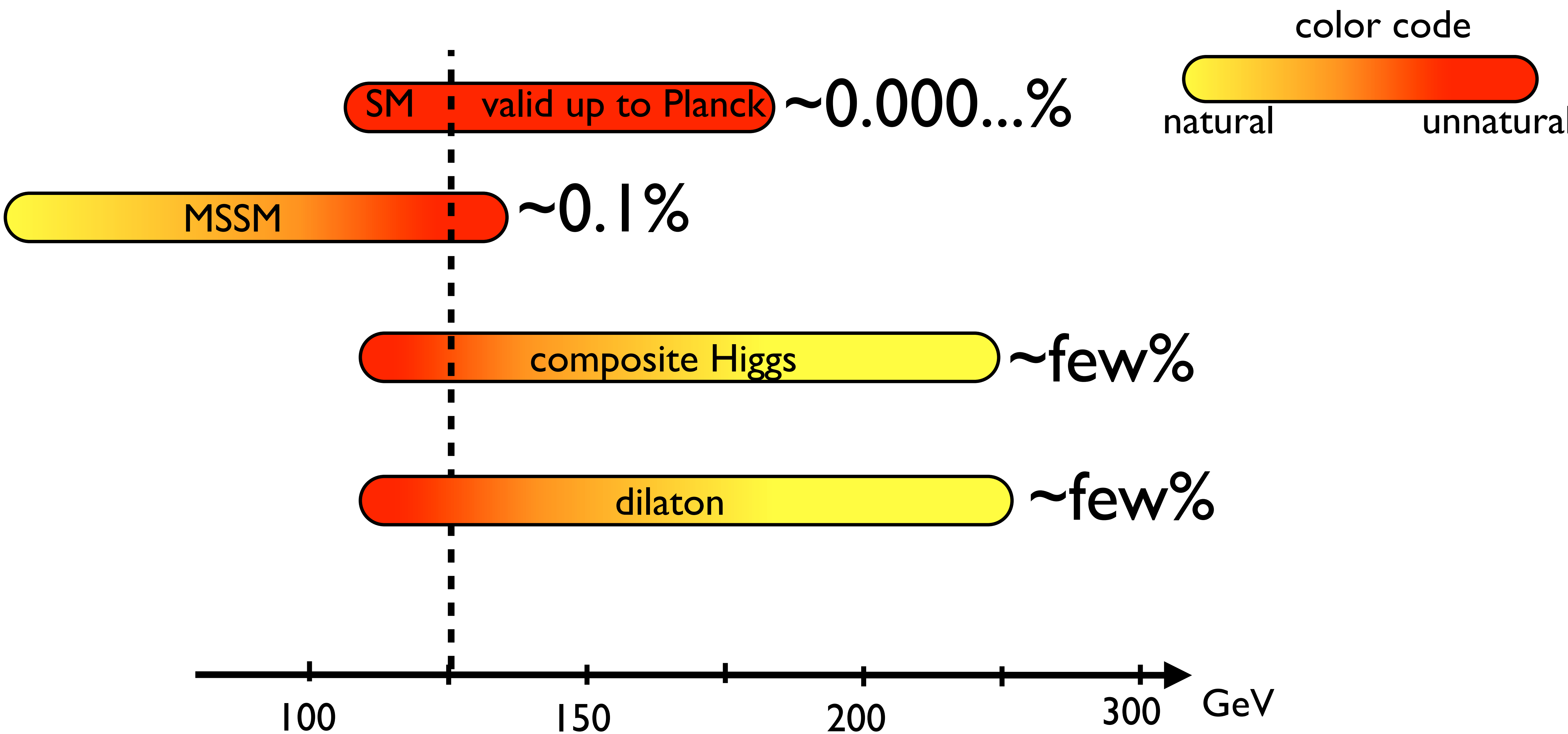
Non-SUSY light dilaton:

$F(\lambda) = a + \delta F(\lambda)$



- Generically, dilaton is not light unless the quartic is suppressed relative to NDA
- To get a light dilaton, need flat direction in vicinity of near-zero in β-function or large N
- While this is natural in SUSY theories, it is not usually the case in non-supersymmetric ones
- When dilaton is light, does not seem very Higgslike

The EWSB line-up



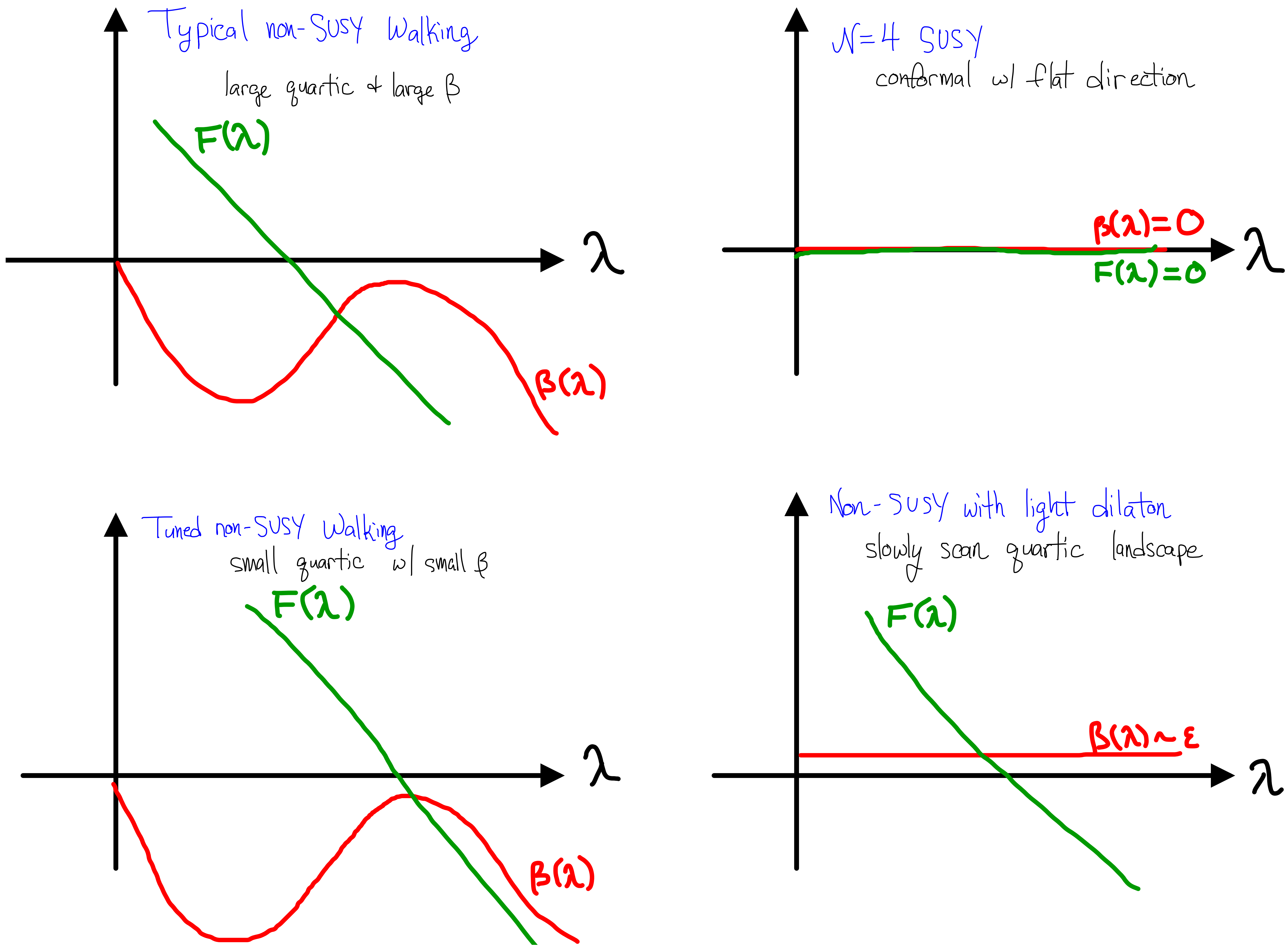
dilaton and composite Higgs seem to be similarly strained

A way out? CPR idea

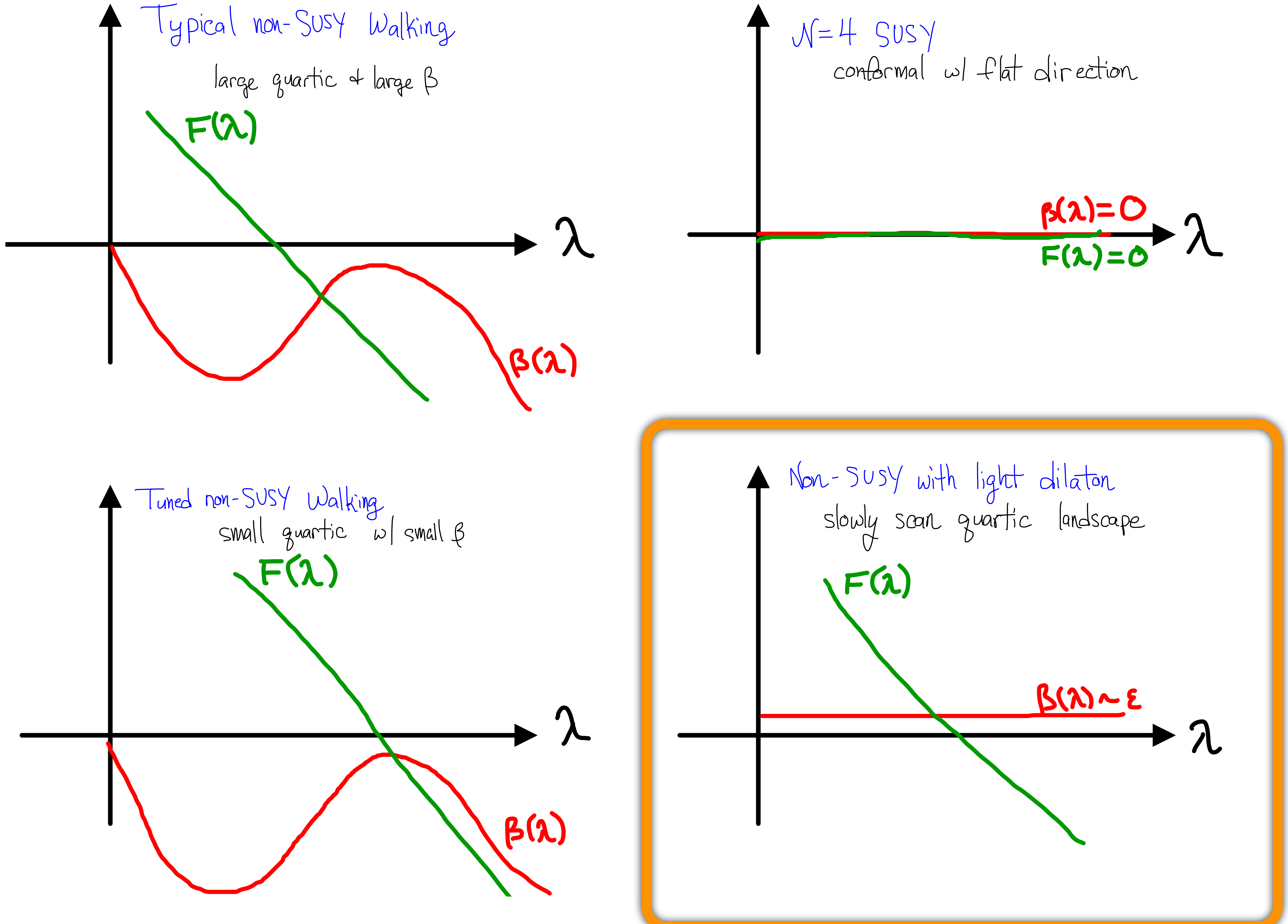
- F(λ) generically large, but if λ near marginal for range of λ, theory will scan over F with scale

$$\frac{d\lambda}{d\log\mu} = \beta(\mu) \equiv \epsilon \ll 1$$

- large F will not generate SBSI - minimum when F ~ 0
- dilaton mass proportional to ε



Typical non-SUSY Walking
large quartic & large β
F(λ)
β(λ)
λ
$\mathcal{N}=4$ SUSY
conformal w/ flat direction
β(λ)=0
F(λ)=0
λ
Tuned non-SUSY Walking
small quartic w/ small β
F(λ)
β(λ)
λ
Non-SUSY with light dilaton
slowly scan quartic landscape
F(λ)
β(λ)~ε
λ



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F(λ)
β(λ)~ε
λ

Holography and light dilatons

$$S=\int d^5x\sqrt{g}\left(-\frac{1}{2\kappa^2}\mathcal{R}+\frac{1}{2}g^{MN}\partial_M\phi\partial_N\phi-V(\phi)\right)+\int d^4x\sqrt{g_0}V_0(\phi)+\int d^4x\sqrt{g_1}V_1(\phi)$$

AdS/CFT:

small β ⇔ nearly constant V(Φ)

$$V(\phi)=\Lambda_5+\epsilon f(\phi)$$

Metric Ansatz - flat 4D slices

$$ds^2=e^{-2A(y)}dx^2-dy^2$$

ID of scale - warping

$$\mu=A'(y=0)e^{-A(y)}=\frac{1}{R}e^{-A(y)}$$

Bulk EOM

$$\begin{aligned}4A'^2-A'' &= -\frac{2\kappa^2}{3}V(\phi)\\ A'^2 &= \frac{\kappa^2\phi'^2}{12}-\frac{\kappa^2}{6}V(\phi)\\ \phi'' &= 4A'\phi'+\frac{\partial V}{\partial\phi}\end{aligned}$$

Boundary conditions:

$$\begin{aligned}2A'|_{y=y_0,y_1} &= \pm\frac{\kappa^2}{3}V_1(\phi)|_{y=y_0,y_1}\\ 2\phi'|_{y=y_0,y_1} &= \pm\frac{\partial V_1}{\partial\phi}|_{y=y_0,y_1},\end{aligned}$$

Holography and light dilatons

Imposing bulk eom on V$_{bulk}$ gives pure boundary term

$$V_{bulk} = \frac{2}{\kappa^2}\int_{y_0}^{y_1} dy e^{-4A(y)}(4A'^2 - A'') = -\left[\sqrt{g}\frac{2}{\kappa^2}A'\right]_0^1$$

Other similar terms from brane potentials and metric jump conditions

$$\chi \equiv e^{-A(y_1)}$$

Dilaton effective potential:

$$V_{IR} = \chi^4\left[V_1\left(\phi\left(A^{-1}(-\log\chi)\right)\right) + \frac{6}{\kappa^2}A'\left(A^{-1}(-\log\chi)\right)\right] = \chi^4 F(\lambda(\chi))$$

Automatically minimized when BC's satisfied

Precisely of form quartic modulated by chi dep. of F

Constant Bulk Potential

$$V(\phi) = \Lambda_{(5)} = -\frac{6k^2}{\kappa^2}$$

Solvable:

$$A(y) \quad = \quad -\frac{1}{4}\log\left[\frac{\sinh 4k(y_c - y)}{\sinh 4ky_c}\right]$$

Singularity at y_c

$$\phi(y) \quad = \quad -\frac{\sqrt{3}}{2\kappa}\log\tanh[2k(y_c - y)] + \phi_0$$

Impose UV Boundary Conditions: fix y_c and Φ_0

$$V_i(\phi) = \Lambda_i + \lambda_i(\phi - v_i)^2$$

Boundary conditions generically satisfied for finite y_c

Large AdS deformation!

$$ds^2 = \sqrt{\frac{\sinh 4k(y_c - y)}{\sinh 4ky_c}}dx^2 - dy^2$$

But Still Scale Invariant

explicitly broken by dynamical gravity - finite μ_0

$$V_{UV} \quad = \quad \mu_0^4 \left(\Delta_0 + \mathcal{O}(\chi^8/\mu_0^8) \right)$$

Pure UV Contribution to CC term

$$V_{IR} \quad = \quad \chi^4 \left(a(v_0) + \mathcal{O}(\chi^4/\mu_0^4) \right)$$

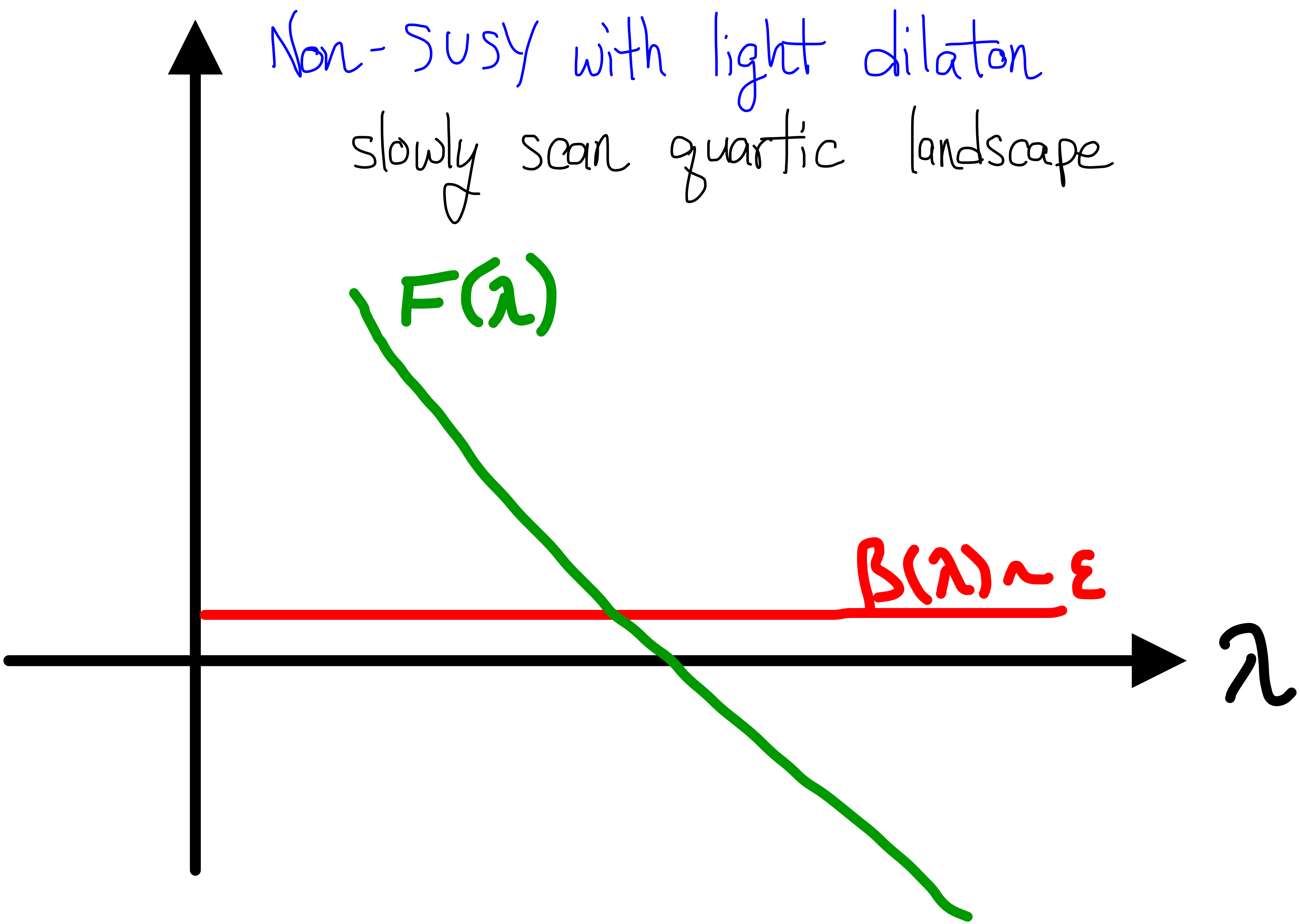
Pure dilaton quartic

Singularity at y_c corresponds to condensate of marginal operator in CFT - spont. breaking of SI

Dilaton quartic is from composite condensates (IR tension) and the condensate of this operator

$$a(v_0) = \Lambda_1 + \frac{6k}{\kappa^2} \cosh\left(\frac{2\kappa}{\sqrt{3}} (v_1 - v_0) \right)$$

can tune this away by adjusting v_0



If β=0, no scanning, have to tune condensates against each other - special value of coupling

Including a bulk mass

CFT coordinates

$$t = \log \mu R = -A(y)$$

Use bulk eom to eliminate A(y):

$$\ddot{\phi} + \left[4\dot{\phi} + \frac{6}{\kappa^2}\frac{\partial \log V}{\partial \phi}\right]\left[1 - \frac{\kappa^2}{12}\dot{\phi}^2\right] = 0$$

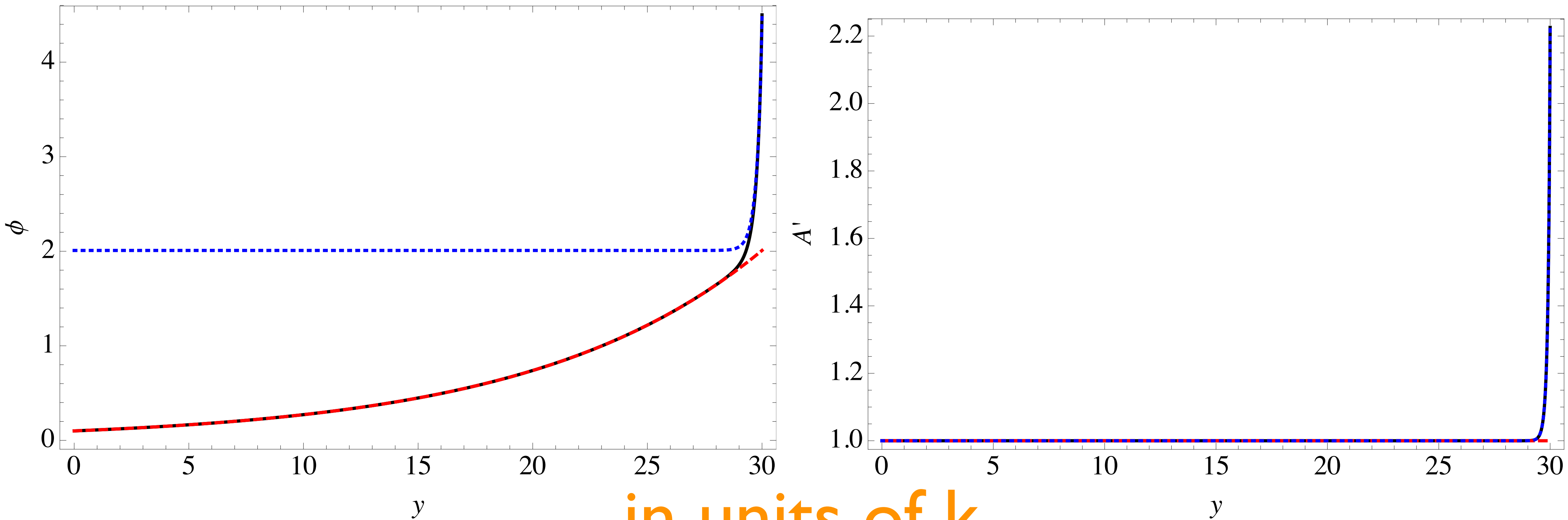
neglecting non-linear terms (small back-reaction):

$$\ddot{\phi} + 4\dot{\phi} - 4\epsilon\phi = 0 \qquad \phi(t) \approx A e^{-(4+\epsilon)t} + B e^{\epsilon t}$$

slowly running piece

now Φ_0 **scans** - finds minimum when quartic small

Boudary layer theory - asymptotic matching



in units of k

Figure 2: Left, bulk scalar profile: ϕ_{full} (solid black), ϕ_r (dashed red), and ϕ_b (dotted blue). Right, effective AdS curvature, $A'(y)$: same color code.

Two regions

$$\ddot{\phi} + \left[4\dot{\phi} + \frac{6}{\kappa^2}\frac{\partial \log V}{\partial \phi}\right]\left[1 - \frac{\kappa^2}{12}\dot{\phi}^2\right] = 0$$

Backreaction term

Eventually, back-reaction comes to dominate

IR Universality - condensate of d ~ 4 operator

(IR region has same behavior as constant bulk potential)

Full matched solution

(boundary layer theory/asymptotic matching)

$$\phi_{\rm full} \;=\; v_0\, e^{\epsilon k(y-y_0)} - \frac{\sqrt{3}}{2\kappa}\log\left(\tanh\left(2k(y_c - y)\right)\right)$$

Including a bulk mass

You get a hierarchy:

$$\frac{\langle \chi \rangle}{\mu_0} = \left(\frac{v_0}{v_1 - \ \mathrm{sign}(\epsilon) \frac{\sqrt{3}}{2\kappa} \, \mathrm{arcsech}(-6k/\kappa^2 \Lambda_1)} \right)^{1/\epsilon} + O(\epsilon)$$

Condensate balances other contributions naturally (IR brane tension mistune)

Dilaton comes out light with suppressed CC:

$$m^2_{\mathrm{dilaton}} \sim \epsilon f^2 \qquad \Lambda_{\mathrm{CC}} \sim \epsilon f^4$$

UV value still tuned to be small

- only erase condensate contributions

Conclusions

- If the 126 GeV resonance is a dilaton, it must be very Higgslike indeed
- Tensions: EWP, Flavor, mass tuning, Higgs fits
  - crucial to pin down properties with more data
- General considerations for light dilatons:
  - theory might be able to scan landscape of quartics to achieve SBSI (CPR)
  - non-supersymmetric models with light dilatons seem very special - constant and small β for large range of strong coupling