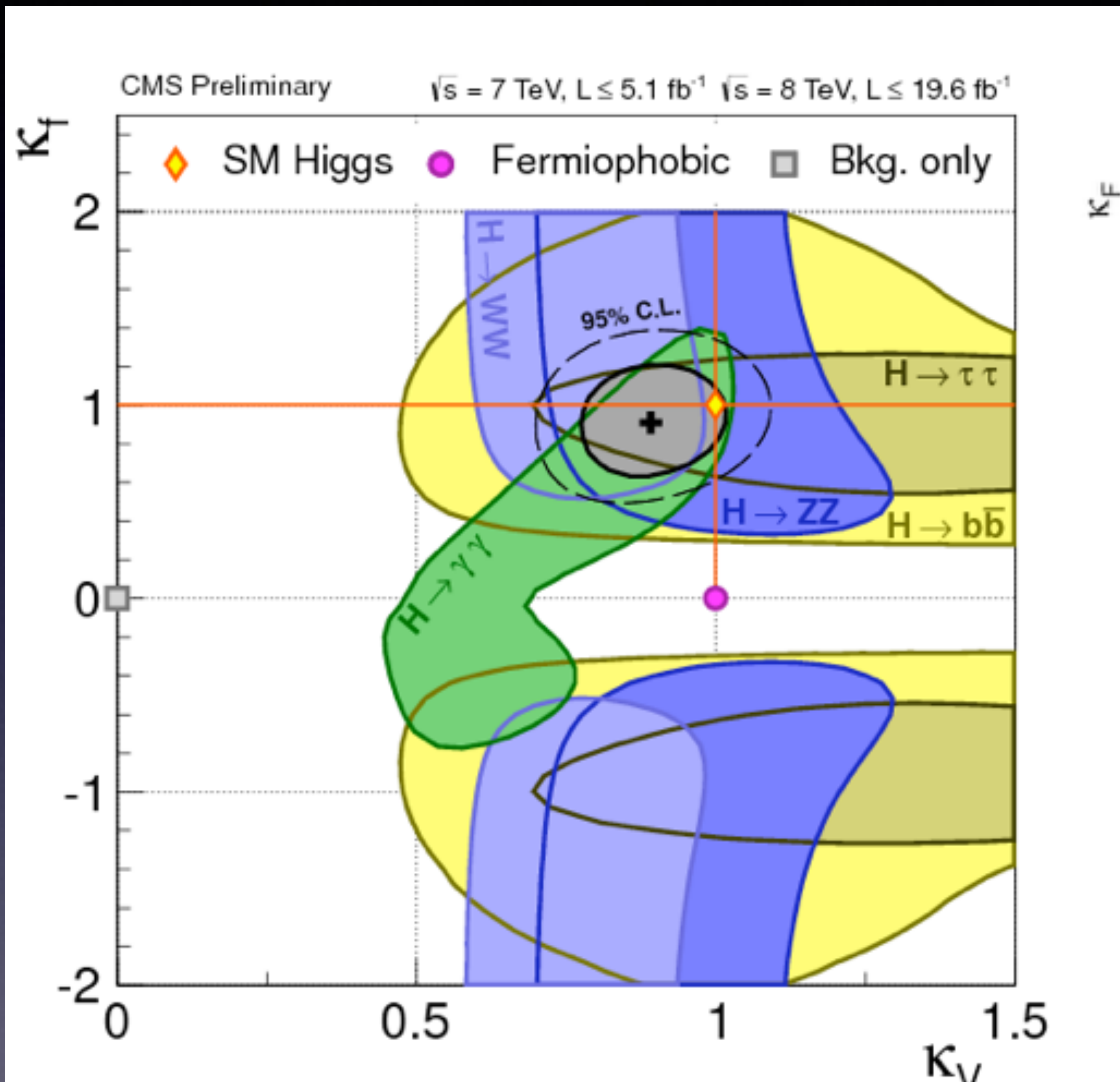
A Recipe for a Light Dilaton from Strong Dynamics

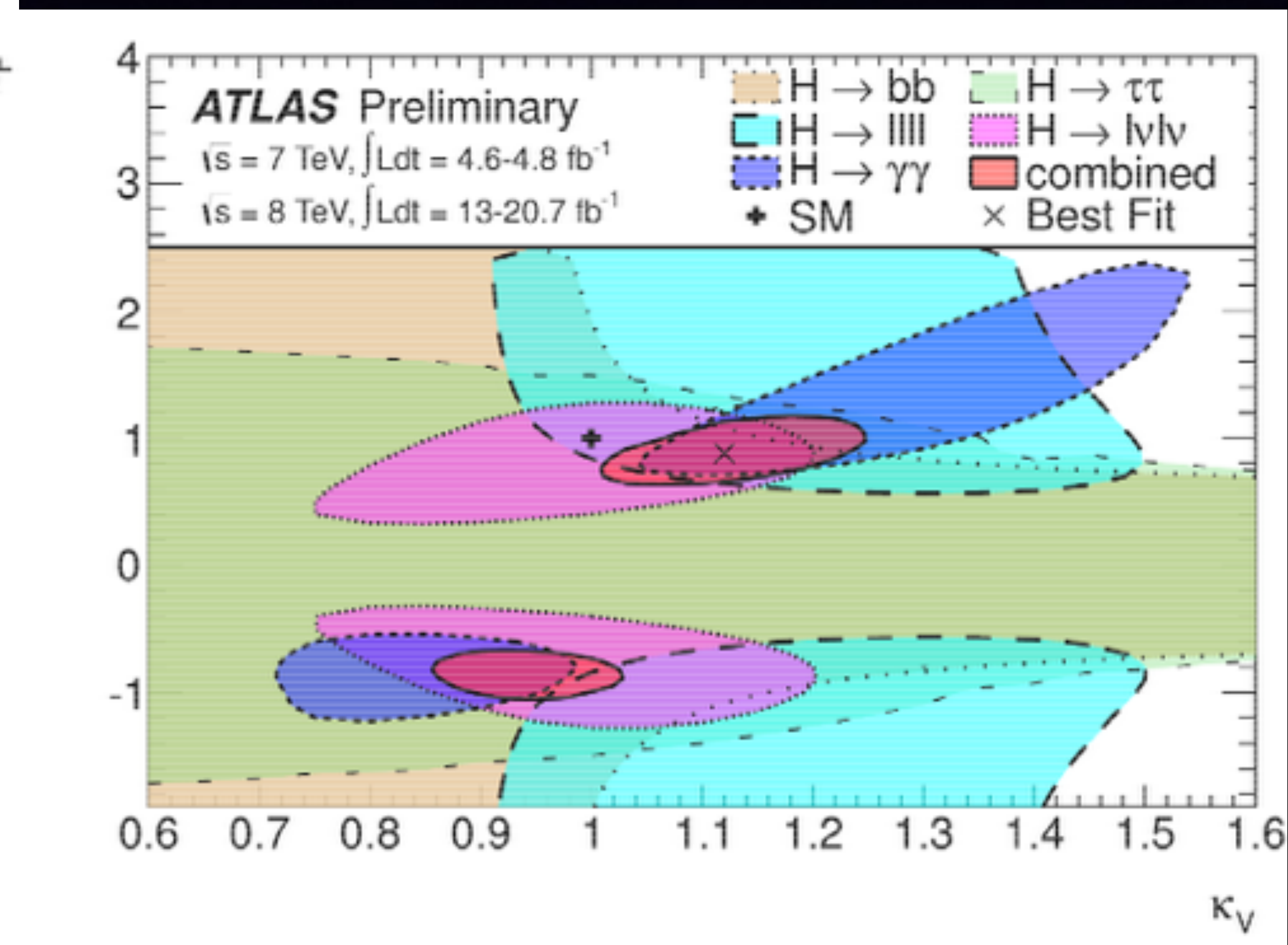
Jay Hubisz
12/6/2013
BNL "Lattice Meets Experiment 2013"
Syracuse University

with: Brando Bellazzini, Csaba Csáki, Javi Serra, John Terning

hep-ph:1209.3299
and hep-th:1305.3919

Higgs-like

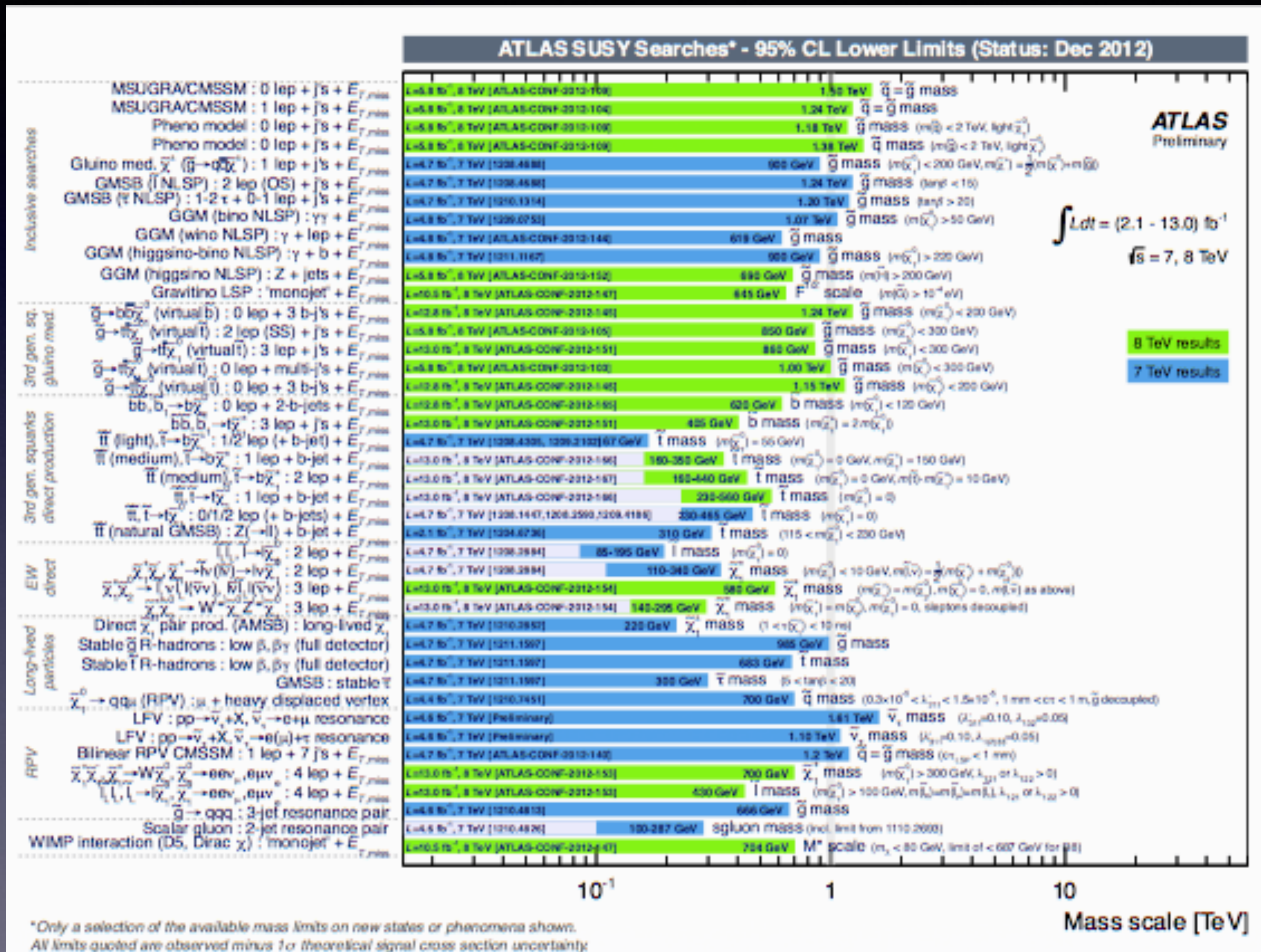




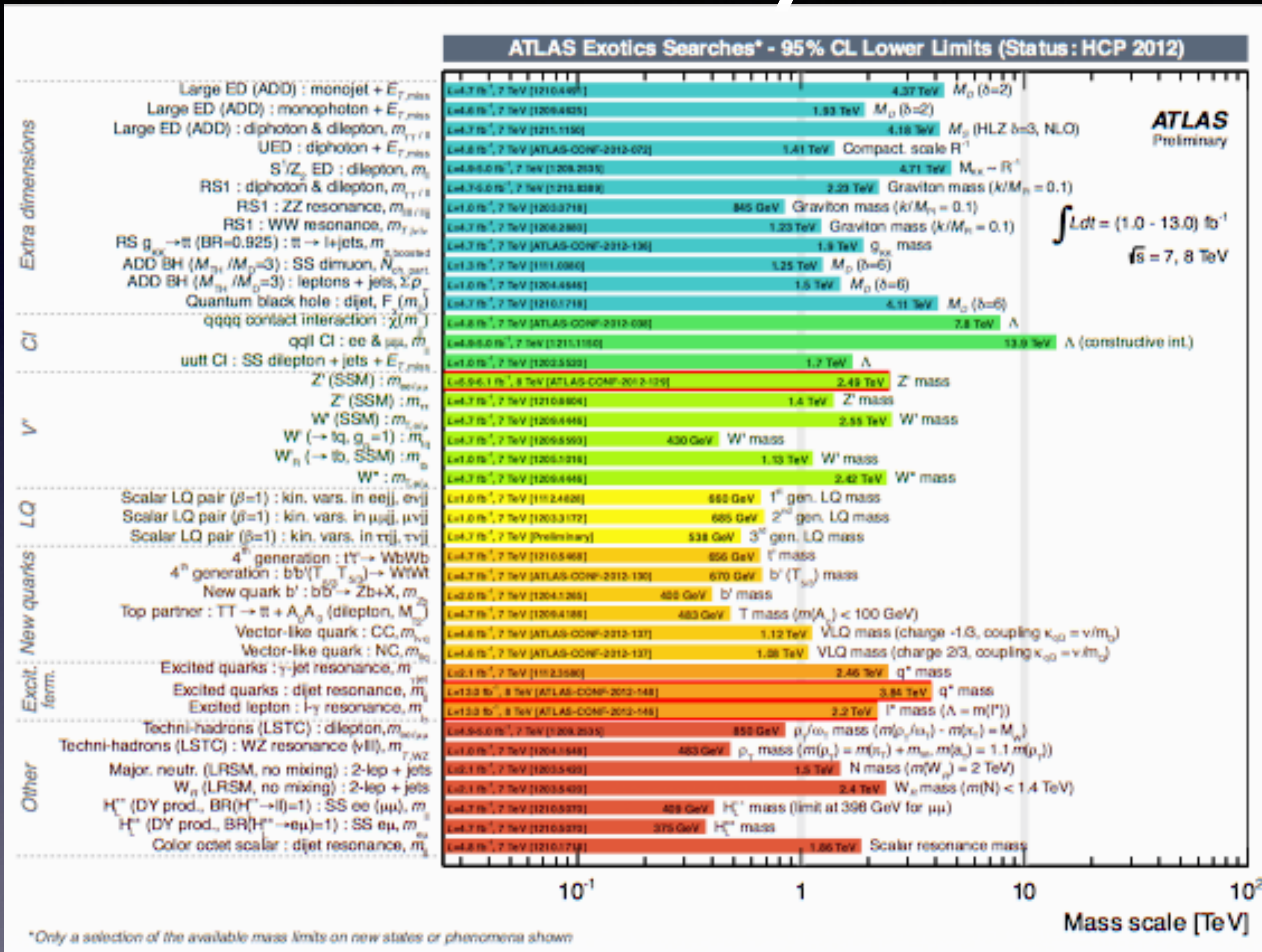
The resonance is at ~126 GeV and it is SM-Higgs-like

10% -ish deviations still allowed

Non-discovery SUSY

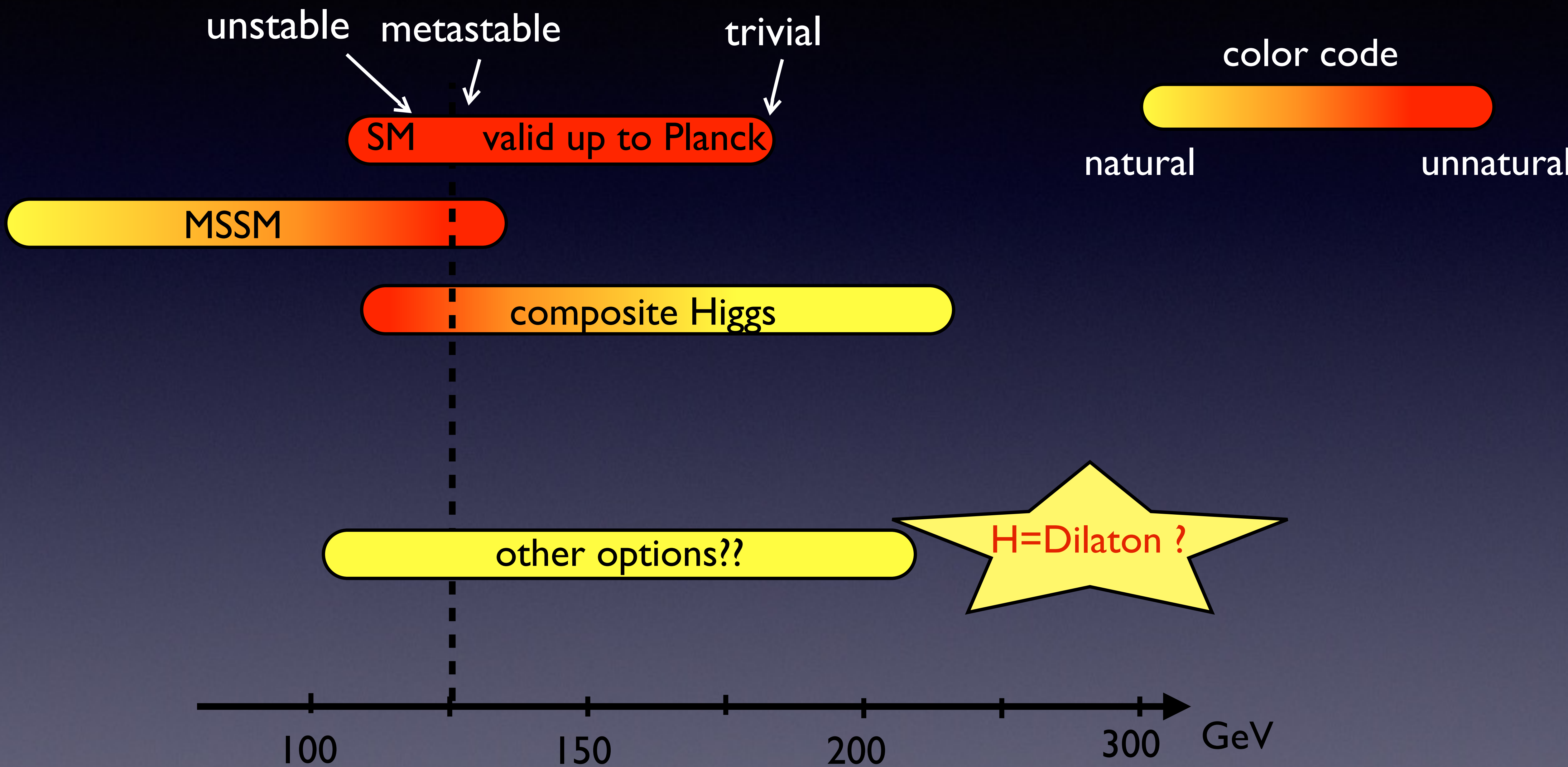


Non-discovery exotics



+electroweak - Gap to new physics - Natural?

Status of light scalars



All models seem to be under strain

S.B. Scale invariance

Dilatations:

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

Operators transform:

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

CFT operator gets VEV:

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

Corresponding goldstone boson:

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

Non-linear realization in effective theory:

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

Restores symmetry to LEEFT

Dilaton Couplings

- Presume a strongly coupled conformal sector coupled to weak elementary sector
- Strong sector has SBSI
- derive interactions of mass eigenstates with dilaton

Dilaton-Composite Couplings

Longitudinal components of W,Z, 3rd generation

UV lagrangian

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

Allow small explicit breaking

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

In IR, different dof

$$\mathcal{L}^{IR}_{CFT} = \sum_j c_j \left(\Pi g_i^{n_i}\right) \mathcal{O}^{IR}_j \chi^{m_j}$$

compensate

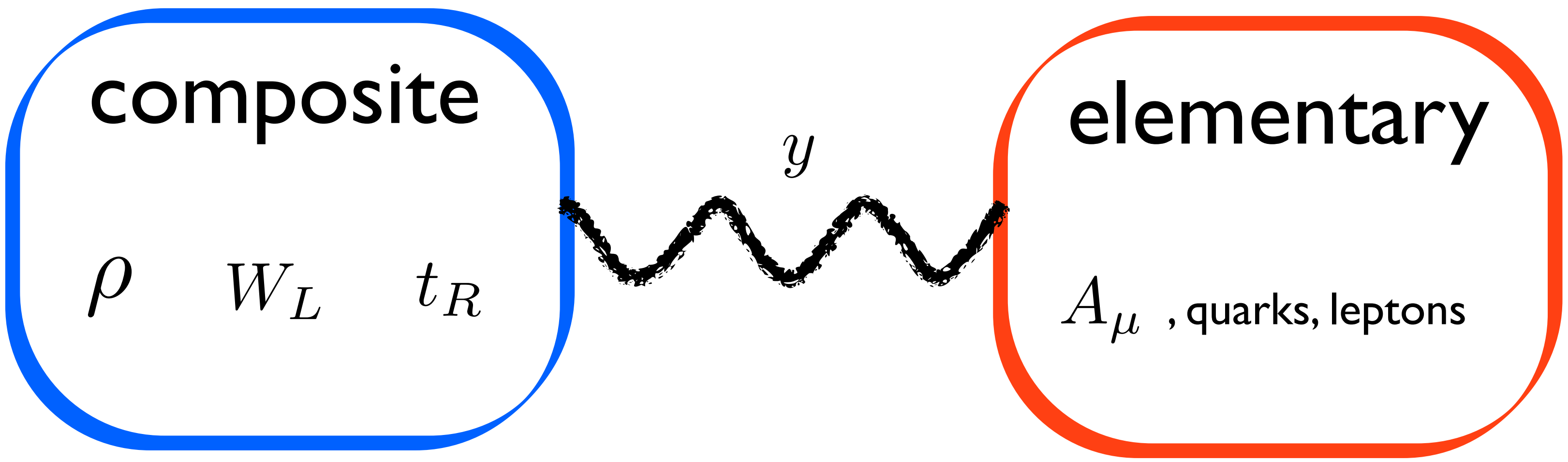
$$m_j = 4 - \Delta^{IR}_j - \sum_i n_i (4 - \Delta^{UV}_i)$$

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

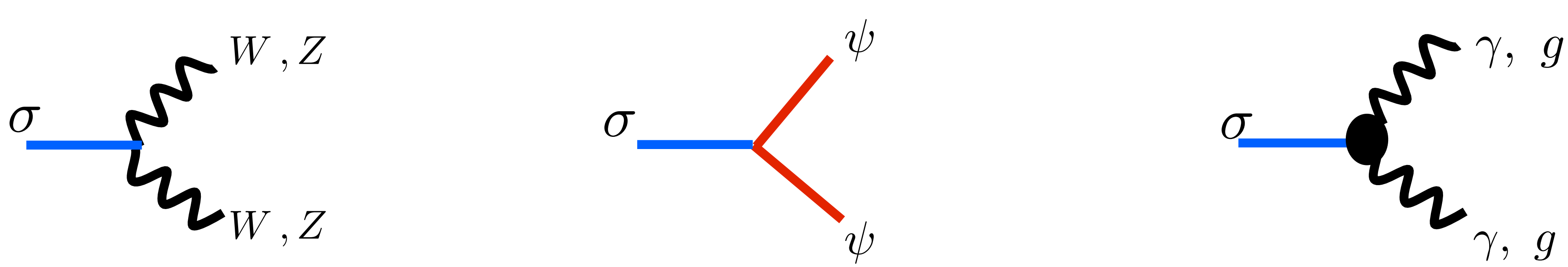
No exp. breaking: $$\mathcal{L}^{IR}_{symmetric} = \sum_j c_j\, \left(4 - \Delta^{IR}_j\right) \mathcal{O}^{IR}_j \frac{\sigma}{f}$$

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

Couplings - Summary



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



$SM \times \frac{v}{f}$ $\qquad$ $SM \times \frac{v}{f}(1+\gamma)$ $\qquad$ $\frac{v}{f}(\beta_{UV} - \beta_{IR} + loops)$

Experiment

- If the 125 GeV scalar is a dilaton we require:
  - v ~ f (Alignment of electroweak vev with CFT operator vev)
  - moderate anomalous dimensions for heavy flavor (b, tau) and flavor symmetry
  - *Significant gap* to scale of strong dynamics

Can it be light?

The Dilaton Quartic

Most general terms invariant under dilatations:

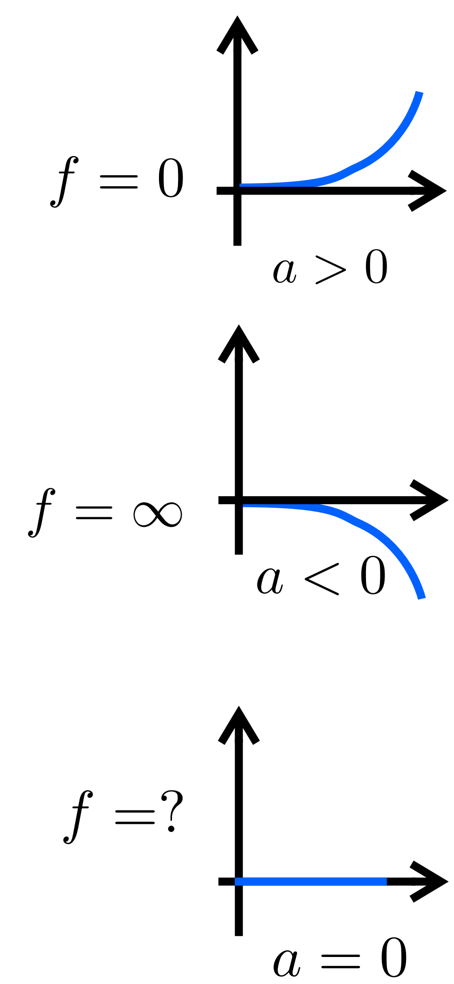
$$
\begin{aligned}
\mathcal{L}_{eff} &= \sum_{n,m\geqslant 0} \frac{a_{n,m}}{(4\pi)^{2(n-1)}\, f^{2(n-2)}} \frac{\partial^{2n}\chi^m}{\chi^{2n+m-4}} \\
&= -a_{0,0}\,(4\pi)^2 f^4\chi^4 + \frac{f^2}{2}(\partial_\mu\chi)^2 + \frac{a_{2,4}}{(4\pi)^2}\frac{(\partial\chi)^4}{\chi^4} + \ldots
\end{aligned}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

dilaton quartic

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

Obstruction to SBSI:

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



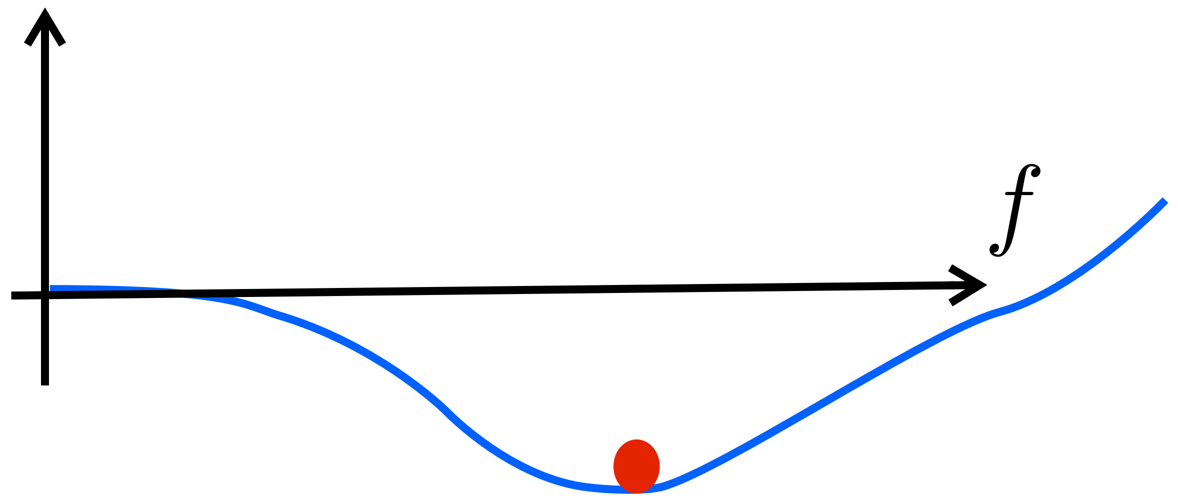
Near-Marginal Deformation

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

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:

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

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

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

Goldberger-Wise

Brane values of GW scalar field

quartic mistune

$$V = f^4 \left\{ (4+2\epsilon) \left[v_1 - v_0 \left(fR \right)^{\epsilon} \right]^2 - \epsilon v_1^2 + \delta a + O(\epsilon^2) \right\} = f^4 F(f)$$

UV IR

bulk potential

scalar - near marginal coupling in CFT

$$f = \frac{1}{R} \left(\frac{v_1 + \sqrt{-\delta a/4}}{v_0} + O(\epsilon) \right)^{1/\epsilon}$$

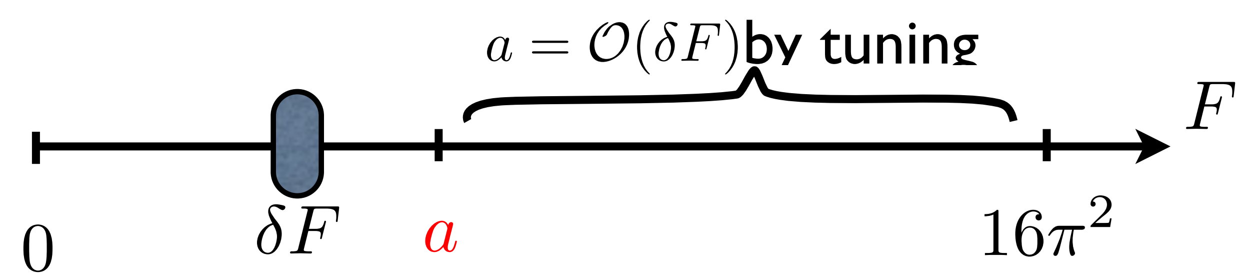
yields hierarchy for $\sqrt{-\delta a/4} \lesssim v_1$

tuning: $\Delta = \frac{a}{|\delta a|} \gtrsim \frac{4\pi^2}{v_1^2}$ typically order 1000

Light Dilaton?

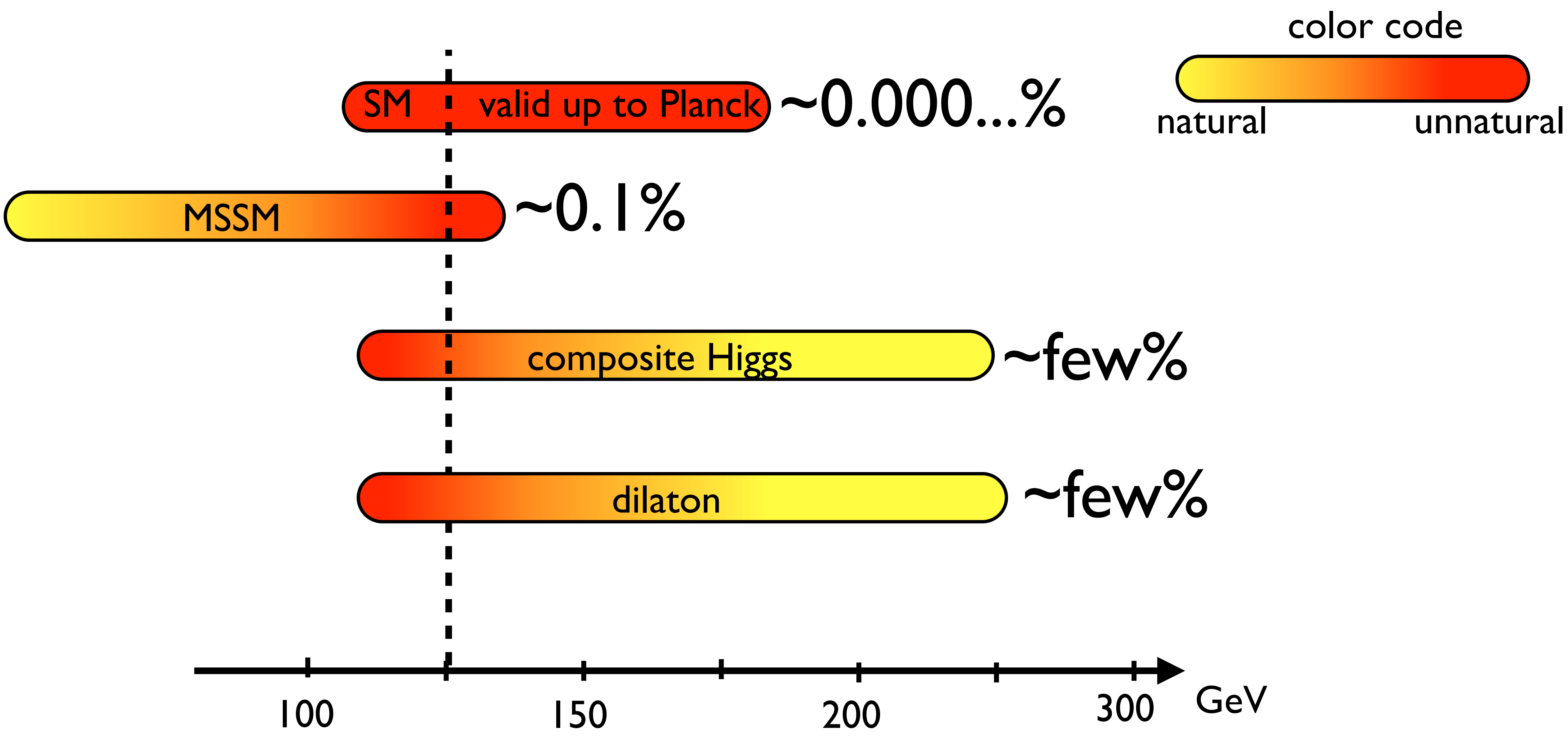
Non-SUSY light dilaton:

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



- 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 the case in non-supersymmetric ones
- When dilaton is light, does not seem very Higgslike

The EWSB line-up



dilaton and composite Higgs in a similar strained state

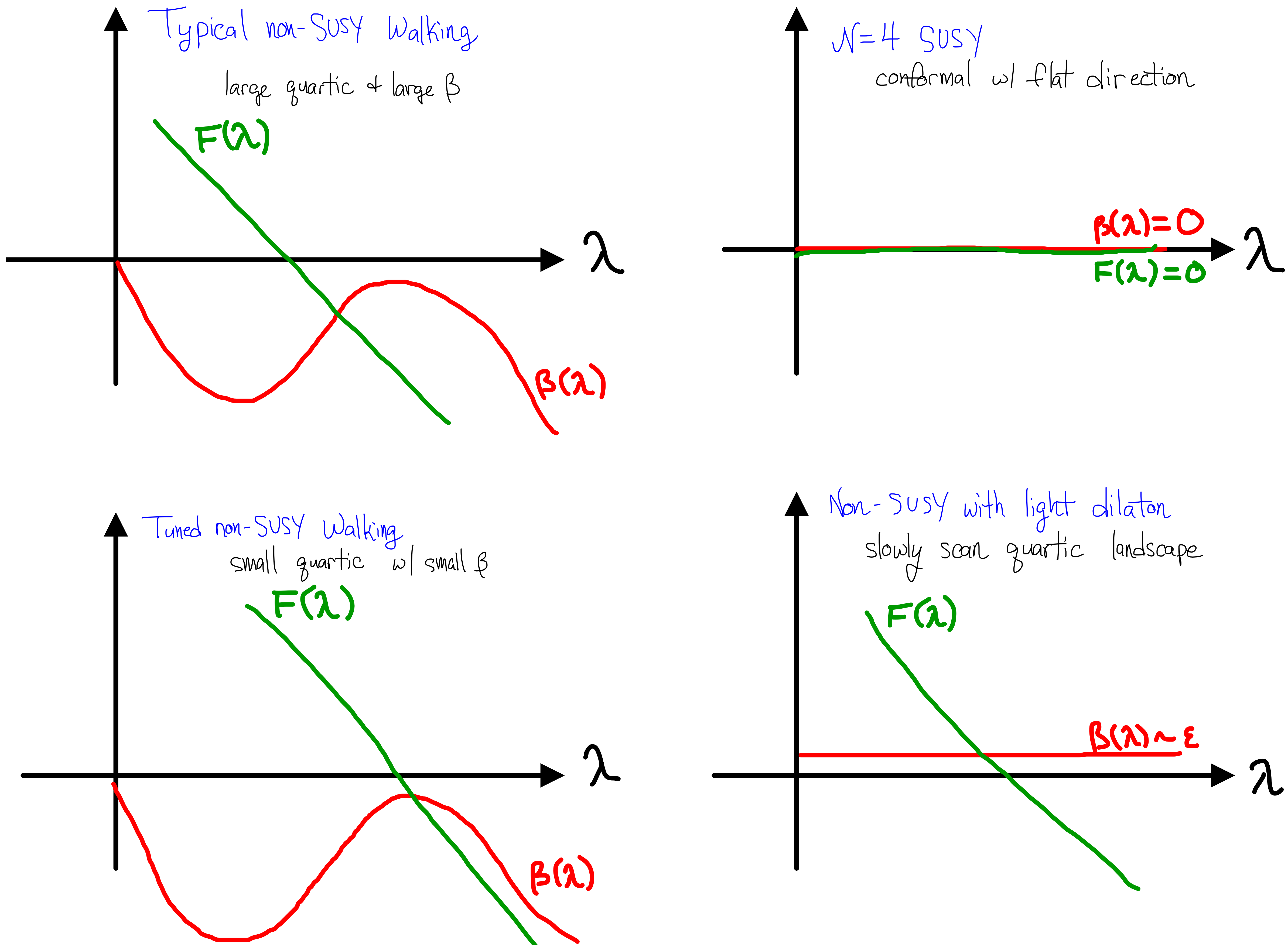
A way out?

CPR idea (Contino - Pomarol - Rattazzi)

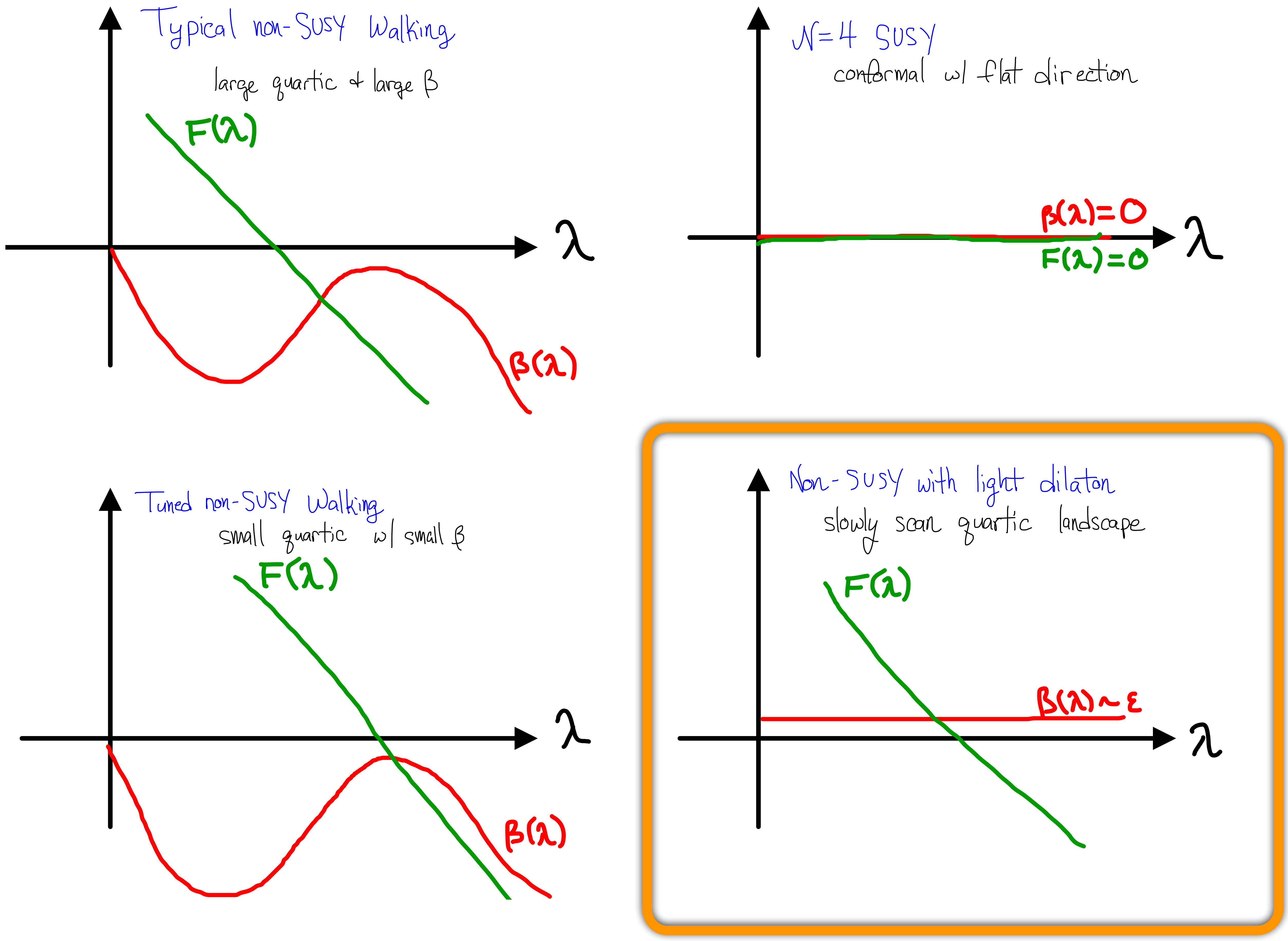
- F(λ) generically large, but if λ near marginal for large range of λ, theory will scan over F with scale

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

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

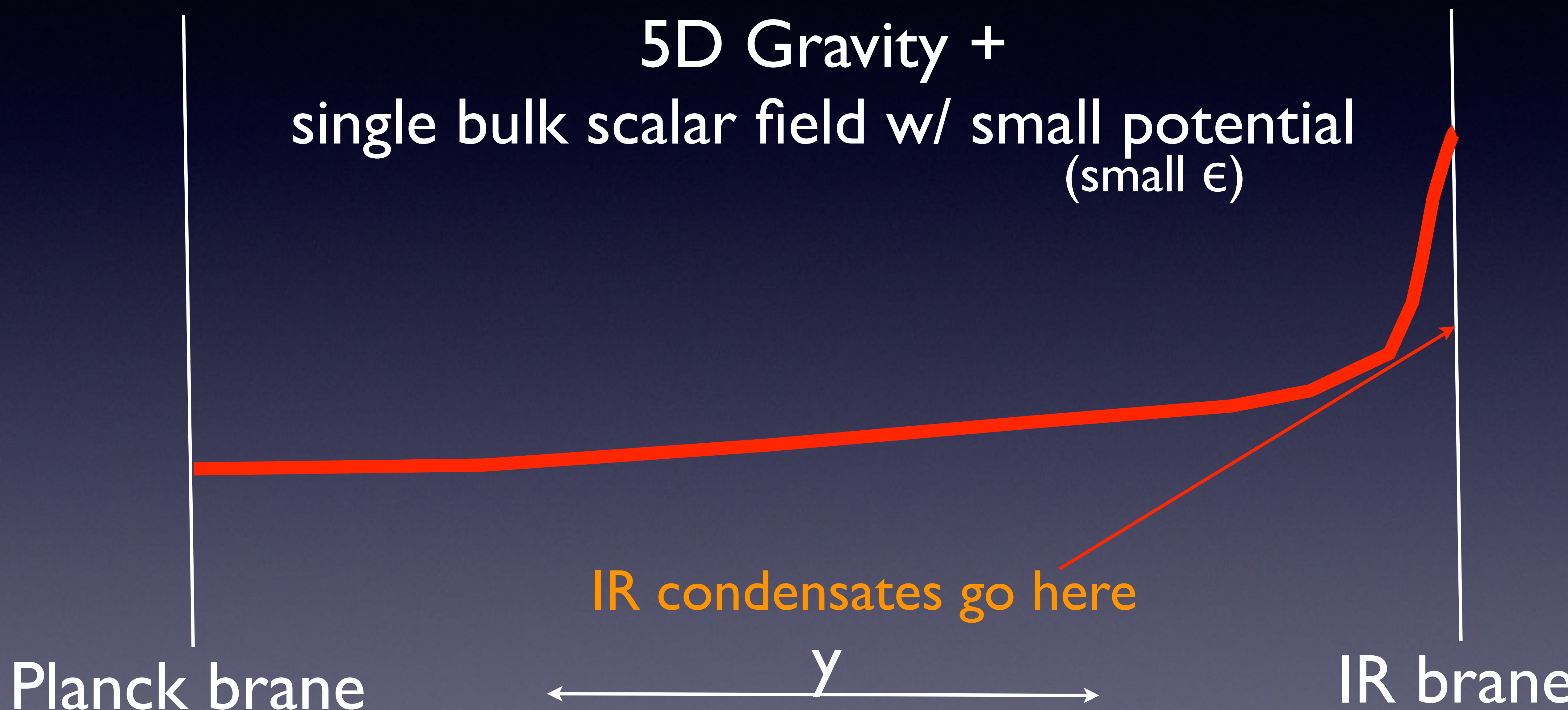


Typical non-SUSY Walking
large quartic & large β
F(λ)
β(λ)
λ
N=4 SUSY
conformal w/ flat direction
β(λ)=0
F(λ)=0
λ
Tuned non-SUSY Walking
small quartic w/ small β
F(λ)
β(λ)
λ
Non-SUSY with light dilaton
slowly scan quartic landscape
F(λ)
β(λ)~ε
λ


Typical non-SUSY Walking
large quartic & large β
F(λ)
β(λ)
λ
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

A Holographic Realization

Holography and light dilatons



system responds by **shifting Planck scale** - CC stays zero

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

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

Exactly 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

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

Pure UV Contribution to CC term

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

Pure dilaton quartic

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

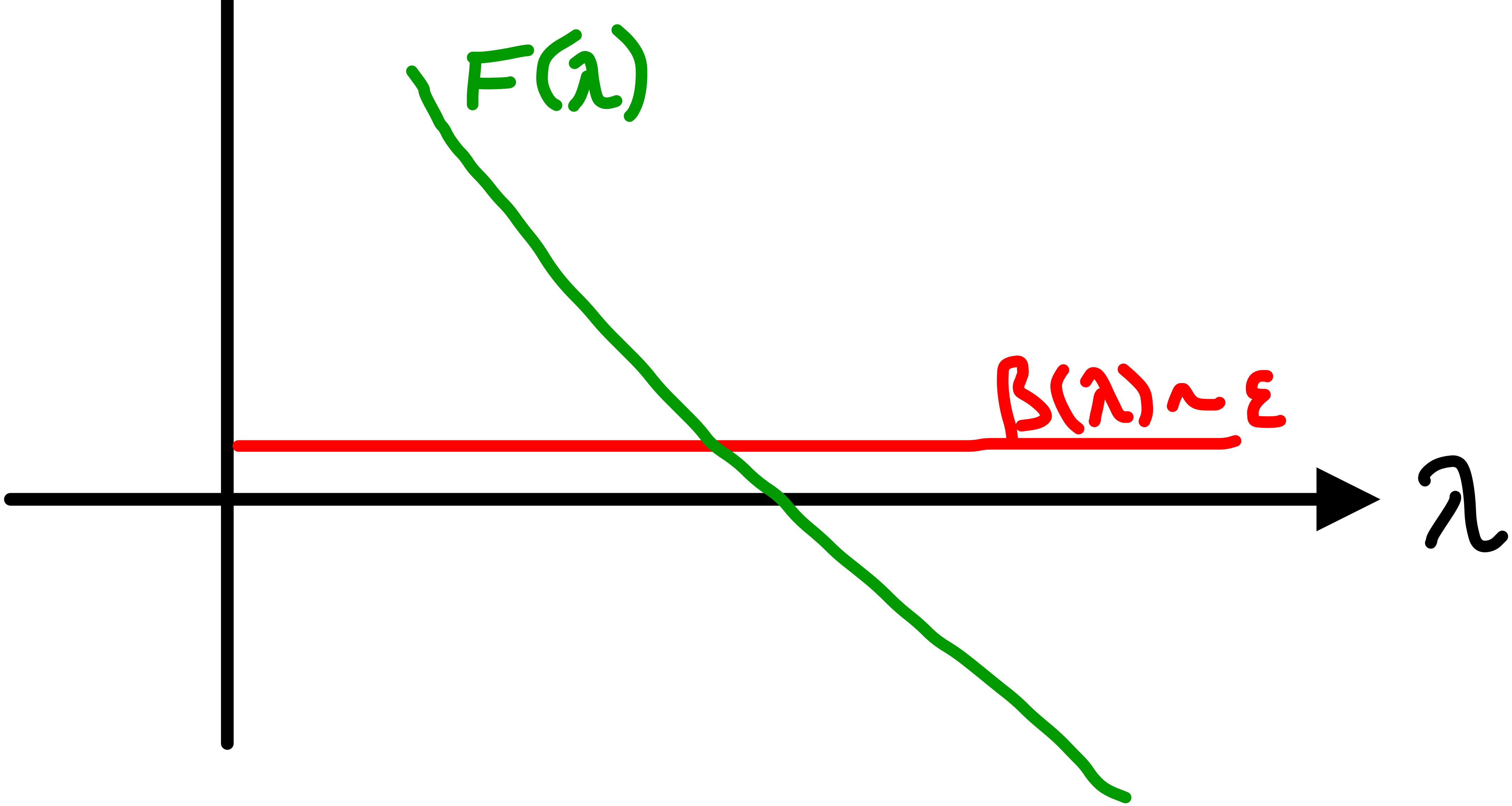
Dilaton quartic is from composite condensates (IR tension) and the condensate of this operator

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

can tune this away by adjusting v_0

Non-SUSY with light dilaton

slowly scan quartic landscape



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):

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

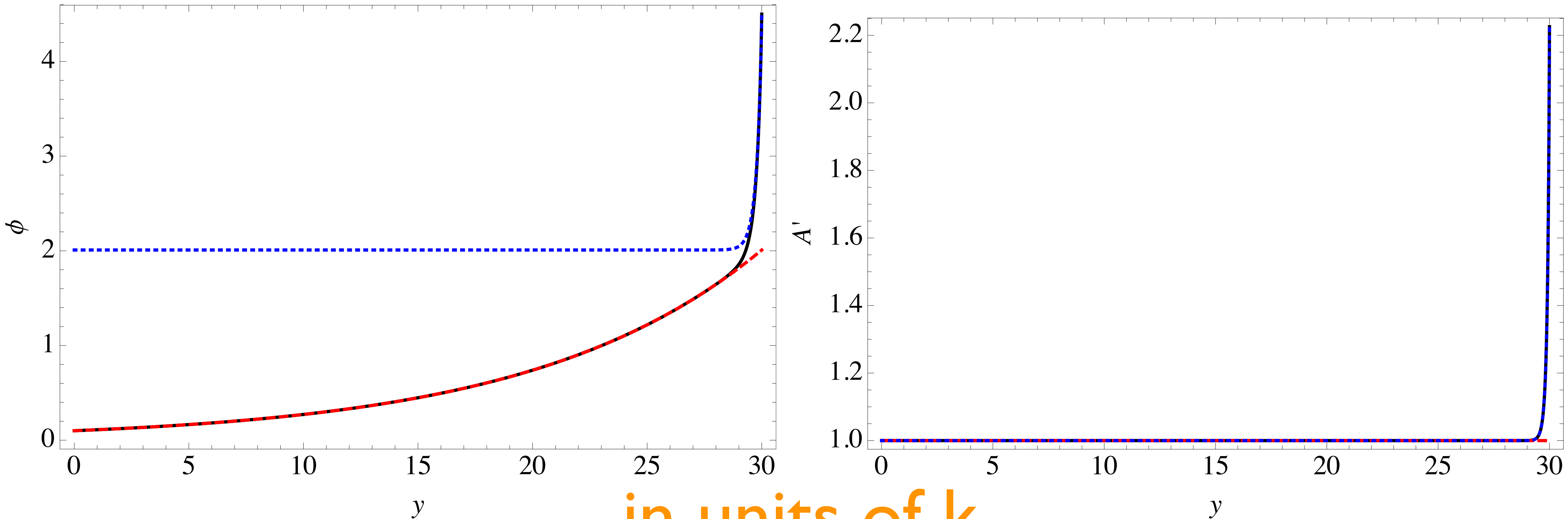
neglecting non-linear terms (small back-reaction):

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

slowly running piece

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

Boundary 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)

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

The Outcome

You get a hierarchy:

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

Condensate balances other contributions naturally
(IR brane tension mistune)

Dilaton comes out light (with suppressed CC):

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

UV value still tuned to be small
- only erase condensate contributions

v/f? - Lessons from Holgraphy

What is f?

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

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

Suppressed by large N (perturbativity of 5D model)

It does suppress mass (once quartic tuning imposed):

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

Large N	Small N
Typical Walking	**Typical Walking**
$m_d^2 \sim \frac{\Lambda^2}{N}$	$m_d^2 \sim \Lambda^2$
$\frac{v}{f} \sim \frac{1}{N}$	$\frac{v}{f} \sim 1?$
Large N	**Small N**
“Scanning”	**“Scanning”**
$m_d^2 \sim \frac{\epsilon}{N} f^2$	$m_d^2 \sim \epsilon f^2$
$\frac{v}{f} \sim \frac{1}{N}$	$\frac{v}{f} \sim 1?$

Conclusions

- If the 126 GeV resonance is a dilaton, it must be uncannily Higgslike
- Tensions: EWP, Flavor, mass tuning, Higgs fits
  - crucial to pin down properties with more data
- Light dilatons:
  - ID'd class of potential theories - "scan" landscape of quartics to achieve SBSI (CPR)
  - non-supersymmetric models with light dilatons seem very special - small β for large range of strong coupling